Introduction to Cognitive Robotics

Module 7: Cognitive Architectures

Lecture 5: The CRAM cognitive architecture: structure

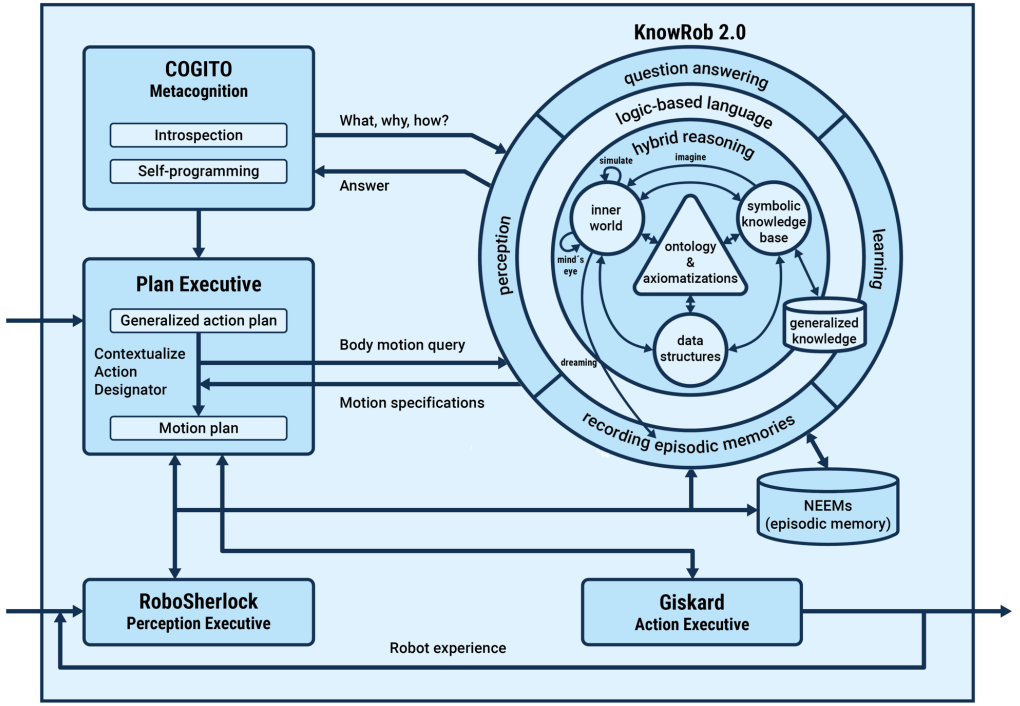
David Vernon
Carnegie Mellon University Africa

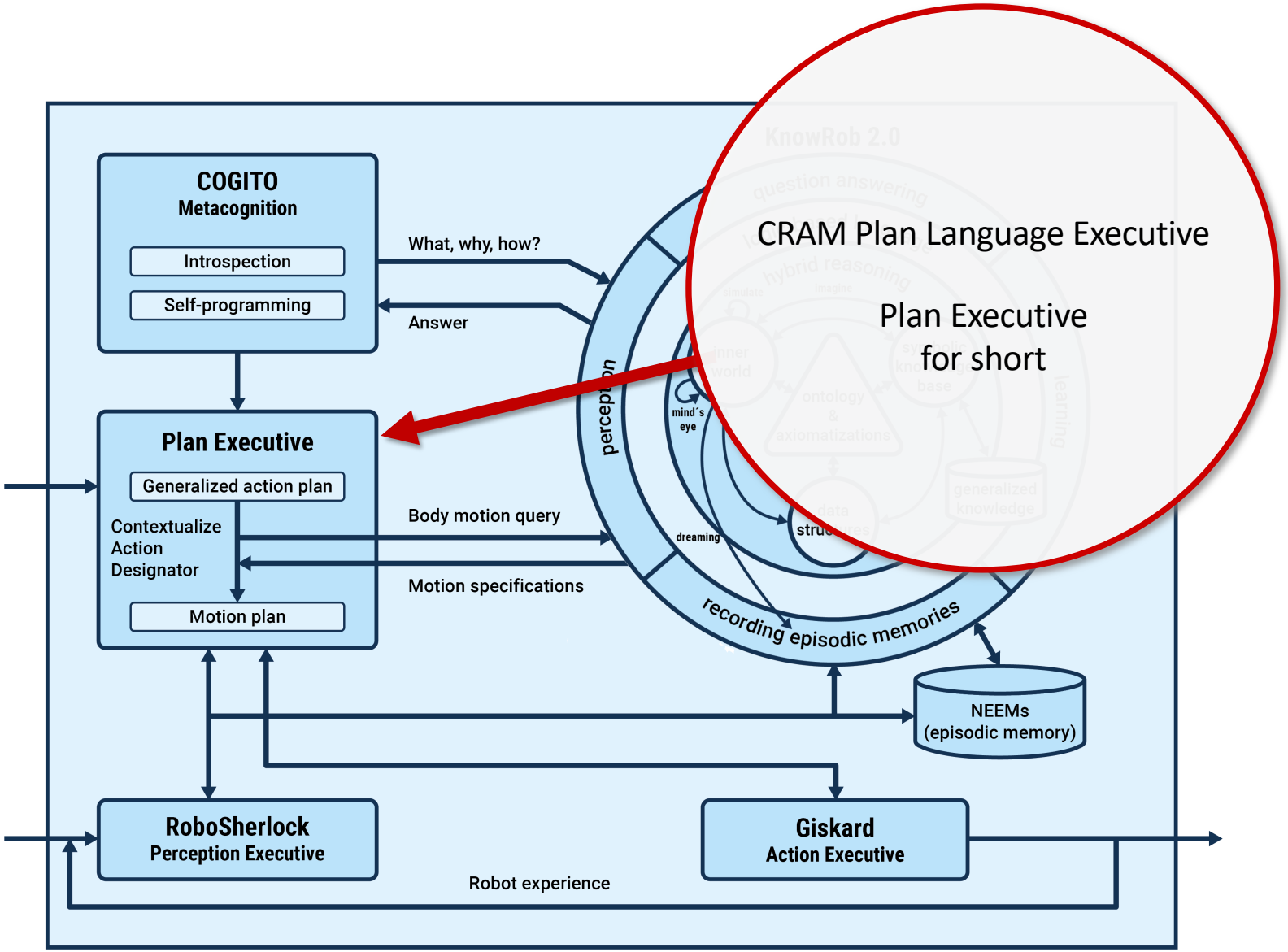
www.vernon.eu

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
RoboSherlock
Perception Executive
Giskard
Action Executive
Robot experience
NEEMs
(episodic memory)
recording episodic memories
perception
mind´s eye
dreaming
CRAM Plan Language Executive
Plan Executive
for short

CRAM Plan Language (CPL) Executive

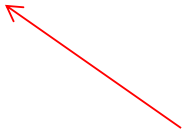
- Tasks are accomplished by executing plans written in the CRAM Plan Language (CPL)
- CPL is an extension of Lisp
- A CPL plan represents all key aspects of the plan as persistent first-class objects in a first-order logic
  - Plans themselves can be reasoned about, even at runtime
  - Particularly relevant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

CRAM Plan Language (CPL) Executive

- Plans specify how the robot should respond to
  - Sensory events
  - Changes in belief states
  - Failures in plans
- All of which can be queried, inspected, and reasoned about

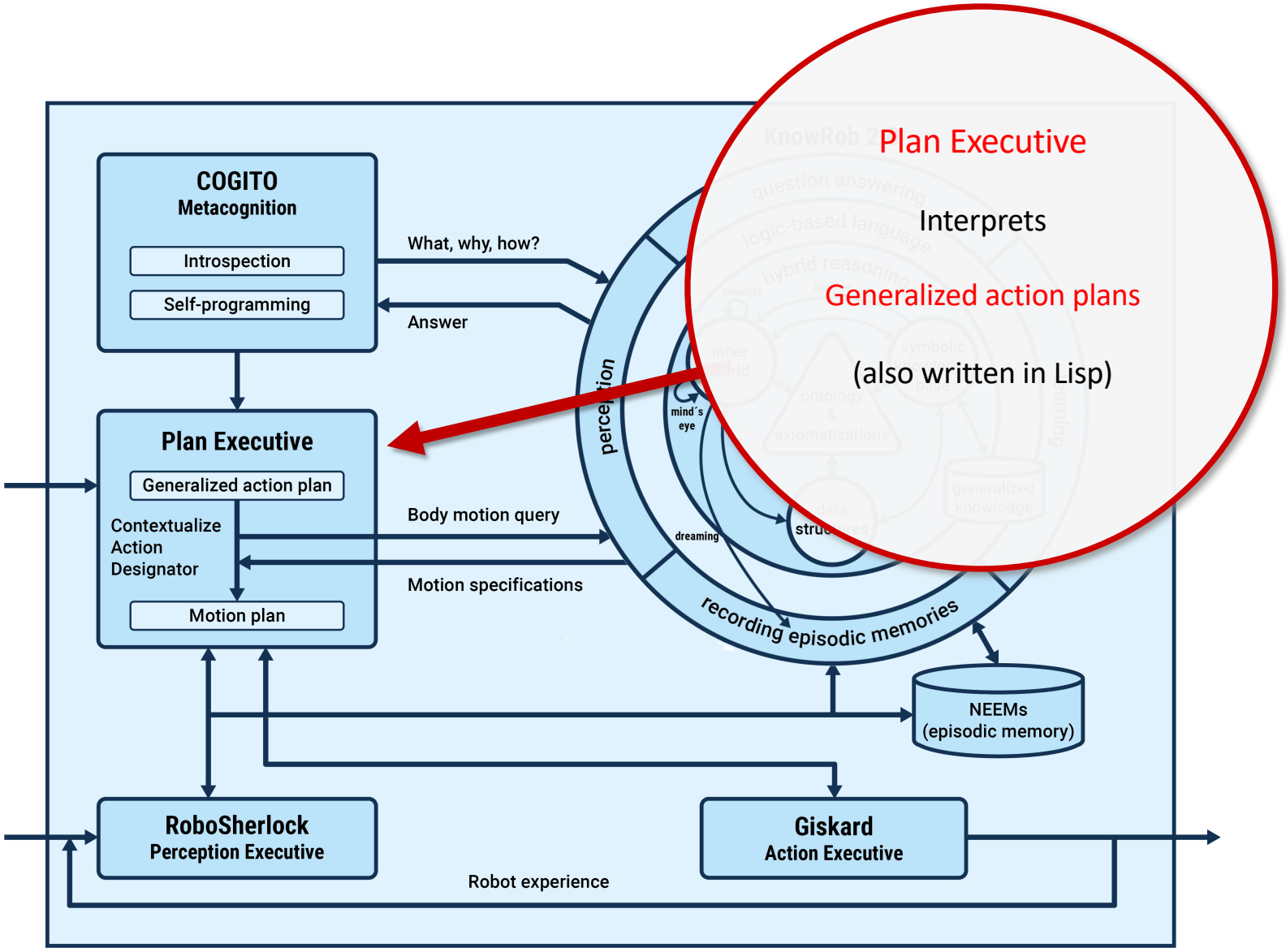
CRAM Plan Language (CPL) Executive

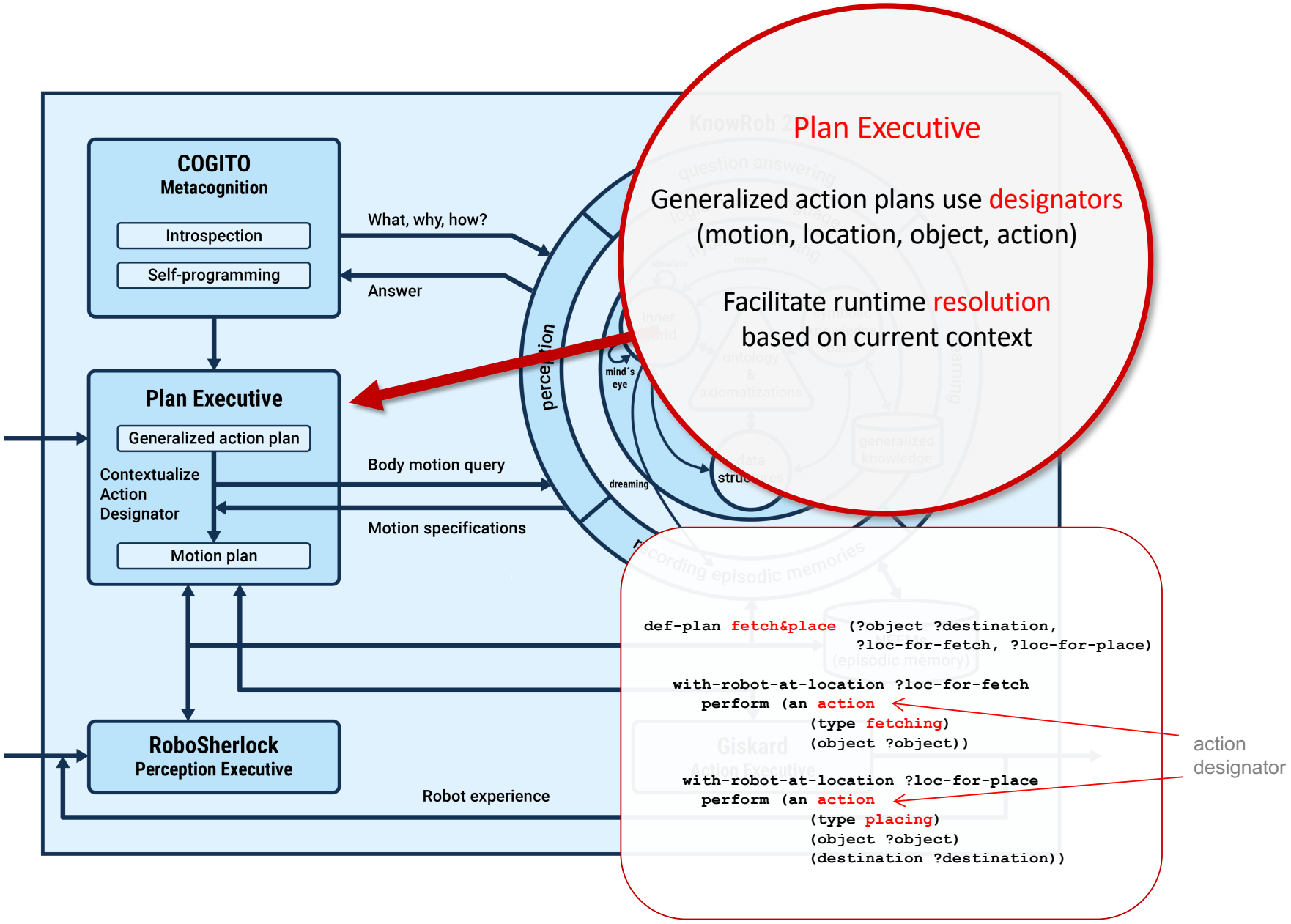
- A plan comprises set of abstract plan designators for
  - actions
  - objects
  - locations
  - motions (i.e. elementary movements)

