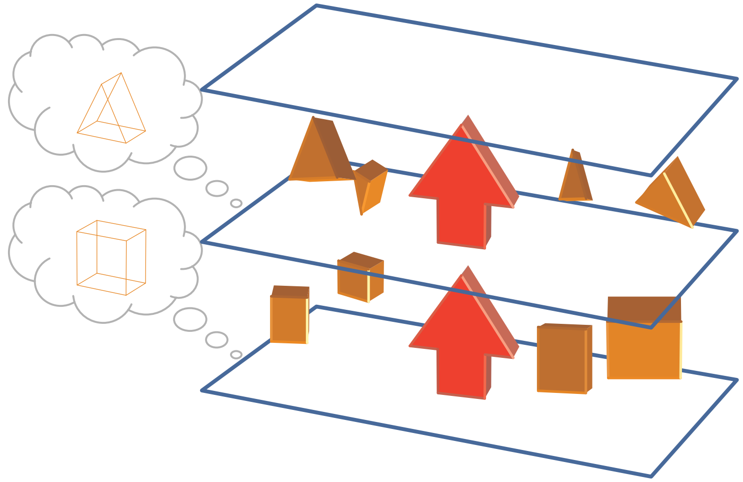


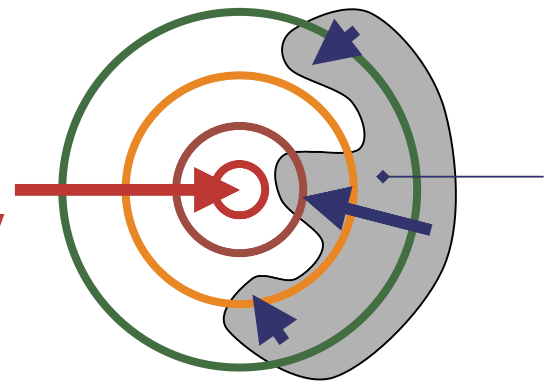
The Composite "Know Thyself"

Fault-Tolerance in Complex Computer Systems Requires an Holistic Approach !

François Taïani

Context

- **Increasingly complex** computer systems are being used for **increasingly critical** applications.



- Complexity ?
  - ➔ In space : - several hundreds of persons
    - numerous components / numerous suppliers
  - ➔ In time : - very long life cycles : 10, 20 years

- Criticity ? : service failure ⇨ major disaster (😐😐 / $$)
  - ➔ Dependability is a major concern.

The Problem

- Dependability is a global property.
  - ➔ Vulnerabilities are scattered all through the system.
  - ➔ The system has to behave safely as a whole.
  - ➔ Fault-Tolerance requires observation + action capabilities.
    - checkpoint, control of non-deterministic decisions, *etc.*

- Controlling complexity relies on locality.
  - ➔ Components are modular, mechanisms are transparent.☺
  - ➔ But implementation remains totally hidden. ☹
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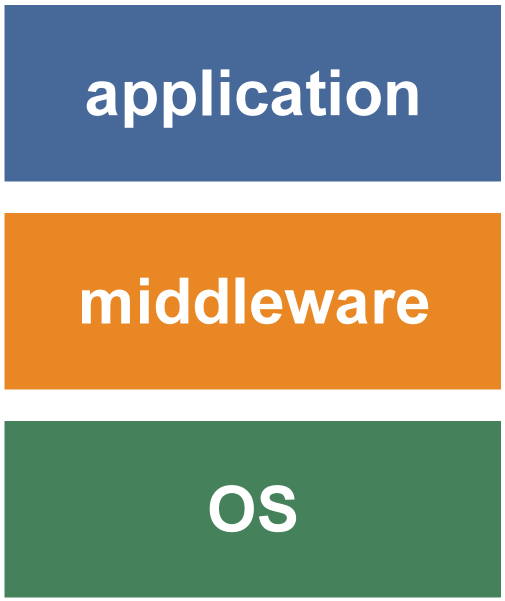

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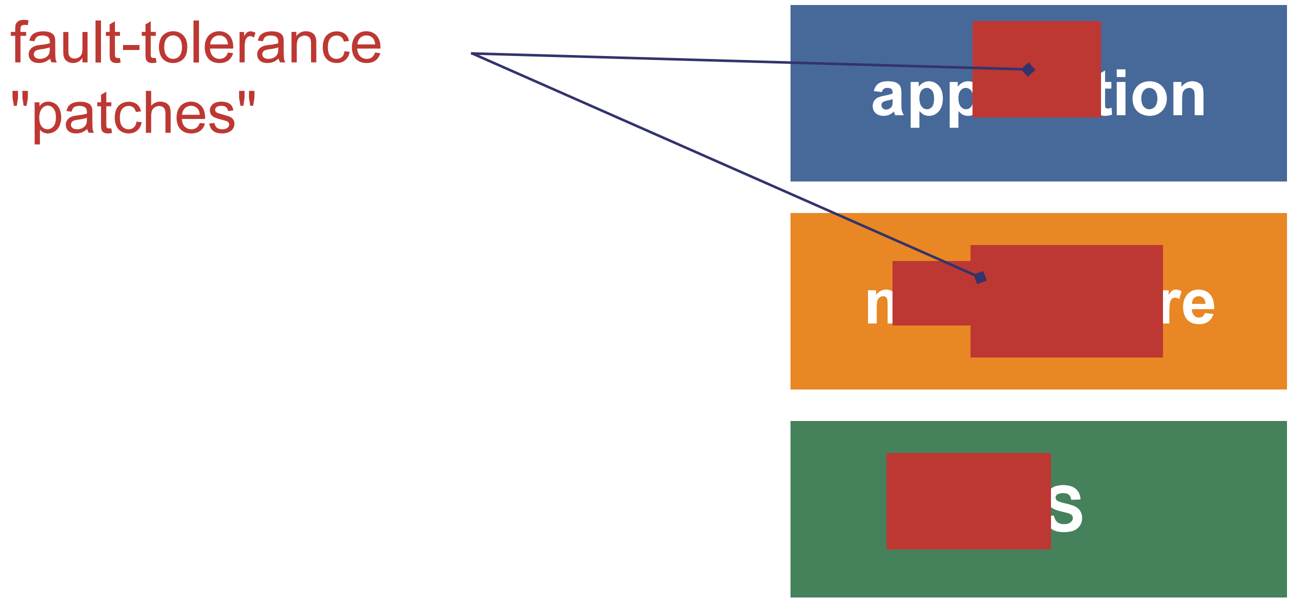

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ad hoc inter-level
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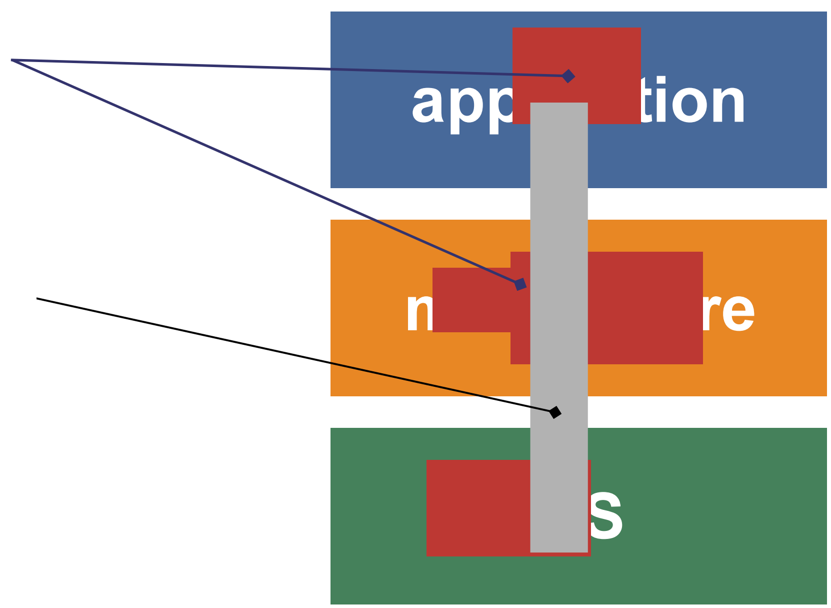

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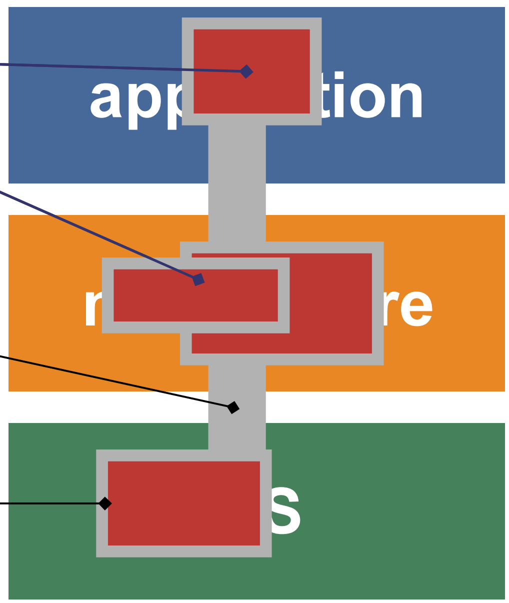
ad-hoc connection
original code ↔ FT patches



Ad Hoc Patches...

- ...cannot be reused.($!)
  - ➔ Ad hoc patches are component specific.
  - ➔ Ad hoc patches decrease system maintainability.
  - ➔ Ad hoc patches cannot evolve easily.
- ...require the collaboration of the component's provider. ($!)
  - ➔ Ad hoc patches often depend on undocumented features.
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⇨ A high cost for an entangled system.

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⇨ **Can reflection be used to realize adaptable fault-tolerance in complex systems ?**

Outline

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What Is Reflection ?

functional interface,
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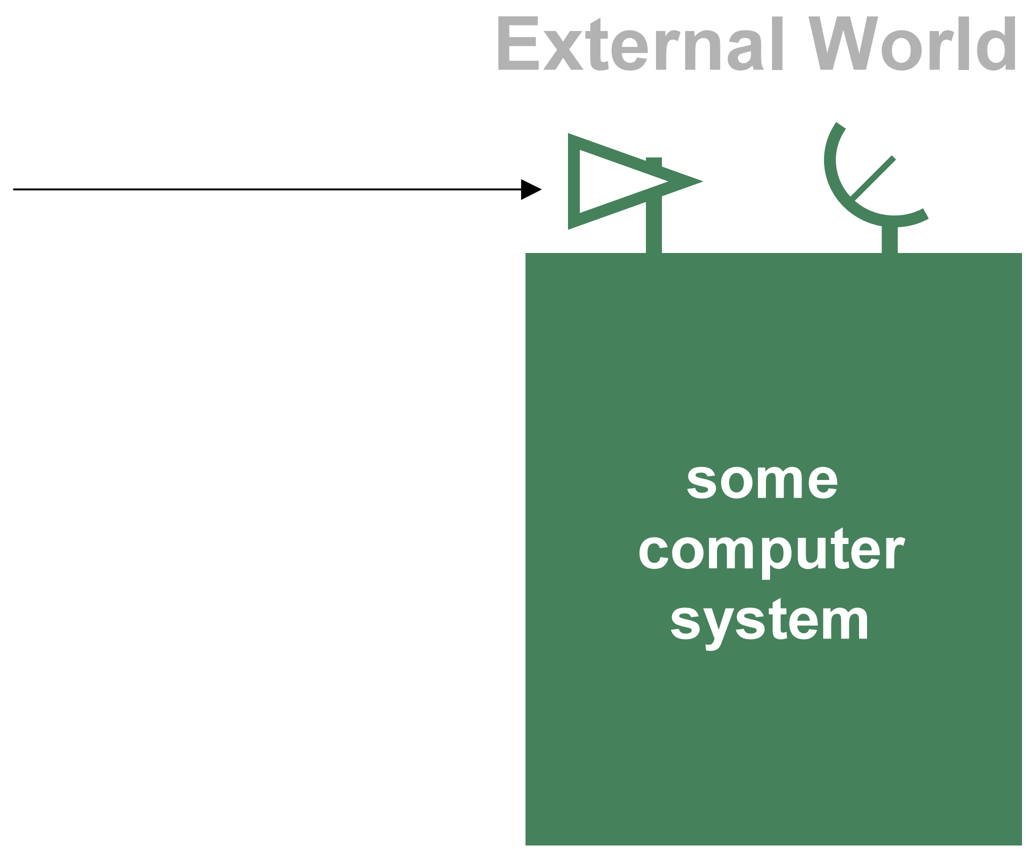

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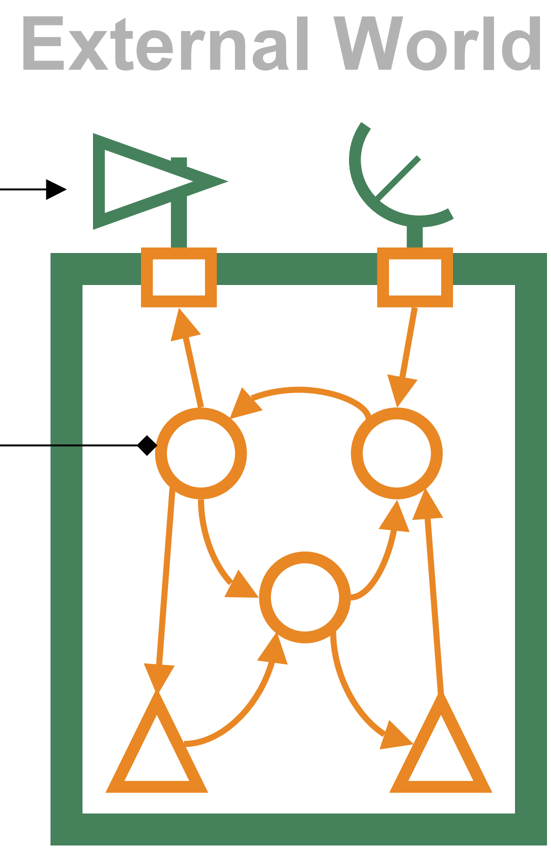

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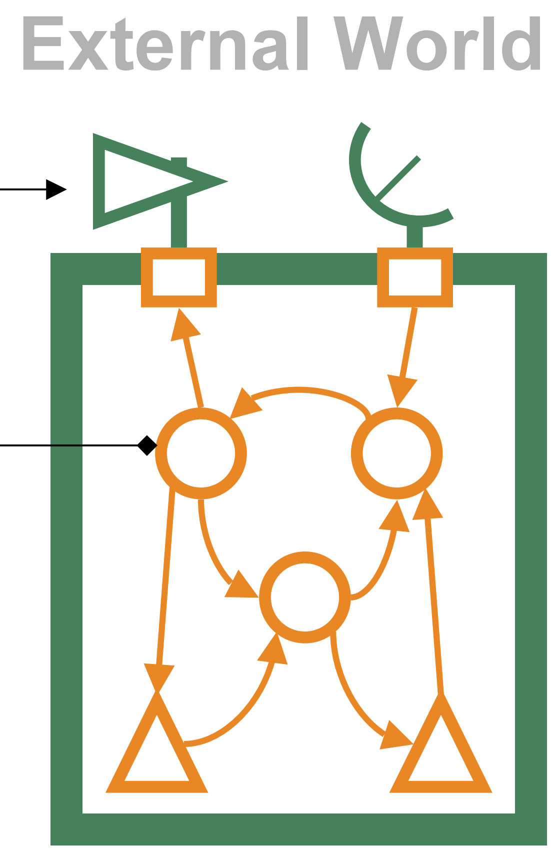

What Is Reflection ?

By default : strict **separation** between a **program** and the **universe** it has effects upon.

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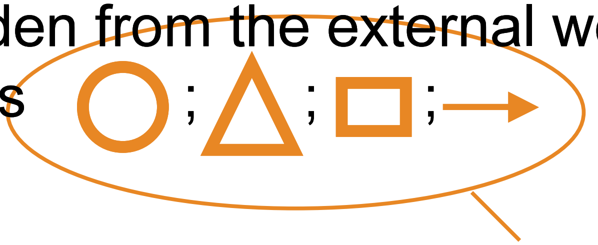
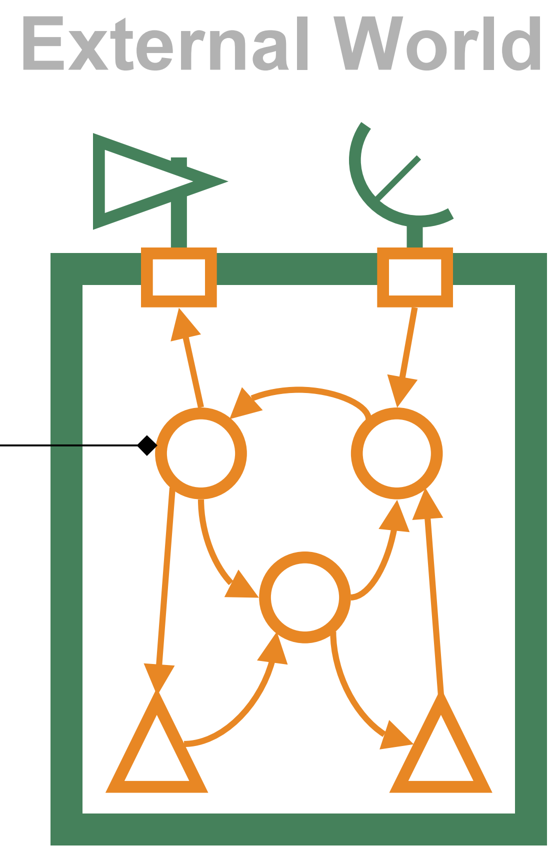
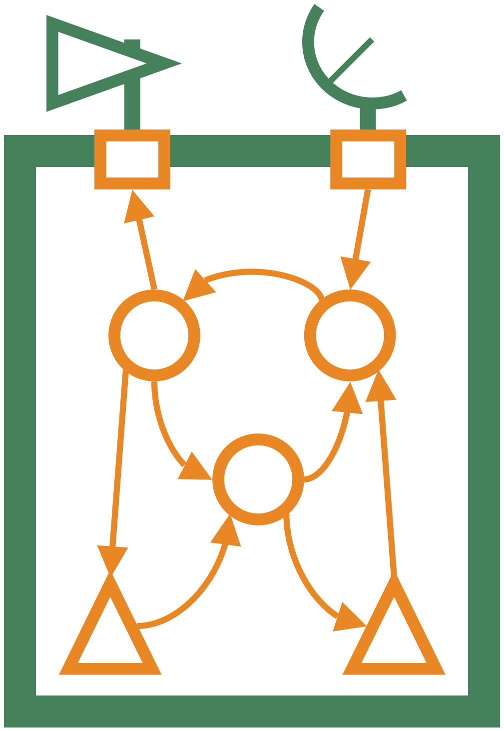
uses 

"programming model" : procedures + variables, objects + methods ...



What Is Reflection ?

Reflection gives access to a system's internals, which can thus be observed and modified.



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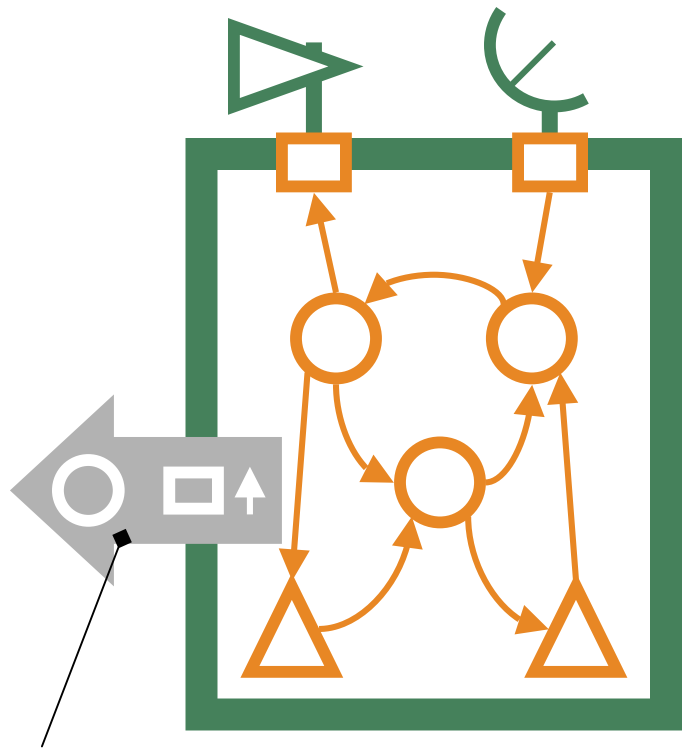

Generic building elements are exported.

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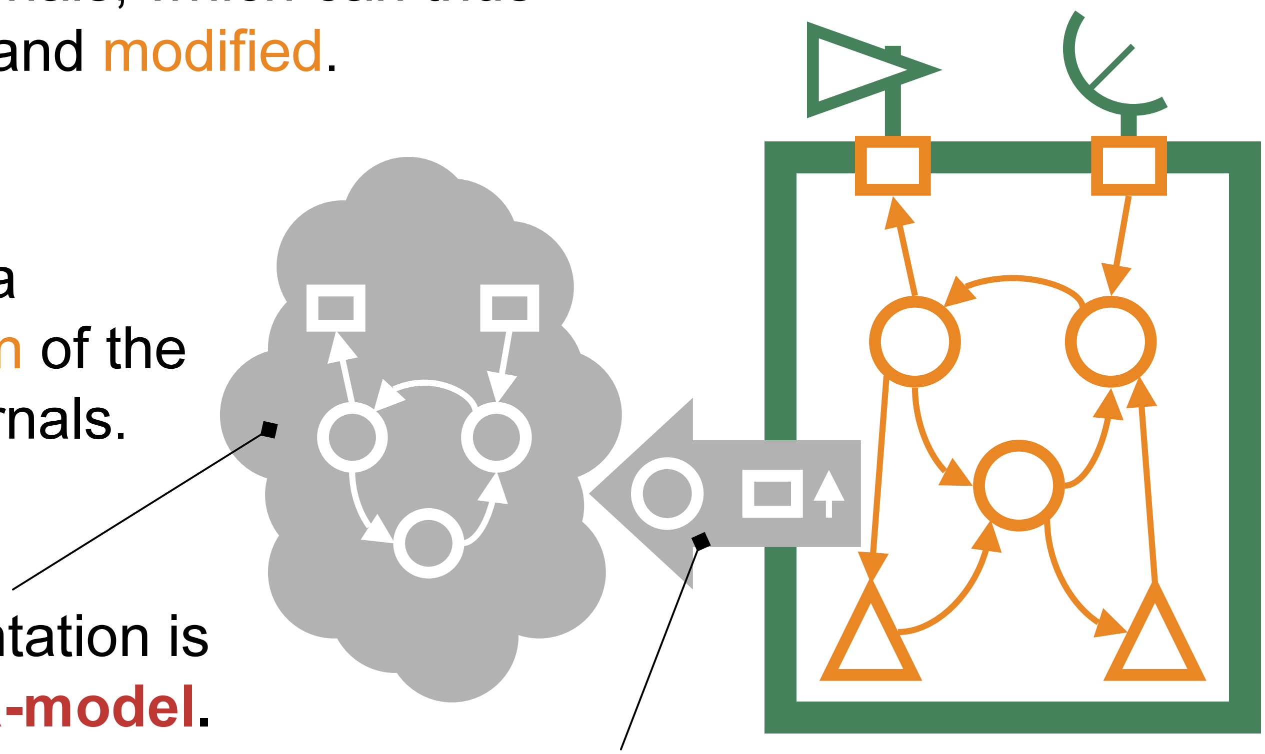
This representation is called a **meta-model**.



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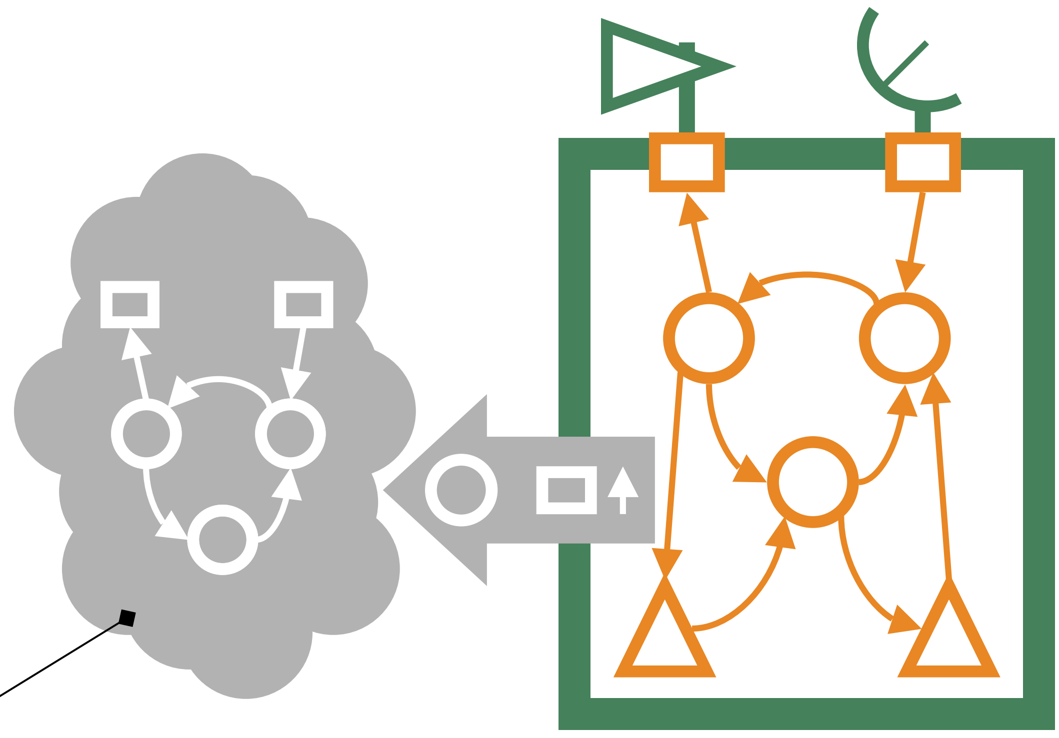
Internal activities are reflected on the meta-model.



