Modeling Cognitive Modules with the Web Ontology Language: A Functional Architecture of the Mind

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Abstract

An important concept in Evolutionary Psychology is the cognitive module. Cognitive modules are hypothesized to be innate in the human genome and form the foundation for basic cognitive functions. Examples include language, causality, contact mechanics, and morality. This is an extension of the work in Biolinguistics pioneered by Chomsky where an innate language faculty is hypothesized to exist and is an alternative approach to the "blank slate" model of psychology that hypothesizes all learning is based on a single general learning process such as Stimulus Response or Hebbian conditioning. Although there has been extensive research on these modules, no one has created a formal model of them. This paper describes an ontology that creates a model based on structures and processes that are commonly ascribed to cognitive modules in evolutionary psychology. This illustrates how OWL can be a powerful tool for cognitive science. One of the biggest obstacles to scientific theories in the "soft" sciences is the difficulty of defining rigorous, testable models. OWL provides a tool that is abstract enough that it can model such concepts while at the same time being rigorous enough that it clarifies issues that go unobserved without a formal model. In this paper I present an ontology that models cognitive modules and describe the research I utilized to define the modules. I present a simple example that models an example of Hunter Gatherer behavior and beliefs. I discuss whether formal methods can be used to study a topic as full of contradictions as the human mind. Specifically, I address anticipated criticism from cognitive scientists such as Lakoff that it is a fantasy to think the universe, much less the mind, can be modeled by formal methods. I conclude with a brief discussion of the implications of the current model.

Keywords

Evolutionary Psychology, Cognitive, Module, Biolinguistics, Cognitive Psychology, OWL, SWRL

1. Introduction

Evolutionary psychology was created by researchers such as Cosmides and Tooby [1] who were influenced by the biolinguistic approach to linguistics (also called computational linguistics[2]) pioneered by Noam Chomsky. [2] At the time he pioneered his ideas in the 1950's, Chomsky's approach was a radical departure from the "blank slate" [3] approach that dominated psychology at the time. Chomsky presented compelling arguments that language acquisition in humans could not be the result of some general purpose blank slate learning model.

More recently, researchers such as Cosmides and Tooby, [1] Premack [4], Kurzban [5], Hirschfeld and Gelman [6], Atran and Medin [7], and Hauser [8] have hypothesized that there are other modules in addition to the Language Faculty that are innate and that serve as a scaffold for human learning. These are typically called cognitive modules. The evidence for them includes:

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[2] I will use the term *computational linguistics* to refer to ideas and terminology from the 1950's to the 1990's and the current term: *biolinguistics* to refer to the latest theories.

- Experimental evidence from pre-verbal infants that demonstrate an understanding of these modules. These experiments typically videotape eye movements of the infants and determine what sort of phenomena are expected vs. what sort generate a surprise reaction. [4] [6] Such research provides evidence that humans have concepts from the modules even before they can acquire them via learning through language. I.e., it supports the hypothesis that they are innate in the genome.
- Experimental evidence from verbal infants. Concepts in some modules (e.g., essential properties, number) are difficult to study in pre-verbal infants and hence experiments are done with young children who have just learned to speak but have had minimal language experience or learning. Such research is not as persuasive as that from pre-verbal infants, but it still supports some of the modules discussed. [9]
- Experimental evidence from what Christopher Boehm calls Late Pleistocene Authentic (LPA) hunter gatherer tribes indicates they all have such modules. LPA tribes are tribes such as the !Kung that were completely insulated from modern culture, including farming techniques, when first discovered and studied. Such tribes are the closest scientists can find to our Hunter Gatherer ancestors as they existed prior to culture in the Late Pleistocene era. [10]
- Experimental evidence that indicates these concepts are present and (at least the core, what is considered the module) function the same across all people regardless of culture, time, and geography. [1]
- Experimental evidence that some of the modules are present in other primates, especially our nearest living relatives: chimpanzees and bonobos. [4] [10] [11]

Although there has been extensive research on cognitive modules, to my knowledge no one has attempted a formal model of any module with the exception of my Universal Moral Grammar (UMG) ontology. [12] In the UMG ontology, my goal was to demonstrate that the ontology could model human moral decision making and could model the most well-known models such as Utilitarianism, Jonathan Haidt's model, Kant's Categorical Imperative, etc.

My previous work on the UMG ontology did not attempt to distinguish what concepts were innate in the genome vs. those that are learned. To use an analogy with biolinguistics I did not in that paper attempt to distinguish what is I-Language[3] [13] from what are natural languages such as English, Hindi, and Cantonese.

In this paper I present an ontology that attempts to model the hypothesized modules.[4] This is an approach to cognitive psychology called functionalism. It focuses not on the brain hardware but on a higher-level analysis in terms of functions, their inputs and outputs, the way they are organized, and most importantly experimental evidence from cognitive science that focus on behavior rather than neurons. Functionalism is currently out of favor due to advances in technology to record and analyze physical brain states. However, to analyze something as complex as the mind only at the level of neurons is contrary to one of the most fundamental principles in engineering and science: that complex processes and structures inevitably are hierarchical and must be studied at all levels of the hierarchy. [14] Models of the natural sciences are inherently hierarchical from the subatomic, to chemicals, to stars and galaxies.

