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Towards a Theory Grounded Theory of Language

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Abstract

In this paper, we build upon the idea of theory grounding and propose one specific form of theory grounding, a theory of language. Theory grounding is the idea that we can imbue our embodied artificially intelligent systems with theories by modeling the way humans, and specifically young children, develop skills with theories. Modeling theory development promises to increase the conceptual and behavioral flexibility of these systems. An example of theory development in children is the social understanding referred to as "theory of mind." Language is a natural task for theory grounding because it is vital in symbolic skills and apparently necessary in developing theories. Word learning, and specifically developing a concept of words, is proposed as the first step in a theory grounded theory of language.

1. Introduction

Symbol grounding, as defined by [19], has stimulated much thought and associated work has led to advances in artificial intelligence (AI). For example, behavior-based robotic systems ground their reactive controllers using sensors and enable coordination of various levels of activity patterns such as standing up, walking, and prowling ([4]). The vision though, of symbol grounding, has barely begun to be tapped. Symbolic skills imply a far greater cognitive capacity than just connecting a few layers of abstraction in a robot to a sensori-motor system. The richness of conceptual structure, linguistic flexibility, and adaptation, all considered to be aspects of symbol usage ([19]; [25]; [28]), should be a driving force behind our eventual goals related to grounding symbols.

In establishing a sensory connection of the world to symbols, [19] initiated our train of thought. To pursue a broader and more human sense of "symbol," one including the conceptual and linguistic flexibility we tend to expect and retaining the ideas already present in symbol grounding, we have introduced the idea of *theory grounding*. Theory grounding ([33]; [34]) suggests that enabling our embodied AI systems to acquire theories can provide greater generalization and adaptability. In terms of symbol grounding, we propose that symbols don't fully become symbols in a situated or robotic system until they are part of a theory—a system enabling inferences over various kinds of states, events, and actions, which can be used to make predictions (e.g., [32]).

Theories are used formally and informally by adult humans. As adults we reap many benefits by using theories. We can simulate, in our minds, the effects of actions, construct predictions, and let "our [mistaken] hypotheses … die in our stead" (p. 375, [9], citing Popper). Our theories help us in reasoning about many domains spanning the physical, social, and psychological worlds ([8]; [17]; [42]). The skills underpinning theory usage in adults have a basis in our development as young children. For example, in developing from age three to four, human children advance in their social understanding and their reasoning changes in a marked way. They change from reasoning based on object-specific desires to reasoning about propositional beliefs and desires ([42]). At four years of age children start to understand that they and others can not only represent but also *misrepresent* the world ([30]). These and related skills have been called "theory of mind" ([32]; [42]). Theory changes are key to the development of theory skills. Theory skills come into play in children through a series of interwoven cognitive and linguistic developments. We propose that precisely these changes can guide us in theory grounding. By modeling the development of theoretical skills in a young child, we hope to enable a progression, from an initial endowment (e.g., preprogramming), to a system that can flexibly deploy theory acquisition and understanding, based on a series of theory developments or changes. While the initial system will only have neonatal infant-like skills, a developmental "program," and an appropriate environment (e.g., see [34]), the resulting system, after extended developmental phases in which theory skills themselves are acquired, should be able to learn new theories and adapt its existing theories.