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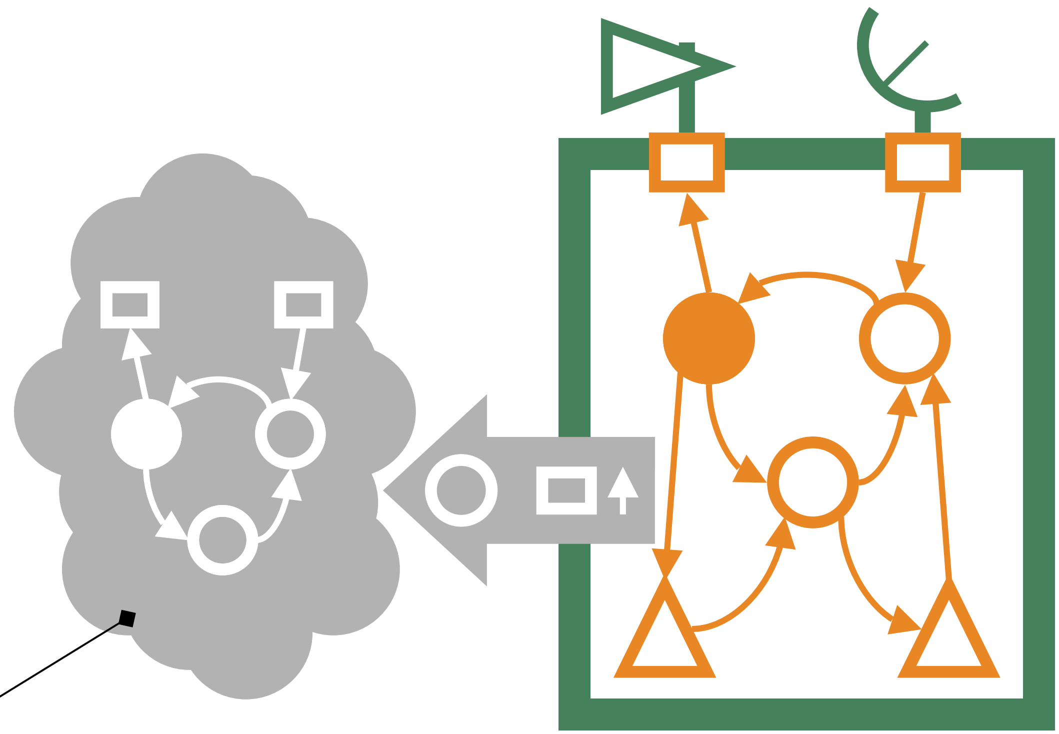

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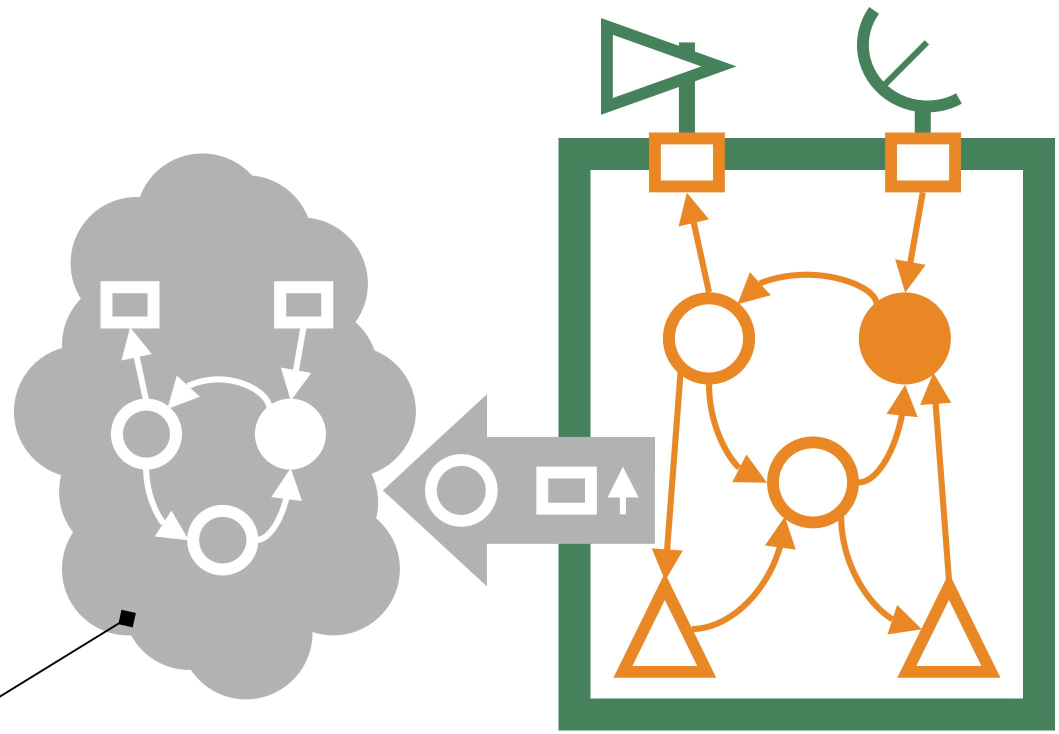

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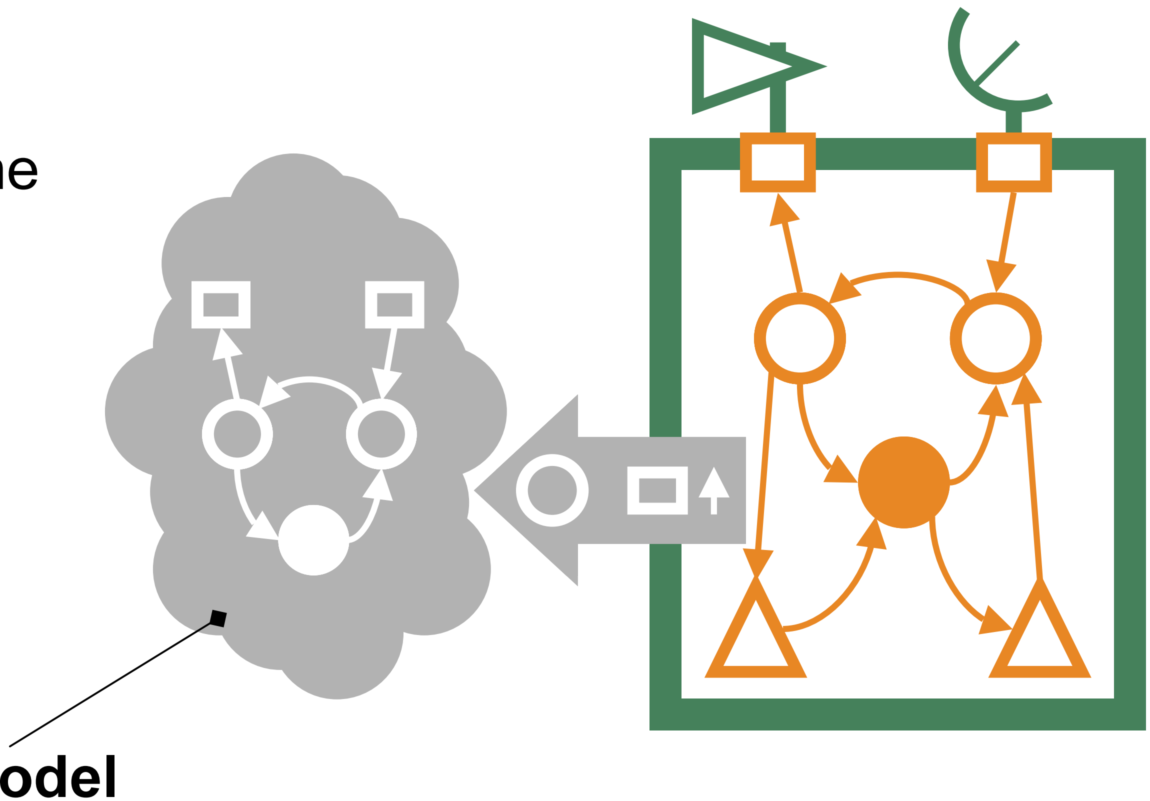

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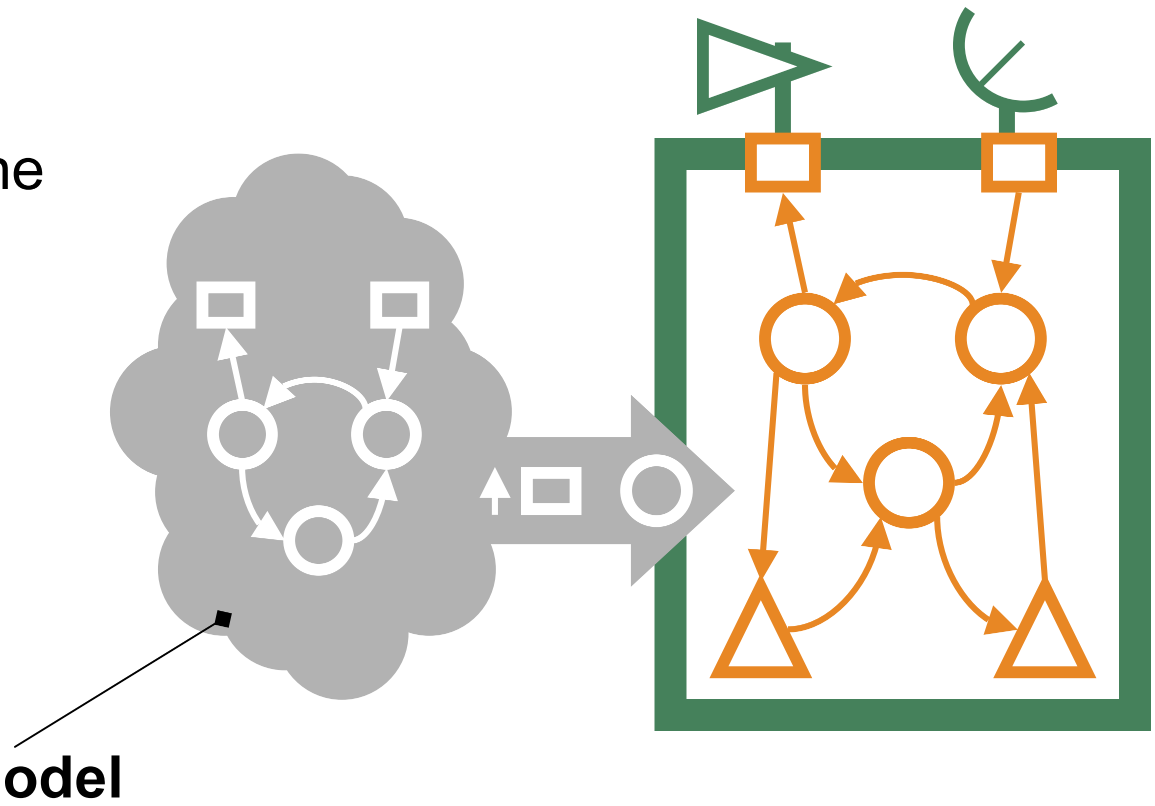

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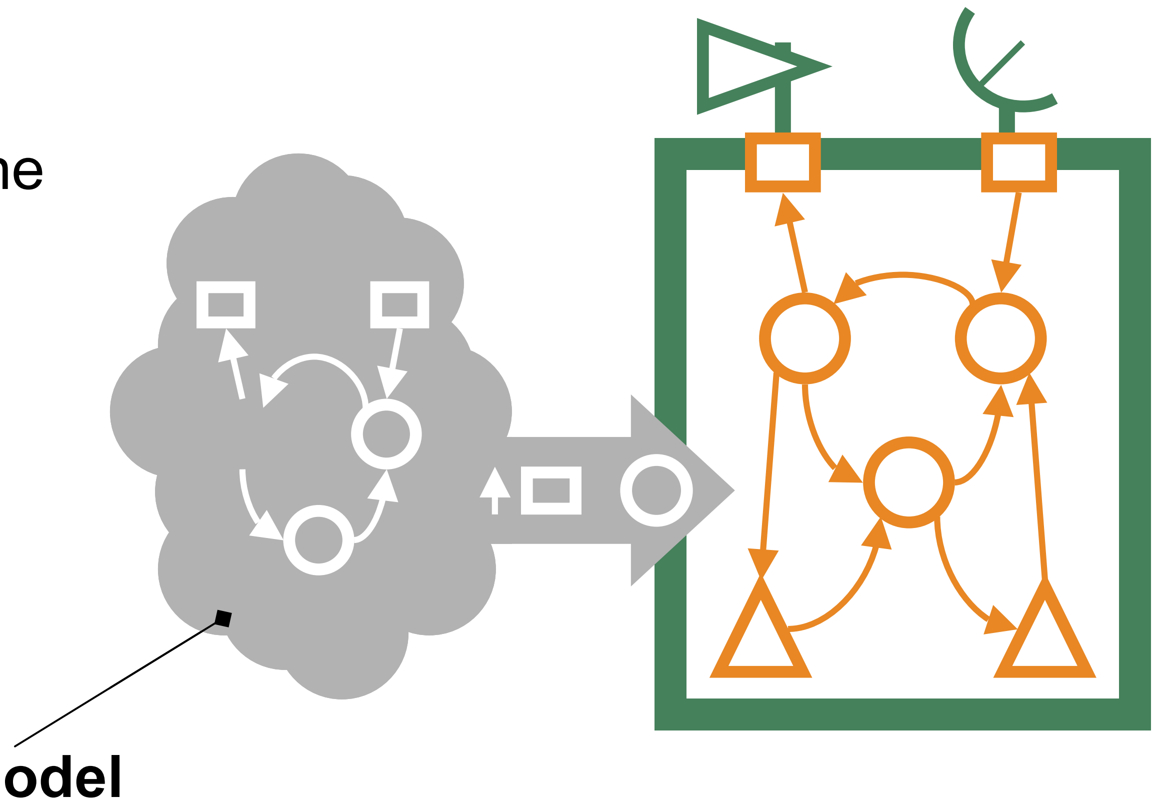

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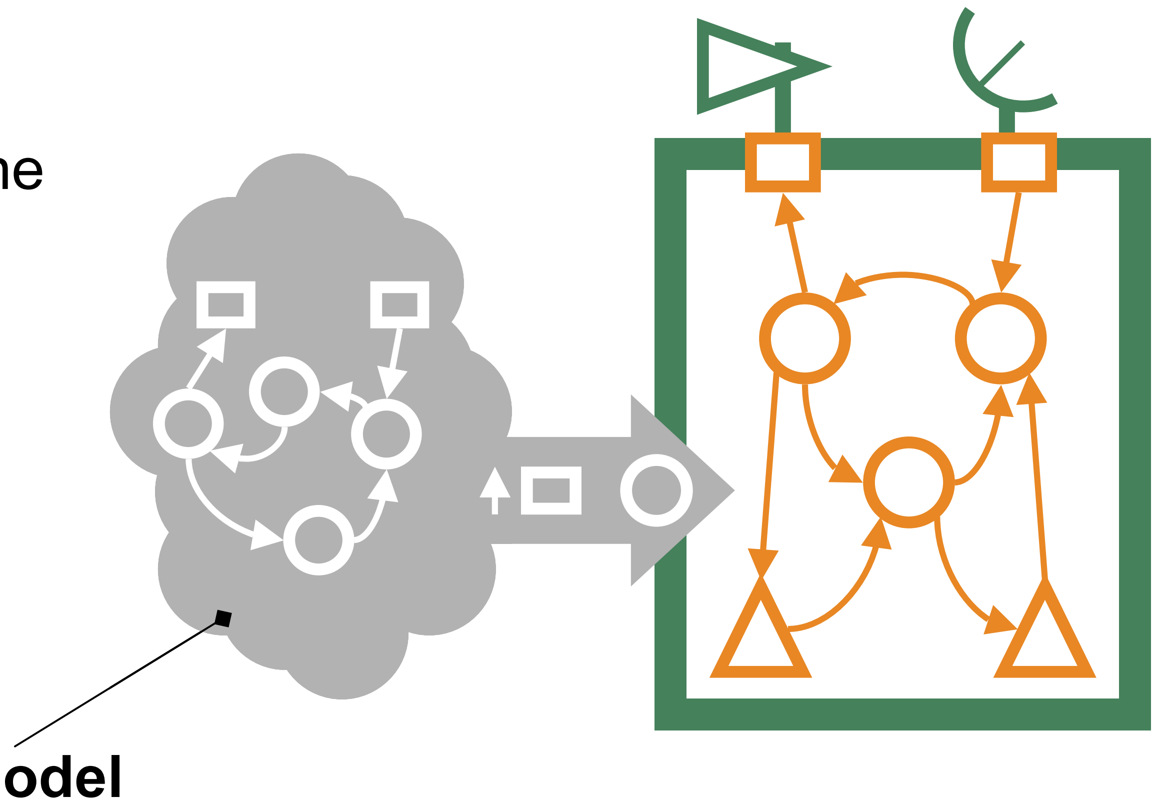

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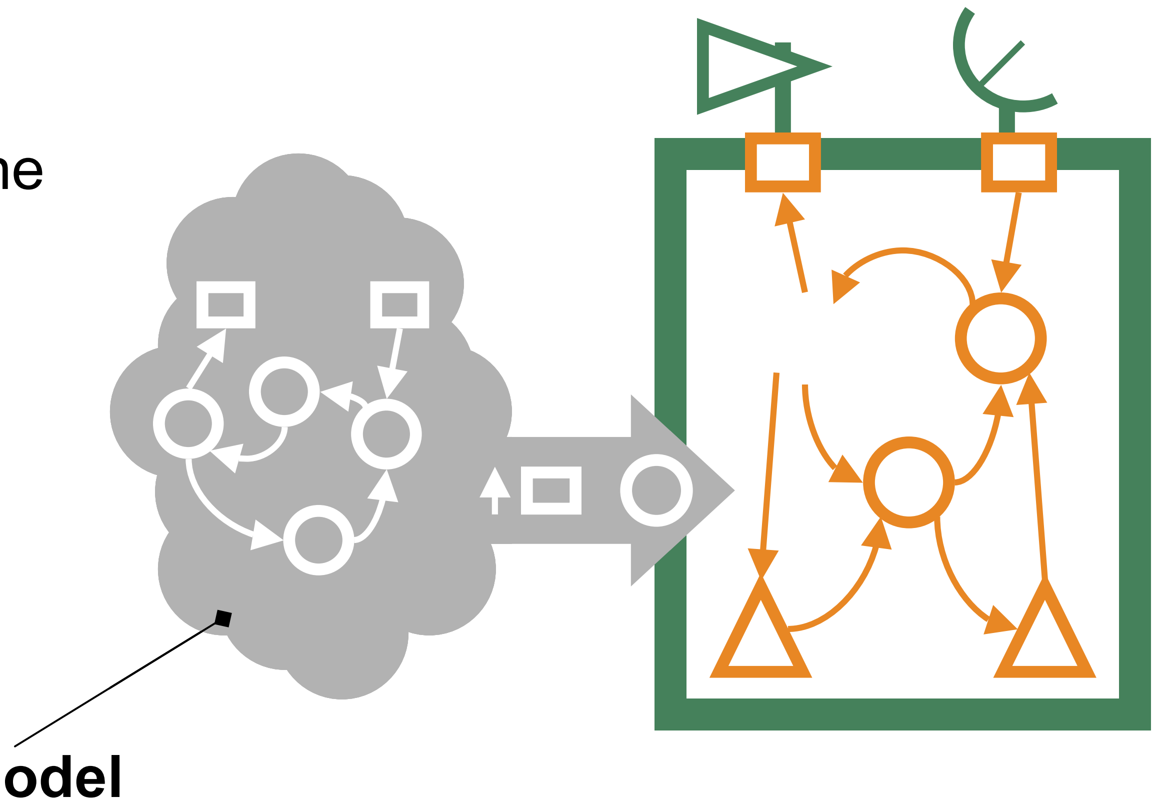

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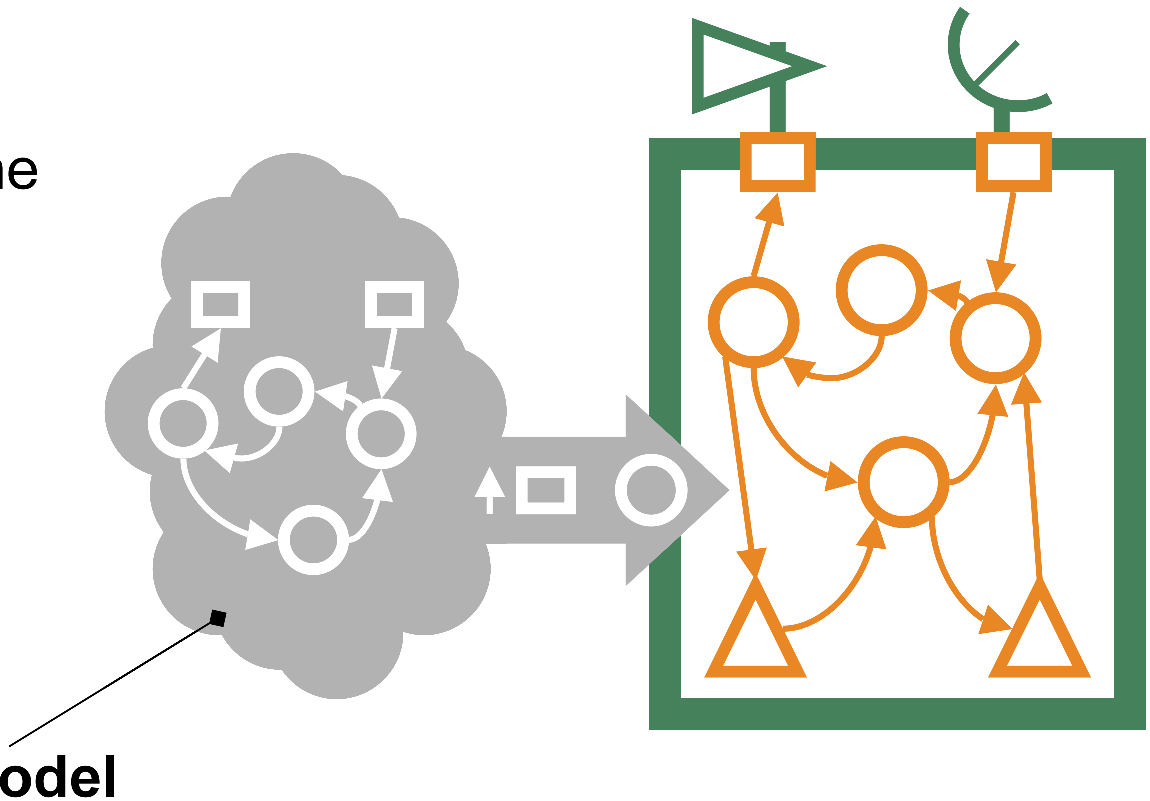

What Is Reflection ?

With reflection, the **program** becomes a **data** than can be manipulated.

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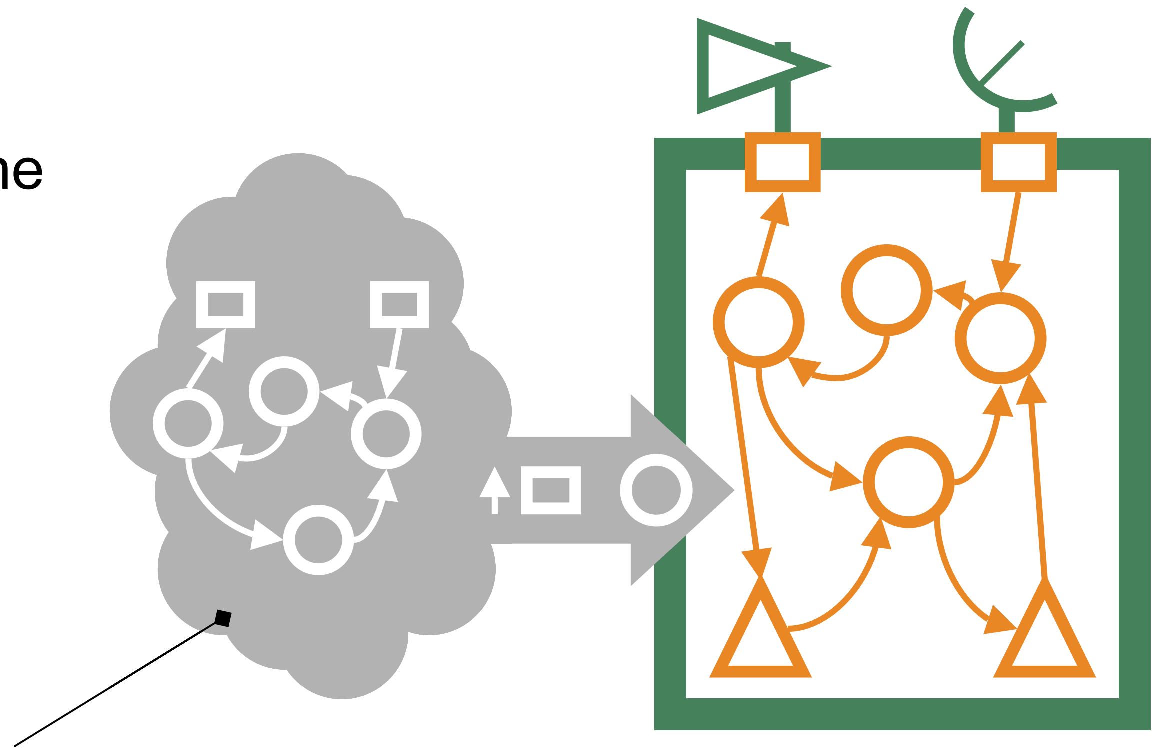

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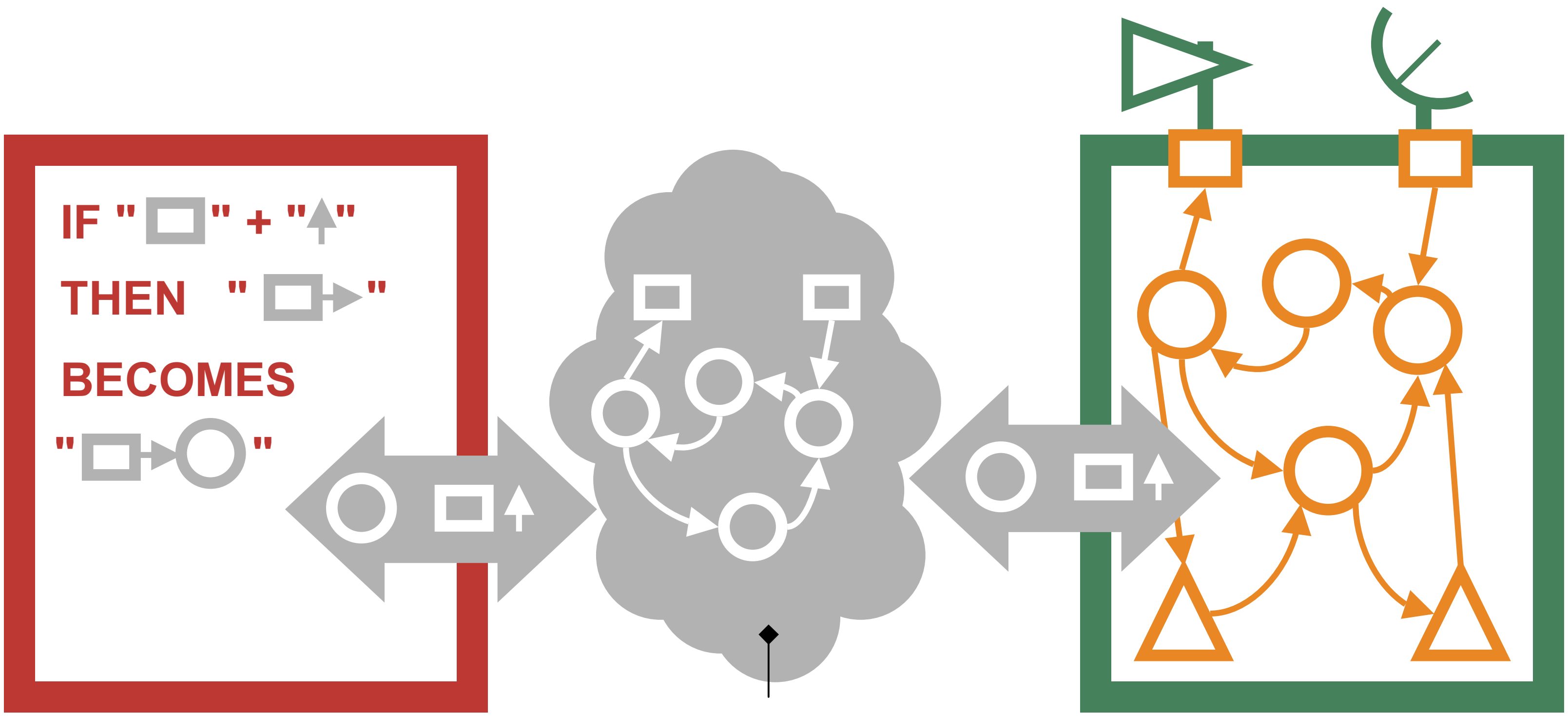
Reflection & Transversal Concerns



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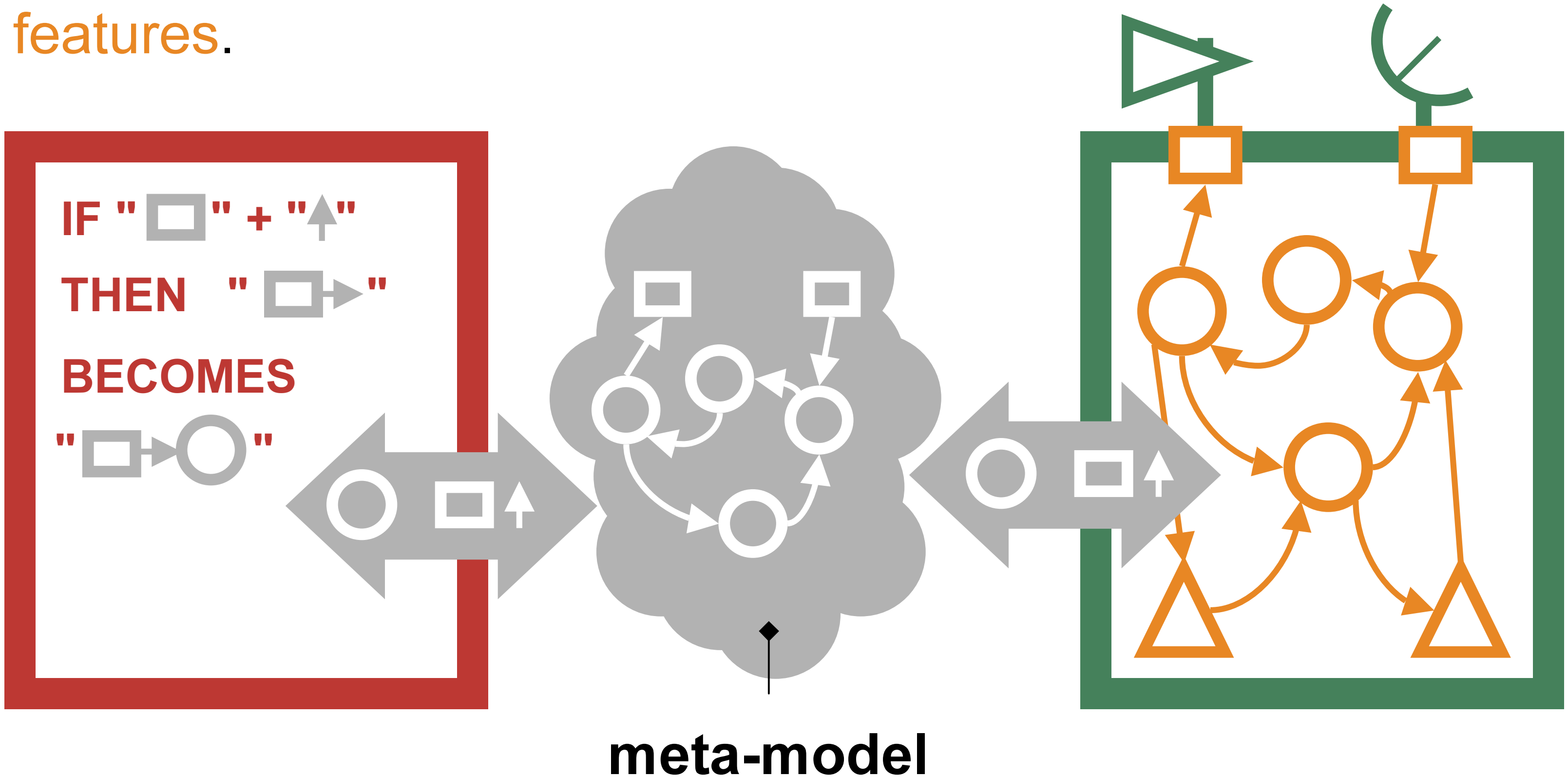
Reflection & Transversal Concerns

With reflection, generic programs can be written to manipulate the system independently of its functional features.