This does not mean that we ignore the physical level. E.g., one of the advances in biolinguistics is research in cognitive neuroscience that demonstrates support for biolinguistic theories. For example, when people are given invented languages to learn, different brain areas are active depending on if the invented language conforms to the structures hypothesized by X Bar theory. If the languages do conform to biolinguistics, areas associated with language are active. If they do not conform to those structures (e.g., word order rather than recursive structure is used to parse them) then other centers of the brain are active. [15] In the same way, one potential for this research is to identify functional modules in the mind and connections from one module to another and to search for physical realizations of such structures and pathways in the brain.

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[3] Computational Linguistics used the term Universal Grammar (UG). Biolinguistics calls this concept I-Language.

[4] The ontology is freely available via an open source license at: https://github.com/mdebellis/Cognitive_Module_Ontology

2. Framework: The Strong Minimalist Program in Biolinguistics

My starting point for the model is the Strong Minimalist program in linguistics defined by Chomsky. [16] Since the beginning of computational linguistics, one of the most difficult obstacles was the complexity of grammars such as the early work of Chomsky in Aspects of a Theory of Syntax. [17] This complexity seems incompatible with the hypothesis that there is an innate[5] Language Faculty. It is counter intuitive that evolution could produce large numbers of transformations in the genome. A significant advance in the field was the development of X Bar theory. [18] In X Bar theory, Chomsky and others were able to demonstrate that large, highly complex grammars could be defined in terms of a few basic concepts such as Head, Specifier, Adjunct, and Complement. In addition, the large number of transformation rules required to parse natural languages could be grouped according to a few fundamental principles such as the headedness principle, the binarity principle, and projection. This simplification was possible because these concepts and transformations had parameters similar to functions in mathematics. That is the X in X-bar theory.

Support for this theory has been demonstrated by research in Principles and Parameters that illustrates impressive regularities in all known languages. For example, two parameters are:

1. Head Initial or Head Final. The position of a head parameter in a language phrase relative to its complement.
2. Pro-drop. Whether or not the language allows pronouns to be dropped when they aren't required to resolve ambiguity in a sentence.

Head-initial languages tend to prohibit pro-drop, while head-final languages tend to allow it. For example, Japanese and Spanish are head-final languages and allow pro-drop while English is a head-initial language and typically disallows pro-drop. This is but one of thousands of regularities that have been found across languages that often share no known common roots. These principle and parameter regularities have prompted Massimo Piattelli-Palmarini to describe the findings as a "periodic table for language". I.e., just as the periodic table of the elements describes the possible combinatorial space of atoms that can form elemental molecules, so principles and parameters have the potential to define the possible space of all human languages in terms that are independent of the specific dictionary and grammar of the language. [19]

Most recently, Chomsky has hypothesized an even simpler reduction than X Bar theory. This is the Strong Minimalist hypothesis. In this framework all rules of language essentially can be defined in terms of recursion and set formation.

The use of the term "recursion" in the biolinguistic literature can be a bit confusing to computer scientists, because the emphasis is simply on set formation which is typically considered independent from recursion in computer science and mathematics where a recursive definition is simply one that has at least one base condition and at least one recursive step. A common example is the definition of factorial as:

1. Base Condition: Factorial (0) = 1
2. Recursive Step: Factorial (n) = Factorial (n-1) * n

However, this is simply a matter of terminology, not of an actual theoretical difference in the disciplines. Indeed, Chomsky's work is grounded in previous work by Turing, Church, and Gödel on the theory of computation. In the strong minimalist framework, Chomsky often talks about recursion as simply being Merge (set formation) but a careful reading of his work shows that he indeed is talking not just about sets but sets capable of discrete infinity via recursive rules of grammar. [16] This also goes back to Chomsky's earliest work in Syntactic Structures [2] where he discussed different

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[5] Chomsky objects to the term "innate" because for many people it implies that the function is completely defined in the genome which would be absurd given the heterogenous landscape of human language. I use it here only because in my experience that is how most people understand concepts such as universal grammar. However, it should be emphasized that innate does not mean genetically determined. Whether it is body structure or cognitive architecture, the genome gives predispositions that will always be triggered and shaped by environmental stimuli.

computing models from finite state machines to Turing machines that are capable of generating ever more complex sets. The sets that Turing machines can generate are recursively enumerable sets. [20]

It is this strong minimalist framework that will be the foundation for the model of cognitive modules. One of the attempted contributions of this work is to unite what to this point have been two disparate research programs: evolutionary psychology research on cognitive modules and biolinguistic research on language.

