From Predicate Modeling to Semantic Analysis of Predicates: The Use of Logic in Computer Science

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Abstract: Since the introduction of independent data storage mechanisms in the 1970s, database design has been characterized by the modeling of predicates, or attributes, and their interrelationships. This paper critiques prevailing data modeling methodologies – relational data modeling and AI-based fact modeling in RDF and OWL – as leading to the unrestrained creation of predicates in information models. The absence of a principle controlling when new predicates should no longer be created is fundamentally rooted in the theoretical basis of these information modeling techniques – first order logic (FOL) – which also lacks such a principle of restraint. The paper then proceeds to revisit the larger logical project within which FOL emerged, semantic analysis, which does guide the selection of appropriate predicates. It is claimed that the purpose of FOL was never to express any and all predicates that could ever been spoken or written. Rather, FOL provides a grammar suitable for expressing the results of semantic analysis. If computer science and artificial intelligence seek fidelity to logic, it is claimed here, then semantic analysis must become a central discipline and critical first step in computation. The paper reviews approaches to semantic analysis and makes recommendations for the future of semantic analysis. Finally, a thorough history of the concerns of modern logic that led to semantic analysis and FOL is provided, with a concluding revision of the common misconception that the formality of FOL implies lack of intentionality or semantics in FOL.

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1. Introduction

Declarative software architectures are anchored in a logical model of a domain. In particular, states of a domain are modeled as a collection of fact types, which provide semantic details to an otherwise formal system of functional predicates rooted in first order logic. This model of fact types then constrains a set of stateful facts that describe isolated states of the domain and physically persist in a data store whose design – from relational databases to triple stores – is based on the same formal system from first order logic. This paper questions this predominant manner of using first order logic (FOL) as a purely formal system in computer science by revisiting the history of FOL. The absence of a principle controlling when new predicates should no longer be created is fundamentally rooted in FOL as the theoretical basis of these information modeling techniques, as FOL also lacks such a principle of restraint. This paper suggests that, based on the history of FOL, the more appropriate use of FOL is as a grammar for expressing the results of semantic analysis. It is claimed that the purpose of FOL was never to express any and all predicates that could ever been spoken or written, but to express the predicates emerging from semantic analysis as relational, functional predicates. Semantic analysis thus constitutes the overarching logic program of which FOL is merely a part. If computer science and artificial intelligence seek fidelity to logic, it is claimed here, then semantic analysis must become a central discipline and critical first step in computation. The paper reviews approaches to semantic analysis and makes recommendations for the future of semantic analysis. Finally, a thorough history of the concerns of modern logic that led to semantic analysis and FOL is provided, with a concluding revision of the common misconception that the formality of FOL implies lack of intentionality or semantics in FOL.

2. The Uncontrolled Role of Predicates in Computer Science

Overview of Uncontrolled Predicate Identification

Predicate-based facts have always played a special, central role in artificial intelligence and computer science more generally as the conceptual unit constituting a computer's state. Any system for automated reasoning requires a corresponding representation of the world about which a system is to reason, and the traditional foundation of representation of knowledge of the world is a foundation of facts made up of predicates. The oft-cited knowledge representation hypothesis of Brian Smith asserts that any "mechanically embodied intelligent process will be comprised of structural ingredients that we as external observers naturally take to represent *a propositional account* of the knowledge that the overall process exhibits". [2, my italics] The assumption that reality consists of a set of atomic facts is so central to artificial intelligence that it is one of the targets of Dreyfus' critique of AI (Dreyfus calls it the "ontological assumption"). [1]

The primary role played by predicate-based facts in intelligent systems has been formulated in very influential terms by the business rules consulting community, the leaders of which formed the Business Rules Manifesto: "Terms express business concepts; facts make assertions about these concepts; rules constrain and support these facts." [4]

This section argues that predicates, while obviously critical to the definition of an information model, are currently uncontrolled in their assignment to particular models. That is, methods for information modeling – e.g. relational data modeling and OWL modeling – are essentially methods for attribute identification that themselves do not clearly prescribe when attributes should *not* be added to a model, and should instead be defined in logical terms based on existing attributes (e.g. as business rules). This lack of a principle of limitation on the attributes included in an information model is rooted in a similar lack of such a principle in first order logic, which provides the theoretical foundation for these modeling methods. It is to first order logic that we thus now turn.

First Order Logic

Facts express atomic states of the world via tuples consisting of a subject and a predicate. A predicate, in turn, consists of an object and a value, as is demonstrated in the example below.

Fact: The sky is blue.
- *Subject* = the sky
- *Predicate* = is blue
    - *Object* = has a color
    - *Value* = blue

The primacy that facts have in knowledge representation owes in large part to the primacy facts have in first order logic (FOL). Facts are the atomic elements of FOL, whose breakthrough was to take a functional approach to predicates of facts. Specifically, FOL treats predicates as functions that map bare particular instances (x) to a predicate class of instances ($F(x)$). This hard distinction between class terms and terms for bare particulars or naked instances is central to FOL. For example, the fact "Acme Supply is a customer" is denoted in predicate logic as $C(x)$, where C=Customer and the function maps to true when x=Acme Supply.