In this paper we explore the potential for theory grounding in one particular domain, the domain of language. We focus on language as opposed to other theory domains (e.g., social understanding) for several reasons. First, language appears fundamental to the development of social understanding (theory of mind). [1] has found that earlier developing language abilities are related to later social understanding performance, but not vice versa. Second, language itself may be theoretical in its very nature. The *theory-theory* indicates that "children's … conceptual development is theory formation and change, and that their semantic development is theory-dependent" (p. 11, [17]). The theory-theory suggests we may acquire a theory of language in much the same way that we acquire a theory of mind. Third, an active, exploring theory-view of language acquisition is compatible with some existing theories of language acquisition ([14]; [23]; [24]). [24] views language as just another problem space for children to explore. In word learning, children acquire a series of principles, heuristics that constrain the language search space ([23]). "From the multiple cues surrounding them in word learning contexts, children gradually cull more sophisticated heuristics for word learning. They implicitly test their current theories, shift the weights of the cues, and subsequently alter their word learning principles" (p. 26, [23]). Fourth, language has been considered vital to the properties of productivity and systematicity. These concepts characterize a good deal of the linguistic flexibility we expect from symbol systems ([12]). Productivity refers to a system being able to encode indefinitely many propositions, and systematicity refers to a system as being able to represent related propositions (e.g., a system representing $a\mathbf{R}b$ implies it can also represent $b\mathbf{R}a$). Fifth, we are exploring the generality of theory grounding. To a degree then, we are accepting the tenets of the theory-theory ([17]). We are positing that theory acquisition is an important driving force behind various domain developments in children. From a modeling and artificial intelligence view, we want to assess the usefulness of this general framework.

The remainder of this paper proceeds as follows. First, we elaborate on the idea of theory grounding, further considering aspects of theory of mind development, and touching on relevant robotics literature. Second, we move on to language, our target domain for constructing theory grounded systems, and outline major developments that occur in word learning in infancy. Next, we consider examples from language development that appear theory-like, and targets for our approach. We also outline the beginnings of our own research. Last, we end with discussions and conclusions.

2. Theory Grounding

Clearly, skills with theories are not innate in the young child. These skills involve a series of developmental phases, the interaction of environment and biological endowment, and successive growth (see also [11]). Initially, as a pre-linguistic young infant, a child starts to acquire social skills such as primary intersubjectivity, or the basics of one-on-one reciprocal interactions with a caregiver. Secondary intersubjectivity (or joint attention), where the child and adult involve an item or event (e.g., a toy) in their interactions, starts shortly thereafter ([41]). The representational skills or understandings of a young infant of this age (e.g., 9 months) appear largely perceptual (although the area has controversy; see: [18]). It is not until about 18 months, when words often start to be acquired at a much faster rate (the "naming explosion"; [15]; [29]), and other developments such as pretend play (e.g., [10]) occur, that the child starts to represent situations other than the immediate reality of a present situation. That is, "the child can [now] think of alternatives to reality" (p. 168, [30]). It seems that prior to this point in development, the young child literally has not yet developed the mental apparatus to enable this first step in theoretical understanding: an initial ability to reason explicitly about hypotheses.

The study of social understanding or theory of mind has shown us another vital step in the child's mental skills. In the typical psychological developments from age three to age four, the young child starts to understand that what people (including themselves) know is not necessarily correct. Sometimes people represent reality with their mental states, and other times people *misrepresent* reality ([30]). This phenomenon was initially explored in the context of young children's understanding of false-belief ([43]). These experiments studied children of ages three to seven. They were told stories such as "Maxi and the Chocolate" where Maxi first places some chocolate in the GREEN cupboard, and then unknown to Maxi, his mother places the chocolate in the BLUE cupboard. The experimenters then ask the child a test question "Where will Maxi look for the chocolate?" Children younger than four nearly always indicated Maxi would look in the BLUE cupboard. Children four and older answer correctly (GREEN cupboard), starting to understand that Maxi has a false belief, incorrectly representing the present reality. At age four, the child can now distinguish between what a belief is intended to represent (e.g., the location of the chocolate) versus what it actually represents (e.g., the empty GREEN cupboard). Prior to this, while a child can think of alternatives to a present reality, they seem unable to hold in mind conflicting representations of the present reality ([30]).

