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Adaptive AI-BDI Architecture for Robotic Autonomy in Human-Centric Dynamic Environments

21 maig 2025

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Adaptive AI-BDI Architecture for Robotic Autonomy in Human-Centric Dynamic Environments

Magí Dalmau

Cap del Grup de Robòtica Cognitiva

Eurecat

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Co-autors del Grup de Robòtica Cognitiva a Eurecat

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Presentation outline

- Reasoning in our open world
- Why Traditional Approaches Fail & Why Modern Approaches Fail
- Objective & Vision
- Pioneering Hybrid Solutions
- Proposed Solution Overview
- Implementation Details & Execution Flow
- Demonstration Scenario & Results
- Impacts of the Solution
- Limitations & Future Work
- Q&A Session

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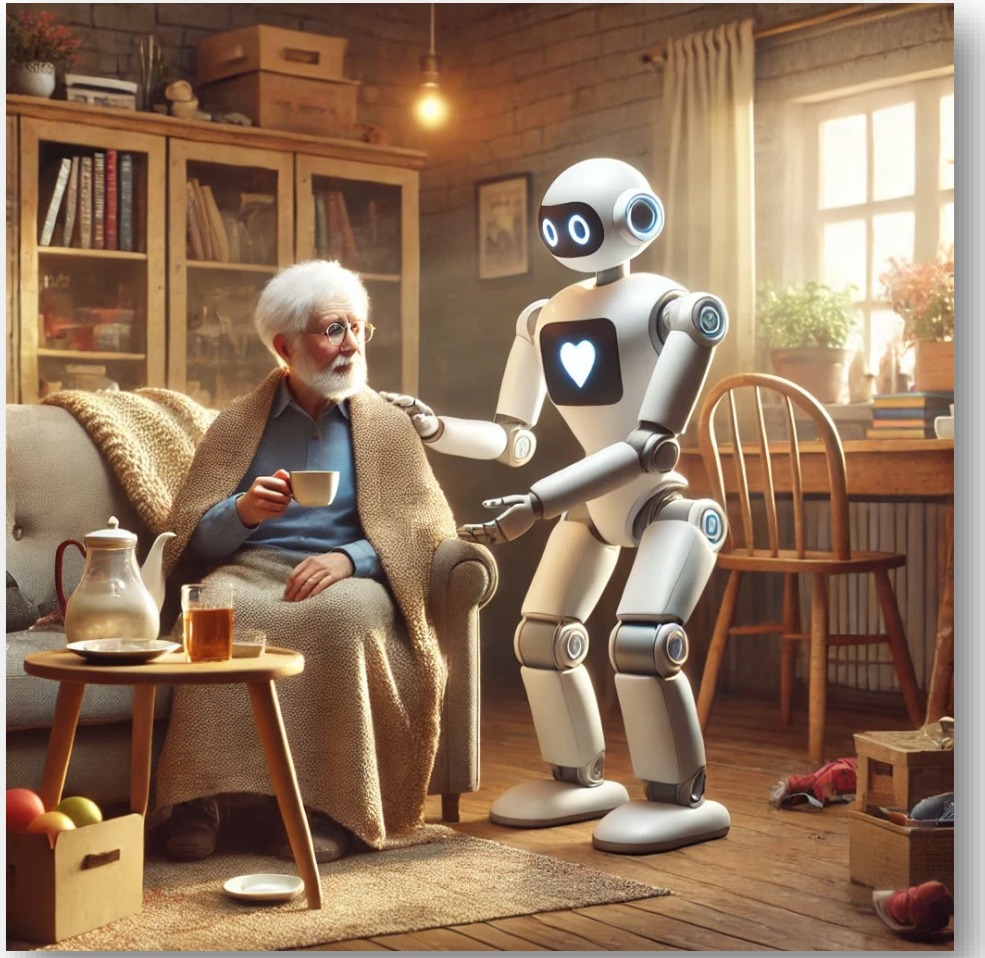
Reasoning in our open world

Why simple tasks are not so simple



“Bring some tea please”

- Should it be sweetened?
  User preferences
- Is the tea hot enough?
  Uncertain knowledge
- The tea is expired - what does "expired" mean?
  Unmodelled knowledge
- The grandson starts playing with the robot
  Uncontrolled agents, Task prioritization
- The apartment is messy and always changing
  Dynamic environment
- The robot spoils a surprise
  Conflicting agent goals

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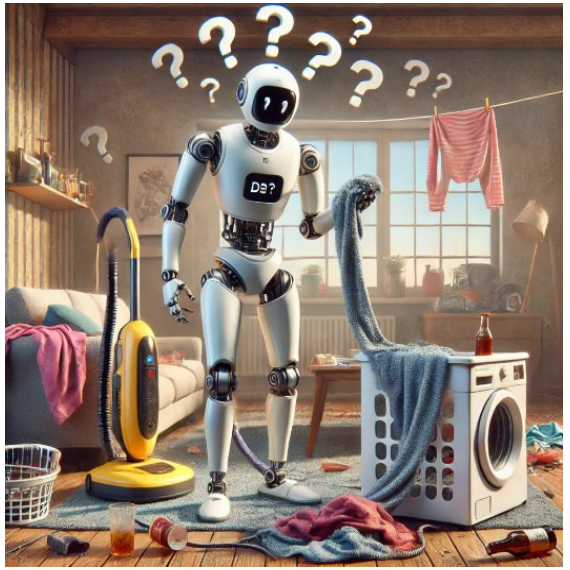
Why Traditional Approaches Fail

