Design & Implementation of Cognition-enabled Robot Agents

Module 10: Cognitive Architectures
Lecture 3: The CRAM Cognitive Architecture – Part 1

Institute for Artificial Intelligence
Universität Bremen

Winter Term 2020/21

Lecture Contents

1. Theoretical foundations and design principles
2. Overview of CRAM components
3. Lecture summary
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Design Principles

- CRAM: Cognitive Robot Abstract Machine
- Hybrid cognitive architecture (symbolic & sub-symbolic representations & processes)
- Introduced by Michael Beetz in 2010
  - developed significantly since then based on several research projects
- Designed to address robot manipulation tasks in everyday activities
  - tasks that would typically be carried out by people in household settings, e.g. in a kitchen.

Design Principles

End-to-end manipulation, using

- Explicitly-represented knowledge and behaviour descriptions
- Prospection & memory mechanisms based on an inner world model

Vaguely-stated high-level goal → Specific low-level motions required to accomplish the goal

Design Principles

CRAM focusses on abstract specification of robot actions that are underdetermined

- The action specifications are framed in terms without all knowledge required to complete the action

  e.g "fetch the milk and pour it in the bowl"

- The knowledge required to complete the action is resolved at run-time during plan execution
- by querying in real-time a multi-element knowledge-base
  - *A priori* knowledge
  - Current world states
  - Robot's sensorimotor state

Design Principles

The control program is stated as a generalized action plan

- One plan for each category of underdetermined action description, e.g. fetch, place, pour, cut, …
- The plan can be executed
- The plan can be reasoned about and transformed
  - Self—programming
  - Development and self-improvement through automatic generation of new plans

Design Principles

The control program is stated as a generalized action plan

Generalized Action Plan → Motion Plan

This is the key concept in CRAM

3-step refinement process:
contextualization
Identify the values of the parameters to the motion plan that maximize the likelihood that the associated body motions successfully accomplish the desired action

The motion parameter values are provided by the generative model

Design Principles

The control program is stated as a generalized action plan

Generalized Action Plan → Motion Plan

This is the key concept in CRAM

The motion parameter values are provided by the generative model

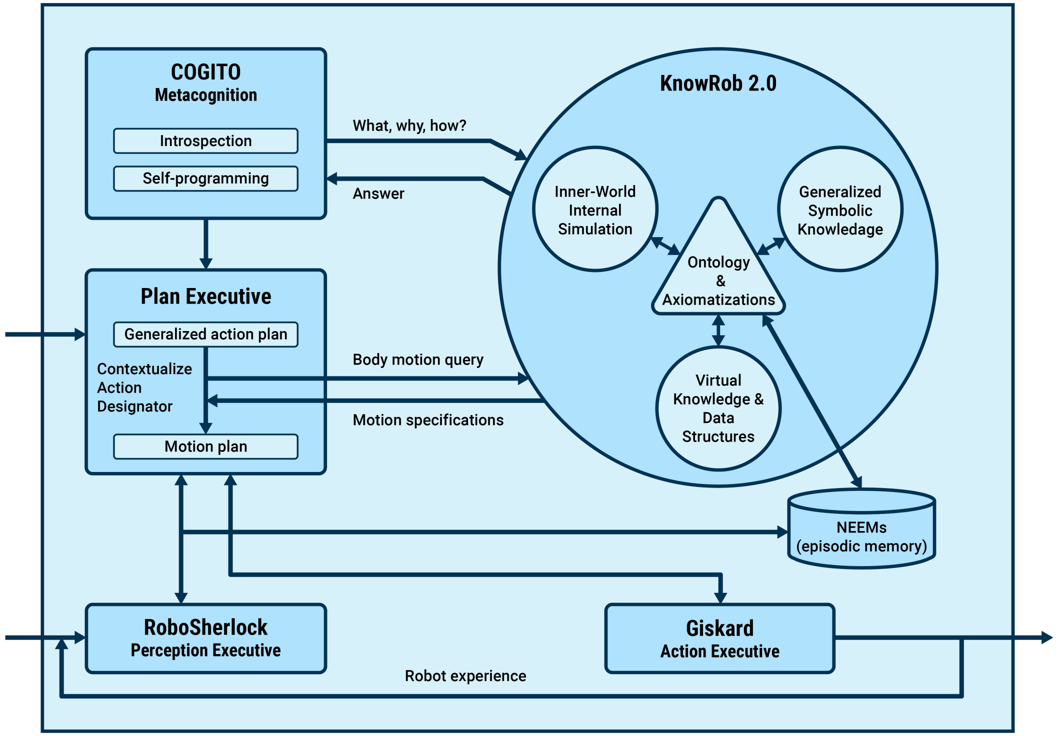
Equivalent

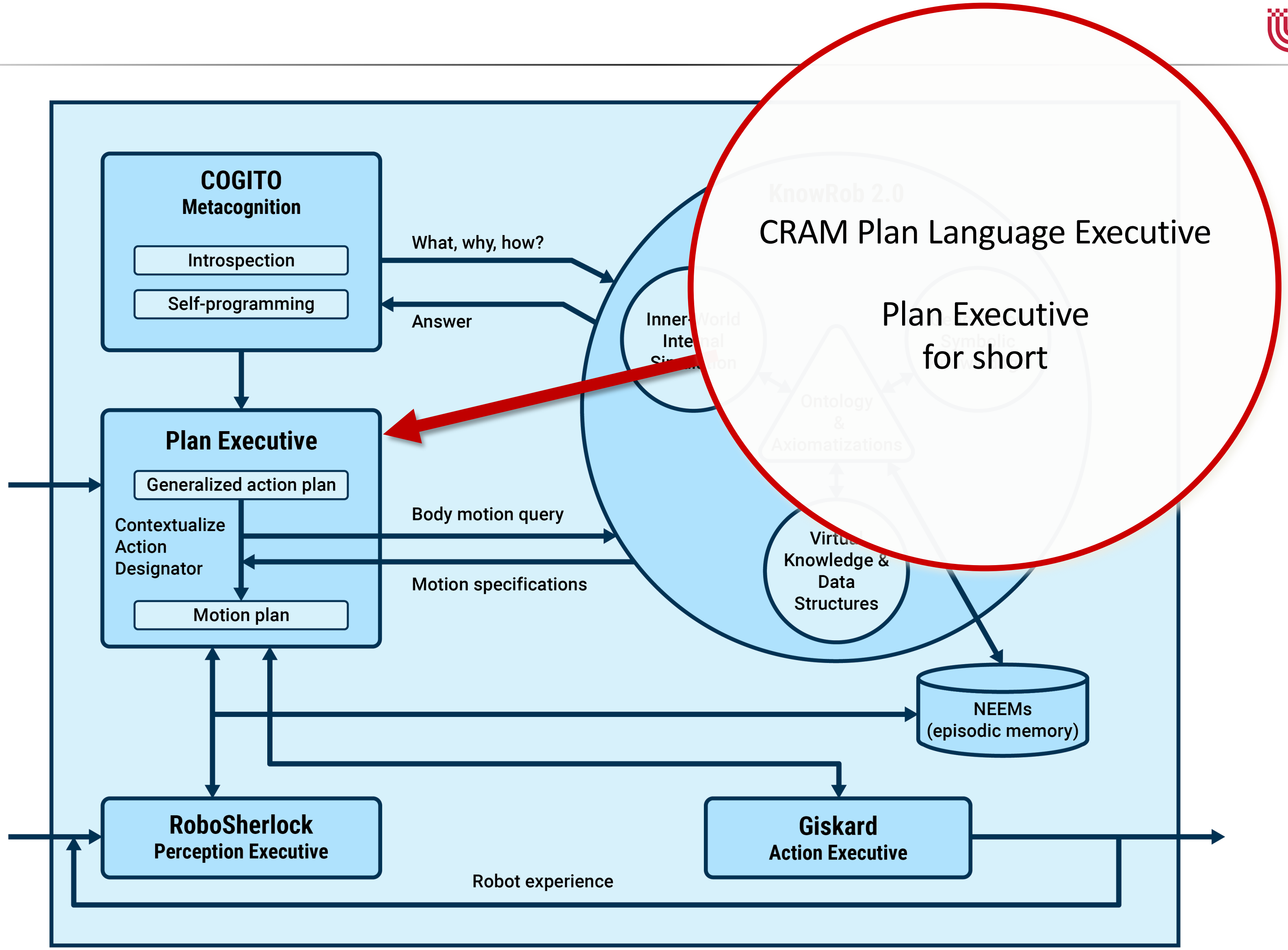
- Performing an underdetermined action description
- Executing (interpreting) a generalized action plan
- Resolving a high-level action designator in a generalized action plan (explained in next few slides)

The CRAM Cognitive Architecture

CRAM has five core elements:

1. CRAM Plan Language (CPL) executive
2. KnowRob2.0 knowledge-bases and associated reasoning processes
3. RoboSherlock, the perception executive
4. Giskard, the action executive
5. COGITO, a metacognition system




COGITO
Metacognition
Introspection
Self-programming
What, why, how?
Answer
Plan Executive
Generalized action plan
Contextualize Action Designator
Motion plan
Body motion query
Motion specifications
Inner-World
Virtu
Knowledge &
Data
Structures
NEEMs
(episodic memory)
RoboSherlock
Perception Executive
Giskard
Action Executive
Robot experience
CRAM Plan Language Executive
Plan Executive
for short

CRAM Plan Language (CPL) Executive

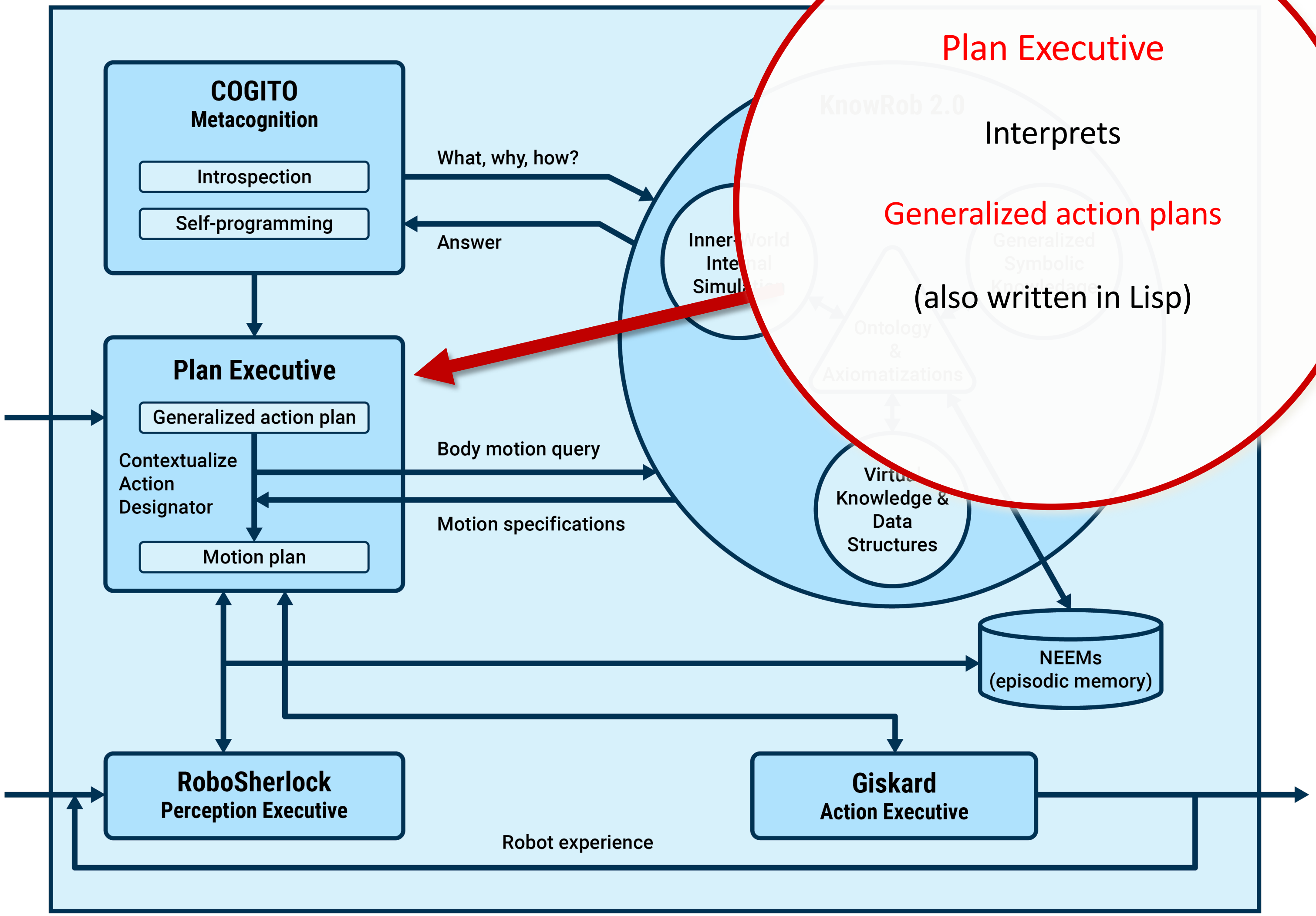
- Tasks are accomplished by executing plans written in the CRAM Plan Language (CPL)
- CPL is an extension of Lisp
- A CPL plan represents all key aspects of the plan as persistent first-class objects in a first-order logic
  - Plans themselves can be reasoned about, even at runtime
  - Particularly relevant for the meta-cognition system, COGITO