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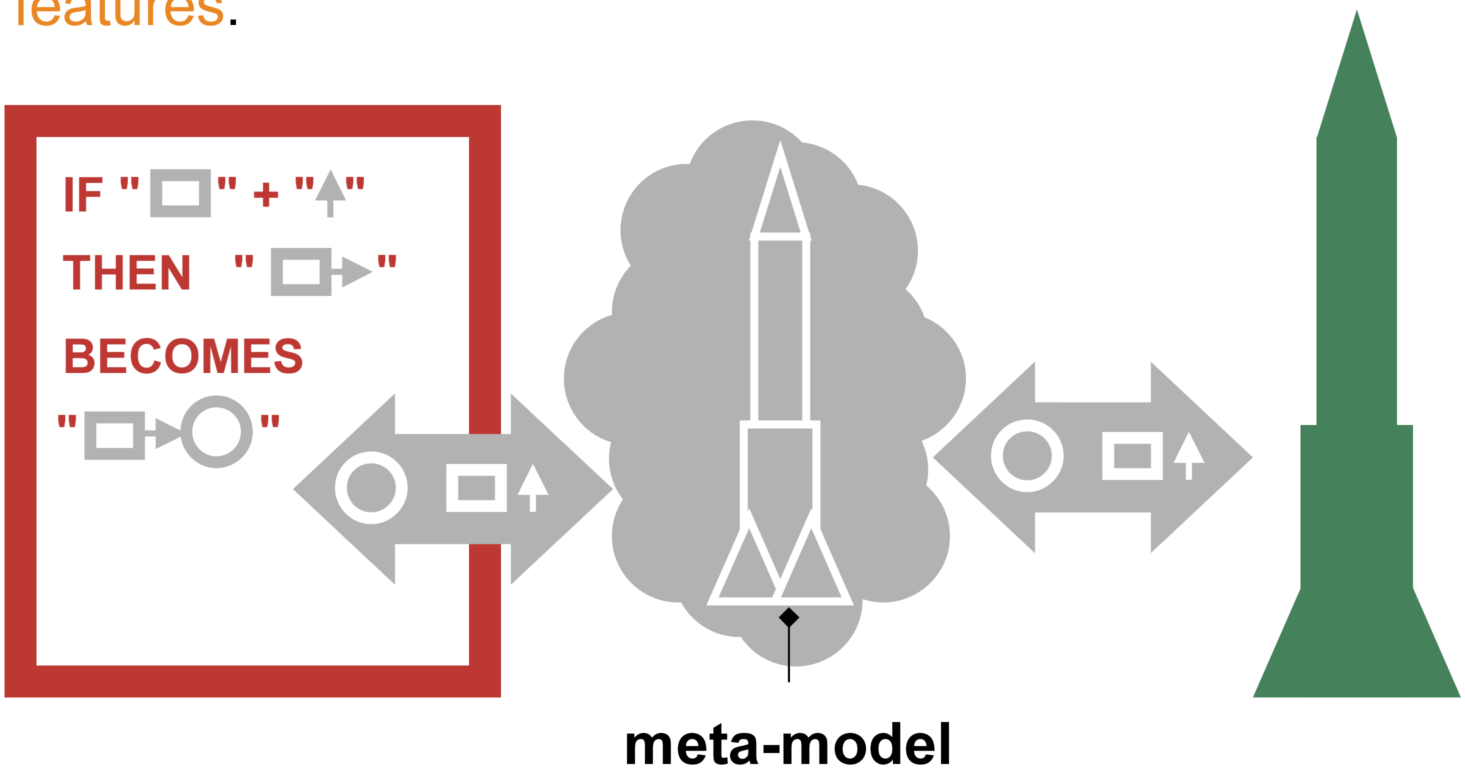

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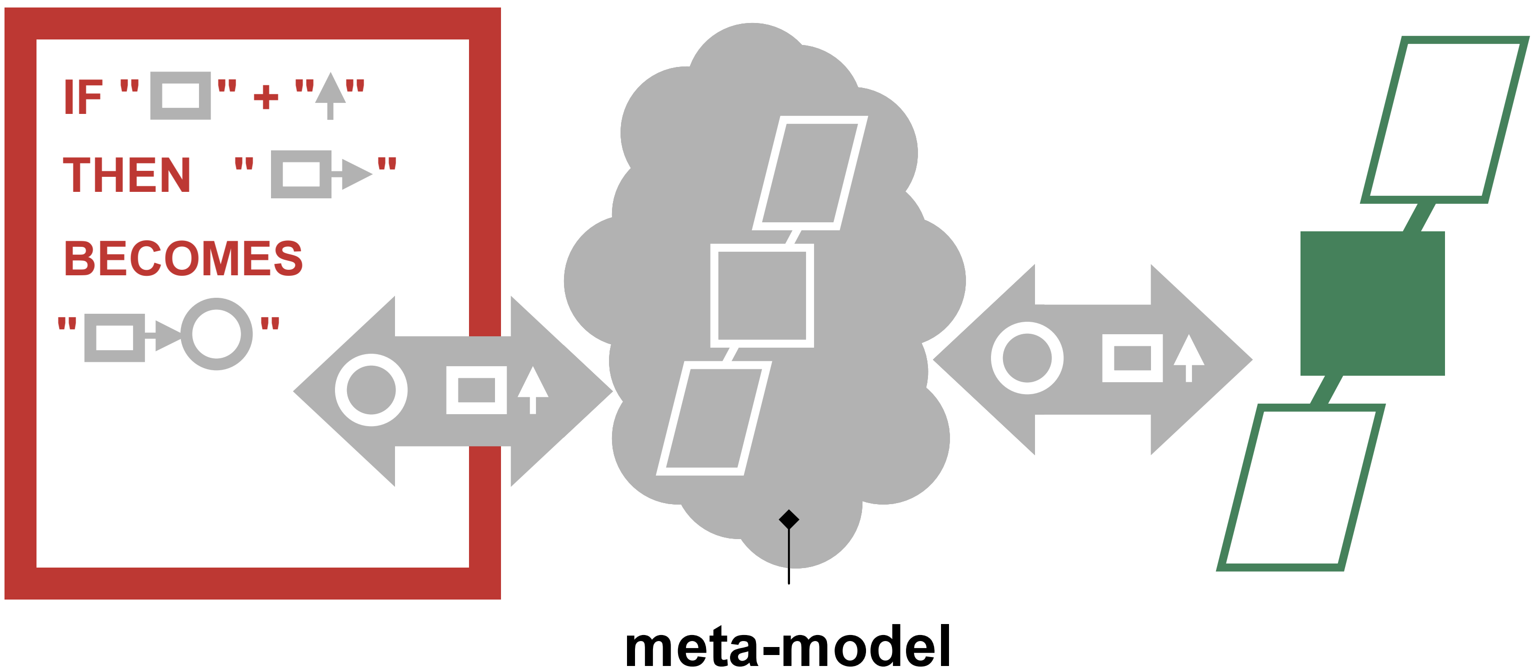

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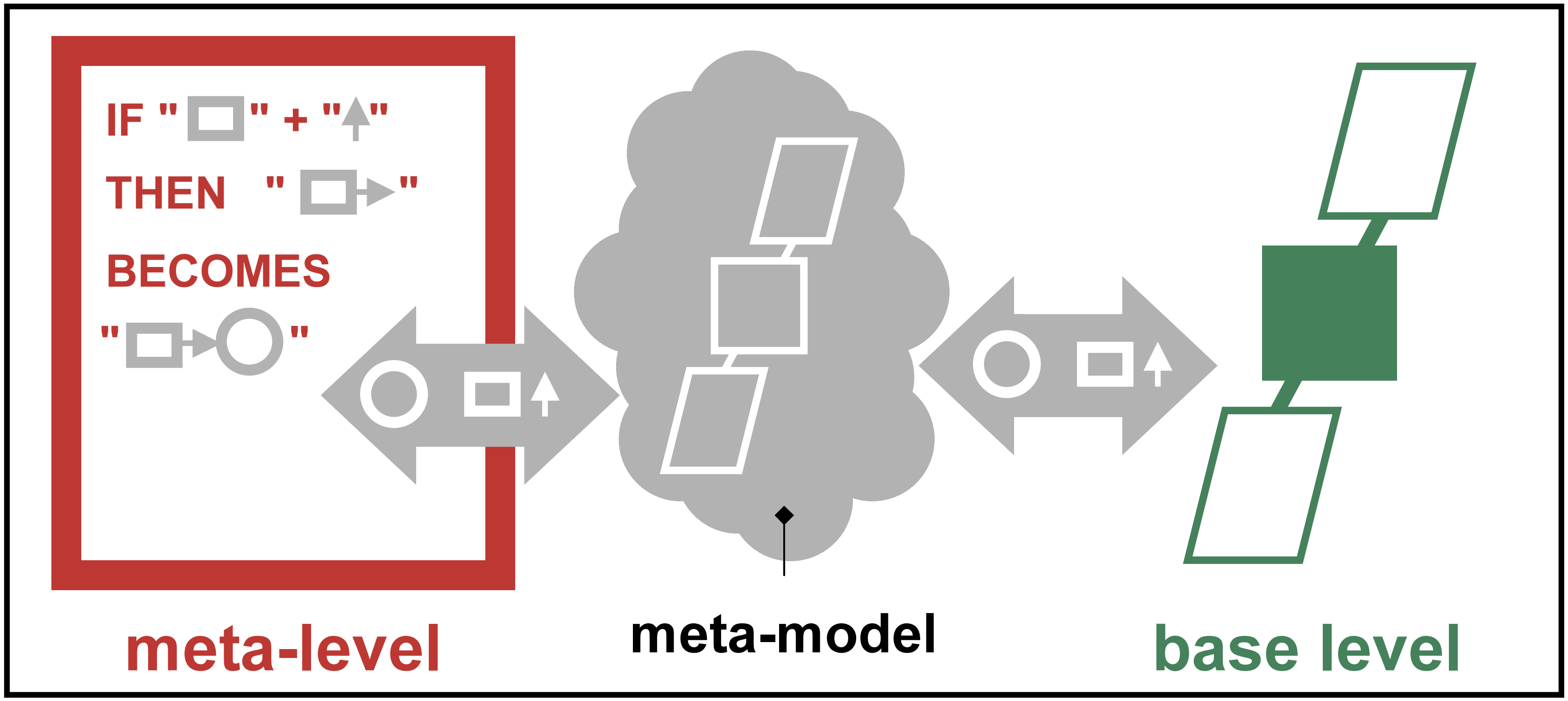
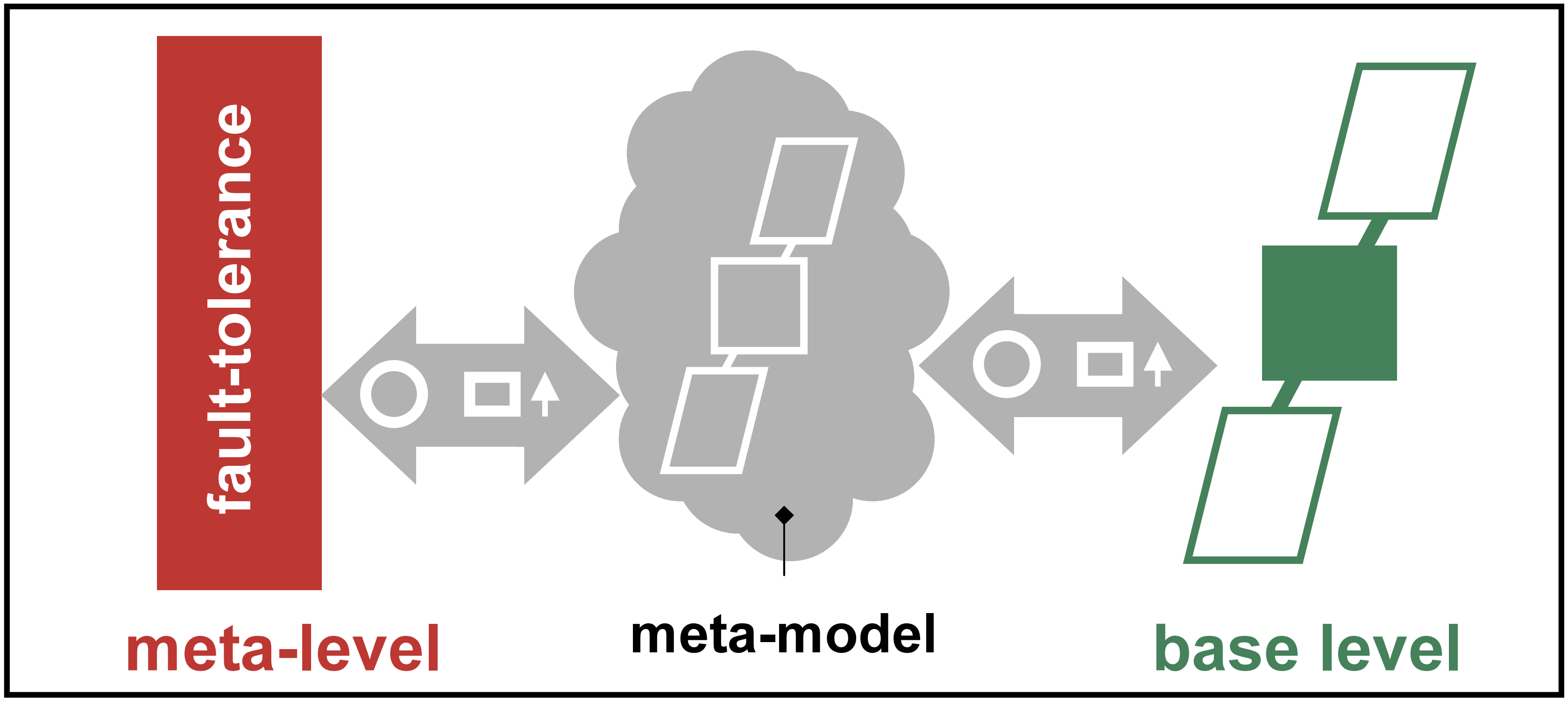


reflexive system

Reflection & Transversal Concerns

⇨ **With reflection, fault-tolerance can be addressed independently of the rest of the system.**

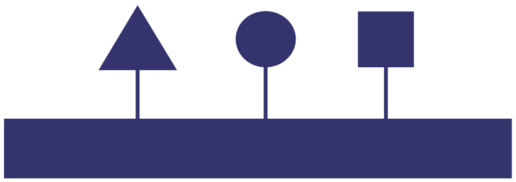


reflexive system

Reflection & Complexity

- Implementing a reflexive architecture requires to find out which information is needed, and where to find it.

machine instructions
(interruptions,
basic logical operations, ...)



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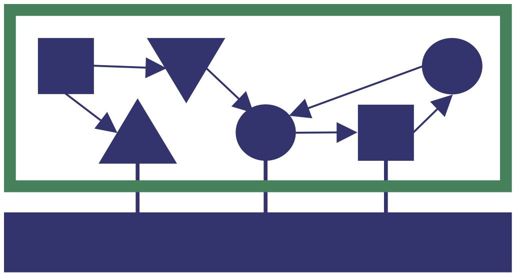

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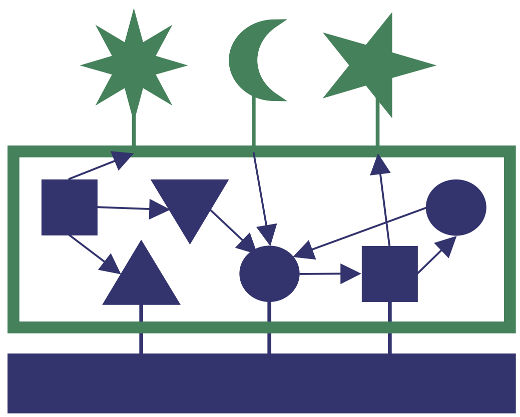

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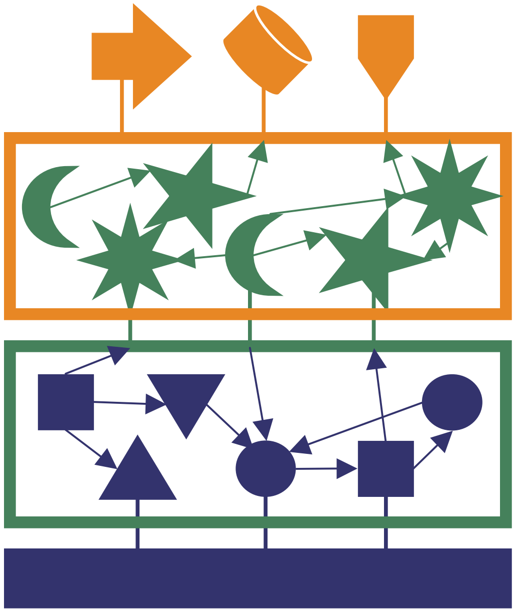

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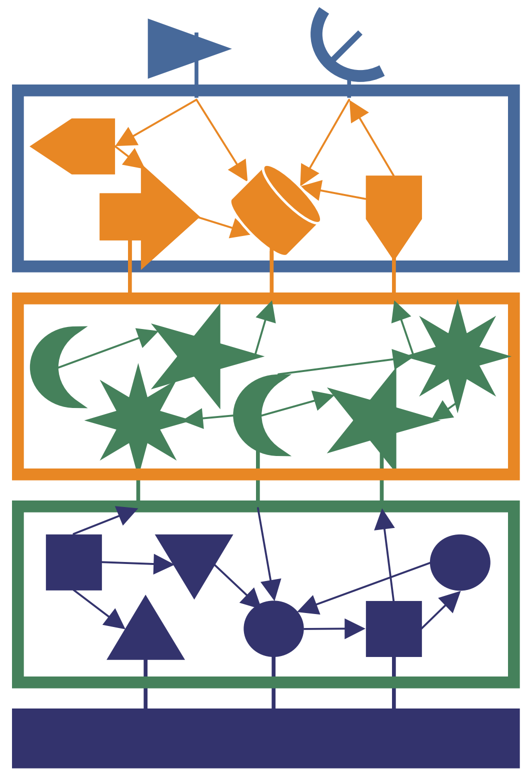
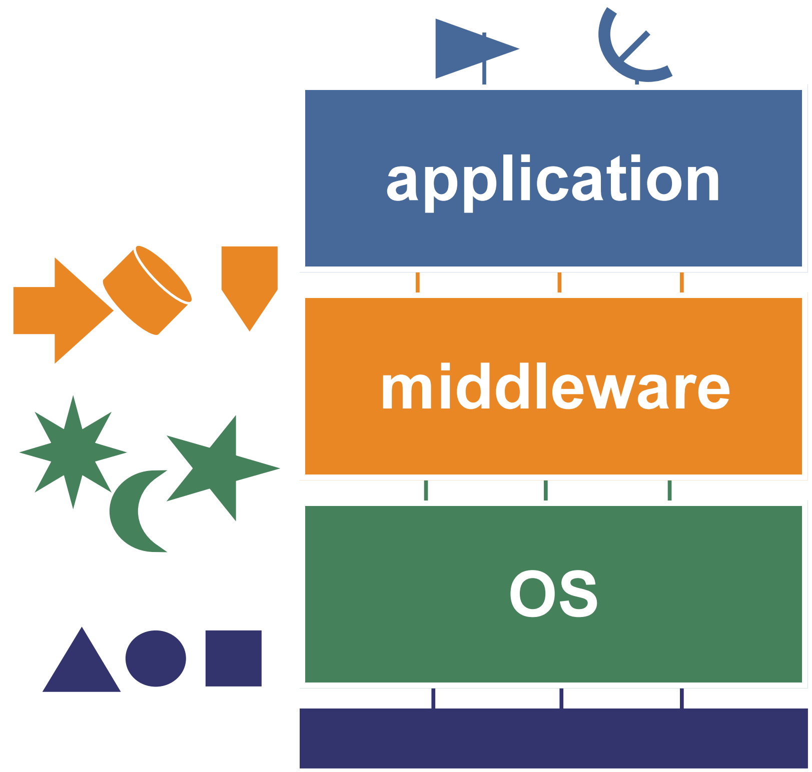


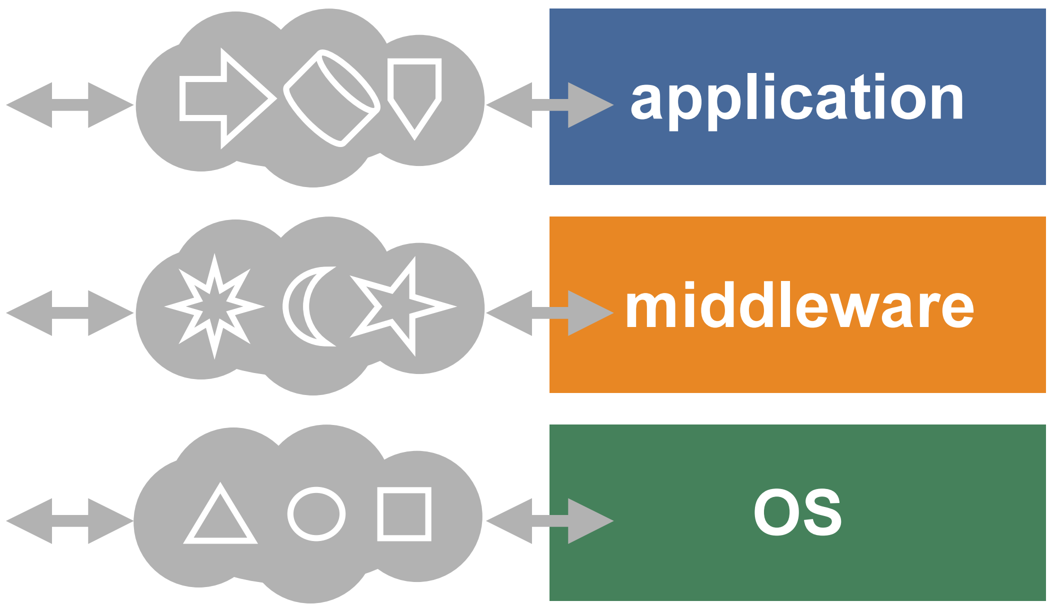
Reflection & Complexity

- Implementing a reflexive architecture requires to find out which information is needed, and where to find it.
- Complex systems are organized in many heterogeneous abstraction levels.
- The different levels are coupled, but this coupling remains hidden.



Reflection & Fault Tolerance

- In complex systems:
  - ➔ Each layer possesses its own programming model.
  - ➔ The respective meta-models are heterogeneous/ incompatible.



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- Reflection has been used to add FT to complex systems but:
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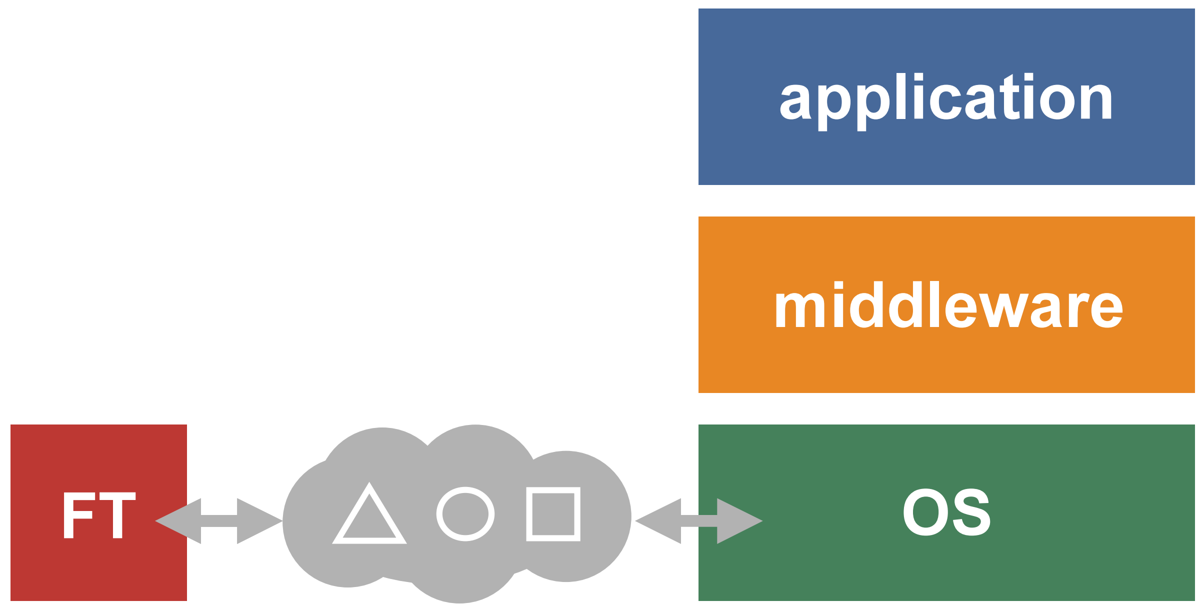

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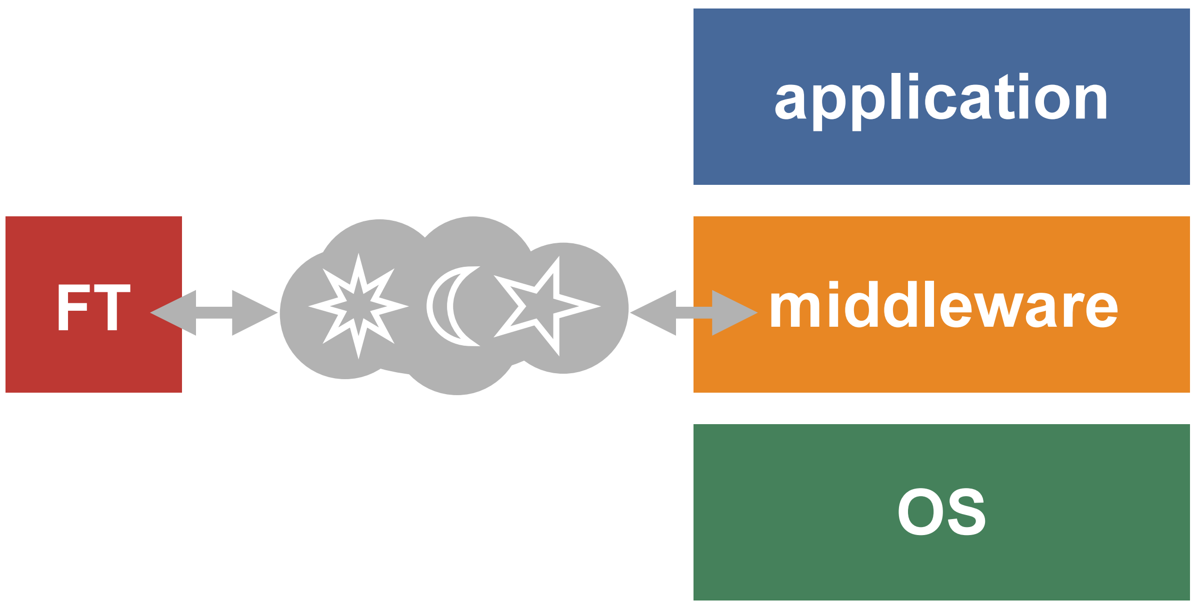

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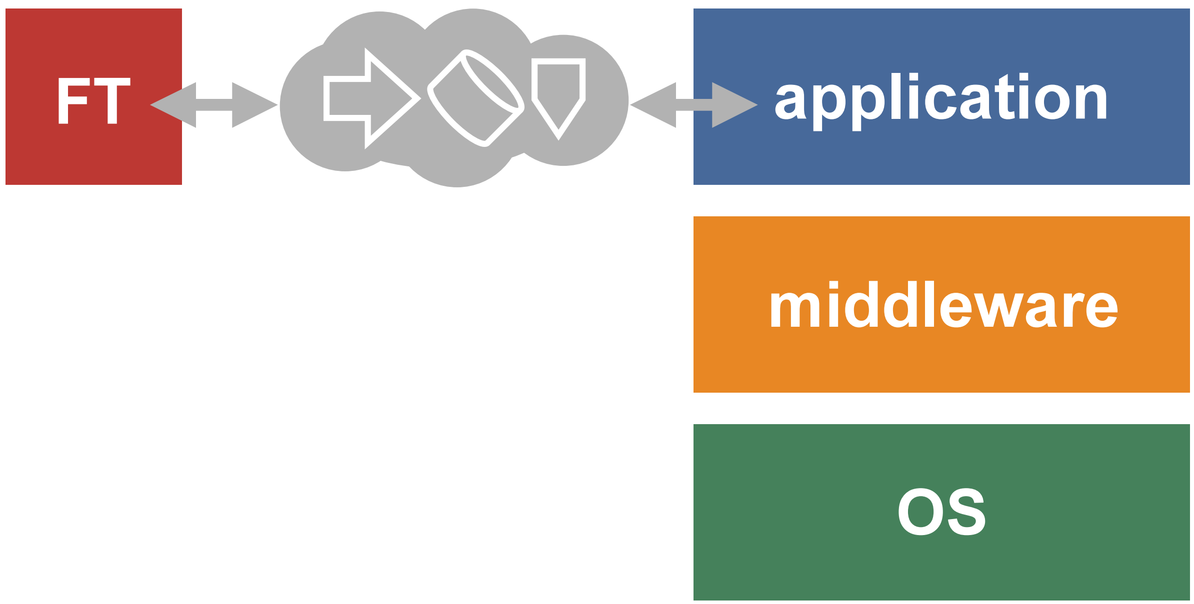

Revisiting our Goals

- Our original goal:

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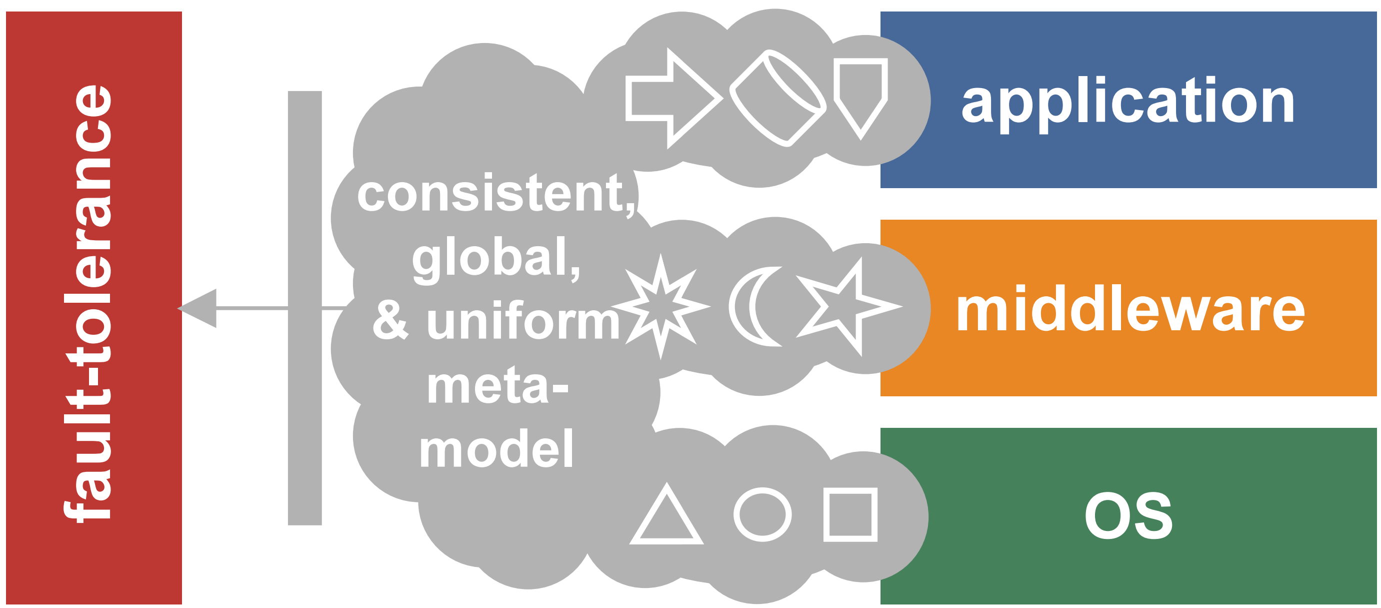
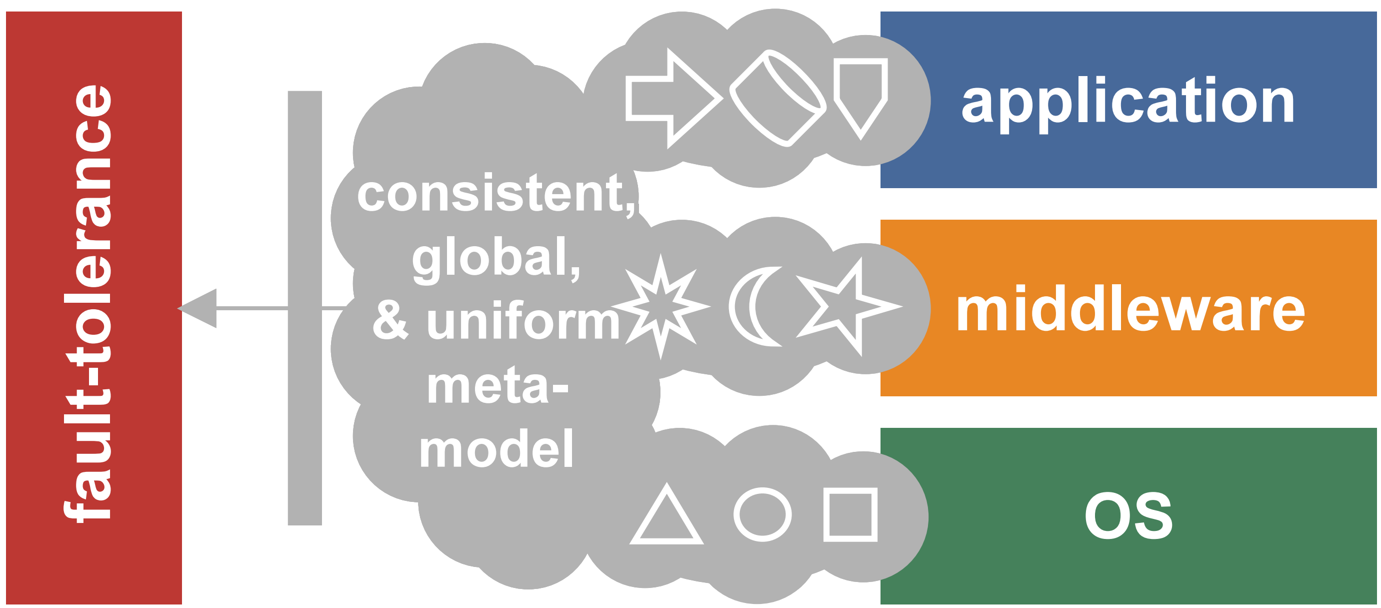


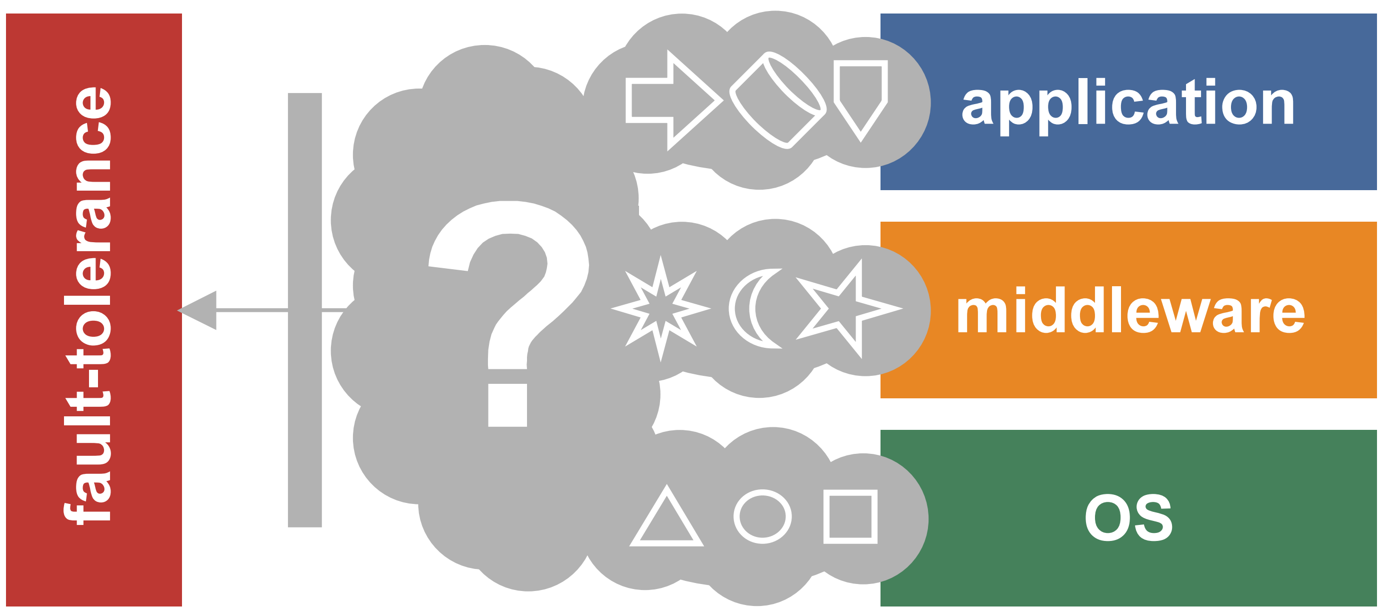
Revisiting our Goals

⇨ **How to integrate the views provided by each component into an holistic and consistent meta-model of the system ?**



Revisiting our Goals

What does fault-tolerance requires?



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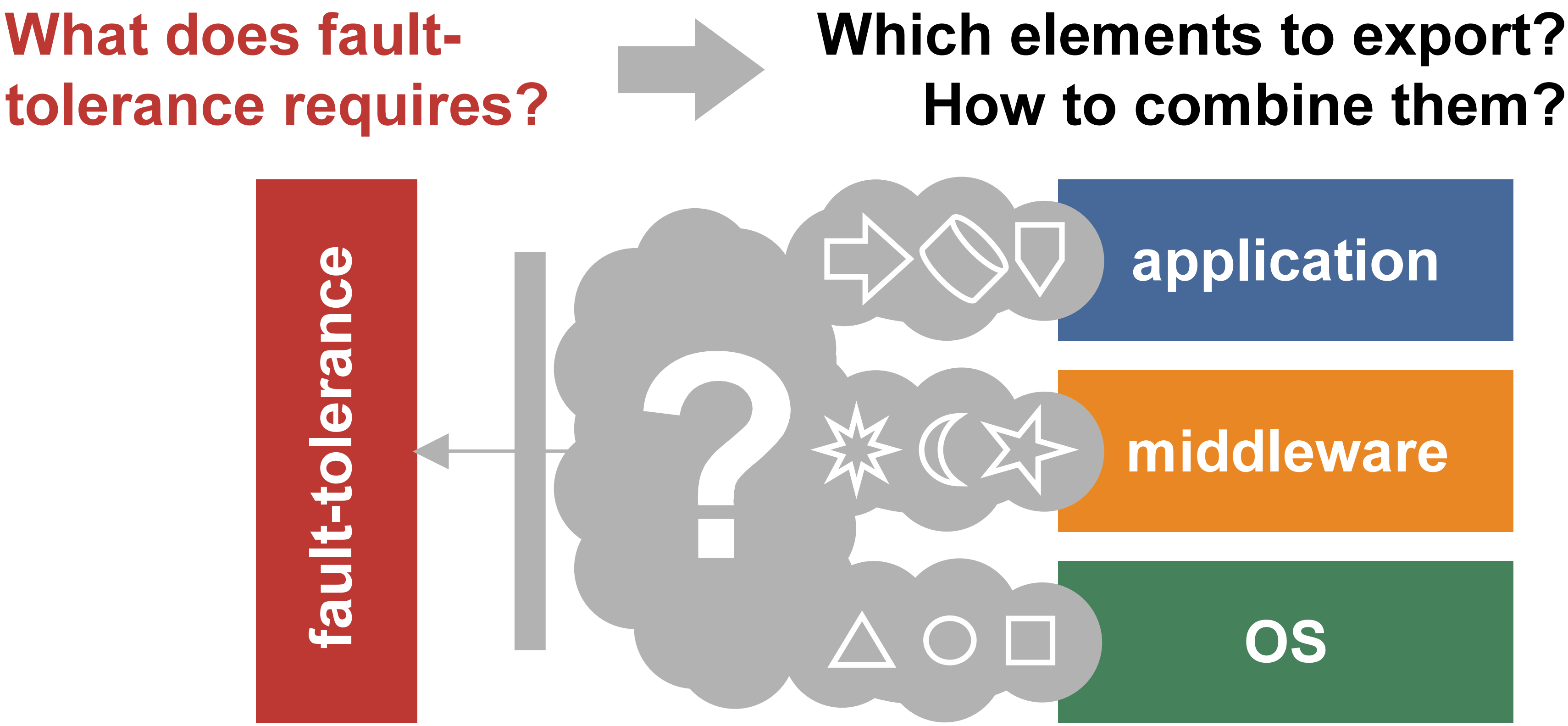
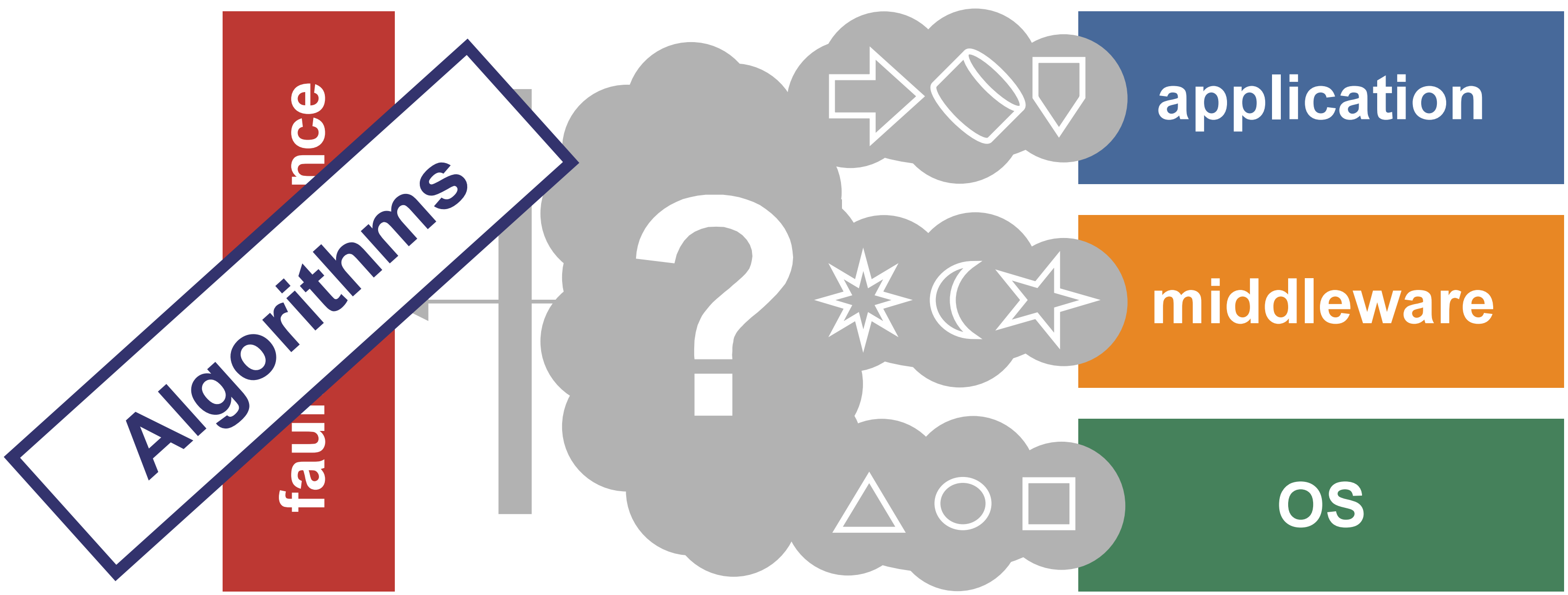


Revisiting our Goals

What does fault-tolerance requires? → Which elements to export? How to combine them?



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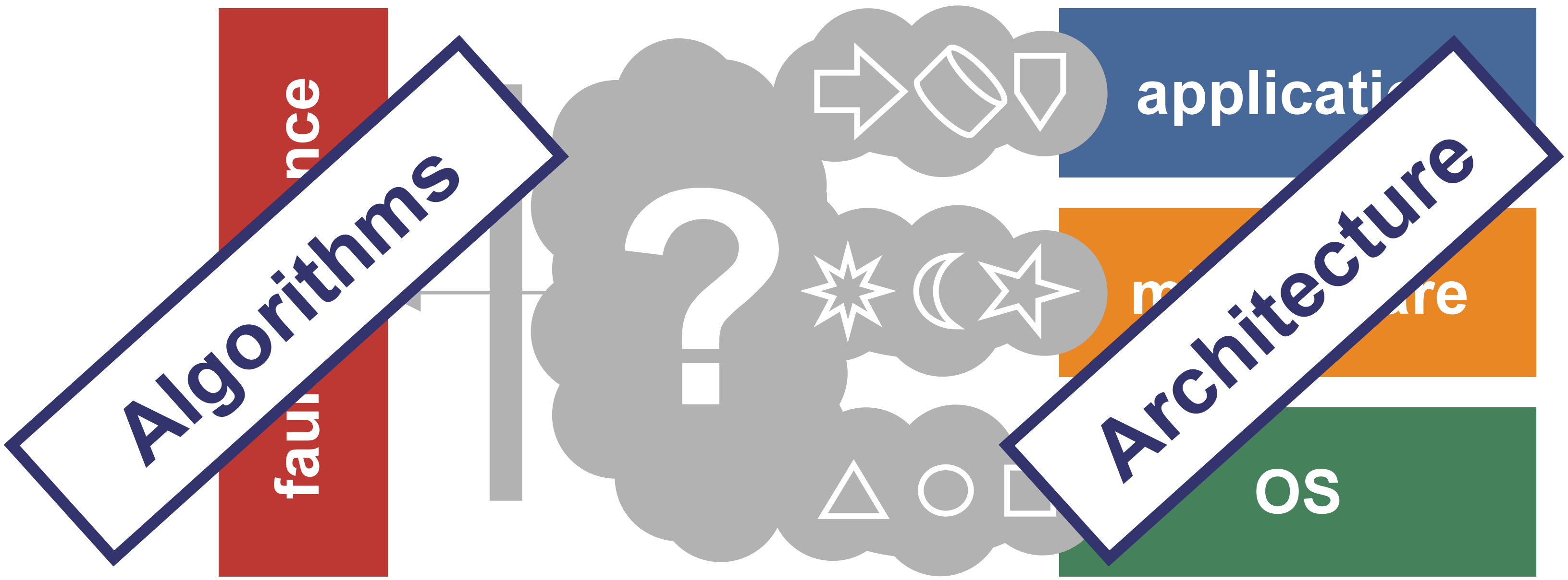

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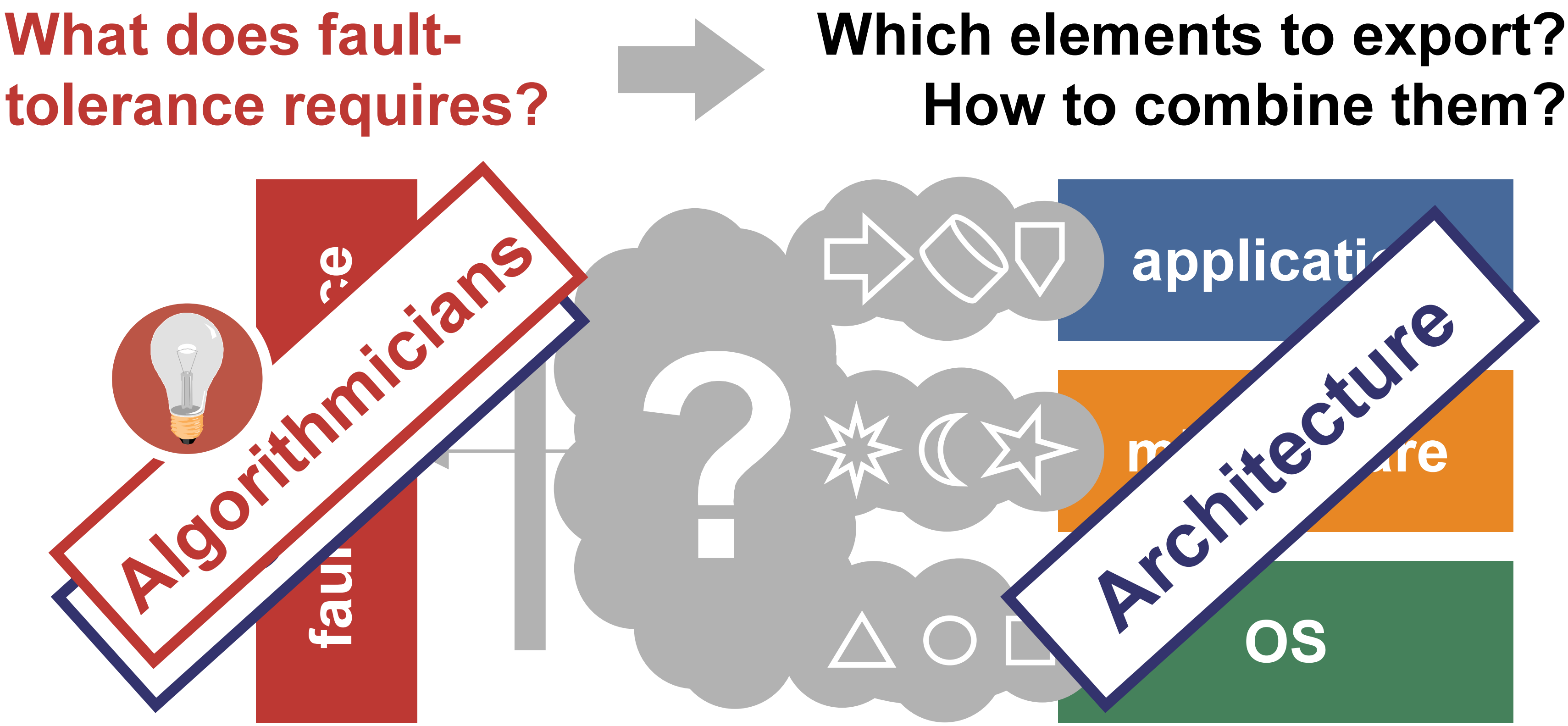

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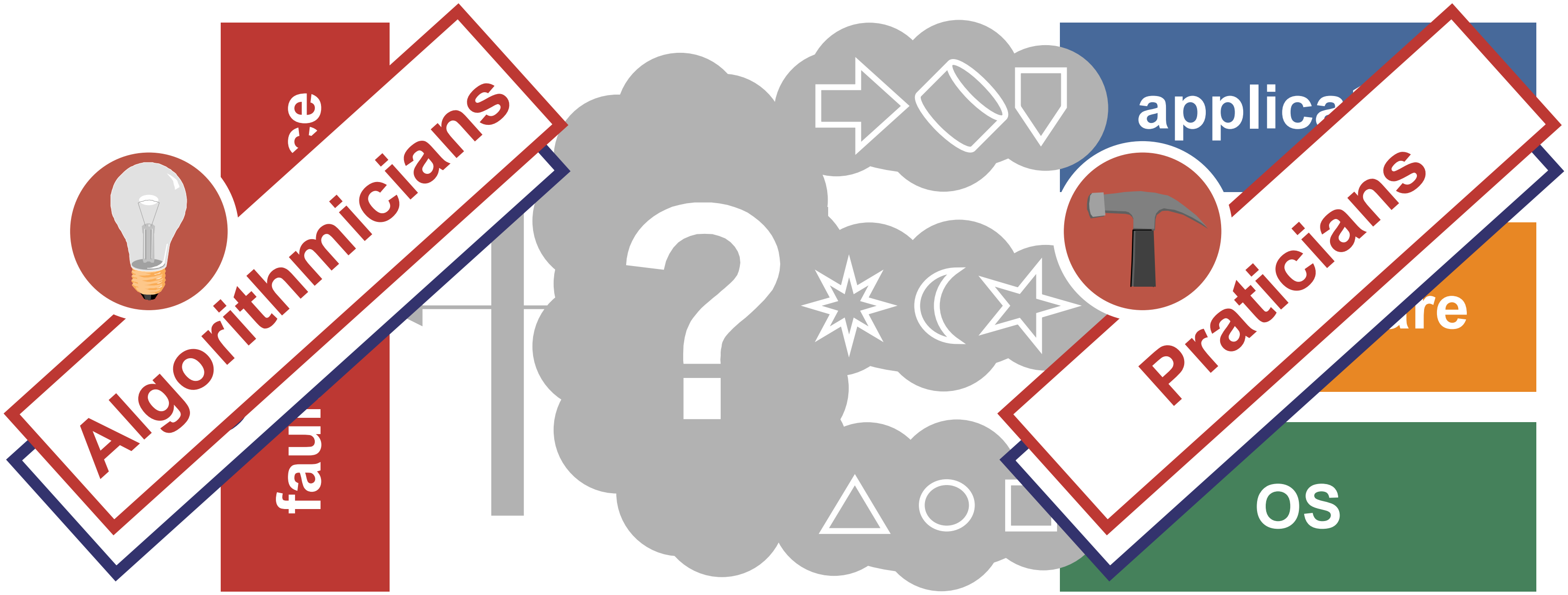
What does fault-tolerance requires? → Which elements to export? How to combine them?



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Operating Needs & Performances

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- A generic fault-tolerance algorithm ...
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  - ➔ In a complex system : "good" capacities are difficult to realize within a unique layer.
- **In a complex system, the precision of action and observation capacities is essential for fault-tolerance.**

Capturing Fault-Tolerance Needs

- Our proposal : Reflective Footprints
  - ➔ They explicitly capture the reflexive capacities that are needed by a family of mechanisms.
  - ➔ They uncouple algorithmic core from concrete instrumentation.
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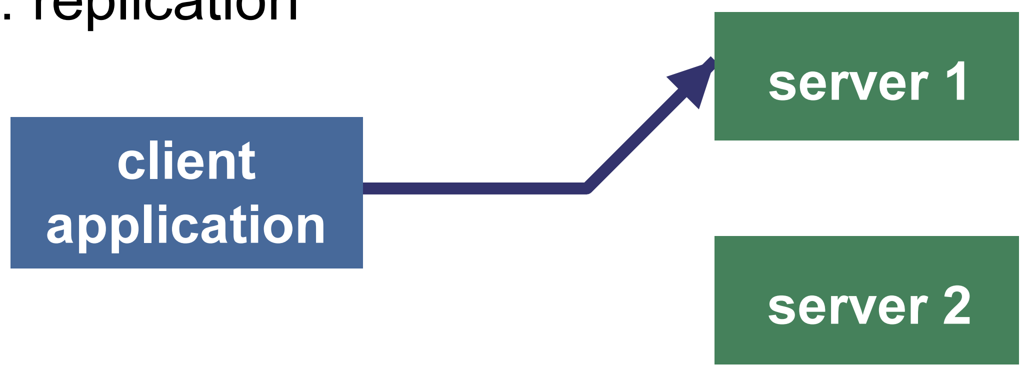

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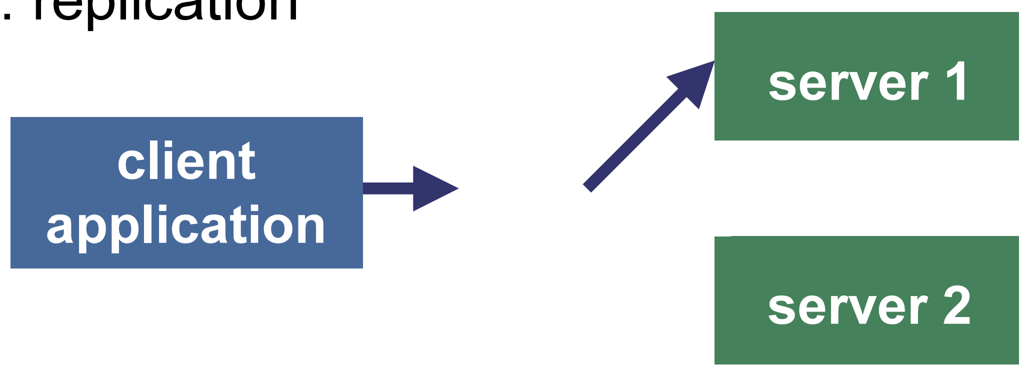

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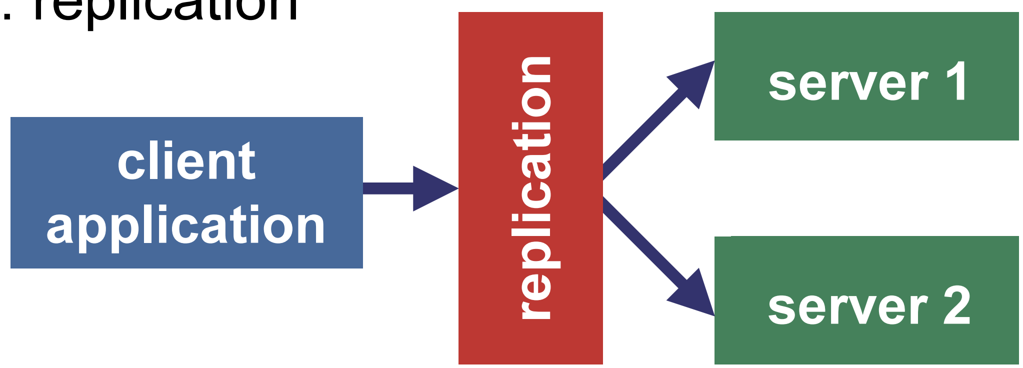

  - ➔ reflective footprint: a) message interception from client to servers
    b) state transfer
    c) controlling non-determinism … etc.

