

# Axiom Learning and Belief Tracing for Transparent Decision Making in Robotics

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## Abstract

A robot’s ability to provide descriptions of its decisions and beliefs promotes effective collaboration with humans. Providing such transparency is particularly challenging in integrated robot systems that include knowledge-based reasoning methods and data-driven learning algorithms. Towards addressing this challenge, our architecture couples the complementary strengths of non-monotonic logical reasoning, deep learning, and decision-tree induction. During reasoning and learning, the architecture enables a robot to provide on-demand relational descriptions of its decisions, beliefs, and the outcomes of hypothetical actions. These capabilities are grounded and evaluated in the context of scene understanding tasks and planning tasks performed using simulated images and images from a physical robot manipulating tabletop objects.

## 1 Introduction

Consider a robot estimating the occlusion of objects and stability of object structures while arranging objects in desired configurations on a table; Figure 1a shows such a scene. To perform these tasks, the robot extracts information from on-board camera images, reasons with this information and incomplete domain knowledge, and executes actions to achieve desired outcomes. The robot also learns previously unknown axioms governing domain dynamics, and provides on-demand descriptions of its decisions and beliefs. For instance, assume that the goal in Figure 1b is to have the yellow ball on the orange block, and that the plan is to move the blue block on to the table before placing the ball on the orange block. When asked to justify a plan step, e.g., “why do you want to pick up the blue block first?”, the robot answers “I have to put the ball on the orange block, and the blue block is on the orange block”; when asked, after plan execution, “why did you not pick up the pig?”, the robot responds “Because the pig is not related to the goal”.

Our work seeks to enable such on-demand *explanations* of a robot’s decisions and beliefs, and hypothetical situations, in the form of descriptions of relations between relevant objects, actions, and domain attributes. This “explainability” can help improve the underlying algorithms



(a) Test scenario. (b) Robot’s camera image.

Figure 1: (a) Motivating scenario of a Baxter robot arranging objects in desired configurations on a tabletop; (b) Image from the camera on the robot’s left gripper.

and establish accountability. This is challenging to achieve with integrated robot systems that include knowledge-based reasoning methods (e.g., for planning) and data-driven (deep) learning algorithms (e.g., for pattern recognition). Inspired by research in cognitive systems that indicates the benefits of coupling different representations and reasoning schemes (Laird 2012; Winston and Holmes 2018), our architecture combines the complementary strengths of knowledge-based and data-driven methods to provide transparent decision making. It builds on our prior work that combined non-monotonic logical reasoning and deep learning for scene understanding in simulated images (Mota and Sridharan 2019). A recent paper described our architecture’s ability to learn previously unknown constraints and extract relevant information to construct descriptions of decisions and beliefs (Mota and Sridharan 2020a). Here, we summarize these capabilities and describe extensions to:

- Incrementally acquire previously unknown action preconditions and effects, exploiting the interplay between representational choices, reasoning methods, and learning algorithms to construct accurate explanations.
- Automatically trace and explain the evolution of any given belief from the initial beliefs by inferring the application of a suitable sequence of known or learned axioms.

In our implementation, non-monotonic logical reasoning is achieved using Answer Set Prolog (Balduccini and Gelfond 2003), and existing network models are adapted for deep learning. We illustrate our architecture’s capabilities in the context of a robot (i) computing and executing plans to arrange objects in desired configurations; and (ii) estimating occlusion of objects and stability of object configurations.

## 2 Related Work

Early work on explanation generation drew on research in cognition, psychology, and linguistics to characterize explanations in terms of generality, objectivity, connectivity, relevance, and information content (Friedman 1974); studies with human subjects have supported these findings (Read and Marcus-Newhall 1993). Computational methods were also developed for explaining unexpected outcomes (Genesereth 1984; de Kleer and Williams 1987).

There is much interest in understanding the operation of AI and machine learning methods, and making automation more acceptable (Miller 2019). Existing work on *explainable AI/planning* can be broadly categorized into two groups. Methods in one group modify or transform learned models or reasoning systems to make their decisions more interpretable, e.g., by tracing decisions to inputs (Koh and Liang 2017), learning equivalent interpretable models of any classifier (Ribeiro, Singh, and Guestrin 2016), or biasing a planning system towards making decisions easier for humans to understand (Zhang et al. 2017). Methods in the other group focus on making decisions more transparent, e.g., describing planning decisions (Borgo, Cashmore, and Magazzini 2018), using partial order causal links for explanations (Seegebarth et al. 2012), combining classical first order logic-based reasoning with interface design to help humans understand a plan (Bercher et al. 2014), or using rules associated with monotonic operators to define *proof trees* that provide a declarative view (i.e., explanation) of a computation (Ferrand, Lessaint, and Tessier 2006). There has also been work on describing why a particular solution was obtained for a given problem using non-monotonic logical reasoning (Fandinno and Schulz 2019). These methods are often agnostic to how an explanation is structured or assume comprehensive domain knowledge. Methods are also being developed to make the operation of deep networks more interpretable, e.g., by computing gradients and constructing *heat maps* of relevant features (Assaf and Schumann 2019; Samek, Wiegand, and Müller 2017), or in the context of deep networks trained to answer questions about images of scenes (Yi et al. 2018).

