ABSTRACT
Semantic properties are domain-specific specification constructs used to augment an existing language with richer semantics. These properties are taken advantage of in system analysis, design, implementation, testing, and maintenance through the use of documentation and source-code transformation tools. Semantic properties are themselves specified at two levels: loosely with precise natural language, and formally within the problem domain. The refinement relationships between these specification levels, as well as between a semantic property’s use and its realization in program code via tools, is specified with a new formal method for reuse called kind theory.

1. INTRODUCTION
Ad hoc constructs and local conventions have been used to annotate program code since the invention of programming languages. The purpose of these annotations is to convey extra programmer knowledge to other system developers and future maintainers. These comments usually fall into that gray region between completely unstructured natural language and formal specification.

Invariably, such program comments rapidly exhibit “bit rot”. Over time, these comments, unless well maintained by documentation specialists, rigorous process, or other extra-mile development efforts, become out-of-date. They are the focus for the common mantra: an incorrect comment is worse than no comment at all.

Recently, with the adoption and popularization of lightweight documentation tools in the literate programming tradition \[17\] \[18\], an ecology of semi-structured comments is flourishing. The rapid adoption and popularity of Java primed interest in semi-structured comment use via the Javadoc tool. Other similar code-to-documentation transformation tools have since followed in volume including Jakarta’s Alexandria, Doxygen, and Apple’s HeaderDoc. \[\text{SourceForge}\] reports thirty-six projects with “Javadoc” in the project summary. \[\text{FreshMeat}\] reports another thirty-five, with some overlap.

While most of these systems are significantly more simple than Knuth’s original CWEB, they share two key features.

First, they are easy to learn, since they necessitate only a small change in convention and process. Rather than forcing the programmer to learn a new language, complex tool, or imposing some other significant barrier to use, these tools actually reward the programmer for documenting her code.

Second, a culture of documentation is engendered. Prompted by the example of vendors like Sun, programmers enjoy the creation and use of the attractive automatically-generated documentation in a web page format. This documentation-centric style is only strengthened by the exhibitionist nature

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Categories and Subject Descriptors
D.1.0 [Software]: Programming Techniques—General; D.2 [Software]: Software Engineering; D.3.1 [Software]: Programming Languages—Formal Definitions and Theory; D.3.2 [Software]: Programming Languages—Language Classifications [design languages]; D.3.4 [Software]: Programming Languages—Processors [preprocessors]; F.3.1 [Theory of Computation]: Logics and Meanings of Programs—Specifying and Verifying and Reasoning about Programs; F.4.1 [Theory of Computation]: Mathematical Logic and Formal Languages—Mathematical Logic; F.4.3 [Theory of Computation]: Mathematical Logic and Formal Languages—Formal Languages

General Terms
documentation, semantic properties, specification languages, formal methods, kind theory, specification reuse, documentation reuse

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\[\text{SourceForge}\] \[1\] \[\text{FreshMeat}\] \[2\]

FSE-10 2002 Charleston, South Carolina, USA
The primary problem with these systems, and the documentation and code written using them, is that even semi-structured comments have no semantics. Programmers are attempting to state (sometimes quite complex) knowledge but are not given the language and tools with which to communicate this knowledge. And since the vast majority of developers are unwilling to learn a new, especially formal, language with which to convey such information, we must look for a happy-medium of informal formality.

That compromise, the delicate balance between informality and formality, and the lightest-weight aspect of our Knowledgeable Software Engineering program, is what we call semantic properties.

Semantic properties are domain-independent documentation constructs with intuitive formal semantics that are mapped into the semantic domain of their application. Semantic properties are used as if they were normal semi-structured documentation. But, rather than being ignored by compilers and development environments as comments typically are, they have the attention of augmented versions of such tools. Semantic properties embed a tremendous amount of concise information wherever they are used without imposing the often insurmountable overhead seen in the introduction of new languages and formalisms for similar purposes.

2. SEMANTIC PROPERTIES

The original inspiration for semantic properties came from three sources: the use of tags, (e.g., @author and @param), in the Javadoc system, the use of annotations and pragmas in languages like Java and C for code transformation and guided compilation, and indexing clauses in Eiffel. All of these systems have a built-in property-value mechanism, one at the documentation level and one within the language syntax itself, that is used to specify semi-structured information.