These changes in the skills and knowledge of a child, from initial social skills (e.g., primary intersubjectivity), to thinking about alternatives to reality at two years of age, and to understanding that people can represent and misrepresent reality at four years of age have been termed representational change (e.g., [31]). These developments indicate a path towards a full-fledged concept of symbol grounding, i.e., theory grounding. We continue to use the term symbol grounding here because part of the skills that the child is developing are surely symbolic skills. And it is this developmental progression of skills that gives us insight into how to ground symbols in a robotic system. Symbol usage is a combination of social and object-related skill that makes perhaps its first appearance in word learning, and initial skills with representing alternative situations. More robust skills in understanding that beliefs can conflict with reality make their appearance at age four.

Some progress has been made in robotic systems towards these goals. *Kismet* ([3]) is a "head" robot and models infant caregiver interaction (e.g., primary intersubjectivity). The robot regulates intensity in human-robot social interaction by providing facial cues to the human indicating its level of "arousal" (e.g., surprise vs. tiredness). Part of the goals of the *Cog* robot ([5]) include modeling the development of theory of mind skills of a child ([36]). Cog is an upper-torso humanoid robot on which various behaviors have been implemented. These behaviors include the beginnings of an implementation of joint attention comprising finding faces, determining the location of eyes within a face, and saccading to center the face in the peripheral image ([37]). Learning methods were used to train saccade and foveal mappings. *Infanoid* is also an upper-torso humanoid robot and the project has goals including modeling the acquisition of intentionality or using cause-effect associations as method-goal associations ([27]). Infanoid also has the beginnings of an implementation of joint attention. In this case, the robot first visually searches for a human face, saccades to the face, estimates the direction of gaze, and then searches for a salient object in the direction of gaze.

3. Word Learning in Language Development

Theory grounding emphasizes ongoing development of theory skills through sensori-motor interaction with the world. In the language domain, sensory-motor interaction is an important facet of language development. A child uses her sensori-motor system to hear and produce language and to interact with the social and physical world. In this section, we sketch the development of word learning in infants. We emphasize a particular theory of language development, the *emergentist coalition theory* ([23]).

The first words learned by children (e.g., first words are produced at about 12 months; [13]) are rather different than later words. Children learn these first words slowly and deliberately, the words may be context-bound, and they learn words based on attentional and linguistic information, and to a lesser extent, social information. These "words" appear less linguistic and more rote in their basis in that it takes numerous experiences with the word and its referent for the child to learn ([20]; [21]). [22] used a connectionist model to model this early word learning in part because it seems appropriate to characterize these learning mechanisms as *associative*. [2] suggests that "at the start [of word learning], the word is not separate from the episode in which it was first encountered, and it enters the memory [of the child] as a virtual fusion of form and content—a 'word-image representation'" (p. 25). The reason why these words are more rote and not separate from the initial learning episode (context-bound), appears to be that the infant has not yet integrated all of the informational cues comprising "words" into the word learning situation. In short, the child has not yet learned that words are *words*, and is using more general learning mechanisms to acquire word-object (for example) associations.

This is perhaps not surprising. Word learning, as a part of language learning, is a complex endeavor and certainly it takes the child some time to master the process. Emergentist coalition theory posits that children use a range of attentional, linguistic, and social cues or information types in learning words. Attentional cues involve information comprising the "earliest influences on word learning … such as perceptual salience, temporal contiguity, and novelty" (p. 18, [23]). Linguistic cues "are cues from the language input itself, which help infants to find the words in the speech stream and identify their part of speech" (p. 20, [23]). For example, the difference between the mother's speech sounds and the sounds made by animals, the child's crib toy, and the beep of a microwave oven. In learning their first words, children make primary use of attentional and linguistic cues. For example, objects that are brightly colored and moving may be perceptually salient to a child, and draw her attention. A caregiver uttering the word "ball" when she is playing with an object that has captured her attention may start the young infant on the path to learning that word.

