War of Ontology Worlds: Mathematics, Computer Code, or Esperanto?

Andrey Rzhetsky1,2,3,4*, James A. Evans4,5

1 Department of Medicine, University of Chicago, Chicago, Illinois, United States of America, 2 Department of Human Genetics, University of Chicago, Chicago, Illinois, United States of America, 3 Institute of Genomics and Systems Biology, University of Chicago, Chicago, Illinois, United States of America, 4 Computation Institute, University of Chicago, Chicago, Illinois, United States of America, 5 Department of Sociology, University of Chicago, Chicago, Illinois, United States of America

Abstract: The use of structured knowledge representations—ontologies and terminologies—has become standard in biomedicine. Definitions of ontologies vary widely, as do the values and philosophies that underlie them. In seeking to make these views explicit, we conducted and summarized interviews with a dozen leading ontologists. Their views clustered into three broad perspectives that we summarize as mathematics, computer code, and Esperanto. Ontology as mathematics puts the ultimate premium on rigor and logic, symmetry and consistency of representation across scientific subfields, and the inclusion of only established, non-contradictory knowledge. Ontology as computer code focuses on utility and cultivates diversity, fitting ontologies to their purpose. Like computer languages C++, Prolog, and HTML, the code perspective holds that diverse applications warrant custom designed ontologies. Ontology as Esperanto focuses on facilitating cross-disciplinary communication, knowledge cross-referencing, and computation across datasets from diverse communities. We show how these views align with classical divides in science and suggest how a synthesis of their concerns could strengthen the next generation of biomedical ontologies.

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Introduction

Historically, ontology was defined as philosophical inquiry into the nature and categories of existence. At the turn of the 20th century, logicians extended and formalized the notion of ontology as a system for describing entities that exist in the world [1], their properties, interrelations, and inferential mechanisms for reasoning about them. In the 1990s, computer scientists reinvigorated and popularized the term by applying it to a wide range of machine-readable knowledge representations. Ontologies could be reused and shared as information schemas [2]. With the rise of scientific databases that are increasingly complex and persistent

and require interoperability, ontologies have become enlisted in scientific databases that are increasingly complex and persistent reused and shared as information schemas [2]. With the rise of machine-readable knowledge representations. Ontologies could be reused and shared as information schemas [2]. With the rise of scientific databases that are increasingly complex and persistent and require interoperability, ontologies have become enlisted in scientific databases that are increasingly complex and persistent.

An example of a biomedical terminology is the American Medical Association’s list of Current Procedural Terminology (CPT) codes [3–6]. A commonly used taxonomy is the International Classification of Diseases (ICD), which organizes disease categories by hierarchical “is-a” relations (e.g., “Breast Cancer is-a Malignant Neoplasm”) [7]. Progressively richer formal ontologies with multiple types of relations include the Gene Ontology (GO), used to annotate gene products from many model organisms. The GO contains hierarchical “is-a”, “part-of”, and “regulates” relations [8]. Even more involved is the Foundational Model of Anatomy (FMA), which contains a rich set of entity properties and relations that correspond to the networked components of the human body [9], and the BioCyc and MetaCyc ontologies that describe genetic, regulatory, and metabolic cellular pathways of various organisms and enable formal reasoning across those paths [10]. There is disagreement in the community, however, about even these classifications, with some viewing ICD and GO primarily as controlled terminologies with minimal, inconsistent structure.

Ontologies are used for a variety of purposes, from billing patients for medical procedures by a hospital (CPT, ICD) to annotating experimental findings with computer-readable codes for biomedical applications (GO) to reasoning across annotated findings for novel insight (FMA, BioCyc). Biomedical ontologies are often engineered by heterogeneous groups of computer scientists, bench biologists, bedside physicians, programmers, philosophers, and self-identifying ontologists we hereafter collectively refer to as “ontologists.”

Ontologists frequently collaborate on large ontology projects like ICD or GO, but their assumptions about the same ontologies are not universally shared. Publications and conferences about ontologies typically focus on the details of ontology construction and use, but rarely provide a setting for experts to reflect on their understanding of ontologies as knowledge representations. When public reflection does occur, it often escalates to a scuffle of emotionally charged opinion. In seeking to elaborate and compare assumptions about ontologies, we collected and recorded views.