CRAM Plan Language (CPL) Executive

- A plan comprises set of abstract plan designators for
  - actions
  - objects
  - locations
  - motions (i.e. elementary movements)

Designators are effectively placeholders

require runtime resolution based on the current context of the task action

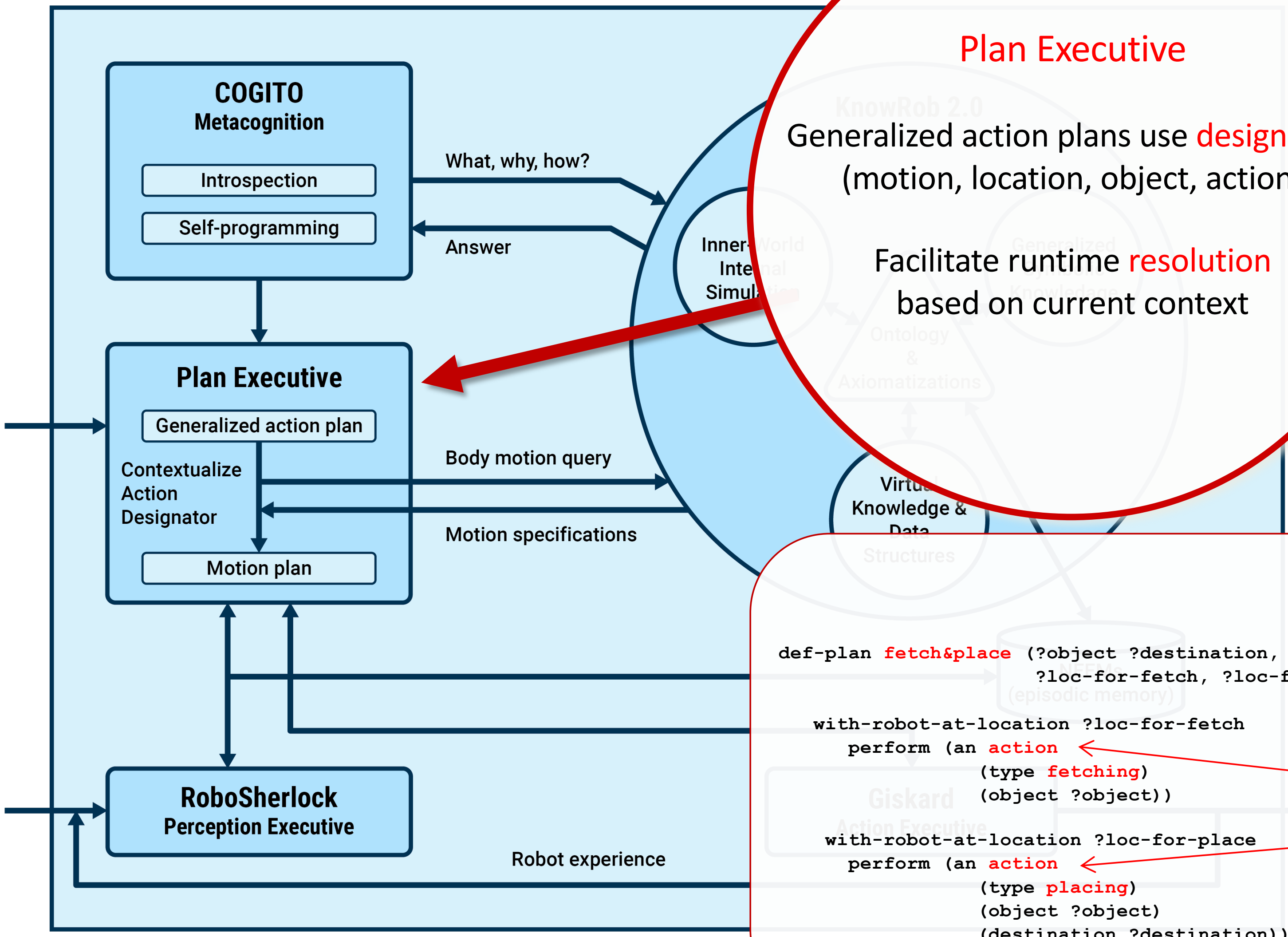


Plan Executive

Interprets

Generalized action plans

(also written in Lisp)



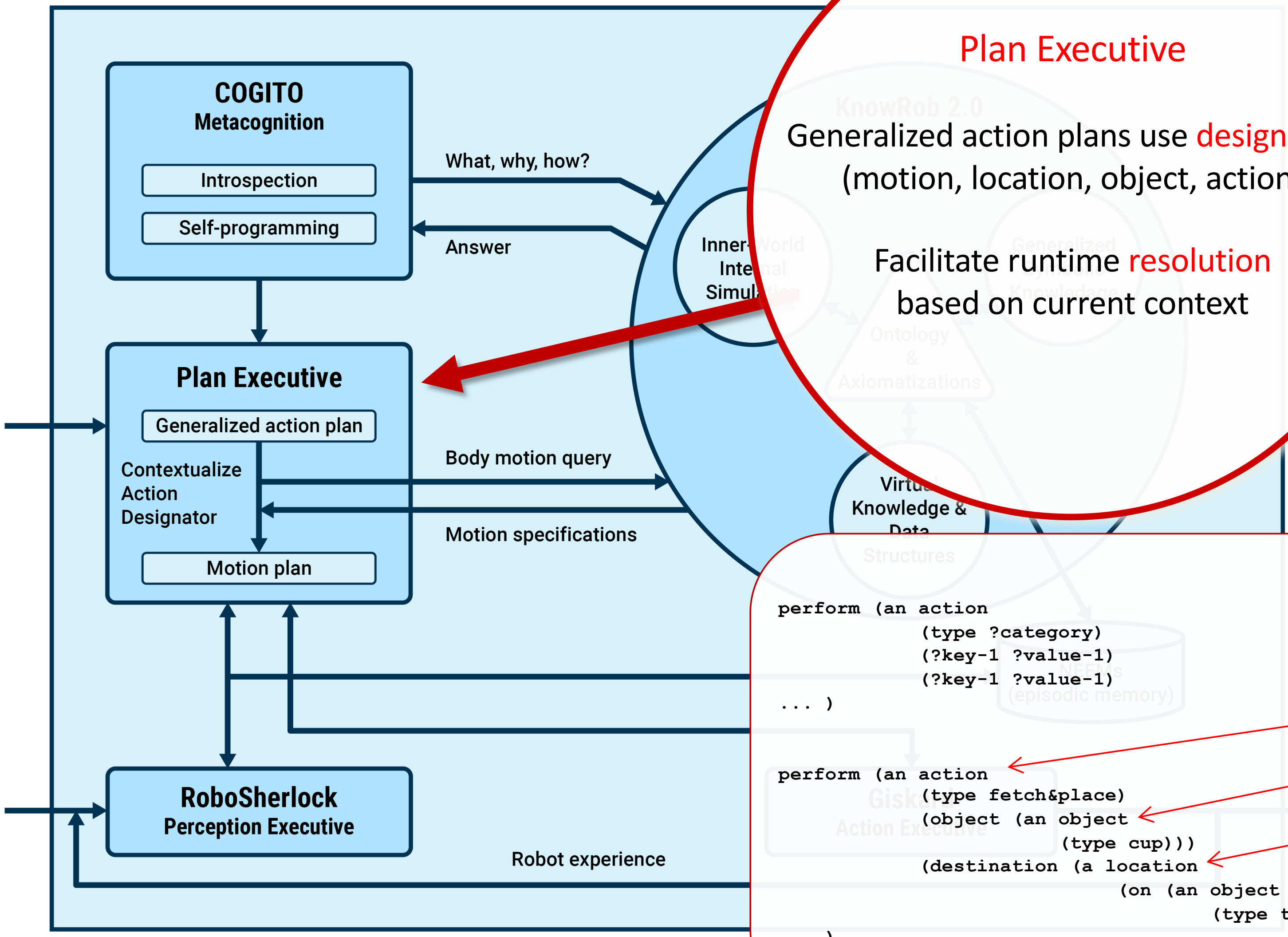
Plan Executive

Generalized action plans use designators (motion, location, object, action)

Facilitate runtime resolution based on current context

```
def-plan fetch&place (?object ?destination,
                      ?loc-for-fetch, ?loc-for-place)

  with-robot-at-location ?loc-for-fetch
    perform (an action
                (type fetching)
                (object ?object))

   with-robot-at-location ?loc-for-place
    perform (an action
                (type placing)
                (object ?object)
                (destination ?destination))
```

action designator



Plan Executive

Generalized action plans use designators (motion, location, object, action)

Facilitate runtime resolution based on current context

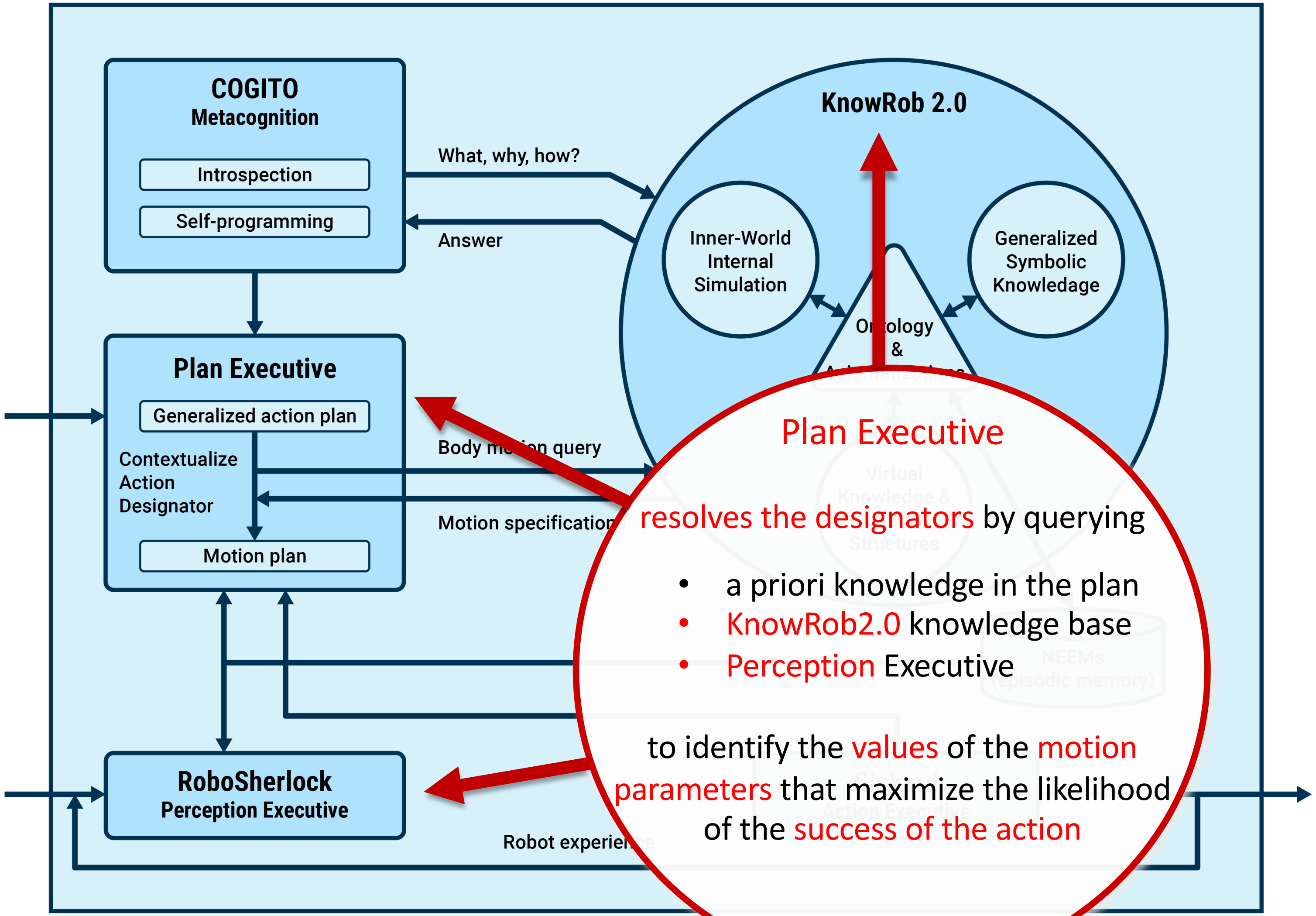
```
perform (an action
            (type ?category)
            (?key-1 ?value-1)
            (?key-1 ?value-1)
... )

perform (an action
            (type fetch&place)
            (object (an object
                        (type cup)))
            (destination (a location
                            (on (an object
                                    (type table)))))
... )
```