Reflective Footprints & Adaptation

- The reflective footprint of a set of FT mechanisms ...
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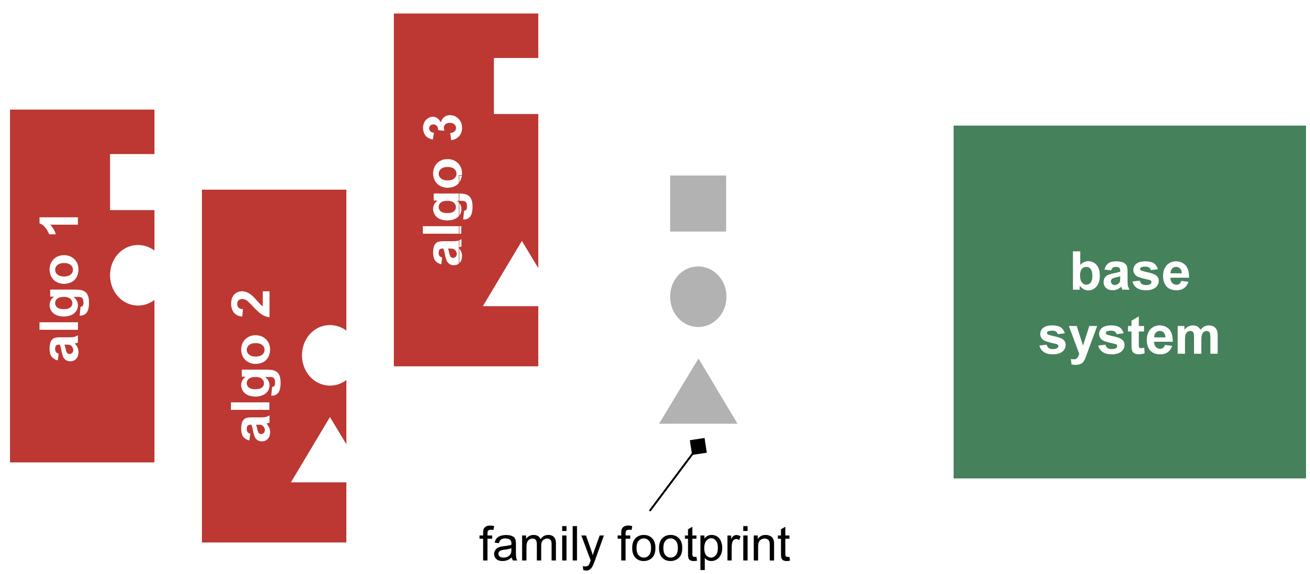

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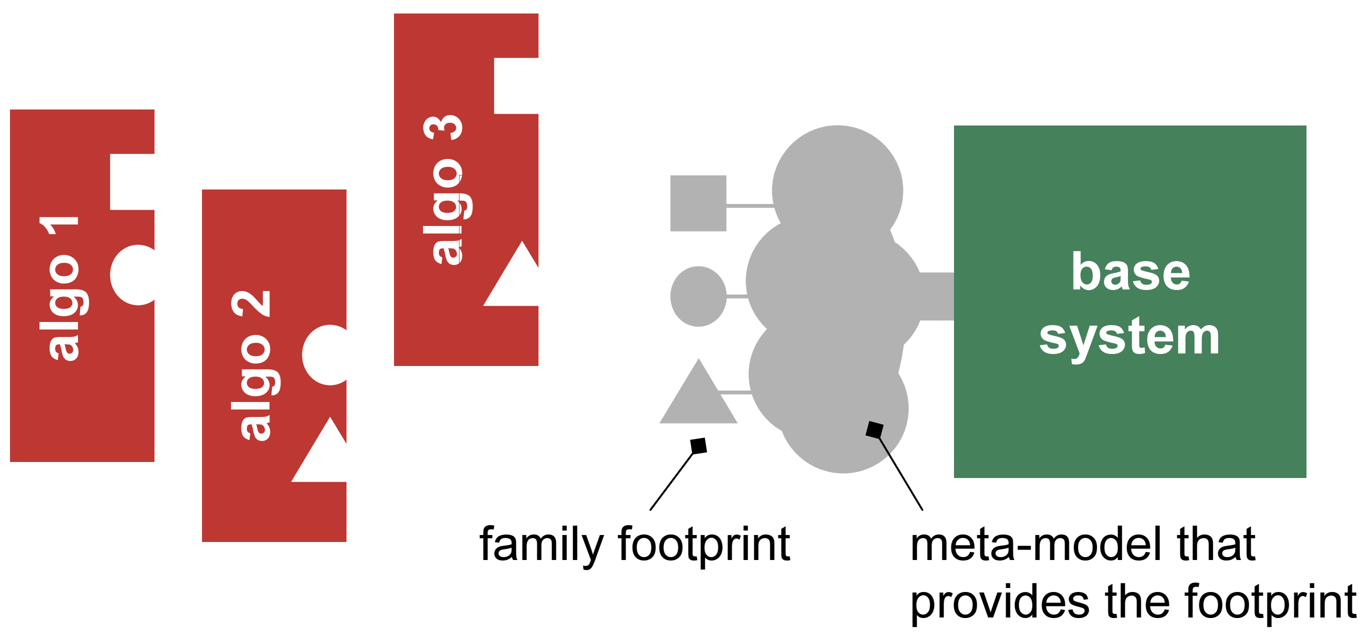

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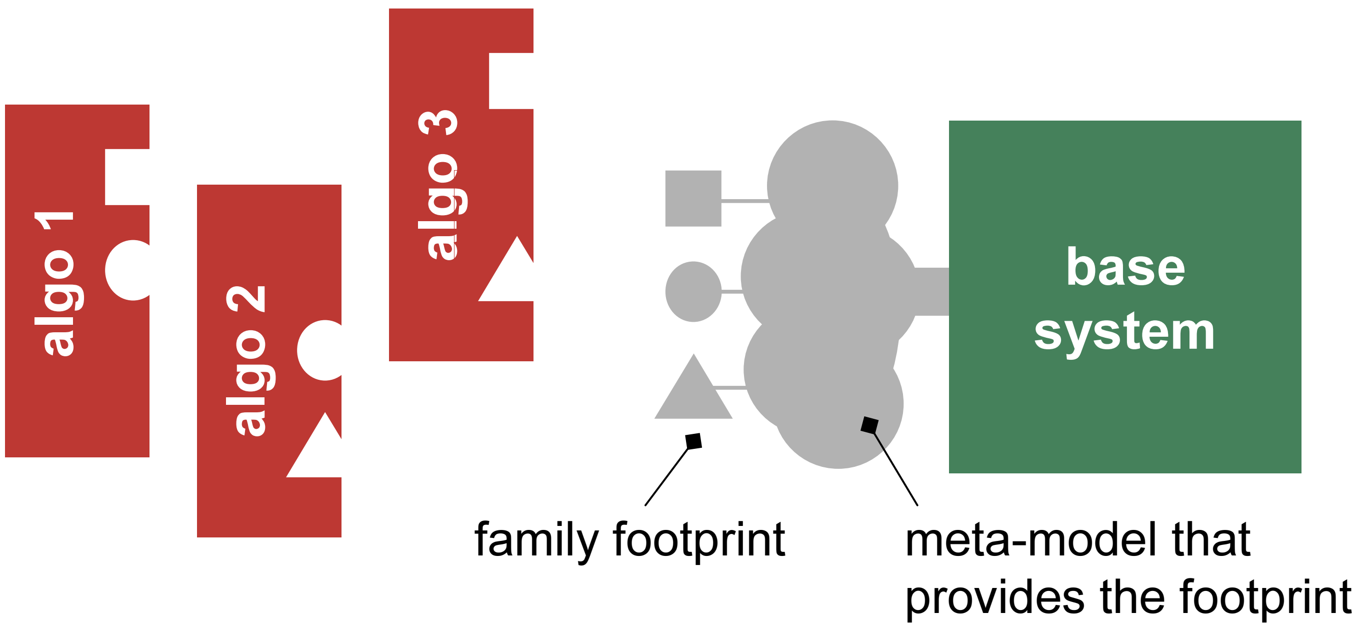

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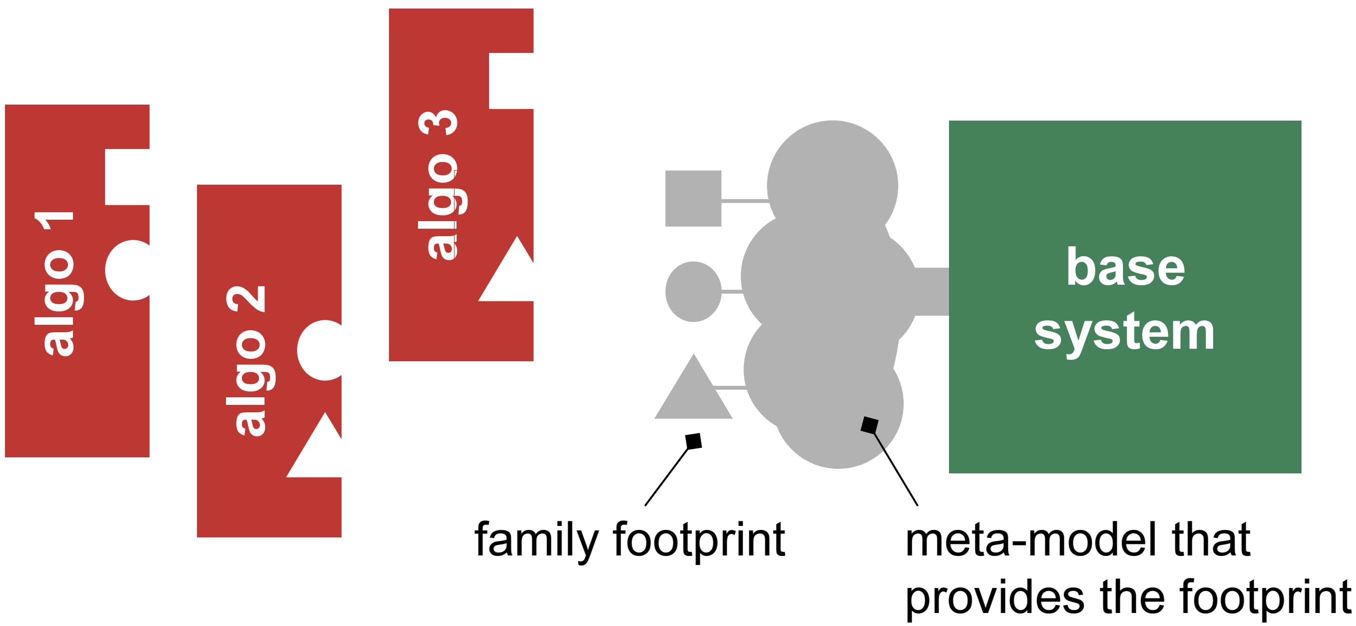

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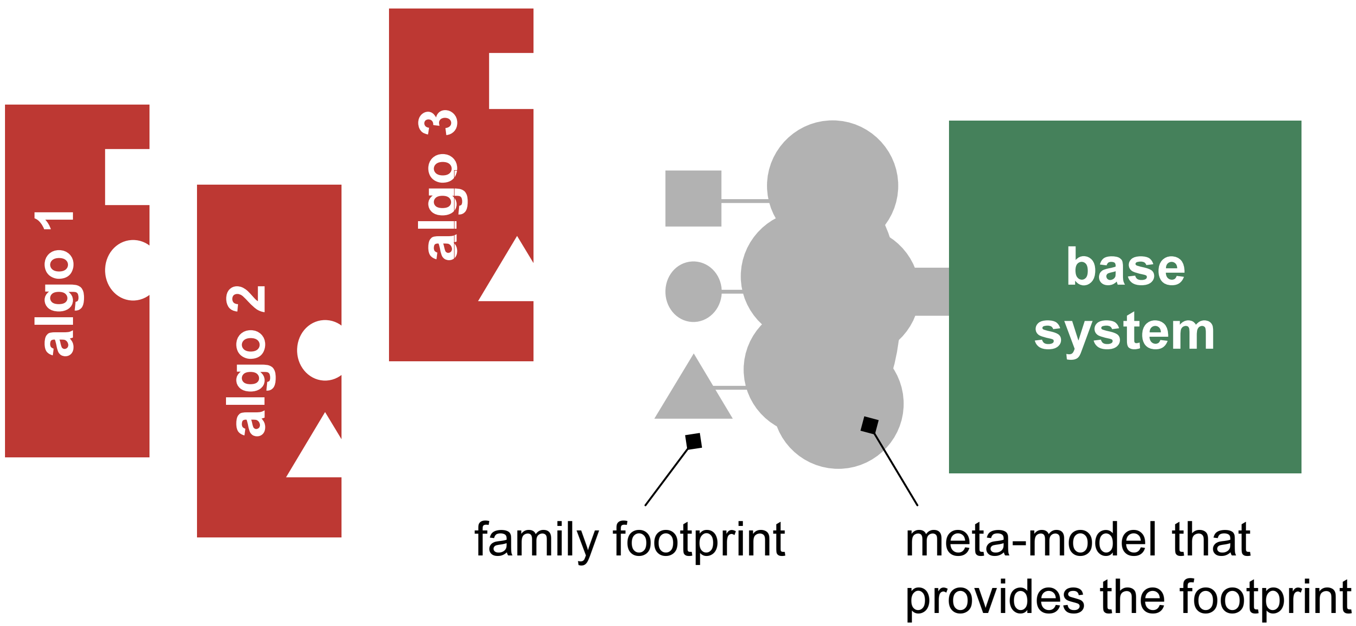
  - ➔ Lays the path for dynamic adaptation.



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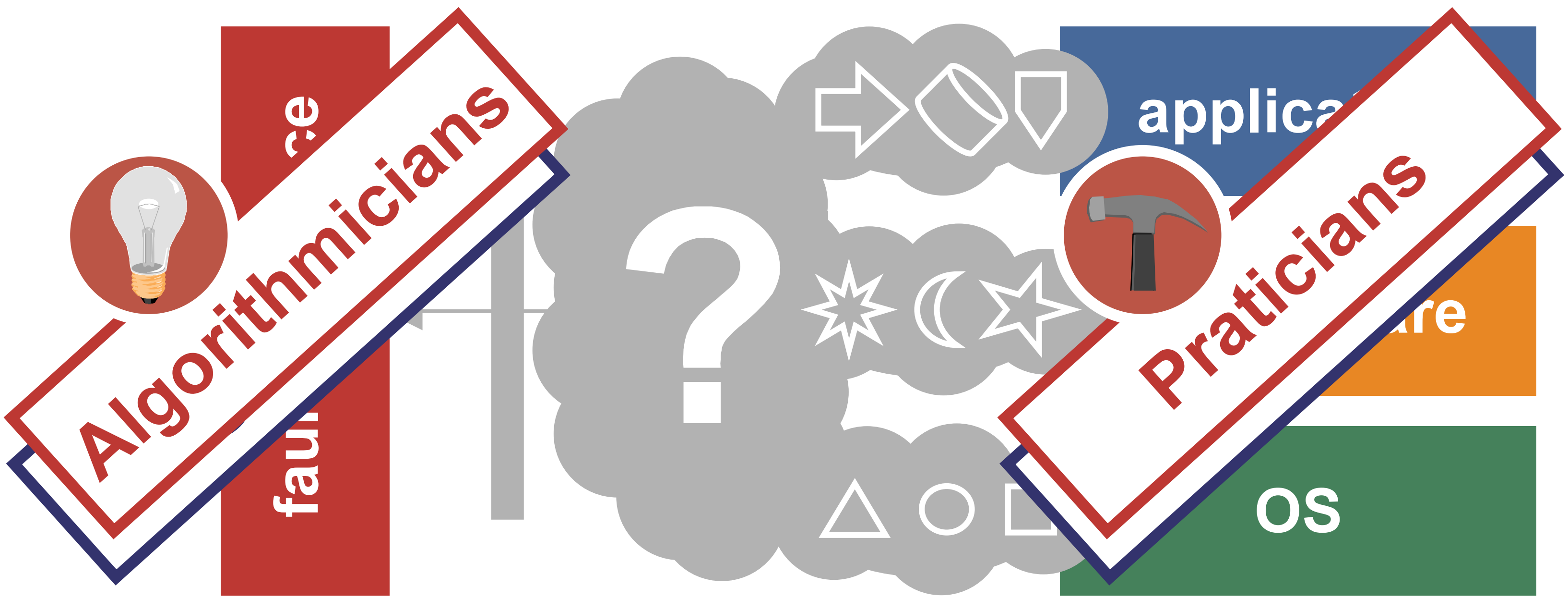

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Reflective footprints capture the reflexive needs for adaptable fault-tolerance.

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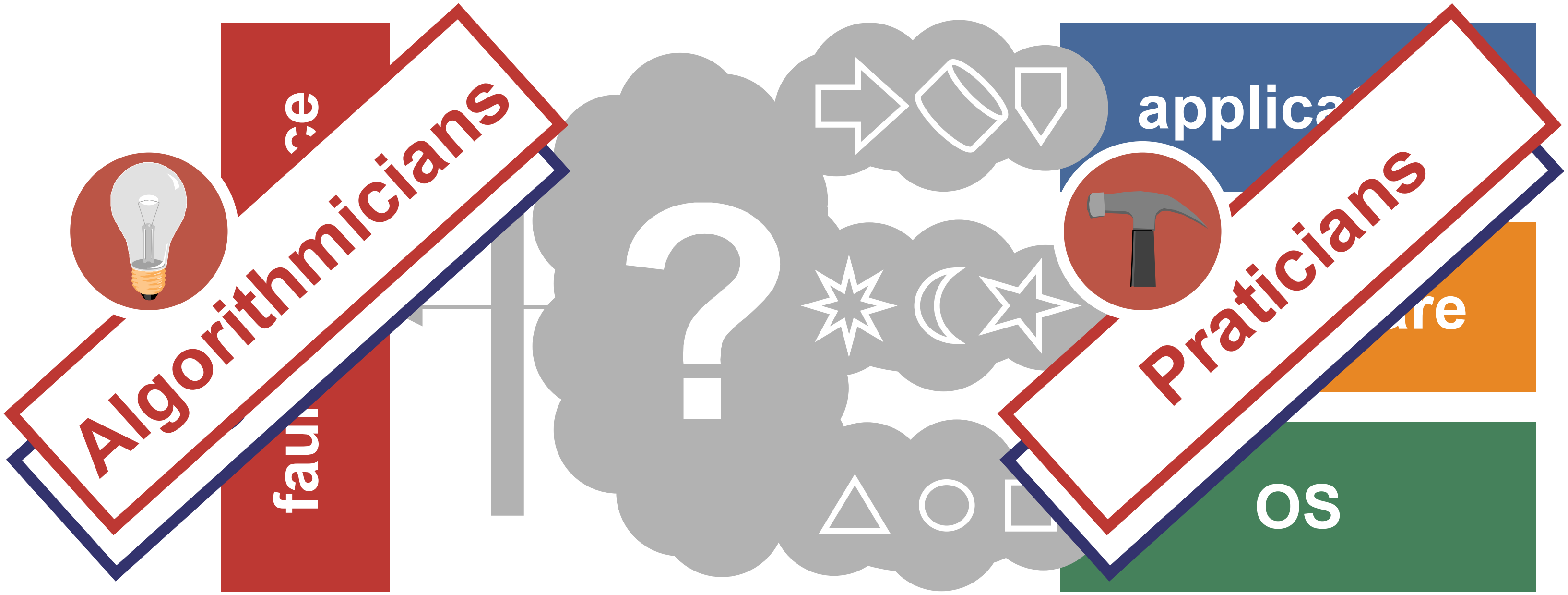

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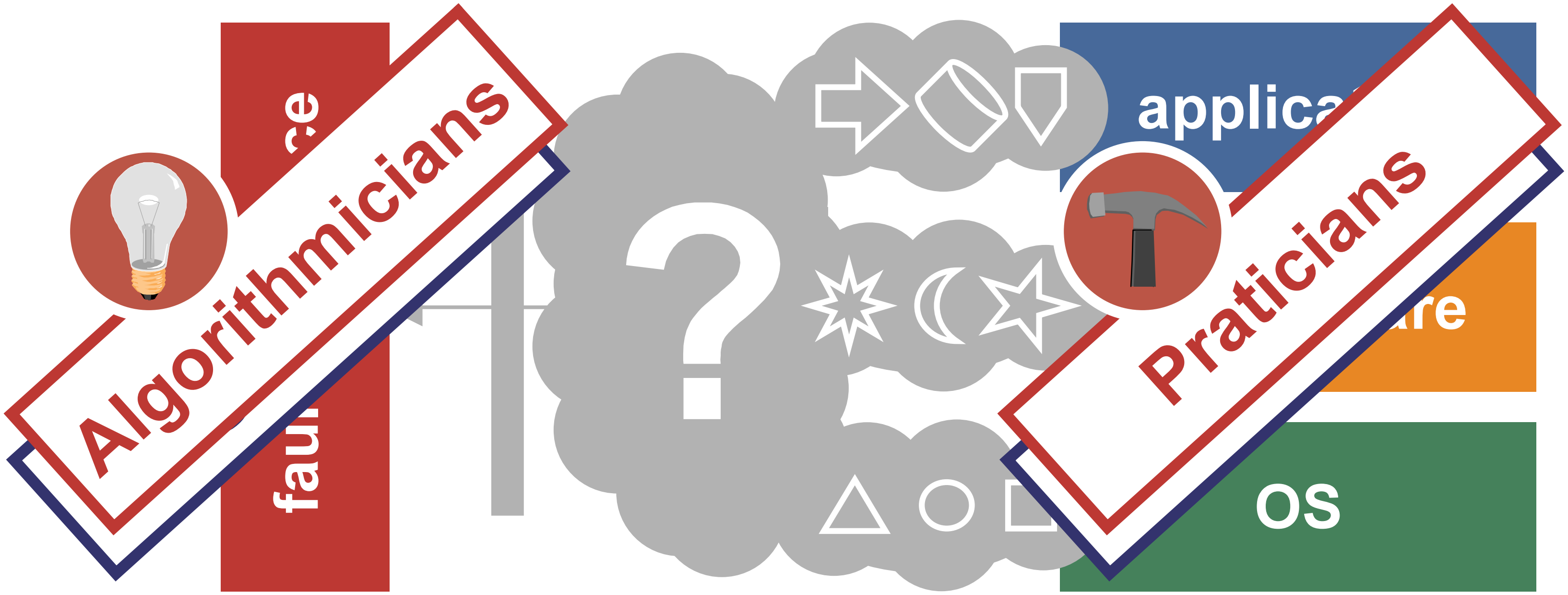
⇨ Where should we find the elements of a reflective footprint?



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Abstraction & Information

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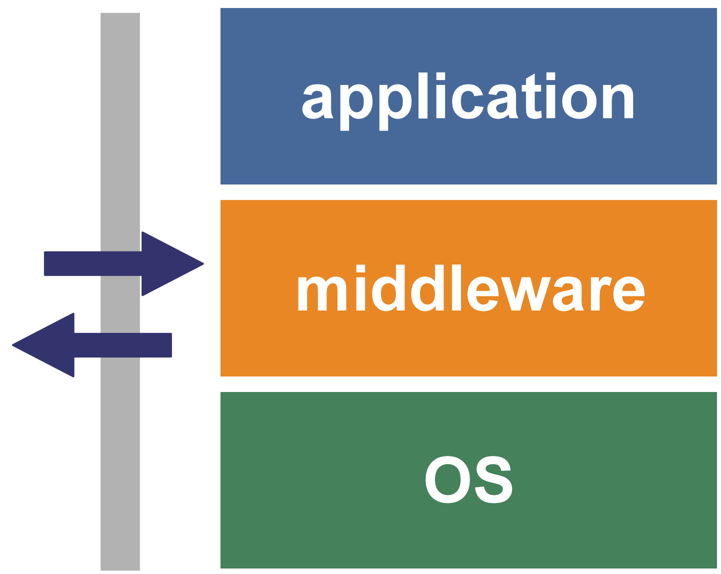

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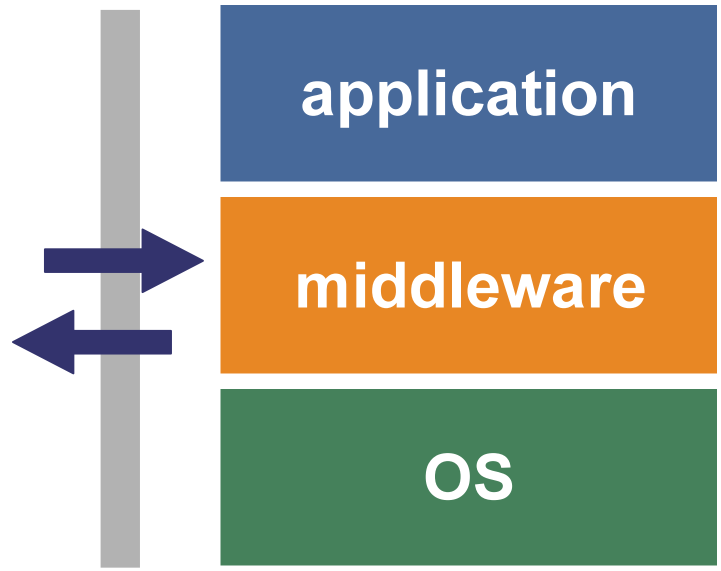
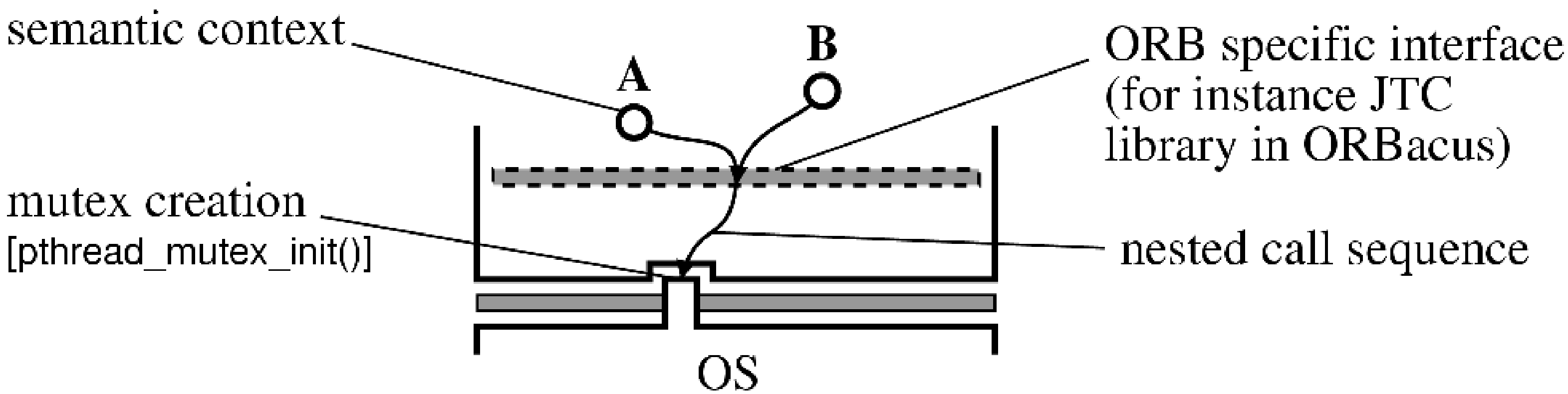


- **Mono-level approaches work poorly in complex systems:**
  - ➔ Lacking information: some mechanisms can't be implemented.
  - ➔ Lacking semantics ⇨ resulting solution gets intractable.

Transcending Software Boundaries

- A system's global semantics **transcends** its lower levels.
  - ➔ For instance: observing a POSIX (OS-level) socket creation
    - It could be the start of a CORBA request.
    - It could also be some part of a X11 invocation.
- Introducing **semantic contexts** : example on an ORB



- Intercepting lower level activities:
  On behalf of whom are we intercepting?

Inter-Level Mapping

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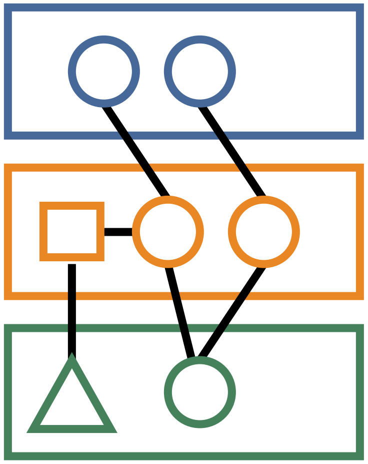

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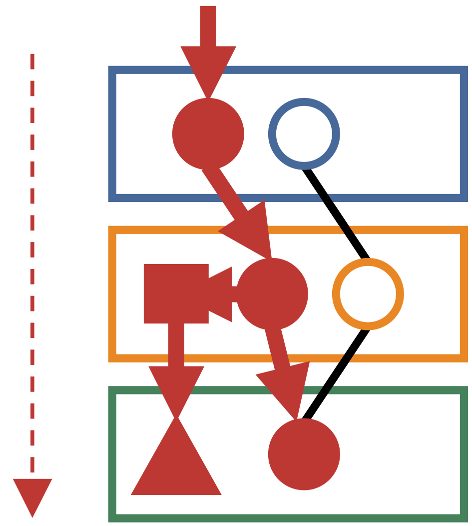

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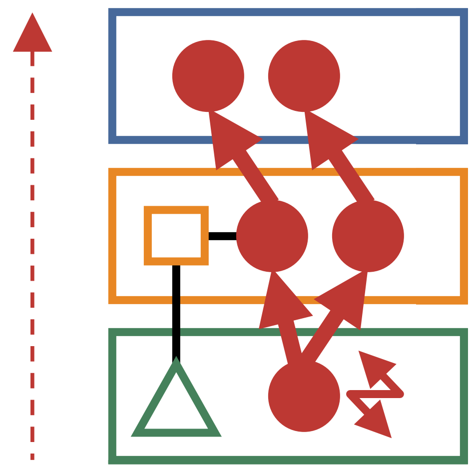
- Bottom-up use
  - ➔ error propagation analysis
  - ➔ forward recovery



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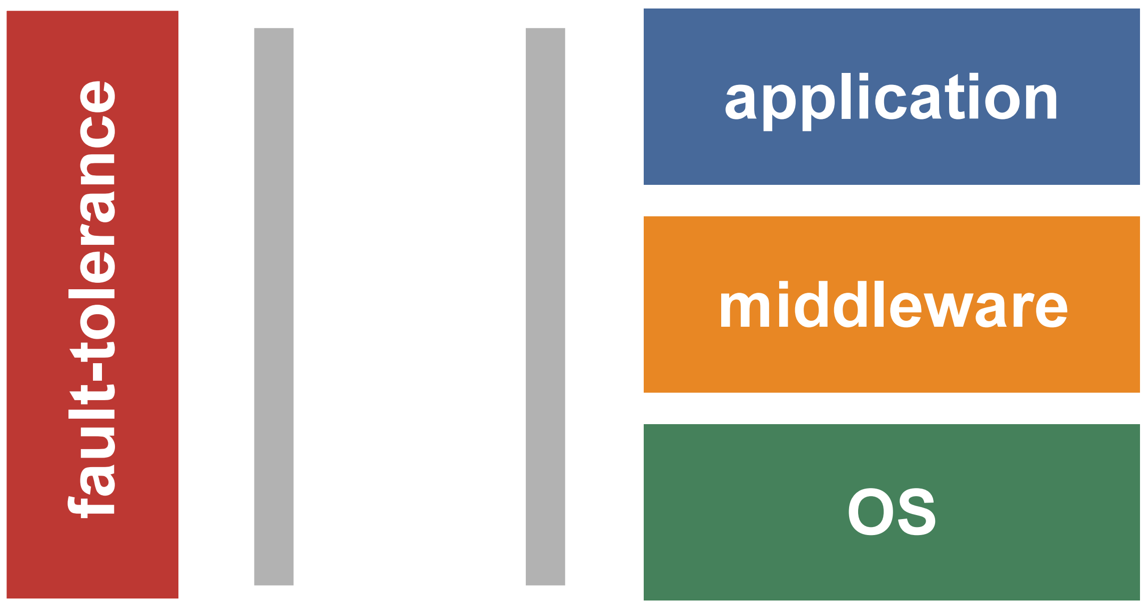