What is most significant about the functional approach to predication in FOL is its use of relations as the basis of logic. In contrast to Aristotelian logic's grounding in entities that have properties and may enter into relations with each other, FOL is based on relations themselves. Common relations (e.g. 'John gave Mary a ring') are treated as many-place predicates or relations (e.g. 'Gave (John, Mary, ring)') while common predicates (e.g. 'Socrates is a man') are treated as one-place predicates or relations (e.g. 'Is a man (Socrates)').

FOL simply provides a grammar for the relational treatment of predicates, and does not itself include any principle that would restrain which predicates should be expressed in a FOL-based model of a domain. This is because FOL is not itself a modeling methodology, but is itself merely a tool of modeling methodologies that were formulated and developed prior to and during the development of FOL. These previous methodologies, known as analysis or semantic analysis, are the topic of the next section. What is demonstrated here is that the modeling methodologies used in computer science drew on FOL, but not on the broader semantic analysis methodologies that had provided the overarching purpose and use for FOL.

FOL-Based Information Modeling

The specific influence of FOL on information models has been felt in two important areas: relational data models and Semantic Web standards such as RDF. The result of this influence is that both information modeling techniques provide formal structure that was missing in previous approaches to data modeling, a structure based on the functional approach to predication taken by FOL.

Relational data models emerged in a time when data was stored in files tightly integrated with particular applications. Because there was no possibility of sharing application-specific data with other applications, the structure of such files was not designed independently of the application. A common element of such databases – found in both hierarchic and network databases – was that relations (e.g. employment, parenthood) were stored in links between tables while tables stored information about entities. While this enabled fast performance of data retrieval operations, the encoding of relations in links between tables prevented tables from entering into different relations to meet the needs of other applications.

In 1969, Codd turned to FOL to provide a formal basis for a database model in which data could be stored in a declarative model, independent of the algorithmic needs of particular applications. Rather than encoding relations in the links between entity-based tables, Codd makes relations the basis of the tables themselves by leveraging the unique ability of FOL facts to express all information as relations. Instead of 'employment' being stored in the link between a 'company' fact and a 'person' fact, 'has employer' is a column of a 'person' table with employers as values, a structure based on the FOL expression of 'has employer' as a two-place predicate relating persons and employers. Each row of a table in the relational data model is a set of such relations, or, FOL facts. The table structure of Codd's relational data model is thus based on FOL tuples, such that, in the words of Codd's first rule of relational databases, "All information is represented in relational tables."

Another conceptual modeling approach rooted in FOL is the Resource Description Framework (RDF) standard for modeling information that is a foundational element of the

Semantic Web. RDF is a framework for XML metadata tagging according to which content is tagged within a simple triple structure (subject, predicate, object). On top of this simple RDF triple structure are then applied expressive ontology-based schemas based on more expressive standards (RDFS and OWL).

This 3-part structure for modeling facts as predicates that relate subjects to objects is of course common to all classical modeling approaches, including relational data modeling as discussed above. In contrast to the relational model, which groups facts within tables, RDF stores facts as standalone triples. RDF triples are often stored in data storage known as triple stores.

RDF is thus viewed as a more faithful use of FOL to model information. As Alesso and Smith write, "We can think of the triple (*x*, P, *y*) as a logical formula P (*x*, *y*) where the binary predicate P relates the object *x* to the object *y*." [9]

However, faithfulness to FOL is an inadequate standard for information modeling methodologies. Designing a logic that could express anything and everything that people would ever say or think was never the purpose or intended use of FOL. Instead, FOL was designed within a rich tradition of semantic analysis as a tool of such analysis. Thus, fidelity to, and development of, this larger logic of semantic analysis should provide the standard for information modeling methodologies in computer science.

3. Semantic Analysis: The Critical Step Prior to Computation

This section describes the method of semantic analysis that provided the overarching framework within which FOL is a particular tool. Semantic analysis is described here with only essential historical references for brevity and clarity. The following section provides a more in-depth history of FOL as a tool of semantic analysis that, while supporting the central argument of this paper, is optional for the reader.

Classical Semantic Analysis in Logic

FOL, as explained in the previous section, takes a relational approach to predicates in that it describes instances of a predicate in terms of the relations of one or more objects to each other. As was described above, common relations (e.g. 'John gave Mary a ring') are treated as many-place predicates or relations (e.g. 'Gave (John, Mary, ring)') while common predicates (e.g. 'Socrates is a man') are treated as one-place predicates or relations (e.g. 'Is a man (Socrates)').

This treatment of a predicate as a function that relates, or maps, one or more terms to each other may appear algebraic. In fact, FOL was the culmination of a century or more of algebraic analysis of propositions. While the key figures in algebraic analysis of propositions include Viète, Descartes, Leibniz, Bolzano and Frege, this section overlooks much of this history to provide a straightforward account of such semantic analysis.