Our work focuses on integrated robot systems that use a combination of knowledge-based and data-driven algorithms to represent, reason with, and learn from incomplete commonsense domain knowledge and noisy observations. We seek to enable such robots to generate relational descriptions of decisions, beliefs, and hypothetical or counterfactual situations. Recent surveys indicate that these capabilities are not supported by existing systems (Anjomshoae et al. 2019; Miller 2019). Our architecture builds on existing work on making decisions more transparent, and on work in our group on explainable agency (Langley et al. 2017), a theory of explanations (Sridharan and Meadows 2019), and on combining non-monotonic logical reasoning and deep learning for scene understanding (Mota and Sridharan 2019).

## 3 Architecture

Figure 2 shows the overall architecture. Components to the left of the dashed vertical line combine non-monotonic log-

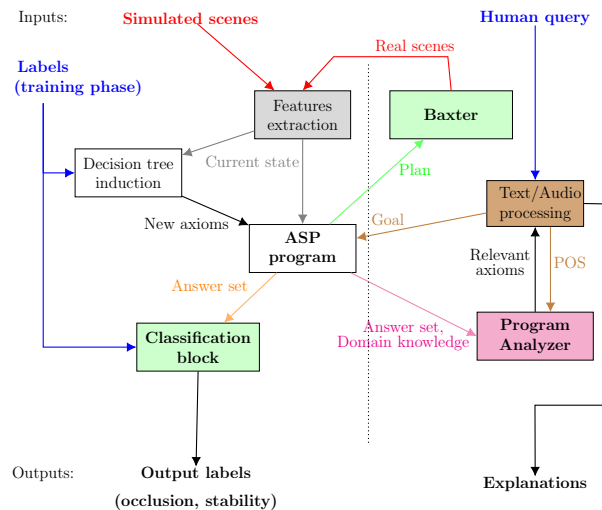


Figure 2: Architecture combines non-monotonic logical reasoning, deep learning, and decision-tree induction. Components to the right of the dashed line support explainability.

ical reasoning, deep learning, and decision-tree induction for classification in simulated images (Mota and Sridharan 2019). Components to the right of the dashed line expand reasoning to explain decisions, beliefs, and hypothetical situations (Mota and Sridharan 2020a). This paper extends the reasoning and learning capabilities to: (a) learn action preconditions and effects from experience; and (b) trace any given belief’s evolution from the initial beliefs through the application of specific axioms. We focus on the new components but summarize all components for completeness, using the following example domain.

### Example Domain 1 [Robot Assistant (RA) Domain]

A robot: (i) estimates occlusion of scene objects and stability of object structures, and arranges objects in desired configurations; and (ii) provides on-demand relational descriptions of decisions, beliefs, and hypothetical situations. There is uncertainty in the robot’s perception and actuation, and probabilistic algorithms are used to visually recognize and move objects. The robot has incomplete domain knowledge, which includes object attributes such as *size* (small, medium, large), *surface* (flat, irregular) and *shape* (cube, apple, duck); spatial relations between objects (above, below, front, behind, right, left, in); some domain attributes; and some axioms governing domain dynamics such as:

- Placing an object on top of an object with an irregular surface results in an unstable object configuration.
- For any given object, removing all objects blocking the view of its frontal face causes it to be not occluded.
- An object below another object cannot be picked up.

This knowledge may need to be revised over time, e.g., some actions, axioms, and values of some attributes may be unknown, or the robot may find that placing certain objects on an object with an irregular surface does not cause instability.

### 3.1 Representation, Reasoning, Learning

We first describe the knowledge representation, reasoning, and learning components.

**Non-monotonic logical reasoning** To represent and reason with domain knowledge, we use CR-Prolog, an extension to Answer Set Prolog (ASP) that introduces *consistency restoring* (CR) rules; we use the terms “CR-Prolog” and “ASP” interchangeably. ASP is a declarative language that represents recursive definitions, defaults, causal relations, and constructs that are difficult to express in classical logic formalisms. ASP is based on the stable model semantics, and encodes *default negation* and *epistemic disjunction*, e.g., unlike “ $\neg a$ ”, which implies that “*a is believed to be false*”, “ $\text{not } a$ ” only implies “*a is not believed to be true*”. Each literal can hence be true, false, or unknown. ASP supports non-monotonic logical reasoning, i.e., adding a statement can reduce the set of inferences, which helps recover from errors due to reasoning with incomplete knowledge.