action designator

object designator

location designator

object designator

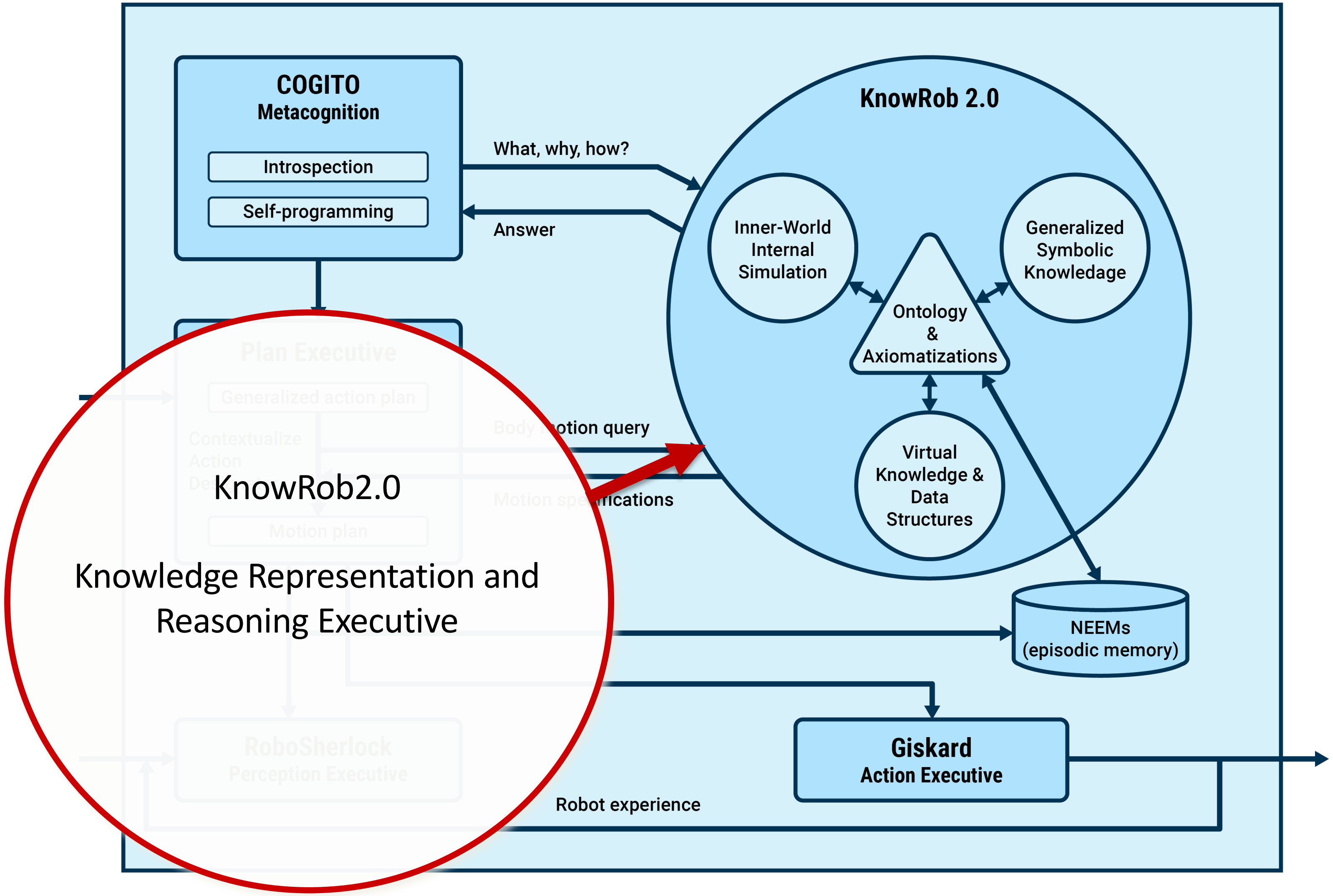


Plan Executive

resolves the designators by querying

- a priori knowledge in the plan
- KnowRob2.0 knowledge base
- Perception Executive

to identify the values of the motion parameters that maximize the likelihood of the success of the action

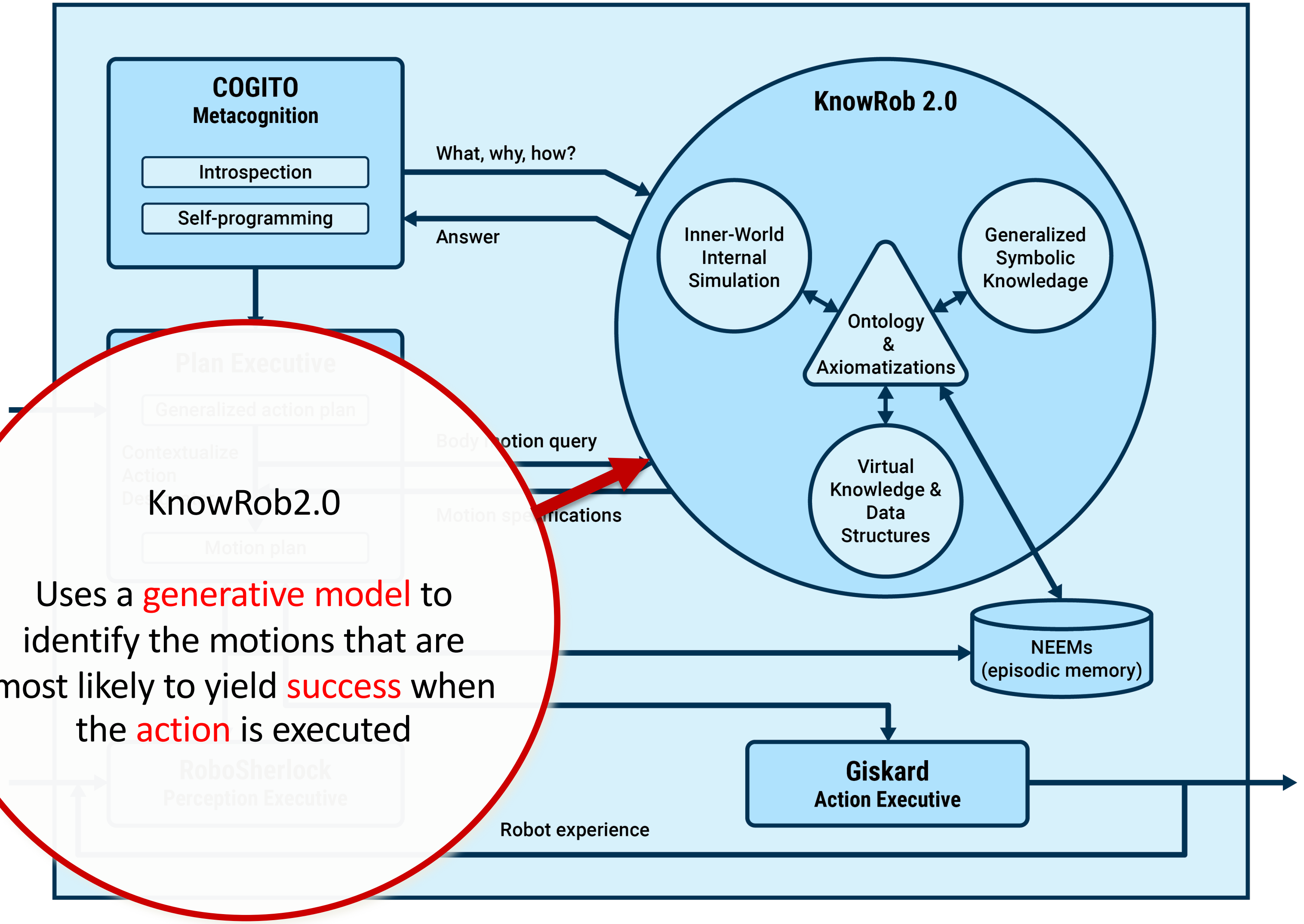

COGITO
Metacognition
Introspection
Self-programming
What, why, how?
Answer
KnowRob 2.0
Inner-World Internal Simulation
Generalized Symbolic Knowledge
Ontology & Axiomatizations
Virtual Knowledge & Data Structures
NEEMs (episodic memory)
Giskard
Action Executive
Robot experience
KnowRob2.0
Knowledge Representation and Reasoning Executive

KnowRob2 Knowledge Base

- Provides the background commonsense intuitive-physics knowledge required by the CPL executive to implement its goal-directed under-determined task plans, e.g.
  - How to grasp an object (depending on the object's shape, weight, softness, and other properties)
  - How it has to be held while moving it (e.g. upright to avoid spilling its contents)
  - Where the object is normally located.

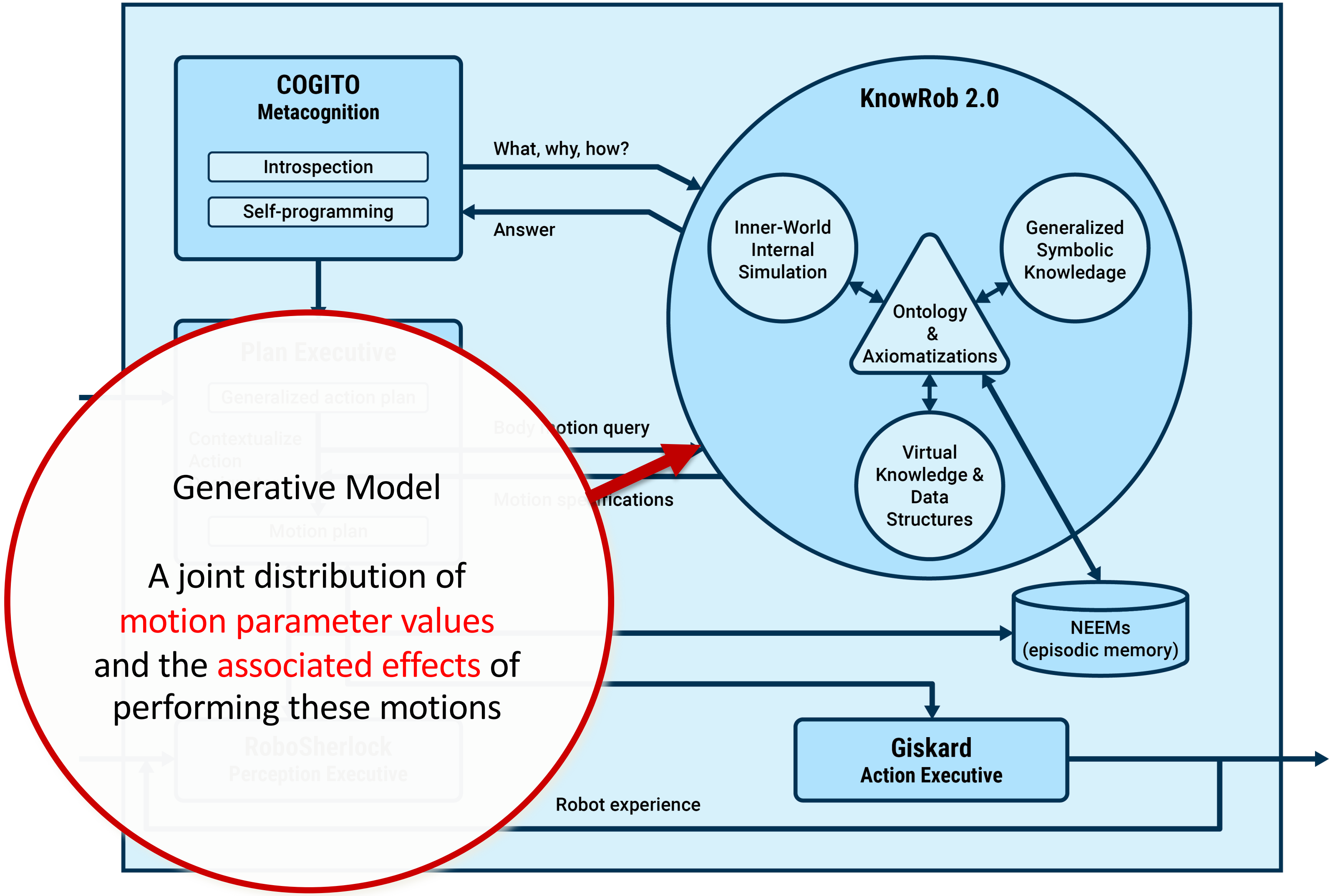
KnowRob2 Knowledge Base

- Source of knowledge:
  - Some is specified a priori
  - Some is derived from experience
  - Some is the result of simulated execution of candidate actions using a high-fidelity virtual reality physics engine simulator
- All represented by a first-order time interval logic expression, and reasoned about as needed.