In Java, tags are the basic realization of our semantic properties. They are used for documentation and formal specification, as we will discuss in more detail in Section 3.1. Tags are not part of the language specification. In fact, they are entirely ignored by all Java compilers.

Annotations and pragmas come in the form of formal tags used for some Design by Contract tools like Jass which happen to be realized in Eiffel with first-class keywords like require, ensure, and invariant.

Eiffel provides first-class support for properties via indexing clauses. An Eiffel file can contain arbitrary property-value pairs inside of indexing blocks. This information is used by a variety of tools for source code search, organization, and documentation.

2.1 Documentation Semantics

Recently, Sun has started to extend the semantics of these basic properties with respect to language semantics, particularly with regards to inheritance. If a class $C$ inherits from a parent class $P$, and $P$’s method $m$ has some documentation, but $C$’s overridden or effective (in the case where $P$ and/or $m$ is abstract) version of $m$ does not, then Javadoc inherits $C.m$’s documentation for $P.m$, generating the appropriate comments in Javadoc’s output.

This change in behavior of the tools is an implicit change in the semantics of the documentation. While straightforward and useful in this example, the meaning of such inheritance is undocumented and often unclear.

The situation in Eiffel is less confusing. The semantics of properties, as realized by indexing clauses and formal program annotation via contracts, are defined in the language standard [23].

Even so, no mechanism exists in either system for extending these semi-structured comments with new semantics beyond simple plug-ins for documentation (e.g., doclets in Java and translators in EiffelStudio).

Also, the semantics of current annotations are entirely specified within a particular language or formalism. No general purpose formalism has been used to express their extra-model semantics.

2.2 Semantics of Semantic Properties

We specify the semantics of semantic properties in a new formalism called kind theory. Kind theory is a logic used to describe, reason about, and discover reusable assets of arbitrary sorts. Kind theory is an higher-order, autoepistemic\(^4\), paraconsistent\(^5\), categorical logic with a type theoretic and algebraic model, and is described in full detail in Kiniry’s dissertation [15].

2.2.1 A Brief Overview of Kind Theory

Kind are classifiers used to describe reusable assets like program code, components, documentation, specifications, etc. Instances are realizations of kind—actual embodiments of these classifiers. For example, the paperback “The Portrait of the Artist as a Young Man” by James Joyce is an instance of kinds PAPERBACK BOOK, ENGLISH DOCUMENT, and others.

In the context of semantic properties, our kinds are the semantic properties as well as the programming language constructs to which the properties are bound. Our instances are the specific realizations of these kinds within a particular input structure, typically a programming or specification language.

Kinds are described structurally using our logic in a number of ways. Classification is covered with the inheritance

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\(^4\)Auto-epistemic: “representing or discussing self-knowledge”.

\(^5\)Paraconsistent: “explicitly representing and reasoning with potential and transitory logic inconsistency”.

\[^{2}\]http://semantik.informatik.uni-oldenburg.de/ jass/
operators $<$ and $\leq_p$; structural relationships are formalized using the inclusion operators $\subset_p$ and $\supset$; equivalence has several forms $=$ and $\equiv$; realization, the relationship between instances and kinds, is formalized with the operators $\subset_p$ and $\supset$; composition is captured in several forms, $\circ$, $\oplus$, and $\odot$; and interpretation, the translation of kind to kind or instances to instances, is realized with the operators $\mapsto$ and $\bowtie$.

Semantics are specified in an autopoietic semantic fashion using what are called truth structures. Truth structures come in two forms: claims and beliefs.

Claims are stronger than beliefs. A mathematically proven statement that is widely accepted is a claim. This phrasing is used because, for example, there are theorems that have a preliminary proof but are not yet widely recognized as being true.

A statement that is universally accepted, but not necessarily mathematically proven, is also a claim. Claims are not necessarily mathematical formulas. The statement “the sun will rise tomorrow” is considered by the vast majority of listeners true and valid, thus is classified as a claim rather than as a belief.

Beliefs, on the other hand, range in surety from completely unsure to absolutely convinced. No specific metric is defined for the degree of conviction, the only requirement placed on the associated belief logic is that the belief degree form a partial order.