A domain’s description in ASP comprises a *system description*  $\mathcal{D}$  and a *history*  $\mathcal{H}$ .  $\mathcal{D}$  comprises a *sorted signature*  $\Sigma$  and axioms encoding the domain’s dynamics. In our prior work that explored spatial relations for classification tasks,  $\Sigma$  included *basic sorts*, e.g., *object*, *robot*, *size*, *relation*, and *surface*; *statics*, i.e., domain attributes that do not change over time, e.g., *obj\_size(object, size)* and *obj\_surface(obj, surface)*; and *fluents*, i.e., attributes whose values can be changed, e.g., *obj\_rel(above, A, B)* implies object *A* is *above* object *B*. Since the robot in this paper also plans and executes physical actions that cause domain changes, we first describe the expanded  $\Sigma$  and transition diagram in action language  $\mathcal{AL}_d$  (Gelfond and Inlezan 2013), and then translate this description to ASP statements. For the RA domain,  $\Sigma$  now includes the sort *step* for temporal reasoning, additional fluents such as *in\_hand(robot, object)*, actions such as *pickup(robot, object)* and *putdown(robot, object, location)*, and the relation *holds(fluent, step)* implying that a particular fluent holds true at a particular timestep. Axioms of the RA domain include  $\mathcal{AL}_d$  statements such as:

$$\begin{aligned} & \text{putdown}(rob_1, Ob_1, Ob_2) \text{ causes } obj\_rel(on, Ob_1, Ob_2) \\ & obj\_rel(above, A, B) \text{ if } obj\_rel(below, B, A) \quad (1) \\ & \text{impossible } pickup(rob_1, Ob_1) \text{ if } obj\_rel(below, Ob_1, Ob_2) \end{aligned}$$

which encode a causal law, a state constraint, and an executability condition respectively. Also, the domain’s history  $\mathcal{H}$  comprises records of fluents observed to be true or false, and of the execution of an action, at a particular time step. We also expand history to include initial state defaults.

The domain description is translated automatically to a CR-Prolog program  $\Pi(\mathcal{D}, \mathcal{H})$ , which includes  $\Sigma$  and axioms of  $\mathcal{D}$ , inertia axioms, reality checks, closed world assumptions for actions, and observations, actions, and defaults (with CR rules) from  $\mathcal{H}$ ; the program for the RA domain is available online (Mota and Sridharan 2020b). Planning, diagnostics, and inference can then be reduced to computing *answer sets* of  $\Pi$  (Gelfond and Kahl 2014). Any answer set represents the beliefs describing a possible world; the literals of fluents and statics at a time step represent the corresponding *state*. Non-monotonic logical reasoning allows the robot to recover from incorrect inferences drawn due to incomplete knowledge, noisy sensors, or a low threshold for elevating probabilistic information to logic statements.

**Classification:** For any given image, the robot tries to estimate the occlusion of objects and the stability of object configurations using ASP-based reasoning. If an answer is not found, or an incorrect answer is found (on labeled training examples), the robot automatically extracts relevant regions of interest (ROIs) from the corresponding image. Parameters of Convolutional Neural Network (CNN) architectures (Lenet (LeCun et al. 1998), AlexNet (Krizhevsky, Sutskever, and Hinton 2012)) are tuned to map information from each such ROI to the corresponding classification labels.

**Decision tree induction:** Images used to train the CNNs are considered to contain previously unknown information related to occlusion and stability. Image features and spatial relations extracted from ROIs in each such image, along with the known labels for occlusion and stability (during training), are used to learn a decision tree summarizing the corresponding state transitions. Next, branches of the tree that satisfy minimal thresholds on purity at the leaf and have sufficient support from labeled examples are used to construct candidate axioms. Candidates are validated and those without a minimal level of support on unseen examples are removed. Also, we use an ensemble learning approach, retaining only axioms that are identified over a number of cycles of learning and validation, and axioms are merged to remove over-specifications. In addition, each axiom is associated with a *strength* that decays exponentially over time if the axiom is not used or learned again. Any axiom whose strength falls below a threshold is removed.

Our previous work only learned state constraints. In this paper, the robot also learns previously unknown causal laws and executability conditions if there is any mismatch between the expected and observed state after an action is executed. Any expected but unobserved fluent literal indicates missing executability condition(s), and any observed unexpected fluent literal suggests missing causal law(s).

1. To explore missing executability conditions, the robot simulates the execution of the action (that caused the inconsistency) in different initial states and stores the relevant information from the initial state, executed action, and a label indicating the presence or absence of inconsistency. Any fluent literal in the answer set or initial state containing an object constant that occurs in the action, with variables replacing ground terms, is relevant.
2. To explore a missing causal law, training samples are collected as in Step 1, but the robot label is the unexpected fluent literal from the resultant state.
3. Separate decision trees are created with the relevant information from the initial state as the features (i.e., nodes) and the output labels (presence/absence of inconsistency for executability condition, unexpected fluent for causal law). The root is the executed action.

Axioms are constructed from the decision trees as before.

### 3.2 Relational Description as Explanation

The interplay between representation, reasoning, and learning is used to provide relational descriptions of decisions, beliefs, and the outcomes of hypothetical events.