Spoken propositions generally conceal as much as they reveal of their full intended meaning, or more simply, their intention. A common example is the absence of a time indication (referred to by philosophers as a time index) for many propositions whose truth depends upon time. "A gallon of gasoline costs $2.50" is an example of a proposition that conceals as much as it reveals, and requires semantic analysis to uncover its full meaning. For a gallon of gasoline costs $2.50 at a certain time, and at a certain place. Thus price is not a simple predicate of gasoline that is true of gasoline in virtue of it being gasoline and not milk, but is a relational predicate that is based (or literally, predicated) on a particular relationship of product, place, time, and possibly other factors.

This relational treatment of predicates is fundamentally an algebraic treatment of predicates, in that it defines a predicate in terms of a particular relationship between other terms just as algebra defines an unknown variable (E) in terms of a particular relationship between known variables (MC^2).

This semantic analysis of a spoken proposition reveals that many simple subject-predicate propositions are in fact intending more complex events or policies. For example, "A gallon of gasoline costs $2.50", once analyzed, is revealed to intend either an event ("A gallon of gasoline at the Shell station on 123 Main Street was purchased for $2.50 on Jan 1, 2009") or a policy ("A gallon of gasoline at the Shell station on 123 Main Street is offer for $2.50 from Jan 1, 2009 to Jan 30, 2009"). This in fact reveals a central strength and purpose of FOL, the ability to model change, motion and events using multi-term predicates (e.g. Purchased (Gallon of Gasoline, Shell Station on 123 Main Street, $2.50, Jan 1, 2009). The role played by FOL and semantic analysis in the analysis and modeling of change and motion (the central concerns in mathematical physics) is addressed in the following section on the history of semantic analysis and FOL.

FOL was a breakthrough in that it provided a grammar for expressing the results of the algebraic analysis of the full semantic intention of a proposition. But the goal of such analysis was never to simply transform a proposition or predicate into FOL grammar. The goal of such analysis was to reveal the more fundamental, atomic predicates, and the particular relation between them, that constitute the full meaning of a spoken predicate.

If this type of semantic analysis is the larger framework of modern logic within which FOL is a tool, then what are the steps for carrying out semantic analysis? The steps taken by logicians, both before Frege (notably Bolzano) and after, can be summarized as linguistic analysis. Spoken propositions are collected and intensely analyzed to uncover unspoken constituents of such propositions, as in the case of the "cost of gasoline" given above.

Modern Semantic Analysis in Computer Science

The development of the first computers in the middle of the 20th century built on the logical connectives of mathematical logic (AND, OR, XOR) and not FOL. It was only with the introduction of independent data storage mechanisms in the early 1970s, as described in the previous section, that FOL had a direct influence in computer science. In response to the introduction of independent data storage, research began to be carried out in the 1970s, particularly in Europe, in the modeling of such systems via semantic analysis of natural language. This began as the NIAM methodology (Natural Language Information Model) most associated with Nijssen and evolved into the ORM methodology (Object Role Modeling) most associated with Halpin.

While independent of the semantic analysis conducted by logicians before and after the introduction of FOL, the same general approach of semantic analysis of spoken propositions to reveal constituent, though unspoken, atomic propositions was taken. Halpin summarizes ORM as fact-based information modeling in contrast to the attribute-based information modeling found in relational data modeling and object-oriented modeling. In particular, ORM (1) collects as many facts about a user's domain as possible, (2) transforms these facts into elementary facts, (3) abstracts from these elementary facts to fact types, which are types or kinds of facts and then (4) analyses the roles played by objects in these fact types to reveal opportunities for merging of separate objects into more atomic, fundamental objects.

For example, an ORM model may begin with the following facts from a domain.

1) Matt Damon and Meryl Streep are vegetarian.
2) Tom Cruise is a vegan.
3) If Harrison Ford eats all food then he eats vegetables.

Table 1: ORM Step 1

Step 2 of ORM would transform these facts into elementary facts, which occurs by decomposing facts into smaller facts without loss of information. Fact #1 is a conjunction that can be decomposed into 2 elementary facts, while Fact #3 is an implication that can be decomposed into 2 elementary facts, with the implication stored in code as a rule or constraint.

1) Matt Damon is a vegetarian
2) Meryl Streep is a vegetarian
3) Tom Cruise is a vegan.
4) Harrison Ford eats all food.
5) Harrison Ford eats vegetables.

Table 2: ORM Step 2

Step 3 of ORM abstracts from these elementary facts into fact types of objects and predicates, or, roles, again by selecting as few fact types as possible with no loss of information.

1) Actor is a Vegetarian.
2) Actor is a Vegan.
3) Actor eats Food.

Table 3: ORM Step 3

One quickly sees an opportunity to collapse the first 2 fact types into the third fact type, with no loss of information.

1) Actor eats Food.

Table 4: ORM Step 3

Finally, step 4 of ORM analyses the roles played by objects in these fact types to reveal opportunities for merging of separate objects into more atomic, fundamental objects. Let's imagine that a new fact was introduced into the domain: "Barack Obama is a vegetarian". This would result, via steps 1-3, in the addition of a 2nd elementary fact type.

1) Actor eats Food.
2) President eats Food.

