Cognitive Affordance Representations in Uncertain Logic

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Introduction to the Problem

Natural human activities involve applying cognitive skills to use and manipulate objects around us, often several at a time, simultaneously and continuously. Consider the simple act of doodling, which requires several cognitive skills: (1) choosing how to grasp a pencil, (2) sequencing actions like drawing and erasing, and (3) reasoning about various social norms like if the paper were not scrap, then it might be inappropriate to scribble on it. Additionally, the doodler must make creative decisions about the content and form of the drawing itself.

Learning how to use objects is a highly desirable skill for artificial agents, as well. Helper agents are becoming a part of the vision of our future: helping our elderly and disabled in assisted living facilities, conducting search-and-rescue missions in unforgiving terrain to save human lives, assisting our astronauts on the space station, or even monitoring our surroundings to keep us safe from national security threats. Unfortunately, although artificial agents are proficient at recognizing object features, they are less-skilled at recognizing what can be done with these objects (i.e., they cannot perceive complex object affordances).

My research seeks to build an integrated computational framework for representing and reasoning about not only an object's physical features, but also higher-order functional, social, aesthetic, ethical and moral aspects (i.e., cognitive affordances). Towards this goal, I am developing a novel approach based on first-order "uncertain logic" and Dempster-Shafer (DS) probabilistic theory for inferring cognitive affordances.

My Motivation for Addressing the Problem

"Oh, if only it were so simple." That was the caption in a 1987 New Yorker cartoon featuring two scientists standing before an equation-filled chalkboard. It captures so many things that I enjoy art, mathematics, science, human thought process, creativity, insight and, of course, cartoons. It is my love for cartoons and the desire to unwrap the mystery of human creativity that brought me to Tufts University, where I was awarded the Adams Fellowship, the schools most prestigious award, to pursue a joint PhD in Cognitive Science and Computer Science.

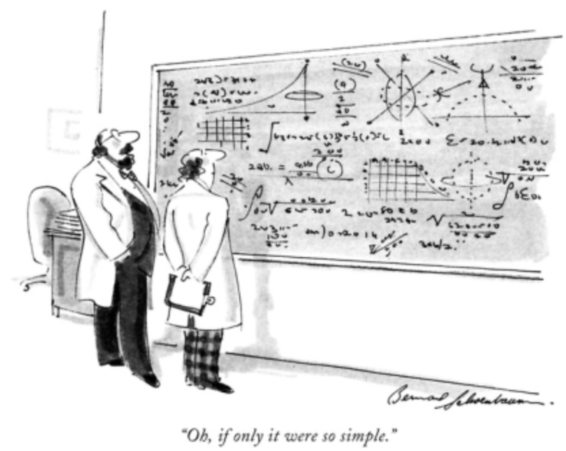

Figure 1: New Yorker, 1987

As a cartoonist myself, I have discovered many parallels between cartooning and studying cognitive sciences. Both endeavors involve modeling human creative thinking and representing knowledge in a form that influences sense-making and reasoning. Now at Tufts, I have started using the tools of mathematics, computing and robotics to generate and test models of cognition that will shed some light into what makes us go Eureka or Aha, I get it now or "Haha".

At the heart of creativity lies our ability to learn how to use and reason about objects in our environment. As I see it, affordance perception is a basic prerequisite to tool-use and creative problem solving. We experience this fact everyday when we use objects in creative ways, not contemplated by the original designers, for e.g., using coffee mugs as paperweights or using books to prop open doors. Representing affordances and reasoning with them, formally, is the focus of my thesis work, which I will summarize in more detail in the below sections.

Background and Existing Literature

Gibson introduced the concept of affordance to represent the relationship between an agent and its environment (Gibson 1979). Past work in formalizing this relationship has largely focused on modeling affordance using either statistical formalisms or ontology-based approaches. For example, Montesano et al. have developed statistically inspired causal models of affordance using Bayesian Networks to formalize the relationship between object features, actions and effects (Montesano et al. 2007). Varadarajan et al. (Varadarajan and Vincze 2011; Varadarajan 2015) developed a detailed knowledge-ontology based on conceptual, functional and part properties of objects, and then used a combination of detection and query matching algorithms to pinpoint the affordances for objects.