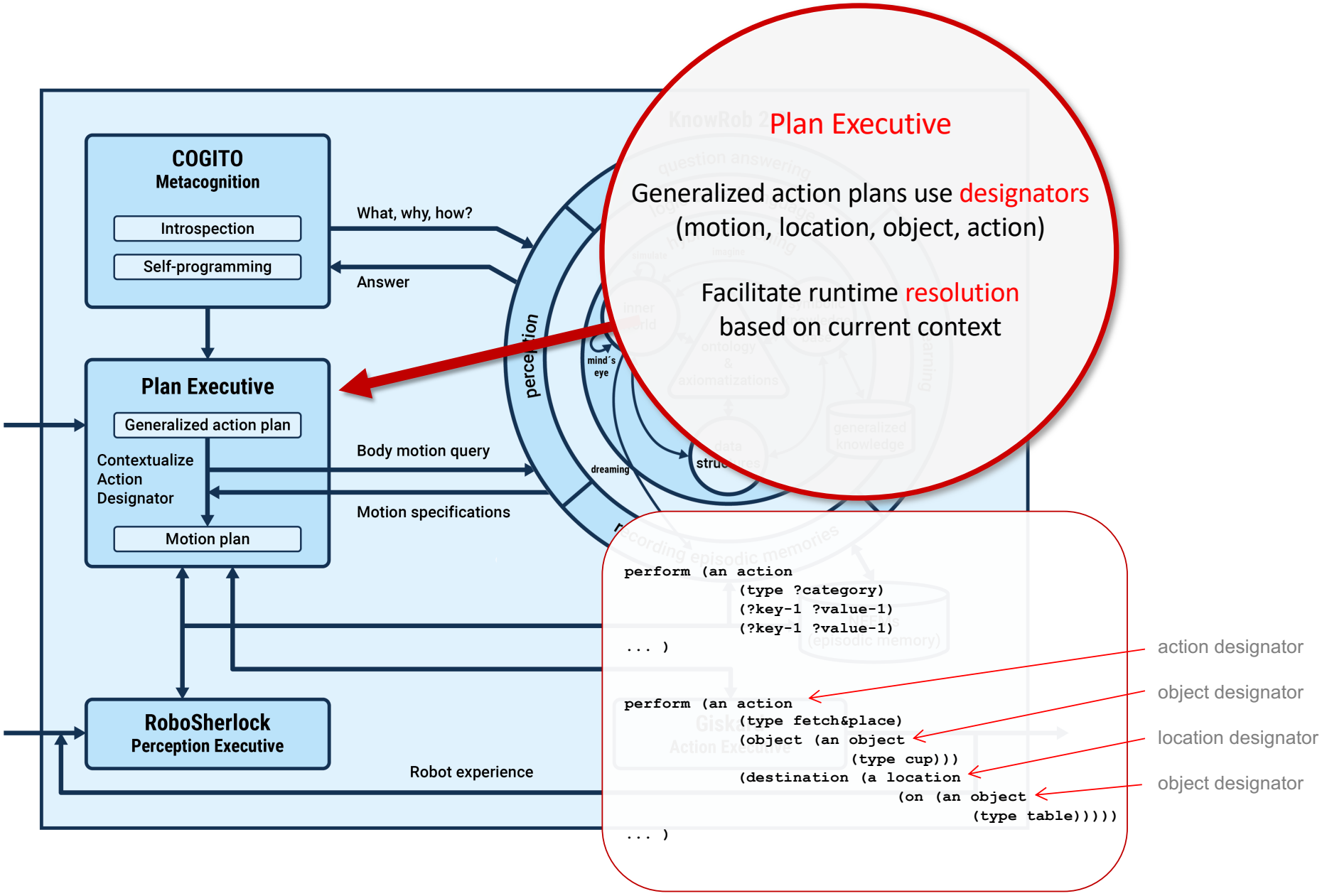


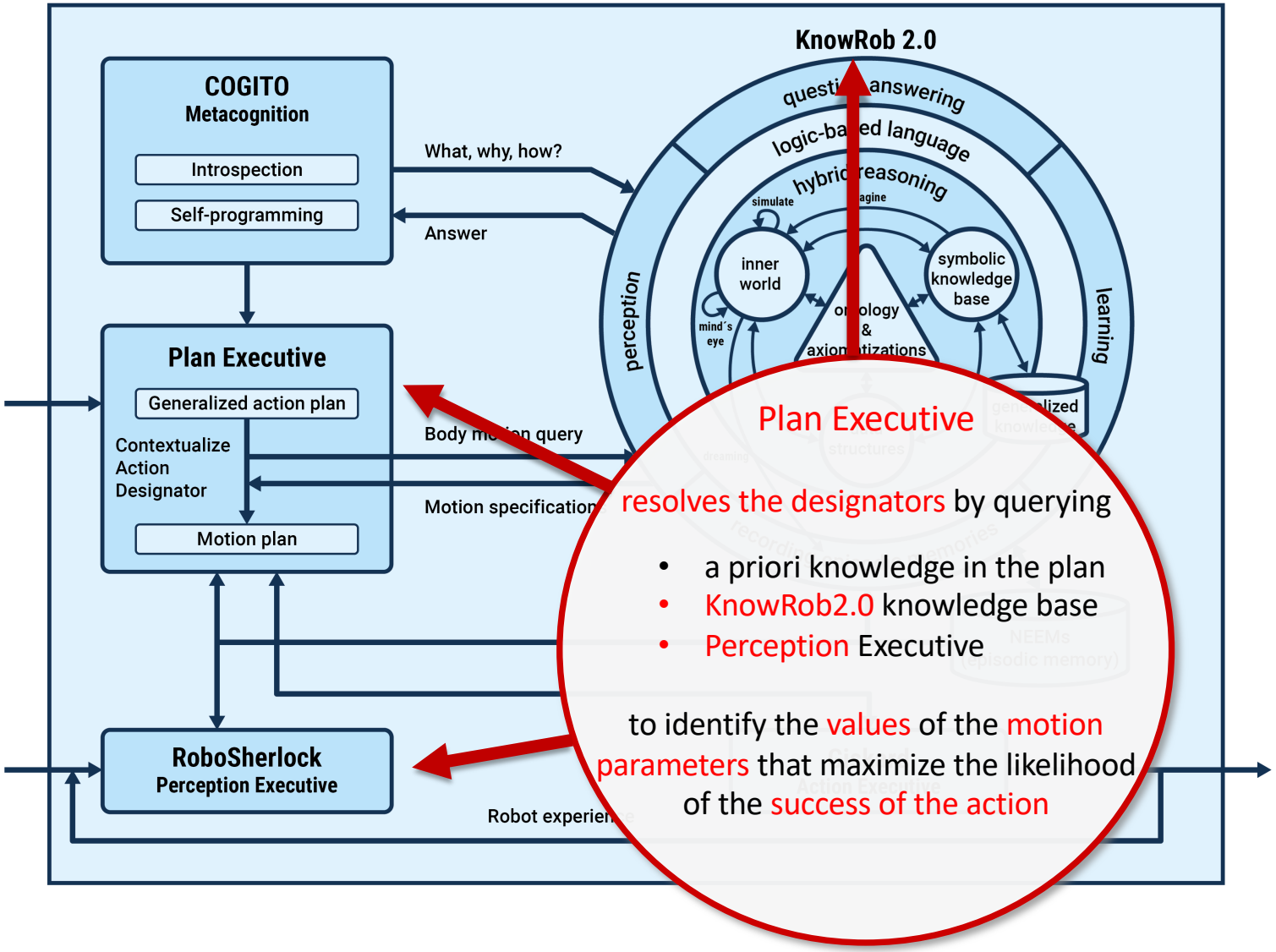
Designators are effectively placeholders

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


COGITO
Metacognition
Introspection
Self-programming
What, why, how?
Answer
Plan Executive
Generalized action plan
Contextualize
Action
Designator
Motion plan
Body motion query
Motion specifications
perception
mind´s eye
dreaming
recording episodic memories
NEEMs
(episodic memory)
RoboSherlock
Perception Executive
Giskard
Action Executive
Robot experience
Plan Executive
Interprets
Generalized action plans
(also written in Lisp)

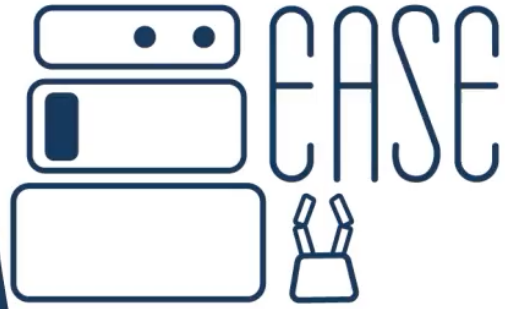

COGITO
Metacognition
Introspection
Self-programming
What, why, how?
Answer
Plan Executive
Generalized action plan
Contextualize
Action
Designator
Motion plan
Body motion query
Motion specifications
RoboSherlock
Perception Executive
Robot experience
Plan Executive
Generalized action plans use designators
(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


COGITO
Metacognition
Introspection
Self-programming
What, why, how?
Answer
Plan Executive
Generalized action plan
Contextualize
Action
Designator
Motion plan
Body motion query
Motion specifications
RoboSherlock
Perception Executive
Robot experience
Plan Executive
Generalized action plans use designators
(motion, location, object, action)
Facilitate runtime resolution
based on current context
perception
mind´s eye
dreaming
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


KnowRob 2.0
COGITO
Metacognition
Introspection
Self-programming
What, why, how?
Answer
Plan Executive
Generalized action plan
Contextualize
Action
Designator
Motion plan
Body motion query
Motion specification
RoboSherlock
Perception Executive
Robot experience
perception
learning
inner world
symbolic knowledge base
simulate
mind´s eye
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

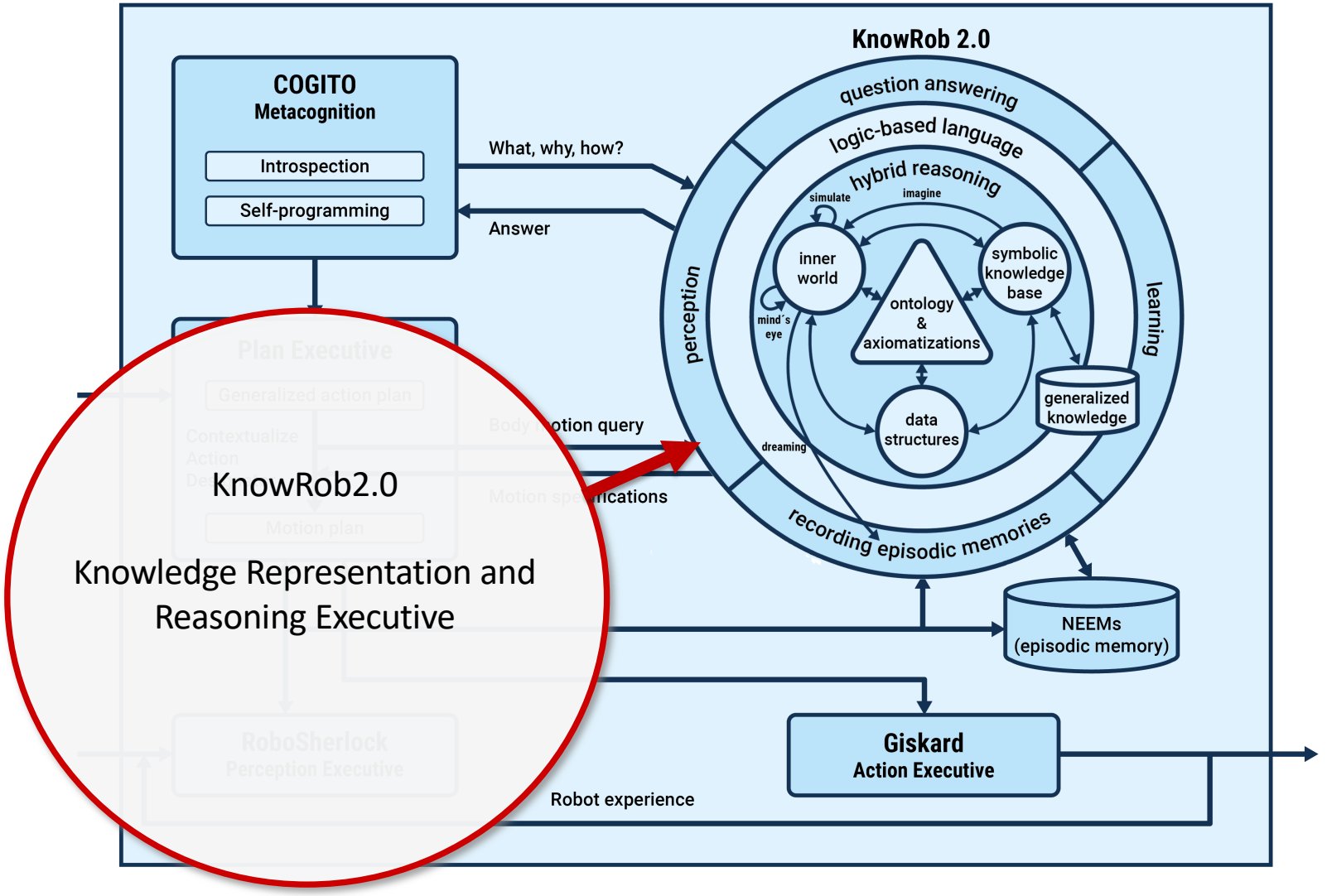
Programming Robotic Agents with Action Descriptions

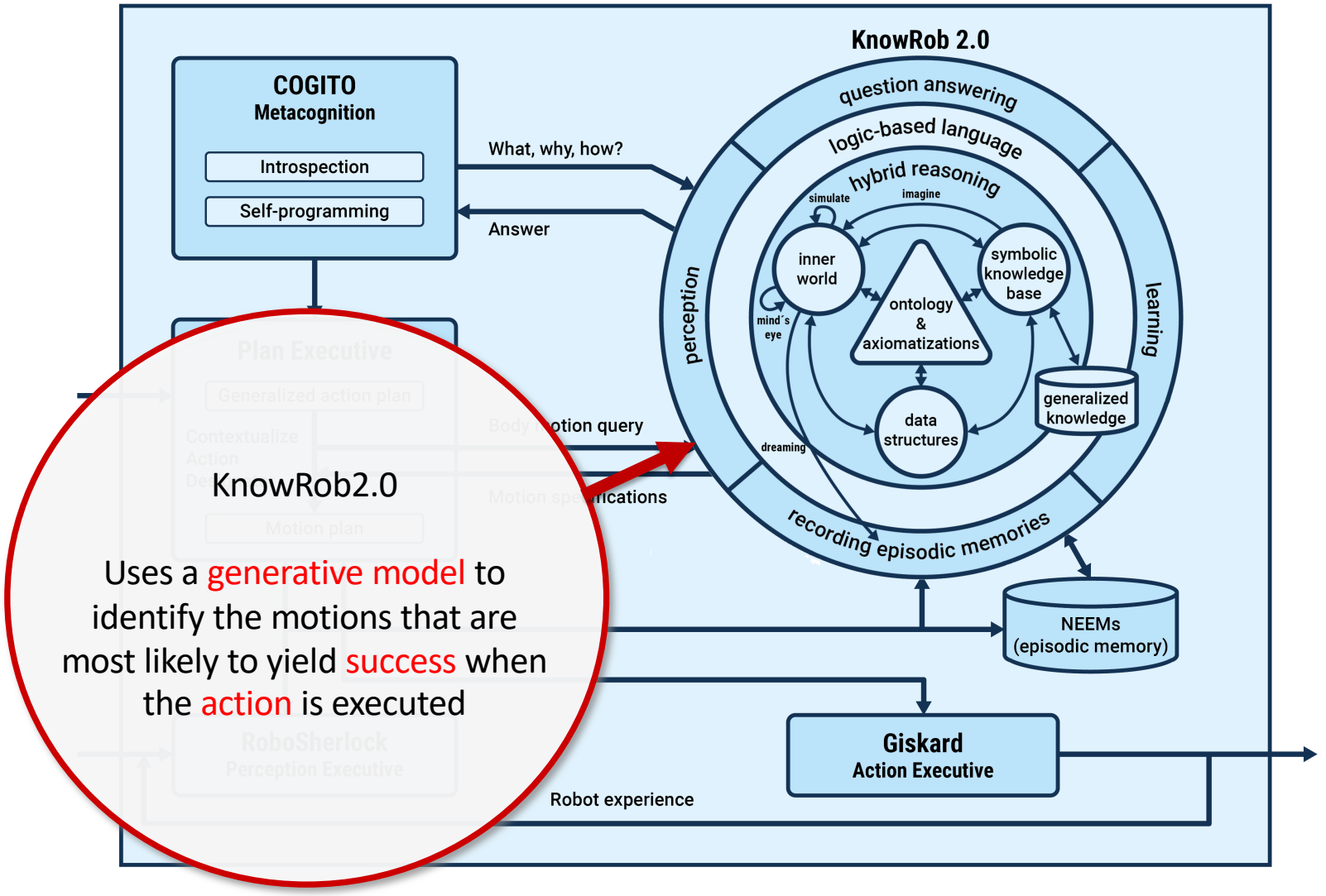
Gayane Kazhoyan and Michael Beetz

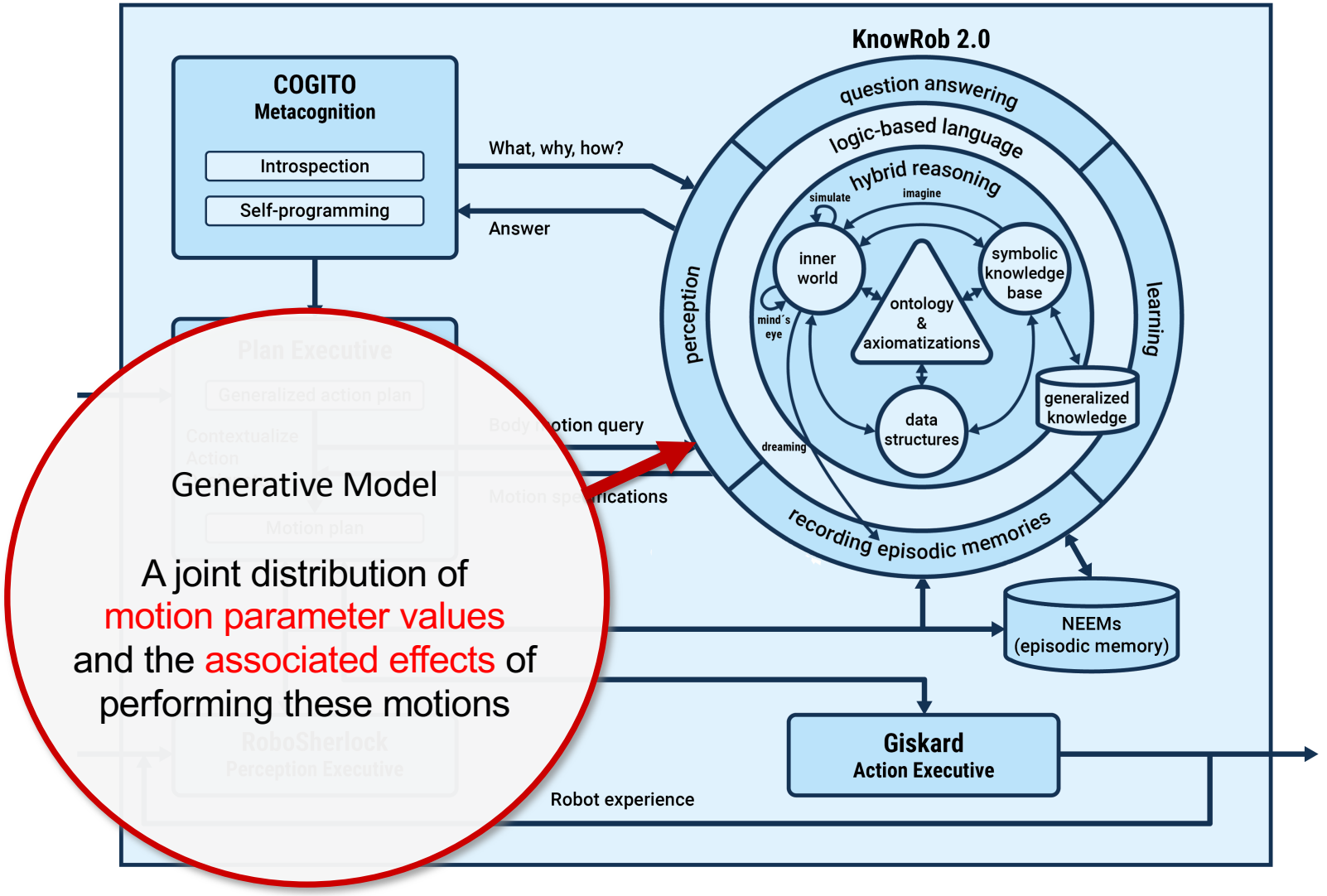


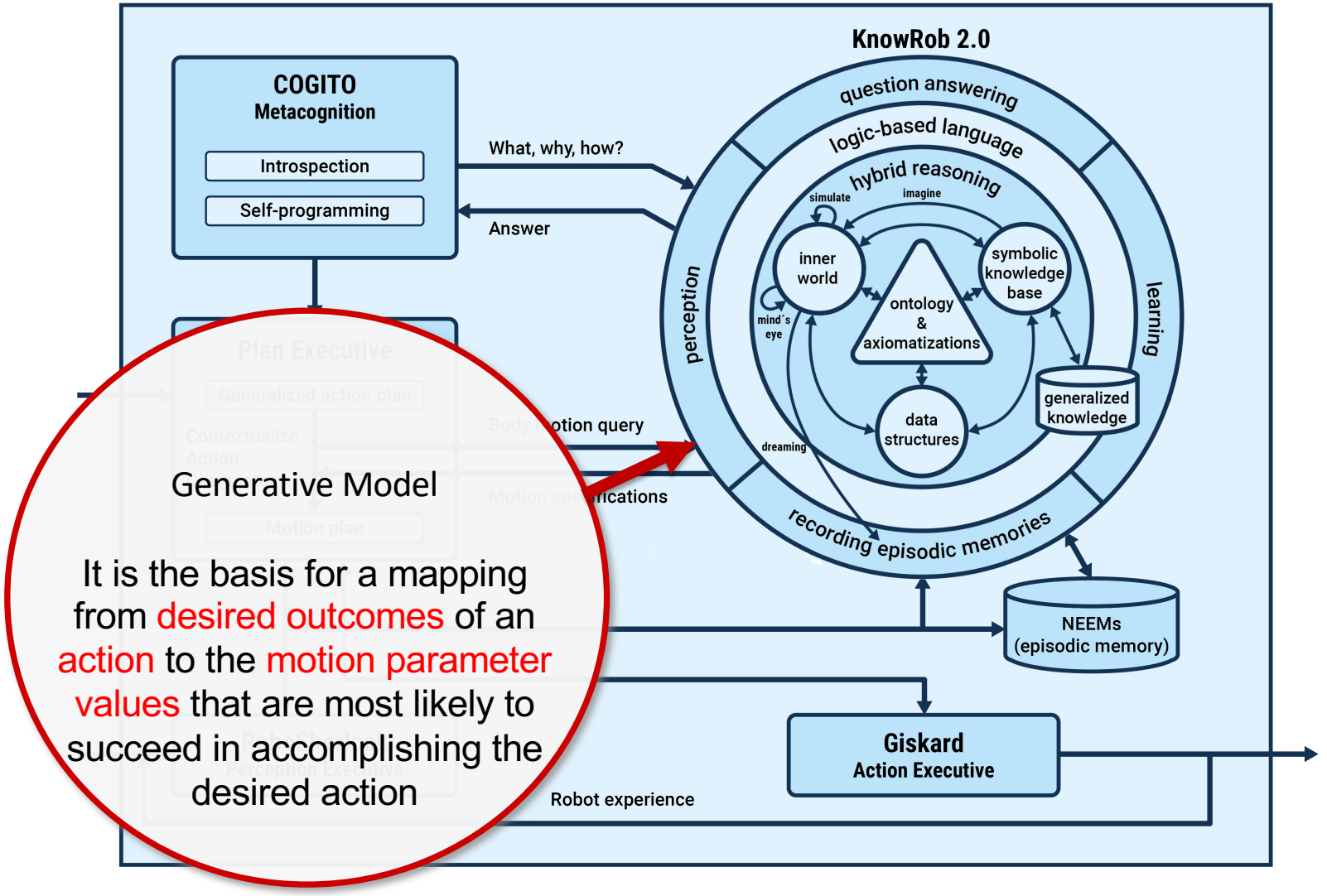
Artificial Intelligence

Universität Bremen


KnowRob 2.0
COGITO
Metacognition
Introspection
Self-programming
What, why, how?
Answer
question answering
logic-based language
hybrid reasoning
simulate
imagine
inner world
symbolic knowledge base
ontology & axiomatizations
mind´s eye
data structures
generalized knowledge
dreaming
perception
learning
recording episodic memories
NEEMs (episodic memory)
Giskard
Action Executive
Robot experience
KnowRob2.0
Knowledge Representation and Reasoning Executive