Robotic decision-making | **Handcrafted** | **Model-based** | **Learning-based**

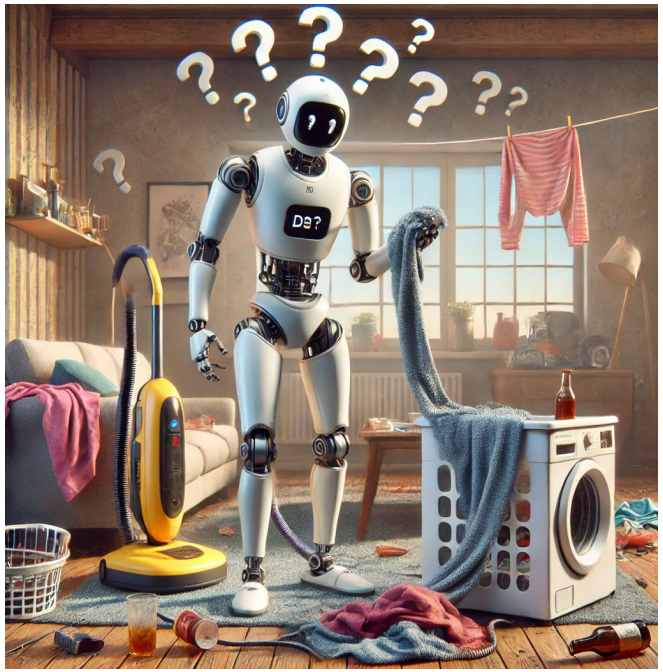
- **Traditional methodologies fail on dealing with:**
  - Abstract Instructions
  - Highly dynamic processes
  - Imperfect knowledge & uncertainty
  - Humans (desires, preferences, goals ...)
  - Task prioritization
  - Uncontrolled agents
  - Highly-coupled task and motion reasoning



Why Modern Approaches Fail

Challenges - From Abstract Intelligence to Physical Action

- Long-term planning and finite context length
- Evaluation (lack of datasets, generalized human alignment)
- Robustness & Reliability
- Transparency & Knowledge Boundary
- Efficiency & Scalability



Additional challenges in Robotics!! The physical frontier

- **Hardware** limitations
- Even more lack of **data**
- **Multimodality**

- **Grounding** abstract knowledge to physical constraints

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Objective & Vision

Objective

- Novel **architecture** for autonomous robots in **dynamic, human-centric environments**.
- Enable **dynamic** reasoning, **multimodal** interactions, and **adaptive** decision-making.

Vision

- **Hybrid** solution combining **classical** methodologies with **LLMs**.
- Robots intuitively **interpret** abstract **human instructions**.
- **Shift** from detailed programming to autonomous collaboration. Vision
- **Hybrid** solution combining **classical** methodologies with **LLMs**.
- Robots intuitively **interpret** abstract **human instructions**.
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Pioneering Hybrid Solutions

Traditional Methods
Logical Reasoning & Grounding

(M)LLMs
Adaptability & Generalization

Hybrid Solution

LLMs for High-Level Reasoning

Goal distillation from abstract instructions using commonsense understanding.

VLMs for Perception and Action

Combine vision and language for action refinement and issue resolution in real time.

Adaptive Planning & Scheduling

Continuous task refinement while respecting human-defined rules and task dependencies to ensure safe, predictable behavior.

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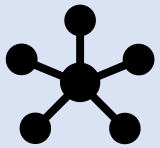
Proposed solution overview

AI-BDI Architecture

- Integrates **perception, belief management, reasoning, planning**, and **execution**.
- Built upon advancements of **ROS2-BDI**:
  - **Multi Agent System (MAS)** framework implementing **Belief-Desire-Intention (BDI)** architecture over ROS2
  - **PDDL**-based planner (**PlanSys2**) for means-end reasoning

Key Components

Multimodal perception (visual, linguistic, sensor-based)



