

CREATING A UNIVERSAL INFORMATION LANGUAGE

OSCAR BENDER-STONE

ABSTRACT. Welkin is a formalized programming language to store information. We introduce its use cases and rigorously define its syntax and semantics. From there, we introduce the bootstrap, making Welkin completely self-contained under the meta-theory of Goedel’s System T (equi-consistent to Peano Arithmetic).

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1. INTRODUCTION

Undergraduates are taught many things in lecture, books, and papers, but there is one unspoken truth: researchers have extremely *diverse* communities. Each community has their own approaches, their own conferences, and their own formatting. They even have a distinct preference to chalk, dry erase marker, or neither. For a long time, I didn’t notice this aspect about research. I started my mathematics journey in secondary education, independently reading papers from set theory, logic, and more. I was fortunate to have vast archives available on the internet, but my ability to *collaborate* in research was limited. This quickly changed in college[TODO: maybe make this a stronger sentence?]. Everywhere I went, I saw the multitude of research groups, from those mentioned in lecture to the experiences I worked in to the faculty panels in the COSMOS math club. I worked in several research groups and found how rich and fulfilling each was. This fundamentally changed my perception of research as a whole. I learned that diversity *drives* research, including in the sciences, liberal arts, and many more subjects I have hardly explored.

Because of how diverse research is, these communities are extremely independent and build separate repositories of knowledge. For example, I wrote a poster for a cryptography class, concerning an MIT researcher who created programs of common cryptographic schemes and mathematically proved their correctness. I met this

researcher at a conference and discovered that *neither* knew about the other! They provided their own contributions, but I initially assumed that *everyone* contributing to cryptography work on common projects. As another example, at my time in the Budapest Semesters in Mathematics, I explored a key tool in program verification to find proofs for a combinatorial problem. According to my advisor, that approach had *never* been considered before. The boundaries between these communities isn't so clear, and it seems to take years to begin to *remotely* find them.

The separation of these communities raises a key question: *can* knowledge across disciplines be bridged together?

In addition to this [FIRST CLASS OF PROBLEMS NAME], another major hurdle is truth management. [DISCUSS Problems with truth + corrections from papers don't propagate!] What can be done is addressing *information*, the storage of the *asserted* facts themselves, regardless of truth. As one example, suppose a scientist claims, "X is true about Y". One could debate the veracity of that claim, but what we can say is, "This scientist claims, 'X is true about Y'". Even if we doubt that, we could do: "This claim can be formulated: 'This scientist claims 'X is true about Y''". By using these justifications, stating that a claim is expressible, the *syntactic expression* of the claim can be separated from its *semantic truth value*.¹ I will make this more rigorous in later sections, but this enables a truth checking to be a *flexible extension* to an information system.

Information systems have been extensively studied via *measurements* in Algorithmic Information Theory (AIT). The founding idea of AIT is Minimum Description Length (MDL) principle, that the best definition for an object is the smallest thing that describes it. This is formalized as Kolmogorov complexity of a binary string, the length of the smallest program that computes that string. Being described by a smaller program indicates a string that is easier to describe and thus has less information. But being described by a larger program indicates more *randomness* string and thus more information. A modern figure in this field, Chaitin, describes this relationship as compression. He states this as follows: "A useful theory is a compression of the data; comprehension is compression" [1]. I do not define the claim that comprehension is compression, as that creates similar problems with managing truth. Instead, this is a statement on *representations*, the best we can do with Turing machines as an established notion of computability. [LIST CONTRIBUTIONS OF AIT. WHAT IS GOOD]. [GOOD TRANSITION TO NEXT PARAGRAPH]

- Summarize information theory here. Let's get the intro done in one place (besides goals and organization)! May be easier to focus on AIT (Algorithmic Information Theory) for our purposes.
 - Main problem: *how* do we manage information? This thesis is ALL about the organization of information! That is, reuse! This is exactly in line with compression, but the *how*!
 - * Connects back to Turing machines - we can *use* Turing machines as our

¹One might be worried about a paradox, such as "This claim is expressible: this claim is not expressible." We will avoid this using a clear separation of the overarching metatheory and object theory, with the former being syntactical in nature. To express this separation, we write quotes around the claim itself.