One of the criticisms that is often levied against the biolinguistic approach is that it ignores issues such as metaphor that are essential to a complete understanding of language. [21] To address these issues Hauser, Chomsky, and Fitch wrote a paper where they defined an architecture based on the strong minimalist hypothesis that distinguished between what they defined as Language Faculty Narrow (LFN) and Language Faculty Broad (LFB). LFN is recursion and other basic principles from the strong minimalist version of X-Bar theory. LFB is what they called the Conceptual Intentional system. This was meant to be a term for all the concepts required to completely understand language that were beyond the scope of the strong minimalist program. The hypothesis pursued here is that what Chomsky calls the Conceptual Intentional system is essentially what evolutionary psychology researchers call Cognitive Modules. Figure 1 illustrates the framework that will be our foundation. This is an adaptation of the architecture described in figure 2 in [13].[6]

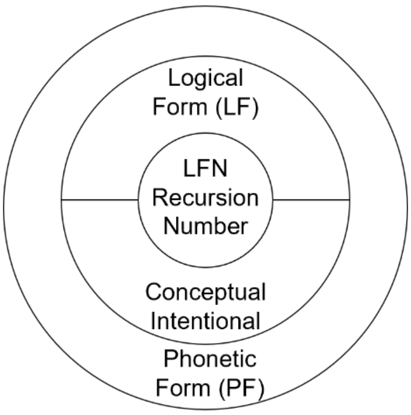

Figure 1: Cognitive Modules and the Minimalist Architecture

3. The Modules

In this section I describe each of the modules, the basic concepts in each module, and the research that is the foundation for them. Some of the top-level classes for the ontology are illustrated in a screen print from Protégé in figure 2.

Each module is organized around a top-level class that has the suffix "Domain". In addition, the ontology contains an annotation property called inModule[7] that tracks which module a given class or property belongs to. For ease of reading, I will use the rdfs:label values for each class and capitalize any terms that are names of a class. Following the model defined by Hauser, Chomsky, and Fitch [13] the modules are broadly divided into four systems (see figure 1):

1. Language Faculty Narrow (LFN). This is the core system that all other systems use. In their paper, they limit this to recursion. I also add two other modules: Number and Symbolic Reference.

2. Logical Form. In [13] they did not go into detail about the other modules of the language faculty, but this is a standard part of the current theory. This is the system that used to be called "deep structure" in computational linguistics and is sometimes called a *Language of Thought* (LoT) by people such as Fodor. [22] Chomsky is often critical of the LoT hypothesis. However, he has said that if an LoT exists it is the Logical Form. [23]

3. Conceptual Intentional system. This is the system that holds the modules that have been extensively studied by evolutionary psychology and that will be the focus of this paper.

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[6] Figure 1 is based on but also different than figure 2 in [13]. That paper did not go into details of the various sub-systems in the minimalist program, and I also change the nature of LFN slightly (although in a way consistent with hypotheses from Chomsky in that paper and other works) based on research conducted by Gallistel and Gelman discussed below.

[7] An annotation property was utilized merely as a convenience to avoid having to pun every class and property in the ontology. Since these are the subjects that are in a module, to use an object property we would need to pun every class and property in the ontology.

4. Phonetic Form. This is the interface from/to the mind to/from the external world. This is the last system used that generates speech from thought and the first system used to recognize speech of others.

The strong minimalist framework in figure 1 implies that classes outside LFN inherit from classes inside LFN but not vice versa. This is the case. Figure 3[8] shows how many of the classes in other modules are defined in terms of the LFN classes such as set and sequence.

Chomsky has speculated that basic numeric reasoning may be part of the language faculty. [13] Research by Randy Gallistel [9] and others has indicated that this hypothesis seems probable and hence that is where I place that module. Note that as with all modules we are not including all or even most concepts required for a modern adult to use these cognitive functions. Rather, we are attempting to focus on the specific functions that seem, based on experimental evidence, to be good candidates for innate concepts in the human genome. Hence, the Number Domain does not include rational numbers, multiplication, or other concepts that are understood by most literate children. There is no evidence from pre-verbal infants that they understand such concepts and there is strong evidence from LPA hunger gatherer tribes that they do not have these concepts. Most LPA tribes only have words for "one", "two", and "many" in their language. Rather, the basic concepts in this module are to specialize the set concept in LFN to be an ordered set, i.e., a sequence that supports a successor and predecessor function. There is strong evidence for these concepts in the relevant populations.

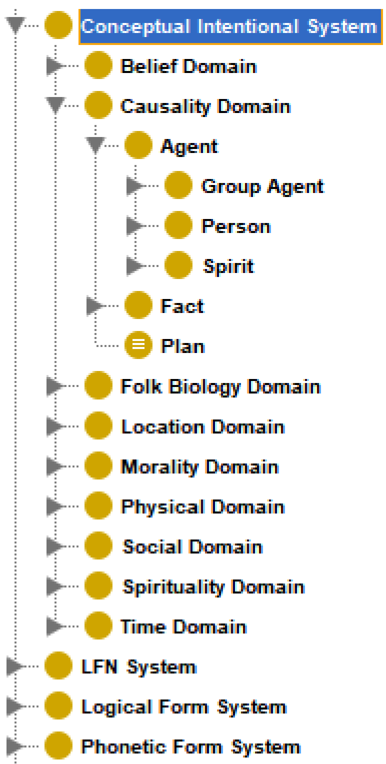

Figure 2. Classes Defining the Modules

The concept of a successor function is the essence of Peano arithmetic which is the formal foundation from which all of modern mathematics is derived. [9] [24] This is not the only such commonality between well understood foundational concepts in science and technology and the cognitive modules that we will observe. This commonality is quite consistent with the hypothesis of innate concepts in the genome. The presence of a concept in the modules does not indicate that it is true of course. It is quite possible that concepts that were useful for hunter gatherers in the Late Pleistocene era do not conform to scientific reality. In fact, an important result of this research is to identify concepts that are a result of our evolutionary past that are not supported by modern scientific theory and that may stand in the way of scientific and social progress. Examples include contact mechanics, biological essence, causality, and tribalism. At the same time, since the hypothesis is that these concepts are a result of evolution, they should offer some evolutionary advantage to understand and function in the world, and it is likely that some concepts may be important foundations for mathematical, scientific, and engineering theories.