Belief Manager and Knowledge Graph

Multimodal Large Language Model (MLLM) for reasoning

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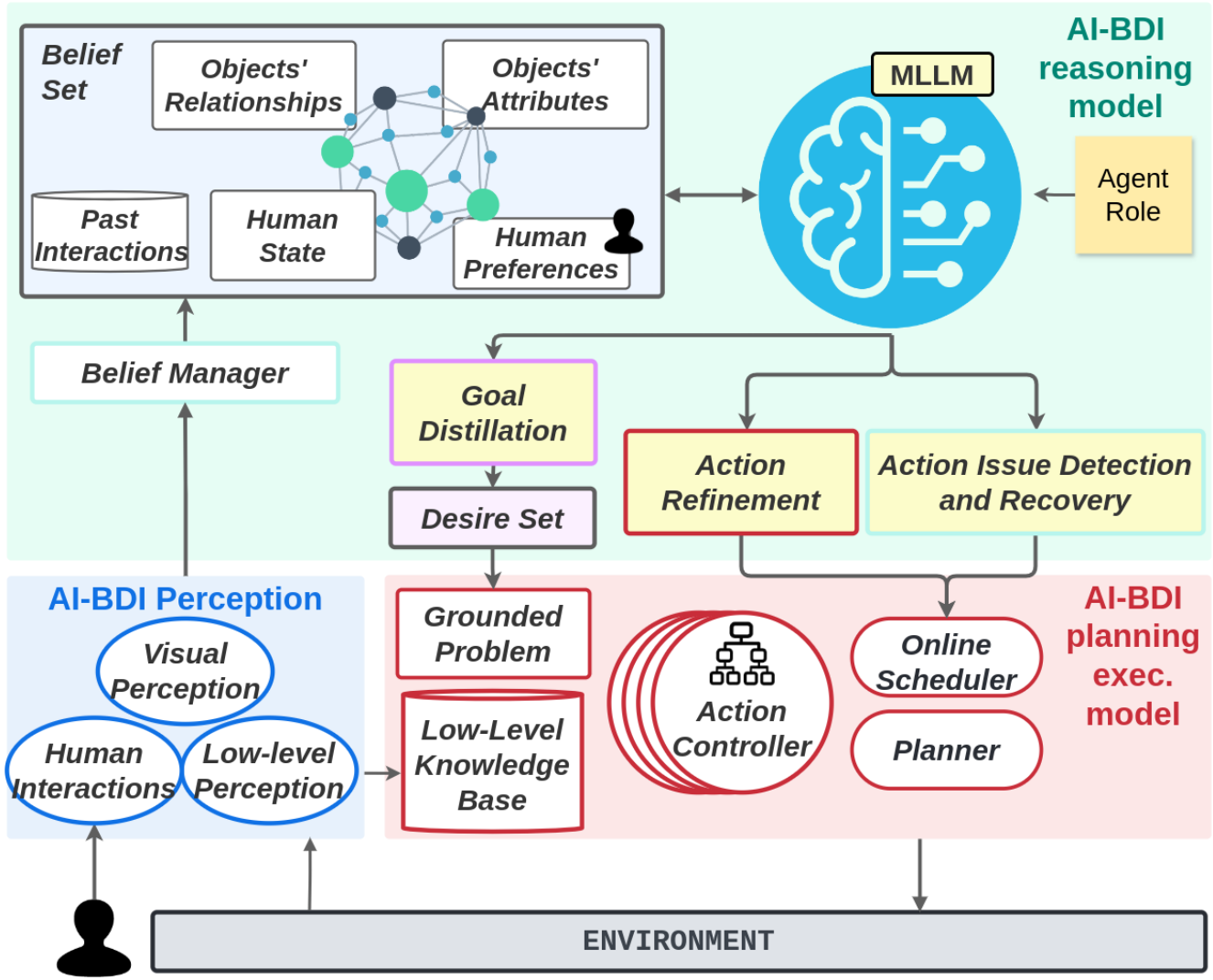
Implementation details