KnowRob2.0

Uses a generative model to identify the motions that are most likely to yield success when the action is executed


COGITO
Metacognition
Introspection
Self-programming
What, why, how?
Answer
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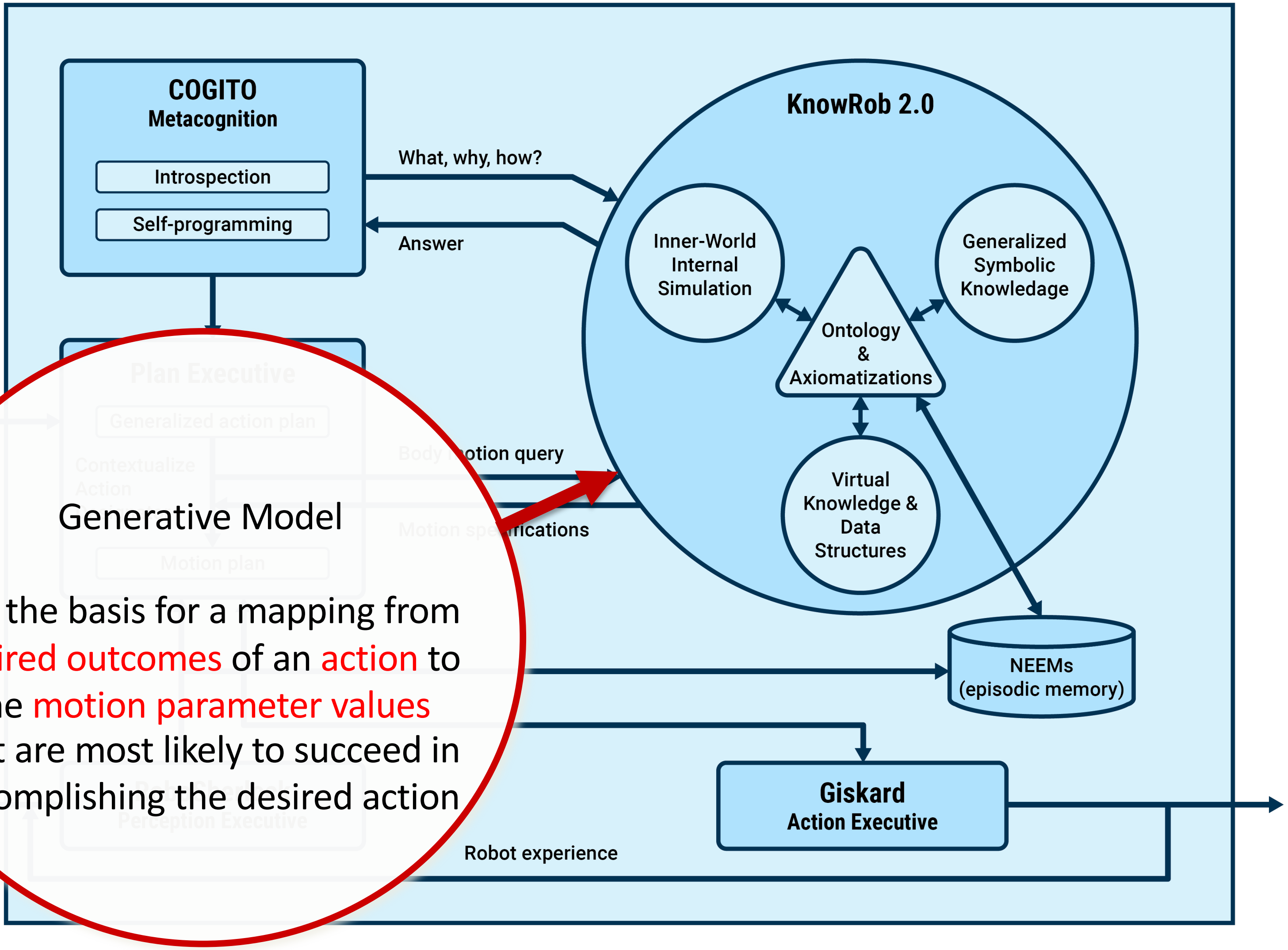
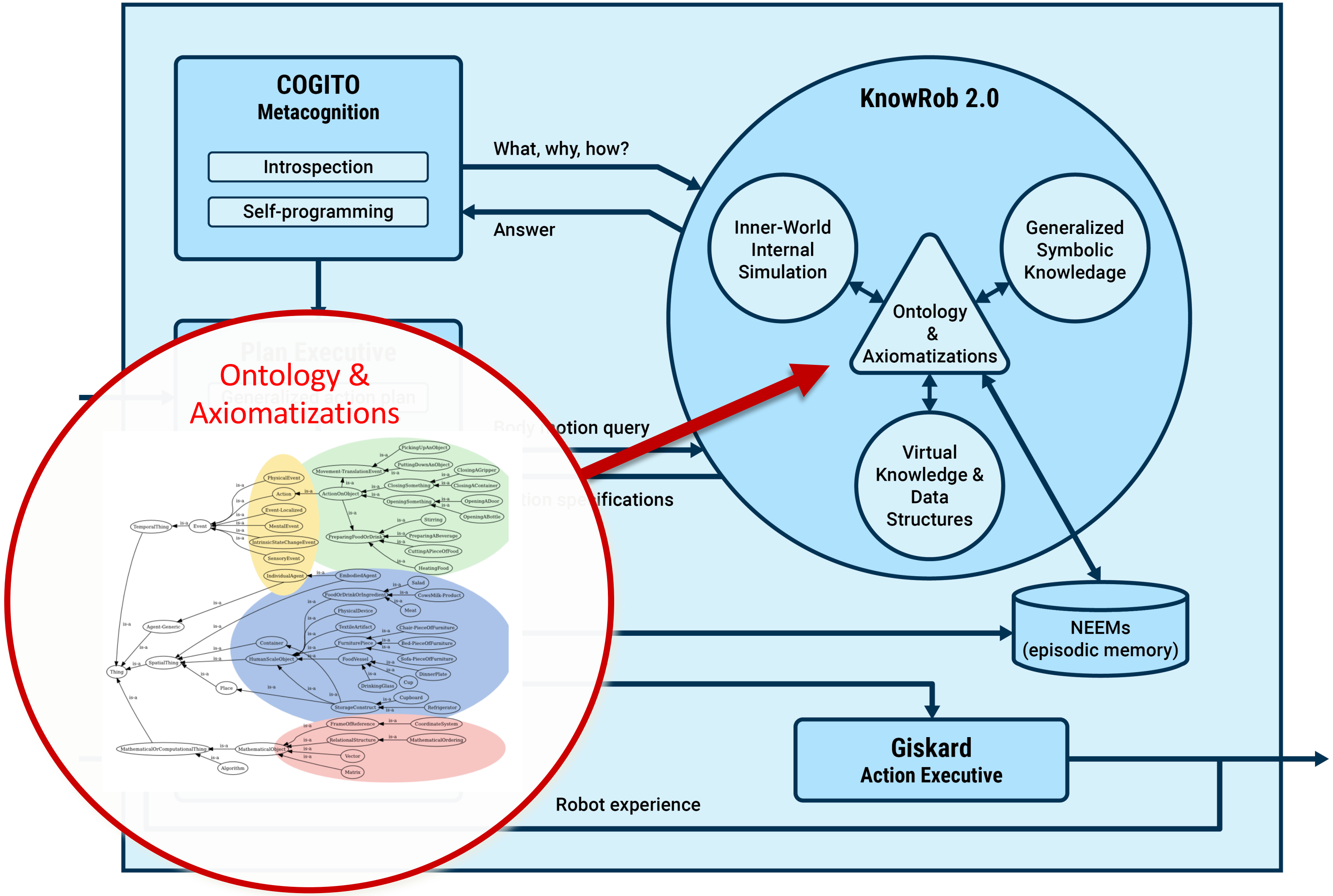
Giskard
Action Executive
Robot experience
Generative Model
A joint distribution of motion parameter values and the associated effects of performing these motions



Generative Model

It is the basis for a mapping from desired outcomes of an action to the motion parameter values that are most likely to succeed in accomplishing the desired action