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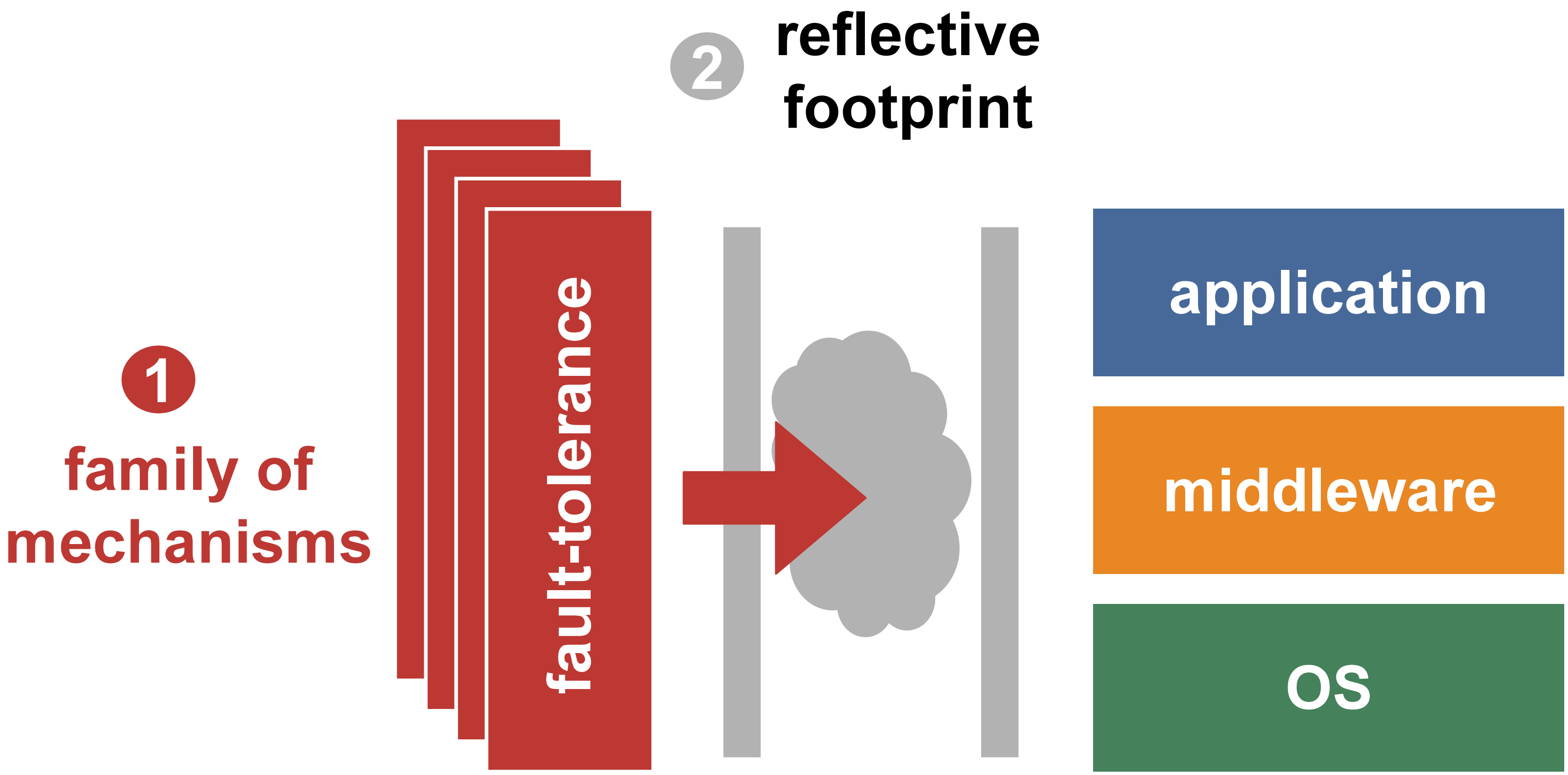

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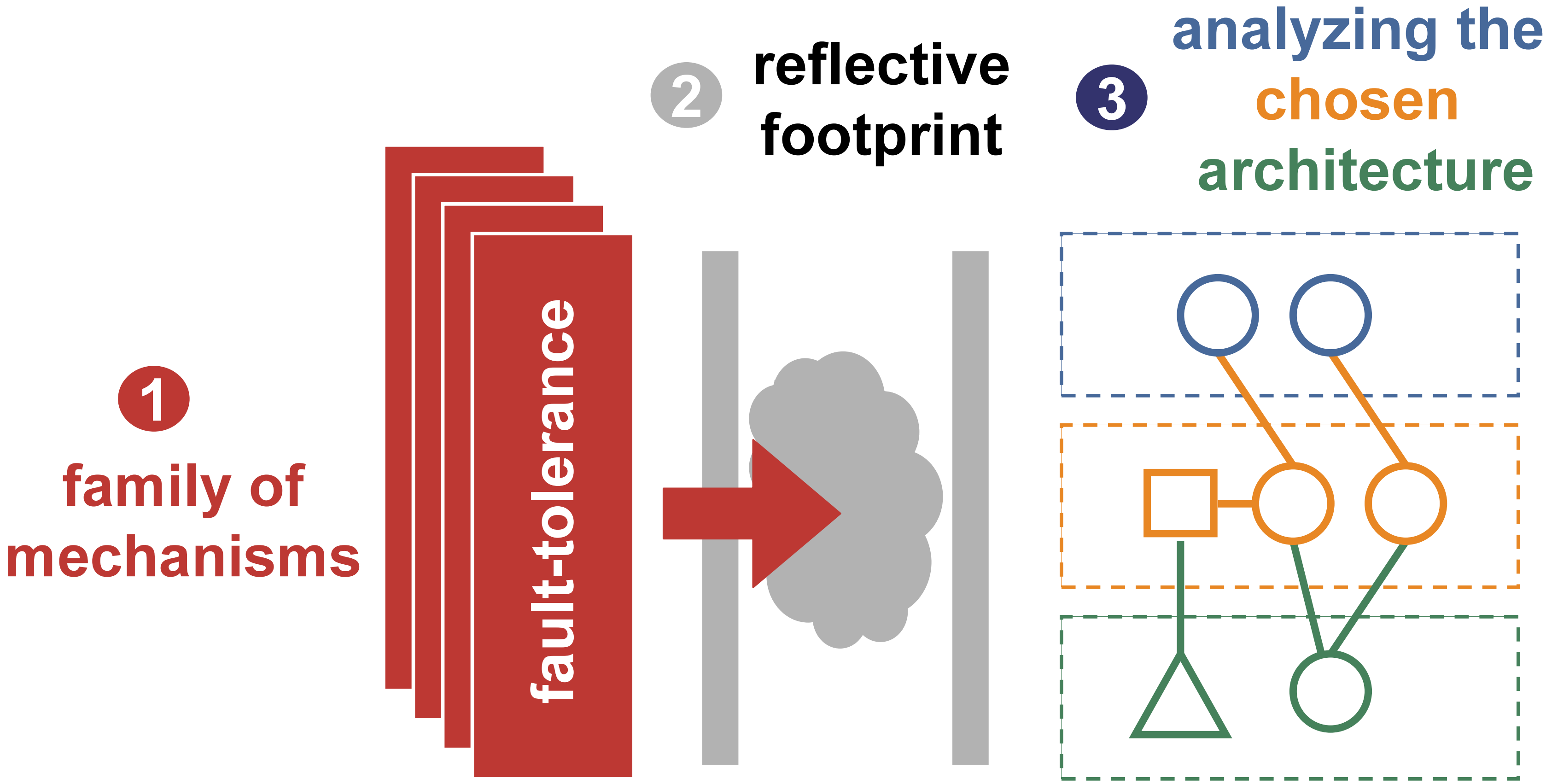

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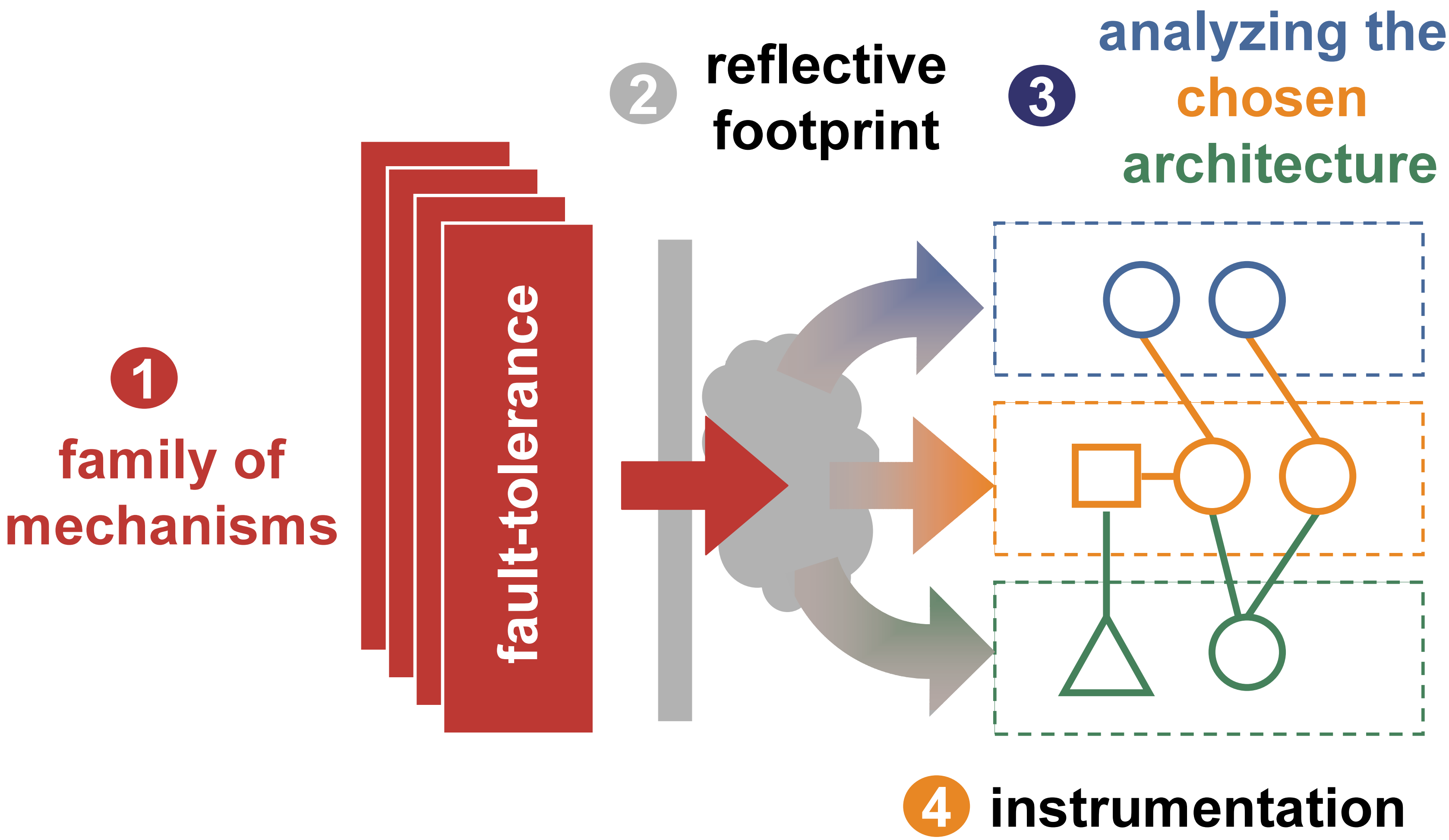

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Case Study: Replication & Multithreading

- **Goal**: Transparent replication of a CORBA server
  - ➔ multi-layer: **POSIX** (OS) + **CORBA** (middleware)
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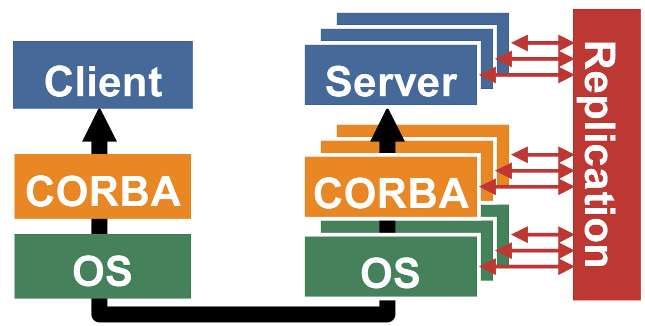

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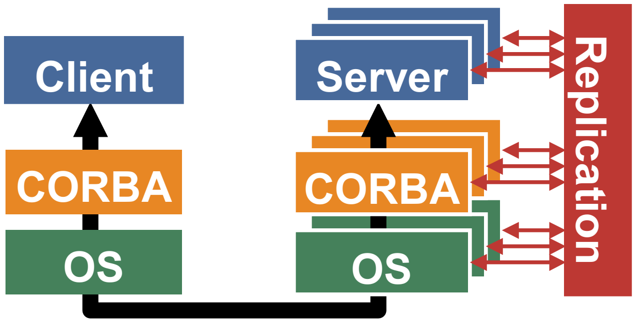
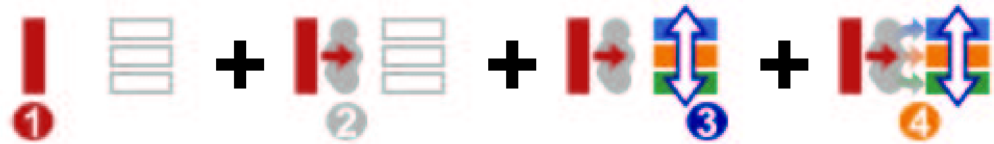


⇨ We use the 4 steps of our approach.



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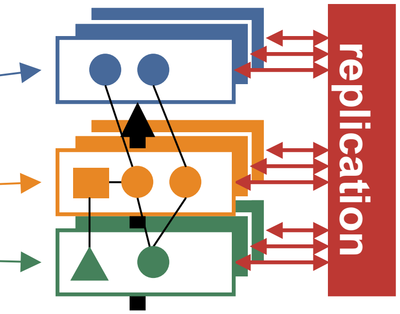

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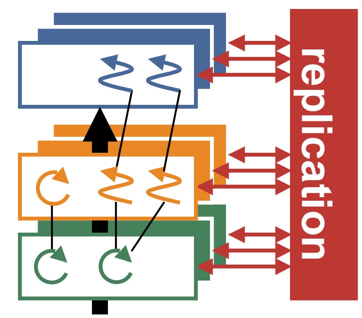

- ***Problem 1:*** state capture / restoration
  - ➔ application state
  - ➔ middleware + OS state
- ***Problem 2:*** control of non-determinism
  - ➔ assumption: multi-threading only source of non-determinism
  - ➔ how to replicate non-deterministic scheduling decisions?

Replication's Footprint

Reflexive Facets

	Communication	***Execution***	***State***
Observation	RequestReception RequestSending ReplySending ReplyReception	ExecutionPointStart ExecutionPointEnd ExecutionPointReach NonDeterministicFlowChange	NonDeterministicPlatformCall
	getRequestContent getReplyContent	getExecutionPoint	getServerState getPlatformState
Action	doSend doReceive	createExecutionPoint setExecutionPoint forceResultOfFlowChange	forceResultOfPlatformCall
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Implementing the Footprint

- Some elements of a software architecture are more stable than others.
  - ➔ Standard interfaces (CORBA, POSIX) remain (for a while).
  - ➔ Implementations (ORBacus, GNU/Linux) change (rapidly).

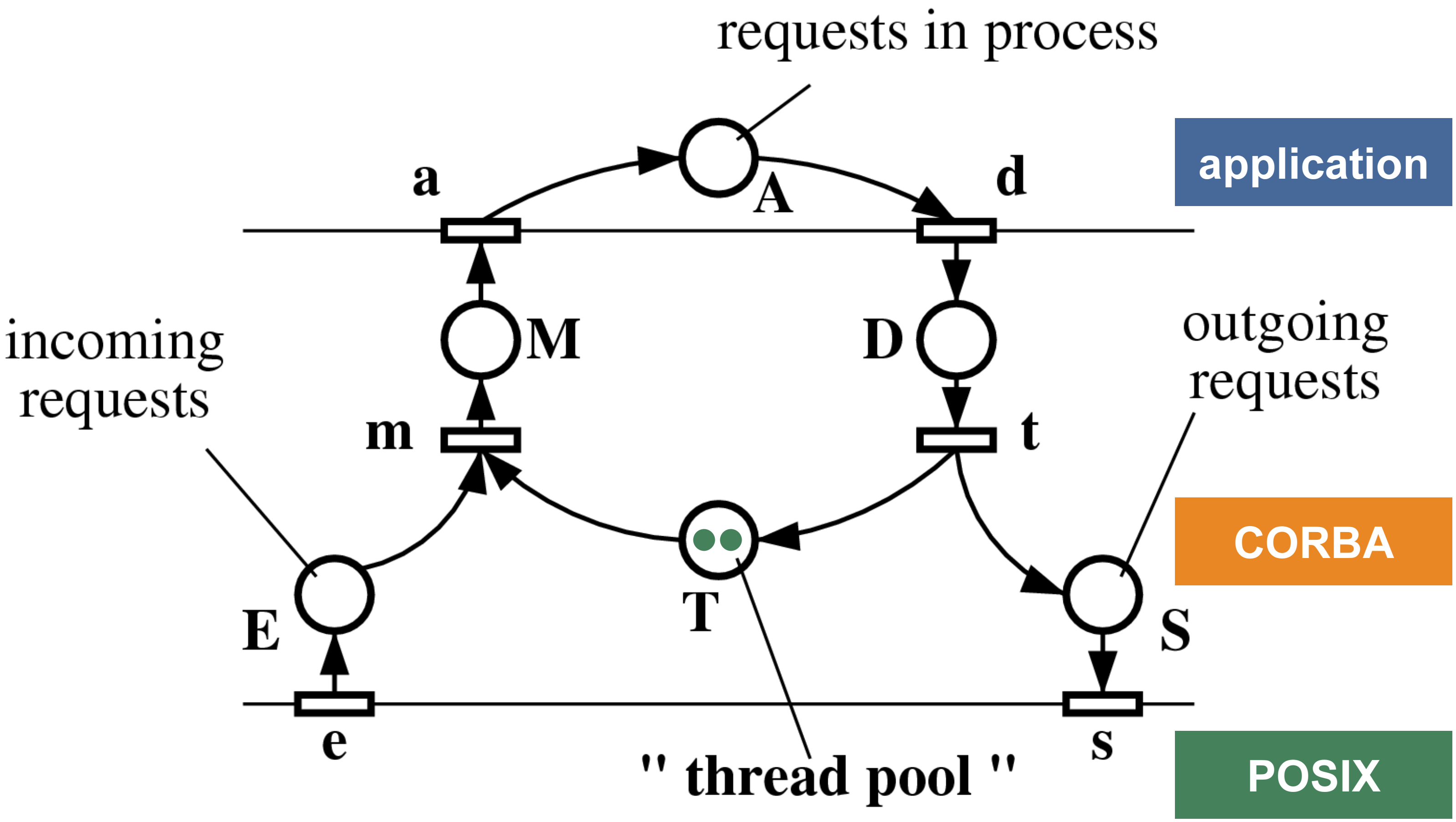
➔ Footprint **implementation** in **2 steps :**

Analysis : investigating the CORBA⬄ POSIX mapping

- ➔ By factorizing our knowledge of several ORBs
- ➔ The resulting (meta-)model covers all implementations.
- ➔ We use the model to identify instrumentation points.

Concrete implementation on ORBacus + GNU/Linux

Investigating the CORBA⇔ POSIX Mapping



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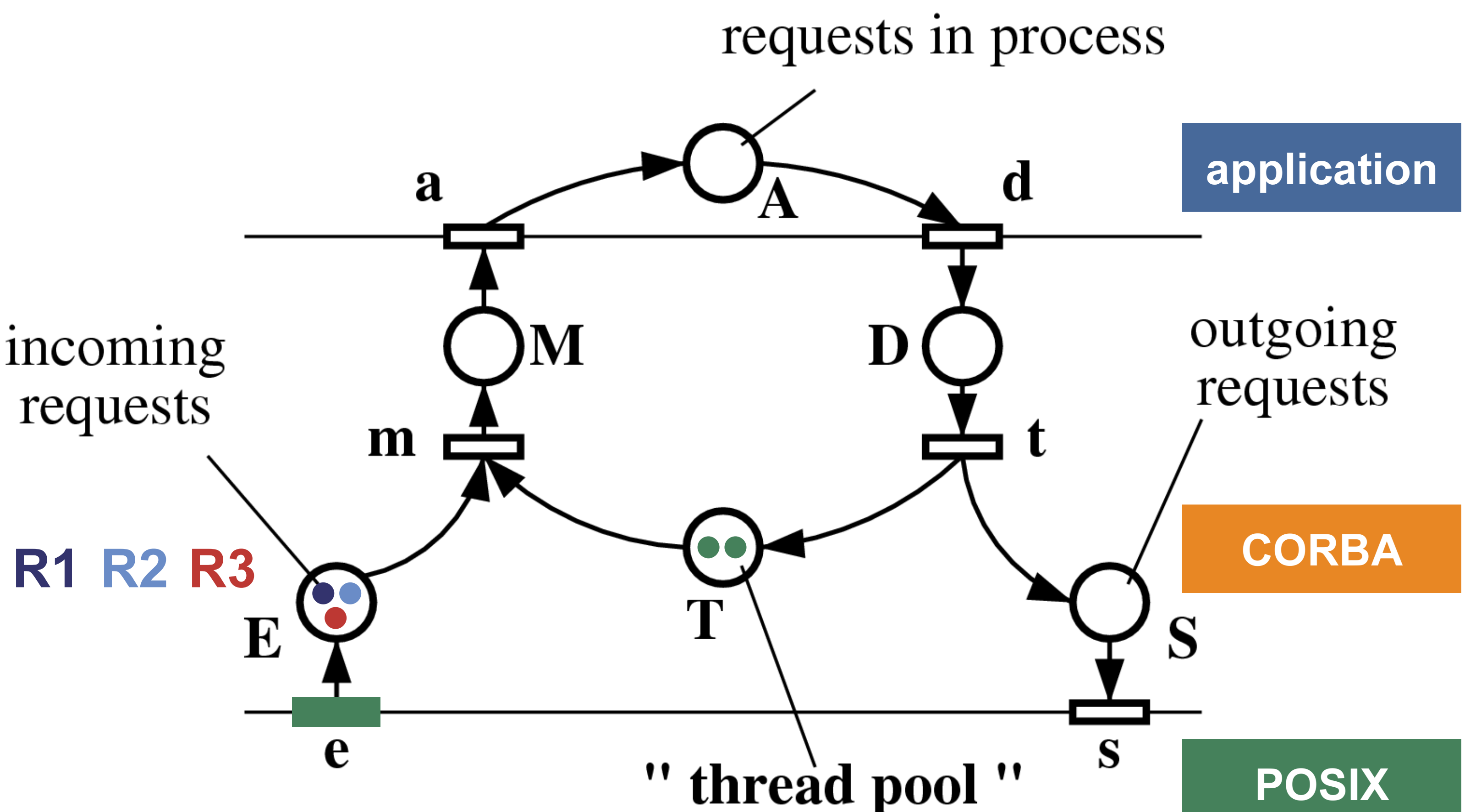

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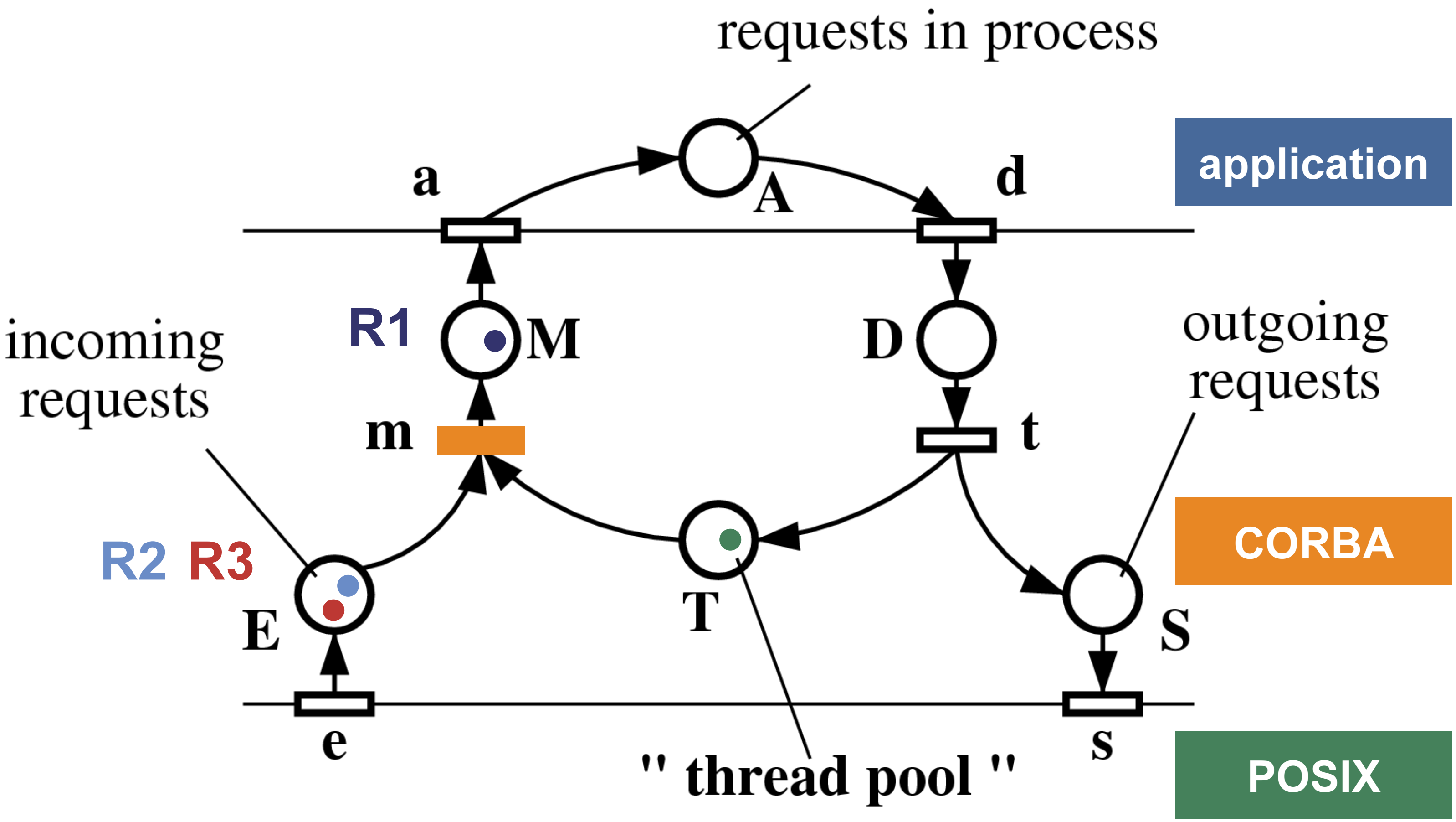

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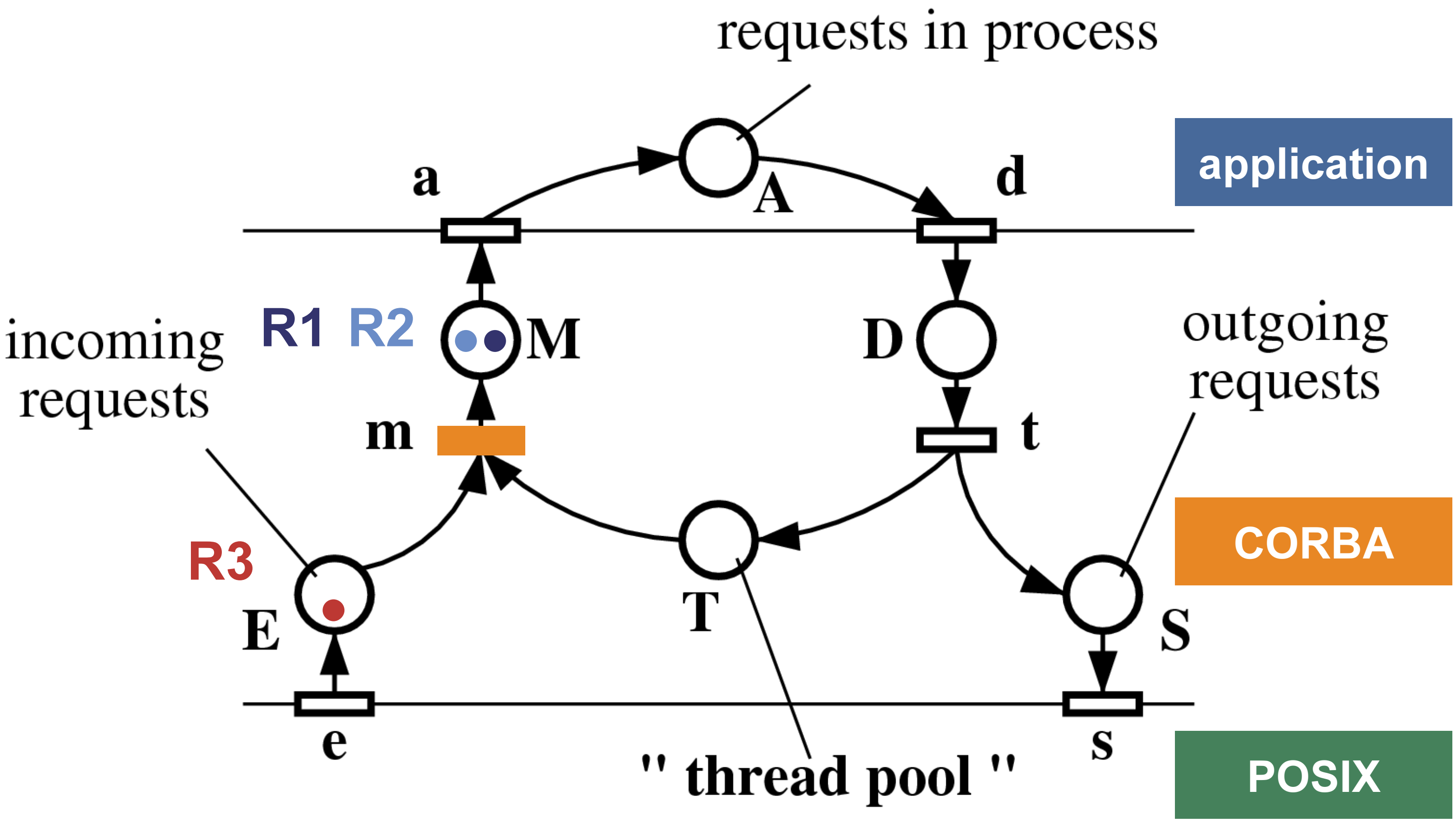