Architecture overview

Three main subsystems

- Perception
- Reasoning subsystem

  (AI-BDI Reasoning Model)
- Task Planning and Execution



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Implementation details

Perception

Perception

- **Human Interaction:**

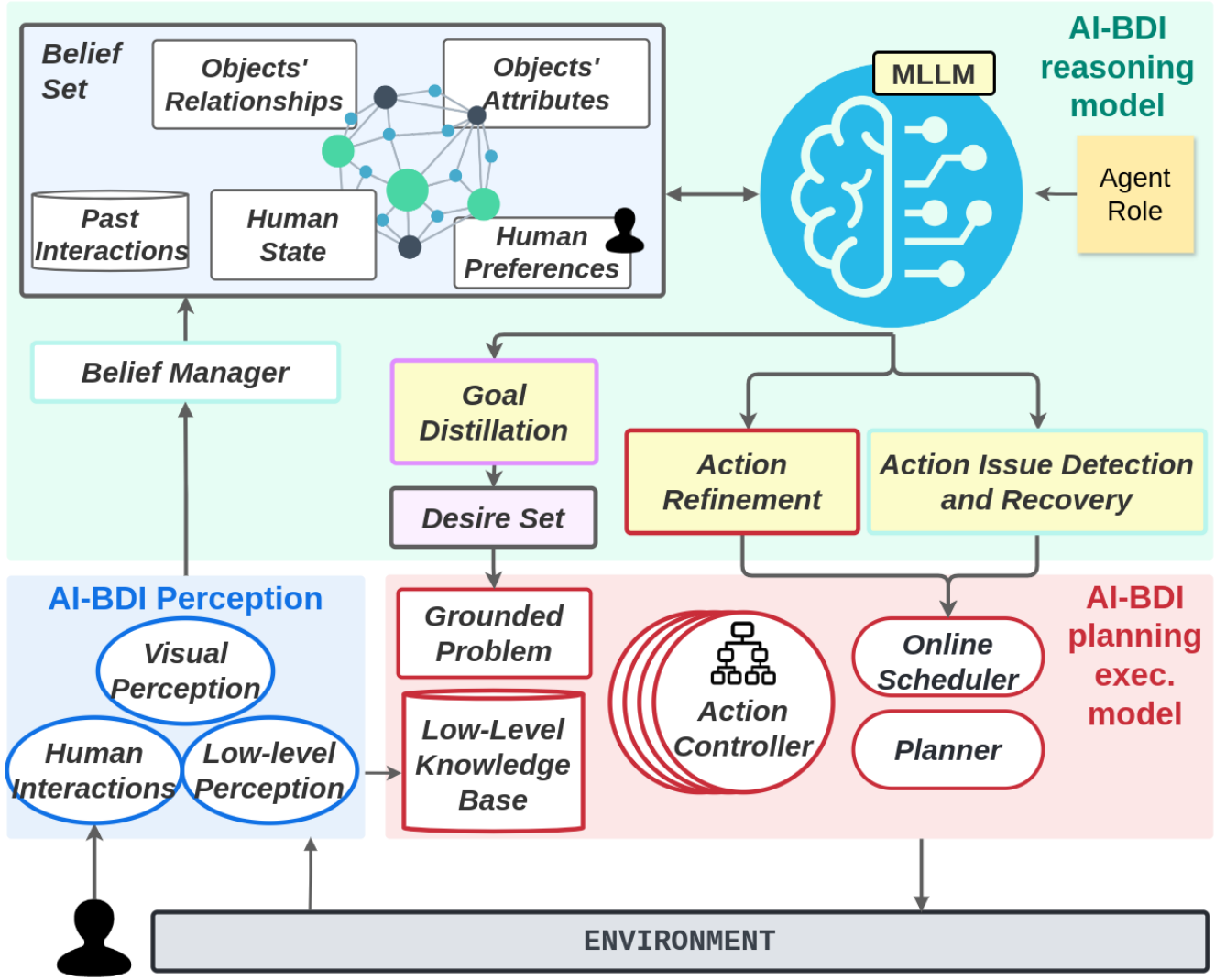
Natural Language Input Handling

- **Visual Perception:**

Object Identification and Tracking

- **Low-level Perception:**

Sensor Data Integration



Implementation details

AI-BDI Reasoning Model

