Adaptive Fault Tolerant Systems: Reflective Design and Validation

Marc-Olivier Killijian

Dependable Computing and Fault Tolerance
Research Group – Toulouse - France

Motivations

- Provide a framework for FT developers
  - Open
  - Flexible
  - Dependability of both embedded and large scale distributed systems
  - Adaptation of fault tolerance strategies to environmental conditions and evolutions
- Validate this framework
  - Test
  - Fault-injection

History

- Reflection for Dependability
  1. Friends v1 - off-the-shelf MOP
     - Limits: static MO, inheritance, etc.
  2. Friends v2 - ad-hoc MOP / CT reflection
  3. Multi-Level Reflection
- Validation of the platform
  - Test of MOP based architectures
  - Fault-injection and failure modes analysis

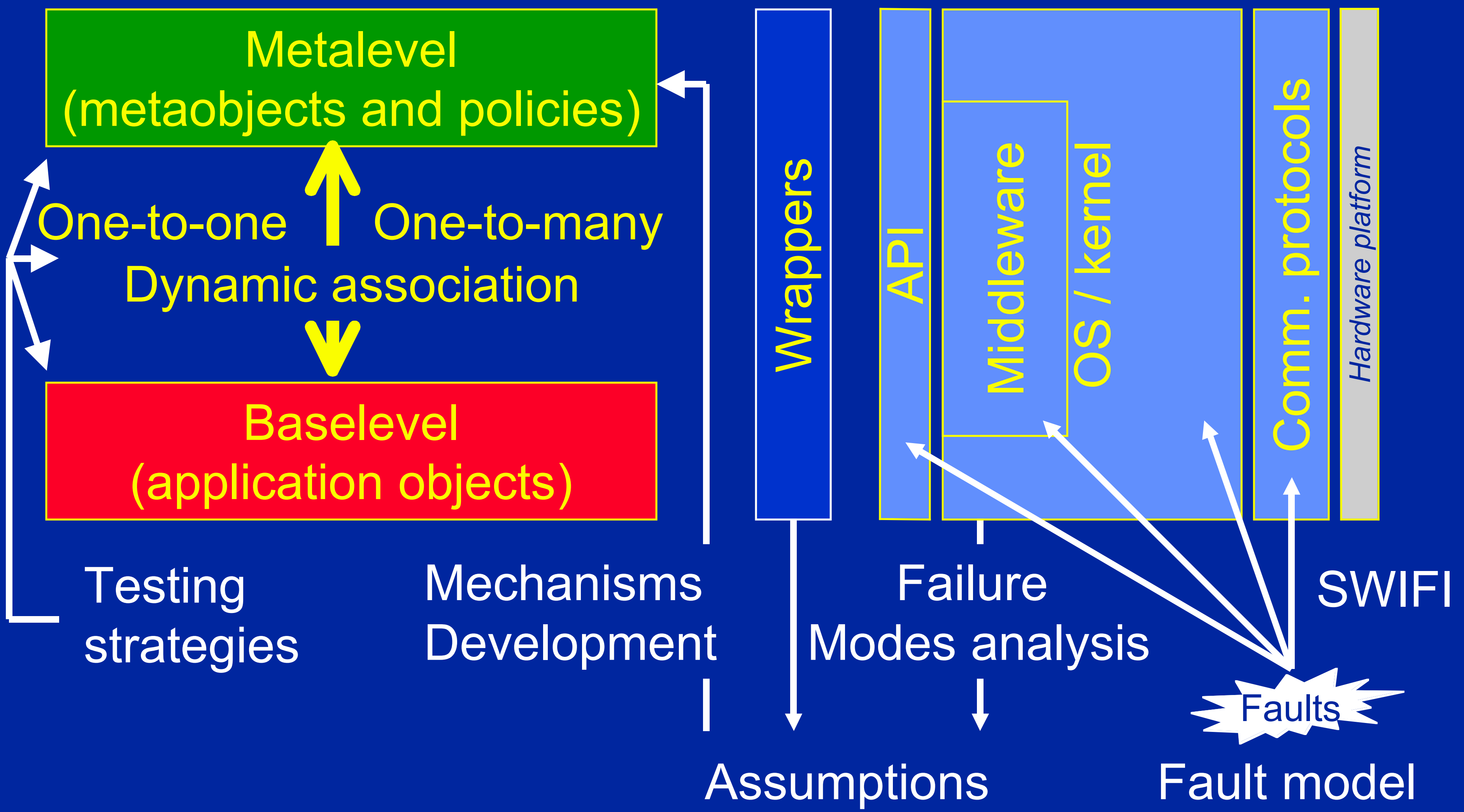
Outline

- Reflection for Dependability
  1. Friends v1 - off-the-shelf MOP
     - Limits: static MO, inheritance, etc.
  2. Friends v2 - ad-hoc MOP / CT reflection
  3. Multi-Level Reflection
- Validation of the platform
  - Test of MOP based architectures
  - Fault-injection and failure modes analysis

Why Reflection?

- Separation of concerns
  - Non functional requirements
  - Applications
- Adaptation
  - Selection of mechanisms w.r.t. needs
  - Changing strategies dynamically
- Portability/Reuse
  - Reflective platform (relates to adaptation)
  - Meta-level software (mechanisms)

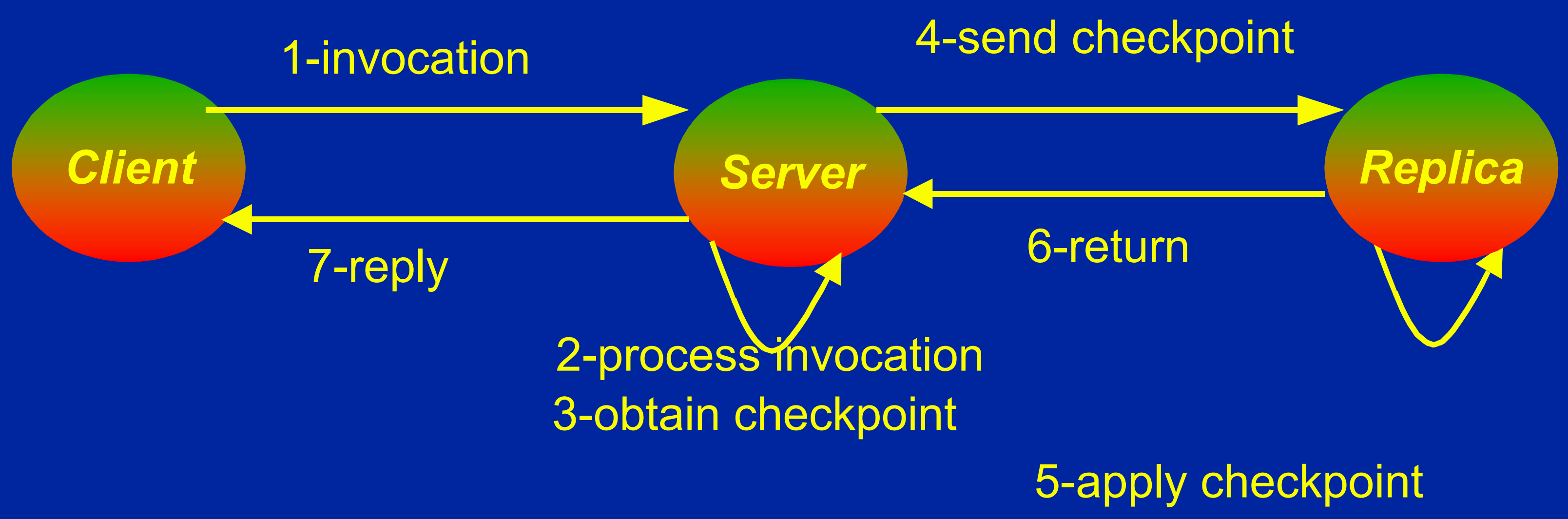
Overall Philosophy



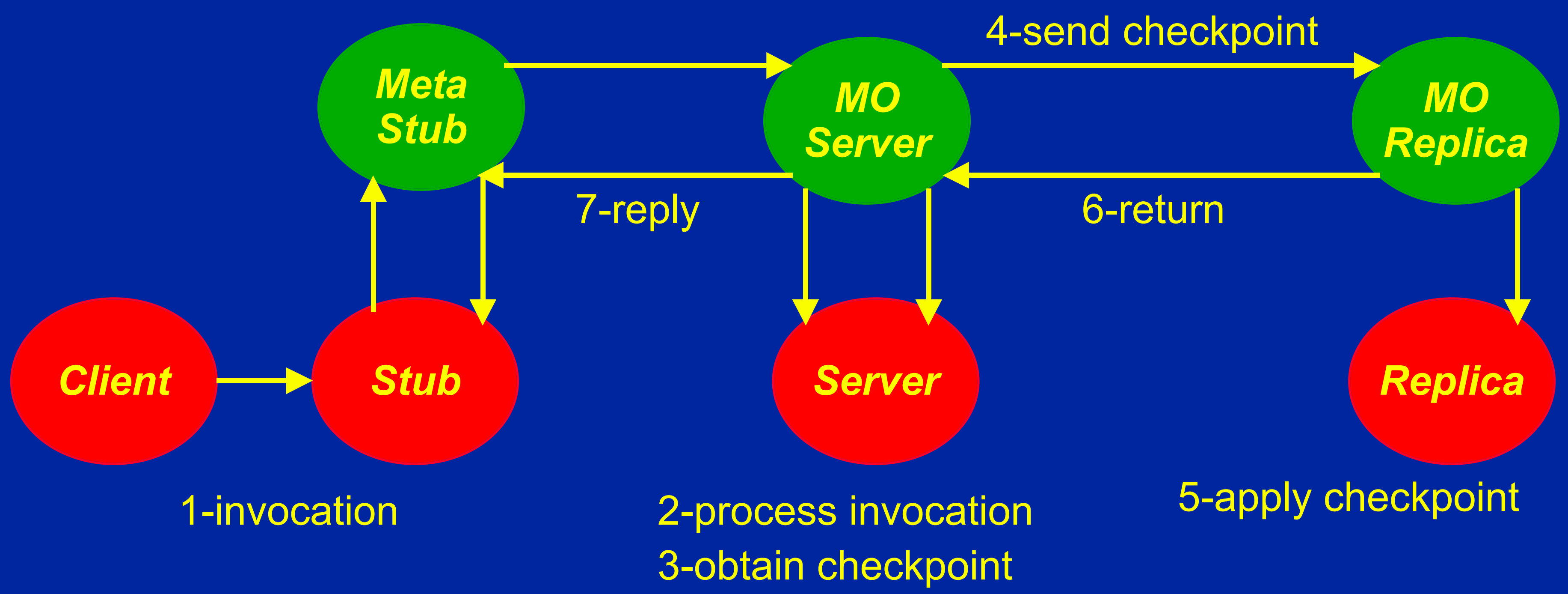
Friends v2 : A MOP *on* Corba

- MOP design
  - Identify information to be reified and controlled
- MOP implementation
  - Compile-time reflection
  - Using CORBA facilities
- Prototype for illustration
  - Architecture and basic services
  - Fault tolerance mechanisms
  - Preliminary performance analysis

Necessary information :
integrated mechanism example



Necessary information :
metaobjects example



Observation
- invocations
- state capture

Control
- method calls
- state restoration

Which protocol?