One caveat is that we are using OWL as a logical language here not as a language to model software. I.e., the normal *kindOf* semantics that hold between subclasses are not meant to always hold in this case. Similarly, upper models meant to promote software reusability are irrelevant to our requirements. We are only discussing sets and relations in the formal sense and a subclass relation means nothing other than that one set is a subset of another. We will discuss potential criticisms regarding the use of OWL to model cognitive modules in section 5.

One area where this model deviates from Chomsky's approach is that I include Symbolic Reference as a class in LFN. Chomsky is quite critical of the concept of symbolic representation. However, I believe what he specifically (and correctly) critiques is the wide-spread view that the meaning of nouns is defined by a context independent mapping from a noun to some set of objects in the world. Chomsky points out that this is far too simplistic because natural languages are highly context dependent. E.g., the idea that *London* is defined by a reference to some geographical area or *water* is defined by the

[8] Figure 3 and all subsequent figures were created with the Gruff visualization tool in the AllegroGraph knowledge graph tool from Franz Inc.

formula H_2O is seldom true in realistic discourse. London may refer to the people who live in a geographic area or the government of the UK. Similarly, the water that comes out of our taps, flows through our rivers, and into lakes and oceans never contains only the chemical H_2O. Chomsky has always been clear that he is not against *any* concept of reference in relation to language, only that such a concept needs a rigorous, scientific definition which the common "semantics as context independent mapping between nouns and objects" does not have. That is what I am attempting to do. Symbolic reference refers to the fact that the Logical Form system can represent agents, states, and events in the past, present, and future (both actual and potential), utilizing concepts from the Conceptual Intentional system described below. More importantly I use the phrase symbolic reference specifically to differentiate it from the type of reference that Chomsky criticizes. I use the term symbolic here in the sense first defined by C.S. Peirce's theory of semiotics. Peirce distinguishes between indexes and symbols for communication. Indexical reference is the type of reference that Chomsky criticizes. With an index there is a one-to-one mapping from the symbol to the thing that it represents. Examples of indices are clocks and weathervanes, and I would argue the conventional (incorrect) way many believe nouns are defined by context free mappings to real world objects. Symbolic reference is context dependent. Symbols such as characters and words in a human language (and nucleotides in DNA) are capable of infinite combinations where the meaning can change dramatically with the same words used in a different order or different context.

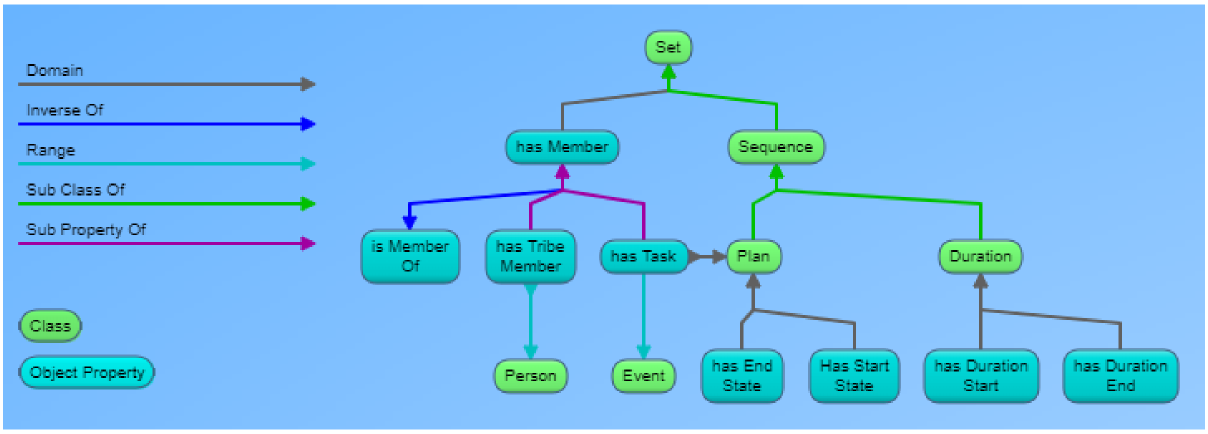

Figure 3. The Set and Sequence Classes are Essential for the Model

I believe that although some researchers such as Deacon [25] severely criticize Chomsky for what they believe to be his complete rejection of the importance of symbolic reference that my position is quite consistent with what Chomsky has said. For example, in [26] he said: "I have always explicitly denied… [a] position which has often been ascribed to me: namely that the study of meaning and reference… should be excluded from the field of linguistics. What I said [in LSLT and Syntactic Structures] was exactly the opposite."

Note that explicit representation of most classes in LFN is not really required for the model because most of these concepts exist in the underlying OWL language. They are modeled here to make explicit where they exist in the theory.

Classes in the Logical Form system are Concept, Predicate, Statement and Fact. The properties hasSubject, hasPredicate, and hasObject are utilized by the Fact class to model States and Events in the past, present, or future as reified triples.