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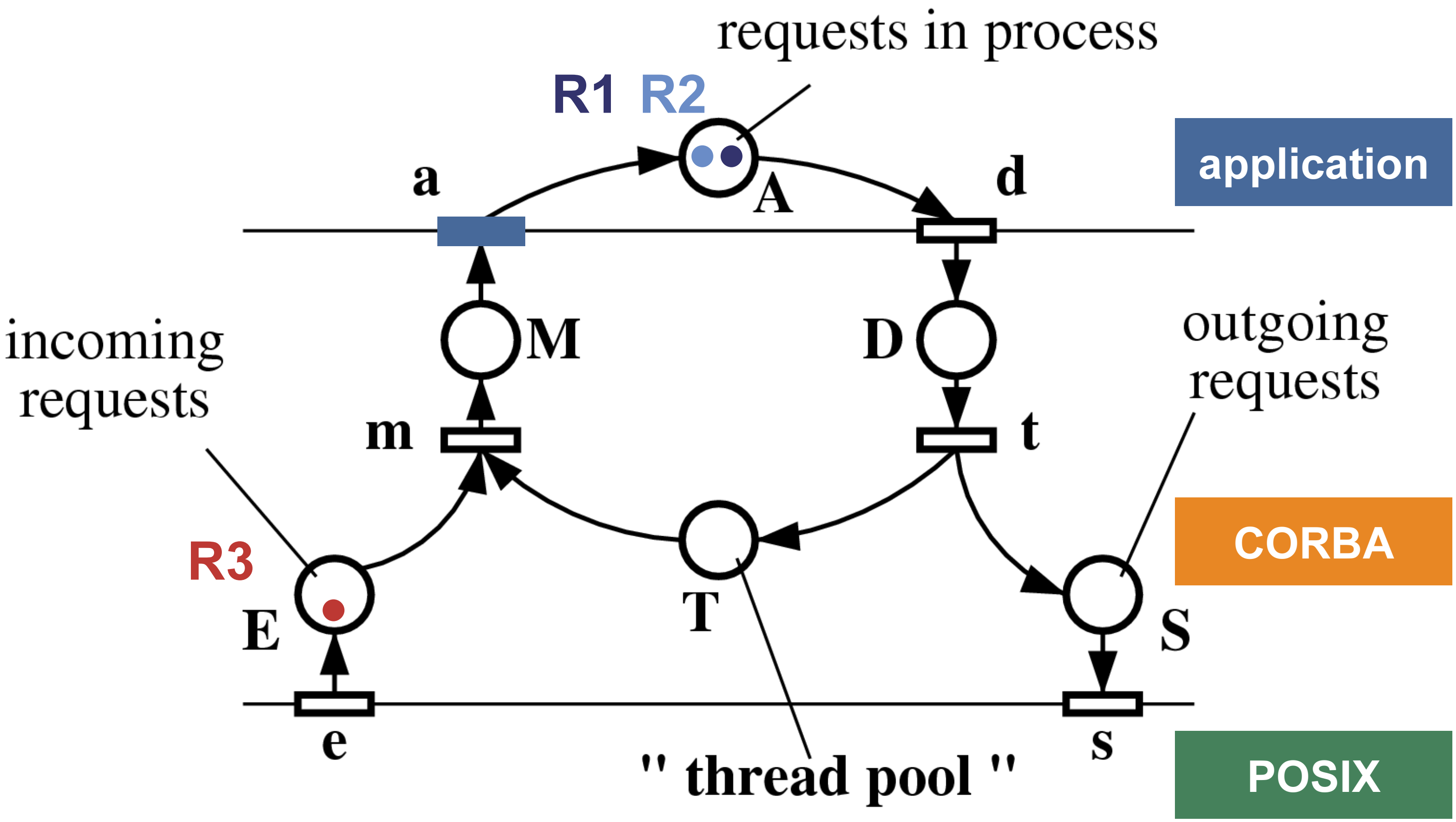

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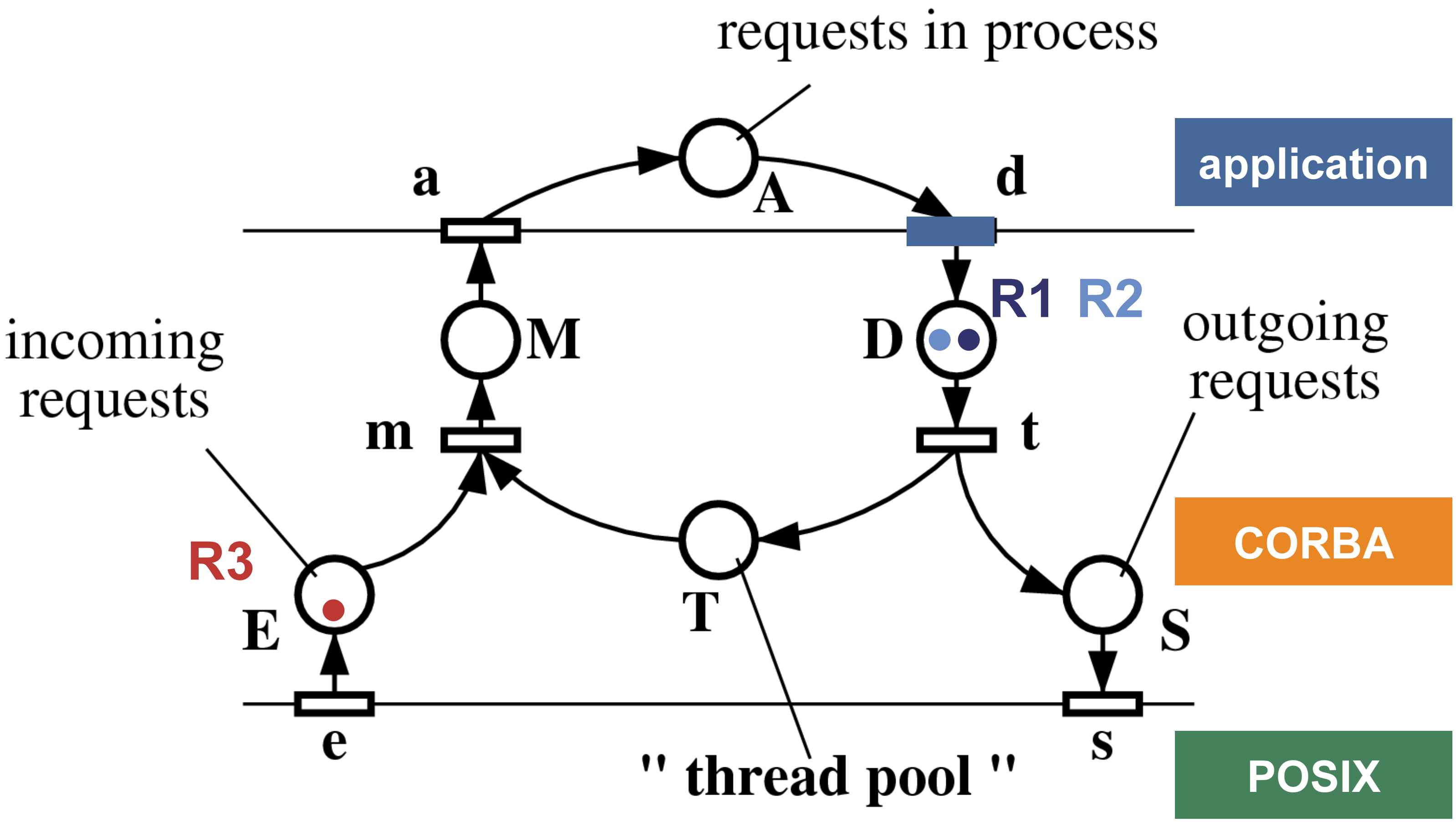

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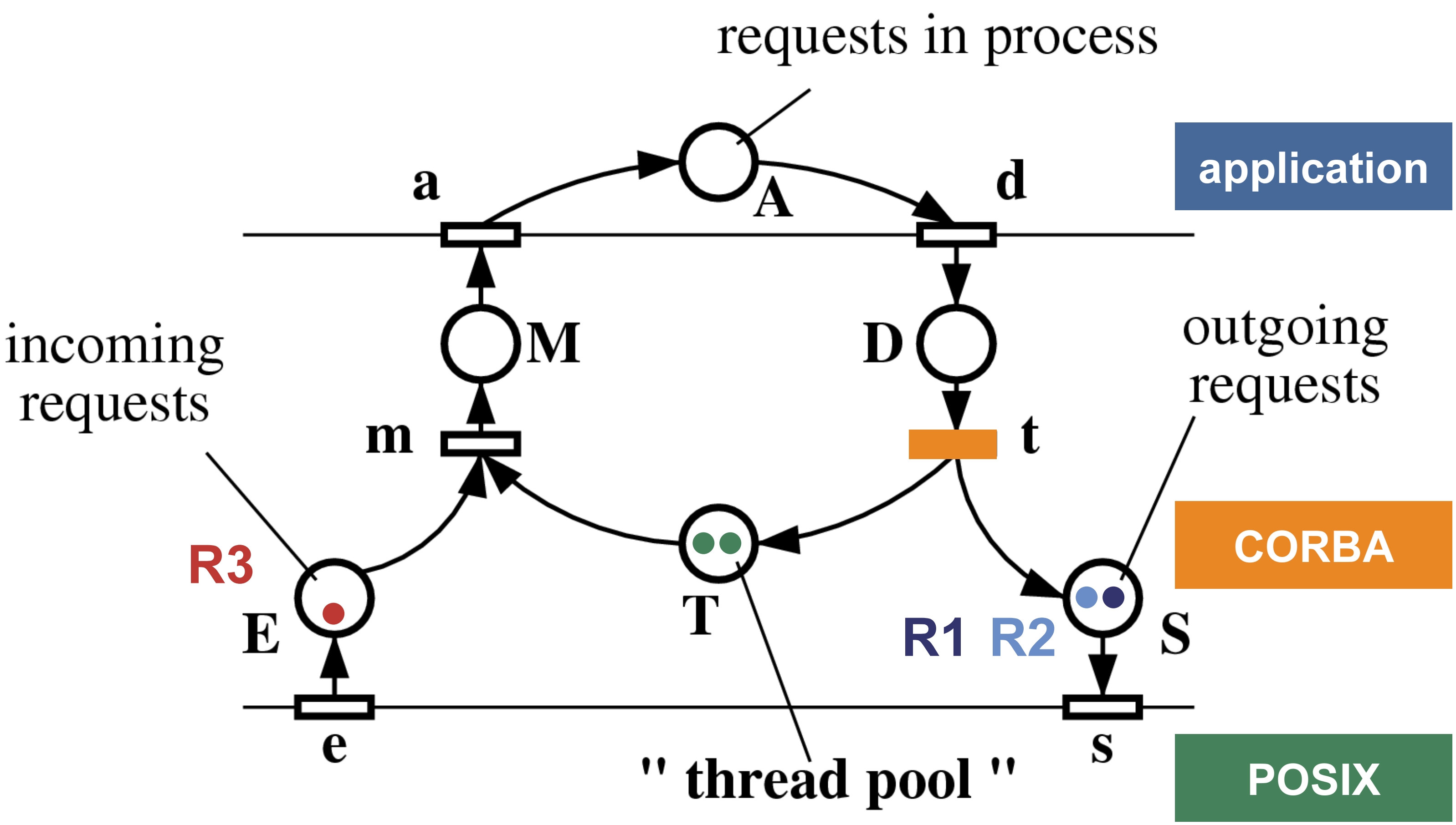

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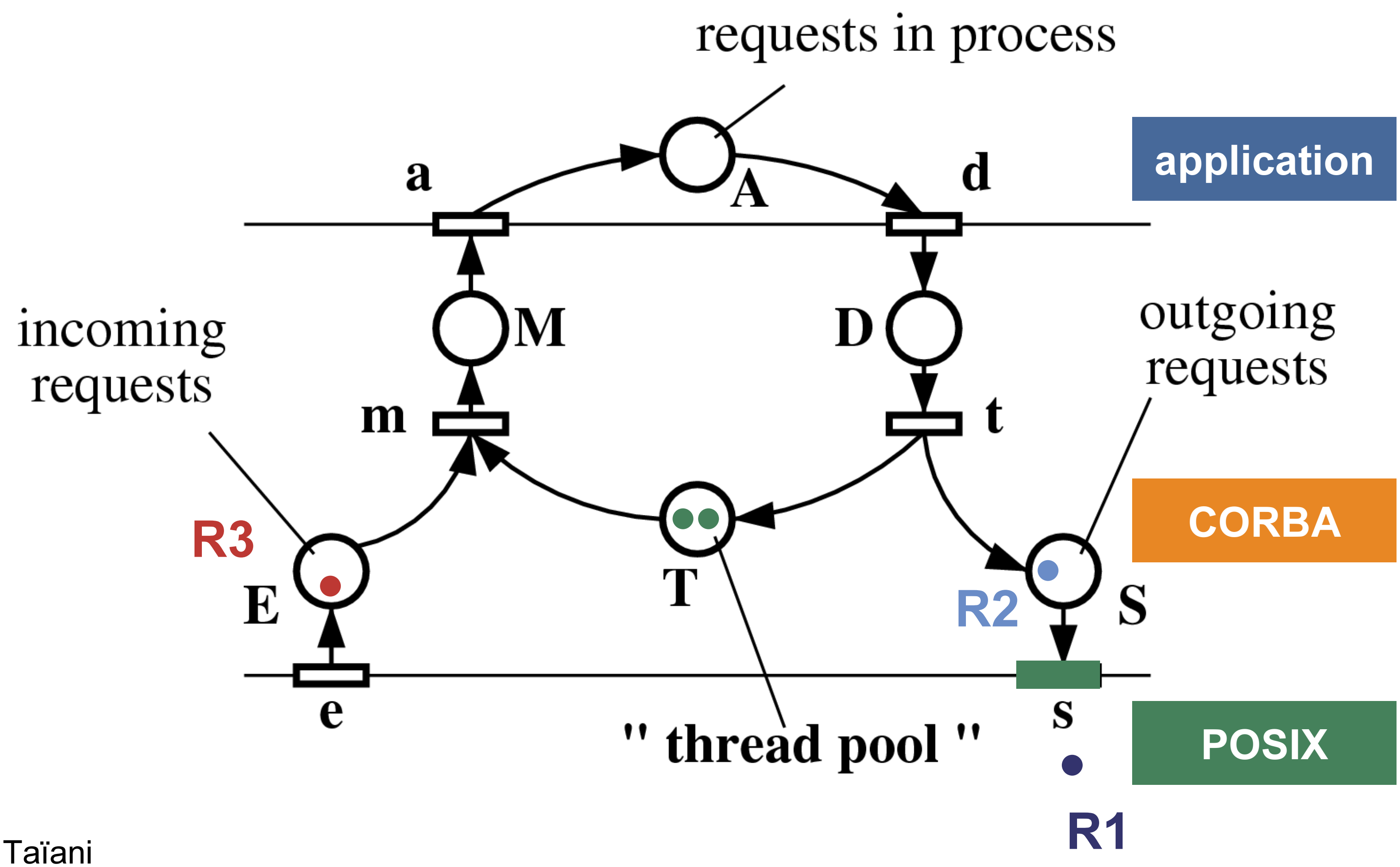

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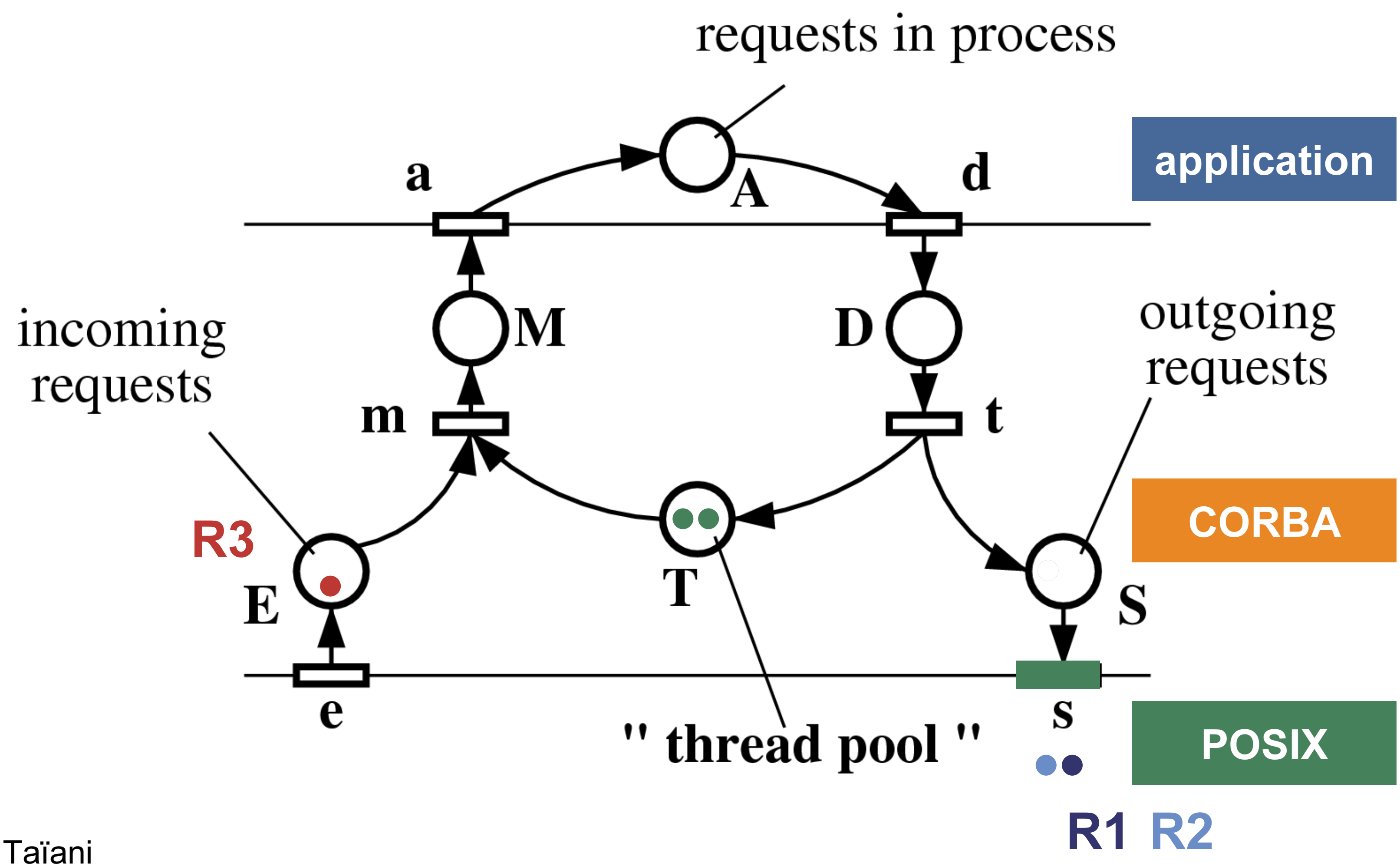

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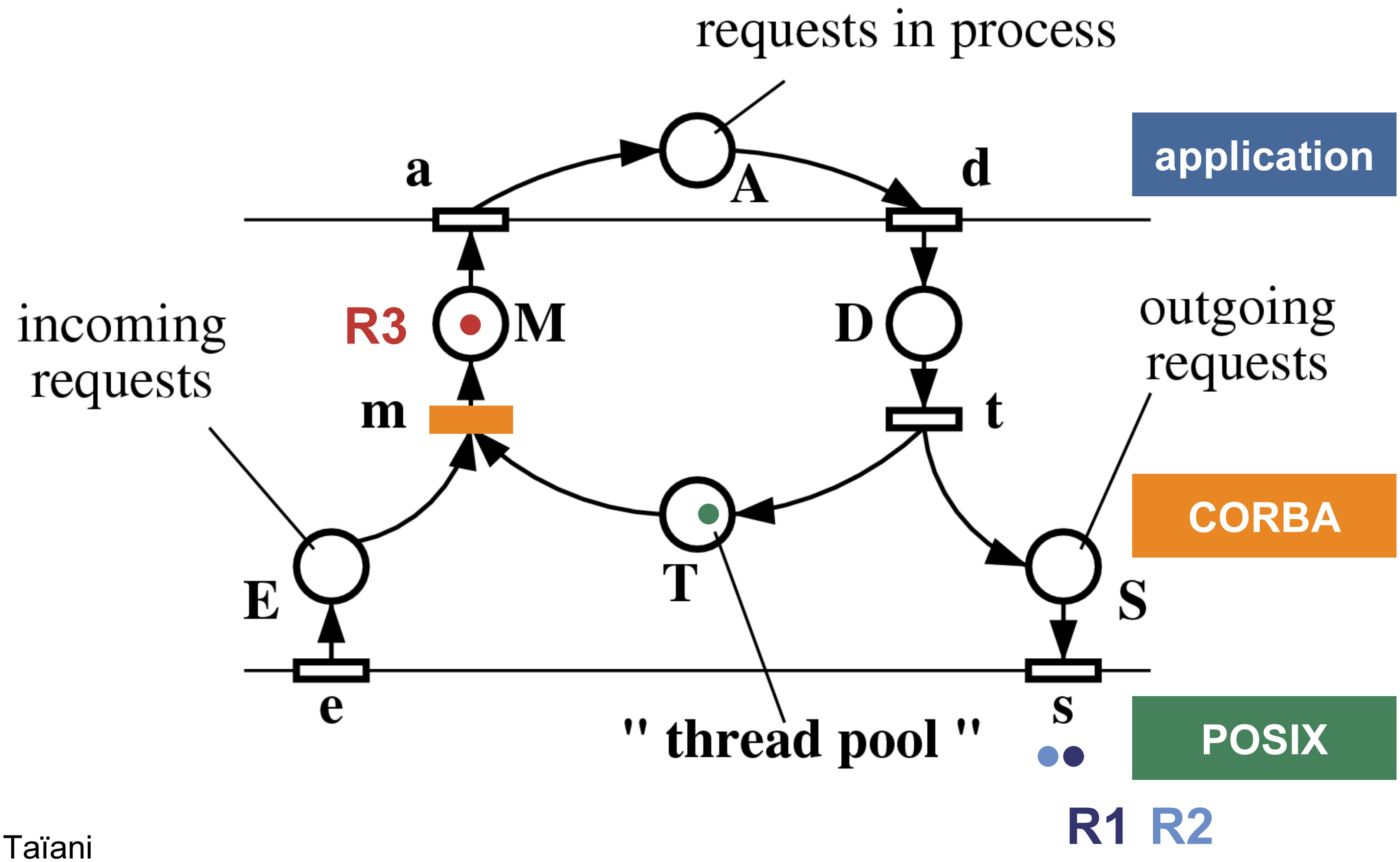
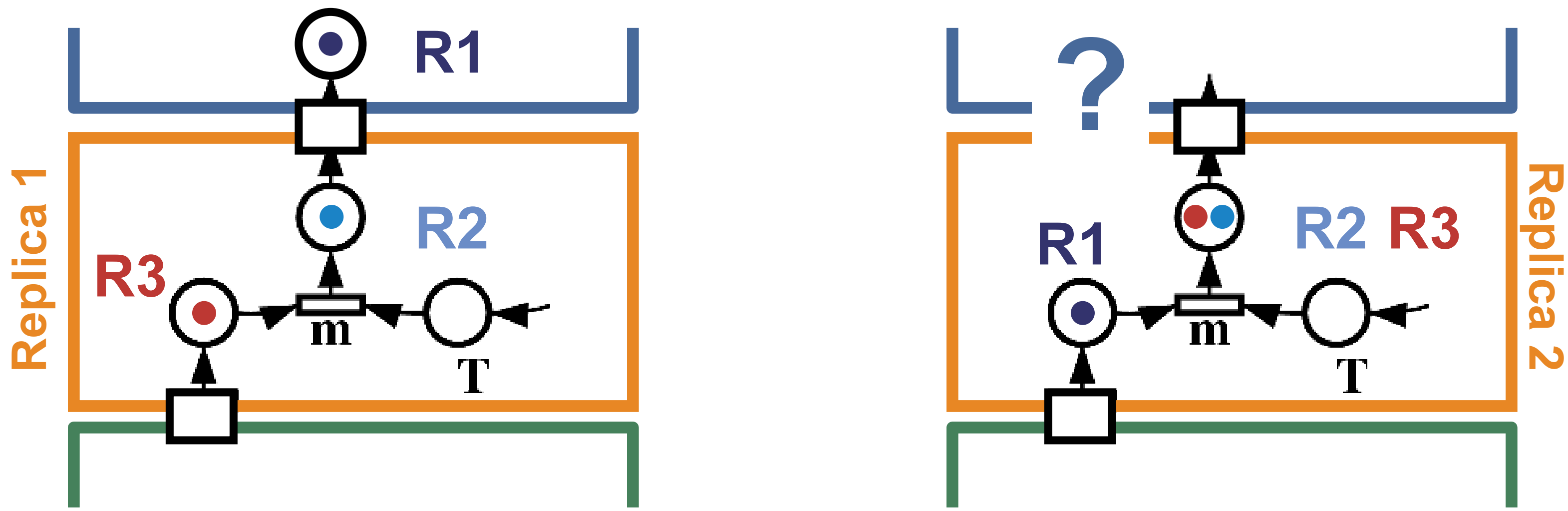


Controlling Non-Determinism at the Application Level only

- Arbitrary scheduling of requests by middleware.



Appli

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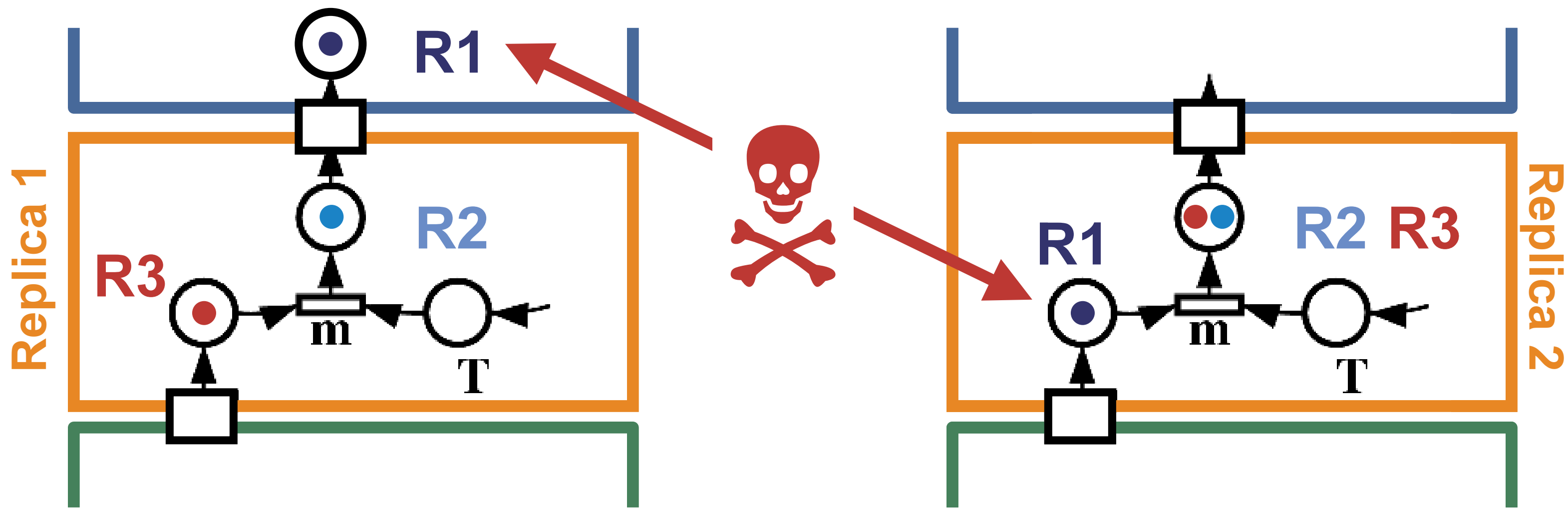

- Replicating scheduling decisions observed at the application level only leads to a **deadlock ...**
  - ➔ ... caused by the thread pool (here of size 2).
  - ➔ The decisions taken by the middleware regarding dispatching can't be controlled from the application.