While social cues such as eye gaze and pointing start to be recognized earlier outside of the language context, it takes the child time to incorporate this social information into word learning. For example, while a nine-month-old can perceptually recognize aspects of the eye-gaze of an adult ([6]), they don't start to cognitively utilize adult eye-gaze as a social cue in word learning until about 12 months of age ([23]). This difference between availability and utilization of a stimulus cue (e.g., eye gaze) typifies the progressive utilization of cue information proposed by the emergentist coalition theory. Attentional, linguistic, and social cues are posited as available to the child from the start of word learning but children progressively utilize the cues in their language acquisition, over the course of development. It is interesting to note that even after a child has come to utilize social cues such as eye gaze and pointing, much of their word learning is still based on their own attentional interests as opposed to another's focus (e.g., a caregiver: [2]; [40]; [39]). That is, infants often learn what *they* care about ([2]).

Emergentist coalition theory suggests that the child uses "guided distributional learning" to incorporate additional stimulus cues into their word learning. For example "children may come to realize, pragmatically, that eye gaze is a good indicator of the consistent mapping [of words to objects], and they may come to follow it, or make use of it in directing attention" (p. 25, [23]). Children are viewed as evaluating and weighing the kinds of cues that can be used to best inform the "word" learning process. The problem being solved by the infant is that of actively integrating and making sense of the flow of attentional, social, and linguistic information. The social cue of eye gaze comes to be selected as an integral piece of information, assisting in making the word-learning situation coherent. Eye-gaze comes to indicate the "referent" of a word, precisely because of its co-occurrence with speech utterances.

Starting at 19 to 21 months, when a child has 30 to 100 words in their productive vocabulary, a marked transition occurs in the child's word learning—the vocabulary spurt or naming explosion ([13]). It is at this time that children typically start learning words far more rapidly than before—in a "fast mapping" manner, where they may need only one learning experience with a word to learn its basics ([7]). Children at this age can now think of alternatives to reality ([30]), a vital mental basis on which to start to formulate explicit hypotheses. It seems that what the child is doing with their first "fragile, tentative, and imprecise" words is to "grope to find the associations that connect the different circumstances in which words are experienced" (p. 25, [2]) and piece together the word-puzzle itself at a higher level. That is, this vocabulary spurt appears to indicate a conceptual insight that objects have names ([16]). Presumably this insight, or theoretical leap, is based on the coherent integration of the complete set of attentional, linguistic, and social cues in word learning.

4. A Theory Grounded Theory of Language

We are viewing the child as learning various theories about the world, including a theory of language. As a normal linguistic environment has other children and adults speaking, the language learning child will be faced with forming a theory of language that includes the various elements of the language being spoken, including concepts relating to words.

The challenge facing a theory grounded theory of language is to construct a robotic model that gradually acquires language skills based on interaction with a language environment. For example, we might start with a robotic system that has already achieved skills of basic social interaction approximating primary and secondary intersubjectivity (e.g., [3]; [5]; [27]). Based on these social skills and structures, we would need to acquire initial words based on general (associative) learning mechanisms—in accord with the emergentist coalition theory. Of course, these early "words" should not be preprogrammed linguistic entities for the robotic model. At 10 to 12 months of age, a young infant has presumably not yet learned what "words" are, and is using general learning mechanisms to acquire the data upon which the world can be further organized. It is just that a basic aspect of the language environment is comprised of units of speech (words) that designate (refer to) objects, events, emotions, actions etc. in the environment. As the young child uses general learning mechanisms to learn various features of the environment, including context-bound word-image representations, he will gradually start to make use of more and more information comprising the word learning situation, such as the social cues of eye gaze and pointing. In fact, it likely takes some time for the child to learn that speech sounds themselves are special in the word-learning context, and that linguistically it is not just any sound that is associated with a referent object, event or action (e.g., Experiments 10-12, [23]). A task facing the theory building skills of the child is exactly the problem of separating the language input (e.g., the words) from the rest of what is being learned. The naming explosion is an excellent example of the child solving this problem. When the child starts to fast map words ([7]), it seems clear that they have formed a cornerstone of their theory of language. They have figured out that, in fact, objects have names in the environment, and that an important linguistic element is that of a "word".