3.1. Causal Domain, Belief Domain, and Physical Domain

The Causal Domain consists of the disjoint classes: Agent, State, and Event. It consists of the properties hasCause with domain Fact and range Causal Domain and hasPreCondition/PostCondition with domain Event and range State. A graph of some of the most important classes and properties in this module is shown in figure 4.

One of the most important classes in the ontology is the Plan class. Plan is a subclass of the Sequence class in LFN and the Task class in the Causal Domain. A Task is some Event that hasCause some Agent.

A Plan is a sequence of one or more Tasks (and is also itself a Task) that take the environment from a start State to an end State. The State that is the post condition of a Task is now called a Goal. This is another example of a concept that I hypothesize to be innate in the genome that has already been discovered by other researchers. This model of planning dates back to the earliest days of AI and general problem solving systems such as the SOAR system developed by Allen Newell, John Laird, and Paul Rosenblum, [27] and the Planner programming language developed by Carl Hewitt at MIT. [28] My Knowledge-Based Software Assistant (KBSA) team at Accenture's CSTaR laboratory also used this formalism to model software engineering methodologies and the work done by developers to give them feedback and guidance. [29]

The Belief Domain is also known as the Theory of Mind (ToM) Domain. [6] It is common in infants and hunter gatherers to ascribe beliefs to other Agents and to explain their behavior based on those beliefs. Also, to infer beliefs based on behavior. It consists of one class: Belief. A Belief is one or more Facts that an agent holds to be true with some level of certainty between 0 and 1. This may at first seem to be inconsistent with the fact that rational numbers are not included in the Number Domain, however it isn't. The hypothesis is not that humans are consciously aware of ranking beliefs by some percentage of probability. Rather that there are cognitive modules in their minds that function in a way that can be modeled this way. See the discussion of internal vs. conscious representations in section 5.

The Physical Domain consists of one class: Physical Thing and two disjoint properties: inContactWith and notInContactWith. There is also a SWRL rule to represent the concept of contact mechanics:

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hasCause(?o1, ?o2) ^ PhysicalObject(?o1) ^ PhysicalObject(?o2)
-> isInContactWith(?o1, ?o2)
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This is based on evidence from pre-verbal infants by several researchers. [6] [4] The concept of causality seems to be understood by infants at a very young age. What's more, they also seem to have the concept of contact mechanics as well. The concept of contact mechanics is an example of a concept that has benefit to functioning in the everyday world but that was a major obstacle to scientific advancement. When Newton created his theory of gravity, it was considered a major problem by virtually all the learned people of his day (including Newton himself) that the theory relied on what at the time were described as "occult forces", i.e., the concept of a gravitational field that could influence an object without physical contact. [30]

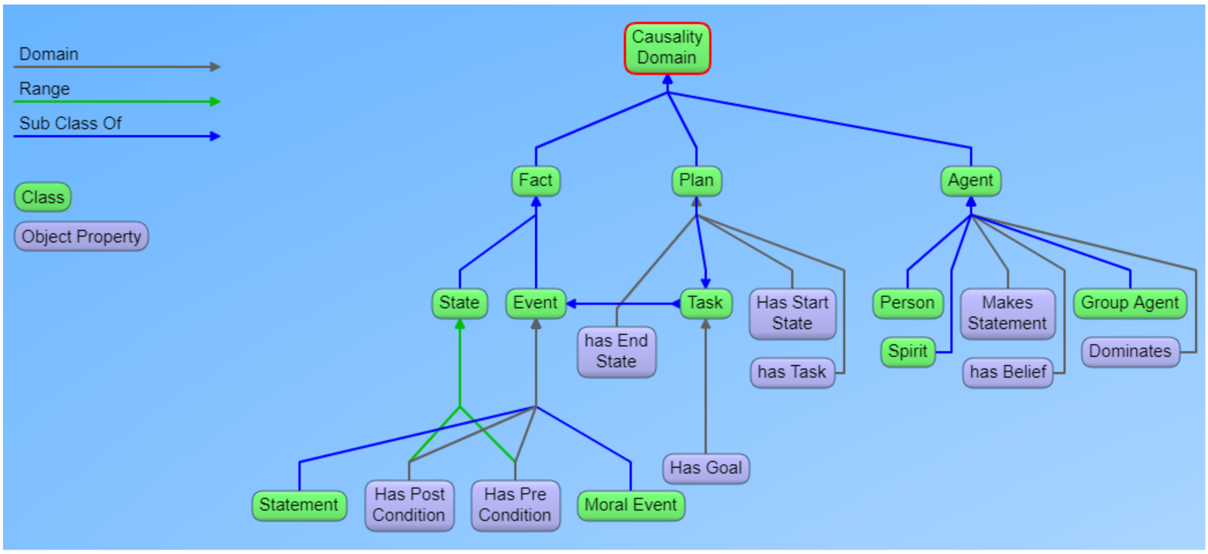

Figure 4. Important Classes and Properties in the Causal Domain

3.2. Social Domain, Moral Domain and Spiritual Domain

The social domain is primarily made up of properties such as the property hierarchy under hasKin (e.g., hasParent, hasMother, etc.). This module also models dominance relations and tribal affiliation. My hypothesis is that this module was essentially inherited from our primate ancestors. [11] The most important class is Tribe with subclasses My Tribe and Enemy Tribe. Tribalism is widely observed in hunter gatherers as well as in many other primates such as Chimpanzees. In both species, it is common to be highly altruistic with members of one's own tribe but to view members of other tribes as inherently evil. In both Chimpanzees and LPA hunter gatherers it is common for members of a tribe to kill members of another tribe who are found wandering into their territory. [31]