Meta Object

Observation

- Interception
  - Creation
  - Destruction
  - Invocations (In and out)
- State capture
- Links control
  - Object/metaobject
  - Clients/servers

Control

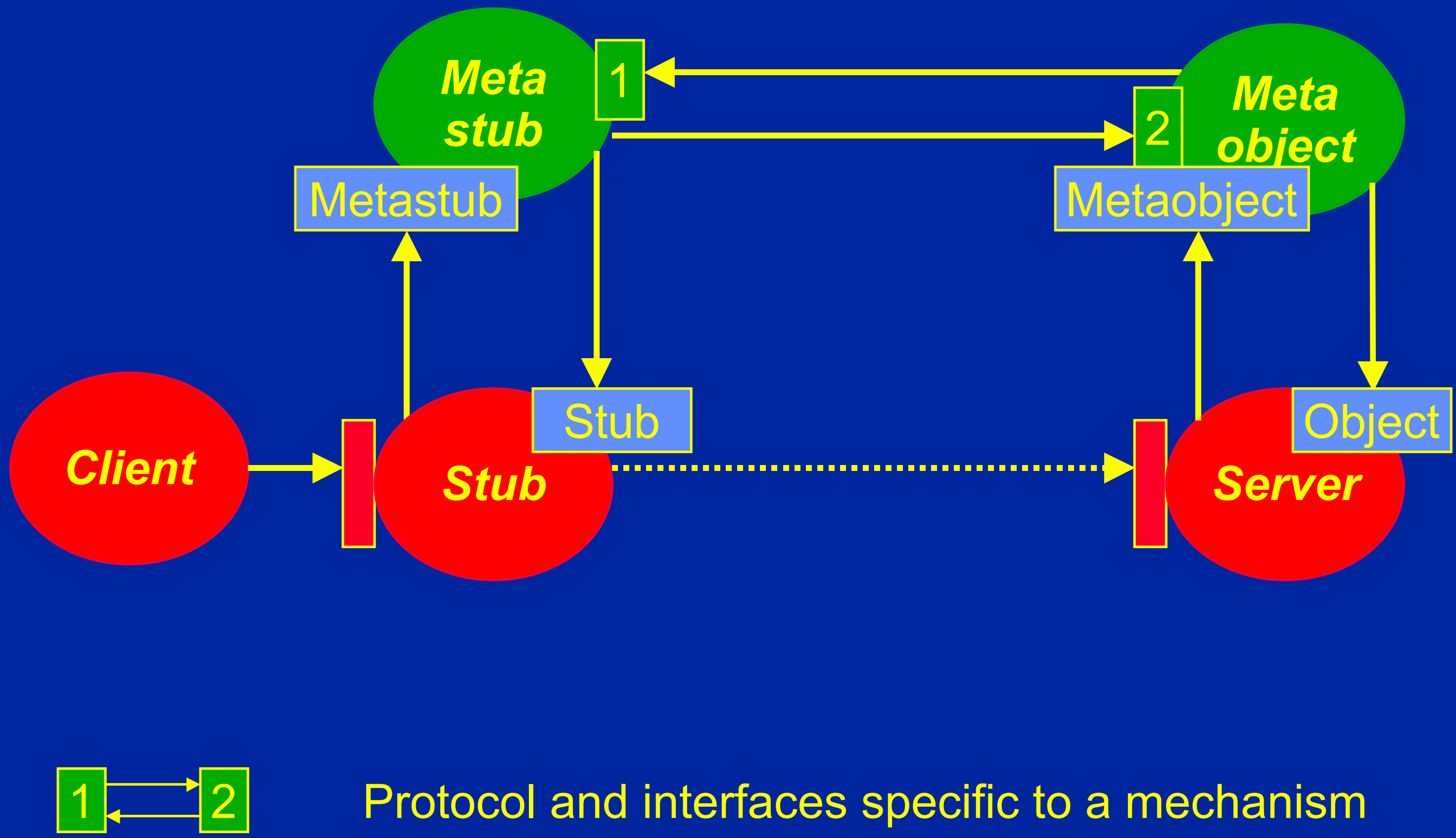
- Activation
  - Creation
  - Destruction
  - Invocations
- State restoration
- Links control
  - Object/metaobject
  - Clients/servers

Reification

Intercession

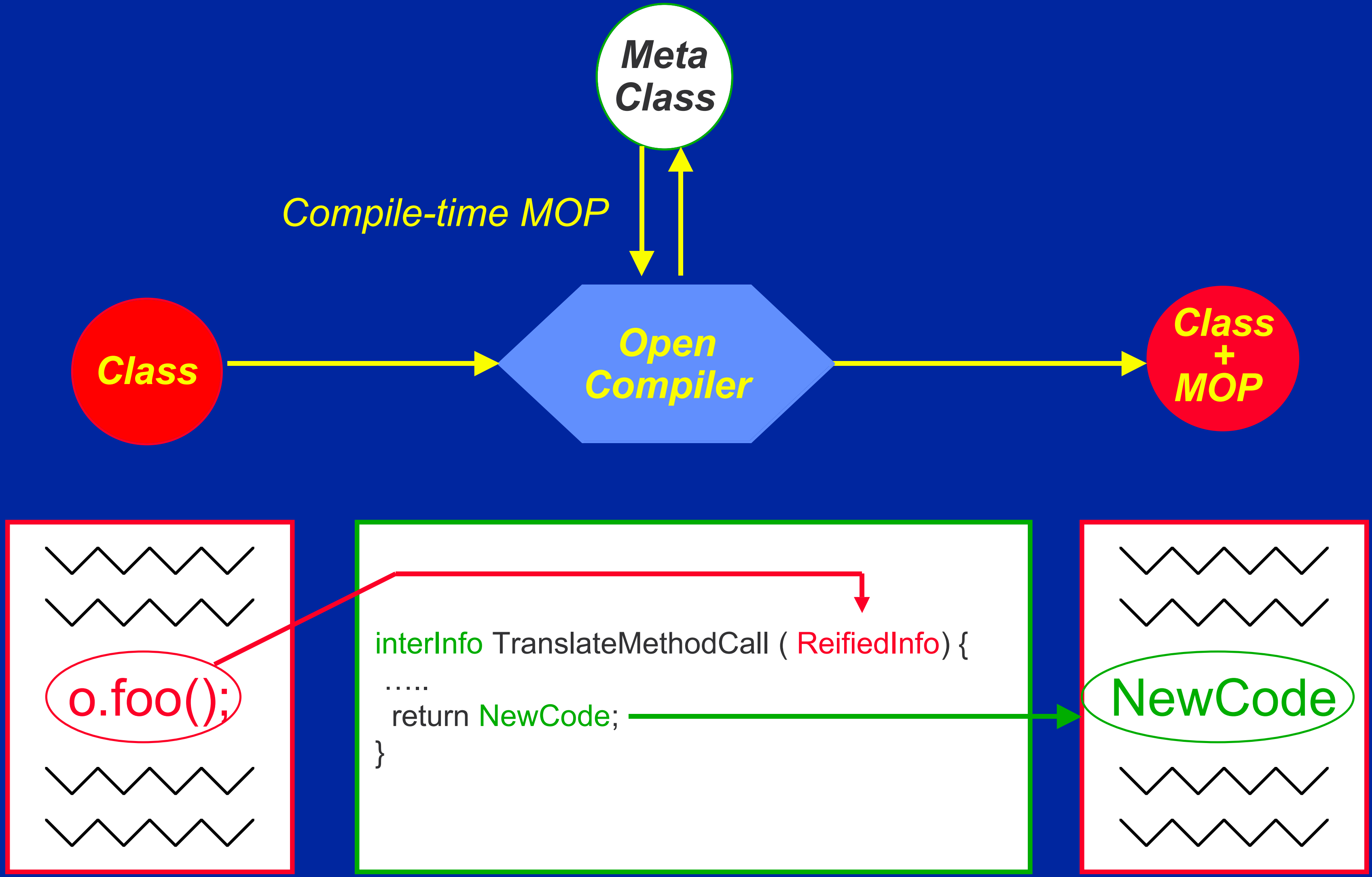
Object

Protocol definition

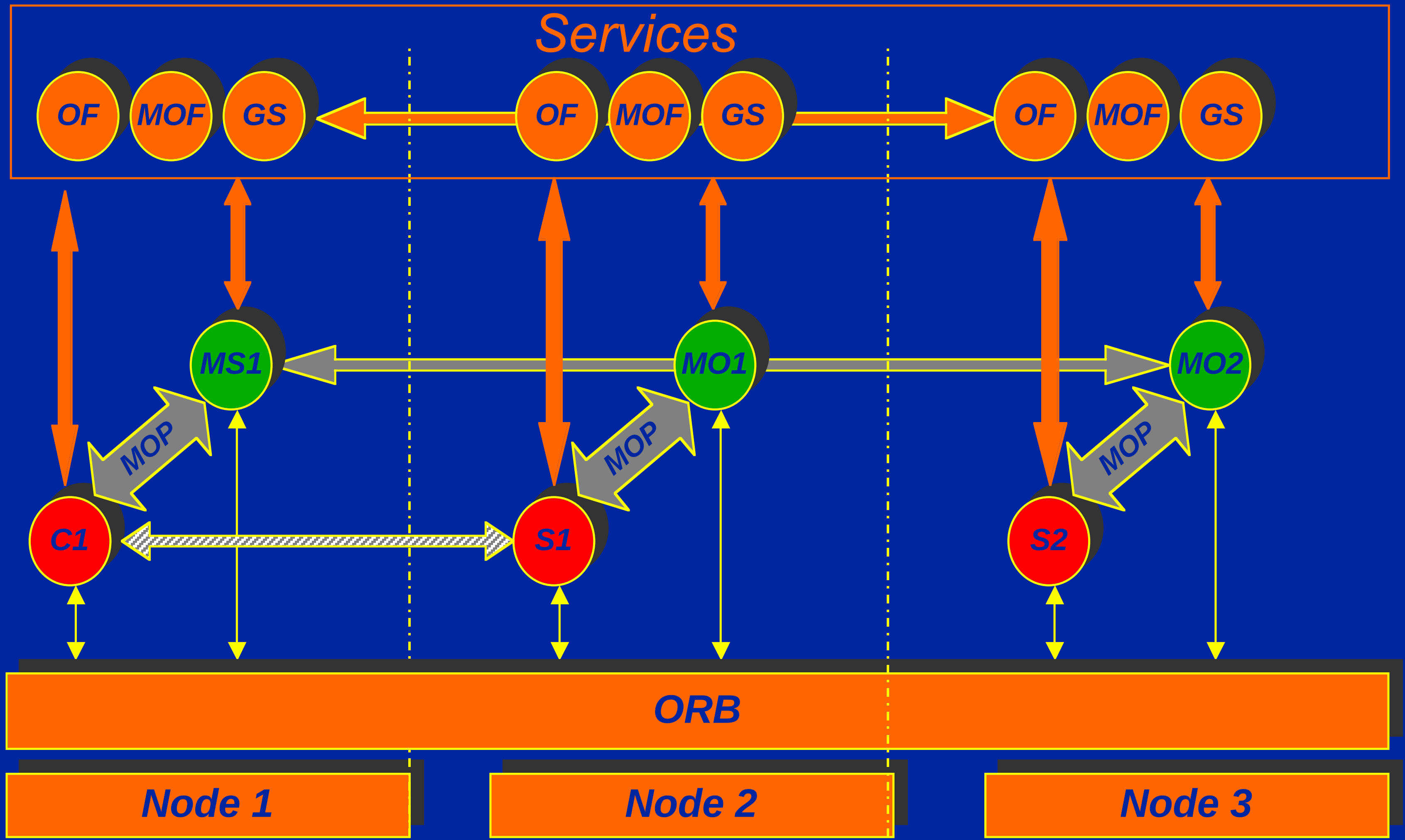


Protocol and interfaces specific to a mechanism

Using Open Compiler



Architecture

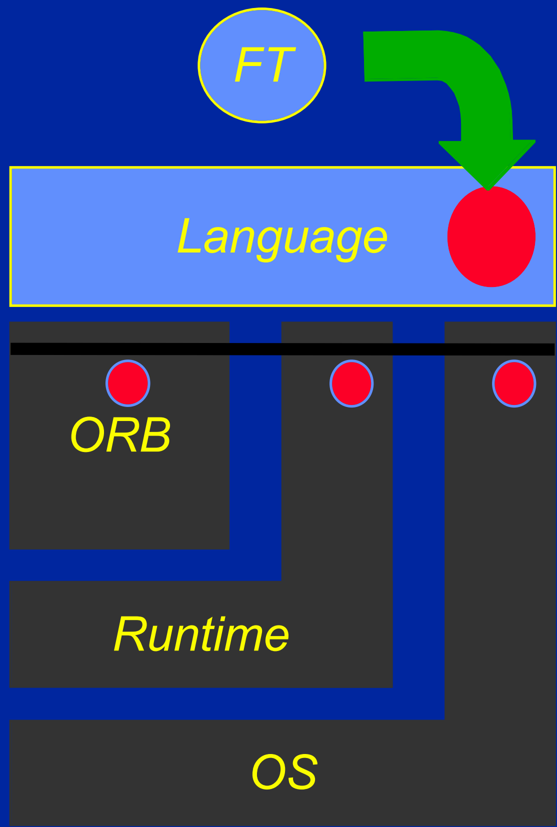


Results

- A method for designing a MOP
  - Analysis of mechanisms' needs ⇨ MOP features
- Metaobject protocol for fault tolerance
  - Transparent and dynamic association
  - Automatic handling of internal state (full/partial)
    - Portable serialization [OOPSLA'02]
  - Smart stubs delegate adaptation to meta-stubs
  - CORBA compliant (black-box)
  - Some programming conventions

Lessons Learnt

- Generic MOP
  - No assumption on low layers
  - Based on CORBA features
- ➡ With a platform «black-box»
  - Language dependent
  - Limitations
    - external state
    - determinism
- "Open" platform (ORB , OS and language)
  - ➡ Additions of new features to the MOP
  - ➡ Optimization of reflective mechanisms
  - ➡ Language level reflection still necessary



Limits to be addressed

- **Behavioral issues**
  - Concurrency models: Middleware level
  - Threading and synchronization: Middleware/OS level
  - Communication in progress: Middleware/OS level
- **Structural/State issue**
  - Site-independent internal state : Open Languages
  - Site-dependent internal state:
    - Problems: Identification, handling
    - Available means: Syscall interception, Journals and replay monitors
  - External state
    - Middleware level
    - OS level

☞ **Concept of multilevel reflection**

Which protocol?