COGITO
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What, why, how?
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Virtual Knowledge & Data Structures
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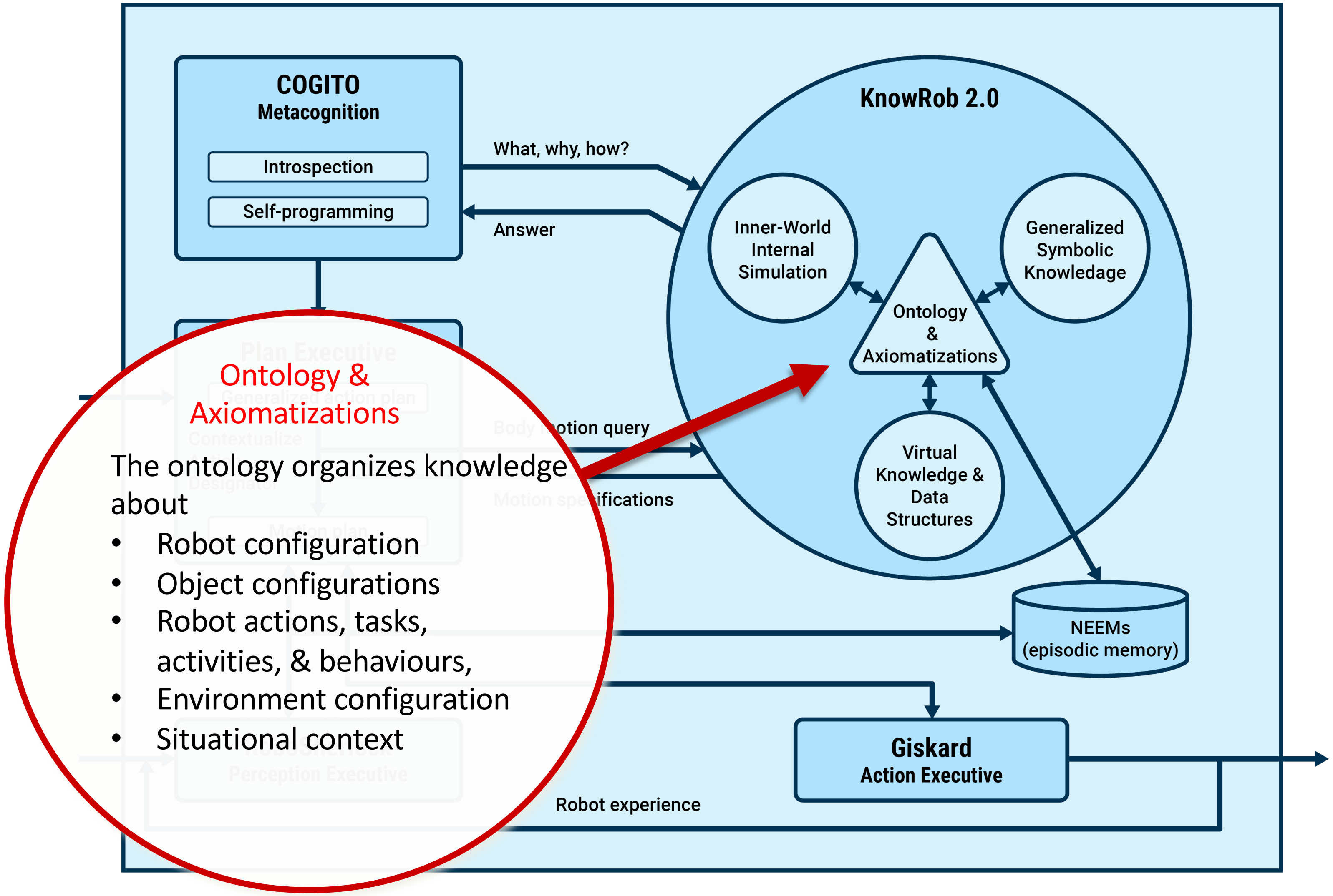
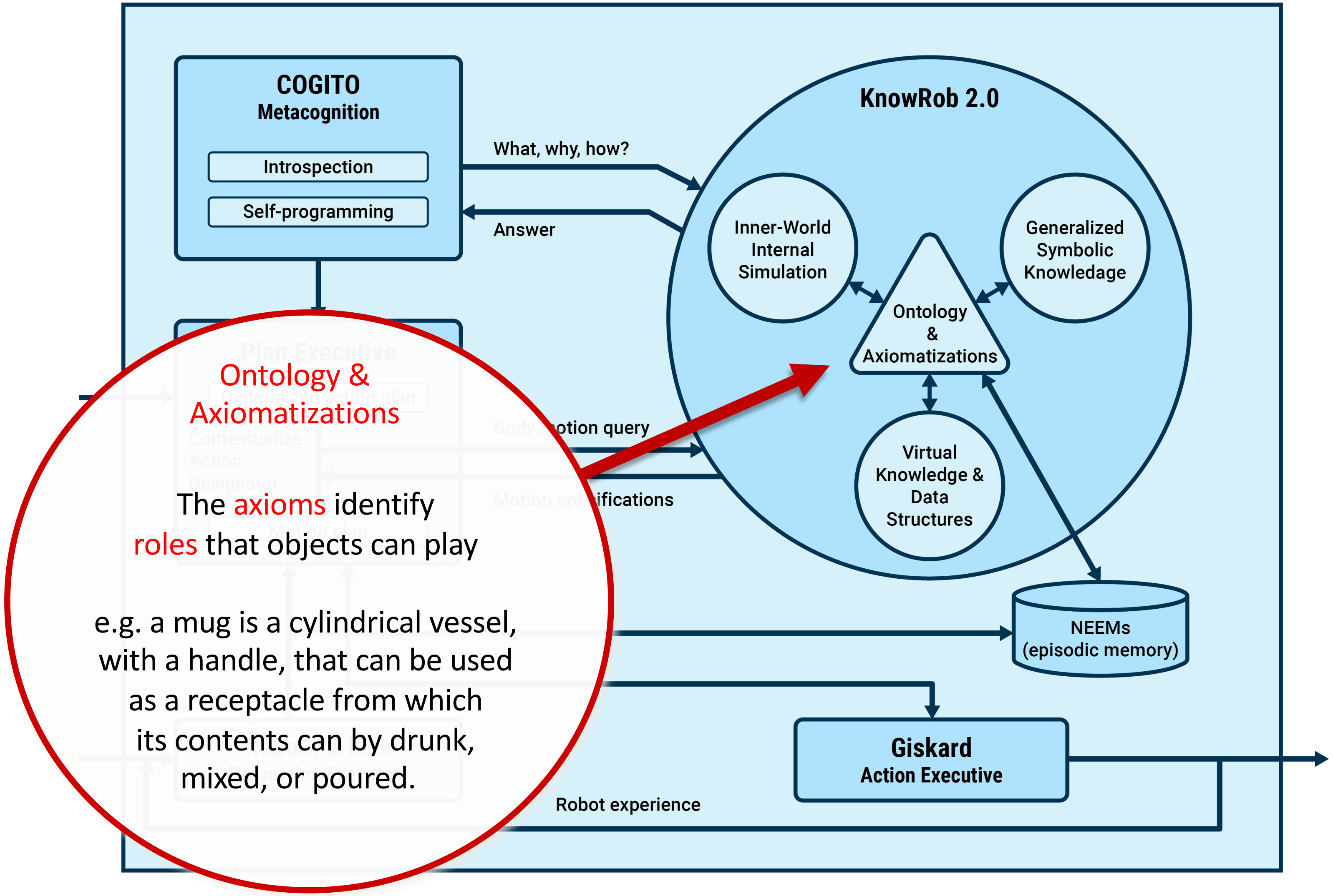
Giskard
Action Executive
Robot experience
Body motion query
Ontology & Axiomatizations



Ontology & Axiomatizations

The ontology organizes knowledge about

- Robot configuration
- Object configurations
- Robot actions, tasks, activities, & behaviours,
- Environment configuration
- Situational context