Table 5: ORM Step 3

The roles played by the two objects – actor and president – are identical, revealing the likelihood that the objects should be consolidated, as is done below.

1) Person eats Food.

Table 6: ORM Step 4

"Person eats Food" is a two-term relation of the predicate "eats", declared in FOL as follows: Eats (Person, Food). The growth of predicates has been constrained through a semantic analysis of the spoken (or, written) propositions in a domain, revealing the underlying intention of these propositions in terms of more basic, atomic predicates.

Recommended Development of Semantic Analysis

Informed by the larger purpose of semantic analysis, and the two primary forms that semantic analysis has taken in logic and in computer science, what recommendations can we make for the future development of semantic analysis and, by extension, the use of logic in computer science and artificial intelligence? There seem to be three specific claims that we can now make for semantic analysis and logic in computer science.

(1) Existence/Policy Distinction

Semantic analysis of propositions in a domain of discourse results in fundamental, atomic fact types. These fact types always refer to things that exist in positive, material reality. In particular, they refer either (a) to discrete objects that exist in positive, material reality (e.g. persons, companies, buildings) or (b) to discrete events that exist in positive, material reality at a particular place and time (e.g. Buys (Company, Building, Time), Eats (Person, Food, Time)).

This distinction between objects that exist in positive, material reality and events that exist in positive, material reality reflects the distinction made in philosophy between endurants and perdurants. *The reason that semantic analysis of propositions results in that which exists in positive, material reality is that positive reality is the essential ontological basis for all discourse and thus for all predicates*. It is thus the most expressive and elementary basis of facts underlying any spoken or written proposition.

All else, it seems, refers to policies or rules (whether personal or institutional) that are imposed on things and constrain events. For example, "Eats (Person, Food)" would thus appear to be a personal policy that is imposed on "Eats" events.

For architectural simplicity as a rule of thumb, then, perhaps we can say that information modeling distinguishes between things and events that exist in positive reality and policies and rules that are imposed on and constrain things and events.

This conceptual distinction between things and events in positive reality on the one hand, and policies and rules imposed on events on the other, would then be physically realized by the use of databases to store information exclusively about things and events. Policies and rules that are imposed on these things and constrain events would appear to be the special role of a programming language (whether in direct code or in business rules).

(2) Add ORM Step 5: Reduction of Fact Types to Event Types

A central strength and purpose of FOL is the ability to model change. As mentioned above, the many-termed predicates introduced by FOL provided a logical grammar to describe change in terms of the relation between the components of a change.

If an information model is properly focused on that which exists in positive, material reality (things and events), then fact types resulting from ORM semantic analysis should perhaps be analyzed in one more step to reveal events that are the true, elementary basis for these fact types. This could be done by applying a model from Aristotelian logic of the roles played in any change: actor, patient, instrument, time and place.

The example from the previous section, "A gallon of gasoline costs $2.50", would like result via ORM steps 1-4 in the following elementary fact type.

Beginning Fact: A gallon of gasoline costs $2.50.
Final Fact Type: Product costs Amount
Table 7: ORM Steps 1-4

By applying the model of change, we uncover the event that is the basis for this fact.

Sold (Actor, Patient, Instrument, Time, Place)
Sold (Shell Station on 123 Main Street, Unknown, Gallon of Gasoline, Jan 1 2009, 123 Main Street).
Table 8: New ORM Step 5

This reveals the need, perhaps, for a data model of purchases, rather than a data model of product prices. This reflects the more fundamental purpose of databases to store events and things – what exist in positive, material reality – rather than predicates that can be reduced to events and things with no loss of information.

(3) Limit Use of FOL to Expression of Complete Knowledge

While facts are the primary element of FOL, complete knowledge of facts is rarely available. For that reason, the breakthroughs of FOL (functional predication and existential quantification) have been leveraged extensively to express incomplete knowledge. Brachman and Levesque illustrate this as follows.

> 1. $\neg$ Student(john).
> This sentence says that John is not a student without saying what he is.
>
> 2. Parent(sue, bill) V Parent(sue, george).
> This sentence says that either Bill or George is a parent of Sue, but does not specify which.
>
> 3. $\exists x$ Cousin(bill, x) $\wedge$ Male(x).
> This sentence says that Bill has at least one male cousin but does not say who that cousin in.
>
> 4. $\forall$x Friend(George, x) $\rightarrow$ $\exists$y Child (x, y).
> This sentence says that all of George's friends have children without saying who those friends or their children are or even if there are any.
>
> The main feature of these examples is that FOL is not used to capture complex details about the domain, but to avoid having to represent details that may not be known. *The expressive power of FOL determines not so much what can be said, but what can be left unsaid.* [3]

The consequence is that there are many domains of incomplete knowledge that, in addition to complete knowledge of facts, must be expressed in a knowledge representation system. The critical distinction between complete and incomplete knowledge of facts in a domain is seen in the role it plays in the expressiveness-tractability trade-off that is a central dynamic of any such knowledge representation system.