Meta Object

Observation

- Interception
  - Creation
  - Destruction
  - Invocations (In and out)
  - Threading
  - Synchronization
  - Communication
- State capture
  - Internal objects
  - Site-dependent objects
  - External objects (MW+OS)
- Links control
  - Object/metaobject
  - Clients/servers

Control

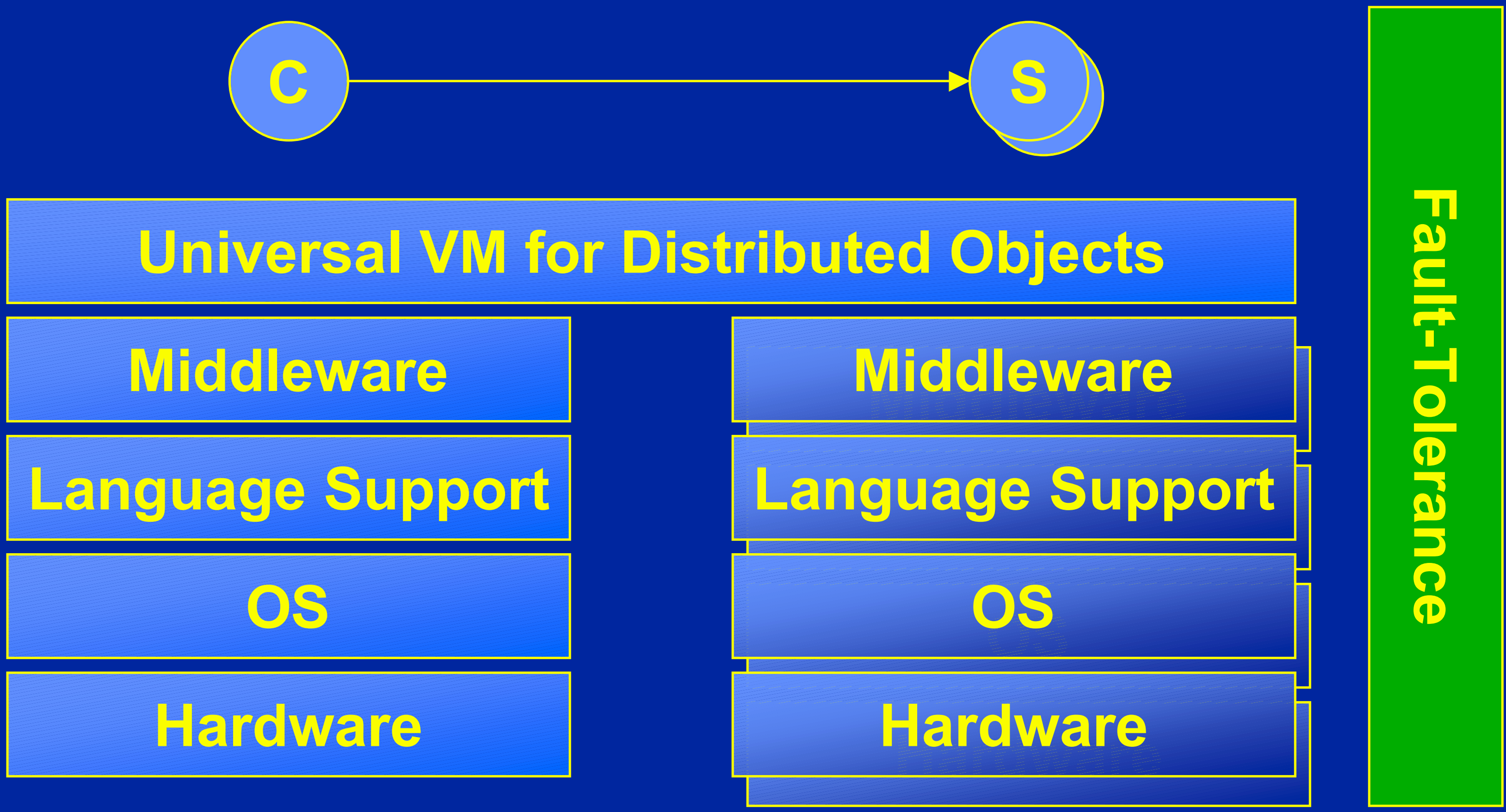
- Activation/control
  - Creation
  - Destruction
  - Invocations
  - Threading
  - Synchronization
  - Communication
- State restoration
  - Internal objects
  - Site-dependent objects
  - External objects (MW+OS)
- Links control
  - Object/metaobject
  - Clients/servers

Object

Reification

Intercession

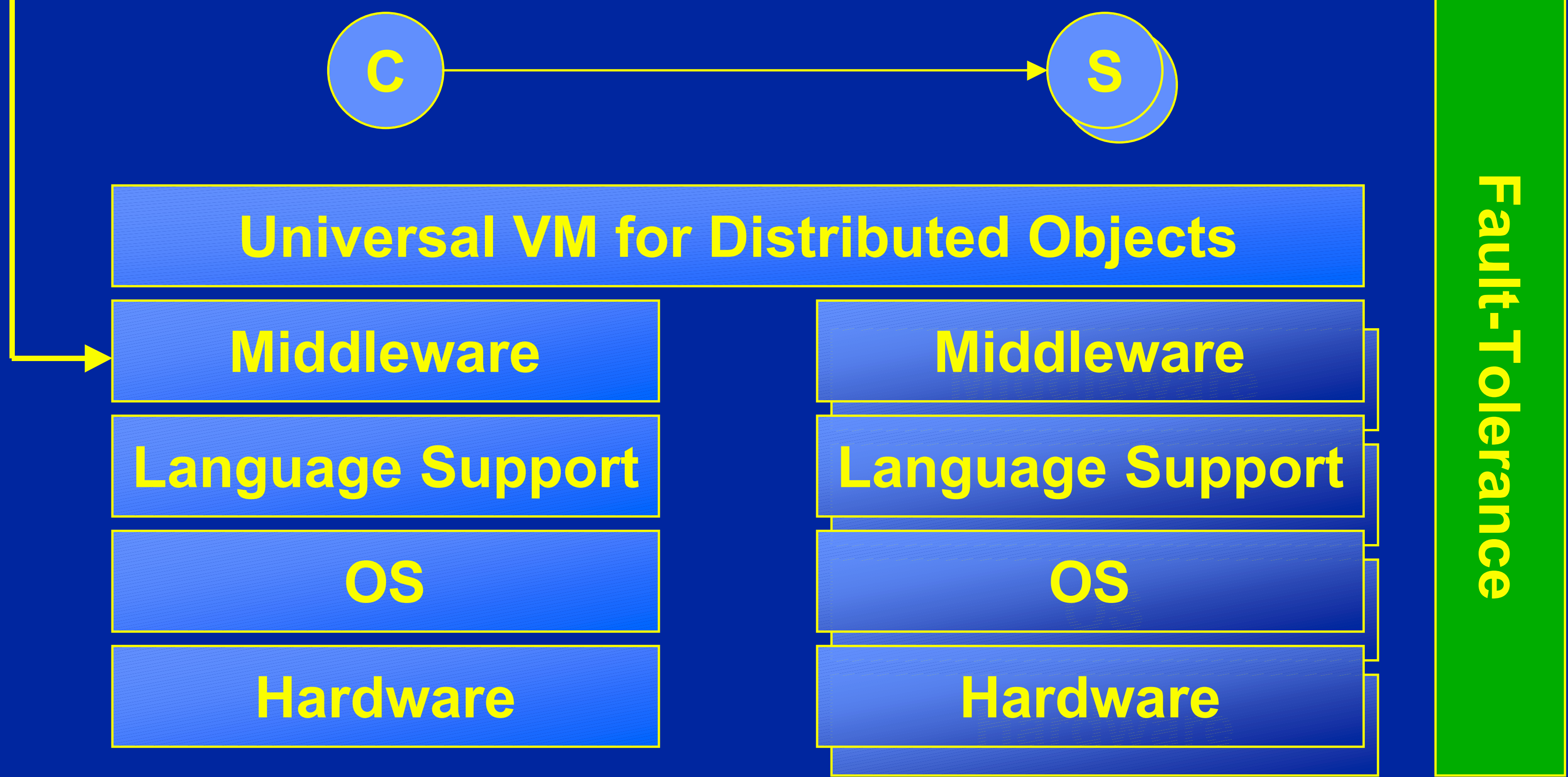
Which Platform ?



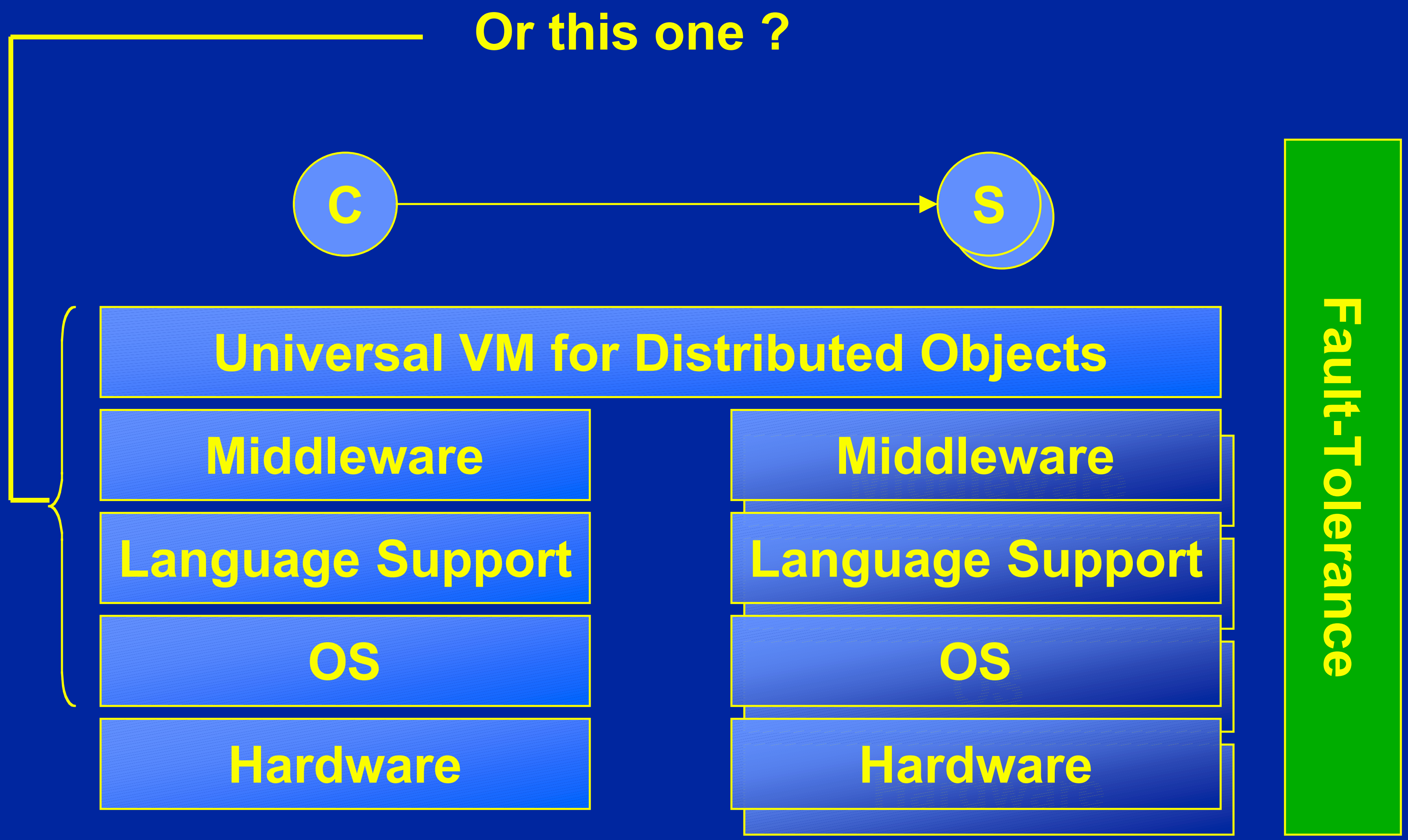
Which Platform ?