“generalized theories”. Main philosophy: represent things by how they are *checked*. So this is done by a total Turing machine!

- * We also need *computable* ways to encode, which is what Chaitin’s theory describes. But it doesn’t show us *how* to organize things!
- * Also helps to explain overhead in representing things. Might be different depending on base representation used. Chaitin says this doesn’t matter in the limit (CITE.) **The goal of this thesis is to RESOLVE this problem, on the query end!**
- Why is Chaitin’s work so useful here? Because it explains WHAT EXACTLY we need in the metatheory! **Enough information to encode itself to talk about all other theories!**
 - * Address Trusted Computing Base here or in next paragraph!
- Main point from Chaitin: need an *open* model for theories, NOT a closed one.

Although AIT has major accomplishments with measuring information, this field does not indicate *how* to measure information. [DISCUSS CONNECTION TO ORGANIZATION. MAKE THIS A KEY WORD FOR THE WHOLE THESIS!]. The main theorem on this is that any programming language can be used to prove these claims. These translations have not been specifically addressed in the literature, and remain a prolific part in software for actual machines. [DESCRIBE PROBLEMS HERE CONCISELY.]

Our inquiry can now shift onto a formal representation of information. Formal representations, in general, are sets of strings that are computable, i.e., accepted by a computer. The standard notion of computability is being computed by a Turing machine, and by taking this, we are now *exactly* discussing the problem of interoperability of programming languages. These, too, are extremely distinct and built for different purposes. Semantic preserving and reflecting translations between these, also known as *transpilation*s, are incredibly difficult, as they are generally equivalent to the Halting Problem. An alternative approach is to create an Intermediate Representation (IR) that other languages can compile into (*frontends*), and then compiled onto multiple machine architectures (*backends*). The driving standard in industry and research for this purpose is the LLVM compiler project [2]. However, this project faces ongoing challenges, with a brief list including breaking changes and a massive packaging task across different Operating Systems. One approach that addresses a subset of these problems is MILR [3], another IR to abstract away from the original. Implementing these systems for *general* programs is not the intent of this thesis, and instead, is to *bridge* information *about* programs. Therefore, we are interested in *unifying representations* of these languages.

To demonstrate the difficulty of a unified representation, we provide an example with Python and C Listing 1. [PROVIDE DETAILS ON EXAMPLE] Using LLVM IR would not remove this issue. The fundamental differences in memory management would persist, and while this is possible to some extent, it’s not completely seamless. Manual work is generally required. [TODO: what manual work? Why?]

```

int main() {
    return 0;
}

def main():
    pass

if __init__ == "__main__":
    pass

```

LISTING 1. Example programs in C (left) and Python (right).

Creating bridges between formal representations does require a historical change in perspective: *embracing reflection rather than focusing on a single theory*. This train of thought comes from Universal Logic, initiated by Béziau [4]. Previously, during the rapid expansion of foundations in the 20th century, logicians sought the “one true logic”, a system to be the basis for all mathematics. Such a system was quickly shown to be impossible by Gödel’s incompleteness theorems, with certain results requiring an infinite chain of increasingly more powerful theories. But this was a symptom of a larger problem: translating into the *exact* language of a base logic can be unnatural, just as it is unnatural to represent quotient types in Rocq without an additional theory ontop. To work back in the original logic, a key requirement is *faithfulness*, that isomorphisms in a theory must be reflected, a notion called “ ε -representation distance” by Meseguer [5]. However, the researchers surrounding Universal Logic are, too, their own community, and have their own broad definition of a logic, which is distinct from those in Categorical Logic, Type Theory, and others.