**Interaction interface and control loop** Existing software and a controlled (domain-specific) vocabulary are used to parse human verbal (or text) input and to provide a response when appropriate. Verbal input from a human is transcribed into text based on the controlled vocabulary. This (or the input) text is labeled using a part-of-speech (POS) tagger, and normalized with the lemma list (Someya 1998) and related synonyms and antonyms from WordNet (Miller 1995). The processed text helps identify the type of a desired goal or a request for information. Any given goal is sent to the ASP program for planning, with the robot executing the plan (and replanning when needed) until the goal is achieved. To address a request for information, the “Program Analyzer” identifies the relevant axioms and literals in the existing knowledge and inferred beliefs. These literals are inserted into generic response templates based on the controlled vocabulary, to provide textual or verbal responses.

**Beliefs tracing** A key capability of our architecture is to infer the sequence of axioms whose application explains the evolution of any given belief. Our approach adapts prior work on constructing such “proof trees”, which used monotonic logic statements to explain observations (Ferrand, Lessaint, and Tessier 2006; Genesereth and Nilsson 1987), to our non-monotonic logic formulation and traces the evolution of beliefs corresponding to fluents or actions.

1. Select axioms whose head matches the belief of interest.
2. Ground the literals in the body of each selected axiom and check whether these are supported by the answer set.
3. Create a new branch in a proof tree (with target belief as root) for each selected axiom supported by the answer set, and store the axiom and the related supporting ground literals in suitable nodes.
4. Repeats Steps 1-3 with the supporting ground literals in Step 3 as target beliefs in Step 1, until all branches reach a leaf node with no further supporting axioms.

The paths from the root to the leaves in these proof trees help construct the desired explanations. As an example, for the initial scenario in Figure 1b, if the goal is to place the red cube on the orange cube, and the robot is asked (after plan execution) why it did not pick up the purple cube at time step 3, the corresponding proof tree would be as shown in Figure 3; the path highlighted in green contains the information needed to answer the question.

**Program analyzer** We illustrate our approach for constructing explanations (in the form of relational descriptions) in the context of four types of *explanatory* questions or requests. The first three were introduced as question types to be considered by any explainable planning system (Fox, Long, and Magazzeni 2017); we also consider a question about the robot’s beliefs at any point in time.

1. **Plan description** When asked to describe a plan, the robot parses the related answer set(s) and extract a sequence of actions such as *occurs(action1, step1), ..., occurs(actionN, stepN)* to construct the response.
2. **Action justification: Why action X at step I?** To justify the execution of an action at a particular time step:

- (a) For each action that occurred after time step  $I$ , the robot examines relevant executability condition(s) and identifies literal(s) that would prevent the action’s execution at step  $I$ . For the goal of picking up the *orange\_block* in Figure 1b, assume that the executed actions are *occurs(pickup(robot, blue\_block), 0)*, *occurs(putdown(robot, blue\_block), 1)*, and *occurs(pickup(robot, orange\_block), 2)*. If the focus is on the first *pickup* action, an executability condition related to the second *pickup* action:

$$\neg \text{occurs}(\text{pickup}(\text{robot}, A), I) \leftarrow \\ \text{holds}(\text{obj\_rel}(\text{below}, A, B), I)$$

is ground in the scene to obtain *obj\_rel(below, orange\_block, blue\_block)* as a literal of interest.

- (b) If any identified literal is in the answer set at the time step of interest (0 in this example) and is absent (or its negation is present) in the next step, it is a reason for executing the action under consideration.
- (c) The condition modified by the execution of the action of interest is paired with the subsequent action to construct the answer to the question. The question “Why did you pick up the blue block at time step 0?”, receives the answer “I had to pick up the orange block, and the orange block was below the blue block”.

A similar approach is used to justify the selection of any particular action in a plan that has not been executed.

3. **Hypothetical actions: Why not action X at step I?** For questions about actions not selected for execution:

- (a) The robot identifies executability conditions that have the hypothetical action in the head, i.e., conditions that prevent the action from being selected during planning.
- (b) For each such executability condition, the robot checks if literals in the body are satisfied by the corresponding answer set. If yes, these literals form the answer.

Suppose action *putdown(robot, blue\_block, table)* occurred at step 1 in Figure 1b. For the question “Why did you not put the blue cube on the tennis ball at time step 1?”, the following executability condition is identified:

$$\neg \text{occurs}(\text{putdown}(\text{robot}, A, B), I) \leftarrow \\ \text{has\_surface}(B, \text{irregular})$$

which implies that an object cannot be placed on another object with an irregular surface. The answer set states that the tennis ball has an irregular surface and the robot answers “Because the tennis ball has an irregular surface”. This process uses the *belief tracing* approach.