COGITO
Metacognition
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What, why, how?
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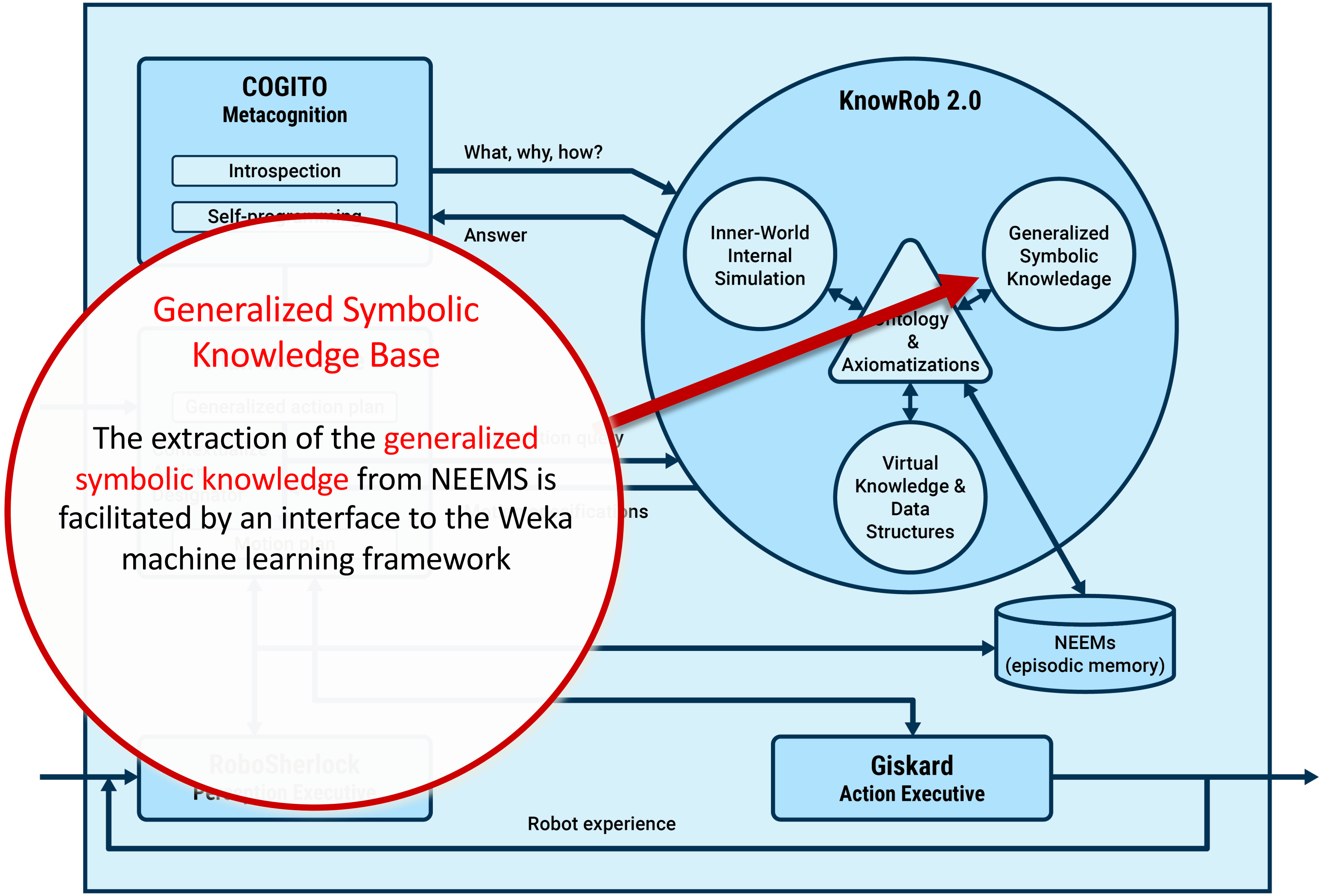
Ontology & Axiomatizations
The axioms identify roles that objects can play
e.g. a mug is a cylindrical vessel, with a handle, that can be used as a receptacle from which its contents can by drunk, mixed, or poured.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What, why, how?
Answer
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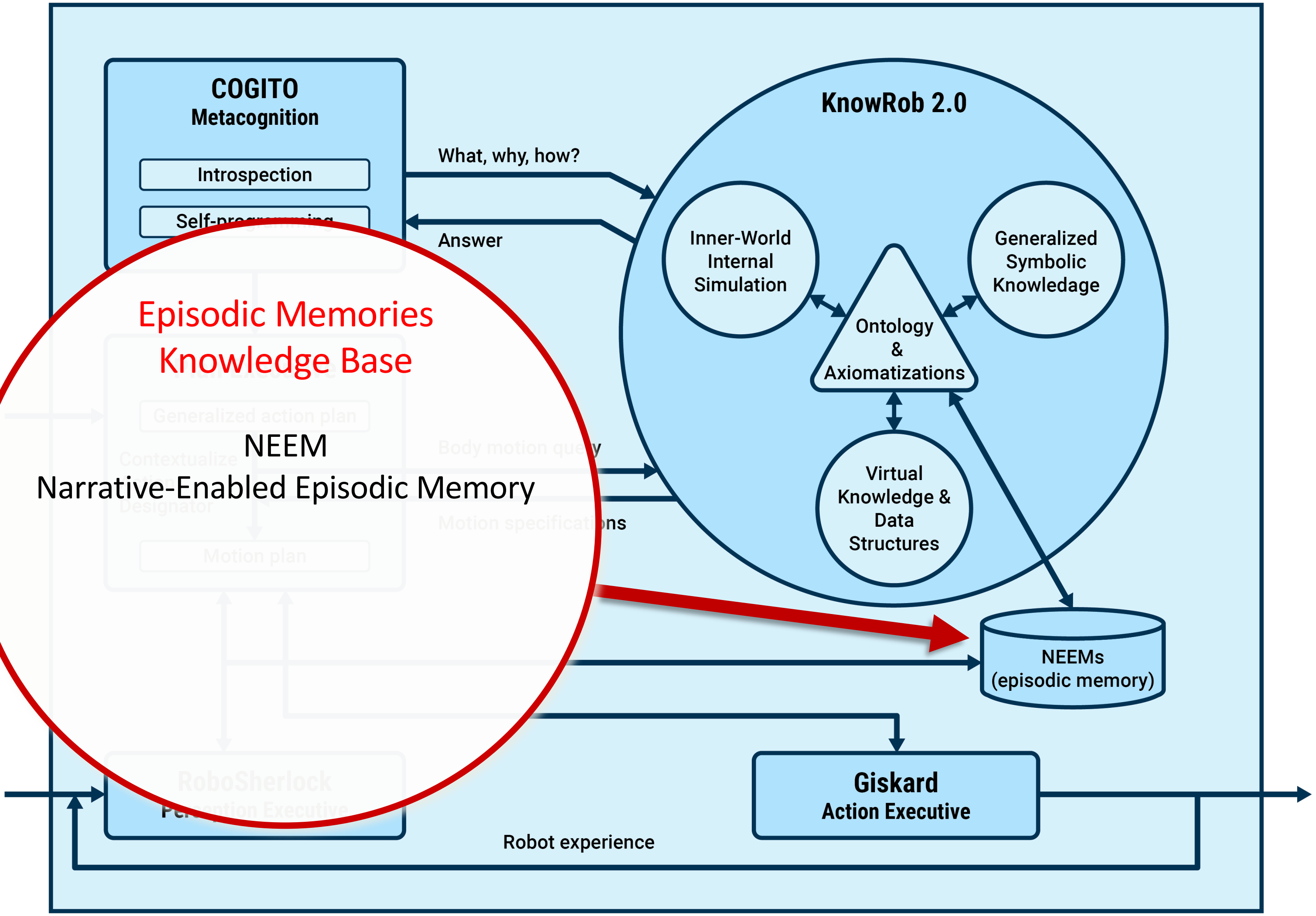
Ontology & Axiomatizations
Virtual Knowledge & Data Structures
NEEMs (episodic memory)
Giskard
Action Executive
Robot experience
Generalized Symbolic Knowledge Base
The extraction of the generalized symbolic knowledge from NEEMS is facilitated by an interface to the Weka machine learning framework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What, why, how?
Answer
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Inner-World Internal Simulation
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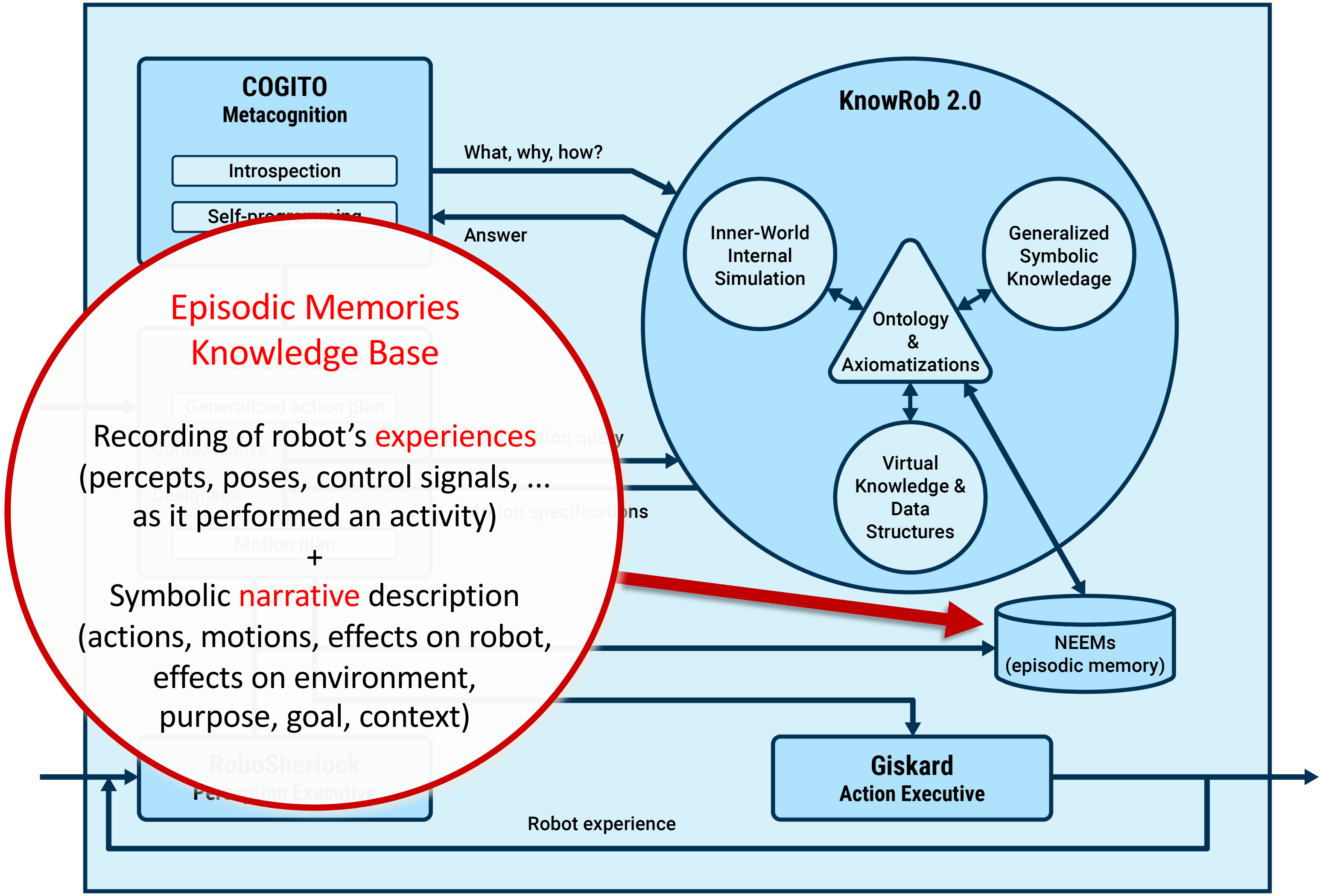
Ontology & Axiomatizations
Virtual Knowledge & Data Structures
Episodic Memories
Knowledge Base
NEEM
Narrative-Enabled Episodic Memory
NEEMs (episodic memory)
Giskard
Action Executive
Robot experience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Introspection
What, why, how?
Answer
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Inner-World Internal Simulation
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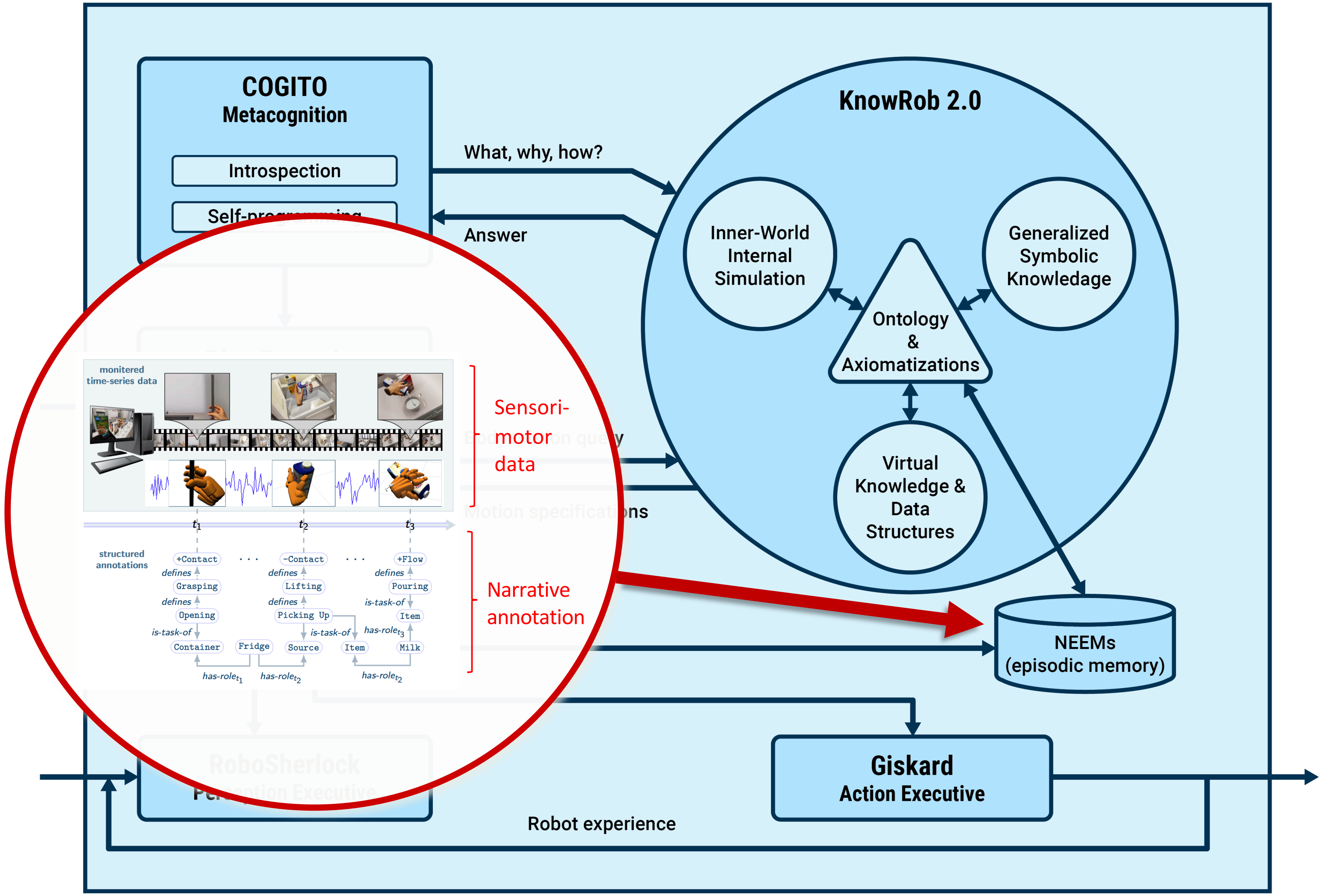