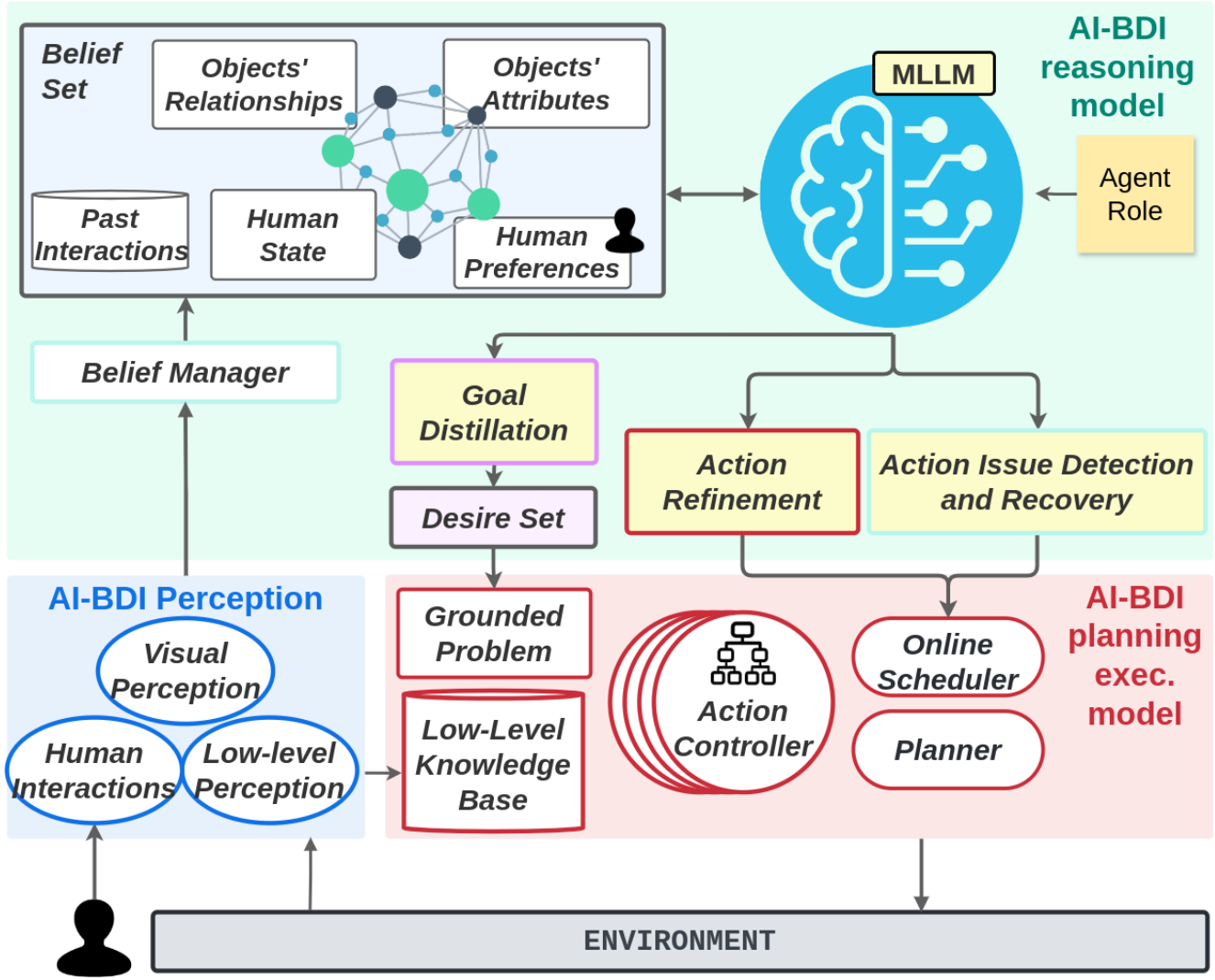
AI-BDI Reasoning Model

Belief Manager

- Maintains and dynamically updates beliefs (objects, relationships, human preferences)

MLLM Integration for Reasoning

- Goal distillation (translating abstract instructions into specific subgoals)
- Action refinement (real-time refinement of ambiguous tasks)
- Issue detection and recovery (adaptive to unexpected issues)



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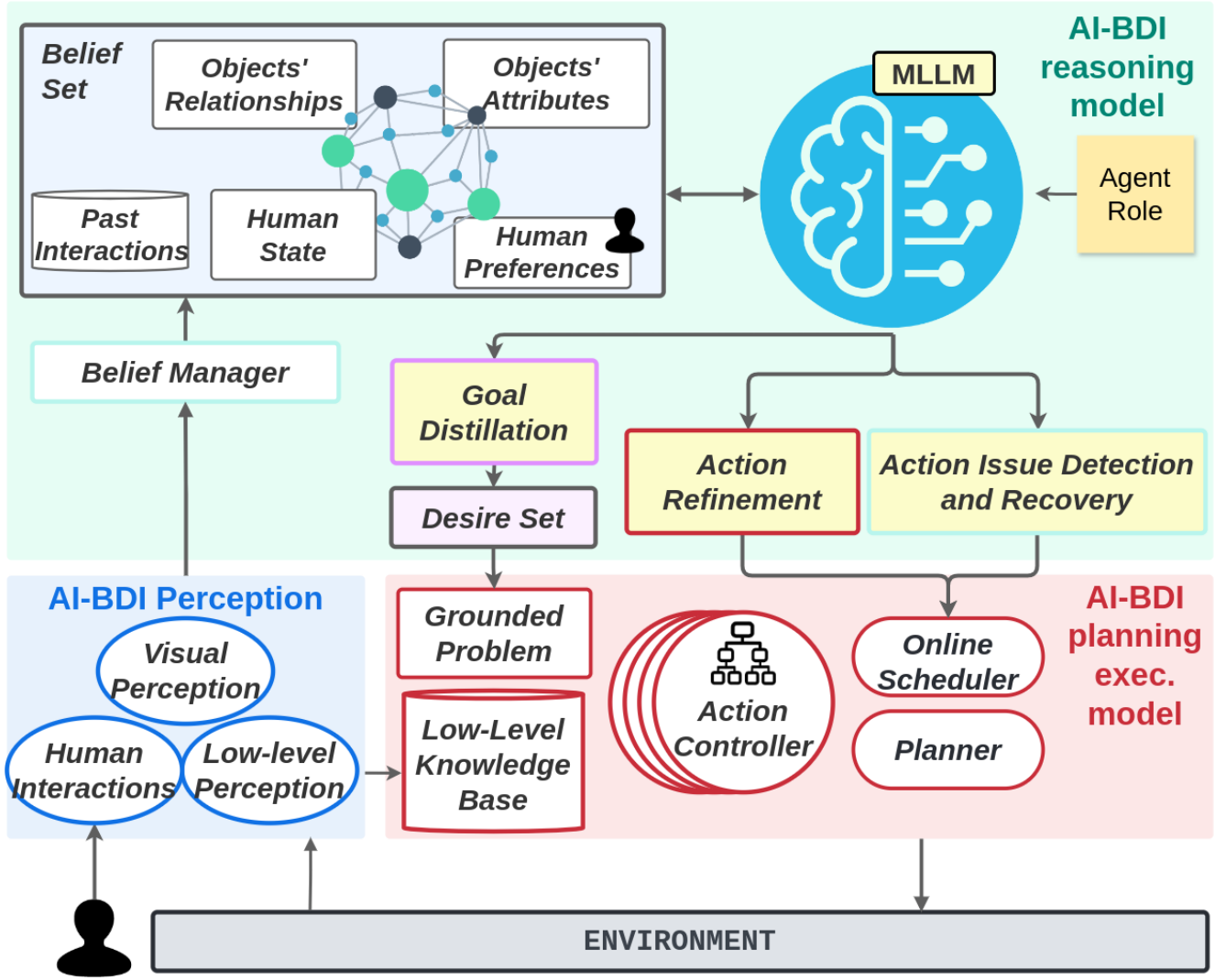
Implementation details