Beyond Universal Logic, a further leap is needed, from the idea a *universal theory* to *universal building blocks*. To support the wide diversity of languages, a spectrum of these building blocks, which we consider to be *information*. This thesis creates a universal information language for this purpose, to express information about *any formal representation*. This includes improving the representation itself!

Our overarching architecture is based on a key idea: separate *cheap queries* from *expensive search*. We develop the entire theory of queries and enable arbitrary extensions to the search procedures. This is inspired by and generalizes DPLL(T) [6] for SMT-LIB solvers. In DPLL(T), the goal is to find a proof of a first-order statement into two parts: solve propositional statements in a SAT solver, and solve theory-specific problems with theory solvers.

In addition to this architecture, we establish a small Trusted Computing Base (TCB). In our base logic, uses a novel technique: Artemov’s Logic of Proofs [7]. This establishes our metatheory, which is equi-consistent to [TODO: find this!] (Section 2). [TODO: talk about prototype! Key!]

1.1. Goals.

The aim of this thesis is to create a universal information language to standardize *all* formal representations. I call this language **Welkin**, an old German word meaning cloud [8]. This aim will be made more precise in the later sections, where we will formally define a verifier for a programming language.

- **Goal 1:** universality. This language applies to ANY checker. Needs to be extremely flexible towards this goal, so we can ONLY assume, at most, we are getting a TM as an input, or it’s somehow programmed.
- **Goal 2:** standardized. Needs to be rigorously and formally specified.

- **Goal 3:** optimal reuse. With respect to some criterion, enable *as much* reuse on information as possible.
- **Goal 4:** efficiency. Checking if we have enough information *given* a database much be efficient!

1.2. Organization.

- Section 2. Foundations: define the meta-theory used + verifiers. Also outline the Trusted Computing Base.
- Section 3. Information Systems: explore information in the context of verifiers. Then synthesize a definition to satisfy Goal 1.
- Section 4. Information Reuse. Develops the optimal informal system (w.r.t to a metric defined in this system) to satisfy Goal 3.
- Section 5. Syntax: Go over the simple LL(1) grammar, which is similar to JSON and uses python syntax for modules.
- Section 6. Semantics: Defines information graphs and their correspondence with the optimal informal system in Section 3.
- Section 7. Bootstrap. Fulfill Goal 2 with both the Standard AND the complete bootstrap.
- Section 7. Prototype. Time permitting, develop a prototype to showcase the language, implemented in python with a GUI frontend (Qt) and possibly a hand-made LL(1) parser.
- Section 8. Conclusion. Reviews the work done in the previous sections. Then outlines several possible applications.

2. FOUNDATIONS

Our first step is to define the set of verifiers, a subset of the computable functions. Based on our architecture to separate *query* from *search*, we focus this subset to primitive recursive functions.

To explore verifiers, we need a reliable metatheory, establishing our logical TCB. How can we establish what *reliable* means? [TODO: cite that ZFC, or ZFC + inaccessible, is common in literature.] However, each of these are *specific theories*, and while ZFC + inaccessible likely suffices for, e.g., formal verification, what about other subjects? We want to make this *as extensible* as possible, akin to an infinite hierarchy of theories via reflection. So we will need a different approach.

The key problem to reliability is, while we can easily verify if a given input is accepted by a verifier, how do we tell when there is *no* such input? We use a novel criterion developed by Artemov's Logic of Proofs [7]. [TODO: bridge this with selector proofs. Also, make sure to explain WHY the arithmetic hierarchy is enough. We JUST want to explore properties of naturals. We can't do beyond. But we should prove this!]

This is where our metatheory come in. [TODO: explore arithmetic hierarchy briefly? How do we know *which* results on computability are trustworthy? This is ESSENTIAL for the TCB!]

2.1. Logic of Proofs.

2.2. Computability.

2.3. Verifiers.

Given a partial computable function φ , let $L(\varphi)$ be the language recognized by φ .