We use kind theory to specify semantic properties because it provides us with an excellent model-independent (i.e., it is not bound to some specific programming language) reuse-centric formalism. Kind theory’s whole purpose is the specification of such reusable concepts.

We have insufficient space to summarize kind theory here, so we will simply provide some basic definitions, examples, and motivation of its use within the context of semantic properties.

2.2.2 Kind Theory and Semantic Properties
Using kind theory, we specify the semantic relationships between specifications and their realization. With regards to semantic properties, these relationships formally explain which properties exist, how they can be structured, how they can be applied in a specific language or system, and how they are interpreted into alternative forms like documentation and test code.

First, we denote the classification relationships between kinds using inheritance operators. Properties are classified using standard conceptual data modeling and ontology engineering techniques into a kind hierarchy. Details about these classifications for semantic properties are discussed in Section 2.3.

Next, the structural relationships between kinds are specified using the inclusion operators. Structural relationship denote the contexts in which a kind can be used and how kinds are composed to create new kinds. We discuss structural relations in more detail in Section 2.4.

Finally, equivalence relations and interpretations are defined on kinds. Equivalence relations help refine concepts embodied as kinds for particular domain models by folding and simplifying kind hierarchies. They also let the user pick representative structures, called canonical forms, that are used to represent and reason about (semi-)equivalent kind interpretations, which are structure-preserving functions, are defined to help capture notions of inheritance, equivalence, and other inter-domain translations.

The formal aspects of kind theory, the specification of kind domains for things like semantic properties, is performed by an expert. The typical software engineer never needs to learn or witness the formalism to benefit from its availability.

2.2.2.1 A Kind Example
Consider a loop in any standard programming language. Loops come in many syntactic forms. For example, in the C programming language there are three primary loop constructs: for, while, and do. Fundamentally, all loop constructs are equivalent to each other at some abstraction level; they are each just syntactic variations on a common theme. That theme is specified by the kind LOOP.

We classify loops as a computational structure. This classification states that the notion of a loop is going to be bound to a specific syntax and can be interpreted in some programmatic context. We state this relation as

\[ \text{LOOP} \subset \text{COMPUTATIONAL STRUCTURE} \]

By the rules of inheritance, all the structure inherent in the parent kind, that of COMPUTATIONAL STRUCTURE, is realized in the child kind LOOP as well.

Additionally, an interpretation exists of the form

\[ \text{LOOP} \mapsto \text{COMPUTATIONAL STRUCTURE} \]

that takes kinds or instances of loops to kinds or instances of computational structures, respectively. This function is called a partial interpretation because it eliminates all of the semantics of loops that differentiates them from general computational structures. Interpretations are realized by categorical forgetful functors in kind theory.

The structure of loops is straightforward. Each loop has an initial state, an increment function, a guard, and a body. We state this kind theoretically as

\[ \text{INITIAL STATE} \subset_p \text{LOOP} \]
\[ \text{INCREMENT FUNCTION} \subset_p \text{LOOP} \]
\[ \text{GUARD PREDICATE} \subset_p \text{LOOP} \]
\[ \text{LOOP BODY} \subset_p \text{LOOP} \]

Each of these kinds, in turn, has its own structure associated with it. GUARD PREDICATE $\prec$ PREDICATE, for example.
Interpretations let us do two primary things. First, we use interpretations to translate among different forms of loops, converting a while loop into a do loop, for example. Second, they are used for interpreting the generic semantics of loops in a specific language or formal context.

For instance, a generic specification of a loop instance can be translated to and from a specific syntactic structure realized in the Java programming language. Additionally, a formally specified loop, (the kind FORMALLOOP), complete with a loop variant function and invariant predicate, can be translated into a proof structure in our logical framework. This opens up the opportunity for statically proving the correctness of such formally specified loops.

All of the above details are fully formalized in a kind domain in the basic kind system.[5]

A kind domain is simply a set of kind and instances that are specific to some domain of knowledge. In this case, that domain is one of language-generic computational structures, and we call that domain COMPUTATIONAL STRUCTURES.