Despite these efforts, affordance learning faces many challenges not overcome in the previous work including: accounting for contextual information, representing affordances in dynamic environments, inferring causal and counterfactual relationships from highly-limited data, and representing uncertainty in knowledge and beliefs. Past approaches have not developed a generalized approach to representing affordances and therefore fail to provide flexibility with which to reason about them in the open world, where they are influenced by changing context, social norms, historical precedence, and uncertainty. For example, these current approaches cannot reason that coffee mugs afford grasping and drinking, while also affording serving as a paperweight or cupholder, or depending on the context, as family heirloom not meant to be used at all.

Plan of Research

Research Objectives

To address these challenges, I am investigating the following research questions:

R1: How should affordances be modeled to account for not only an object's physical features, but also more complex functional, social, ethical, aesthetic and moral aspects?

R2: What formalisms are suitable for representing affordances, contextual information, uncertainty, and other relationships present in affordance-based reasoning systems?

R3: What is the role of affordance-based reasoning in other higher-level cognitive tasks?

R4: How should these affordances be learned from observation during the continuum of learning and problem-solving experiences? How should these experiences be represented computationally?

Research Hypothesis

As a preliminary hypothesis, I expect that:

H1: An improved affordance model would be rules-based, and would have a probabilistic framework to reason under uncertainty. It would incorporate a set of rules relating available affordances with perceivable features in the environment and contextual elements of a situation.

H2: A logical formalism that derives from classical first-order logic, and coupled with an uncertainty framework would be best suited to allow deductive and abductive inferences about affordances.

H3: An affordance-based reasoning engine can not only guide agents in their next actions, but I expect an affordance-based reasoning approach can be helpful in tackling commonsense and creative reasoning challenges.

H4: Short exploratory actions combined with commonsense reasoning and mental simulations will enable agents to learn new affordance rules. The continuum of experiences should be segmented in a way that retains the overall narrative role of each segment, much like how each panel in a comic strip plays a role in the overall story.

My approach is to combine knowledge representation techniques, mathematical analysis, algorithm design, computer simulations, robotic implementation and human-subject experiments to develop and test these hypotheses. To do so, I plan to develop and formalize a computational model for affordance-based reasoning and investigate its performance on various benchmarked open problems in robotics and AI (e.g., object grasp and handover), in knowledge representation (e.g., commonsense spatial reasoning problems like the "handle problem"), in computer vision and perception (e.g., scene representation and sense-making), and in computational creativity (e.g., tool discovery and creative reasoning).

Preliminary Work

Computational Model (R1 and R2)

As a first step, I developed and presented a model for cognitive affordances, along with a preliminary example of its use, at IROS 2015 to affordance researchers from various disciplines including AI, robotics, neuroscience, child psychology and animal intelligence (Sarathy and Scheutz 2015).

I propose a novel model and formal rules-based logical representational format for cognitive affordances, illustrated in Fig. 2, in which an object's affordance (A) and its perceived features (F) depend on the context (C). I use Dempster-Shafer (DS) theory for inferring affordance (A) from object features (F) in contexts (C). DS theory is an uncertainty processing framework often interpreted as a generalization of the Bayesian framework (Shafer 1976).