Brachman and Levesque write that a "fundamental fact of life is that there is a tradeoff between the expressiveness of the representation language and the computational tractability of the associated reasoning task". As knowledge representation languages expand to express various forms on incomplete knowledge, the ability to reason over such knowledge becomes more complex and slow. [5]

However, while limiting a knowledgebase to incomplete knowledge would be unsatisfactory, limiting a knowledgebase to complete knowledge of facts would be acceptable if such knowledge was sufficiently available. Brachman refers to this type of knowledge as “vivid knowledge”, and argues that a vivid knowledge representation – “one that bears a strong and direct resemblance to the world it represents” – would not have to resort to methods to reduce intractability because it would pose no tractability challenges. Elsewhere, Brachman defines a vivid knowledgebase as “a complete database of ground, atomic facts” that “has symbols that stand in a one-to-one correspondence to objects of interest in the world, with connections between those symbols corresponding to relationships of concern”. [6]

Brachman’s vivid knowledgebase is equivalent to the elementary facts that result from Halpin’s fact-driven modeling approach, ORM. Elementary facts, again, are “assertions that particular objects play particular roles”, providing semantic stability to an information system. Examples such as “Ann smokes” are elementary because “the fact cannot be split into smaller units of information (with the same objects) that collectively provide the same information as the original.” Non-elementary facts include examples such as “Ann smokes and Bob smokes”, “Ann smokes or Bob smokes” and “If Bob smokes then Bob in cancer prone”. [7] Notice the correspondence between Halpin’s non-elementary facts and Brachman and Levesque’s incomplete factual knowledge.

Given that the overarching purpose of semantic analysis and thus of FOL is precisely to discover the set of elementary facts that Brachman refers to, the result is that the focus of AI research should be in the development of semantic analysis, not the development of FOL-based languages for storing and reasoning with incomplete knowledge.

4. History of First Order Logic as a Tool of Semantic Analysis

Reasons for Replacing Parts of Aristotelian Logic in Modern Logic

The algebraic approach of semantic analysis of predicates in order to uncover the more basic predicates and interrelation between is driven by concerns that animate modern logic and its rejection of certain aspects of Aristotelian logic. An understanding of this history is critical to understand the concerns that led to semantic analysis and FOL.

The foundational role of facts whose predicates relate terms to each other is not an insight of computer science or even of FOL. The founder of FOL, Frege, inherited a philosophical tradition that included many of the founders of computation, such as Boole and Leibniz, according to which relational facts are the essential foundation of any scientific body of knowledge. The computationalist approach to knowledge begins most clearly with Leibniz, who converted the propositional structure of Aristotelian logic (subject *is* predicate) into an equation (subject = predicate). This conversion was grounded in Leibniz’ computationalist view of knowledge that “in every affirmative true proposition, …the notion of the predicate is contained in some way in that of the subject, *praedicatum inest subjecto*. Or else I do not know what truth is.” With the relation between predicate and subject within a fact expressed in such algebraic terms, future logicians like Frege could then conceive of facts as functions.

While this transformation of the propositional structure of Aristotelian logic (subject *is* predicate) into an equation (subject = predicate) may appear trivial, it is anything but trivial. One should enquire, in fact, whether this conversion is made without any loss of information. Logician Henry Veatch explains what information is lost.

> But, unhappily, all this just won’t wash! And the reason it won’t wash is that the revised subject-predicate schema, or, as the Fregeans would prefer to call it, the function-argument schema, of modern logic does violence to the “logical grammar” of the word “is,” or of the “is”-relationship. [8]

The connector, “is”, was held before the computationalist turn to express multiple possible ways in which a subject reveals itself. The subject could reveal what is generic about itself (“Turing is an animal”), what differentiates itself from other subjects within its genus (“Turing is rational”), what is specific to itself as subject (“Turing is a man”), a property of itself as subject that follows of necessity from its species (“Turing is a language-user”) and what is accidental to itself as subject (“Turing is British”). The predicate in each case is dependent on the subject, and is there to reveal for the subject an aspect of its being. The intention was not to relate a subject and predicate to each other. Furthermore, even if some Aristotelian logicians had sought to express propositions in Leibniz’ algebraic form, the relation between subject and predicate was not a single relationship that could be converted into “=”, as ‘is’ disclosed various aspects of the being of the subject listed above. When the foregoing subject-predicate propositions are collapsed into a single equality relationship, then content would seem to be lost.

But what is gained? Formal logic from Leibniz forward provided a language for expressing the proofs and results of mathematical physics that Aristotelian logic was unable to express. This is evident in the tight connection of every major advance in formal logic, from Leibniz to Frege, with an attempt to establish a foundation for modern mathematics (the effort to establish a foundation for mathematics was concerned with all mathematical sciences).

Aristotelian logic, as was just mentioned, was unable to provide a foundation for the rapid developments of the mathematical sciences central to the Scientific Revolution.

The reason for this inability of Aristotelian logic to provide a foundation and a language for modern mathematical science, discussed below, reveals the specific purpose and intentional focus of modern logic. In short, whereas Aristotelian logic starts from the premise that logical form reflects an account of predicates in terms of the natures of subjects, modern logic accounts for predicates in terms of the more phenomenal relation of one or more elements of reality to each other that holds whenever the predicate is present. This account of predicates basically grounded logic in algebra and enabled scientists to describe predicates of change and motion not in terms of the natures of changing and moving subjects but in terms of functional relations between elements of a change itself.