A kind system is an actual computational system that realizes kind theory. Our first realization is witnessed both in a logical framework, that of SRI's Maude[4], as well as in software engineering tools like the jiki[6] (used as an open, collaborative knowledge repository), the JPP[16], and the EBON tool suite[7] (a design model checker). Some of these tools are discussed in more detail in Sections 2.7 and 3.

2.3 Properties and Their Classification

We have defined elsewhere thirty-five semantic properties. All semantic properties are enumerated in Table 1 in the appendix. Since we have only a limited amount of space in this paper, we will summarize some of the more interesting properties, their semantics, and our experiences with their use in a number of software engineering projects, large and small, over the last five years.

To derive our core set of semantic properties, we abstracted and unified the existing realizations that we have used in two languages for many years. First, we gathered the set of predefined Javadoc tags, the standard Eiffel indexing clauses, and the set of basic formal specification constructs. After that set was made self-consistent, that is, duplicates were removed, semantics were weakened across domains for the generalization, etc., we declared it the core set of semantic property kind.

These properties were then classified according to their general use and intent. The classifications are: meta-information, pending work, contracts, concurrency, usage information, versioning, inheritance, documentation, dependencies, and miscellaneous. This classification is represented using kind theory's inheritance operators.

Many of these semantic properties are used solely for documentation purposes. The title property documents the title of the project with which a file is associated; the description property provides a brief summary of the contents of a file. We call these informal semantic properties.

Another set of properties are used for specifying non-programmatic semantics. By “non-programmatic” we mean that the properties have semantics, but they are not, or cannot, be expressed in program code. For example, labeling a construct with a copyright or license property specifies some legal semantics. Tagging a method with a bug property specifies that the method has some erroneous behavior that is described in detail in an associated bug report. We call these properties semi-formal because they have a semantics, but outside of the domain of software.

Finally, the balance of the properties specify structure that is programmatically testable, checkable, or verifiable. Basic examples of such properties are require and ensure tags for preconditions and postconditions, modifies tags for side-effect semantics, and the concurrency and generate tags for concurrency semantics. These properties are called formal because they can be realized by a formal semantics.

The KindSoftware coding standard[?] summarizes our current set of semantic properties. Each property has a syntax, a correct usage domain, and a natural language summary. The formalization of semantic properties is found in Kiniry’s dissertation[15].

2.4 Context

Each property has a legal scope of use, called its context. Contexts are defined in a coarse, language-independent fashion using inclusion operators in kind theory. Contexts are comprised of files, modules, features, and variables.

Files are exactly that: data files in which program code resides. The scope of a file encompasses everything contained in that file.

A module is some large-scale program unit. Modules are typically realized by an explicit module- or class-like structure. Examples of modules are classes in object-oriented systems, modules in languages of the Modula and ML families, packages in the Ada lineage, etc. Other words and structures typically bound to modules include units, protocols, interfaces, etc.

Features are the entry point for computation. Features are often named, have parameters, and return values. Functions and procedures in structured languages are features, as are methods in object-oriented languages, and functions in functional systems.

Finally, variables are program variables, attributes, constants, enumerations, etc. Because few languages enforce any ac-
Each property listed in the appendix has a legal context. The context *All* means that the property can be used at the file, module, feature, or variable level. Additional contexts can be defined, extending the semantics of contexts for new programming language constructs that need structured documentation with properties.

### 2.5 Visibility

In languages that have a notion of *visibility*, a property’s visibility is equivalent to the visibility of the context in which it is used, augmented by domain-specific visibility options expressed in kind theory.

Typical basic notions of visibility include `public`, `private`, `children` (for systems with inheritance), and `module` (e.g., Java’s `package` visibility). More complex notions of visibility are exhibited by C++’s notion of `friend` and Eiffel’s class-based feature scoping.

Explicit visibilities for semantic properties are used to refine the notion of specification visibility for organizational, social, and formal reasons.

For example, a subgroup of a large development team might choose to expose some documentation for, and specification of, their work only to specific other groups for testing, political, or legal reasons.

On the social front, new members of a team might not have yet learned specific tools or formalisms used in semantic properties, so using visibility to hide those properties will help avoid information overload.

Lastly, some formal specification, especially when viewed in conjunction with standard test strategies (e.g., whitebox, greybox, blackbox, unit testing, scenario-based testing), has distinct levels of visibility. For example, testing the postcondition of a private feature is only reasonable and permissible if the testing agent is responsible for that private feature.