This one ?

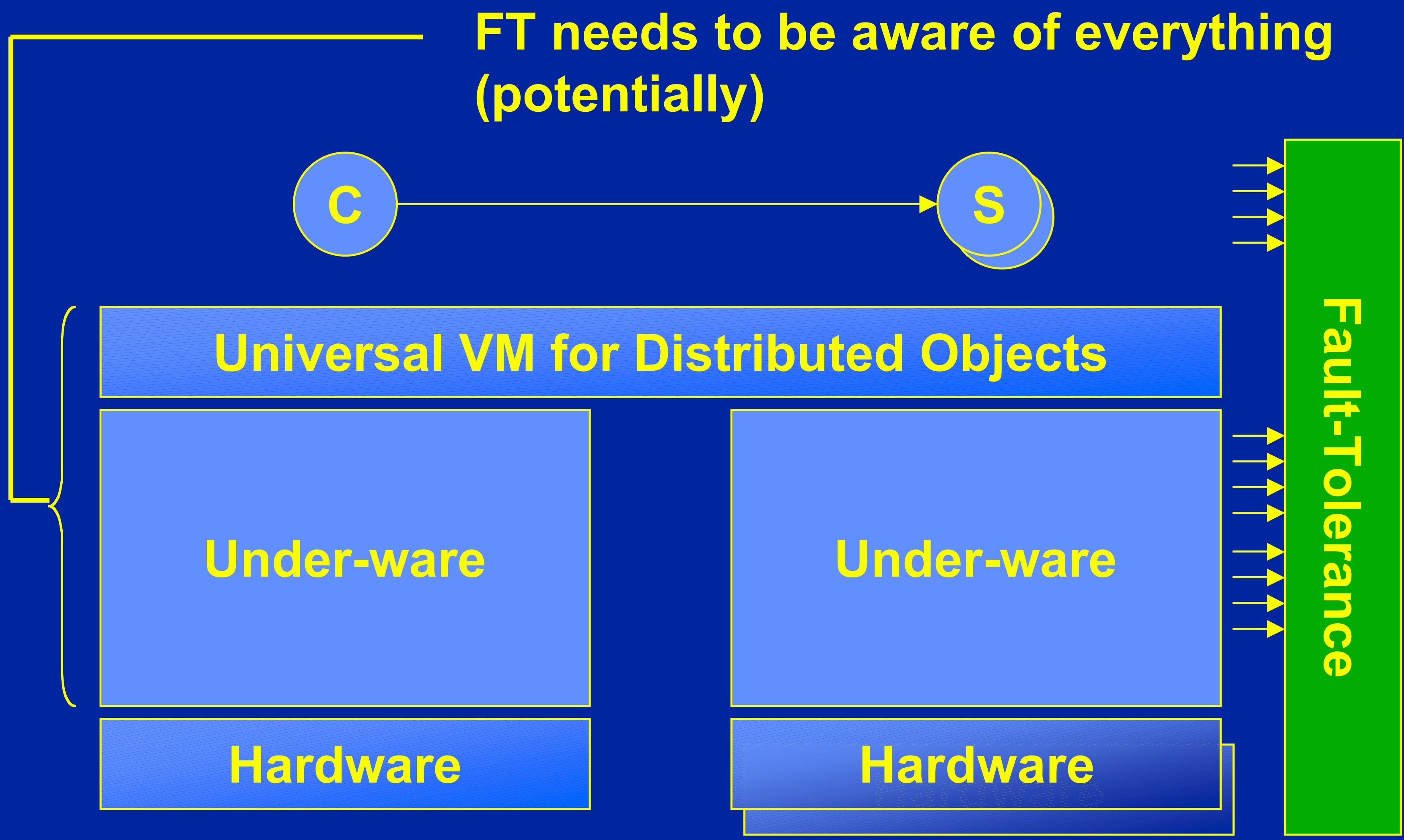
But difference between OS/MW … LS/MW?



Which Platform ?

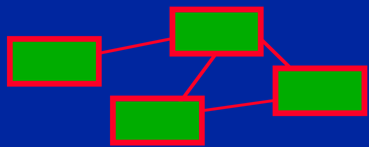


Which Middleware ?

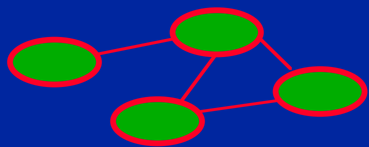


Which Middleware ?

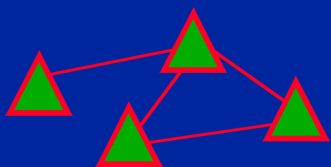
FT needs to be aware of everything (potentially) but how ?



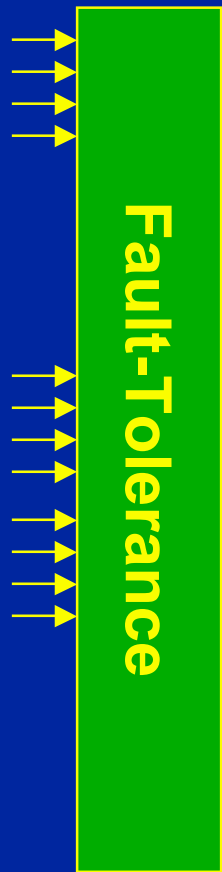
Reflective languages …



Reflective middleware …

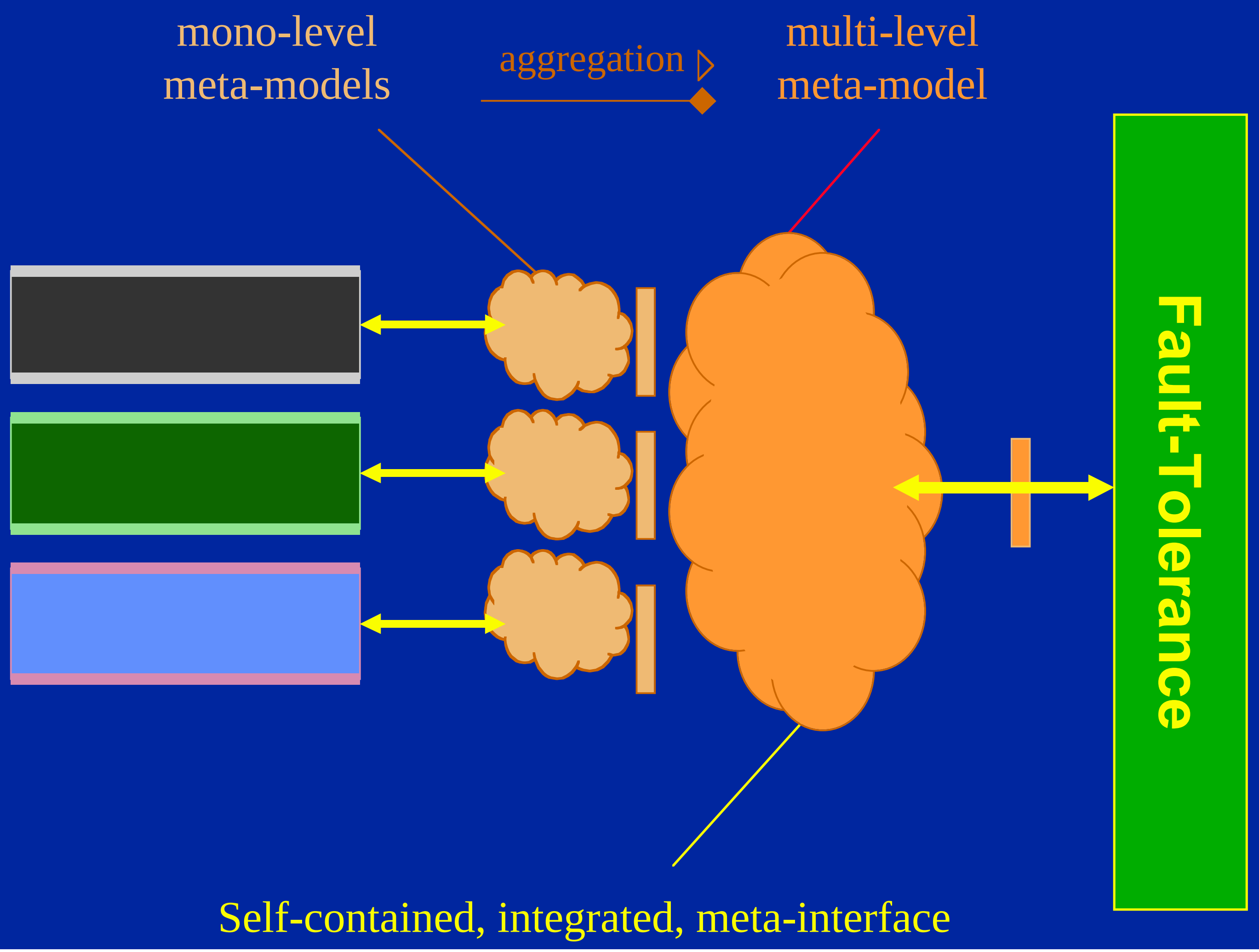


Reflective OS …



A lot of different concepts to manipulate

Multi-level Reflection

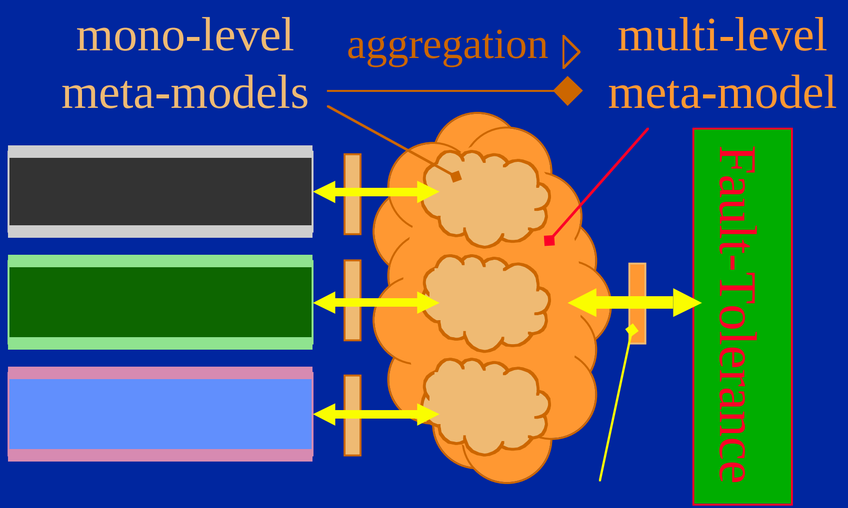


Multilevel Reflection

- Apply reflection to a complete platform
  - Application, Middleware, Operating System
- Consistent view of the internal entities/concepts
  - Transactions, stable storage, assumptions
  - Memory, data, code
  - Objects, methods, invocations, servers, proxies
  - Threads, pipes, files
  - Context switches, interrupts
- Define metainterfaces and navigation tools
  - Which metainterface (one per level? Generic?)
  - Consistency → metamodel

Different Aspects

- Intra-level information
  - Necessary for FT
  - Efficiency (lowest possible? Same concepts at ≠ levels?)
- Inter-level information
  - ML management (inter-level coupling)
  - Adaptation
  - Concepts/levels navigation



Self-contained, integrated, meta-interface

Requirements of FT-Mechanisms?