The Foundations of Mathematics and Development of Modern Logic

The gap between the explanatory power of the mathematical sciences and the inability of Aristotelian logic to provide a foundation and language for these sciences was a growing concern throughout the 18th and 19th centuries. These mathematical sciences – optics, mechanics and astronomy, in particular – experienced such growth through many factors, among them the roles played by the printing press and scientific societies to enable an unprecedented spread of scientific research. Chief amongst these factors, however, was the application of mathematical, and specifically algebraic, analysis to explicate these domains on a material level. Algebraic analysis of the sciences of motion enabled scientists to formally describe and control motion for the first time, but in an algebraic manner that could not be expressed in Aristotelian logic.

Historically, these sciences were considered mathematical only inasmuch as they explained immaterial, and thus immobile and quantitative, aspects of these domains. This approach to these mathematical sciences followed from the three-fold division of the theoretical sciences presented by Aristotle, Boethius and Aquinas, according to which natural philosophy treats of what exists in matter, mathematics treats of what exists in matter but doesn't require matter to be understood and metaphysics treats of what exists without matter and motion.[1] Astronomy, optics and mechanics were considered middle sciences because they can be treated either at one level of abstraction in terms of principles of matter and motion (as natural philosophy), or at a further level of abstraction in terms of principles that don't include matter or motion (as mathematics). While debates occurred as to whether these sciences were more properly considered natural philosophy or mathematics, the distinction between natural philosophy and mathematics was not in doubt (in fact, it was agreement concerning this distinction that sustained the debate over the proper placement of the middle sciences).

The momentous change that is primarily responsible for bringing about the Scientific Revolution, as historians of science such as Edward Grant have made clear, was the merging of the middle sciences of motion into natural philosophy. This integration meant that mathematics was no longer restricted to seeking immaterial and immobile first principles, but was also applied to what exists in virtue of material causes.[2] The result of this integration was innumerous scientific projects to reveal the causes of natural phenomena using forms of mathematical analysis rather than the philosophical analysis central to classical natural philosophy.

The corresponding growth and success of mathematical natural philosophy, or, mathematical physics, was accordingly deprived of the logic for expression of a science had been provided by Aristotelian logic. This is because the early modern forms of scientific analysis that became the central method of mathematical physics introduced an algebraic approach to the study of natural science that, while critical to the analysis and understanding of motion, was alien to classical scientific analysis and Aristotelian logic.

Key to this new form of scientific analysis was the algebraic turn in analysis introduced by Viète in 1591, according to which known facts and unknown reasons in traditional analysis could be assigned letter variables and then subjected to algebraic decomposition until the unknown variables are defined, when possible. While Viète considered his "art of analysis" to be a restoration of ancient analysis using "a new vocabulary"[3], the historical connection was gradually lost to mathematicians and scientists enthralled by the potential to bring ancient mysteries of the physical world to the light of day though mathematical analysis.

The three most responsible for this application of the new algebraic analysis to physical science were Descartes, Leibniz and Newton. Descartes' *Discourse on Method* was published in 1637 together with his *Geometry*, which explicated the method used in the *Discourse* and begins, "Any problem in geometry can easily be reduced to such terms that a knowledge of the lengths of certain straight lines is sufficient for its construction." While the result of this approach to geometry was analytic geometry in which geometric problems are transformed into algebraic problems and thus more easily solved, the result of this approach to philosophy in general is a new form of philosophical analysis in which any problem is transformed into algebraic form and then subjected to algebraic decomposition.[4]

Analysis for Leibniz *is* analysis of concepts into their parts until one arrives at simple concepts which have no parts, and which form the foundations of science. Leibniz envisioned facilitating this analysis in the physical sciences with an even more broadly applicable symbolic logic that would transform the unknown and known concepts and propositions in any science into symbolic form, as discussed above. His primary success in this regard was one shared with Newton, both of whom discovered a symbolic representation of motion as functions in what came to be called differential and integral calculus. With this discovery, the application of mathematical method to account for matter and motion was literally complete, as motion became the explicit subject of the new mathematical analysis. Perhaps the clearest statement of this transformation of natural philosophy was the title of Newton magnum opus, *Mathematical Principles of Natural Philosophy*.

Calculus Exposes the Need for a New Logic to Ground Mathematics and Mathematical Physics

However, the highest success of the new mathematical physics – the differential and integral calculus – also exposed its glaring weakness. For the mathematical account of motion achieved by Leibniz and Newton required the use of the concepts of infinity and the infinitesimal to account for the unknown variables in the symbolic representations of motion.[5] Without Aristotelian logic as a framework, such analytical steps were not regarded as absurd if they worked in practice, as Leibniz and Newton found that they certainly did. In fact, despite their condemnation by Bishop Berkeley[6], they were indispensible to the applied sciences, for a precise account of motion was required for any engineering construction that needed to account for moving objects.[7]

As the discovery of the calculus in the late 17th century led to the spread of applied sciences of motion across Europe, the problematic state of logic in relation to the new science gradually grew in concern. The beginnings of the solution to the absence of a logic for expressing the work of the new mathematically treatment of motion was already in place in Leibniz' algebraic conversion of subject-predicate statements into statements of equality. It was with Bolzano at the outset of the 19th century that a broader introduction of algebra into logic, corresponding to the earlier introduction of algebra into science, was set in motion.