The Moral Domain consists of the few classes from the UMG ontology [12] that are hypothesized to be innate. As in the UMG, the starting point are subclasses of the causal domain classes: Moral Agent, Moral Event, and Moral State. We call an Event, or State moral when some Agent ascribes some value to it. This is modeled with the data property hasUtility. This value is the result of some utility function as described in game theory. The fact that the range of the property is an xsd:decimal means it will have all the transitive properties required for a utility function. [32]

The Spiritual Domain contains the concepts that religious beliefs are based on. Note that there is no concept of God or gods. Such concepts are mostly absent from LPA hunter gatherer spiritual beliefs and are an invention of human cultures. However, spiritual beliefs are prevalent in every hunter gatherer tribe ever studied by anthropologists. [33] Such tribes always have concepts of spiritual beings and the spirits of dead ancestors and tribe members. As Atran points out [34] this is an evolutionary paradox: "From an evolutionary standpoint, the reasons religion shouldn't exist are patent: religion is materially expensive and unrelentingly counterfactual and even counterintuitive. Religious practice is costly in terms of material sacrifice…, emotional expenditure…, and cognitive effort..." This has led people such as Dawkins to speculate that religion is a "mind virus" that offers no evolutionary advantage and is simply an accidental by product of humans attempting to make sense of their world. [35] However, Dawkins of all people should know better. If this were the case, as Atran and Boyer point out, there would be significant evolutionary selection pressure for atheism when in fact exactly the opposite is the case, some form of spiritual belief has been found in every hunter gatherer tribe studied. The evolutionary advantages of religion are still debated but the most likely hypothesis described by Boyer and Atran [33] [34] is that spiritual beliefs help to enforce tribal cohesion and conformity to tribal rules. This still leaves an open question about group selection because this seems to be for the benefit of the group rather than the individual. This is similar to the problem of human altruism in the Moral Domain. As Boehm and others point out, [10] hunter gatherer tribes are surprisingly altruistic. The biggest crime in the LPA tribes that Boehm studied was not lack of contribution but rather over inflating one's achievements and refusing to share. In contrast with the view that is unfortunately still widely prevalent about evolution and hunter gatherers, status in a tribe was typically achieved by sharing and collaborating far more than dominance. Indeed, Boehm has fascinating examples of "sharing wars" where two high status individuals in a tribe will compete to see who can throw the best banquets for the tribe or give away the most of their surplus hunt or other possessions. Thus, two of the important subclasses of Agent in the Moral Module are Cheater and Collaborator. These terms are used in the game theoretic sense. One of the most prevalent hypotheses about human moral beliefs is that they arose (along with language) so that tribe members could share information about other members (which survives in modern humans as gossip) regarding who is a collaborator and who is a cheater. [32]

One future goal is to utilize this model and the previous UMG model to address a contradiction between two research programs at the present. Researchers such as Dawkins [36] who approach human morality from an evolutionary perspective tend to be highly critical of the concept of group selection because it can be demonstrated mathematically that genes that favor the group at the expense of the individual have little chance to spread or remain in the genome.[9] On the other hand, anthropologists such as Boehm and philosophers such as Sloan and Wilson [37] tend to see group selection as the only possible explanation for the high degree of altruism in LPA tribes. I think it is possible to thread the needle between both camps. I.e., to find mathematical models that are viable based on individual selection and that still explain the highly altruistic behavior of LPA tribes. This will be one important way I plan to use the model for future work.

[9] This applies to organisms such as mammals who reproduce via diploid chromosomes. The math is quite different for eusocial organisms such as termites who reproduce via haploid or haploid/diploid chromosomes. In such hive organisms, group selection is common, and one finds traits such as individuals who are born sterile which could not evolve in diploid species.

3.3. Folk Biology Domain

The classes in this domain are Animal, Plant, and Human. Hunter gatherers conceptualize humans as outside the rest of the animal kingdom and have fundamental distinctions between Plants and Animals. In addition, the concept of an essence is common both in hunter gatherer tribes, infants, children, and adults. [7] This is what distinguishes living things from physical things in cognitive modules. Living things have an essence. When children are told stories of a living thing that transforms into another thing (e.g., a person into a frog or a fox into a rabbit) and asked if it is still the same thing, they regularly reply that it is. However, if the shape or function of a physical thing is significantly altered (e.g., change a chair into a table) it is perceived to be a different object. [6]