4. **Belief query: Why belief Y at step I?** To explain any particular belief, the robot uses the *belief tracing* approach described earlier. The supporting axioms and relevant literals identified are used to construct the answer. For instance, to explain the belief that object  $ob_1$  is unstable in step  $I$ , the robot finds the support axiom:

$$\neg \text{holds}(\text{stable}(ob_1), I) \leftarrow \text{holds}(\text{small\_base}(ob_1), I)$$

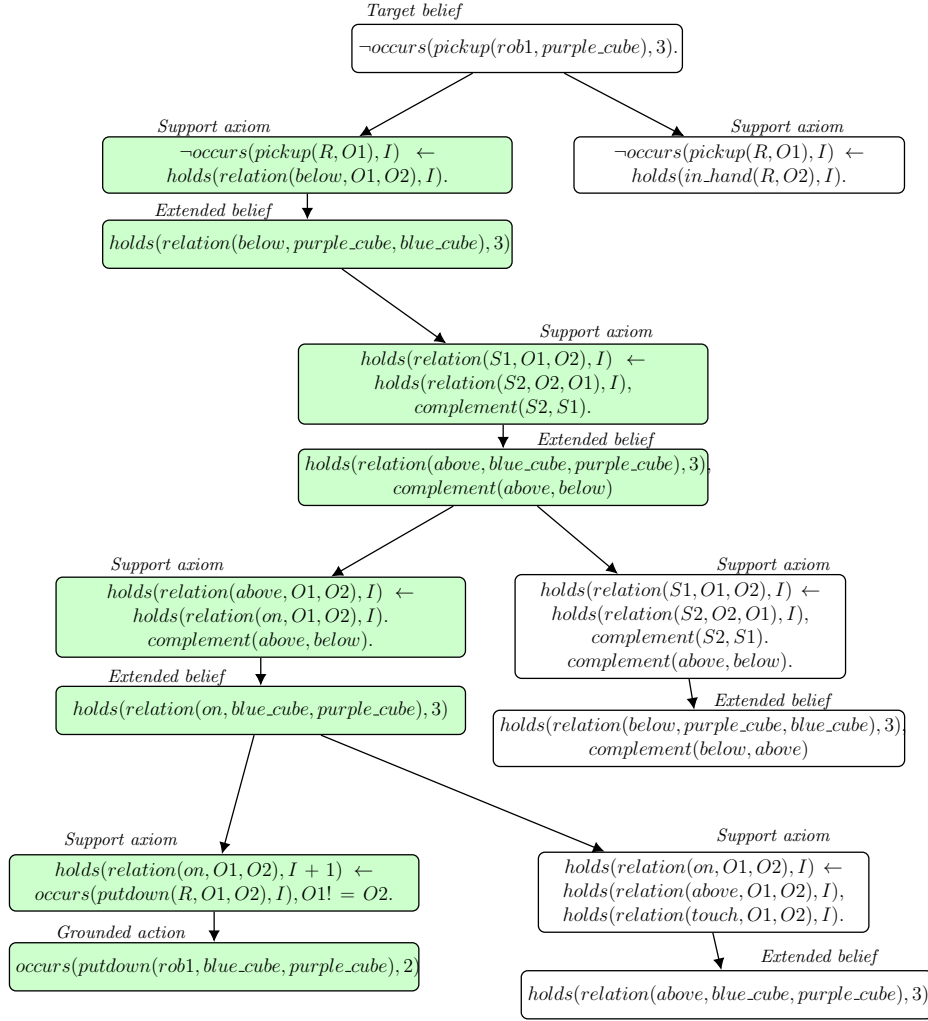


Figure 3: Example of belief tracing in action.

Assume that the current beliefs include that  $ob_1$  has a small base. Tracing this belief identifies the axiom:

$$\begin{aligned} & \text{holds}(\text{small\_base}(ob_1), I) \leftarrow \\ & \quad \text{holds}(\text{relation}(\text{below}, ob_2, ob_1), I), \\ & \quad \text{has\_size}(ob_2, \text{small}), \text{has\_size}(ob_1, \text{big}) \end{aligned}$$

Asking “why do you believe object  $ob_1$  is unstable at step  $I$ ?” would provide the answer “Because object  $ob_2$  is below object  $ob_1$ ,  $ob_2$  is small, and  $ob_1$  is big”.

**Robot platform** As stated earlier, our work consider scene understanding tasks and planning tasks. For robot experiments, we use a Baxter manipulating objects on a tabletop. The Baxter uses probabilistic algorithms to process inputs from its cameras, e.g., to detect objects, their attributes, and the spatial relations between them, from images. It also uses probabilistic motion planning algorithms to execute primitive manipulation actions, e.g., to grasp and pick up objects. Observations obtained with a high probability are elevated to literals with complete certainty in the ASP program.

## 4 Experimental Setup and Results

We present execution traces and quantitative results illustrating the ability to construct relational descriptions of decisions, beliefs, and hypothetical events; and to learn causal laws and executability conditions.