### 2.6 Inheritance

Semantic properties also have a well-defined notion of *property inheritance*. Once again, we do not want to force new and complicated extra-language semantics on the software engineer. Therefore, property inheritance semantics match those of the source language in which the properties are used. Our earlier discussion of basic comments for Java methods (a feature property context) is an example of such property inheritance.

These kinds of inheritance come in two basic forms: *replacement* and *augmentation*.

The *replacement* form of inheritance means that the parent property is completely replaced by the child property. An example of such semantics are feature overriding in Java and the associated documentation semantics thereof.  

**Augmentation**, on the other hand, means that the child’s properties are actually a *composition* of all its parents’ properties. These kinds of composition come in several forms. The most familiar is the standard substitution principle-based type semantics [21] in many object-oriented systems, and the Hoare logic/Dijkstra calculus-based semantics of contract refinement [24].

We can express these formal notions using kind theory because it is embedded in a complete logical framework. For example, we can automatically reason about the legitimacy of specification refinement much like Findler and Felleisen discuss in [5].

### 2.7 Tool Support

We have used these semantic properties for the last five years. We have found that, while an explicit adopted coding standard, positive feedback via tools and peers, and course grade and monetary rewards goes a long way toward raising the bar for documentation and specification quality, these social aspects are simply not enough. Process does help, regular code reviews and pair programming in particular, but tool support is critical to maintaining quality specification coverage, completeness, and consistency.

Templates were the first step taken. We have used raw documentation and code templates in programming environments ranging from `vi` to `emacs` to `jEdit`. But templates only help prime the process, they do not help maintain the content.

Code and comment completion also helps. Completion is the ability of an environment to use partial input to derive a typically more lengthy full input. We have experimented with augmented versions of completion in `emacs`, for example.

Likewise, documentation lint checkers, particularly those embedded in development environments and documentation generators are also useful. We view source text highlighting, as in `font-lock` mode in `emacs`, as an extremely weak form of lint-checking. The error reports issued by Javadoc and its siblings are a stronger form of lint-checking and are quite useful for documentation coverage analysis, especially when a part of the regular build process. Finally, scripts integrated into a revision control system provide a “quality firewall” to a source code repository in much the same fashion.

We believe that more can and should be done. Our approach is to build and use what we call *Knowledgeable Development Environments* (KDEs). These development environments use knowledge representation and formal reasoning behind the scenes to help the user work smarter and not harder.

We have started work on such environment. By extending powerful `emacs` modes and tools that are part of our initial development environment (e.g., XEmacs coupled with the object-oriented browser, hyperbole, JDE, semantic, and speedbar) with a kind system, we hope to raise the bar on development environments.
2.7.1 Current Work on KDEs
The first two features that we plan to implement are documentation inheritance and perspective.

Eiffel development environments contain tools that provide what are called the flat, short, and contract views of a class. Flat forms show the flattened version of a class—all inherited features are flattened into a single viewpoint. The short form eliminates the implementation of all methods so that the developer can focus on a class’s interface. The contract form is like the short form except the contracts of the class (feature preconditions and postcondition, and class invariants) are shown. These forms can be combined, thus flat or flat contract forms have the obvious meanings.

Knowledgeable documentation inheritance is an extended version of such views. Rather than manually program the semantics of the “flattening” operation, our formal specification in kind theory automatically interprets the appropriate instances into a new form for rendering within the knowledgeable development environment. And because such interpretations are often fully reversible, the flattened forms can be edited and the changes will properly “percolate” to their original source locations.

Perspectives enable the user to specify which role(s) she is in while interacting with the kind-enabled system. Since kind theory is autoepistemic, the specification of a role (represented by an agent within the theory) permits automatic filtering of information according to, for example, visibility rules as discussed in Section 2.5. This user-centric filtering of information, much like narrowing modes within Emacs, helps the user focus on the problem at hand, ignoring all information that she either is not interested in, concerned with, or should not see.

These are only two of our ideas for how to expose the user-centric aspects of kind theory via development environments, incorporating the use of semantic properties throughout.