- Non determinism of scheduling/execution time

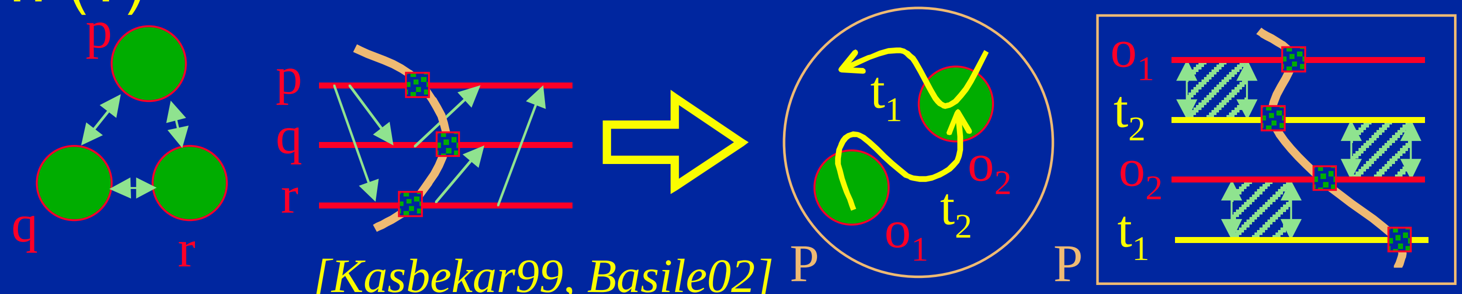
⇨Interlevel interactions mostly asynchronous

Trend: Leverage know-how on FT asynch. distributed sys.

⇨ Causality tracking/ monitoring of non-determinism is needed.

⇨ State capture/ recovery at appropriate granularity is needed.

⇨ … (?)



[Kasbekar99, Basile02]

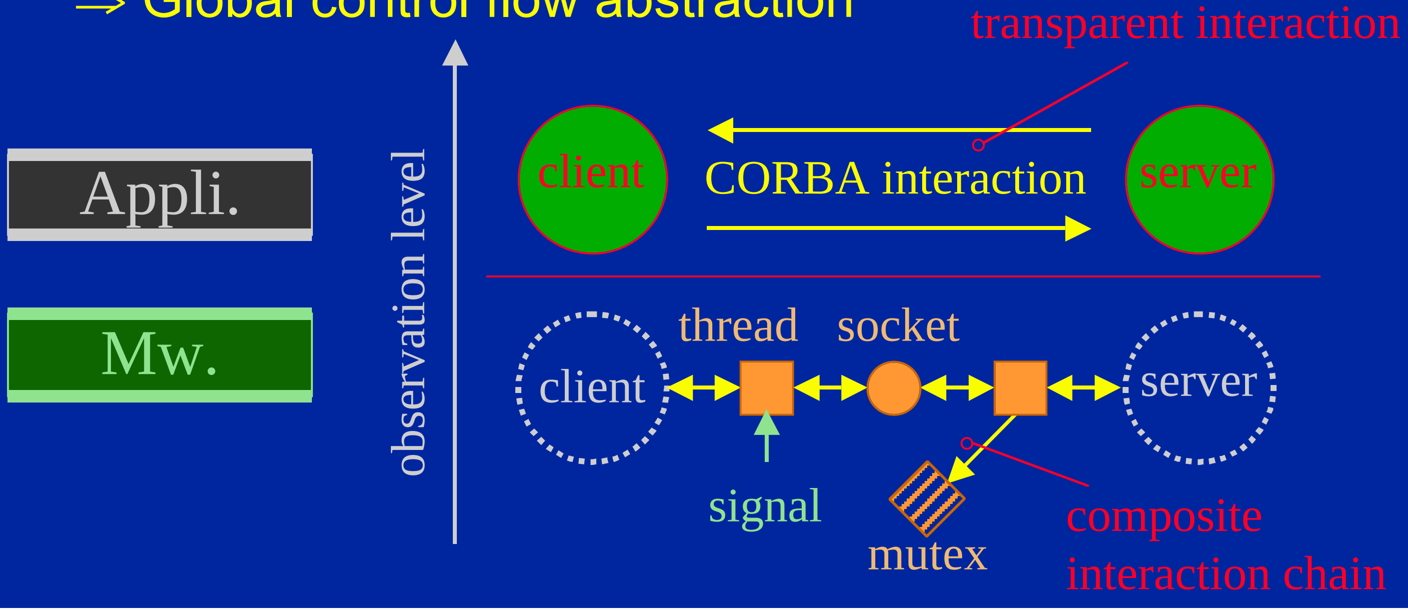
Inter-Level Coupling (I)

- A Level = 1..n COTS = A set of interfaces =
  - Concepts
  - Primitives / base entities (keywords, syscalls, data types, …)
  - Rules on how to use them
- (concepts, base entities, rules) = programming model
  - Very broad notion (includes programming languages)
  - Self contained
- Base entities “a-tomic” within that programming model
  - Can’t be split in smaller entities within the programming model.
  - Implemented by more elementary entities within the component.
  - Implementation is internal $\Rightarrow$ hidden to component user.

Inter-Level Coupling (II)

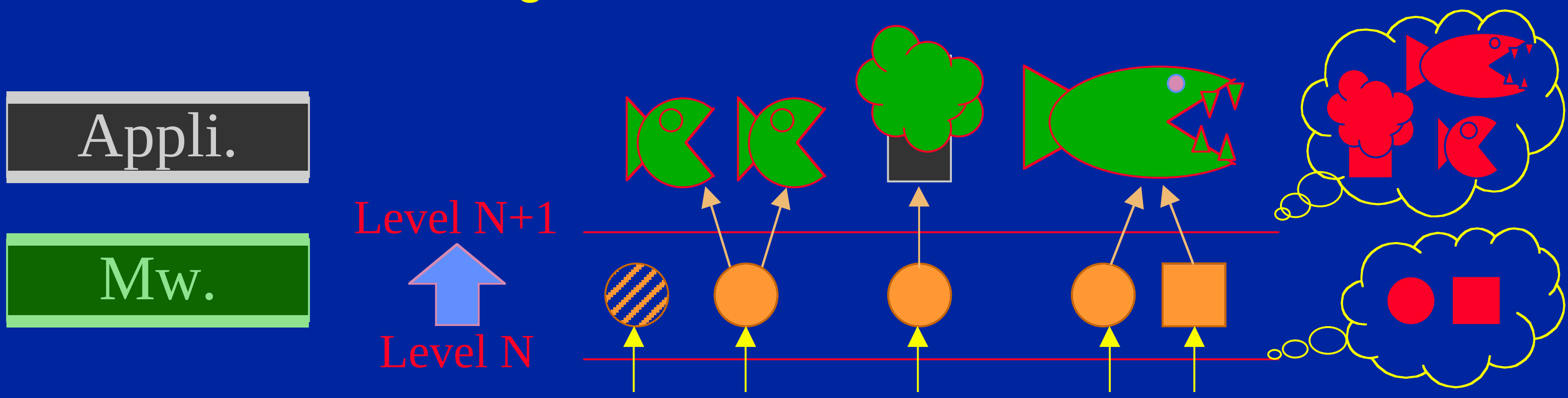
- CORBA : Location transparent object method invocation
- A CORBA request = aggregation
  - Communication “medium” (pipes, sockets, …)
  - Local control flow (POSIX threads, Java threads, LWP, …)

  ⇒ Global control flow abstraction

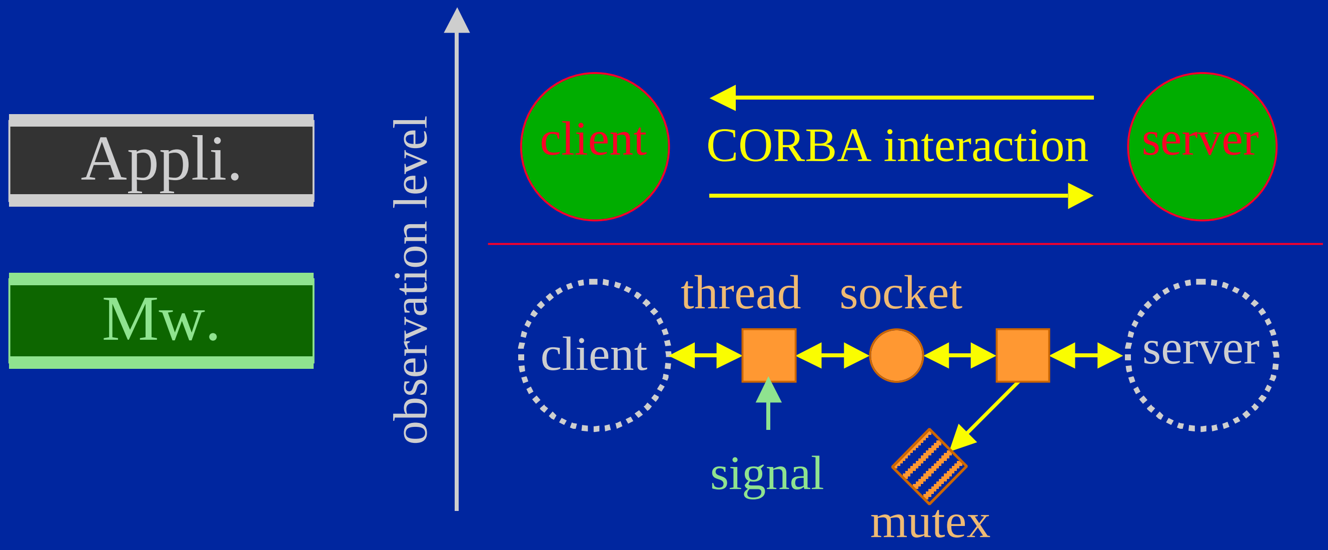


Inter-Level Coupling(III)

- Within a COTS :
  - Coupling between emerging entities of next upper level and implementation entities of lower levels
- Structural coupling relationships ("abstraction mappings")
  - translation / aggregation / multiplexing / hiding
- Dynamic coupling relationships ("interactions")
  - creation / binding / destruction / observation / modification