Planning and execution

Planning and Execution

Multi-Objective Planning & Real-time Execution

- **Knowledge Base:** Stores task-level skills and execution data
- **Planner & Scheduler:** Enables dynamic scheduling and conflict resolution
- **Action Controller:** Executes actions adaptively in real time



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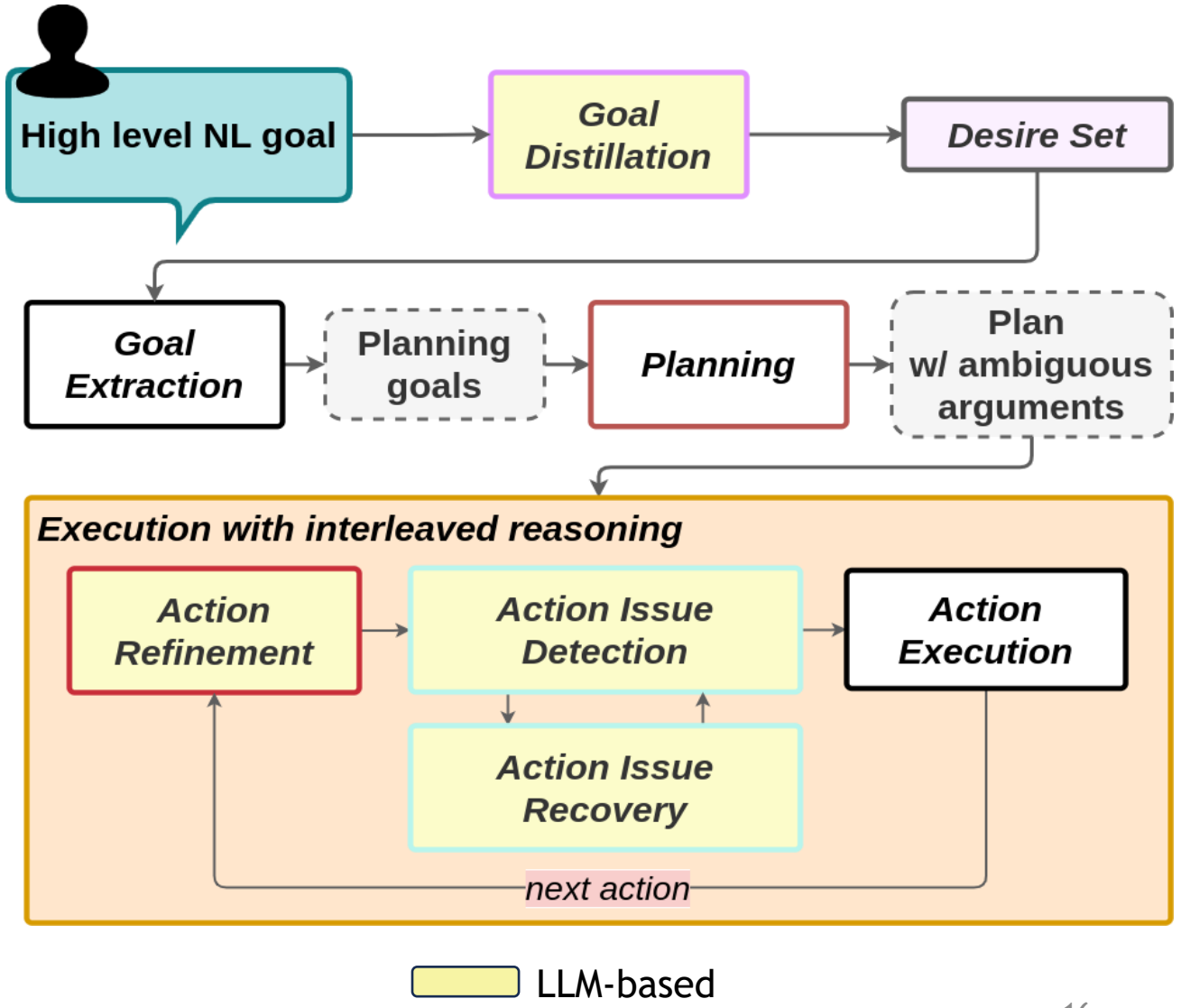
Execution Flow

Perception, Reasoning, Planning and execution

Execution flow:

From high level NL goal to dynamic plan execution

- Goal Distillation
- Goal Extraction
- Planning
- Execution:
  - Action Refinement
  - Action Issue Detection & Recovery
  - Action Execution



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Demonstration

Task

"Hey TIAGo, please help me deliver the medicines to the patients in the room"