3. EMBEDDING SEMANTIC PROPERTIES
When a semantic property is bound to a particular instance, for example, an @author tag is used in some Java source code, what does this formally mean beyond questions of structural conformance? How do these semantic properties help guide the development process and exercise the system during testing? How do new tools take advantage of these properties?

First, we have to embed the semantic properties into the language in which we are working. Second, we need to define domain-specific semantics using kind interpretations. Lastly, we use kind theory’s belief truth structures to guide program development.

We will first look at syntactic embedding for two programming and one specification language. In the latter parts of this next section we will address the other two points.

3.1 Programming Languages

We have used semantic extensions in two programming languages: Java and Eiffel.

3.1.1 Java
Semantic properties are embedded in Java code using Javadoc-style comments. This makes for a simple, parseable syntax, and the kind composition of semantic properties to constructs is simply realized by textual concatenation.

Here is an example of such use, taken directly from one of our projects that uses semantic properties [12].

```java
/**
 * Returns a boolean indicating whether any debugging facilities are turned off for a particular thread.
 * @concurrency GUARDED
 * @require (thread != null) Parameters must be valid.
 * @param thread we are checking the debugging condition of this thread.
 * @return a boolean indicating whether any debugging facilities are turned off for the specified thread.
 * @review kiniry Are the isOff() methods necessary at all?
 */
public synchronized boolean isOff(Thread thread)
{
    return (!isOn(thread));
}
```

Existing tools already use these properties for translating specifications, primarily in the form of contracts, into runtime test code. Reto Kramer’s iContract [19], the University of Oldenburg’s Semantic Group’s Jass tool, Findler and Felliason’s contract soundness checking tool [5], and Kiniry and Cheong’s JPP [16] are three such tools.

3.1.2 Eiffel
In Eiffel, as mentioned earlier, we use indexing clauses as well as regularly structured comments to denote semantic properties. Using comments as well as indexing clauses is necessary because the syntax of Eiffel dictates that indexing clauses only appear at the top of a source file. The syntax of comments that use semantic properties is identical to that of indexing clauses, thus the same parser code can be used in both instances. An example of such use is as follows, directly from one of our Eiffel-based projects that uses semantic properties [14].

```eiffel
/*
 * Facilities are turned off for a particular thread.
 * Returns a boolean indicating whether any debugging facilities are turned off for the specified thread.
 * @review kiniry Are the isOff() methods necessary at all?
 */
public synchronized boolean isOff(Thread thread)
{
    return (!isOn(thread));
}
```

3.2 Specification Languages
We have also used semantic properties to extend the BON specification language.

3.2.1 BON
BON stands for the Business Object Notation. BON is described in whole in Walden and Nerson’s Seamless Object-Oriented Software Architecture [31], extended from an earlier paper by Nerson [25].

3.2.1.1 Primary Aspects
BON is an unusual specification language in that it is seamless, reversible, and focuses on contracting. BON also has both a textual and a graphical form.

BON is seamless because it is designed to be used during all phases of program development. Multiple refinement levels (high-level design with charts, detailed design with types, and dynamism with scenarios and events), coupled with explicit refinement relationships between those levels, means that BON can be used all the way from domain analysis to unit and system testing and code maintenance.

Reversibility summarizes the weak but invertible nature of BON’s semantics. By virtue of its design, every construct described in BON is fully realizable in program code. One can specify system structure, types, contracts, events, scenarios, and more. Each of these constructs can not only be interpreted into program code, but program code can be interpreted into BON. As far as we are aware, this makes BON unique insofar as, with proper tool support, a system specification need not become out-of-date if it is written in BON.

Finally, BON focuses on software contracts as a primary means of expressing system semantics. These contracts have exactly the same semantics as discussed earlier with regards to object-oriented models, because BON is an object-oriented specification language.

BON’s semantics were originally specified informally using Eiffel [22][31]. Paige and Ostroff recently provided an analysis of BON with an eye toward a refinement-centric formal semantics [26][27].

3.2.1.2 BON Technologies
BON has been, and is being, used within several commercial and Open Source tools: Interactive Software Engineering’s EiffelCase and EiffelStudio tools; Ehrke’s BonBon CASE tool; Steve Thompson and Roy Phillips’s BONBAZ/Envision project; Kaminskaya’s BON static diagram tool [11]: Paige, Lancaric, and Ostroff’s BON CASE tool; and Kiniry’s EBON tool suite [14].