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* E-mail: arzhetsky@uchicago.edu or arzhetsk@medicine.bsd.uchicago.edu
from 14 leading ontologists, selected based on their stature within
the ontology community and the diversity of their perspectives.
This essay reflects an attempt to summarize the wide range of
ontology worldviews revealed through these expert interviews and
reflected in ontology projects today. Our summary takes the form
of three archetypal views or caricatures that highlight essential
differences. While at least two ontologists formulated strong
versions of each archetype, others expressed intermediate views.
We argue, however, that virtually every current perspective could
be represented as a weighted mixture of these three archetypes,
much as color visible to the human eye can be expressed as
varying intensities of red, blue, and green.

Several characteristics of ontologies were valued widely within
the community. For example, all agreed that a good ontology
should be logically consistent, structurally acyclic, parsimonious,
and elegant. Nevertheless, our informants placed different weight
on these virtues and several desired qualities that conflicted with
them. Based on these differences, ontology views cohere into three
groups that we call mathematics, computer code, and Esperanto.

Table 1 summarizes the primary training and views of the
ontologists we interviewed. Many of those interviewed, whose
primary training was in linguistics or computer science, are now
predominantly working in computational biology or clinical and
biomedical informatics.

**Mathematics: Ontology as Formal Theory**

The mathematics view places a premium on formal consistency in
ontologies, with the goal of computational reasoning across them.
Some with this view held that a single, unifying ontology covering
the whole of biology and medicine is possible to design and
desirable to pursue. This unifying ontology need not be complete,
and should focus on consensus or uncontested, established
knowledge across biomedicine in order to approximate the
“underlying reality.” One ontologist holding this position argued
that unless you have a core of terms and relations which is
universally valid, however small it might be, then you’re always
going to have a certain kind of slack in your ontology—the
ontology is always going to fall short of being rigorous in the way
that arithmetic or even statistics are rigorous.”

This view holds that there is no need to represent uncertainty,
hypotheses, or speculations. If probability in representation is
combined with a probabilistic form of inference, “then you’re going
to end up with two successive layers of uncertainty, which will mean
that the results will be of quite low value.” First-order logic and
computationally tractable subsets of logic are viewed as appropriate
tools for conducting inference across rigorous ontologies.

Ontologists voicing the mathematics position agreed that despite
the current, “chaotic” diversity of ontologies, “every ontology ever
built should have the same upper level [ontology], ideally.” In this
view, upper level ontologies should precisely define basic
categories, such as entities, characteristics, and processes. A few
candidates for the role of the upper-level ontologies exist currently
e.g., BFO [11], SUMO [12–14], Cyc [15]). Those sharing the
mathematics view believe that upper-level ontologies will compete
for scientific attention until the best emerges and wins out.

**Computer Code: Ontology as a Custom Code**

Another group of ontologists argued that ontologies should be
designed specifically for a range of special or general purposes, like the
programming languages Prolog and C++ and the mark-up language
HTML. One ontologist intimated this metaphor when he revealed
that “I view ontologies primarily as software artifacts.” From this
perspective, an ontology should primarily aim to serve its function and
intended user community, even if small. The specific design choices
made in order to achieve the desired utility were viewed as secondary.

This view explicitly opposes the goal of designing a unified
ontology for the whole of biomedicine. Instead, the number of
ontologies should be equal to or greater than the number of distinct
biomedical problems and research needs requiring structured
knowledge representation. The most reflective in this cluster
described ontologies as “post-modern” traces of conception; “human
constructions” assembled to fulfill different needs in distinct social and
technical environments rather than “grounded in absolute reality.”

One ontologist voiced a concern common to several when he
stated that “overly abstract mathematical ontologies provide a
false sense of certainty. They obscure distinctions that might be
useful to a particular task, and make unnecessary distinctions.”
Practical value should then trump mathematical elegance. These
experts considered abstract, upper-level ontologies as so discon-
ected from the real world that they were dubious about their
utility.

Playfully gesturing to Mao Zedong, one ontologist proclaimed
“Let a thousand flowers bloom,” suggesting that users should be
encouraged to create their own custom ontologies, and that these
should be evaluated with regard to usability and efficiency in the
case of a specific problem. Computer code placed little value on
unification, believing that all ontologies can coexist in peace.
Medical, clinical, and bioinformatics researchers, as well as the
biologists in our sample, most commonly held the view of
ontologies as computer code—crafted for specific medical or
biological projects.