3.4. Location and Time Domain

There is only one class in the Location Domain: Place. The properties nextTo and farFrom are both symmetric. The farFrom property is symmetric and transitive. The nextTo property is simply symmetric. The above and below properties are inverses and transitive. The Location module is interesting in that a core concept that western people take for granted and might be expected to be included in the module is not universal across cultures. In western culture, directional frame of reference is typically indicated in everyday speech with relative (aka egocentric) direction. I.e., dependent on the speaker or hearer's position relative to the object. E.g., if I want to tell someone where the window is as I'm working on my computer, I would say "it's on my left". However, there are two other frames of reference used in other cultures: absolute and intrinsic. These are both allocentric rather than egocentric because they are independent of the speaker or hearer. Absolute uses traditional compass directions of North, South, East, and West even to indicate location of things within a home or other small space. This is foreign to most westerners who seldom have any idea where these directions are inside one's home. Intrinsic is similar to relative, however rather than compass directions, this frame of reference uses some common landmark(s) such as a mountain or sacred tribal object. [38]

The Time Domain contains the classes Duration and Instant. Duration is a subclass of the Sequence class in the Number Domain. Duration is a sequence of Durations or Instants. The start and end of a Duration are defined by the properties hasDurationStart which is an Instant and similarly the end by hasDurationEnd. The before and after properties are transitive. There is a special instance of the Instance class called Now that represents the present. The subclass PastInstant is defined by the DL axiom: *Instant and (before value Now)*. FutureInstant is *Instant and (after value Now)*. Future is a subclass of Duration: *Duration and (hasDurationStart some FutureInstant)*. Similarly, Past is: *Duration and (hasDurationEnd some PastInstant*).

4. A Simple Example

In this section I present a simple example (see Figure 5) based on a case study of the Mbutu tribe discussed by Boehm in [10]. Boehm describes an example of an LPA tribe of Pygmies who hunt small prey with nets. It is possible for one hunter to "steal" the prey of another by violating the tribal norms about the proper way to hunt. Each hunter has an assigned area as the hunting party flush small prey from forest cover. Although this style of hunting will result in some members having better luck on any given day, over time things even out. However, it is possible for one hunter to move into another's zone when he sees prey going toward that zone and intercept the prey before it reaches the hunter who should catch it by the norms of the tribe. In Boehm's example, one hunter (Kenge) accuses another hunter (Cephu) of being an "animal" because he believes Cephu stole his prey. This illustrates several concepts from the model:

- Statements referTo Beliefs
- Beliefs referTo Facts (States or Events) with some degree of certainty
- Folk Biology distinguishes between Humans and Animals
- Facts model ThePast, Now, or TheFuture

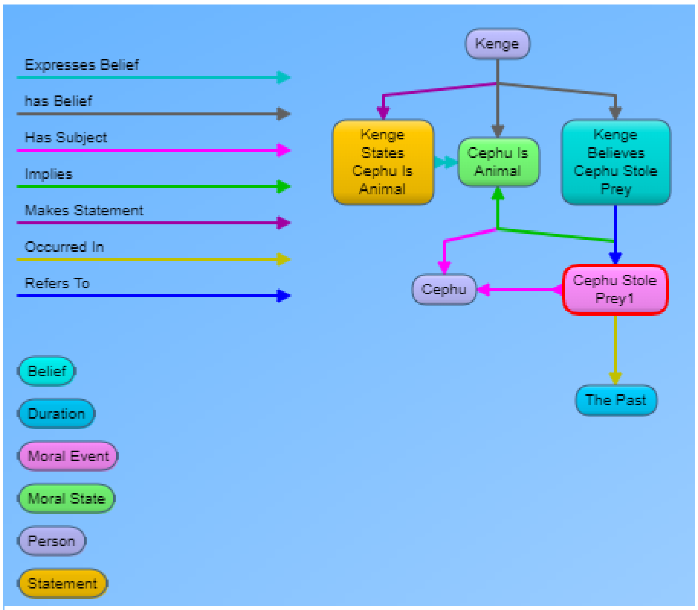

Figure 5. Representing Statements and Beliefs with the Model

5. Potential Criticisms

In this section I examine some potential criticisms of this approach.

5.1. The Mind is not a Formal System

There is significant research in cognitive science that indicates set theory is not completely adequate to represent human concepts and categories. The theory goes back to Wittgenstein and his concept of language as a collection of "games" rather than a formal system with well-defined mathematical rules. [21] The cognitive science evidence for this first came from the work of Eleanor Rosch who conducted experiments where subjects were asked to create new categories based on various types of input such as geometric shapes of various colors. [39] Rosch found that the categories constructed by subjects did not completely follow the rules of set theory. Rosch's work was embraced by Georg Lakoff who went so far as to claim that not only are logic and set theory incapable of modeling human concepts, but they are not even applicable to scientific models. There are at least two issues with this:

1. There is a difference between internal representations and representations utilized by the conscious mind.
2. Exceptions to a model do not necessarily invalidate the model, especially in a domain as poorly understood as the human mind.