My cognitive affordance model consists of four parts: (1) a set of perceivable object features (F), (2) a set of contextual elements (C), (3) a set of object affordances (A), and (4) a set of affordance rules (R) from object features and contextual elements to affordances taking the overall form:

$$r :\equiv f \wedge c \implies_{[\alpha,\beta]} a$$

with $f \in F$, $c \in C$, $a \in A$, $r \in R$, $[\alpha, \beta] \subset [0, 1]$. Here, the confidence interval $[\alpha, \beta]$ is intended to capture the uncertainty associated with the affordance rule r such that if $\alpha = \beta = 1$ the rule is logically true, while $\alpha = 0$ and $\beta = 1$ assign maximum uncertainty to the rule. Rules can then be applied for a given feature percept f in given context c to obtain the implied affordance a under uncertainty about

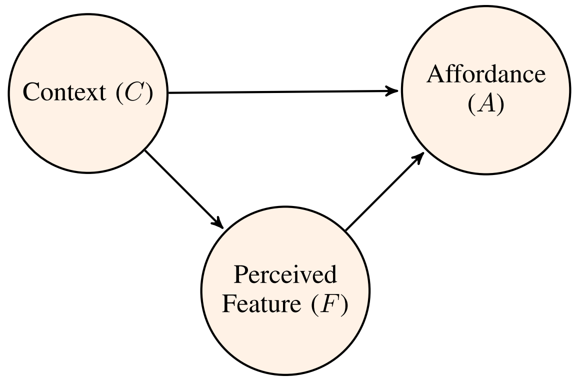

Figure 2: Context-Sensitive Cognitive Affordance Model

f, c, and the extent to which they imply the presence of a. We have previously shown that these types of rules are very versatile and that we can employ DS-theoretic modus ponens to make uncertain deductive and abductive inferences (Williams et al. 2015). Most critically, these rules allow us to address representational challenges with mere Bayesian models such as inferring $P(A|F,C)$ by way of $P(F|A,C)$, $P(A|C)$, and $P(C)$ when we often have no practical way to obtain the necessary probability distributions for all the affordances for an object.

Agent Reasoning Example Consider the example of a robotic assistant helping a human with an assembly task in which the human has asked the robot to tighten a loose screw. We would like for the robot to understand this task from an intuitive standpoint such that even in the absence of a screwdriver, it can reason through alternatives and find another substitute.

The robot may know of a number of rules related to its role as a helper. One rule may be: that if agent X is given a task to tighten a flat head screw S, and X can find an object O that has a flat-head edge, then the object O has a $tightenWith$ affordance. This rule can then be represented in DS-theoretic uncertain logic a follows:

$$r^0_{[\alpha_{R_0},\beta_{R_0}]} :\equiv$$
$$hasFlatEdge(O) \wedge task(X, tighten(S, flat)) \implies$$
$$tightenWith(S, O)$$

The robot may be able to look around the room and determine (within a certain measure of uncertainty) whether or not each of the various objects that it sees has a flat edge.

$$hasFlatEdge(Screwdriver)[0.95, 0.95]$$
$$hasFlatEdge(Knife)[0.9, 0.9]$$
$$hasFlatEdge(Coin)[0.75, 0.95]$$
$$hasFlatEdge(Pencil)[0, 0.95]$$

By applying DS-theoretic logic inference on rules such as the one above, the robot can deduce that knives and coins can be used to tighten screws in the absence of screwdrivers, but pencils cannot. Although, the rule in this example is relatively simple and primarily functional, I do envision scenarios that involve more complicated rules, or bundles of rules that include social and moral norms for a more complex object representation.

AI and Robotics Applications (R3)

One such more complicated scenario is the benchmarked robotics problem of appropriately grasping objects. Past work has focused on techniques for effectively grasping objects without dropping them (Ten Pas and Platt 2014). I am advancing this work by designing and implementing a set of context-based affordance rules to constrain the search space of possible grasp locations. For example, while a screwdriver can be grasped in an infinite number of ways, only a few are useful for tightening screws, and an even fewer that conform to social norms.

A related problem that I am also investigating is one of handing over objects. Handing over involves grasping as well as passing objects to others when serving a helper role. I am investigating affordance-based reasoning approaches to help artificial agents decide when and how to properly use and handover objects. A more detailed treatment of this scenario is presented, along with its implementation, in a paper submitted to KR 2016, and is currently under review.