Definition 2.3.0. An **effective verifier** is a Turing machine that runs in linear time and it accepts an input *must* have read the entire input.

In a refined form of Kleene representability, we show that every RE set corresponds to an effective verifier in an important way.

Lemma 2.3.1. *For every RE set S with recognizer φ , there is an effective verifier V_φ such that $x \in S$ iff there is some trace t that starts with x and $t \in L(V_\varphi)$.*

For the rest of this thesis, all verifiers mentioned will be effective. Note that we will return to practical verifiers, those with realistic constants.

3. INFORMATION SYSTEMS

Now with our meta-theory in Section 2, we can proceed to discuss information systems.

- Now can study the set of *verifiers*. A universal verifier is a verifier of a UTM. So we only need *one* such verifier. We encode the TM AND the input in question, and then simulate the whole TM.
 - Same problems as before: *how* do we organize this?
 - Instead of asking what information is broadly (we'll come back to that in the overarching semantics), we want to ask, what is information *for verifiers*?
 - * Recall translation from before: we *define* things by how they *are checked*. To information on mathematical objects corresponds to *information on how they are checked*.
 - . By how, this includes:
 - *what* things are/are not checked.
 - If it speeds it up/is a slow route.
 - . We capture this how by defining information *as* a relation between an input and a language *per* a trace.
 - . Current idea in a formal setting: *information are traces*.
 - Broadly treat information *as* a relation. Manifested as traces to include source, target, *and* steps inbetween.
 - Problem: this isn't efficient! Come up with non-trivial examples that, while we discern here, doesn't resolve the problem!
 - Also note: may not be *nice* w.r.t. certain systems. E.g., for sequent calculus, composition may not be guaranteed! So we can say a composite exist if *some* steps inbetween do, but this isn't always nice! Not *isomorphic* to sequent calculus proofs (depending on the system)! TODO: cite Strassburger deep inference paper to cite this issue and his approach.

- Currently: we treat *proofs* as being traces. Need to resolve in the meta-theory!
- Assuming we have a representation for traces (maybe via lambda terms? Review!),

we can look at the space of *all* these traces.

- HOW do we organize them? They are *base* information, but pretty dense.
 - Inefficient with equivalence modulo labeling
 - So we explore information systems based on these bounds:
 - (1) explicit = trace(s) \leq faster trace 1 \leq faster trace 2 \leq ... \leq implicit = statement of problem (x in S)
 - * TODO: create diagram that highlights this! Make the outer circle the problem, Halting instance, and then the center is the set of explicit traces. When we union these, then the an explicit trace in one machine is the implicit one for another - maybe show this in a simple lemma?
 - * ... ensured by Blum's speedup theorem - we will make this result self-contained + define Blum complexity measures!
 - * Consider *statement* of problem to be "most implicit" by fiat: even if we use a proof search approach (so this may NOT halt) or use more uncomputable means, that still adds "extra" to the search itself.
 - * Note that \leq here is NOT necessarily implication; we are more thinking about a rough *measure* of being an *exact* trace of a TM
 - * Blum [9] says you can always do better (*in general*).
 - . Cite example: palindromes! Easy to discuss on efficiency
 - * TODO: show that this corresponds to *shorter traces*, fixing the main measure as the size of the trace. Again, to separate *query* from *search*, we do NOT want to involve any aspect of time, so the main other attribute is the space itself.
 - Our goal: how to organize when we have a **space** of things like (1) that are *interconnected*?
 - Old approach (diagram!): show that people had *different* ways to tackle the stuff in-between. That's where most theories like (e.g., dependently typed theories, HOL, etc.)
 - New approach: separate *query* from *search*! Unify the previous approaches by focusing on optimizing the *left side* that we *can* control effectively

3.1. Motivating Examples and Definition.

We start with simple informal examples to explore the concept of information:

- Statements about the world.
- Taxonomies.
- Mathematical relations.
- More sophisticated: formal theories.