### 4.1 Experimental Setup

We experimentally evaluated the following hypotheses:

- H1** : our architecture enables the robot to accurately learn previously unknown domain axioms;
- H2** : reasoning with incrementally learned axioms improves the quality of plans generated;
- H3** : the beliefs tracing approach accurately retrieves the supporting axioms associated with any belief; and
- H4** : exploiting the links between reasoning and learning improves the accuracy of the explanatory descriptions.

These hypotheses and our architecture’s capabilities were evaluated in the context of the four types of requests de-

scribed earlier, but the methodology can be adapted for other types of requests. Plan quality was measured in terms of the ability to compute minimal and correct plans. The quality of an explanation was measured in terms of precision and recall of its literals in comparison with the expected (“ground truth”) response obtained in a semi-supervised manner based on manual input and automatically selected relevant literals.

Experimental trials considered images from the robot’s camera and simulated images. Real world images contained 5 – 7 objects of different colors, textures, shapes, and sizes in the RA domain (Example 1). The objects included cubes, a pig, a capsicum, a tennis ball, an apple, an orange, and a pot. These objects were either stacked on each other or spread on the table—see Figure 1b. A total of 20 configurations were created, each with five different goals for planning and four different questions for each plan, resulting in 100 plans and 400 questions. Since it is time-consuming and difficult to run many trials on robots, we also used a real-time physics engine (Bullet) to create 20 simulated images, each with 7 – 9 objects (3 – 5 stacked and the remaining on a flat surface). Objects included cylinders, spheres, cubes, a duck, and five household objects from the Yale-CMU-Berkeley dataset (apple, pitcher, mustard bottle, mug, and box of crackers). We once again considered five different goals for planning and four different questions for each plan, resulting in (once again) 100 plans and 400 questions.

To explore the interplay between reasoning and learning, we focused on the effect of learned knowledge on planning and constructing explanations. We ran experiments with and without some learned axioms in the knowledge base. Learned axioms were revised over time in our architecture, whereas these axioms were not used by the baselines for planning and explanation generation. During planning, we measured the number of optimal, sub-optimal, and incorrect plans, and the planning time. An *optimal* plan is a minimal plan that achieves the goal; a *sub-optimal* plan requires more than the minimum number of steps and/or has to assume an unnecessary exception to defaults; and an *incorrect* plan leads to undesirable outcomes and fails to achieve the goal.

To test hypothesis **H1** we removed five axioms (three executability conditions and two causal laws) from the agent’s knowledge, and ran the learning algorithm 20 times. The robot executed actions to learn all the missing axioms each time. Each run stops if the robot executes a number of actions without detecting any inconsistency, or if a maximum number of decision trees are constructed. The overall precision and recall are then computed.

## 4.2 Execution Traces

The following execution traces illustrate our approach to construct relational descriptions explaining the decisions, beliefs, and the outcomes of hypothetical actions.

### Execution Example 1 [Plans, actions, and beliefs]

Consider a scene with objects as shown in Figure 4. The robot’s goal is to achieve a state in which the pitcher is on the red block, i.e.,  $holds(relation(on, pitcher, red\_block), 1)$ . The robot answers the following questions *after executing* a plan and successfully achieving the assigned goal:

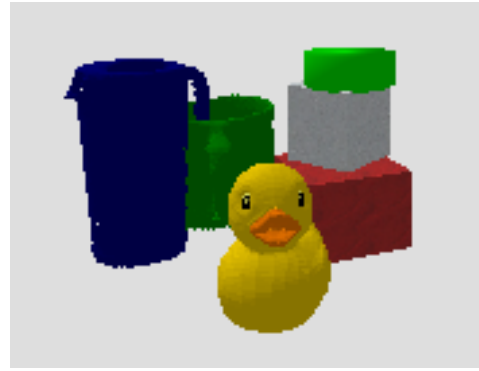


Figure 4: Simulated scene for the execution examples.

- **Human:** “Please describe the plan.”  
**Baxter:** “I picked up the green can. I put the green can on the table. I picked up the white block. I put the white block on the green can. I picked up the pitcher. I put the pitcher on the red block.”
- The human may ask the robot to justify a particular action.  
**Human:** “Why did you pick up the green can at step 0?”  
**Baxter:** “Because I had to pick up the white block, and it was below the green can.”
- The human may ask about actions not chosen.  
**Human:** “Why did you not put white block on the mug?”  
**Baxter:** “Because the mug has irregular surface.” Since there was no reference to a particular time step, the robot responds based on the single instance (in the executed plan) of putting the white block on the mug.
- The human may also ask about particular beliefs.  
**Human:** “Why did you believe that the white block was below the green can in the initial state?”  
**Baxter:** “Because I observed the white block below the green can at step zero.”