The last three are particularly exciting projects because they are currently active and have wide applicability. Kaminskaya’s and Lancaric’s tools generate textual BON, JML, Eiffel, and Java source code from a graphical BON specification.

3.2.2 Extended BON
Kiniry’s EBON tool suite has a different aim. Its secondary purpose is similar to other previously mentioned tools, namely the generation of documentation from BON specifications.

3.2.2.1 Domain-Specific Semantics
Translations from BON to a source language and vice-versa are to be represented by kind theory interpretations. This means that changes to either side of the translation can not only be translated, but can be checked for validity according to its (dual) model. This specification-code conformance (validity) checking is what we call design model checking. We use this terminology because the specification is the theory and the program code is the model, when viewed from the logical perspective.

A change in the source code that is part of an EBON interpretation image will automatically trigger a corresponding change in the EBON specification. Likewise, any change in the EBON specification will automatically trigger a corresponding change in the source code.

Some of these translations entail more than just a transfer of information from a specification to a comment in the source code. For example, an invariant semantic tag is interpreted not only as documentation, but also as run-time test code. We do not have the space in this paper to detail this interpretation. It follows the same lines as related tools that support contract-based assertions in Java and Eiffel mentioned elsewhere in this paper.

3.2.2.2 Belief-Driven Development
Some BON extensions are non-reversible because they represent system aspects that are either very difficult or impossible to derive. For example, the time-complexity semantic property specifies the computational complexity of a feature. It is (rarely) possible to extract such information from an algorithm with automated tools. But the fact is, the algorithm author often knows her algorithm’s complexity. Thus, stating the complexity as part of the algorithm specification with a semantic property is easy and straightforward task.

Now the question arises: How do we know such specifications that are not automatically checkable remain valid? This is where the earlier-mentioned belief truth structures of kind theory come into play.

When the programmer writes the original time-complexity semantic property for a feature, she is stating a belief about that feature. Beliefs in kind theory are autoeptimistic (the representation of the programmer is part of the logical sentence encoding the belief), have an associated “strength” or “surety” metric (recall Section 2.2.1), and include a set of evidence supporting the belief.

But its primary use is design model checking for Eiffel and Java code.

BON is extended with our set of semantic properties by (a) extending the BON language (adding new keywords and expressions), (b) using structured comments, and (c) using indexing clauses like those in Eiffel. More information on these specific extensions is available at the EBON web site [14].
We use a number of techniques to ensure that old or out-of-date beliefs are rechecked. With regards to this example, we define a continued validity condition as part of the evidence, which is machine checkable. Currently, if the program code or documentation to which the complexity metric belief is bound radically changes in size, or if the feature has a change in type, author, or other potentially complexity-impacting specification (e.g., concurrency, space-complexity, etc.), then the validity condition is tripped and the developer is challenged to re-check and validate the belief, restarting the process.

4. EXPERIENCES
We have used semantic properties within our research group, in the classroom, and in two corporate settings.

The Compositional Computing Group at Caltech has used semantic properties in our complex, distributed and concurrent architectures, written in Java and Eiffel, over the past five years. We have witnessed their utility by first-hand experience primarily during the introduction of our complex technologies to new students and collaborators is particularly facilitated by semantic properties.

Students grumble at first when they are told that their comments now have a precise syntax and a semantics. The students initially think of this as being “just more work” on their part—yet another reason to hand in a late assignment. But, as the term goes by, the students incorporate the precise documentation with semantic properties and related tools into their development process. After a few weeks of indoctrination, they not only stop complaining, but start praising the process and tools. We generally see higher quality systems and the students report spending less time on their homework than when they started the course. They have learned how to work smarter, not harder.

These languages, process, and tools were also used in a corporate setting to develop a enormously complex, distributed, concurrent architecture. When showing the system to potential funders and collaborators, being able to present the system architecture and code with this level of specification and documentation invariably increased our value proposition. Uniformly, investors were not only shocked that a startup would actually design their system, but to think that we used light-weight formal methods to design, build, test, and document the system was absolutely unheard of.