KnowRob 2.0
COGITO
Metacognition
Introspection
Self-programming
What, why, how?
Answer
question answering
logic-based language
hybrid reasoning
simulate
imagine
inner world
symbolic knowledge base
ontology & axiomatizations
mind´s eye
data structures
generalized knowledge
dreaming
perception
learning
recording episodic memories
NEEMs (episodic memory)
Giskard
Action Executive
Robot experience
KnowRob2.0
Uses a generative model to identify the motions that are most likely to yield success when the action is executed


KnowRob 2.0
COGITO
Metacognition
Introspection
Self-programming
What, why, how?
Answer
question answering
logic-based language
hybrid reasoning
simulate
imagine
inner world
symbolic knowledge base
ontology & axiomatizations
mind´s eye
data structures
generalized knowledge
dreaming
perception
learning
recording episodic memories
NEEMs (episodic memory)
Giskard
Action Executive
Robot experience
Generative Model
A joint distribution of motion parameter values and the associated effects of performing these motions


KnowRob 2.0
COGITO
Metacognition
Introspection
Self-programming
What, why, how?
Answer
question answering
logic-based language
hybrid reasoning
simulate
imagine
inner world
symbolic knowledge base
ontology & axiomatizations
mind´s eye
data structures
generalized knowledge
dreaming
perception
learning
recording episodic memories
NEEMs (episodic memory)
Giskard
Action Executive
Robot experience
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

KnowRob2 Knowledge Base

- Knowledge representation and reasoning framework for robotic agents
  - Implemented in Prolog
- Exposed as a conventional first-order time interval logic knowledge-base
- However, many logic expressions are constructed on-demand from sensorimotor data computed in real-time

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.

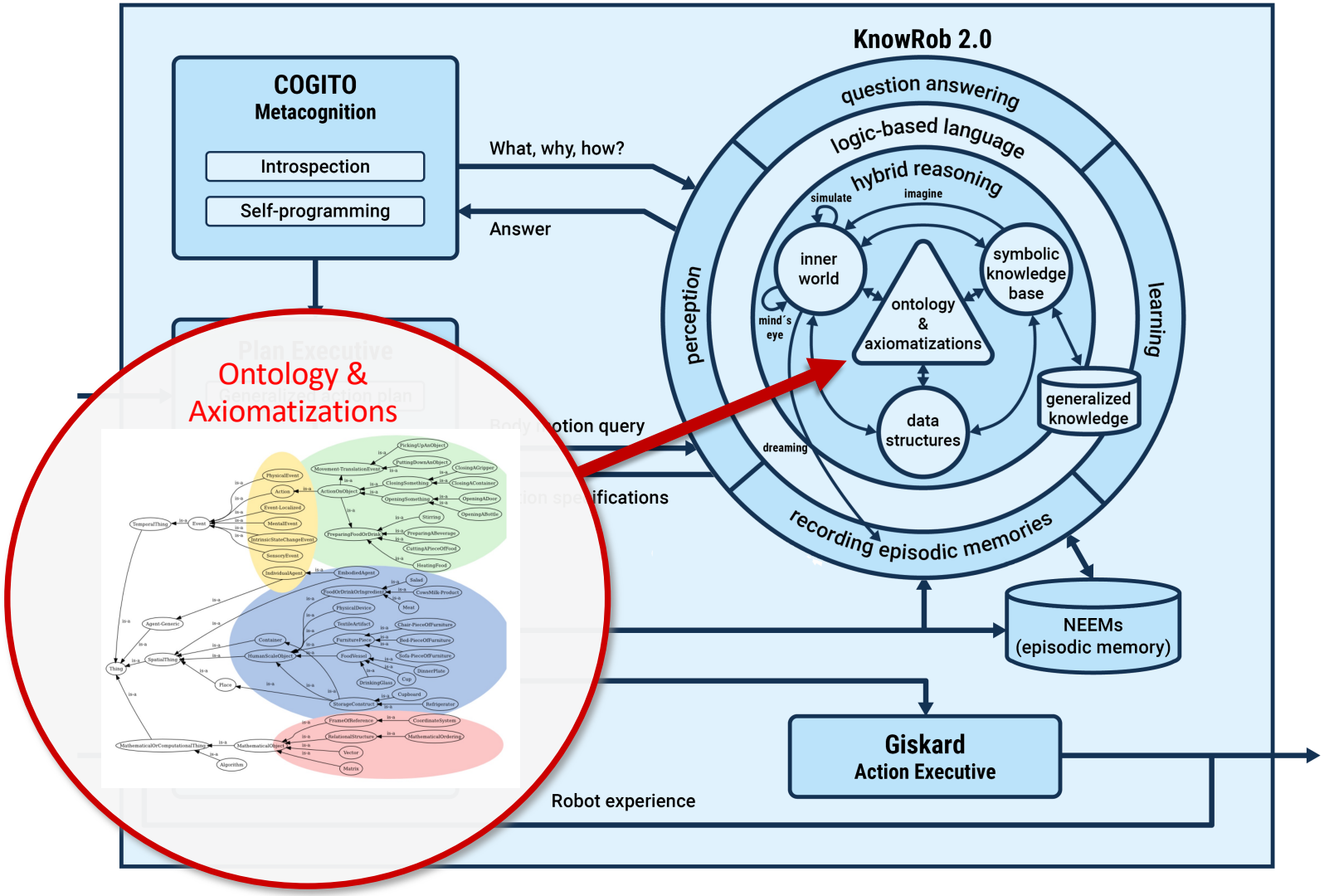
KnowRob2 Knowledge Base

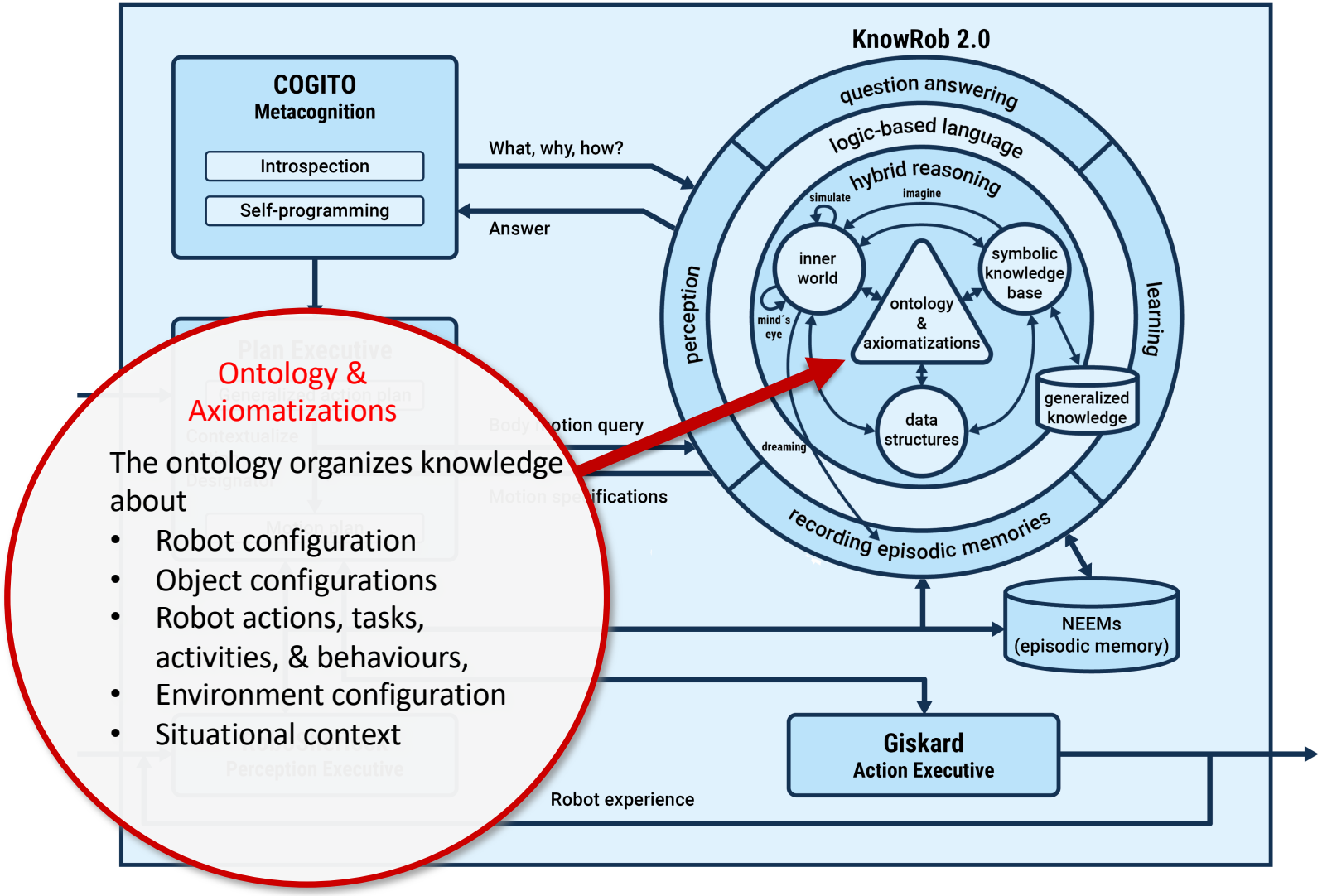
- Source of knowledge:
  - Some is specified a priori
  - Some is derived from experience
  - Some is the result of simulated execution of candidate actions using a high-fidelity virtual reality physics engine simulator
- All represented by a first-order time interval logic expression, and reasoned about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