### Execution Example 2 [Beliefs tracing and explanation]

We continue with our previous example:

- **Human:** “Why did you not pick white block at step 0?”  
The robot uses the belief tracing approach to construct a proof tree with  $\neg occurs(pickup(rob1, white\_block), 0)$  as the root. For each axiom in which this ground literal matches the head, it checks if its body is supported by the answer set. If yes, ground literals in the body are used to expand the tree. According to the third axiom in Equation 1, one of the extended beliefs is  $holds(obj\_rel(below, white\_block, green\_can), 0)$ . Similar searches are repeated until no further supporting axioms are found. In our example, the statement  $holds(relation(on, white\_block, green\_can), 0)$  is output as the leaf of the proof tree, and the agent’s answer to the question is:  
• **Robot:** “Because I observed the green can on the white block at step 0.”

### Execution Example 3 [Learning and explanation]

In some situations, the robot may not possess the knowledge required to address the human request. Continuing with the previous example, the human may ask:

- **Human:** “Why did you not pick up green can at step 5?”  
By creating a proof tree, the answer is found:  
**Robot:** “Because white block was on the green can.”  
The human may need further details and ask:  
**Human:** “Why did you believe the white block was on the green can?”  
To answer this question the robot has to know the causal relation between action *putdown* and the spatial relation *on*—first axiom in Equation 1. After the robot learns this causal law, it produces the correct answer:  
**Robot:** “Because I put the white block on the green can at step 4.”

This example illustrates the benefit of integrating reasoning and learning to justify particular beliefs.

Overall, these (and other) examples show the ability to focus on relevant knowledge, incrementally revise axioms, trace relevant beliefs, and identify attributes and actions relevant to a given scenario. They also support hypothesis **H3**.

### 4.3 Experimental Results

The first set of experiments evaluated **H1**. We removed five axioms (two causal laws and three executability conditions) from the robot’s knowledge, and ran the learning algorithm 20 times. We measured the precision and recall for the missing axioms in each run, and table 1 summarizes the results. The row labeled “Strict” provides results when any variation in the target axiom is considered an error. In this case, even over-specified axioms, i.e., axioms that have some additional irrelevant literals, are considered to be incorrect. Equation 2 shows one example of such an axiom in which the second literal in the body is irrelevant. The row labeled “Relaxed” reports results when over-specifications are not considered errors; the high precision and recall support **H1**.

Table 1: Precision and recall for learning previously unknown axioms using decision tree induction.

Missing Axioms	Precision	Recall
Strict	69.2%	78.3%
Relaxed	96%	95.1%

$$\begin{aligned} \neg \text{holds}(\text{in\_hand}(R1, O1), I + 1) \leftarrow \\ \text{occurs}(\text{putdown}(R1, O1, O2), I), \\ \neg \text{holds}(\text{in\_hand}(R1, O5), I). \end{aligned} \quad (2)$$

The second set of experiments was designed to evaluate hypothesis **H2**.

1. As stated earlier, 20 initial object configurations were created (similar to Figure 1a). The Baxter automatically extracted information (e.g., attributes, spatial relations) from images corresponding to top and frontal views (cameras on the left and right grippers), and encoded it in the ASP program as the initial state.
2. For each initial state, five goals were randomly chosen and encoded in the ASP program. The robot reasoned with the existing knowledge to create plans for these 100 combinations (20 initial states, five goals).

Table 2: Number of plans and planning time with the learned axioms expressed as a fraction of the values without the learned axioms.

Measures	Ratio (with/without)	
	Real scenes	Simulated scenes
Number of steps	1.17	1.21
Number of plans	0.7	1.1
Planning time	0.87	1.08

Table 3: Number of optimal, sub-optimal, and incorrect plans expressed as a fraction of the total number of plans. Reasoning with the learned axioms improves performance.

Plans	Real Scenes		Simulated Scenes	
	Without	With	Without	With
Optimal	0.33	0.89	0.13	0.24
Sub-optimal	0.12	0.11	0.44	0.76
Incorrect	0.55	0	0.43	0

3. The plans were evaluated in terms of the number of optimal, sub-optimal and incorrect plans, and planning time.
4. Trials were repeated with and without learned axioms, and for the simulated images.

Since the number of plans and planning time vary depending on the initial conditions and the goal, we conducted paired trials with and without the learned axioms included in the ASP program used for reasoning. The initial conditions and goal were identical in each paired trial, but differed between paired trials. Then, we expressed the number of plans and the planning time with the learned axioms as a fraction of the corresponding values obtained by reasoning without the learned axioms. The average of these fractions over all the trials is reported in Table 2. We also computed the number of optimal, sub-optimal, and incorrect plans in each trial as a fraction of the total number of plans; we did this with and without using the learned axioms for reasoning, and the average over all trials is summarized in Table 3.

These results indicate that for images of real scenes, using the learned axioms for reasoning significantly reduced the search space, resulting in a much smaller number of plans and a substantial reduction in the planning time. The use of the learned axioms does not seem to make any significant difference with the simulated scenes. This is understandable because simulated images have more objects with several of them being small objects. This increases the number of possible plans to achieve any given goal. In addition, when the robot used the learned axioms for reasoning, it reduced the number of sub-optimal plans and eliminated all incorrect plans. Also, almost every sub-optimal plan was created when the corresponding goal could not be achieved without creating an exception to a default. Without the learned axioms, a larger fraction of the plans are sub-optimal or incorrect. Note that the number of suboptimal plans is higher with simulated scenes that have more objects to consider. These results support hypothesis **H2** but also indicate the need to explore complex scenes further.