**Esperanto: Ontology as Communication Tool**

The ontology as Esperanto perspective holds that ontologies
should facilitate cross-community communication, much like

### Table 1. Training and Views of Ontologists Interviewed.

| Primary Training                    | #    | Mathematics | Computer Code | Esperanto |
|------------------------------------|------|-------------|---------------|-----------|
| Computer Science/Artificial Intelligence | 3    | 1+5+5      | 5+5          |           |
| Linguistics                        | 3    | 3           | 5+5          | 1+5+5     |
| Philosophy                         | 1    | 1           | 1            |           |
| Clinical and Bioinformatics        | 4    | 1+1+1      | 1            |           |
| Biology                            | 3    | 5           | 1+5          | 1         |
| **Total**                          | **14** | **3.5**    | **6.5**      | **4**     |

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Esperanto, the language constructed by Leyzer Zamenhoff at the end of the 19th century to be easy to learn and politically neutral, is held by some to be a model for how ontologies should interact between areas, even if imperfectly. This perspective is motivated by the possibility of making data computable over fields, experimental techniques, countries, and time periods.

Researchers holding the Esperanto view believe that the goal of a single, unified ontology is unrealistic, even if in an ideal world it might facilitate universal scientific communication. The only practical solution is “a federated interlinkage ... a grid of ontologies and vocabularies” made possible primarily through attempts to “invoke concepts that are embedded in another ontology, actually use that ontology to describe that thing.” Like Esperanto, which borrows most of its vocabulary from common, natural languages, this approach of systematically borrowing terms between ontologies is viewed as essential to create productive overlaps that reduce redundancy and facilitate cross-communication. In this scheme, not every term in every ontology is mapped to another, but the mapping is sufficient to enable researchers to compute across datasets as a whole.

Unlike mathematics, where a single person can construct a novel, consistent system (e.g., Hipparchus alone may have invented the foundations of trigonometry), those espousing the Esperanto view believe that to best further biomedical science, ontologies must integrate information widely distributed across research labs and communities. In this view, successful ontology creation requires more than deep domain knowledge and design precision. It also requires diplomatic social activity to coordinate between scientists and fields. An ontology is most useful if it not only helps users perform their work, but also facilitates continuing communication and commerce with the rest of the scientific world. Otherwise it is isolating, and those who use it will neither benefit from nor contribute to advances made elsewhere. Among those interviewed, researchers with linguistics training most frequently held the view of ontologies as Esperanto—facilitating not only scientific clarity but also communication.

How These Groups View One Another

These three ontology perspectives respond directly to one another. In several cases, ontologists drew contrasts explicitly, but in some cases we infer likely differences. On the one hand, ontology as mathematics suggests that computer code and Esperanto approaches are messy and inconsistent, even “silly and childish.” From this perspective, Esperanto and computer code ontologies are inefficient to improve because they lack a clear means of evaluation like logical consistency. One can rarely reason over an ontology produced from these other approaches without using probability to allow for contradiction and error. On the other hand, ontology as computer code and Esperanto view the mathematics approach as utopian, of little practical use, and even potentially sinister: “one mother ontology to serve all purposes and in the darkness bind them.” Specifically, the computer code approach sees mathematics ontologies as incomplete and unrepresentative of relevant knowledge in an area, and hence unproductive. Mathematics ontologies come off as rigid and artificial to domain experts.

The Esperanto approach views the computer code zeitgeist as eclectic “chaos,” multiplying unnecessary redundancy, and failing to exploit natural opportunities to link knowledge across areas. The mathematics approach views Esperanto efforts to integrate domain-specific ontologies as compromising half-measures that abandon the potential strength of unification.

Parallel Divisions

Reminiscent contrasts have animated fierce debates elsewhere in the history of science. In 17th century Europe, the mechanical philosophers, including Descartes, Hobbes, and Spinoza, favored a systemic, logico-deductive approach to science committed to certain truth. This differed from the experimental philosophers, including Bacon, Boyle, and the fledgling Royal Society, that favored experiments and the establishment of a looser, probabilistic notion of truth surrounding the social establishment of “facts” [16]. This also parallels the 1980s fight between “Neats” and “Scruffies” in the Artificial Intelligence (AI) community [17].