Appli

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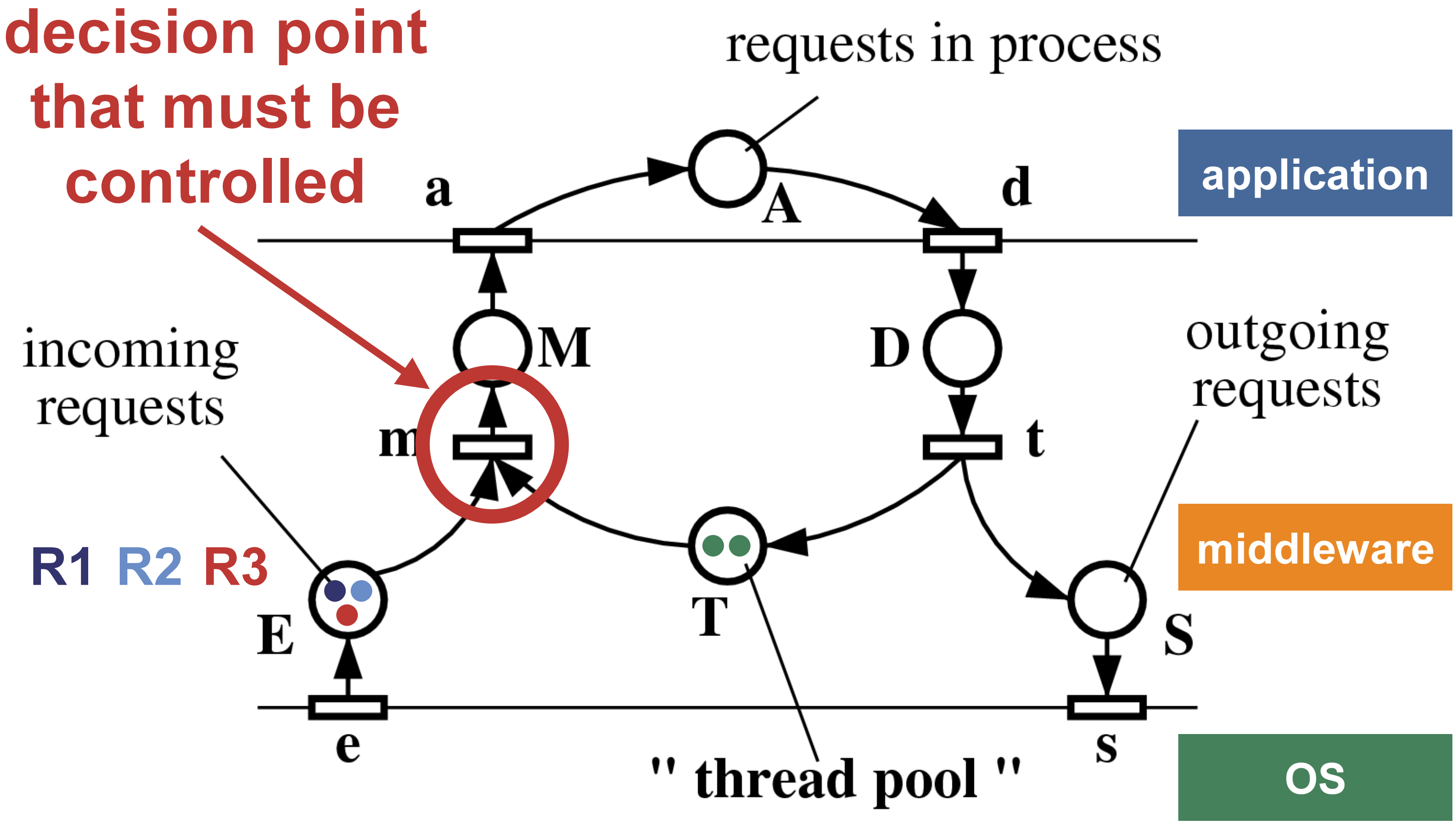
What Causes the Problem



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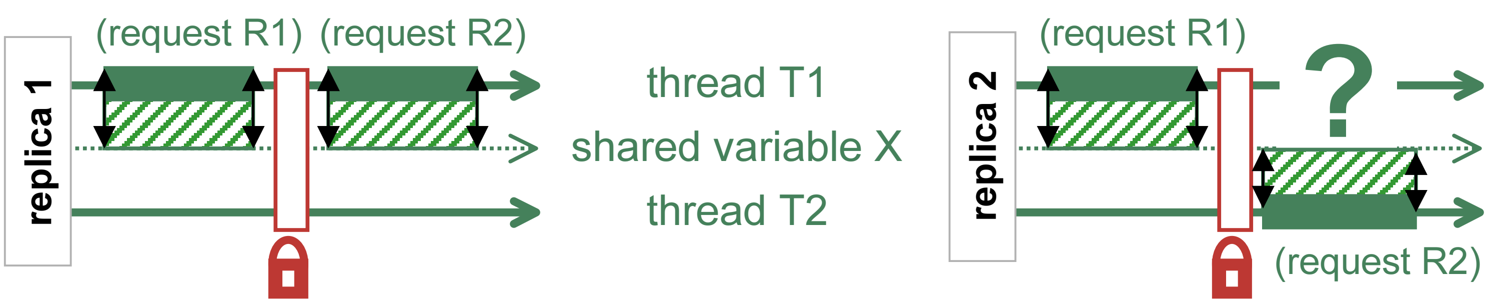
OS

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 reach 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.
  - ➔ All lock operations must be replicated.



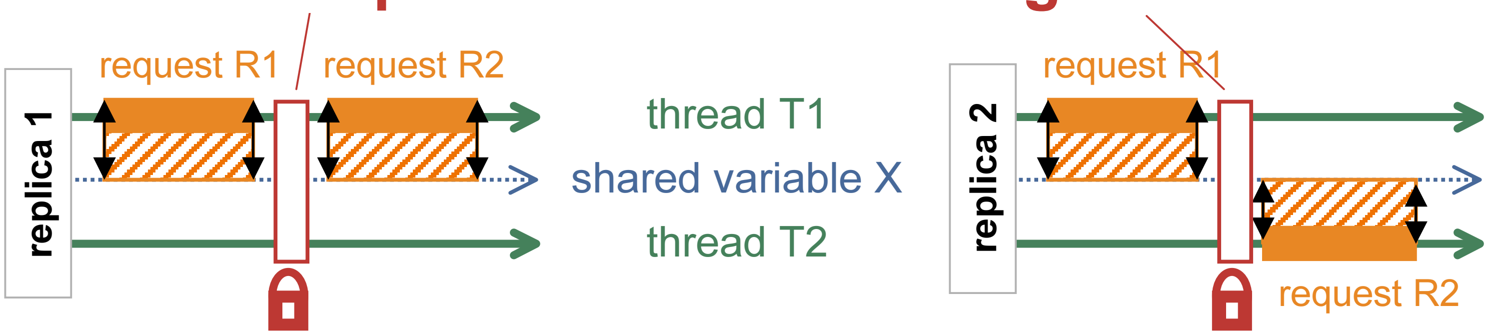
not equivalent ☞ replication of every decision

Appli
CORBA
OS

Smart Scheduling Replication

- With CORBA and application semantics:
  - ➔ Application and CORBA reflection give semantic to OS-level actions.
  - ➔ 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:

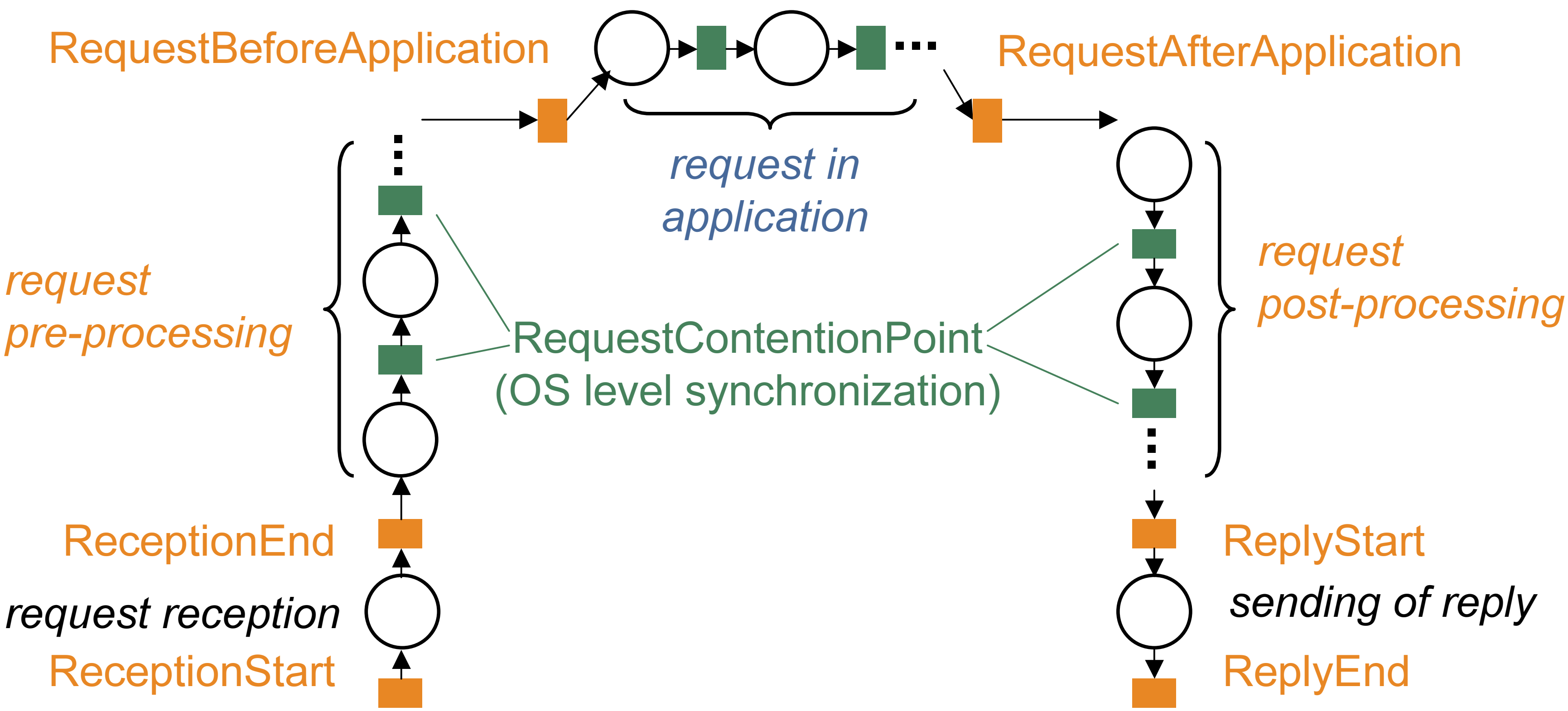
no need to replicate this scheduling decision



The Multi-Layer Meta-Model

Appli
CORBA
OS

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

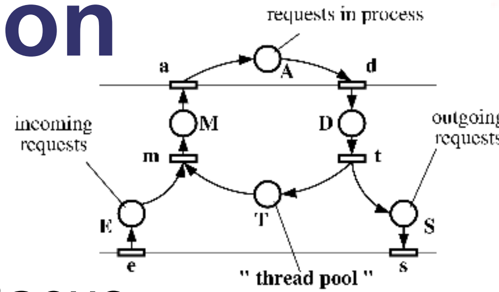


Appli
CORBA
OS

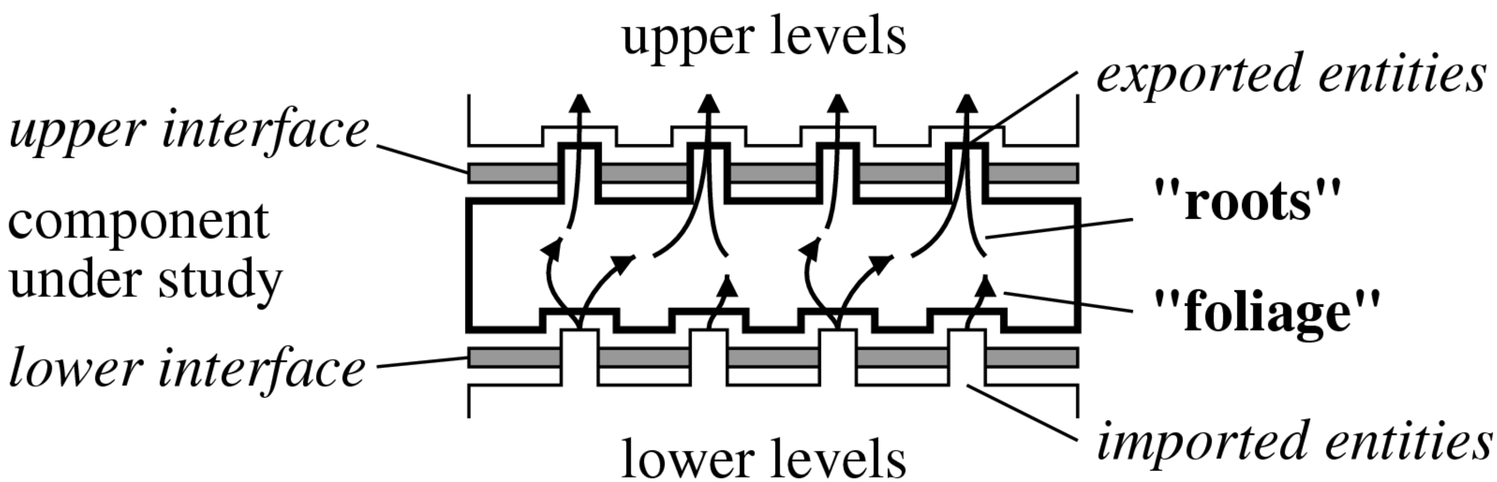
The Meta-Interface

```
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);
}
```

Instrumentation



- CORBA-POSIX mapping is generic.
- Instrumentation on GNU/Linux + ORBacus
  - ➔ The concrete architecture must be bound to the generic mapping.
  - ➔ Complex reverse-engineering : ORBacus > 110 000 LoC
  - ➔ Important abstraction effort (dedicated tool, CosmOpen)
  - ➔ Interface centered approach : « roots » / « foliage » metaphor



Experimental Apparatus

- CosmOpen : semi-automatic reverse-engineering suite
  - ➔ Dedicated to the abstracting effort needed for our work.
  - ➔ Graph manipulation operators, relies on dot (AT&T tool ☺)
  - ➔ Structural & behavioral analysis.
  - ➔ Very useful to handle very large graphs
    - A trace of ORBacus : 2066 invocations ⇨ **2066 nodes**
  - ➔ Free Software : http://www.laas.fr/~ftaiani/7-software

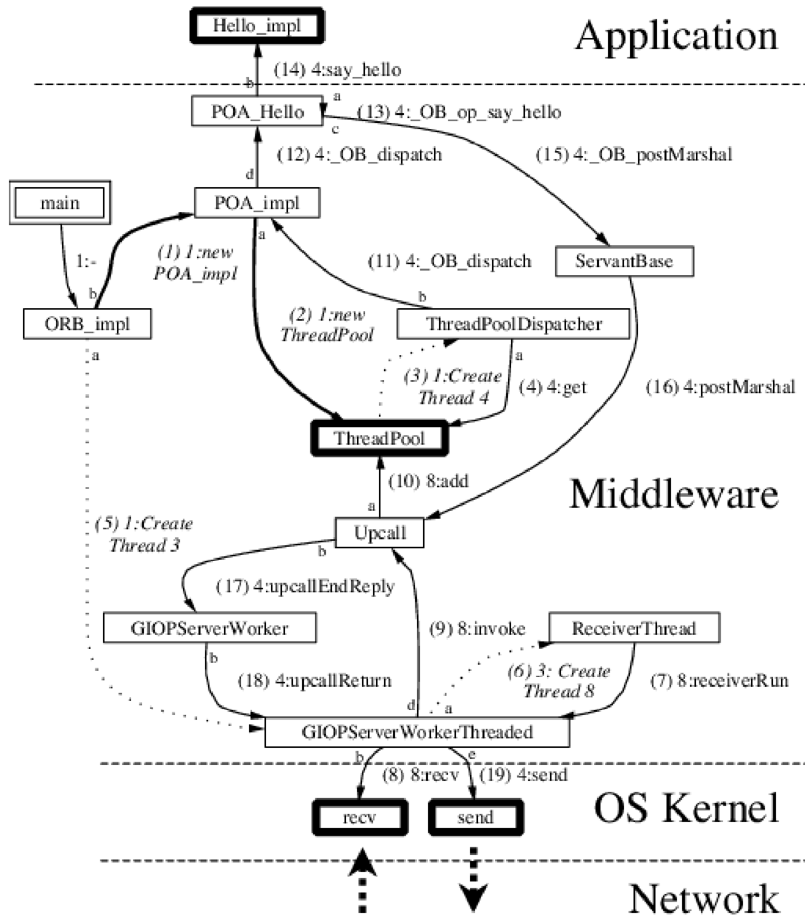
- Model extraction :
  - ➔ Structural extraction : 4280 lines of C++ (with Doxygen)
  - ➔ Behavioral extraction : 1660 lines of C++ (with gdb)

- Graph manipulation : 17010 lines of Java

- CosmOpen **22950** LoC

Instrumentation

- Behavioral middleware model:
  - ➔ obtained with **CosmOpen**
  - ➔ relates OS level actions to application level operations
  - ➔ identifies points of instru-mentation of meta-model



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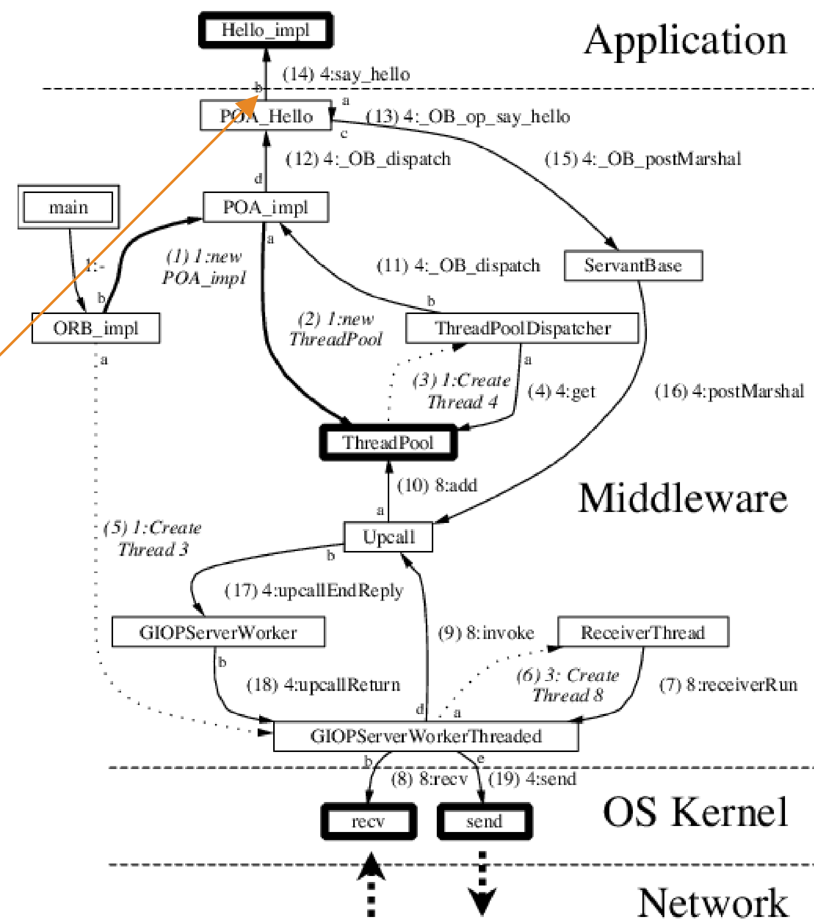
RequestBeforeApplication



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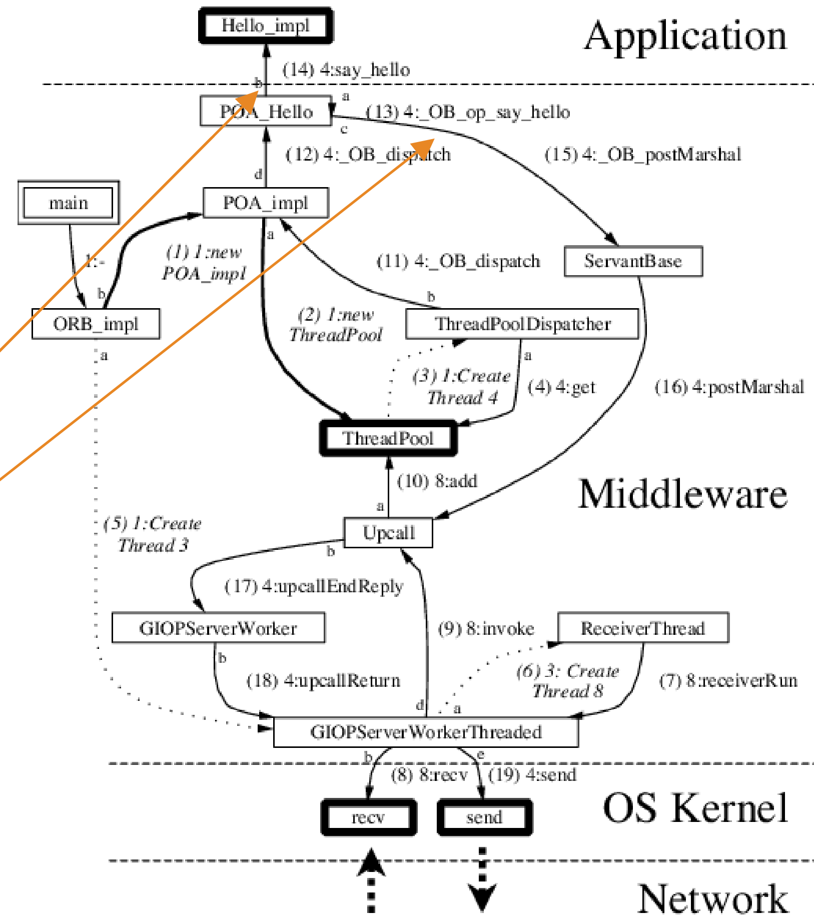

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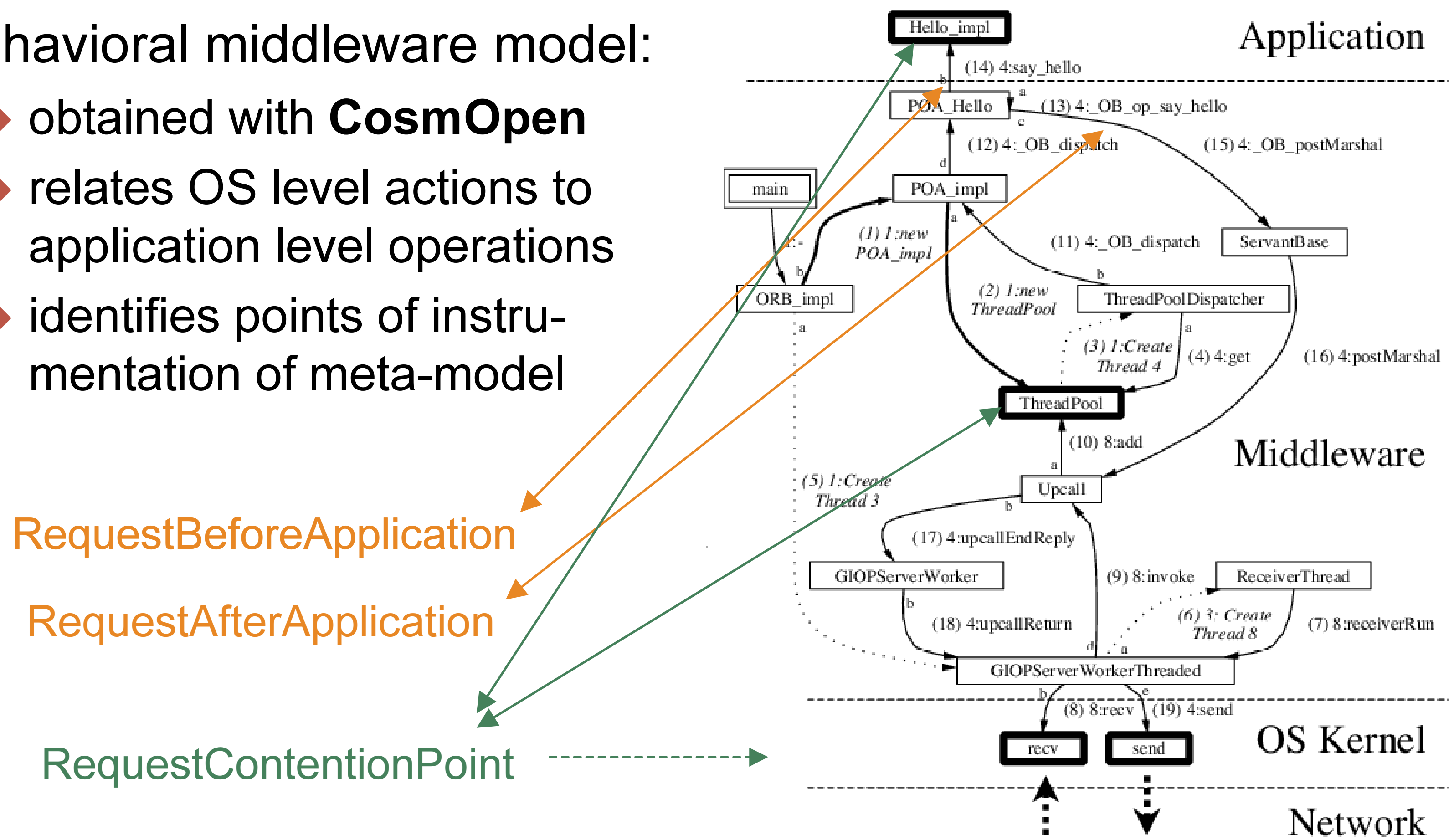


Instrumentation

- Generic shared library (C++) for OS interception
  - 6590 lines of C++
  - meta-classes to intercept locks and mutex individually
    - MetaMutex, MetaSocket
  - supports " transcendence " by piggybacking threads
    - MetaThreadInfo, ThreadMetaMutex, ThreadMetaSocket
- Generic shared library (C++) for multi-level interception
  - 1460 lines of C++
  - uses OS interception to implement its meta-model
    - RequestContentionPoint, MetaRequestLifeCycle
- Instrumenting ORBacus' original code
  - Very low intrusion : 35 new lines
  - **0,02 % of original code**

Lessons Learnt

- The resulting meta-interface is consistent & homogeneous
  - ➔ Supports non-determinism and checkpointing.
- Our prototype implements the part on non-determinism.
- **Efficient**: for instance, replicating synchronization:
  During the processing of one request in ORBacus :
  - ➔ 203 synch operations are observed (pthread_...)
  - ➔ Our prototype only needs to intercept 3 (gain : x 67).
  - ➔ Our previous analysis guaranties that these 3 interceptions are sufficient to maintain the ORB consistency.
- **Very low intrusion** : 0,02 % of original code was modified
- **Reusable** : tool CosmOpen, generic interception libraries

Conclusions

- Comprehensive and adaptable fault-tolerance conflicts with the multi-component and multi-layered nature of modern complex software systems.

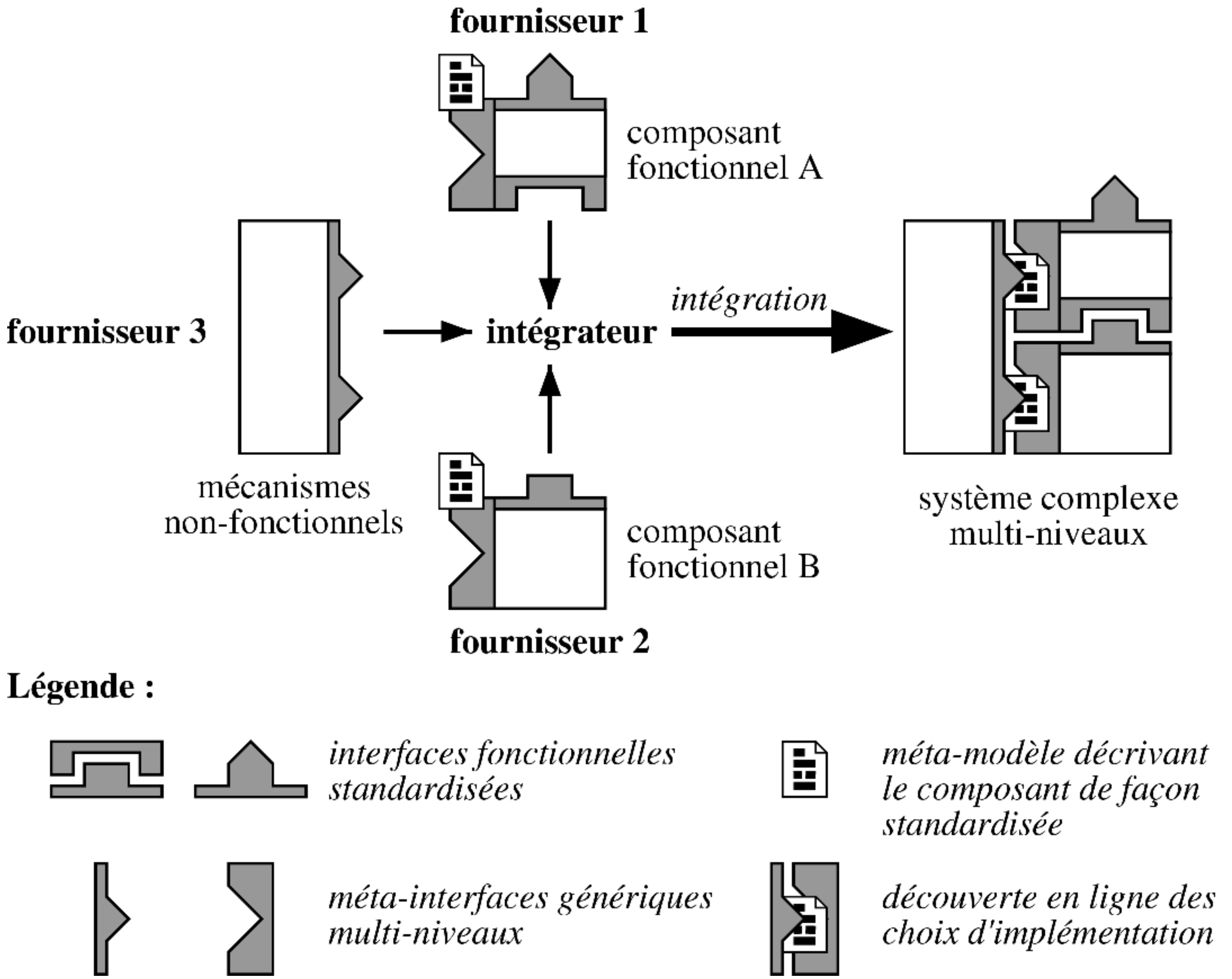
- Our proposal to solve this conflict :
  Multi-Level Reflection :
  - ➔ Combines reflective capabilities found in lower and higher levels in a global system overview.

- Practical validation on an industrial platform.
  - ➔ Analysis and reverse-engineering work (TAO, ORBacus, omniORB) using a dedicated tool (CosmOpen).
  - ➔ Prototype implantation for the control of non-determinism on GNU/Linux + ORBacus.

Outlook

- Strict separation between interface & implementation too constraining for today's large systems
- The present work is only a first step.
- Generic gray-box approaches to gain increasing relevance.
- Consistent and disciplined exposure of implementations by exporting meta-models in a generic, standard format
- Already there for certain applications :
  - ➔ IC synthesis : IP blocks come with their meta-data
  - ➔ Computer Security : Proof Carrying Mobile Codes

Our Vision


fournisseur 1
composant
fonctionnel A
fournisseur 3
intégrateur
intégration
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fonctionnel B
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fournisseur 2
Légende :
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