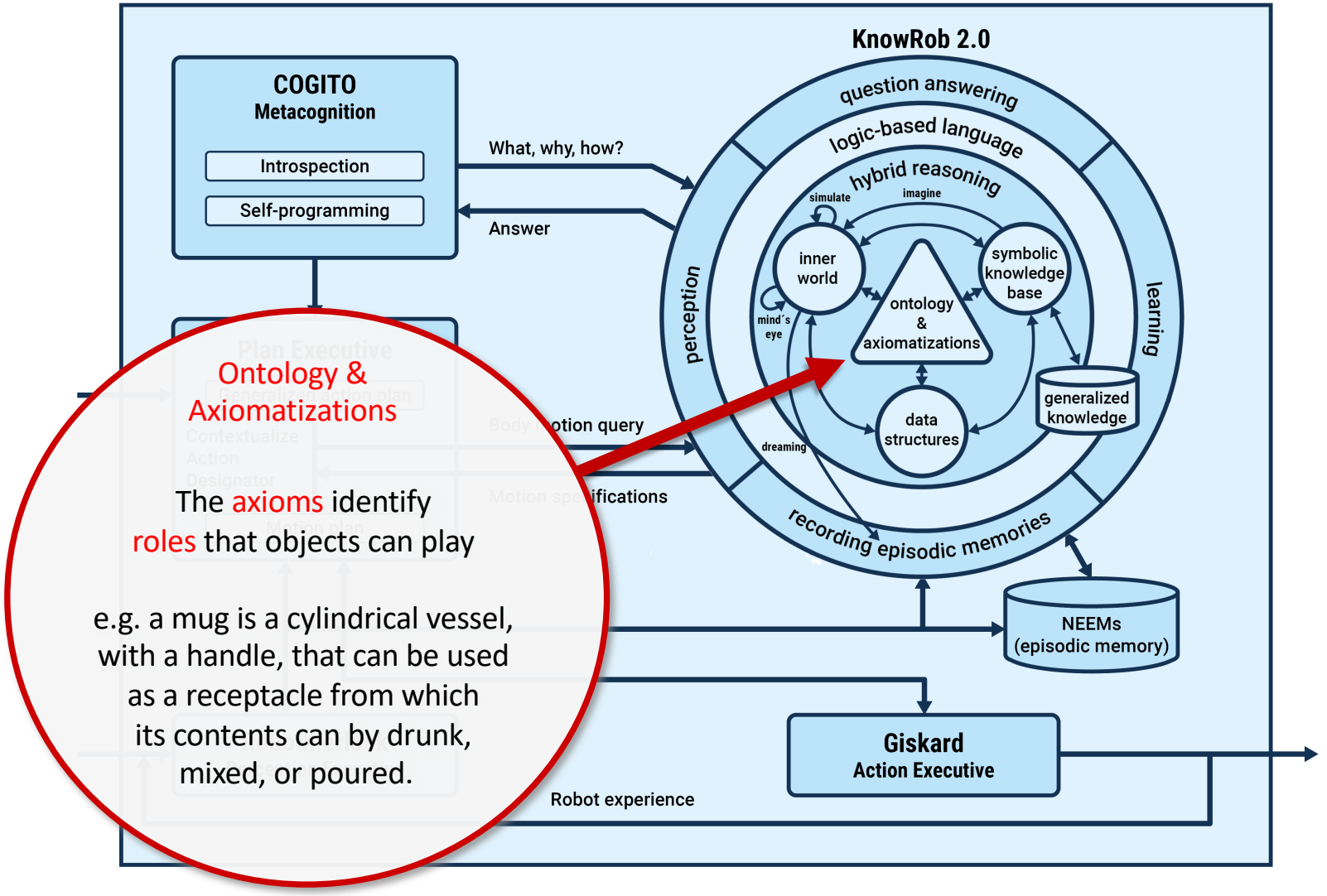
KnowRob2 Knowledge Base

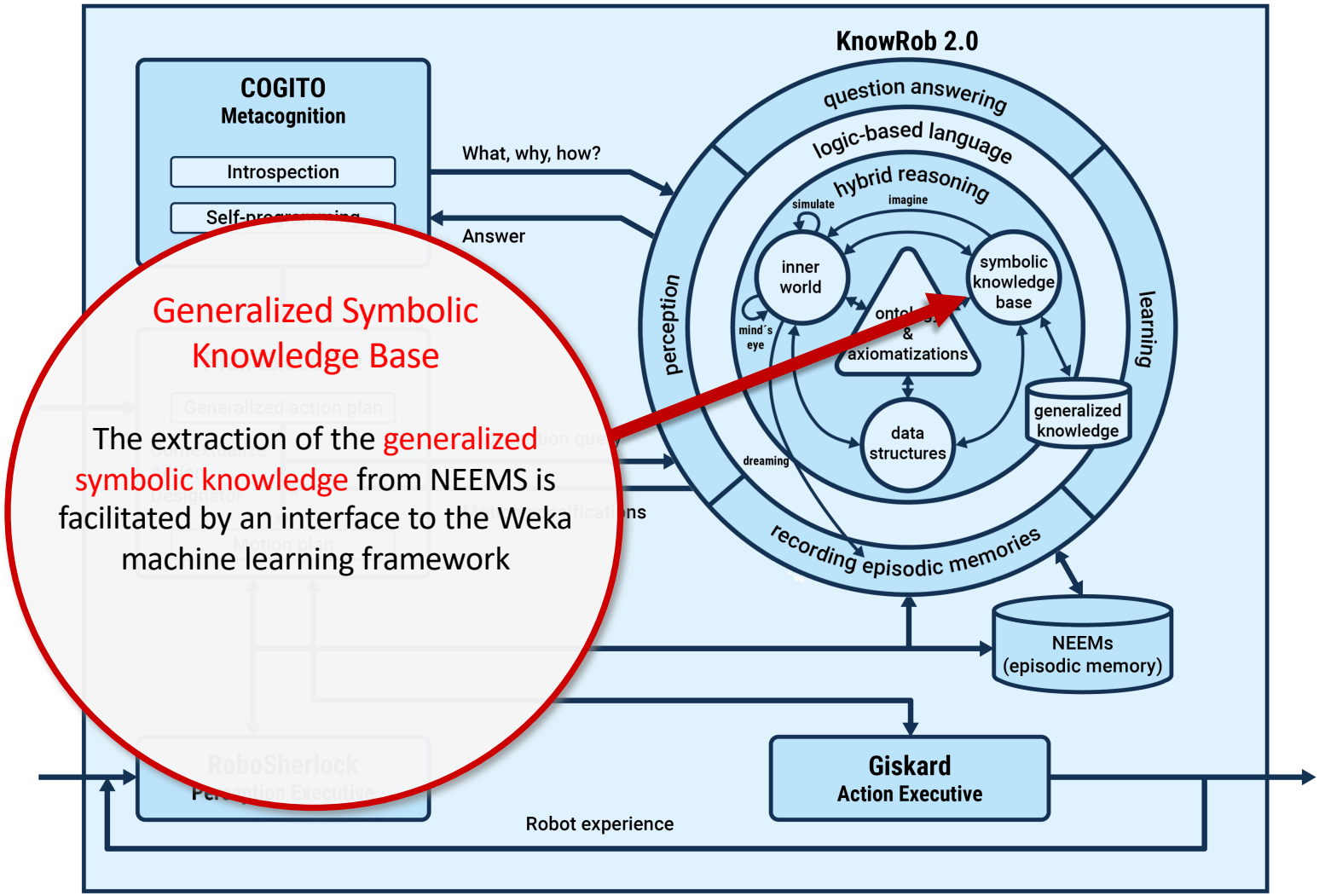
KnowRob2 comprises five core elements

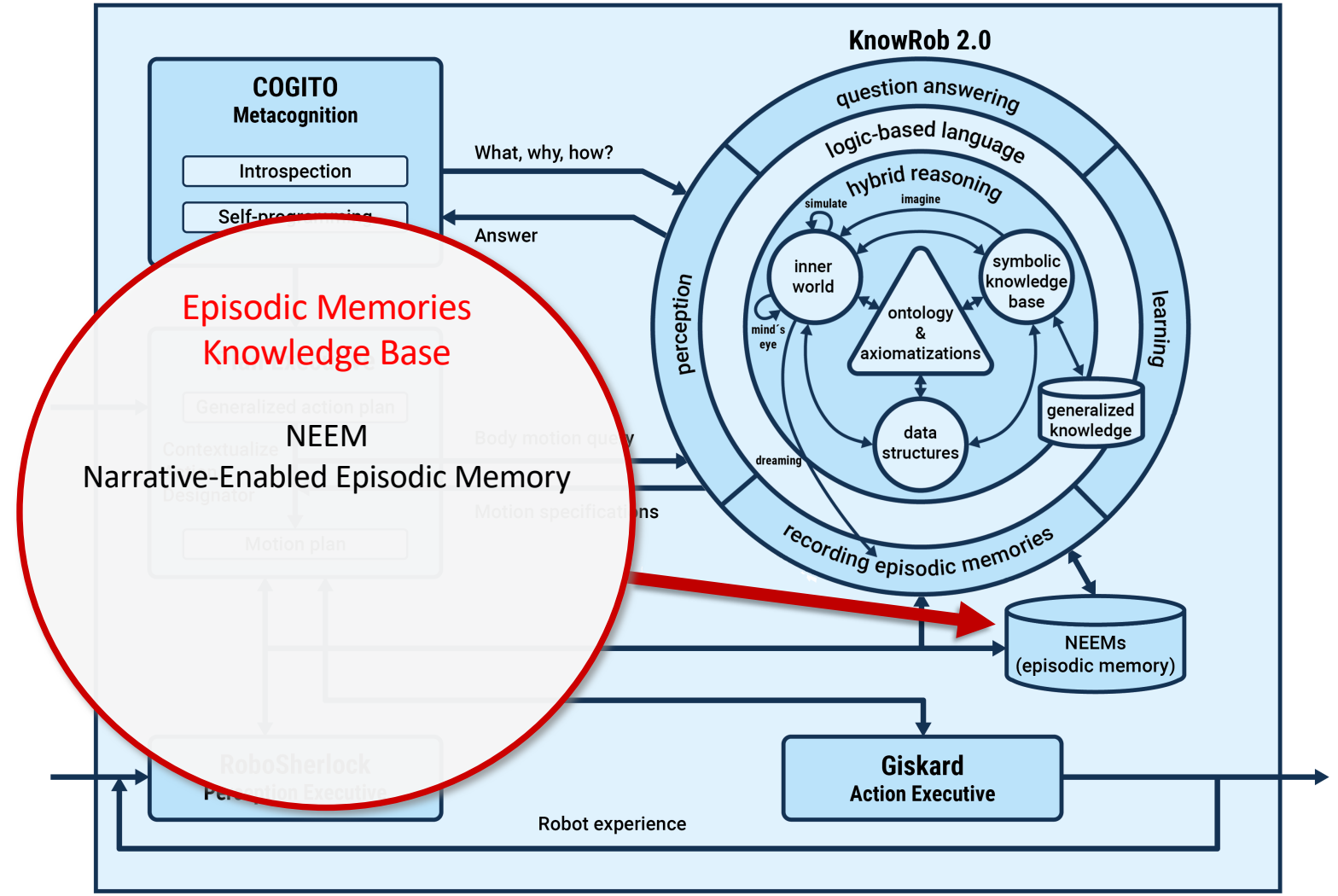
- embedded in a hybrid multi-formalism reasoning shell
- exposed through a logic-based language layer

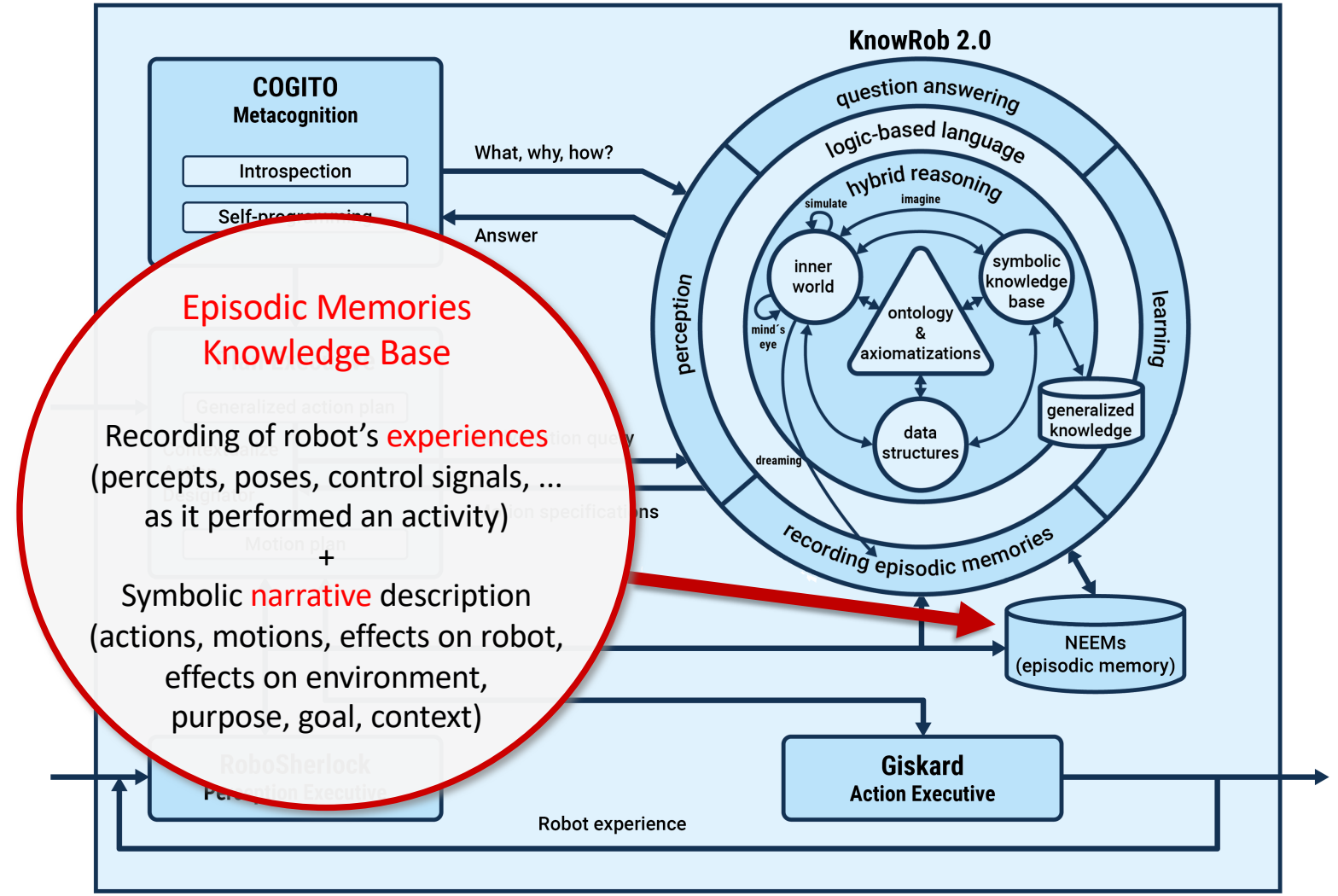

KnowRob 2.0
COGITO
Metacognition
Introspection
Self-programming
What, why, how?
Answer
question answering
logic-based language
hybrid reasoning
simulate
imagine
inner world
symbolic knowledge base
ontology & axiomatizations
mind´s eye
data structures
generalized knowledge
dreaming
perception
learning
recording episodic memories
Ontology & Axiomatizations
NEEMs (episodic memory)
Giskard
Action Executive
Robot experience

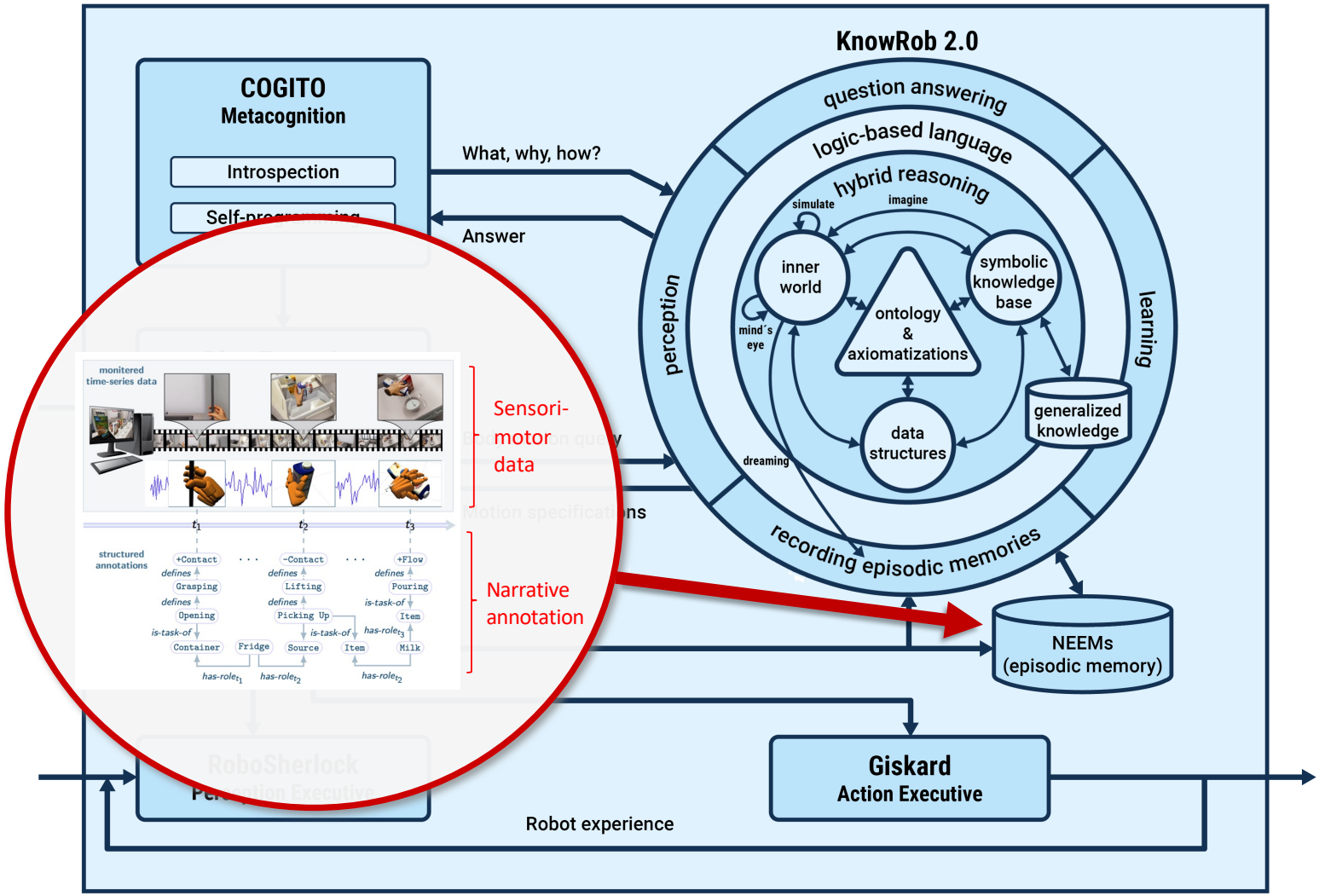

KnowRob 2.0
COGITO
Metacognition
Introspection
Self-programming
What, why, how?
Answer
question answering
logic-based language
hybrid reasoning
simulate
imagine
inner world
symbolic knowledge base
ontology & axiomatizations
mind´s eye
data structures
generalized knowledge
dreaming
perception
learning
recording episodic memories
NEEMs (episodic memory)
Giskard
Action Executive
Robot experience
Ontology & Axiomatizations
The ontology organizes knowledge about
• Robot configuration
• Object configurations
• Robot actions, tasks, activities, & behaviours,
• Environment configuration
• Situational context

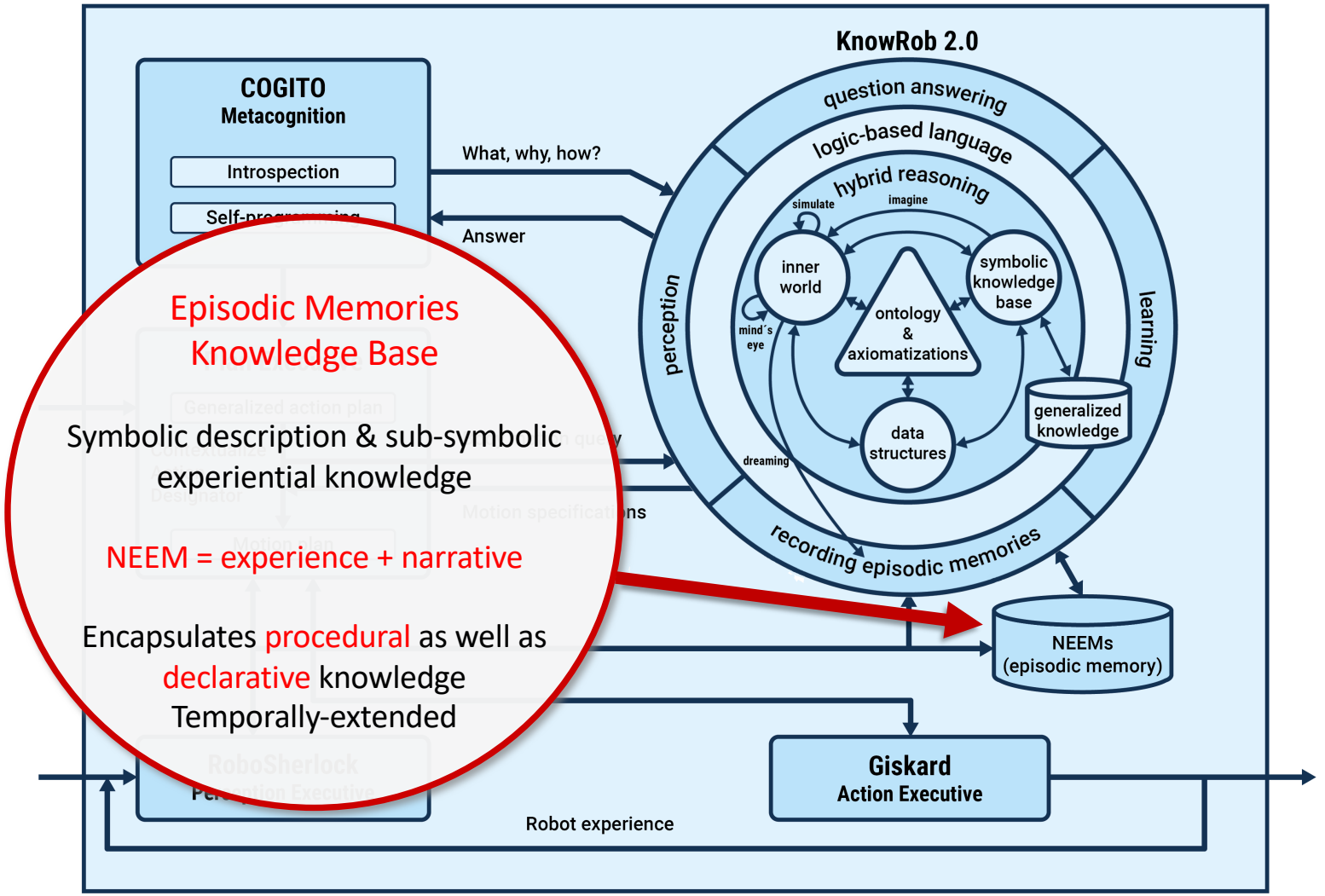

KnowRob 2.0
COGITO
Metacognition
Introspection
Self-programming
What, why, how?
Answer
question answering
logic-based language
hybrid reasoning
simulate
imagine
inner world
symbolic knowledge base
ontology & axiomatizations
mind´s eye
data structures
generalized knowledge
dreaming
perception
learning
recording episodic memories
NEEMs (episodic memory)
Giskard
Action Executive
Robot experience
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.