5.1.1. Internal vs. Conscious Representations

This issue has also been a basic misunderstanding of the biolinguistic approach from the very beginning in the 1950's to the present. Philosophers and psychologists often criticize biolinguistics by pointing out that it is absurd to think that people need to learn complex rules of grammatical syntax. This is true but completely misses the point. The theory of biolinguistics does not assume that speakers must explicitly learn or be aware of rules of grammar, only that internally they have representations that functionally can be modeled by such rules. A compelling analogy can be found in modeling dead reckoning in insects. There is very strong evidence that insects such as bees and ants utilize dead reckoning. At one point this was also considered absurd, and the directional capabilities of insects were assumed to be based on pheromone trails or some other simpler form of navigation. However, sophisticated experiments have ruled out these models and conclusively demonstrated that some insects do perform dead reckoning which requires non-trivial geometry as well as knowing the position of the sun at different times of day and different days of the year. [40] Before global positioning systems, this was the way that sailors navigated and required training in the use of tools such as sextants, geometry such as the Pythagorean theorem, and almanacs that gave the position of the sun and stars for each day of the year and each hour of the day. The fact that insects can perform dead reckoning does not mean that they have mastered elementary school geometry or regularly consult an almanac before leaving the hive. Rather structures have evolved in their brains that can best be modeled by geometric and almanac models.

In the same way, it is possible to use models based on set theory both to represent biolinguistic models and cognitive module models even though it is the case that human concepts and categories do not always adhere to the laws of set theory.

5.1.2. Exceptions Don't Invalidate a Model

There is significant experimental evidence that human categories do not always conform to set theoretic models. However, these experiments are often based on highly contrived and unintuitive examples. The fact that categories generated on the fly in matters of seconds based on colored unusual geometric shapes flashed briefly on a screen don't completely adhere to set theory is hardly conclusive evidence that set theory is irrelevant to all human categories. Indeed, there is significant experimental data that indicates children use set theoretic models in learning actual concepts and that the difficulty of learning a new concept corresponds to the complexity of integrating it into the child's existing subsumption hierarchy. [41]

What's more, as Chomsky often points out, the fact that a model has exceptions does not mean we automatically throw out the model. [26] If it did, we would have thrown out the theories of gravitation and evolution by natural selection long ago. Newton's theory did a good job of predicting the orbits of the planets, but it was far from perfect. The orbit of Uranus deviated significantly from the prediction made by the theory. Rather than throw out the theory this led astronomers to search for an explanation and resulted in the discovery of Neptune. Similarly, eusocial insects were a major problem for Darwin. The fact that many eusocial insects are born sterile and have behavior such as regularly sacrificing their lives for the benefit of the hive contradict Darwin's theory. There seemed no mechanisms that would allow such behavior to evolve by natural selection. It was only when the concept of genes and chromosomes were discovered and the difference between diploid and haploid chromosomes was understood that mathematical models could be created that not only accounted for eusocial species but predicted that they would evolve the traits that they were observed to have.

5.2. OWL is the Wrong Formalism to Model Cognitive Modules

On the other side of the spectrum, from people who resist using formal methods for this type of model there may be some who would say that formal methods are good, but OWL is the wrong formalism to use. One could argue that to model a module one should use an Interface Definition Language (IDL). Or that Description Logic is too limited and that one should use a language that has a more complete implementation of First Order Logic.

I am not claiming that OWL is the only or even the best language to use and I can anticipate using other languages in the future. I found OWL to be a good place to create my first model because it is easy to use, relatively easy (compared to most other formal tools) for non-technical people such as anthropologists and psychologists to understand and very well supported by tools.

There are many ways to model a problem. An excellent example is the proof that there is no general solution to the Entscheidungsproblem. Turing and Church both proved this to be true and their formalisms (Turing Machines and the Lambda Calculus) were vastly different and continued to be used in very different ways. Turing machines as a general model of computation and the Lambda Calculus as the formal model for the Lisp programming language. In addition, a third approach: primitive recursive functions was also used. [24]

6. Discussion

In my initial paper on the UMG ontology, [12] my goal was to show a broad coverage of moral systems. I did not attempt to model what was part of the human genome vs. what is a result of culture. As I attempted to resolve that issue, I realized that it wasn't possible to simply model the UMG because the UMG interacts with other cognitive modules. That was the impetus for this paper.

Clearly, this paper is highly speculative. My goal is to begin to bring some rigor to the discussion of cognitive modules in the field of evolutionary psychology and introduce a framework for future research. A contribution of this paper is that it presents an hypothesis for one of the most important questions facing science: what is the crucial adaptation that allowed the human race to dominate the world? I think the answer to that question is recursion. Recursion enables discrete infinity. There is evidence that other primates can do basic planning which is one of the key functions of the causality module. However, recursion enabled unbounded planning. My hypothesis is that many of the modules described in this paper were present in our hunter gatherer ancestors and even in other primates. However, it was recursion that enabled integration of the modules and knowledge representation that is unbounded except for memory limitations. One can see that in the many concepts in the Conceptual Intentional system that inherit from LFN such as Duration, Past, Present, Group, Fact, and Plan. The hypothesis is that recursion enabled humans to develop theories based on past events, predict behavior of future events, and construct complex plans to help them better adapt to their environment.

The hypothesis that the core adaptation that enabled language also enabled complex thought is not new. Chomsky often says that he believes language to be for internal cognition as much as or more than communication. [13] By language he doesn't mean natural languages such as English but what he calls LFN or recursion. This hypothesis was also stated long ago by George Miller in his book Plans and the Structure of Behavior. [42] In that book, Miller described a model of planning essentially identical to the model described here. Miller also presented evidence that primates had such a model as well as humans and he speculated (based on his collaboration with Chomsky at that time) that it was a recursion adaptation that allowed humans to achieve sentience, language, and the kind of cognition that allows us to shape our environment rather than simply react to it.

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