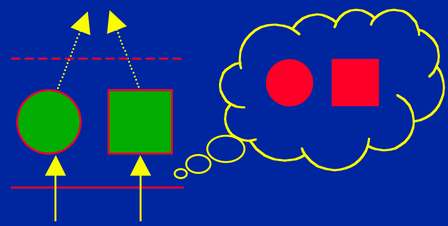


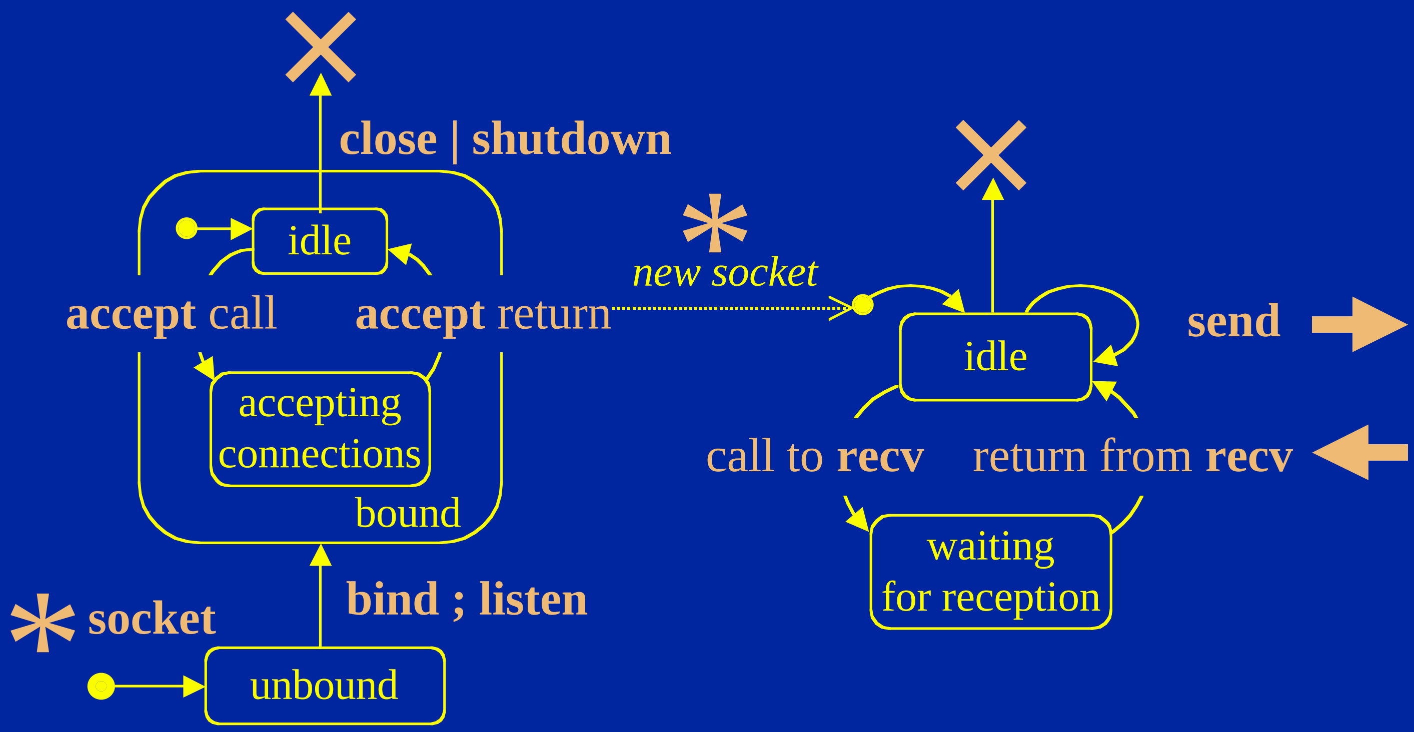
Extracting Coupling in CORBA (I)



Extracting Coupling in CORBA (II)

- Behavioral model of connection oriented Berkeley sockets as seen by the middleware programmer





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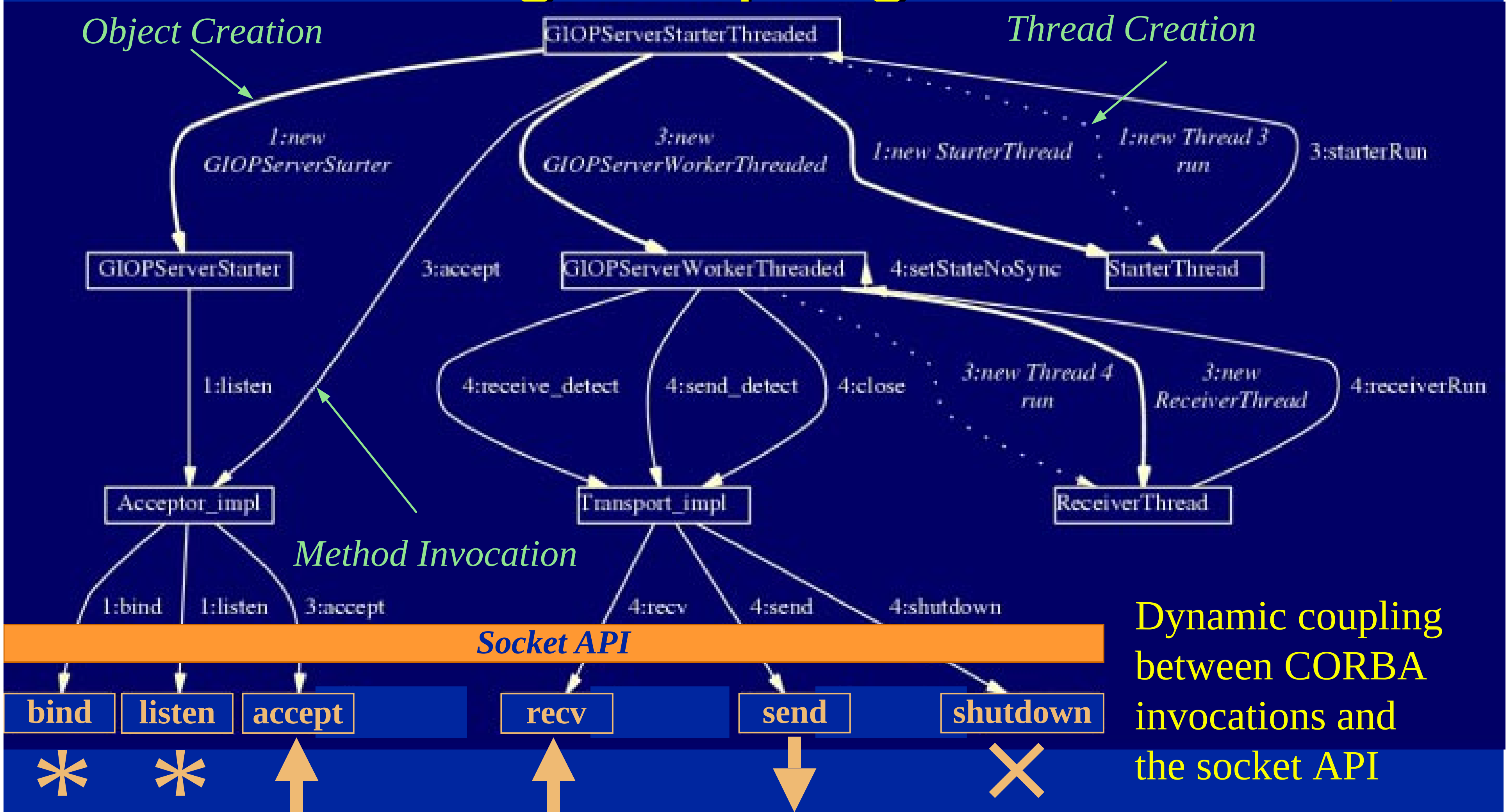
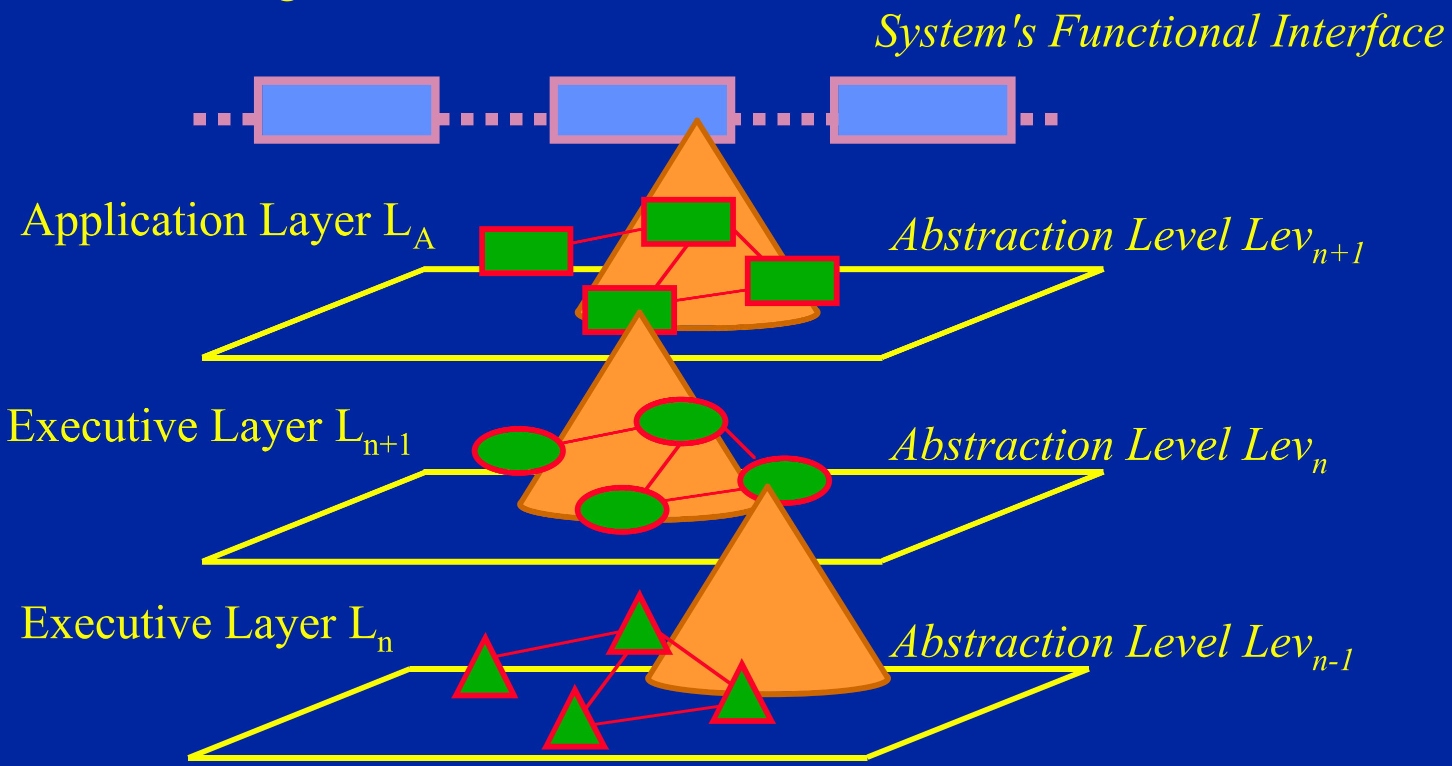


Dynamic coupling between CORBA invocations and the socket API

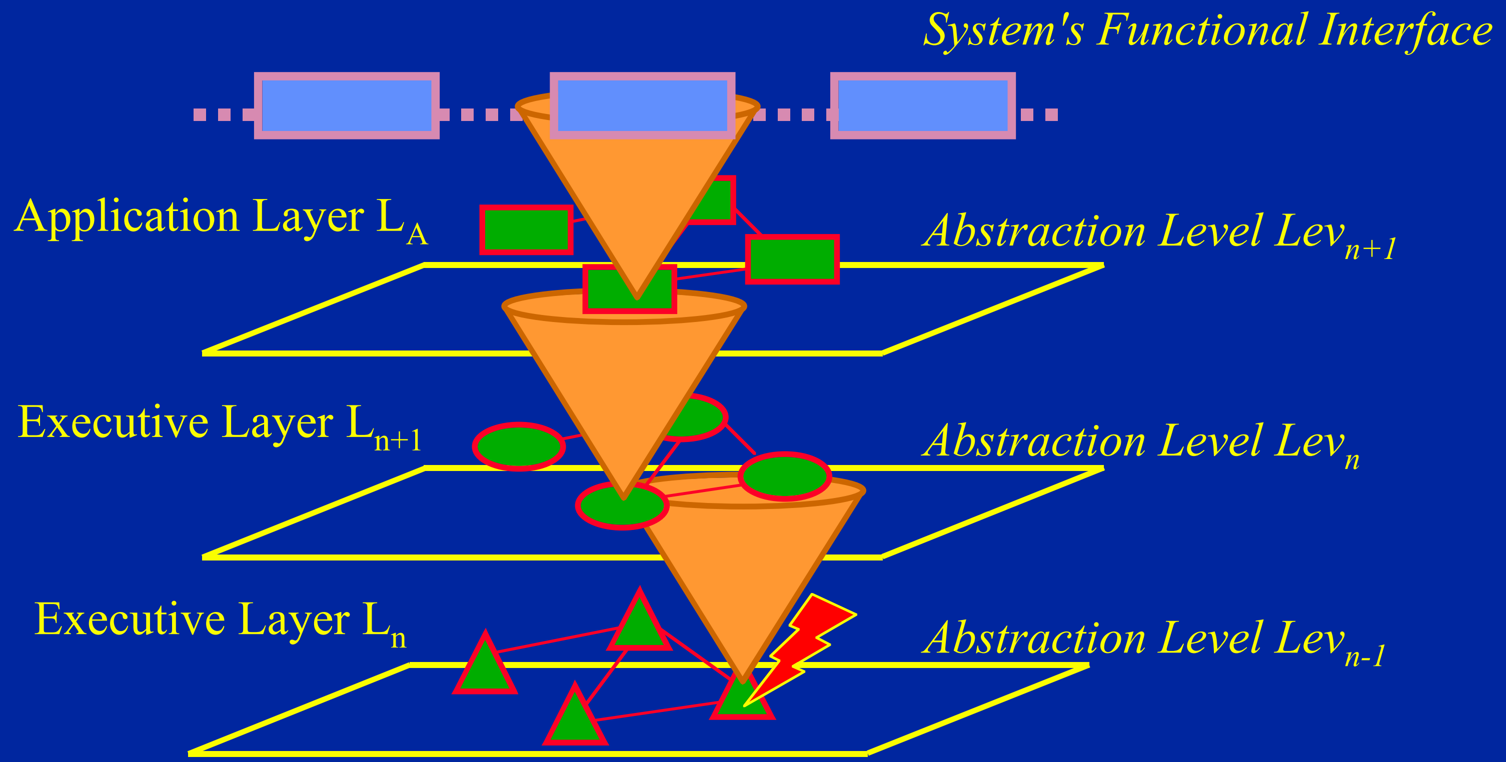
FT + Inter-Level Coupling (I)