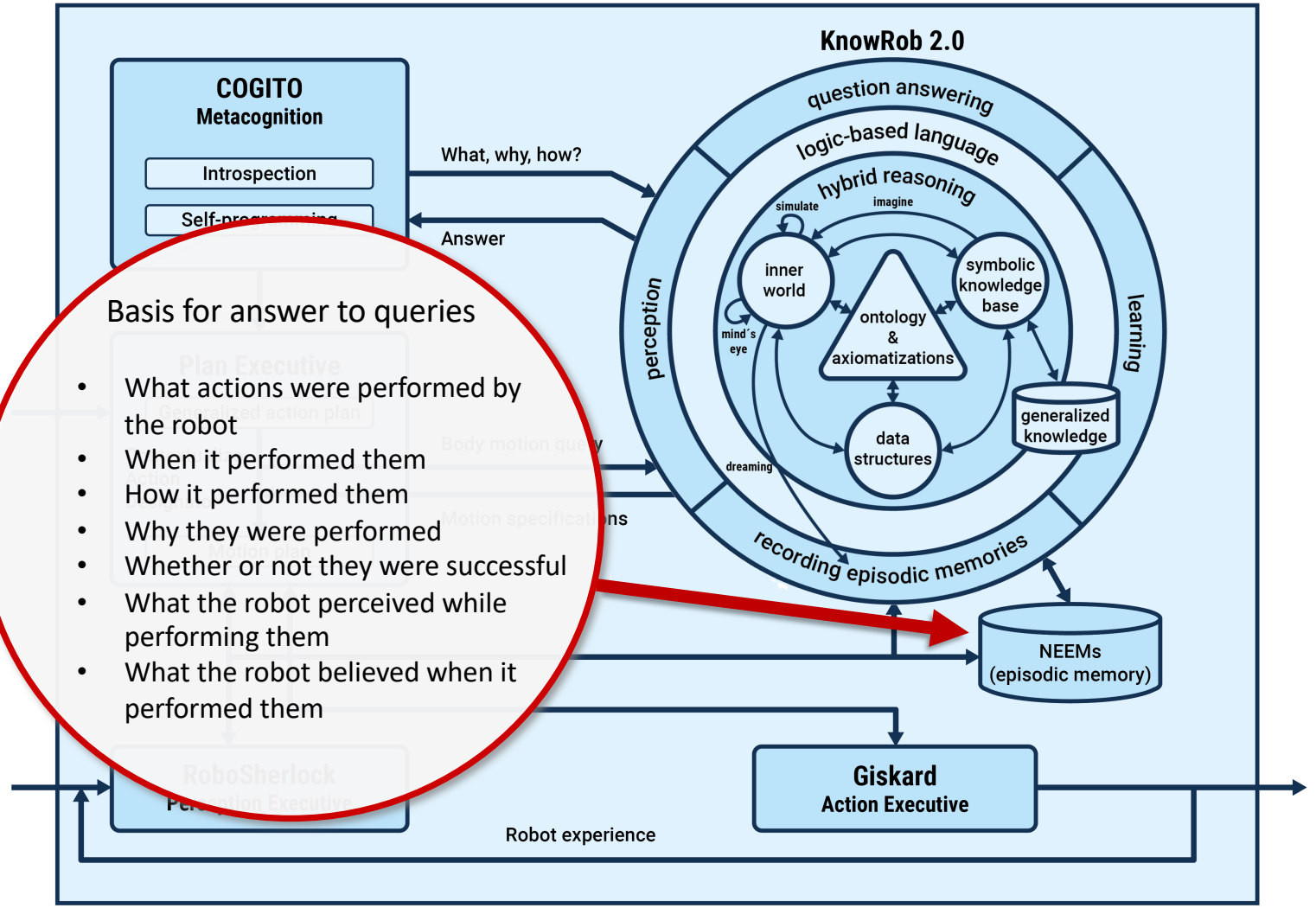

KnowRob 2.0
COGITO
Metacognition
Introspection
What, why, how?
Answer
question answering
logic-based language
hybrid reasoning
simulate
imagine
inner world
symbolic knowledge base
mind´s eye
ontologies & axiomatizations
data structures
generalized knowledge
dreaming
perception
learning
recording episodic memories
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

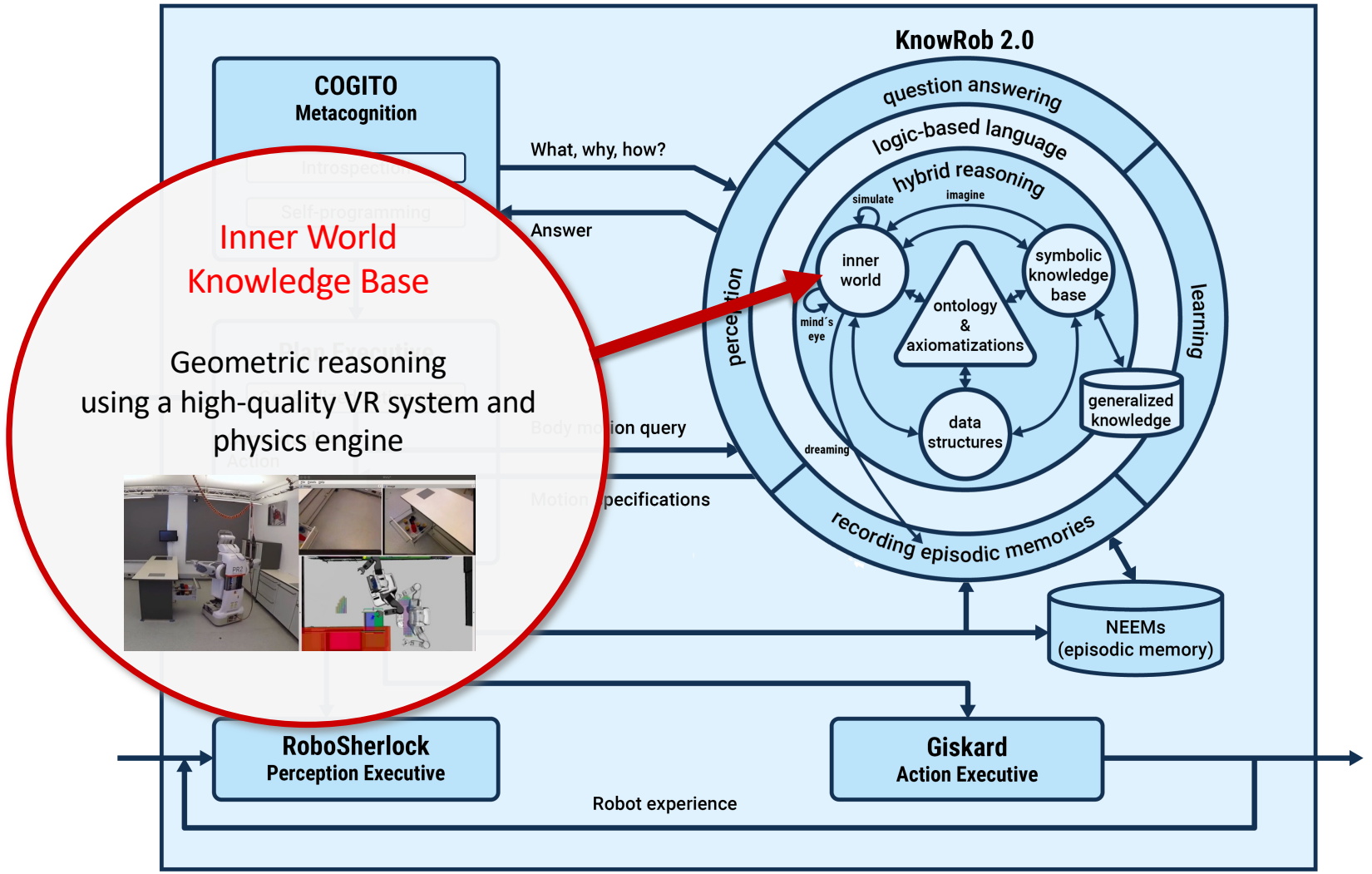

KnowRob 2.0
COGITO
Metacognition
Introspection
What, why, how?
Answer
question answering
logic-based language
hybrid reasoning
simulate
imagine
inner world
symbolic knowledge base
ontology & axiomatizations
mind´s eye
data structures
generalized knowledge
dreaming
perception
learning
recording episodic memories
Episodic Memories Knowledge Base
NEEM
Narrative-Enabled Episodic Memory
NEEMs (episodic memory)
Giskard
Action Executive
Robot experience

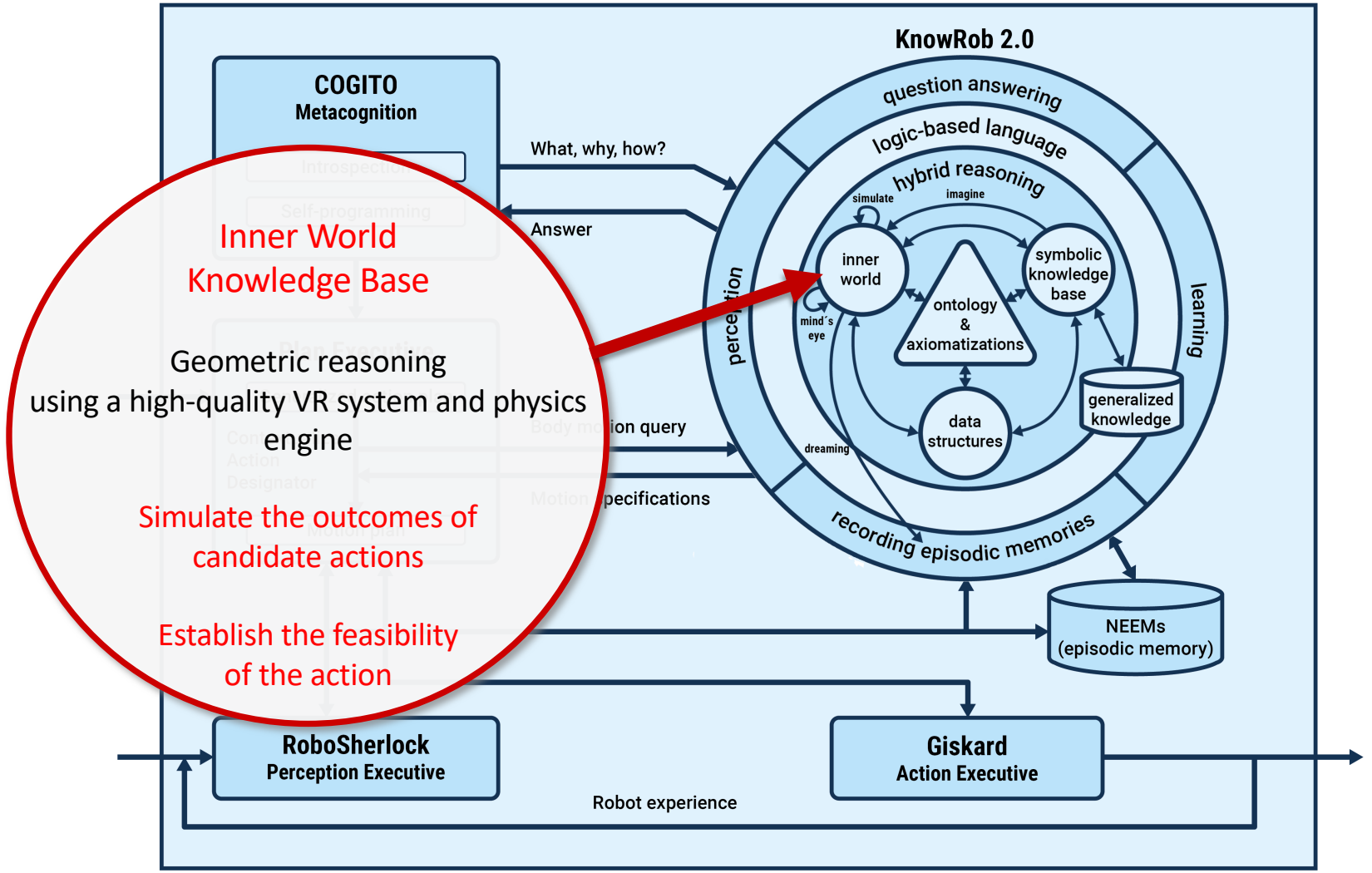

KnowRob 2.0
COGITO
Metacognition
Introspection
What, why, how?
Answer
question answering
logic-based language
hybrid reasoning
simulate
imagine
inner world
symbolic knowledge base
ontology & axiomatizations
mind´s eye
data structures
generalized knowledge
dreaming
perception
learning
recording episodic memories
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)

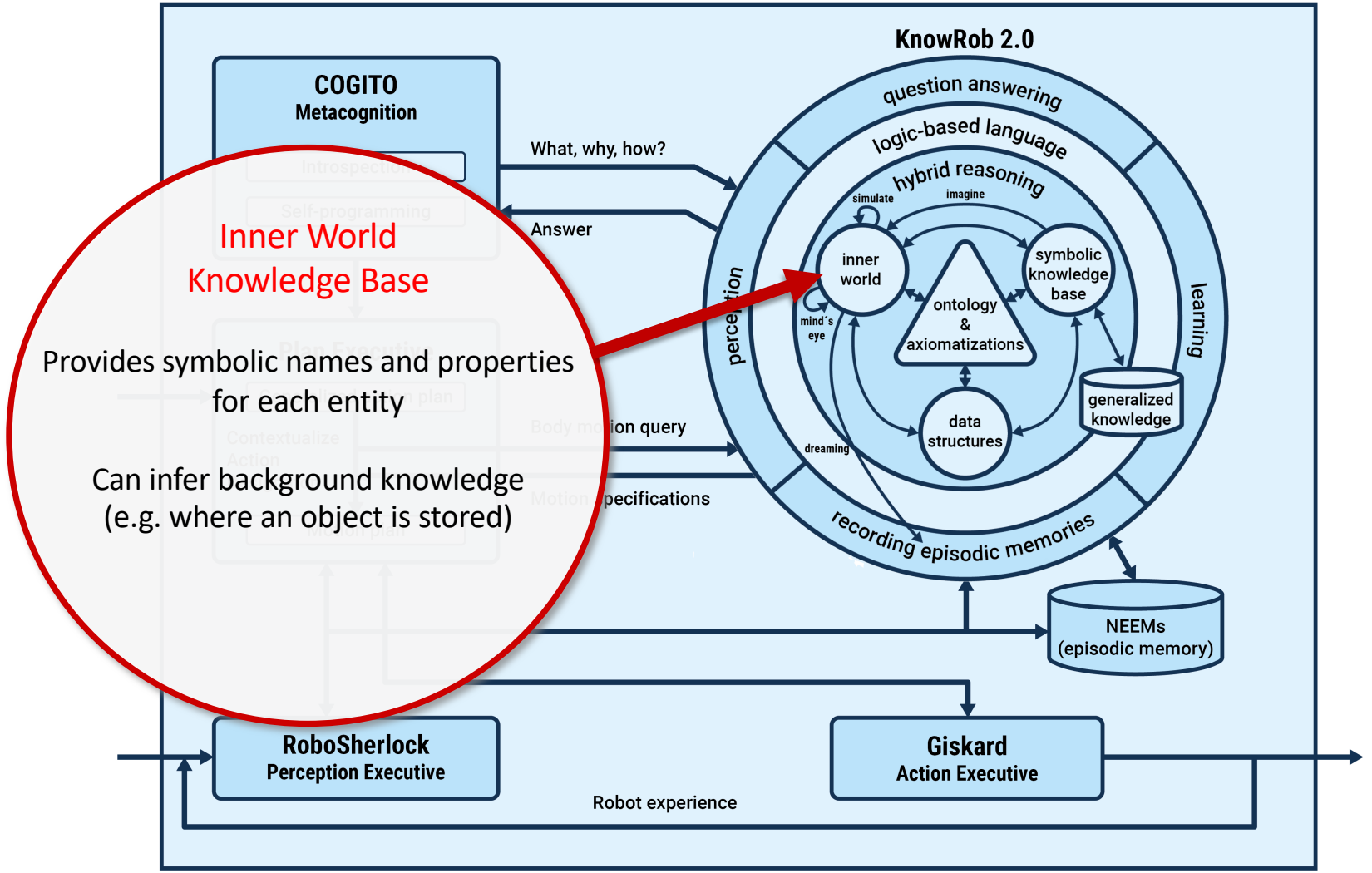

KnowRob 2.0
COGITO
Metacognition
Introspection
What, why, how?
Answer
question answering
logic-based language
hybrid reasoning
simulate
imagine
inner world
symbolic knowledge base
ontology & axiomatizations
mind´s eye
data structures
generalized knowledge
dreaming
perception
learning
recording episodic memories
NEEMs (episodic memory)
monitered time-series data
Sensori-motor data
structured annotations
Narrative annotation
Giskard
Action Executive
Robot experience

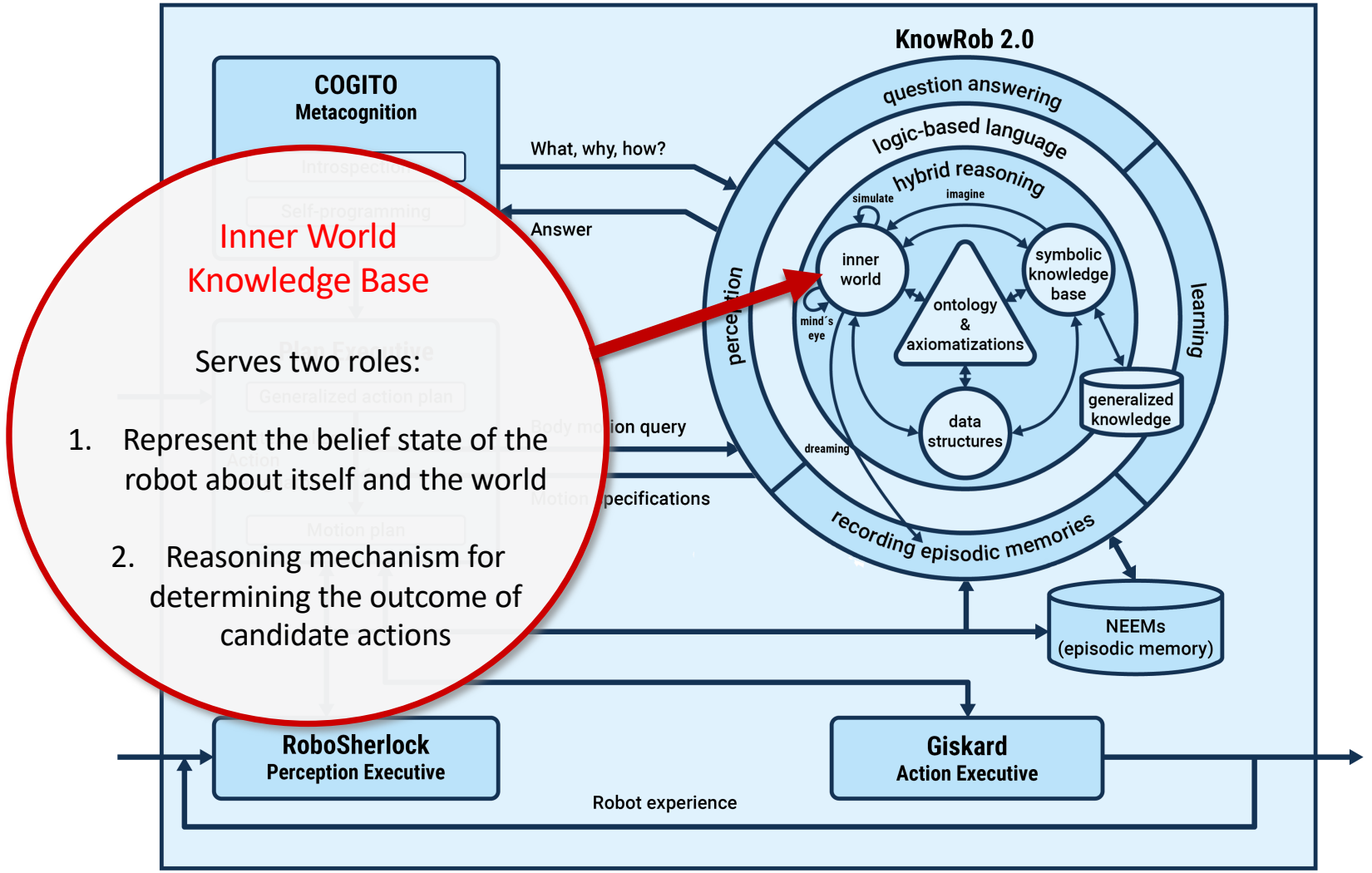

KnowRob 2.0
COGITO
Metacognition
Introspection
What, why, how?
Answer
question answering
logic-based language
hybrid reasoning
simulate
imagine
inner world
symbolic knowledge base
ontology & axiomatizations
mind´s eye
data structures
generalized knowledge
dreaming
perception
learning
recording episodic memories
NEEMs (episodic memory)
Giskard
Action Executive
Robot experience
Episodic Memories Knowledge Base
Symbolic description & sub-symbolic experiential knowledge
NEEM = experience + narrative
Encapsulates procedural as well as declarative knowledge
Temporally-extended