NEEMs (episodic memory)
Giskard
Action Executive
Robot experience
Episodic Memories
Knowledge Base
Recording of robot's experiences
(percepts, poses, control signals, ...
as it performed an activity)
+
Symbolic narrative description
(actions, motions, effects on robot,
effects on environment,
purpose, goal, context)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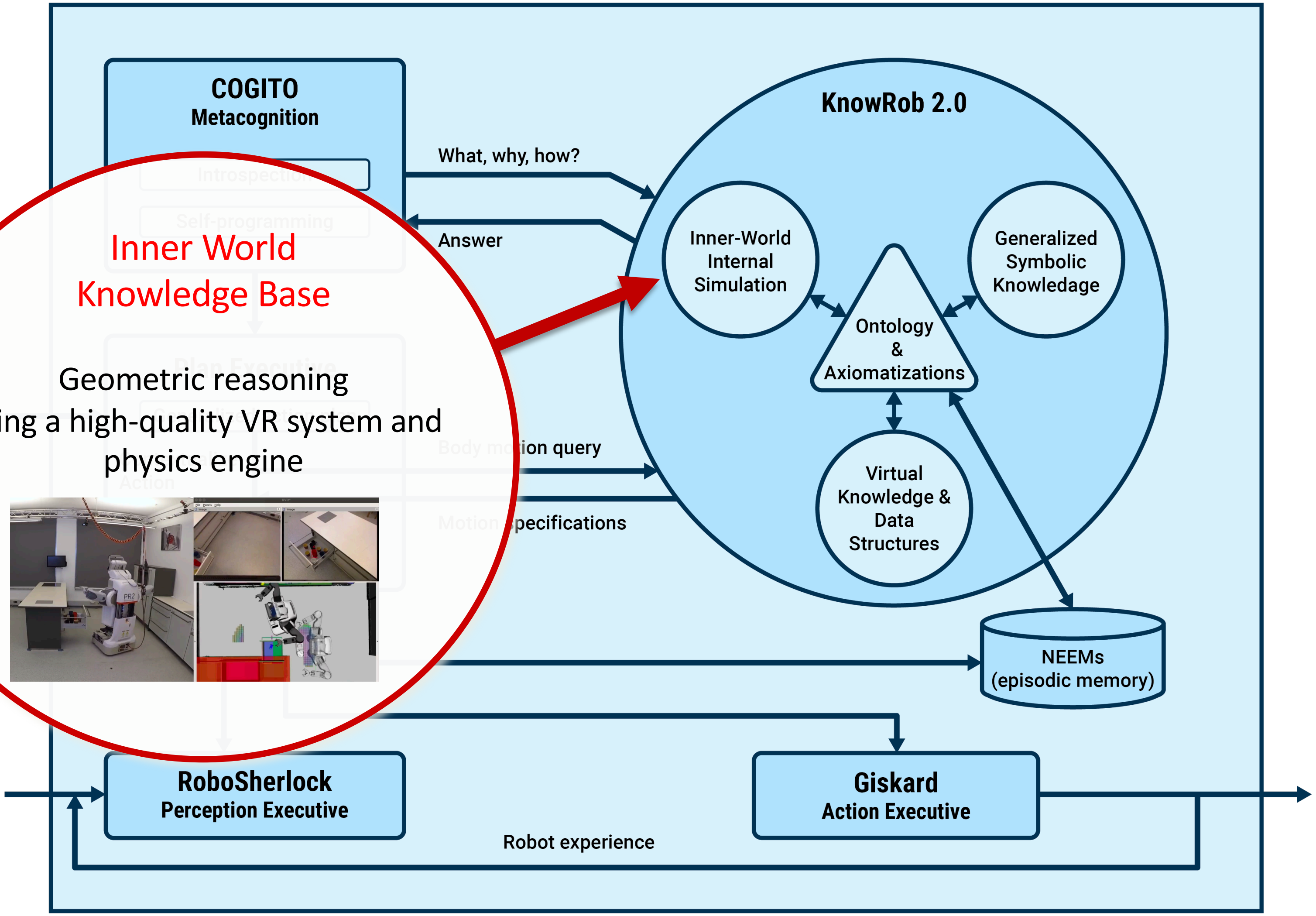
Virtual Knowledge & Data Structures
monitered time-series data
structured annotations
Sensori-motor data
Narrative annotation
NEEMs (episodic memory)
Giskard
Action Executive
Robot experience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Virtual Knowledge & Data Structures
Inner World Knowledge Base
Geometric reasoning using a high-quality VR system and physics engine
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Giskard
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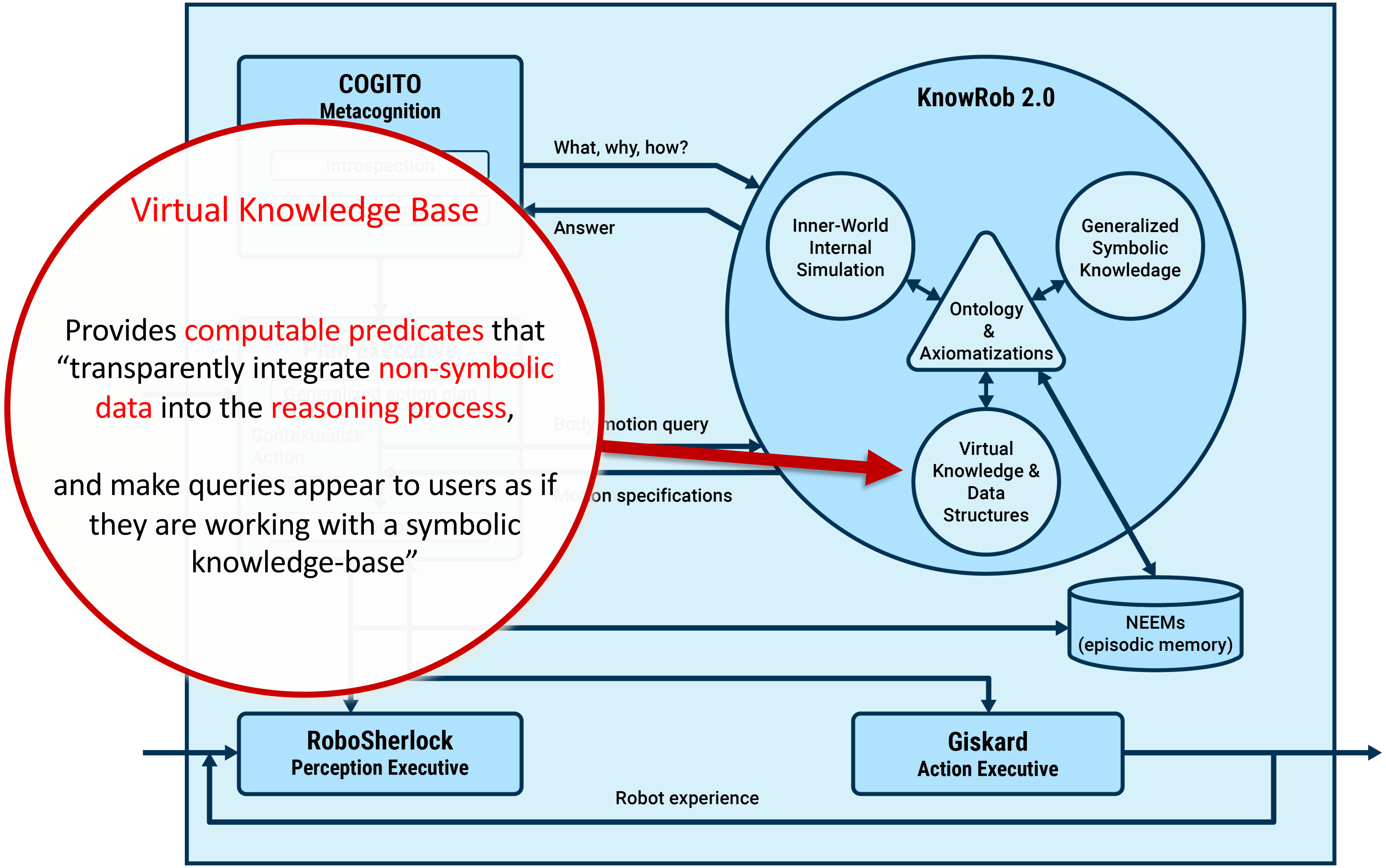
Robot experience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Virtual Knowledge & Data Structures
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on specifications
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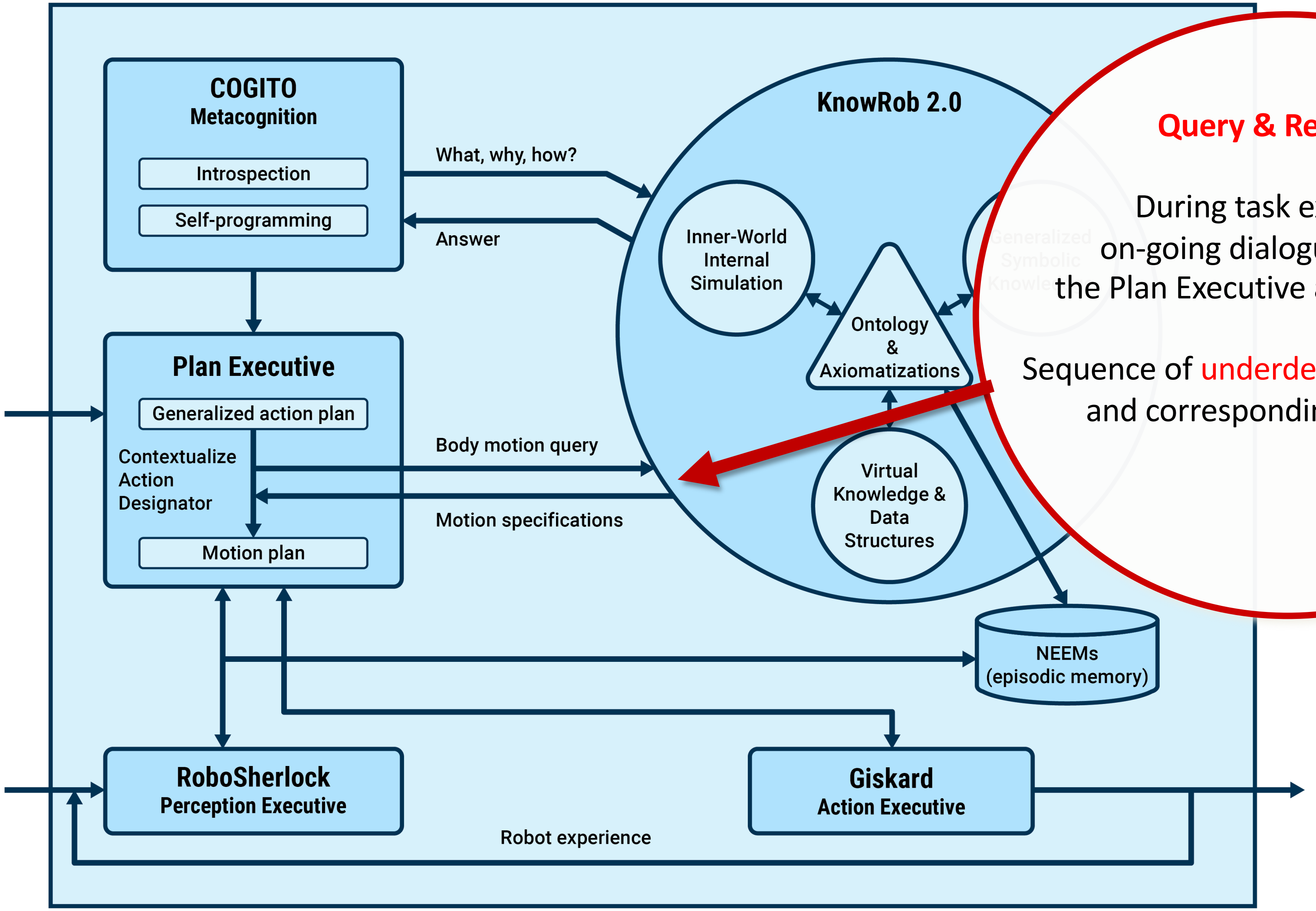
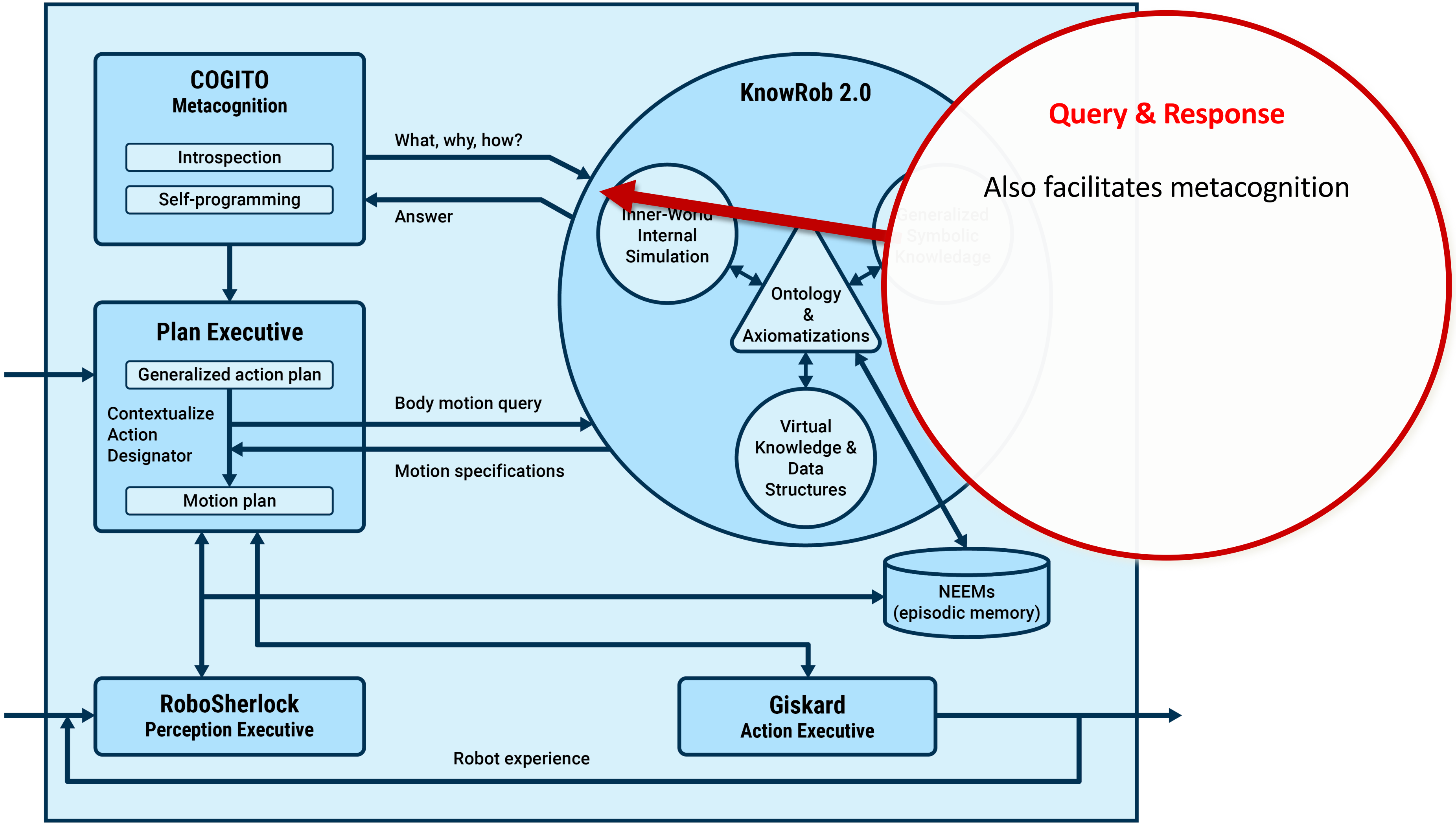
RoboSherlock
Perception Executive
Giskard
Action Executive
Robot experience
Virtual Knowledge Base
Provides computable predicates that "transparently integrate non-symbolic data into the reasoning process,
and make queries appear to users as if they are working with a symbolic knowledge-base"