Each of the previous examples suggests a common definition: *information is a relation*. However, we want to express any formalizable kind of information. A binary relation *can* encode any other computable one, but not without clear reasons or connections.

We add this missing component by using triadic relations instead, building off of semiotics and related schools of thought.

Definition 3.1.0. An **information system** is a pair (D, I) , where:

- D is the **domain**, a finite, computable set of **data** in \mathbb{N}
- I is **(partial) information**, a partially computable subset of $D \times D \times D$. This information is **complete** if I is totally computable.

3.2. Constructions and Reflection.

Let **Info** be the set of all information systems.

A natural construction to include is a system with *indexed information*, akin to indexed families of sets. But we want to have information between information as well. We can think of a disjoint union of systems as the weakest transformation between systems.

Definition 3.2.1. Let $\mathcal{S} = \{(D_i, I_i)\}_{i \in \mathbb{N}}$ be a family of information systems, indexed by a partial computable function. Then the **sum** of \mathcal{S} is $(\bigcup D_i, \bigcup I_i)$. A **transformation** on \mathcal{S} is an information system $(\bigcup D_i, I')$ such that for each $i \in \mathbb{N}$, $I' \cap (D_i \times D_i \times D_i) = I_i$.

As another construction, we can naturally model formal systems by asserting that I is reflexive and transitive in a general sense, formalized by below.

Definition 3.2.2. A **formal system** is an information system such that the information relation is reflexive and “transitive in a general sense” (WIP).

This construction is **information compressing**: we can computably encode information into a different representation and computably decode it back.

Special systems:

- (\emptyset, \emptyset) is the **null information system**
- $(\mathbb{N}, \mathbb{N} \times \mathbb{N} \times \mathbb{N})$ is the **discrete information system**

Lemma 3.2.3. Let $\mathcal{H} \equiv (\mathbf{Info}, \leq)$, where $(D_1, I_1) \leq (D_2, I_2)$ iff $D_1 \subseteq D_2$ and $I_1 \subseteq I_2$. Then \mathcal{H} forms a Heyting Algebra, with bottom element being the null information system and the top element being the discrete one.

Theorem 3.2.4.

- The discrete information system cannot represent \mathcal{H} .
- \mathcal{H} can represent any extension of this structure and therefore induces an idempotent operator.

TODO: Show that a formal system provides a proof system that is a way to *optimize* the search space of information systems.

3.3. Universality.

Theorem 3.3.5. Every universal formal system induces a framework \mathbb{F}' , as the image of the functor $\mathcal{G} : \mathbb{F} \rightarrow \mathbb{F}'$, given by $\mathcal{G}(\mathcal{S}) = (\text{Image}(G_{\mathcal{S}}), \mathcal{R}_{\mathcal{U}} \cap \text{Image}(G_{\mathcal{S}})^2)$. Conversely, every framework induces a universal formal system.

Proof. We must show that \mathbb{F}' is a framework for \mathbb{F} . Clearly this is a computable subcategory. To prove \mathcal{G} is an equivalence, notice that \mathcal{G} is full and faithful as a full

sub-category of \mathbb{F} . Additionally, \mathcal{G} is essentially surjective precisely by construction. This completes the forwards direction.

Conversely, a univocal framework can be formed from a system by creating a computable encoding of the formulas and rules of a system. The family G can then be defined from an equivalence from \mathbb{F} to \mathbb{F}' , which can be easily verified to preserve and reflection derivations. \square

4. SYNTAX

5. SEMANTICS

5.1. Terms.

We expand upon to analyze the ASTs generated from Section 4.

6. BOOTSTRAP

7. CONCLUSION

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DEPARTMENT OF MATHEMATICS, UNIVERSITY OF COLORADO AT BOULDER, BOULDER, CO
Email address: oscar-bender-stone@protonmail.com