Planning and Reasoning

PlanSys2

is_patient Adriana

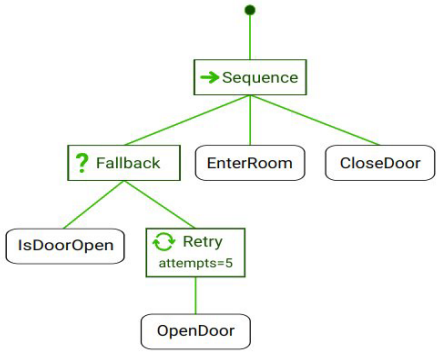
is_patient John

medicines_in medicine_counter

Beliefs

Action Executors

- *approach*
- *pick*
- *handover*
- *ask for info*
- *inform*



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Demonstration

Scenario setup

- Assistive robot (TIAGo) tasked with medication delivery
- Initial instruction provided in natural language

Goal distillation

- Conversion of high-level instructions into actionable desires (specific medicine delivery tasks)

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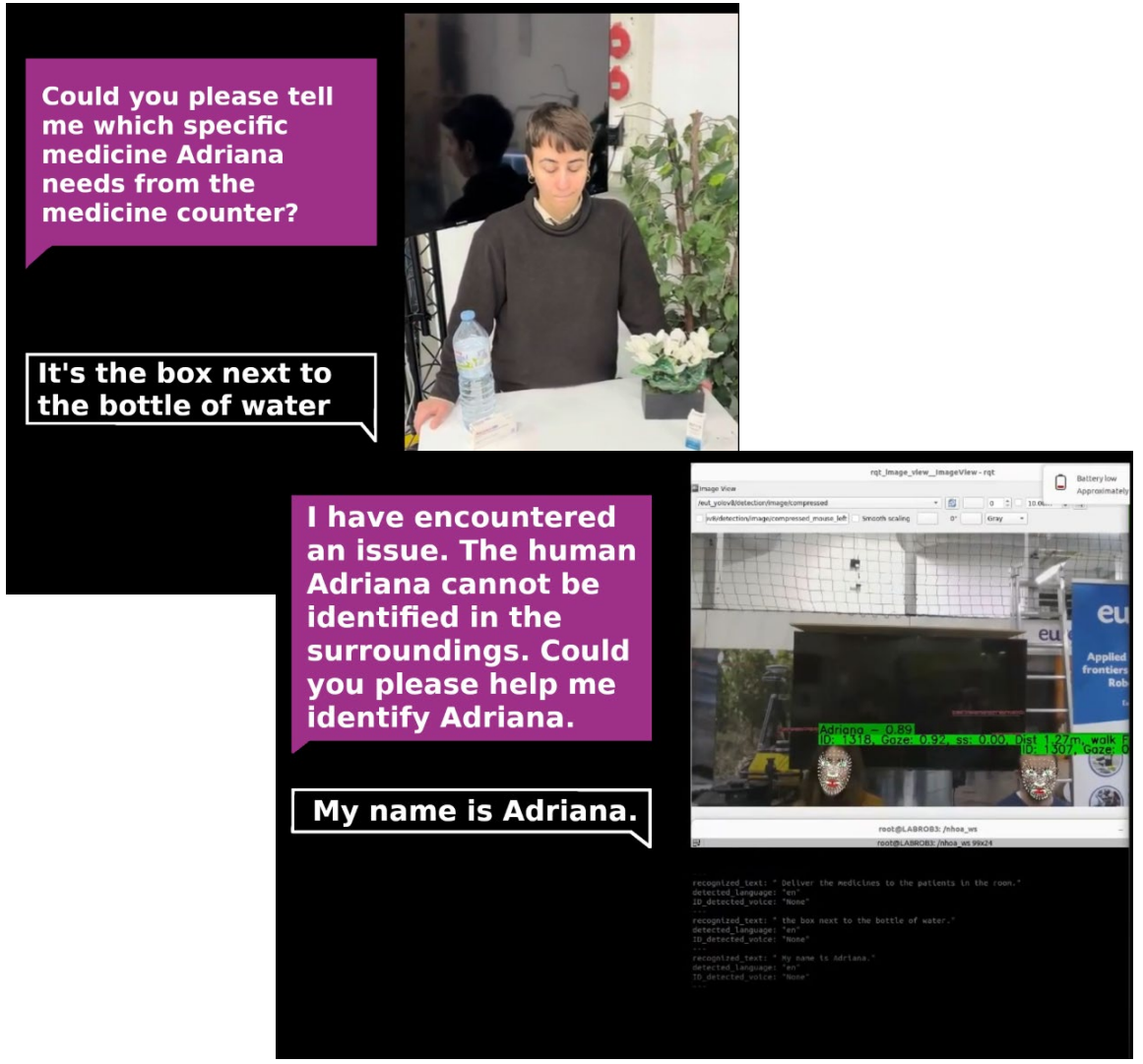
Demonstration

Action refinement

- Refinement of ambiguous instructions (identifying specific medication) through human interaction during execution

Issue detection & Recovery

- Detecting unfeasibilities and unforeseen conditions (identifying human for delivery)
- Interactive and adaptive problem-solving approach