- Top-down observation & control
  - State capture
  - Monitoring of non-determinism



FT + Inter-Level Coupling (II)

- Bottom-up observation & control
  - Fault propagation analysis / confinement
  - Rollback propagation / state recovery



Meta-filters

- All the information is not always necessary
  - Specific mechanisms need specific info
  - Mechanisms can change over time
- Need a way to dynamically filter
  - Efficiency
    - Don’t reify unnecessary things
    - Have hooks ready but passified + subscriptions
- Meta-filters implementation
  - Simple boolean matrices
  - Code-injection techniques

Current & Future Work on MLR

- Still some work on ORB/OS analysis
- Implementation *a la carte* : several « flavours »
  - Radical style ➔ full metamodel
    from scratch or based on modified open-source components
  - Middle-Way
    based on available reflective components + wrappers
  - EZ way
    wrapped COTS ➔ limited metamodel
- Evaluate the benefits on mechanisms
  - Efficiency /ad-hoc /language level reflection
  - Evolution of non-funtionnal requirements/asumptions
  - Environmental evolution
- **Validation**
  - Rigourous testing stategies for reflective/adaptive systems
  - Characterization by various ad-hoc fault injection techniques

Adaptive Fault Tolerant Systems
Part II- Testing Reflective Systems

Reflection'00 - DSN'01- IEEE ToC 03

Ruiz, Fabre, Thevenod, Killijian

Dependable Computing and Fault Tolerance
Research Group – Toulouse - France

Motivations for testing MOPs

- In reflective architectures
  - the MOP is the corner stone
  - FT completely rely on the reflective mechanisms
- Very little work has been done
  - Few on formal verification
  - None on testing
- Validation of the FT architectures
  - Test of the underlying platform
  - Fault-injection

Testing Reflective Systems

1. Test order definition (reification, intercession, introspection)
2. Test objectives for each testing level
3. Conformance checks for each testing level
4. Test environments

Testing MOPs

TL0. Testing preceding the MOP activation

TL1. Reification mechanisms

TL2. Behavioral intercession mechanisms

TL3. Introspection mechanisms

TL4. Structural intercession mechanisms

Incremental Test Order

TL0. ***implementation dependent***

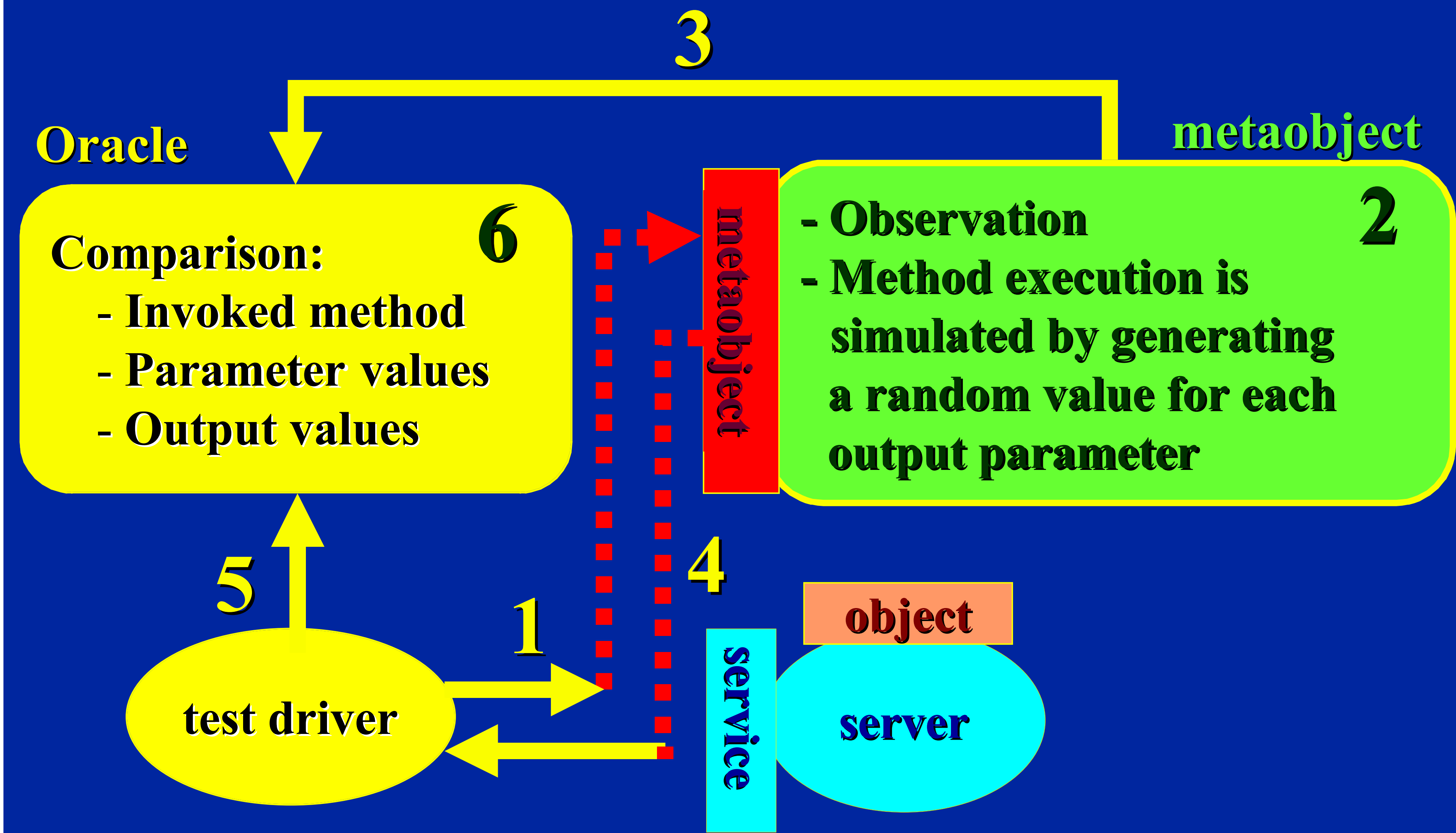
TL1. Reification mechanisms

TL2. Behavioral intercession mechanisms

TL3. Introspection mechanisms

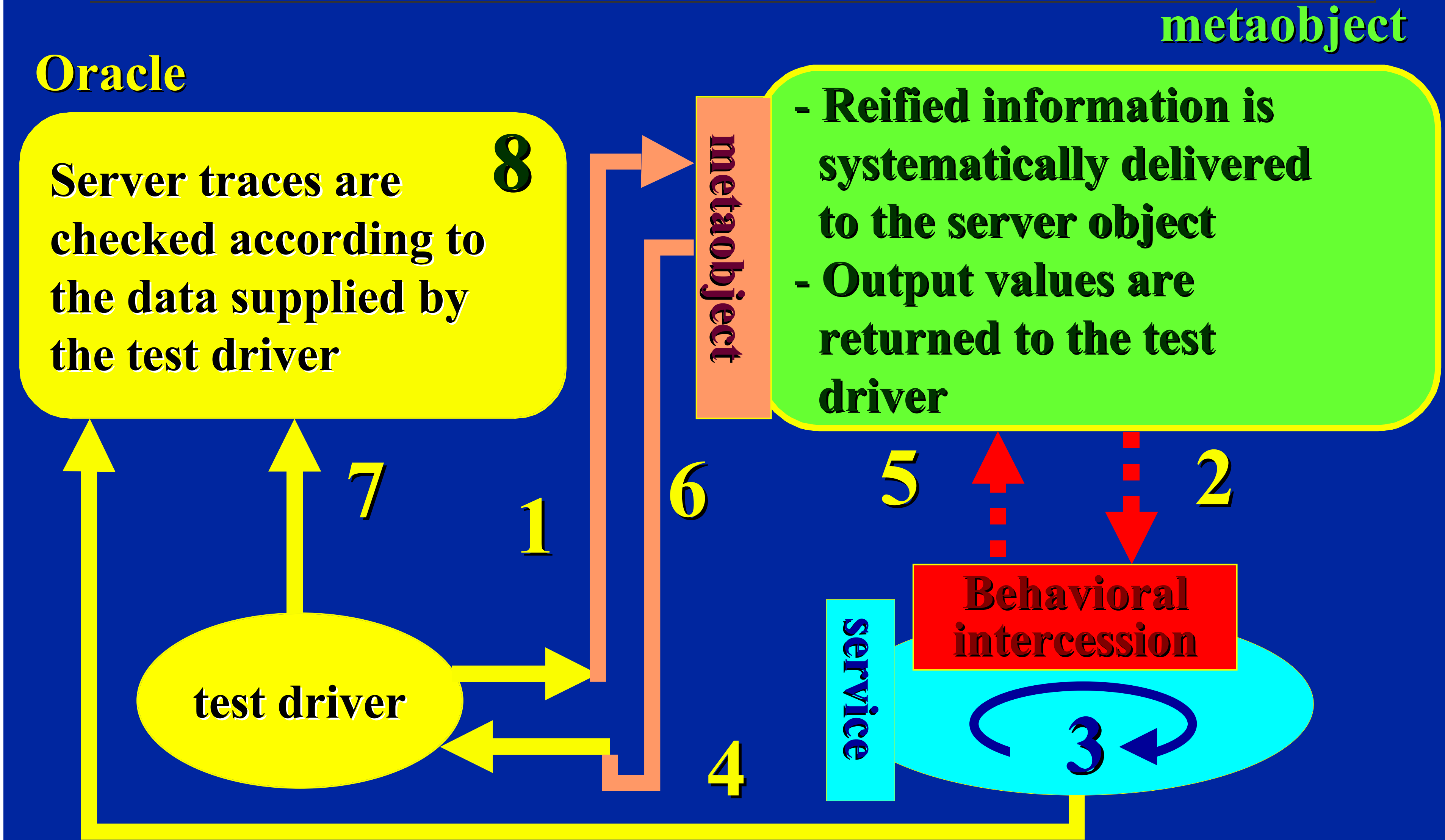
TL4. Structural intercession mechanisms

TL1: Reification
(behavioral observation)