We have incorporated feedback from these three domains into our work. Our set of semantic properties is still evolving, albeit at a rapidly decreasing rate. Our tools see refinement for incorporation into new development processes, better error handling, and more complete and correct functionality. This user feedback is essential to understanding how these technologies and theory can be exposed in academic and industrial settings.

5. CONCLUSION
Documentation reuse is most often discussed in the literate programming [3] and hypertext domains [6]. Little research exists for formalizing the semantics of semi-structured documentation. Some work in formal concept analysis and related formalisms [29,34] has started down this path, but with extremely loose semantics and little to no tool support.

Recent work by Wendorff [32,33] bears resemblance to this work both in its nature (that of concept formation and resolution) and theoretical infrastructure (that of category theory). Our work is differentiated by its broader scope, its more expressive formalism, and its realization in tools. Additionally, the user-centric nature of kind theory (not discussed in this article) makes for exposing the formalism to the typical software engineer a straightforward practice.

Our next steps are on two fronts. First, we are interested in embedding our semantic properties in the Java-centric specification language JML. Second, we are continuing to develop new tools and technologies to realize knowledgeable development environments that use kind theory as a formal foundation.

5.1 JML
JML is the Java Modeling Language [20]. JML is a Java- and model-centric language in the same tradition as Larch and VDM. JML is used to specify detailed semantic aspects of Java code and some tool support exists for type-checking and translating these specifications into documentation and run-time test code [2,7,23]. The formal semantics of JML have been partially specified via a logic as part of the LOOP project [10].

Extending JML with semantic properties would follow the same course that we have used for BON. Because we already have integrated semantic properties with Java, and given the existing tool support for JML, we should be able to realize inter-domain interpretations that preserve a vast amount of information about JML-specified Java systems using kind theory.

5.2 Social Implications
We expect that knowledgeable development environments will have social implications for software development.

First, this challenging, interactive style imposed by knowledgable development environments is not typical—we have to make sure that we are not introducing some kind of formal methods “paper clip”. Thus, the environment needs to “tune” itself to the interactive style and development process of the user. We look forward to theoretically representing such styles in kind theory so that tuning is simply part of the logical context.

Second, in our extensive experience in the research lab, classroom, and corporate office, we have witnessed the fact that most developers are very uncomfortable starting from scratch, especially with regards to system documentation and informal and formal specifications. If some existing documentation or specification exists, developers are much more likely to continue in that trend because they feel that they are contributing rather than creating.
Because the EBON tool suite will automatically generate a base specification from program code, and because the specification-code validity conformance is automatically maintained, we have a primer as well as a positive feedback cycle for lightweight specification with semantic properties. Only time and experience will tell whether this is a sufficient fire to light the correct software fuse.

5.3 Knowledgeable Environments

As mentioned previously, our work on KDEs continues.

We wish to augment our already powerful development environment in two ways. Our first step entails integrating an interactive front-end like XEmacs with our kind system realized in Maude. The availability of Emacs-centric tools for proof system like the excellent Proof General make this a relatively straightforward exercise. The most time-consuming aspect is writing interpretation engines that translate annotated source code to and from a kind representation format. Several such tools are being prototyped now [14, 16].

We also plan on integrating these environments with our reusable knowledge repository known as the Jiki [13]. The Jiki is a read/write web architecture realized as a distributed component-based Java Wiki. All documents stored in the Jiki are represented as instances of kind. Manipulating Jiki assets, including adding or deleting information or searching for reusable assets, is realized through a forms-based web interface as well as through a Java component-based API.

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**APPENDIX**

### A. SEMANTIC PROPERTIES SUMMARY

| Meta-Information: | Contracts | Versioning |
|-------------------|-----------|------------|
| author            | ensure    | version    |
| bon               | generate  | deprecated |
| bug               | invariant | since      |
| copyright         | modifies  |            |
| description       | require   |            |
| history           | concurrency |          |
| license           | title     |            |
| title             |           |            |
| Dependencies      |           |            |
| references        | param     |            |
| use               | return    |            |
| Inheritance       |           |            |
| hides             | exception |            |
| overrides         | idea      |            |
| Pending Work      | review    |            |
|                   | todo      |            |
| Miscellaneous     |           |            |
| guard             | values    |            |
| time-complexity   | space-complexity |  |