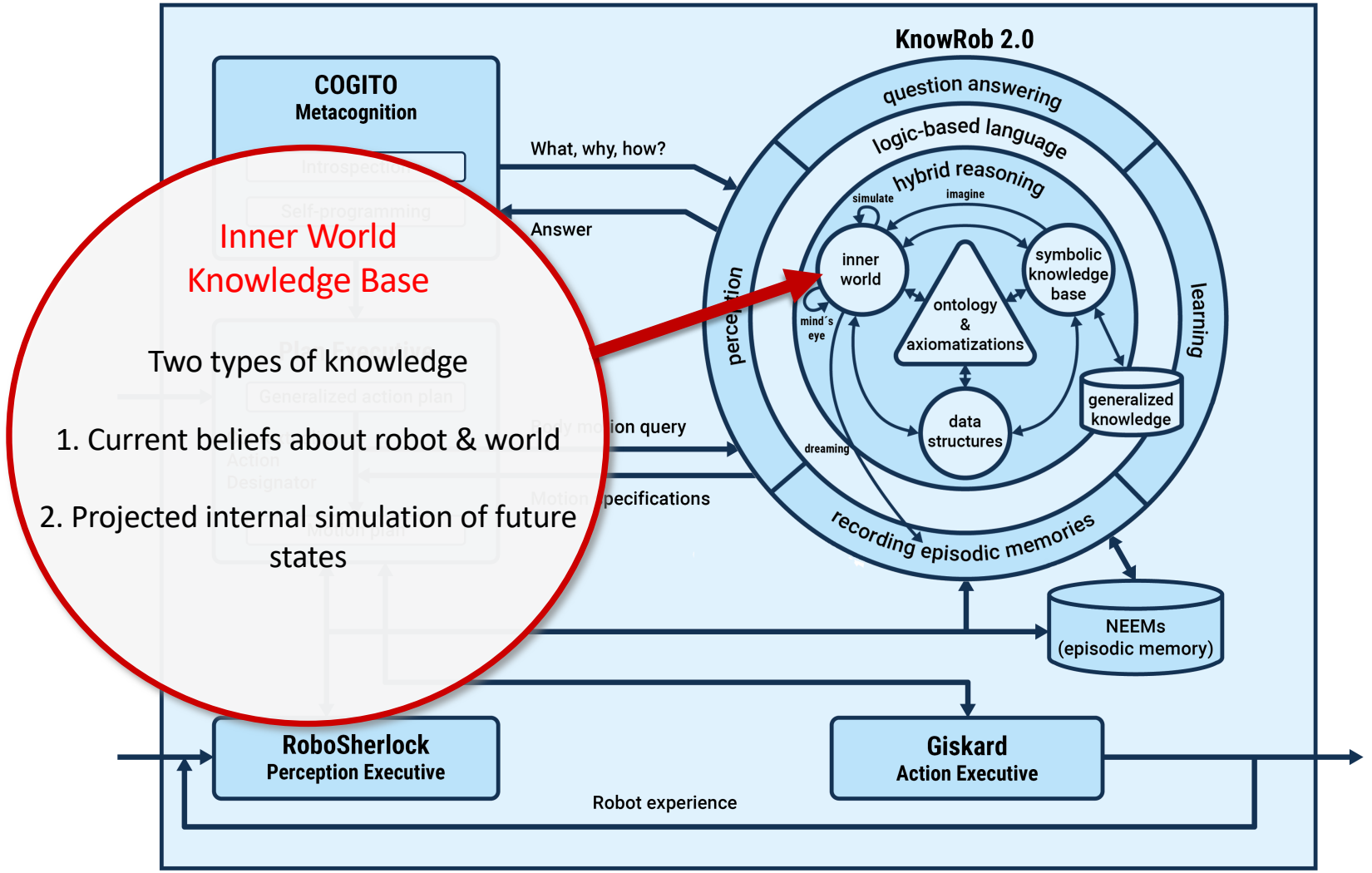

KnowRob 2.0
COGITO
Metacognition
Introspection
What, why, how?
Answer
question answering
logic-based language
hybrid reasoning
simulate
imagine
inner world
symbolic knowledge base
ontology & axiomatizations
mind´s eye
data structures
generalized knowledge
dreaming
perception
learning
recording episodic memories
NEEMs (episodic memory)
Giskard
Action Executive
Robot experience
Basis for answer to queries
What actions were performed by the robot
When it performed them
How it performed them
Why they were performed
Whether or not they were successful
What the robot perceived while performing them
What the robot believed when it performed them

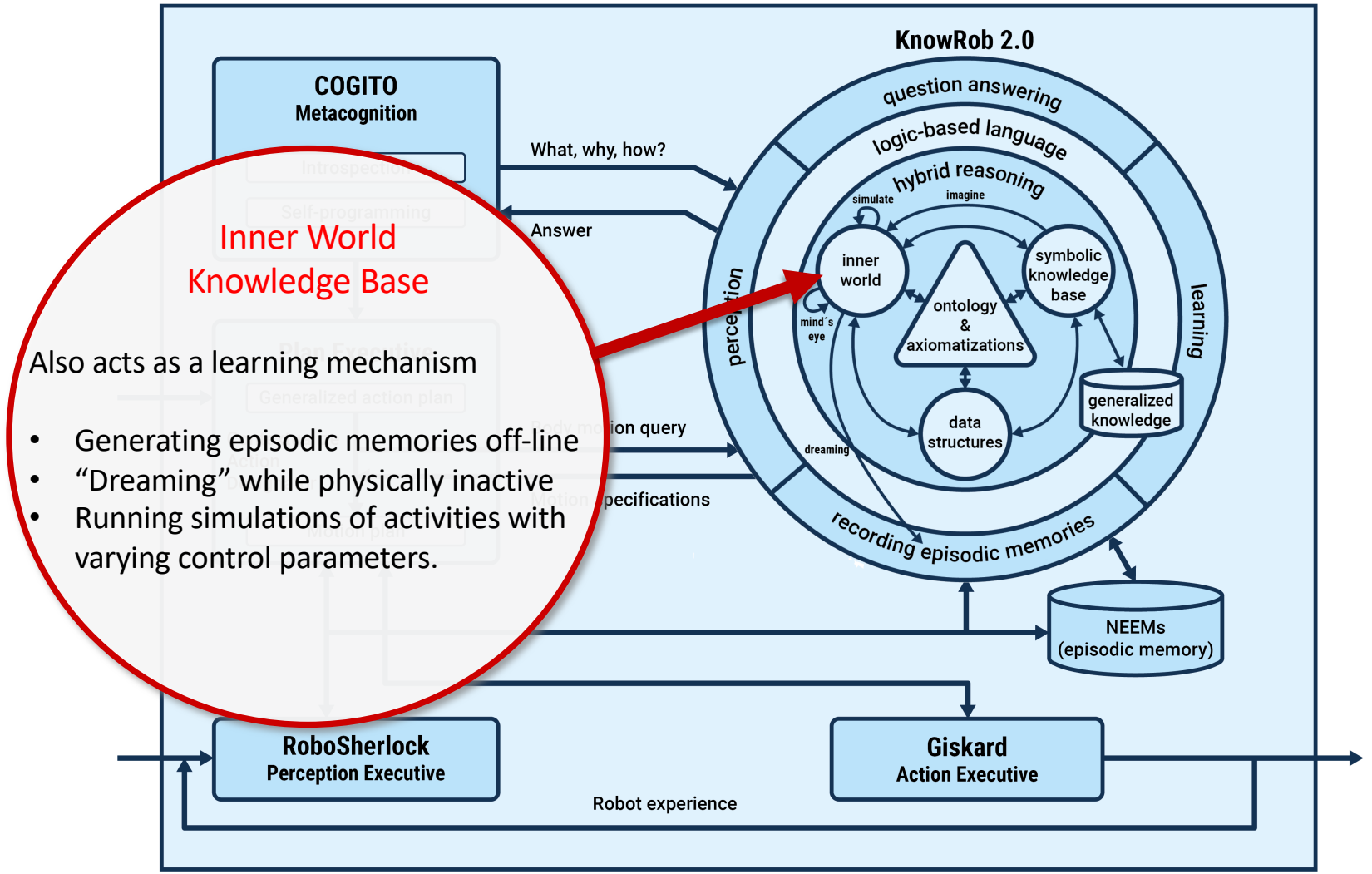

KnowRob 2.0
COGITO
Metacognition
What, why, how?
Answer
Body motion query
Motion specifications
question answering
logic-based language
hybrid reasoning
simulate
imagine
inner world
symbolic knowledge base
ontology & axiomatizations
mind´s eye
data structures
generalized knowledge
dreaming
perception
learning
recording episodic memories
NEEMs (episodic memory)
Inner World Knowledge Base
Geometric reasoning using a high-quality VR system and physics engine
RoboSherlock
Perception Executive
Giskard
Action Executive
Robot experience

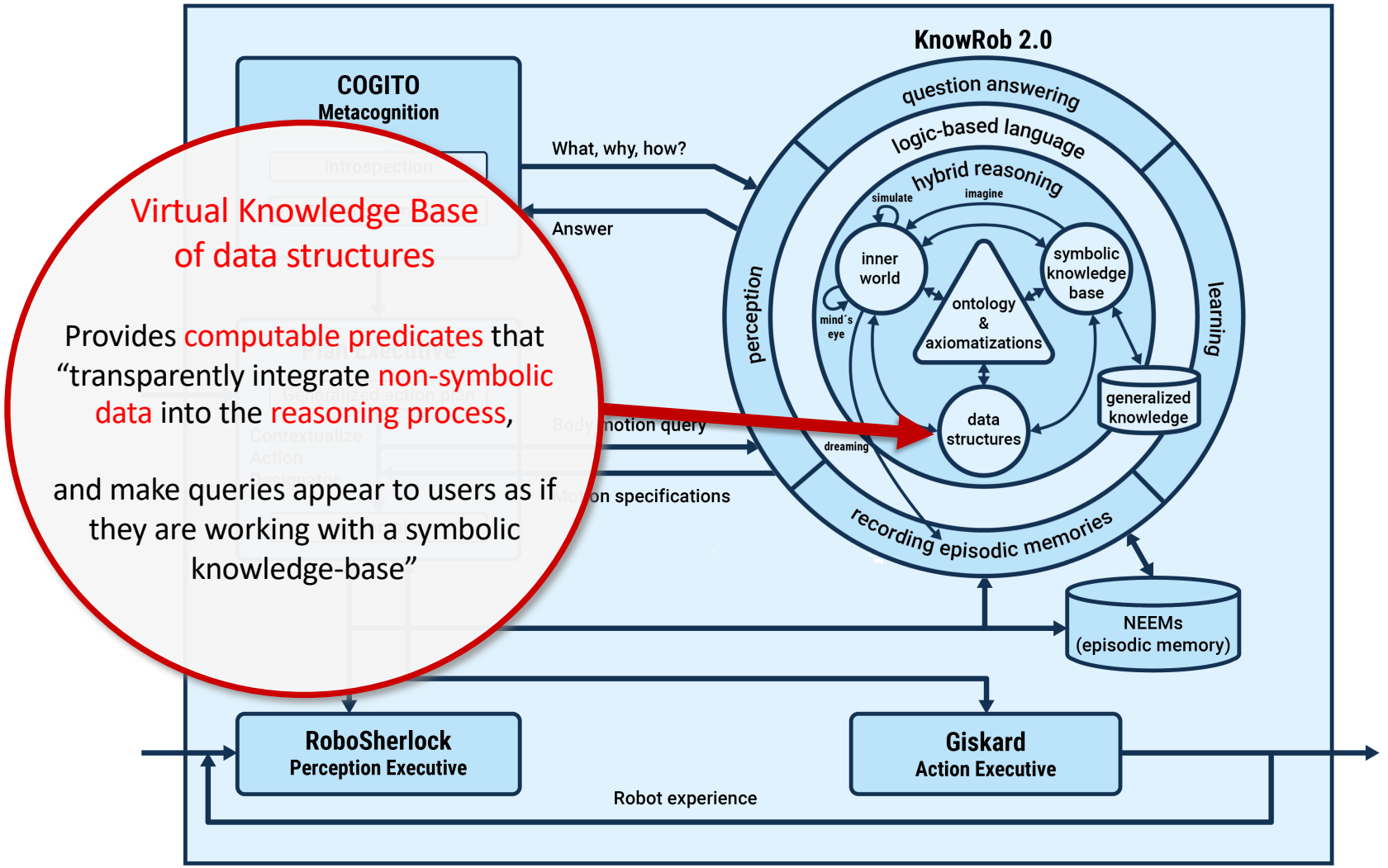

KnowRob 2.0
COGITO
Metacognition
What, why, how?
Answer
question answering
logic-based language
hybrid reasoning
simulate
imagine
inner world
symbolic knowledge base
ontology & axiomatizations
data structures
generalized knowledge
mind´s eye
dreaming
perception
learning
recording episodic memories
NEEMs (episodic memory)
Inner World Knowledge Base
Geometric reasoning using a high-quality VR system and physics engine
Simulate the outcomes of candidate actions
Establish the feasibility of the action
RoboSherlock
Perception Executive
Giskard
Action Executive
Robot experience

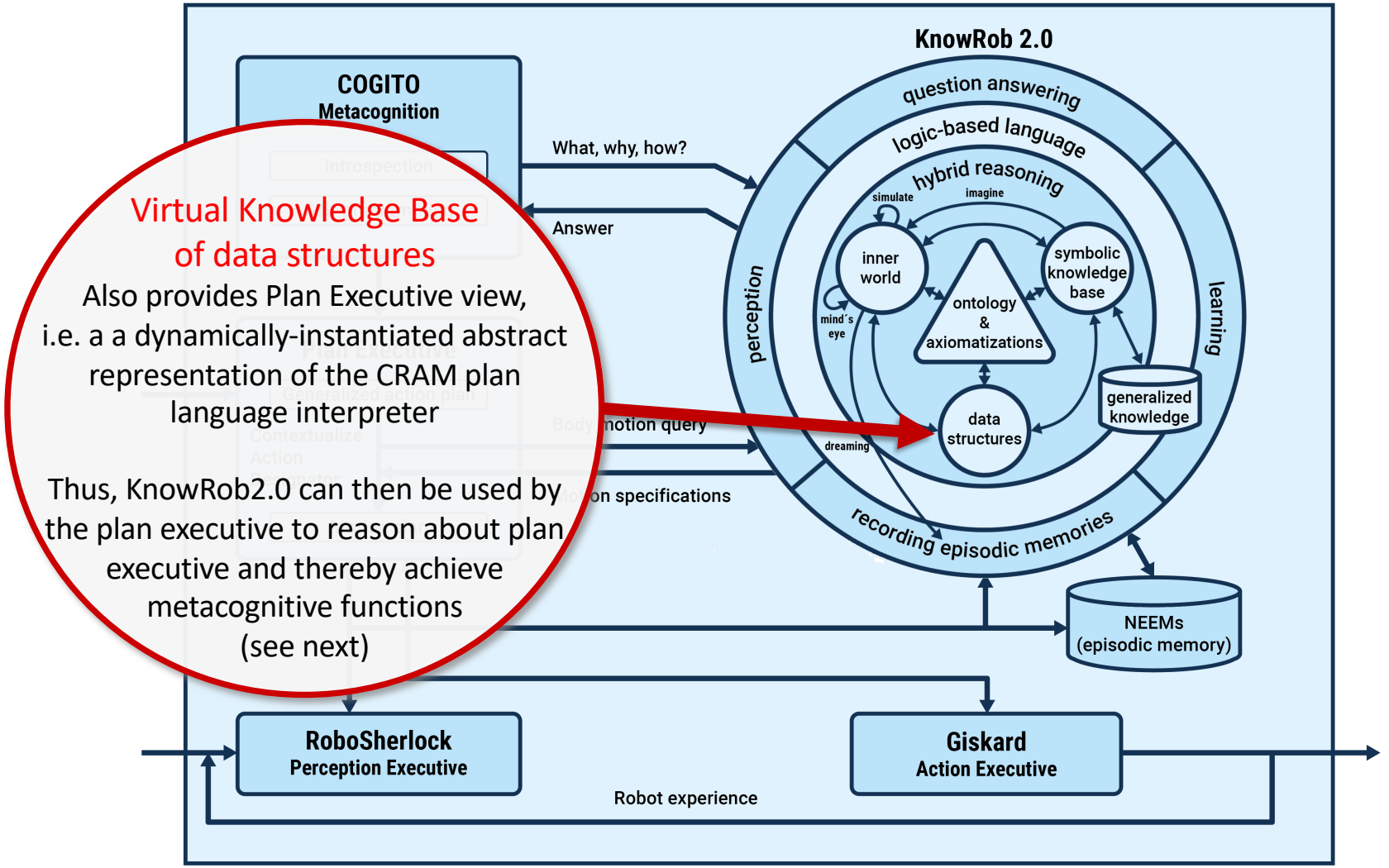

KnowRob 2.0
COGITO
Metacognition
What, why, how?
Answer
Body motion query
Motion specifications
question answering
logic-based language
hybrid reasoning
simulate
imagine
inner world
symbolic knowledge base
ontology & axiomatizations
data structures
generalized knowledge
mind´s eye
dreaming
perception
learning
recording episodic memories
NEEMs (episodic memory)
RoboSherlock
Perception Executive
Giskard
Action Executive
Robot experience
Inner World Knowledge Base
Provides symbolic names and properties for each entity
Can infer background knowledge (e.g. where an object is stored)