[35] and [38] have constructed robotic models that start to learn words. These models face the problem of using general learning methods to associate speech sounds and objects, using robotic sensori-motor systems. [35] used speech segmentation to generate phoneme-based representations for the words uttered by a human when an object was viewed by the camera sensor of the robot. Individual objects are viewed by a camera, and 15 2D views of the object are obtained. Each view is reduced to a shape histogram comprised of distance and angle points for pairs of boundary pixels, and a color histogram. The goal of this model is to discover the words (phoneme sequences) that predict the presence of objects (shape and color representations). Word-object associations were constructed by an information theoretic measure. The visual and acoustic representations used by [38] were similar to those used by [35], and these authors pretrained the speech system with a large vocabulary of common dialog words and used an associative memory, based on reinforcement learning, to store relations between object views and words.

Missing from both of these above models is a method of acquiring the concept of a word itself. That is, while these models learn words using general learning mechanisms, they assume some kind of word learning rather than developing or learning the fact that words are a separate kind of category of elements to be learned about in the environment. It is our research goal to build robotic models that develop word-learning capacities in a theory grounded manner. It is our goal to have a theory grounded robotic model eventually come to form its own concept of words and names.

Our first step towards a theory grounded concept of words is to construct a model that has both acoustic and visual inputs and learns various kinds of associations between sights and sounds. We assume that for the young infant, just starting to learn words, and without having integrated the social cues of eye gaze and pointing, and perhaps even speech per se, into a "word-learning" situation, they will learn various associations between sights and sounds in a similar manner. For example, a child may learn that the sound "apple" is associated with a roughly circular red object because her father utters the word "apple" when she is playing with the fruit. Using similar learning mechanisms, the child may also learn that the sound of an opening door predicts someone coming through the door. Correlated with the sight-sound associations that will eventually be learned to be words are also other kinds of inputs—the sounds themselves are uniquely speech sounds, and there will likely be various social cues: the presence of the face of the caregiver, eye gaze, and perhaps facial, hand, and other body gestures. We are constructing a model designed to learn various sound-object associations from acoustic-visual input. Initially avoiding real-time issues, we are first running offline simulations using prerecorded video. Later, we will move to a robotic platform. The model will have a developmental algorithm to autonomously categorize the kinds of associations learned, and feed that category learning back into the learning of the associations. We are proposing that part of what happens in the child's learning of the category of "words" is that they are categorizing naming itself as different from other learning situations. After all, the naming situation is strongly correlated with cues of speech, and various social cues, while other kinds of learning situations are less strongly correlated with speech and social cues.

5. Discussion and Conclusions

The challenge is as posed by [26]: "to construct adaptive systems that can perform" (p. 356). In the present context, we are working towards creating systems that are not initially programmed with concepts, but that instead develop theories of these concepts based on data acquired by a sensori-motor system. Our goal is to develop a theory grounded theory of language, and we are starting work on developmental algorithms related to word learning. While some prior research ([35]; [38]) has modeled word learning using general learning mechanisms and sensori-motor systems, these systems do not yet learn a concept of words. For example, they do not learn distinctions between word learning and other kinds of learning being carried out, and explore the consequences of the differences between "words" and other kinds of actions and learning. For example, words are different because they have communicative function between social individuals.

We believe a theory grounded approach to cognitive robotics has value for reasons analogous to why "theory of mind" has value in developmental psychology. In psychology, it's a difficult problem to evaluate just exactly what a "mind" is. It appears easier to place objective criteria on having a theory of mind (e.g., false-belief). In cognitive robotics, while grounding symbols is an important and necessary step, many different systems can have grounded symbols. A next step, and one we believe has objective criteria for success, is for us to enable our robotic systems to develop theories of symbols.

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7. References

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