Query & Response

During task execution:
on-going dialogue between
the Plan Executive and KnowRob2

Sequence of underdetermined queries
and corresponding responses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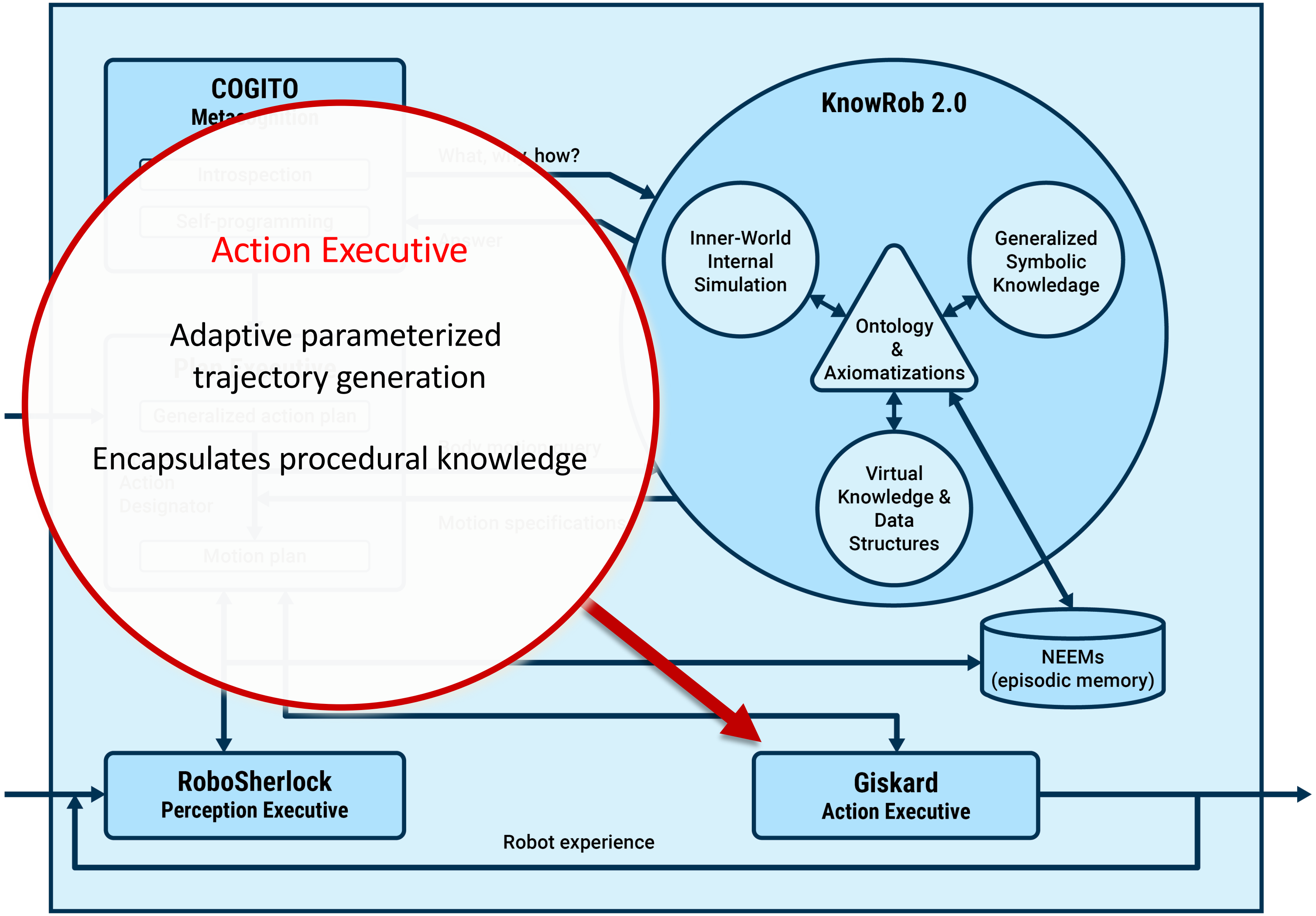
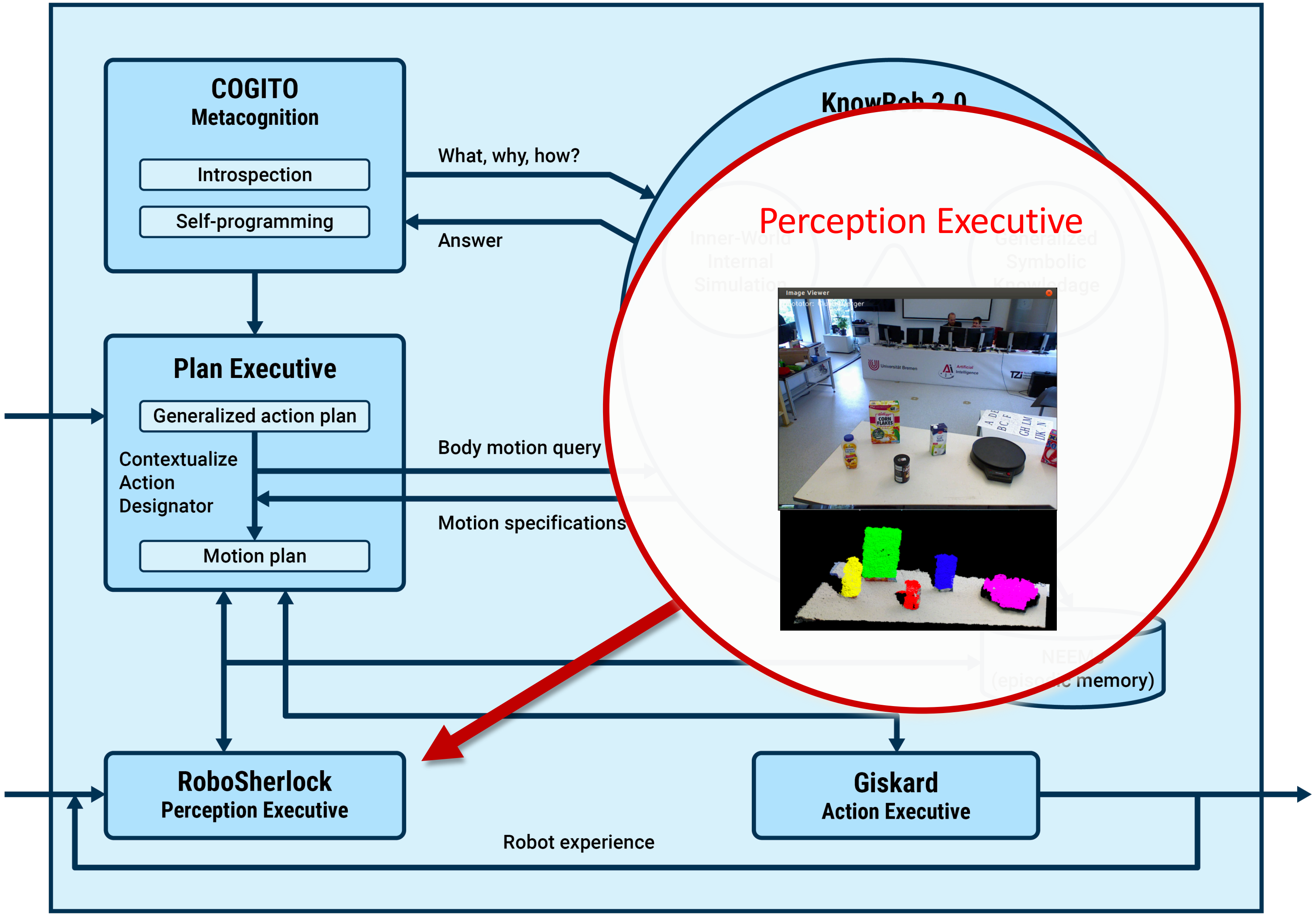
Query & Response
Also facilitates metacognition



Action Executive

Adaptive parameterized trajectory generation

Encapsulates procedural knowledge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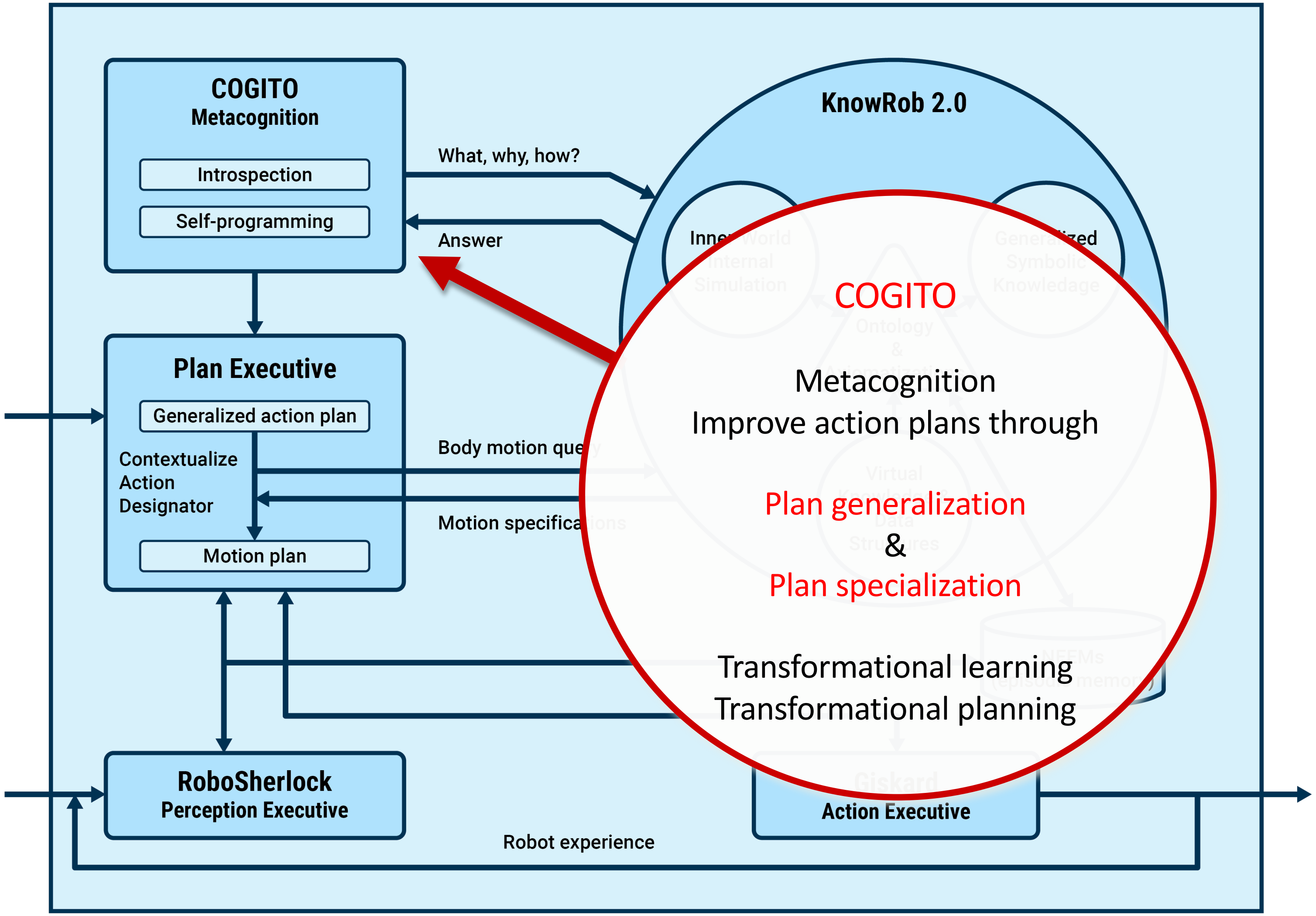
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RoboSherlock
Perception Executive
Action Executive
Robot experience
COGITO
Metacognition
Improve action plans through
Plan generalization
&
Plan specialization
Transformational learning
Transformational planning

Lecture Summary

1. The CRAM cognitive architecture focusses on abstract specification of robot actions that are underdetermined

2. It has five components
   i. CRAM Plan Language and the Plan Executive
   ii. KnowRob2.0 Knowledge Representation and Reasoning Executive
   iii. RoboSherlock Perception Executive
   iv. Giskard Action Executive
   v. COGITO Metacognition

3. The key concept is the generalized action plan which is executed
   – By resolving high-level action designators into a motion plan
   – Though a process referred to as contextualization
   – Which involves querying KnowRob2.0 to identify the motion parameter values that will maximize the likelihood that the action will succeed

Recommended Reading

M. Beetz, L. Mösenlechner, and M. Tenorth. CRAM – A Cognitive Robot Abstract Machine for Everyday Manipulation in Human Environments. In IEEE/RSJ International Conference on Intelligent Robots and Systems, pages 1012–1017, Taipei, Taiwan, October 2010.