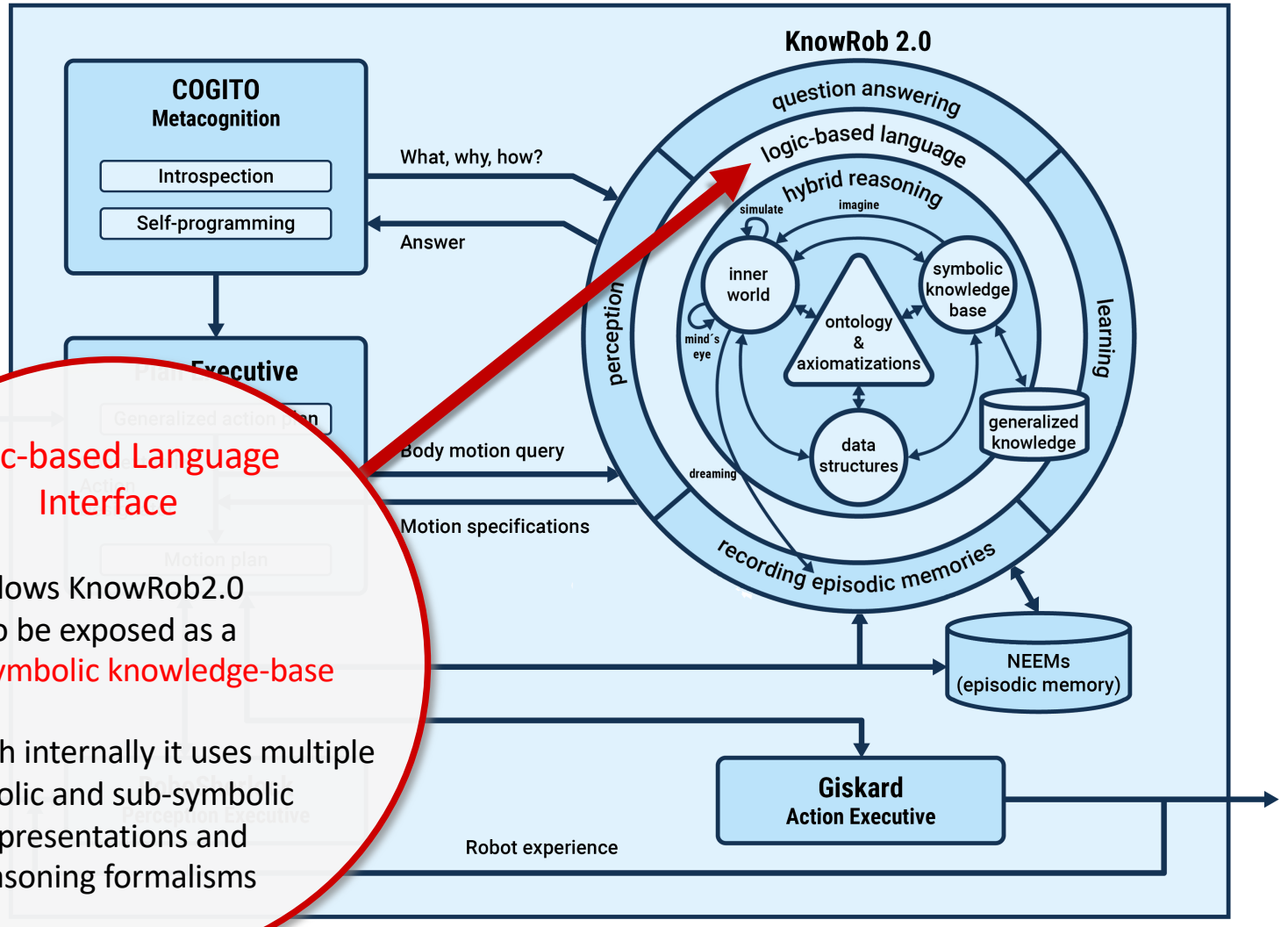

KnowRob 2.0
COGITO
Metacognition
What, why, how?
Answer
Body motion query
Motion specifications
question answering
logic-based language
hybrid reasoning
simulate
imagine
inner world
symbolic knowledge base
ontology & axiomatizations
data structures
generalized knowledge
mind´s eye
dreaming
perception
learning
recording episodic memories
NEEMs (episodic memory)
Inner World Knowledge Base
Serves two roles:
1. Represent the belief state of the robot about itself and the world
2. Reasoning mechanism for determining the outcome of candidate actions
RoboSherlock
Perception Executive
Giskard
Action Executive
Robot experience

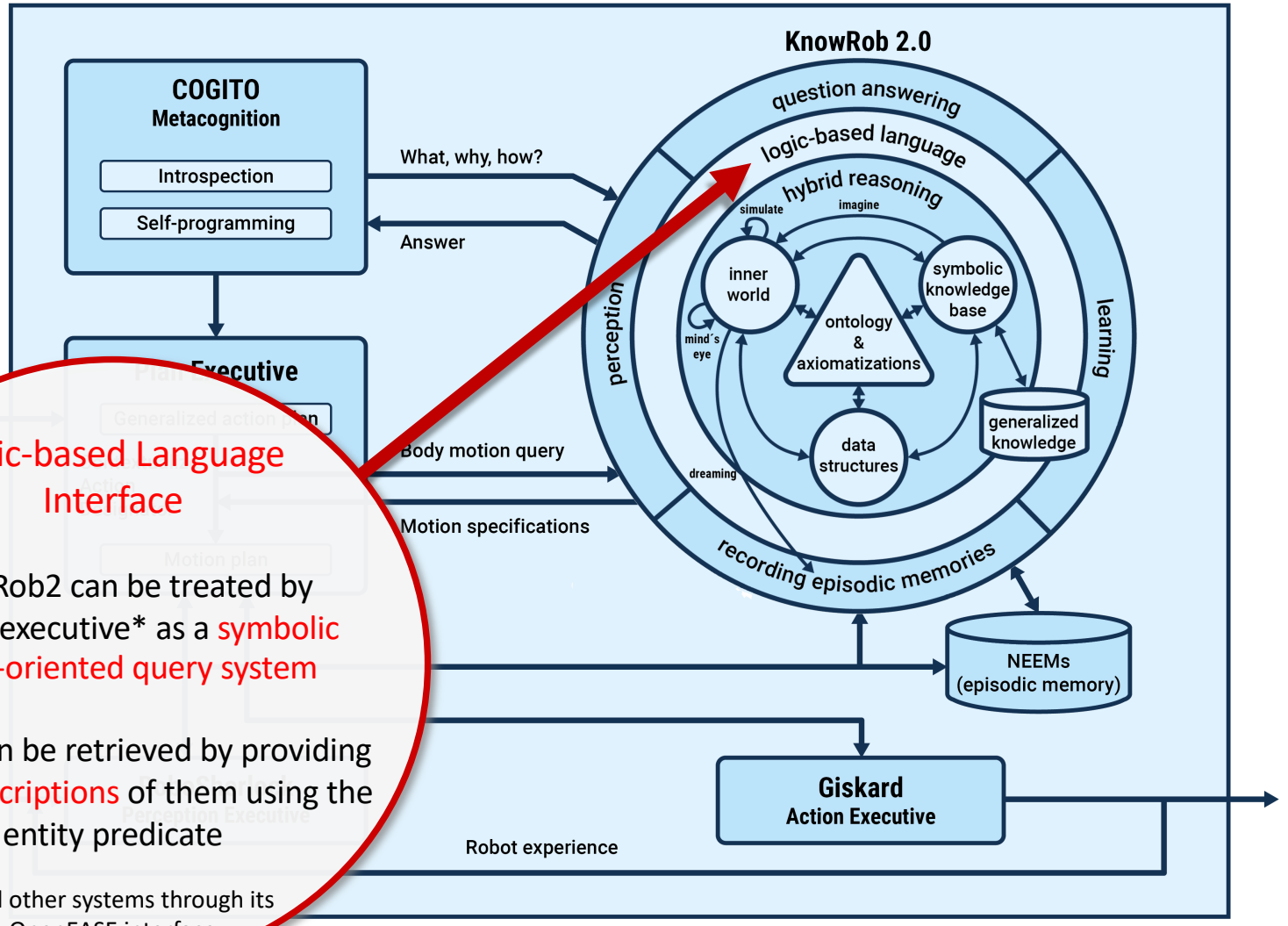

KnowRob 2.0
COGITO
Metacognition
What, why, how?
Answer
Body motion query
Motion specifications
question answering
logic-based language
hybrid reasoning
simulate
imagine
inner world
symbolic knowledge base
ontology & axiomatizations
mind´s eye
data structures
generalized knowledge
dreaming
perception
learning
recording episodic memories
NEEMs (episodic memory)
Inner World Knowledge Base
Two types of knowledge
1. Current beliefs about robot & world
2. Projected internal simulation of future states
RoboSherlock
Perception Executive
Giskard
Action Executive
Robot experience

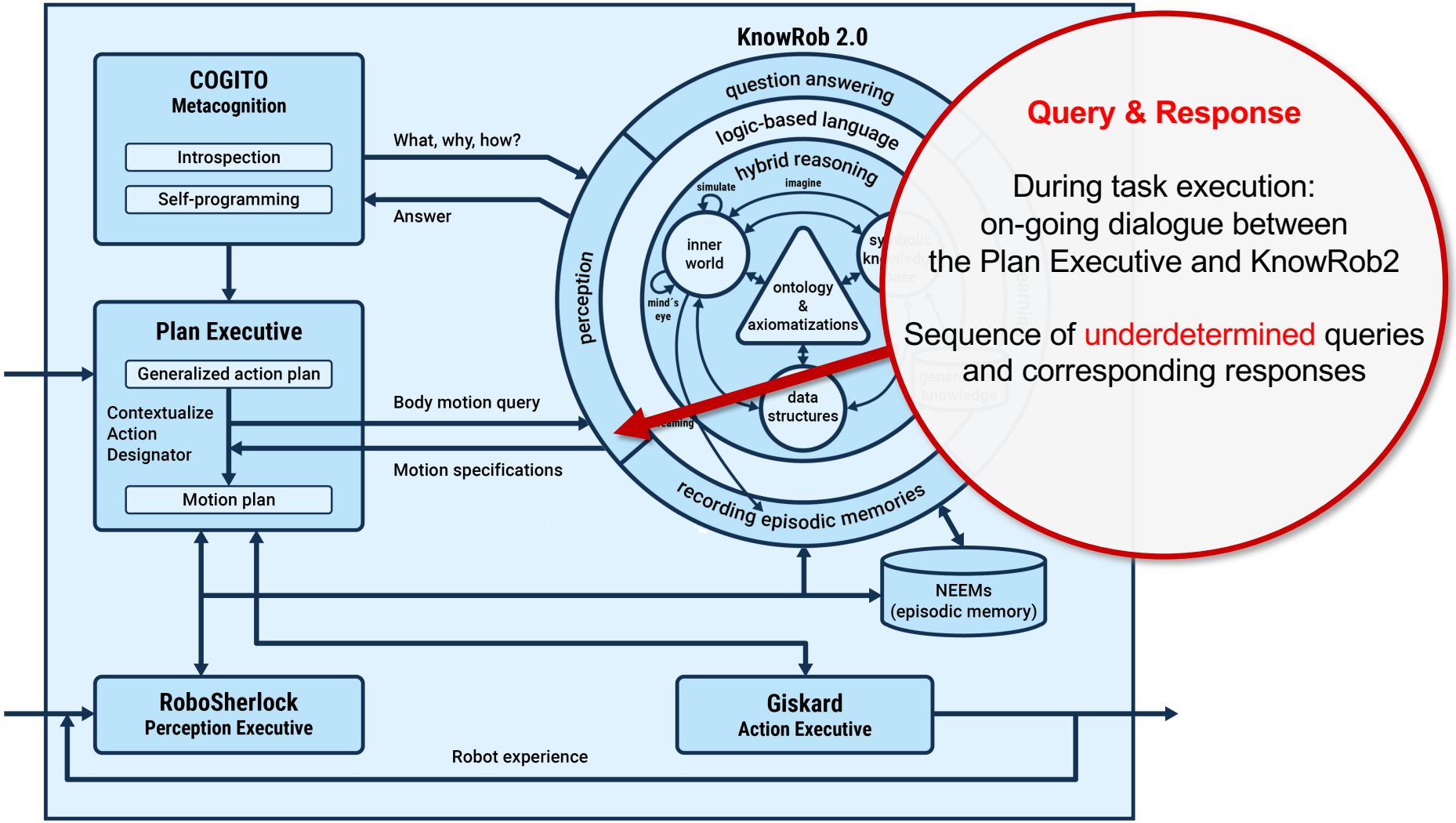

KnowRob 2.0
COGITO
Metacognition
What, why, how?
Answer
question answering
logic-based language
hybrid reasoning
simulate
imagine
inner world
symbolic knowledge base
ontology & axiomatizations
mind´s eye
data structures
generalized knowledge
dreaming
perception
learning
recording episodic memories
Inner World
Knowledge Base
Also acts as a learning mechanism
• Generating episodic memories off-line
• "Dreaming" while physically inactive
• Running simulations of activities with varying control parameters.
NEEMs
(episodic memory)
RoboSherlock
Perception Executive
Giskard
Action Executive
Robot experience

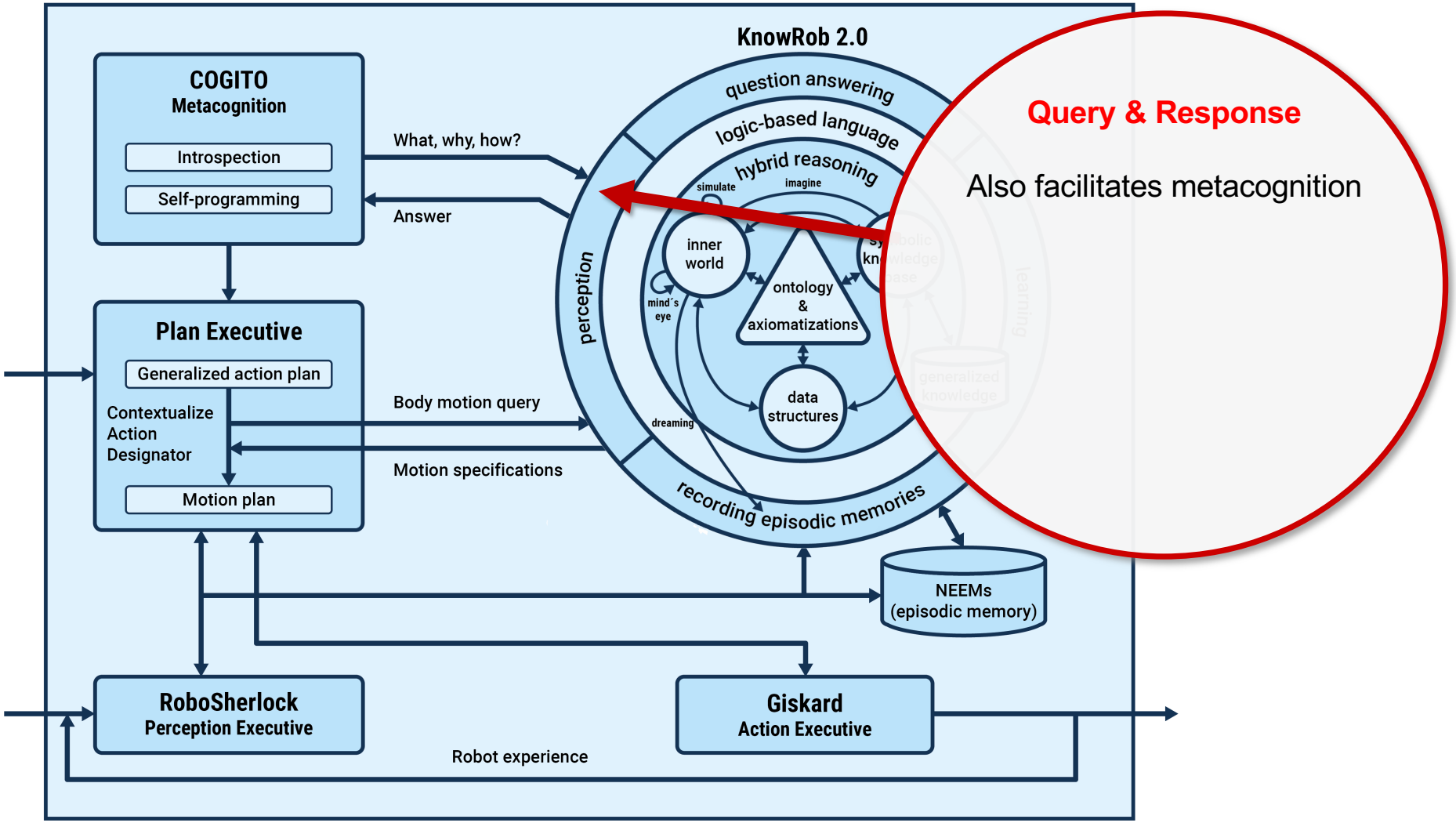

KnowRob 2.0
COGITO
Metacognition
What, why, how?
Answer
question answering
logic-based language
hybrid reasoning
simulate
imagine
inner world
symbolic knowledge base
ontology & axiomatizations
mind´s eye
perception
learning
data structures
generalized knowledge
dreaming
motion query
on specifications
recording episodic memories
NEEMs (episodic memory)
RoboSherlock
Perception Executive
Giskard
Action Executive
Robot experience
Virtual Knowledge Base of data structures
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"