Mechanical philosophers and Neats are close to the mathematics group in the ontology community, seeking provable solutions—although logical consistency is typically sufficient to satisfy many in the mathematics ontology community. Experimental philosophers and Scruffies are closest to the computer code group: they rely on heuristics and the metaphor of probability rather than certainty, claiming that a collection of useful, heterogeneous methods is enough [18].

No direct analog to the Esperanto group exists in AI, but scientific communication projects like review journals have long attempted to facilitate knowledge transfer between domains. Novel challenges have arisen from rapid growth in the number of biomedical scientists and subcommunities over the past half century. Counteracting this trend, the informatics revolution of the past 20 years has created novel opportunities to link information across these domains. With the rise of the Internet and computing power, natural language processing (NLP) methods have increasingly enabled researchers to extract information from older articles and books, which makes it available for computational modeling. While this new source of old information enables a much richer view of the ontologies underlying scientific discourse, it poses challenges and suggests new opportunities for how to construct, evaluate, and use ontologies to further biomedical advances.

Ontology Challenges Posed by Text Mining

First, multiple levels of representational granularity coexist across a scientific corpora and often in a single text. For example, a protein methylation event occurring within a human cell may appear in a molecular biology article as a binary relation between an enzyme and the substrate protein (e.g., “PRMT5 methylates histones H3 and H4”). In a chemical article, methylation is more likely to be described as a multistage process involving additional molecules such as the methyl group donor and transient complexes. If we extract information from text we cannot commit to a single level of representation for a phenomenon if we intend our information to retain the fidelity it possessed in its source.

Second, diversity and disagreement persist within scientific communities—and sometimes even scientists—for long periods and sometimes indefinitely [19]. If we attempt to extract information from text without arbitrary censorship, disagreement must be retained.

Third, objects described in ontologies change in time, so their mentions in text may refer to a spectrum of objects rather than a single one. For example, the Aral Sea, once the fourth largest lake in the world, was reduced to 10% of its original size in just a few years as a result of Soviet irrigation projects; its contour changed dramatically, daily. Even astronomical objects are not immutable: Earth’s perspective on the Big Dipper will change radically in the coming 100,000 years.

Fourth, theories and their symbols change in time. This is not a problem for ontologies that eschew representation of uncertain theories. It becomes a problem, however, if we want to represent
the current state of scientific knowledge. In cell biology research, when tubulin, the globular protein involved in microtubule construction, was discovered, “tubulin” pointed unambiguously to a unique gene and its product. Within the subsequent decade, many other tubulins (α-tubulin, β-tubulin, etc.) were discovered such that “tubulin” now refers to the entire family. Claims about tubulin from the early period become ambiguous with respect to a later ontology.

These challenges suggest a new virtue, most consistent with the Esperanto perspective: representativeness [20]. Insofar as ontologies are employed not only to index biomedical knowledge, but to discover it, they must maintain inconsistent biomedical claims, just as research scientists attempt to do. Inconsistencies should not be ignored, as they point to theoretical weaknesses and opportunities.

In conclusion, we suggest the importance of attending to all three ontology perspectives. Mechanical and experimental philosophers, and Neats and Scruffies advanced science by incorporating the concerns of both. We propose that the usability of an ontology for a particular community and purpose should not be compromised. Additional efforts to maximize an ontology’s mathematical rigor, given this usability, however, will improve its reuse and facilitate novel, integrative efforts that enable analysis and discovery across the fields of biomedicine.

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Authors’ Biographies
Andrey Rzhetsky is a computational biologist at the University of Chicago. He has worked on mathematical modeling for evolutionary biology, approaches to the analysis of large molecular networks, and massive mining of biomedical literature.

James Evans is a sociologist at the University of Chicago whose research focuses on metaknowledge—how social, cultural, and technological institutions shape knowledge and are shaped by it. He is particularly interested in the heuristics by which scientists and their patrons approach research and their consequences for science. Evans also works to develop novel methods to extract, represent, contextualize, and compute over knowledge.