Commonsense Reasoning Applications (R3)

This computational model is general and showcases the potential of an affordance-based uncertain logic reasoning process. A rules-based and context-sensitive representational format for affordances might even be helpful in tackling many commonsense spatial reasoning problems once they are reframed as affordance inference problems. For example, consider the "Handle Problem" problem posed by Pat Hayes (Hayes 1997), which we can reframe as follows:

> Given two objects, reason whether a secondary object has a handle affordance when attached to a primary object.

By re-formulating it in this way, we can apply the rules-based cognitive affordance framework to analyze the various affordances available when the two objects are combined together in different ways. I am completing a more detailed description of a potential solution to the handle problem and plan to submit my approach for peer review in the near future.

Future Work

This affordance model has shown some potential, but much work still remains in addressing various research questions noted above. Below are some of the future work that I intend to explore during my PhD program.

Extended Formalism (R2)

In the above example, I used a very simple predicate-style descriptions for percepts, context and affordances. Our algorithm and inference mechanism are sufficiently general-purpose to work with any suitable formalism. Nevertheless, I will be looking to expand this representation to allow for a more dynamic description, where the agent can not only reason statically about affordance at a given moment, but can plan and combine affordances over a longer period of time. Moreover, a suitable formalism will need to be able to manage dynamic environments where new rules are added and removed, new objects appear and disappear and new contexts rise and fall. In these dynamic environments, the agent must be able to track and account for effects of its actions and realized affordances.

Creative Problem Solving (R3)

An affordance-based approach might shed light on insight or creative problem solving scenarios that require an ability to think about a problem from a different angle, or in our case, a different context. An affordance representation of the form presented in this paper may assist in modeling creative reasoning processes more effectively. To do so, I will be expanding the ontology for context and examining how an agent might move from one context to another. Similar to my approach with the commonsense reasoning problems, I am investigating the prospect of solving creative puzzles by first reframing them as affordance problems and using the DS-theoretic uncertain logic framework to deduce a solution.

Affordance Learning (R4)

I expect the affordance rules can be learned in a number of different ways from observation, demonstration and exploration, and using multiple different modalities including vision, natural language and haptic information. The agent could learn these types of rules from explicit natural language teaching and instruction. The agent could also learn various rules from observation through reinforcement learning (RL) methods. Alternatively, the agent could also acquire these rules through data mining and various association rule-mining techniques. I plan to explore various methods for learning affordance rules from observation, exploration, and demonstration. One approach is to infer commonsense rules from exploratory actions like poking and lifting. In order to represent these actions, I will apply and extend existing action formalisms such as Event Calculus and Situation Calculus.

Role of Affordances in Sense-making (R3)

Our perception of affordances in our environment enable us to not only know what we can do with objects around us, but they also serve to tell a story about our current situation. For example, chairs and tables in a restaurant allow people to sit and eat their food. However, a collection of chairs without any tables in the middle of the restaurant would strike us as a bit unusual. Our need to make sense of the situation drives us to dig deeper and learn more about the reasons why there are no tables. This same need is what allows us to discover problems when there is a mismatch between what we see and what we expect to see. Reasoning about cognitive affordances in a more general way, as outlined in this thesis summary, has the potential to assist in such sense-making, which can be useful for artificial agents navigating in the open world.

Conclusion

In this thesis summary, I have outlined a research plan for representing cognitive affordances and reasoning with them. I have described some progress to date and mapped a path for future work.

The ultimate goal of my research is to endow artificial agents with the ability to find creative ways to use and manipulate objects and their environment, especially when there is minimal and uncertain information. Such abilities will be highly desirable in open-world scenarios.

I have taken the first steps towards my goal and proposed a novel framework and algorithm based on Dempster-Shafer (DS) theory for inferring object affordances. I demonstrated how my framework can handle uncertainties and be extended to include the continuous and dynamic nature of real-world situations. I believe that this, much richer level of affordance representation is needed to allow artificial agents to be adaptable to novel open-world scenarios.

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