For Bolzano, propositions often conceal an inner, semantic structure of multiple propositions that constitute the meaning and intention of the actually spoken or thought proposition. An intense semantic analysis of spoken propositions is thus required to uncover the more basic, atomic propositions that are intended. Bolzano describes this as follows.

> We think a certain representation in itself, i.e. we have a corresponding mental representation, only if we think all the parts of which it consists, i.e. if we also have mental representations of these parts. But it is not necessarily the case that we are always clearly conscious of, and able to disclose, what we think. Thus it may occur that we think a complex representation in itself, and are conscious that we think it, without being conscious of the thinking of its individual parts or beings able to indicate them.[8]

Bolzano's description of this process of semantic analysis in TS, explicated in detail below, is presented as the transformation of propositions into the character of propositions-in-themselves. Bolzano's semantic analysis would lay the broad outline for future axiomatic methods in analytic philosophy that begin with linguistic analysis of what is being said, and then proceed to situate a transformed, symbolic restatement of what is said into an axiomatic system of similarly transformed propositions.

Coffa, who viewed Bolzano as the first of a tradition of philosophers who employed semantic analysis, has presented the clearest articulation of Bolzano's purpose. Coffa answers the question of "the sense and purpose of foundationalist or reductionist projects such as the reduction of mathematics to arithmetic, or of arithmetic to logic".

> It is widely thought that the principle inspiring such reconstructive efforts was epistemological, that they were basically a search for certainty. This is a serious error. It is true, of course, that most of those engaging in these projects believed in the possibility of achieving something in the neighborhood of Cartesian certainty for those principles of logic or arithmetic on which a priori knowledge was to be based. But it would be a gross misunderstanding to see in this belief the basic aim of the enterprise. A no less important purpose was the clarification of what was being said.[9]

The linguistic analysis of the semantic content of statements into their constituent, atomic parts enabled Bolzano and later logicians to articulate proofs from calculus using logic. While the application of mathematics to account for motion in mathematical physics led naturally to an appeal to spatial and temporal intuitions to demonstrate the propositions required in calculus, such demonstrations could certainly not logically ground these propositions for Bolzano. For example, whereas the algebraic approach to motion in the calculus avoided the classical problem of the infinitesimal in measuring motion by simply assigning it a variable in terms of which motion is measured, Bolzano reformulated many proofs from the calculus without reference to intuitionist notions of motion and infinity that are not even intended in the proofs.

The discovery of FOL by Frege, as well, was inseparably bound with the efforts by Frege to provide a logical foundation for modern mathematics and mathematical science. Statements from mathematics, Frege believed along with Bolzano, were bound up with alien intuitions about quantity, motion, infinity, and so on. Through linguistic analysis of the semantics of such statements, the atomic propositions that constitute their actual meaning would be reveals. Frege focused particular attention on the concepts of number and quantity, and analyzed all mathematical statements involving numbers into two constituent statements. First, the item being numbered was revealed to be the most basic element, more basic than the number itself. The numbering of the item followed thereafter.

This was expressed clearly in the grammar of his FOL, of course, as an item (e.g. x) on the basis of which a number property is defined (e.g. $2(x)$). FOL also provided a suitable grammar for expressing the relations between elements of motion and change via its many-termed predicates (e.g. $P(x, y, z)$).

FOL was thus a grammar that became central to the linguistic analysis of statements, particularly statements from mathematics but extending to all statements, into their semantic atoms. It was never meant to be a self-sufficient philosophy, independent of all else. This view of FOL, that conversion into FOL syntax *is* analysis, has led to the misunderstanding of FOL's formality. The notion that the formality of FOL means complete independence of intention or of the semantics of any assertion has taken hold in computer science and artificial intelligence. Yet it is this notion that belies the critical overarching logic of semantic analysis of which FOL is merely a grammar.

5. First Order Logic as Formal *and* Intentional

FOL is universally held to be a formal language. The formalism of FOL, in fact, is often seen as its greatest strength. This property of FOL is what suits it as a foundation for knowledge representation and reasoning in computer science. Information models, such as relational and Semantic Web models, and programming languages, are at their best when they are purely formal, and so leveraging a purely formal logical basis like FOL makes sense. Brian Cantwell Smith, who is most associated with the critique of the assumption that computer science is formal, makes the following observation.