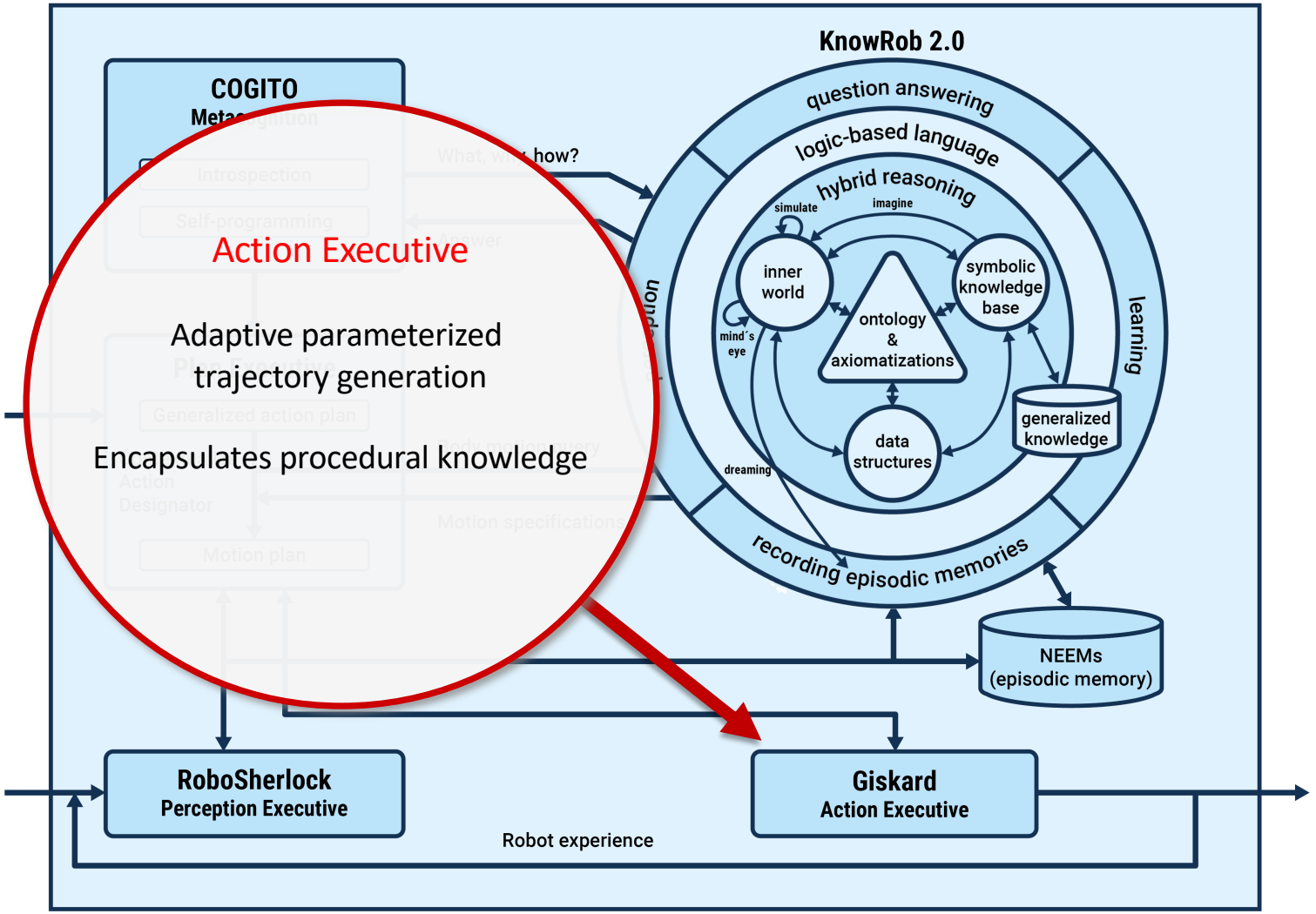

KnowRob 2.0
COGITO
Metacognition
What, why, how?
Answer
motion query
on specifications
question answering
logic-based language
hybrid reasoning
simulate
imagine
inner world
symbolic knowledge base
ontology & axiomatizations
mind´s eye
data structures
generalized knowledge
dreaming
perception
learning
recording episodic memories
NEEMs (episodic memory)
RoboSherlock
Perception Executive
Giskard
Action Executive
Robot experience
Virtual Knowledge Base of data structures
Also provides Plan Executive view, i.e. a a dynamically-instantiated abstract representation of the CRAM plan language interpreter
Thus, KnowRob2.0 can then be used by the plan executive to reason about plan executive and thereby achieve metacognitive functions (see next)

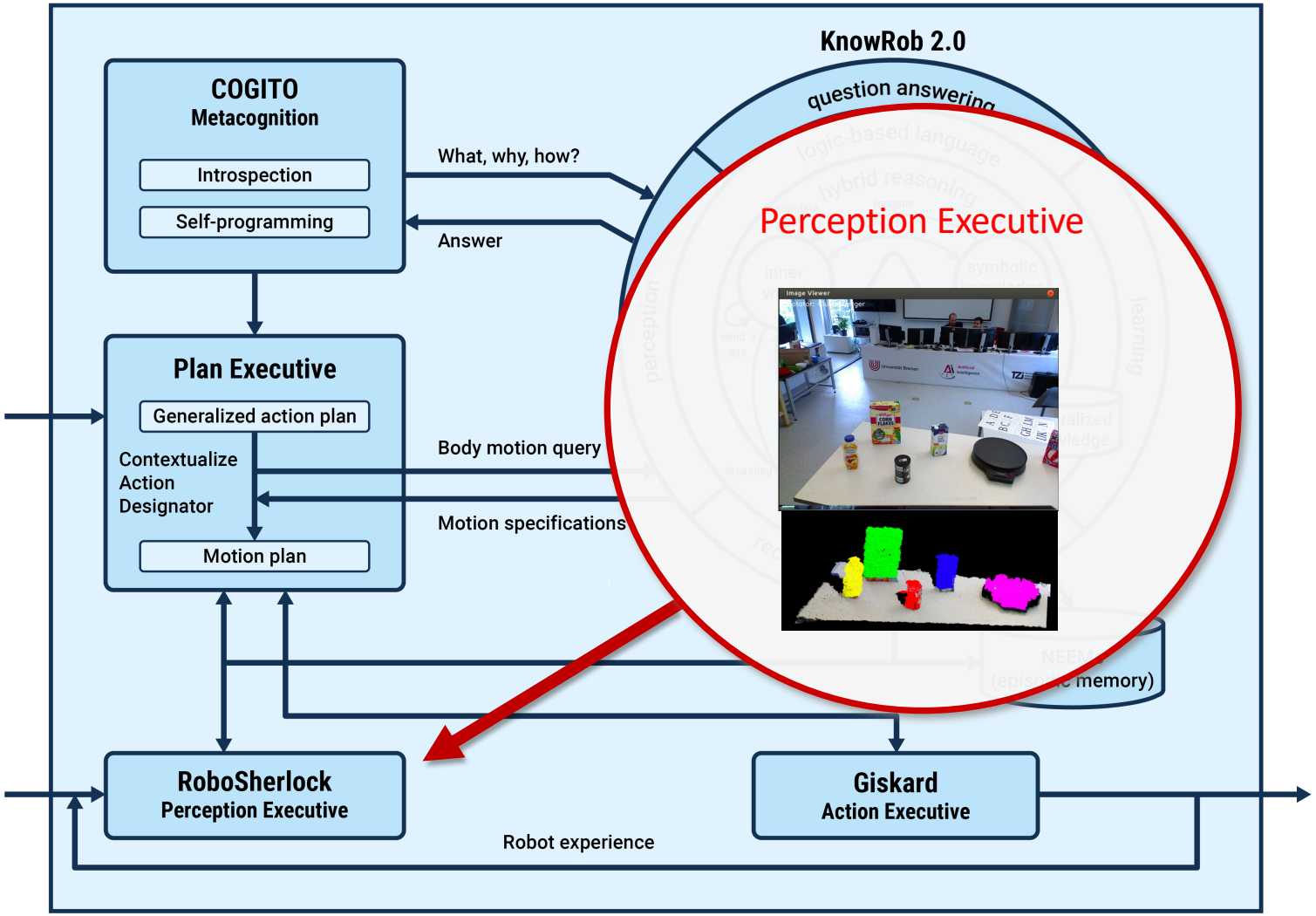

KnowRob 2.0
COGITO
Metacognition
Introspection
Self-programming
What, why, how?
Answer
Executive
Body motion query
Motion specifications
question answering
logic-based language
hybrid reasoning
simulate
imagine
inner world
symbolic knowledge base
ontology & axiomatizations
mind´s eye
data structures
generalized knowledge
dreaming
perception
learning
recording episodic memories
NEEMs (episodic memory)
Giskard
Action Executive
Robot experience
Logic-based Language Interface
allows KnowRob2.0 to be exposed as a purely symbolic knowledge-base
even though internally it uses multiple symbolic and sub-symbolic representations and reasoning formalisms

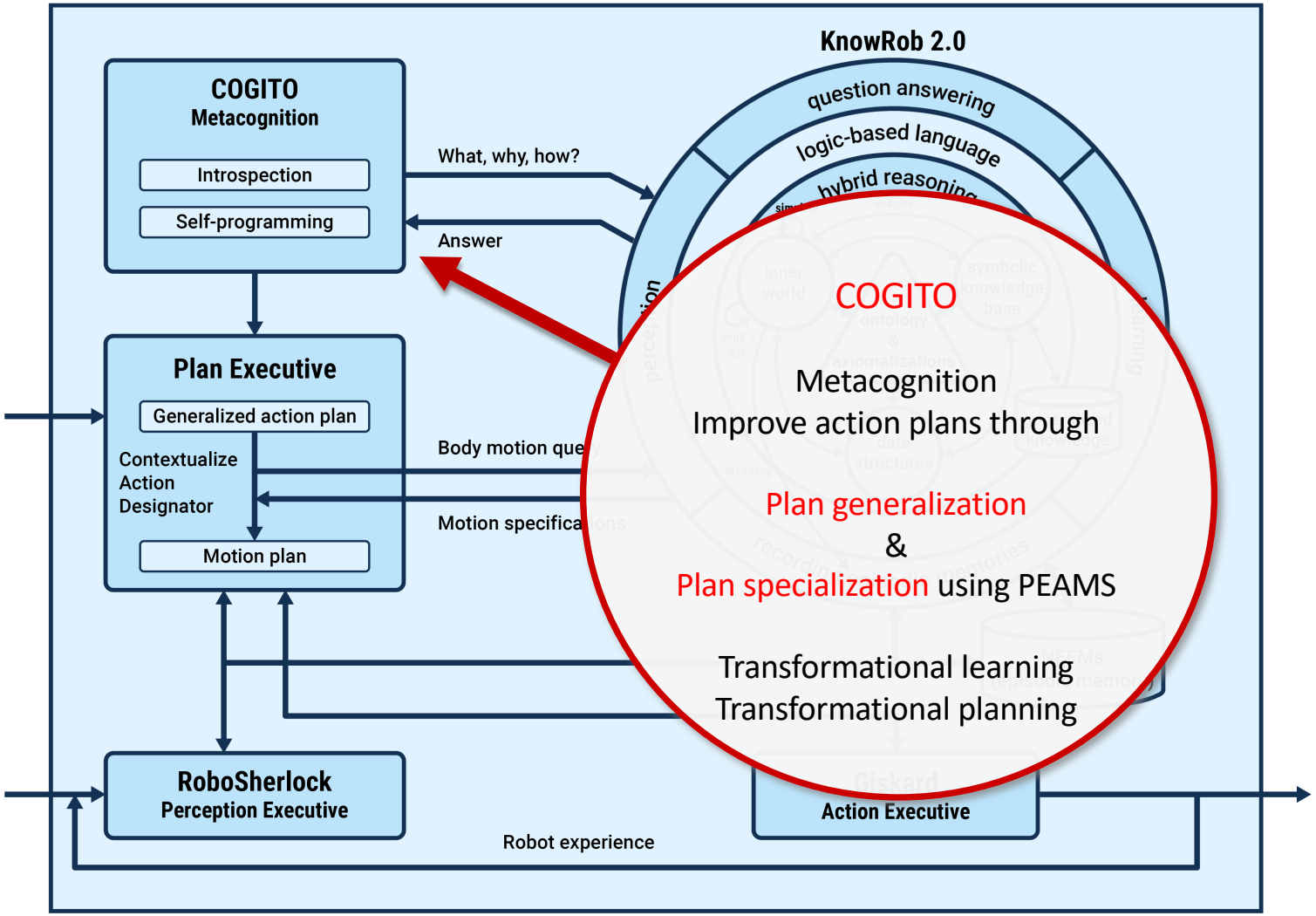

KnowRob 2.0
COGITO
Metacognition
Introspection
Self-programming
What, why, how?
Answer
Executive
Body motion query
Motion specifications
question answering
logic-based language
hybrid reasoning
simulate
imagine
inner world
symbolic knowledge base
ontology & axiomatizations
mind´s eye
data structures
generalized knowledge
dreaming
perception
learning
recording episodic memories
NEEMs (episodic memory)
Giskard
Action Executive
Robot experience
Logic-based Language Interface
KnowRob2 can be treated by the CPL executive* as a symbolic object-oriented query system
Entities can be retrieved by providing partial descriptions of them using the entity predicate
*and other systems through its OpenEASE interface

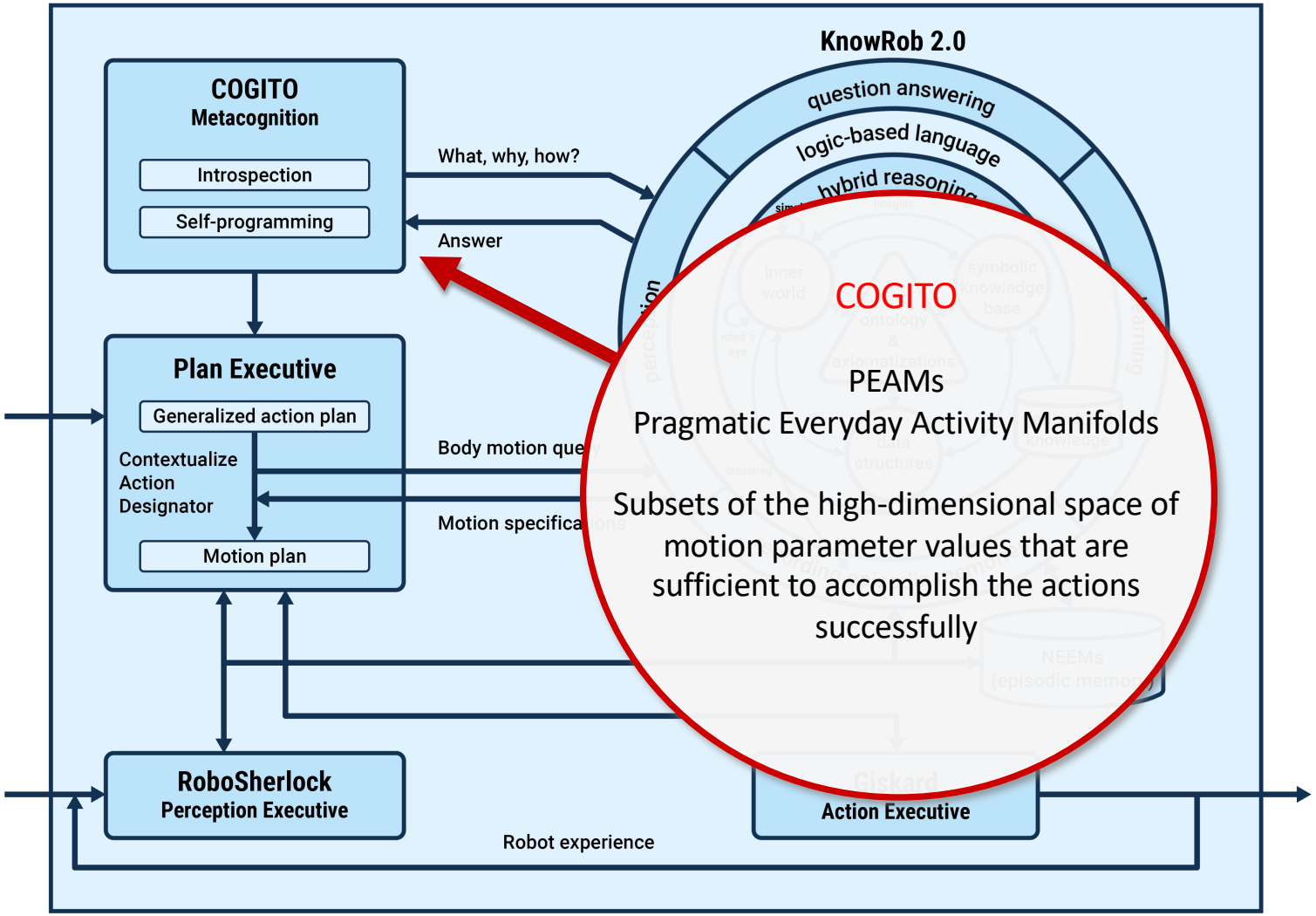

KnowRob 2.0
COGITO
Metacognition
Introspection
Self-programming
What, why, how?
Answer
Plan Executive
Generalized action plan
Contextualize
Action
Designator
Motion plan
Body motion query
Motion specifications
perception
question answering
logic-based language
hybrid reasoning
simulate
imagine
inner world
mind´s eye
ontology & axiomatizations
data structures
recording episodic memories
NEEMs (episodic memory)
RoboSherlock
Perception Executive
Giskard
Action Executive
Robot experience
Query & Response
During task execution:
on-going dialogue between
the Plan Executive and KnowRob2
Sequence of underdetermined queries
and corresponding responses


KnowRob 2.0
COGITO
Metacognition
Introspection
Self-programming
What, why, how?
Answer
Plan Executive
Generalized action plan
Contextualize
Action
Designator
Motion plan
Body motion query
Motion specifications
question answering
logic-based language
hybrid reasoning
simulate
imagine
inner world
mind´s eye
ontology & axiomatizations
data structures
dreaming
perception
recording episodic memories
NEEMs (episodic memory)
RoboSherlock
Perception Executive
Giskard
Action Executive
Robot experience
Query & Response
Also facilitates metacognition


KnowRob 2.0
COGITO
Action Executive
Adaptive parameterized trajectory generation
Encapsulates procedural knowledge
question answering
logic-based language
hybrid reasoning
simulate
imagine
inner world
symbolic knowledge base
ontology & axiomatizations
mind´s eye
data structures
generalized knowledge
dreaming
learning
recording episodic memories
NEEMs (episodic memory)
RoboSherlock
Perception Executive
Giskard
Action Executive
Robot experience


KnowRob 2.0
question answering
COGITO
Metacognition
Introspection
Self-programming
What, why, how?
Answer
Plan Executive
Generalized action plan
Contextualize
Action
Designator
Motion plan
Body motion query
Motion specifications
Perception Executive
RoboSherlock
Perception Executive
Giskard
Action Executive
Robot experience


KnowRob 2.0
question answering
logic-based language
hybrid reasoning
COGITO
Metacognition
Introspection
Self-programming
What, why, how?
Answer
Plan Executive
Generalized action plan
Contextualize
Action
Designator
Motion plan
Body motion que
Motion specifica
RoboSherlock
Perception Executive
Action Executive
Robot experience
COGITO
Metacognition
Improve action plans through
Plan generalization
&
Plan specialization using PEAMS
Transformational learning
Transformational planning


KnowRob 2.0
question answering
logic-based language
COGITO
Metacognition
Introspection
Self-programming
What, why, how?
Answer
Plan Executive
Generalized action plan
Contextualize
Action
Designator
Motion plan
Body motion que
Motion specifica
RoboSherlock
Perception Executive
Action Executive
Robot experience
COGITO
PEAMs
Pragmatic Everyday Activity Manifolds
Subsets of the high-dimensional space of motion parameter values that are sufficient to accomplish the actions successfully

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.

M. Beetz, D. Beßler, A. Haidu, M. Pomarlan, A. Kaan Bozcuoglu, G. Bartels, "KnowRob 2.0 – A 2nd Generation Knowledge Processing Framework for Cognition-enabled Robotic Agents", In International Conference on Robotics and Automation (ICRA), Brisbane, Australia, 2018.