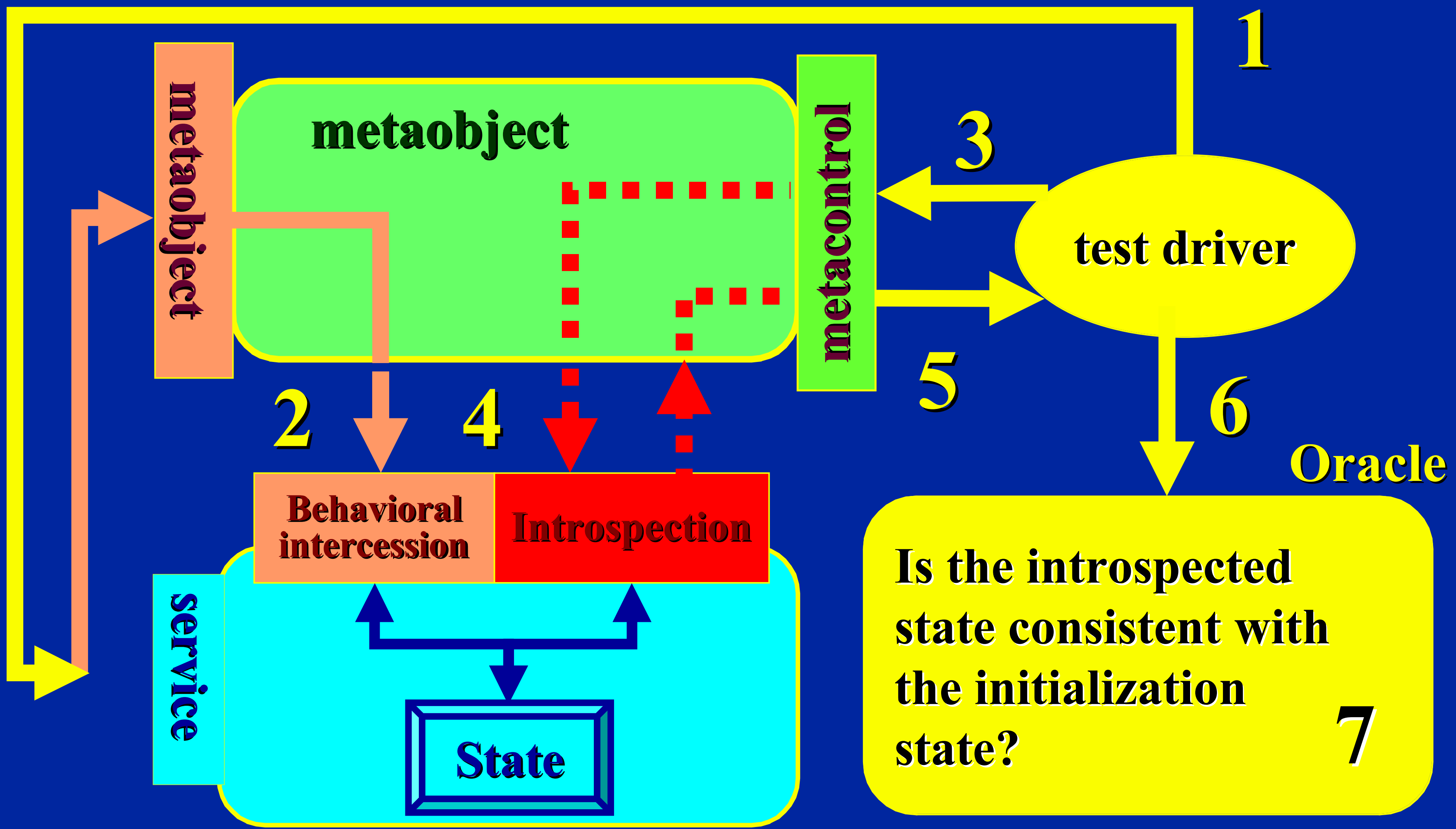
TL2: Behavioral intercession

(behavioral control)



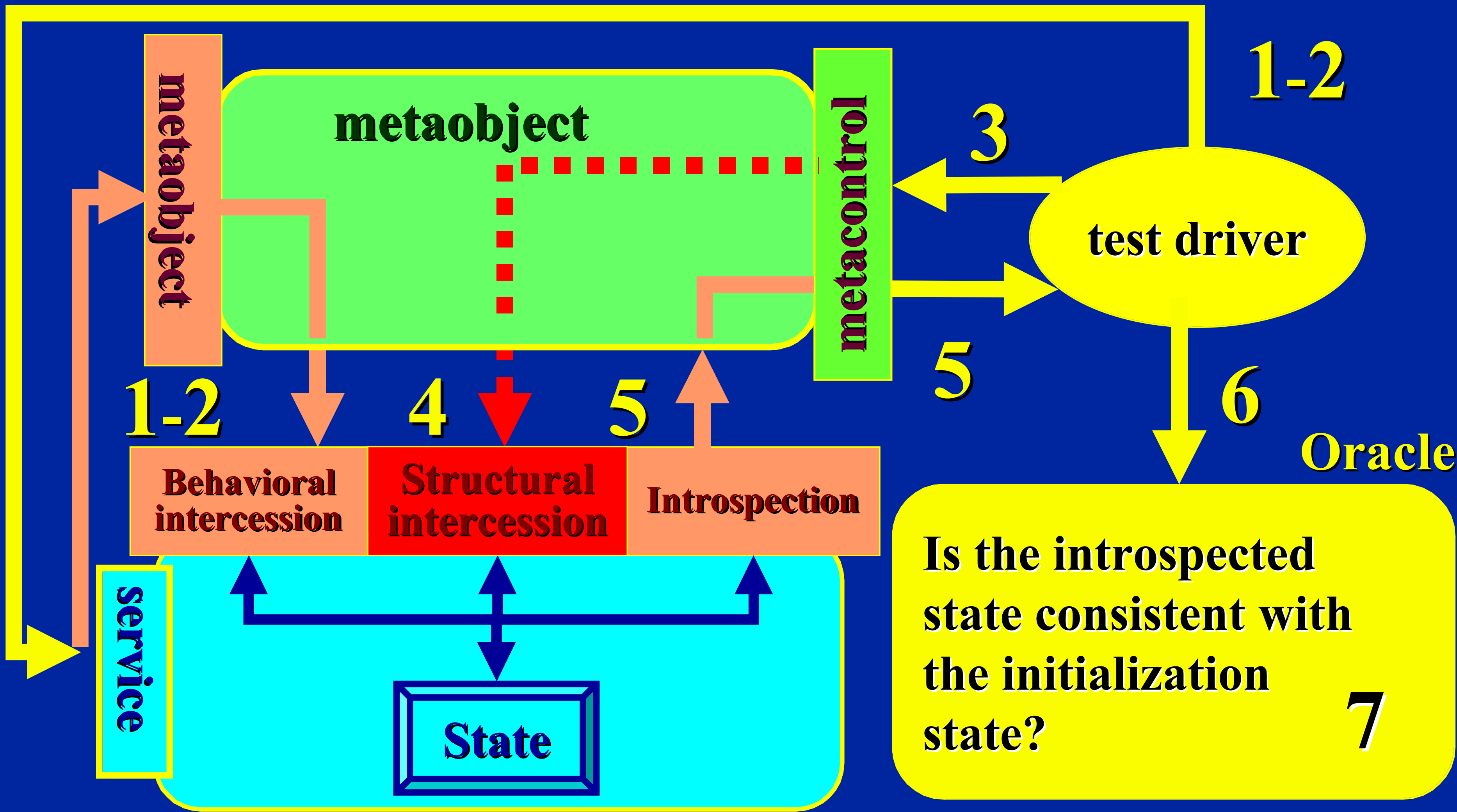
TL3: Introspection

(structural observation)



TL4: Structural intercession

(structural control)



Test Experiments (I)

(Service interfaces)

```
interface shortTypeParameters{
   short ReturnValue ();
   void InValue (in short v);
   void OutValue (out short v);
   void InOutValue (inout short v);
   short All ( in short v1,
               out short v2,
               inout short v3);
};
```

Reification & Behavioral Intercession

Built-in types,
Strings,
Class types,
Structures and Arrays

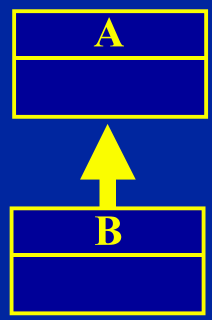
Introspection & Structural Intercession

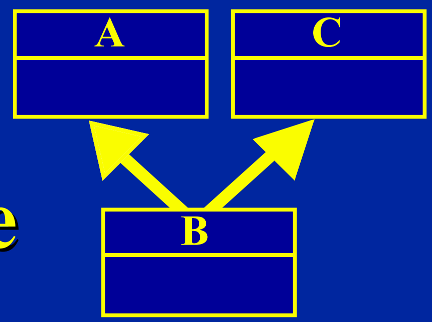
```
interface shortTypeAttributes{
   attribute short ReadWriteValue ;
   attribute readonly short ReadValue ;
};
```

Test Experiments (II)

(object-oriented properties considered)

- **Inheritance:**

simple 

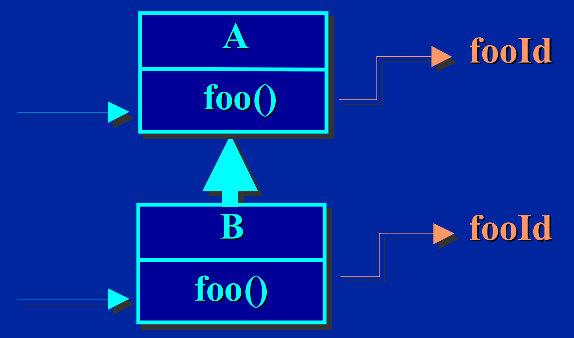
multiple 

- **Encapsulation (methods and attributes):**

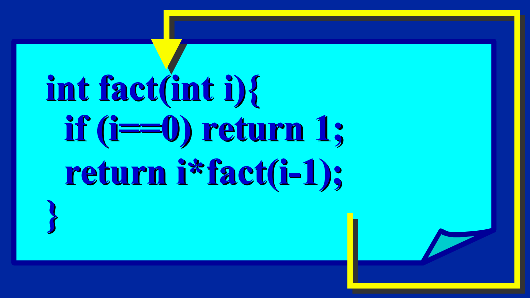
public / protected / private

Experimental results

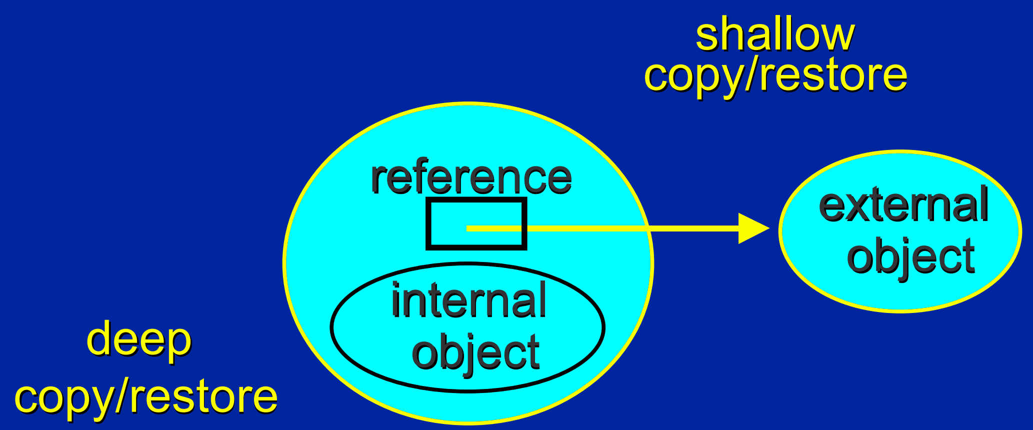
- Reification / Behavioral intercession
  - Method invocations were incorrectly handled using inheritance



  - Internal object activity was incorrectly encapsulated



- Introspection / Structural intercession
  - Object composition
    vs
    Object references



About testing MOPs

- Step forward for testing reflective systems
- Reusing mechanisms already tested for testing the remaining ones.
- Case Study: feasibility and effectiveness of the proposed approach
- Automatic generation of test case input values
- Guidelines for MOP design

Future work

- Generalizing the approach
  - Multi-level reflective systems
  - Aspect-oriented programming
- Testing reflection ➔ Reflection for testing

Conclusion

- MOPs for FT architectures
  - Language reflection / middleware not reflective
  - CORBA Portable Interceptors
    - Support for FT too limited
  - Unified approach for multi layered open systems
    - Multi-level reflection
- Validation of the platform
  - Test : augment the confidence
  - FI : failure mode analysis
    - feedback on FT mechanisms