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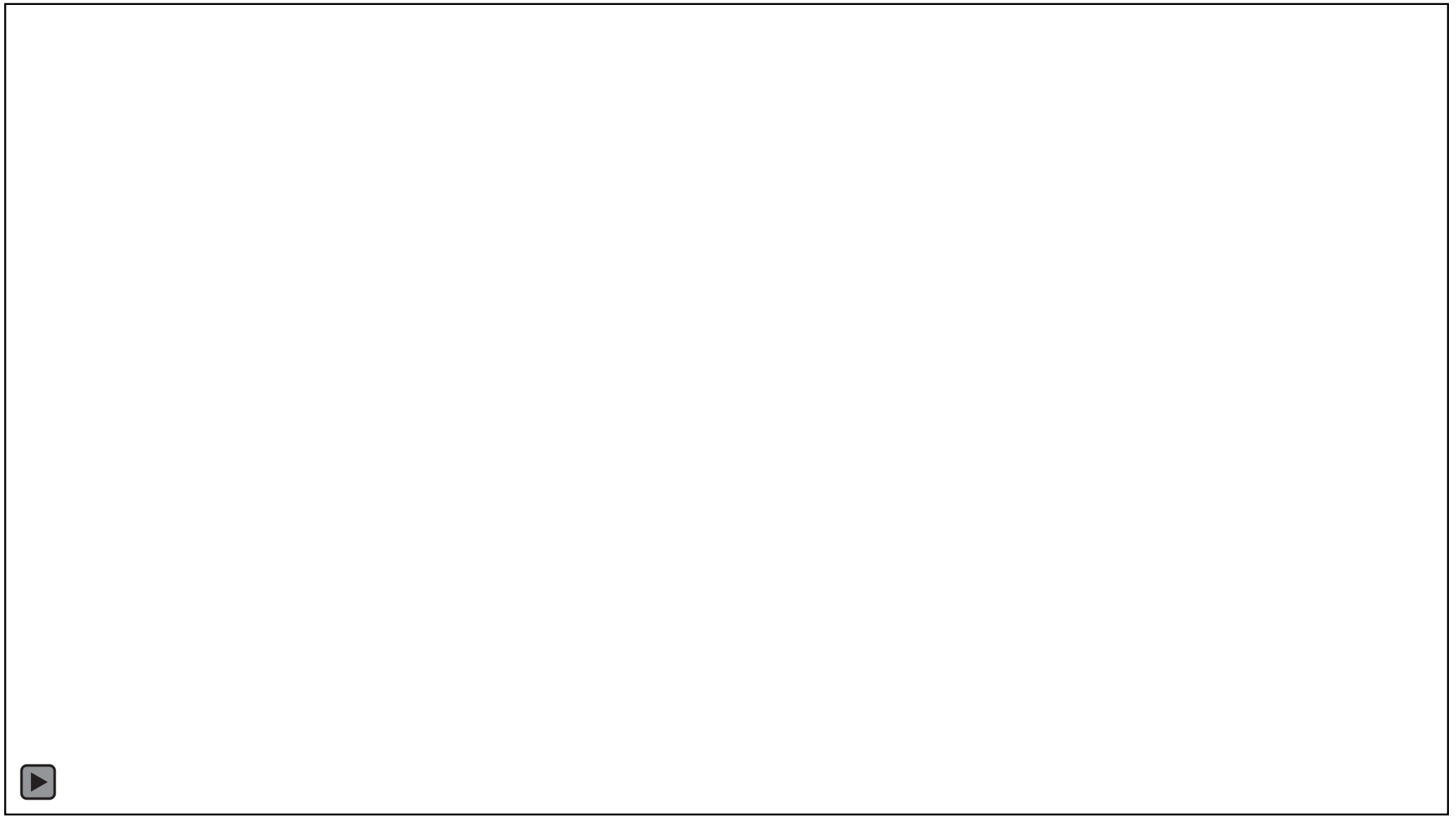
Demonstration

Video



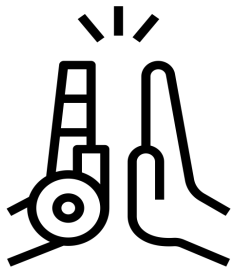
Key Achievements & Impact

Technological key outcomes

- Successfully demonstrated adaptability in dynamic conditions.
- Effective handling of ambiguous, incomplete information.
- Enhanced human-robot interaction through natural multimodal communication.
- Transparent decision-making process reduces AI "black box" risks, essential for safety-critical applications (healthcare, elderly assistance, collaborative tasks).

Impact of the solution

- **Improved Human-Robot Collaboration**: Natural, intuitive interactions and coordination.
- **Adaptability in Dynamic Environments**: Real-time adaptive capabilities.
- **Enhanced Personalization**: Tailored interactions based on evolving human preferences and behaviors.



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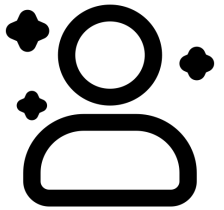

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Current Limitations and Future Directions

Technical Limitations

- Dependence on MLLMs and VLMs: sensitivity to data quality and prompts, hallucinations.
- Limitations in visual perception: contextual accuracy, real-time processing challenges.
- Challenges in extending domain knowledge without significant manual intervention.

Future Directions

- Improvement of MLLMs and VLMs to enhance robustness.
- Automation of domain knowledge integration.
- Expansion of application scenarios beyond healthcare to other complex dynamic environments.

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Gràcies, estem en contacte!

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