> In one way or another…, just about everyone thinks that computers are formal – that they manipulate symbols formally, that programs specify formal procedures, that data structures are a kind of formalism, that computational phenomena are uniquely suited for analysis by formal methods. In fact the computer is often viewed as the crowning achievement of an entire "formal tradition" – an intellectual orientation, reaching back through Galileo to Plato, that has been epitomized in this century in the logic and metamathematics of Frege, Russell, Whitehead, Carnap, Turing, etc. [10]

However, a clear, consistent definition of formality is difficult to find in either logic or computer science. According to Smith, "Almost a dozen different readings of 'formal' can be gleaned from informal usage: *precise, abstract, mathematical, a-contextual, digital, explicit, syntactic, non-semantic, etc*". [10] What generates the broadest agreement is the claim that formal languages are independent of the meaning, semantics or intention of particular assertions that can be made with a formal language.

However, this assumption that formality implies complete independence from meaning, semantics and intention needs to be called into question. Smith, for one, argues that "*the word 'formal' has never meant independence of syntax and semantics in the way that the Formal State Machine claim [about computing] construes it*". In fact, claims Smith, it is the lack of a precise definition of formality that has allowed such "a cluster of ontological assumptions" to be imported into computing and information models. [10]

Smith's claim that computing is fundamentally an intentional and semantical activity, and that information modeling and programming languages are thus fundamentally intentional and semantical, is backed up by the reports of prominent logicians that FOL is itself intentional.

We thus find Russell arguing that "logic is concerned with the real world just as truly as zoology, though with its more abstract and general features". [11] We see a similar claim in Wittgenstein ("Just as the only necessity that exists is logical necessity, so too the only impossibility that exists is logical impossibility") [11].

The most prominent textbook logician of the 20th century, Copi, even makes this claim. "Contemporary logic is both formal AND intentional. It is, in a sense, correct to say that formal logic deals with *forms*, since its products are *formulas*". [12]

Copi's identification of the subject matter of formal logic as forms is a helpful first step in exploring the nature of the intentionality of FOL. For if FOL is not completely independent of semantics and intention, the predominant information modeling practices today that are heavily reliant of FOL must account for the intentional assumptions of FOL, an account which this paper has attempted to provide.

6. Conclusion

This paper has critiqued the use of first order logic in computer science and sought to redirect this use of logic based on an examination of the history of logic. Since the introduction of independent data storage mechanisms in the 1970s, logic has been used to model new and more predicates in information systems, both relational databases and AI-based triple stores using RDF and OWL. This use of first order logic is not faithful to the larger purpose of first order logic which is found in the project of semantic analysis for which FOL was a tool. It was claimed that the purpose of FOL was never to express any and all predicates that could ever been spoken or written. Rather, FOL provides a grammar suitable for expressing the results of semantic analysis. If computer science and artificial intelligence seek fidelity to logic, then semantic analysis must become a central discipline and critical first step in computation. The paper reviewed approaches to semantic analysis and made recommendations for the future of semantic analysis. Finally, a thorough history of the concerns of modern logic that led to semantic analysis and FOL was provided, with a concluding revision of the common misconception that the formality of FOL implies lack of intentionality or semantics in FOL.

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[1] This formulation of the threefold division of the theoretical sciences closely follows that described by Aquinas in his *Commentary on the De Trinitate of Boetheus*, p. 14-15.

[2] As Grant explains while describing what was revolutionary in Newton's *Mathematical Principles of Natural Philosophy*, "To devote a treatise to ascertaining the mathematical principles of natural philosophy qualified as a virtual contradiction in terms. Why? Because natural philosophy in the medieval Aristotelian tradition did not – and could not – have mathematical principles." Grant, Edward. *A History of Natural Philosophy*. P. 313.

[3] "Behold, the art which I present is new, but in truth so old, so spoiled and defiled by the barbarians, that I considered it necessary, in order to introduce an entirely new form into it, to think out and publish a new vocabulary, having gotten rid of all its pseudo-technical terms." Quoted after Klein 1992, 318f.

[4] Descartes' Rule Thirteen describes this new form of analysis, "If we perfectly understand a problem we must abstract it from every superfluous conception, reduce it to its simplest terms and, by means of an enumeration, divide it up into the smallest possible parts". *The Philosophical Writings of Descartes*, I 51. ed. & tr. J. Cottingham *et al.*, Cambridge: Cambridge University Press, Vol. 1 1985, Vol. 2 1984, Vol. 3 1991.

[5] More specifically, the concepts used were the "fluxions" of Leibniz and the "differences" of Leibniz, which today are known as derivatives and differentials and which required the use of the concepts of infinity and the infinitesimal.

[6] "And what are these fluxions? The velocities of evanescent increments. And what are these evanescent increments? They are neither finite quantities, nor quantities infinitely small, nor yet nothing. May we not call them the ghosts of departed quantities?" *The Analyst*, Bishop Berkeley, in Ewald, William, ed., 1996. *From Kant to Hilbert: A Source Book in the Foundations of Mathematics, Vol. 1*. Oxford Uni. Press.

[7] Derivatives and differentials "are the principal concepts of a mathematical discipline which, together with analytical geometry, has grown to be a powerful factor in the development of the applied sciences: the Differential and Integral Calculus." Dantzig, Tobias, *Number*, p. 136. Pi Press, 2005, New York, NY.

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