The third set of experiments was designed as follows to eval-

Table 4: (**Real scenes**) Precision and recall of retrieving relevant literals for constructing answers to questions with and without using the learned axioms for reasoning. Using the learned axioms significantly improves the ability to provide accurate explanations.

Query Type	Precision		Recall	
	Without	With	Without	With
Plan description	74.94%	100%	63.25%	100%
Why X?	72.22%	94.0%	65.0%	94.0%
Why not X?	100%	95.92%	68.89%	100%
Belief	95.74%	100%	95.74%	100%

Table 5: (**Simulated scenes**) Precision and recall of retrieving relevant literals for constructing answers to questions with and without reasoning with learned axioms. Using the learned axioms significantly improves the ability to provide accurate explanations.

Query Type	Precision		Recall	
	Without	With	Without	With
Plan description	71.85%	100%	59.39%	100%
Why X?	66.48%	95.0%	58.5%	95.0%
Why not X?	86.79%	95.24%	63.01%	100%
Belief	94.55%	100%	91.23%	100%

uate hypothesis **H4**:

1. For each of the 100 combinations (20 configurations, five goals) from the first set of experiments with real-world data, we considered knowledge bases with and without the learned axioms and had the robot compute plans to achieve the goals.
2. The robot had to describe the plan and justify the choice of a particular action (chosen randomly) in the plan. Then, one parameter of the chosen action was changed randomly to pose a question about why this new action could not be applied. Finally, a belief related to the previous two questions had to be justified.
3. The literals present in the answers were compared against the expected literals in the “ground truth” response, with the average precision and recall scores reported in Table 4.
4. We also performed these experiments with simulated images, and the results are summarized in Table 5.

Tables 4, 5 show that when the learned axioms were used for reasoning, the precision and recall of relevant literals (for constructing the explanation) were higher than when the learned axioms were not included. The improvement in performance is particularly pronounced when the robot has to answer questions about actions that it has not actually executed. The precision and recall rates were reasonable even when the learned axioms were not included; this is because not all the learned axioms are needed to accurately answer each explanatory question. When the learned axioms were used for reasoning, errors were very rare and corresponded to some additional literals being included in the answer (i.e., over-specified explanations). In addition, when we specifically removed axioms related to the goal under considera-

tion, precision and recall values were much lower. Furthermore, there was noise in both sensing and actuation, especially in the robot experiments. For instance, recognition of spatial relations, learning of constraints, and manipulation have approximate error rates of 15%, 5 – 10%, and 15% respectively. Experimental results thus indicate that coupling reasoning and learning to inform and guide each other enables the robot to provide accurate relational descriptions of decisions, beliefs, and the outcomes of hypothetical actions. This supports hypothesis **H4**. Additional examples of images, questions, and answers, are in our open source repository (Mota and Sridharan 2020b).

## 5 Conclusions

This paper described an approach inspired by cognitive systems and knowledge representation tools to enable an integrated robot system to explain its decisions, beliefs, and the outcomes of hypothetical actions. These explanations are constructed on-demand in the form of descriptions of relations between relevant objects, actions, and domain attributes. We have implemented this approach in an architecture that combines the complementary strengths of non-monotonic logical reasoning with incomplete commonsense domain knowledge, deep learning, and decision tree induction. In the context of some scene understanding and planning tasks performed in simulation and a physical robot, we have demonstrated that our architecture exploits the interplay between knowledge-based reasoning and data-driven learning. It automatically identifies and reasons with the relevant information to efficiently construct the desired explanations, with both the planning and explanation generation performance improving when previously unknown axioms are learned and used for subsequent reasoning.

Our architecture opens up multiple avenues for further research. First, we will explore more complex domains, tasks, and explanations, reasoning with relevant knowledge at different tightly-coupled resolutions for scalability (Sridharan et al. 2019). We are specifically interested in exploring scenarios in which there is ambiguity in the questions (e.g., it is unclear which of two occurrences of the *pickup* action the human is referring to), or the explanation is needed at a different level of abstraction, specificity, or verbosity. We will do so by building on a related theory of explanations (Sridharan and Meadows 2019). Second, we will use our architecture to better understand the behavior of deep networks. The key advantage of using our architecture is that it uses reasoning to guide learning. Unlike “end to end” data-driven deep learning methods, our architecture uses reasoning to trigger learning only when existing knowledge is insufficient to perform the desired task(s). The long-term objective is to develop an architecture that exploits the complementary strengths of knowledge-based reasoning and data-driven learning for the reliable and efficient operation of robots in complex, dynamic domains.

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