Falcon: A Toolset for Analyzing The Real-World Consistency of Software

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Abstract— **Software systems that interact with the real world should observe real-world constraints. In previous work, we introduced *real-world types* and demonstrated their potential to check software for consistency with such constraints. To enable the broader evaluation, improvement, and use of real-world types, we have developed Falcon, a toolset for Java. Two case studies of its use with open source software took reasonable effort and revealed previously unreported faults.**

Keywords— Toolset, real-world types, software assurance

I. INTRODUCTION

Computer systems interact with real-world entities under the control of software to produce desired real-world behaviors. The failure of such software to observe relevant constraints in the real world, e.g. laws of physics, can have serious consequences, especially in safety-critical systems [10].

In earlier work [12], we introduced *interpreted formalisms*: software logic augmented with separate interpretations that document, in computable form, intended correspondences between software logic and the real-world. We also introduced a practical realization in the form of *real-world type systems* and *real-world type checking*, to systematically define and check consistency with real-world constraints. Our experiments with real-world type checking revealed previously unreported faults in subject applications.

The wider use of real-world types in practice requires an approach to integrating them into widely-used languages and development methods. This necessity demands a tool that supports the creation and application of real-world type systems.

In this paper, we present details of *Falcon*, a toolset bringing real-world types to Java. Falcon supports both manual and semi-automated definition of real-world types, interpretations linking logical elements in software to real-world types, and analysis of software for consistency under such interpretations.

We have validated and tested Falcon in two case studies with open-source software projects [12], [14]. The results showed that the toolset supports both user definition of real-world types and semi-automated synthesis of candidate real-world types (based on informal information in code, such as variable names and comments), and that it can successfully locate previously unreported faults due to violations of real-world constraints.

The remainder of this paper is organized as follows. We present objective and goals for Falcon in Section II. In Section III we describe the user's view of the toolset. In Section IV we discuss the architecture of Falcon. In Section V we summarize the results obtained using the toolset in two case studies. In Section VI we review the related literature. We present our conclusions in Section VII.

II. OBJECTIVE

The objective of the toolset is to support efficient and effective application of real-world type systems to practical software systems. To accomplish this objective, we designed the toolset to meet the following goals:

- **Analysis support**. The toolset should support the analysis opportunities introduced by real-world types. These opportunities include real-world type checking, reasonable range analysis, targeted inspection, and synthesis of executable assertions for runtime checking.
- **Immutable code**. The toolset should operate without requiring changes to subject programs. Satisfying this goal enables easier adoption of this technology. Meeting the goal would provide three advantages: (1) real-world type information would not obscure the structure of the code, (2) real-world types can be added to programs under development without modifying them, and (3) real-world types can be added to programs asynchronously, thereby not interfering with current software development techniques and permitting real-world types to be added to legacy software.
- **Ease of use**. The toolset should support engineers in the development and use of real-world types. The effort required can be substantial for large systems. The toolset should provide an integrated development environment and automate tasks that would otherwise require human effort. In addition, the toolset should provide guidance to engineers when developing real-world type systems.
- **Incremental adoption**. The toolset should support incremental adoption with incremental value. Adoption of the technology and successful results are more likely if the technology can be applied incrementally, especially to large existing systems, with benefits

increasing with effort, rather than requiring wholesale change.

- **Reuse**. The toolset should allow the reuse of real-world types. Real-world types and the typing rules they define represent characteristics of real-world entities, which are often unlikely to change. Thus, real-world types are ideal candidates for libraries supporting reuse and associated reductions in human effort.
- **Type system management**. The toolset should support creation and management of real-world type systems by engineers. Therefore, one of the basic operations required for the toolset is to facilitate the manual creation of real-world type systems.

III. The User's View

In related work on units checking [6][7], toolset support has focused on: (a) source code annotations in the form of comments, (b) and command line invocation of analysis. Meeting the objectives listed above for real-world type systems requires a sophisticated interface that provides a number of facilities to the user.

Fig. 1 presents a high-level view of the Falcon user interface. The subject Java program is presented to the user in one window and the real-world type system in a second window. The Java code is developed entirely outside of Falcon. Control of Falcon, including invocation of analyses and display of analysis results, are available through a set of graphic control panels.

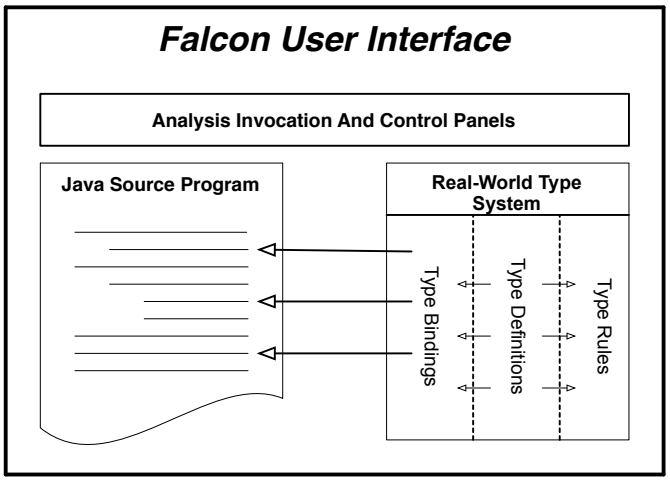

Fig. 1. The Falcon user interface.

The major features of the interface are as follows:

- **Java highlighting**. To assist the user in navigating the source code, the Java display highlights the source code with coloring in a typical fashion.
- **Type bindings**. Each binding of a real-world type to a program element is established by highlighting the element in the source code and then selecting the desired real-world type from a list. By default, bindings are not displayed in the source code. They are displayed via tooltips. As a convenience to the user, Falcon has an option that will inject Java comments into the source code to indicate bindings. These bindings establish an interpretation that links otherwise purely logical elements of the source code to real-world types.
- **Statistics**. Statistics about the real-world type system are displayed including the numbers of types, type rules, and bindings of real-world types to program elements.
- **Real-world types**. The list of type names is presented. For each, the attributes of the type (e.g., measurement units), are listed.
- **Program element types**. In the display of the Java source code, by hovering the mouse over a program element, the real-world type associated with the element is displayed as a tooltip. This mechanism allows the user to review and check the real-world typing for a complete expression by moving the mouse over the expression in an appropriate way.
- **Elements of a type**. All of the program elements of a particular type in the Java source code can be displayed.
- **Libraries**. A real-world type system can be developed and subsequently stored as a library, or an existing library can be read and made available for analysis of a given source program.
- **Type synthesis**. Partial support for synthesis of the real-world type system for a given source program is provided. The Falcon toolset includes a processor that processes the Java source code and parses all of the identifiers. The results are supplied to the user to consider as elements of real-world type definitions. With types defined, the toolset facilitates the establishment of type bindings by providing type propagation of initial bindings seeded by the user [13].
- **Analysis**. All forms of analysis are invoked and all resulting analyses displayed from the user interface. For example, real-world type checking is invoked from a menu item, and any real-world type errors (violation of type rules) are displayed in a separate window.

IV. The Toolset Architecture

Falcon is implemented as an Eclipse Rich Client Platform [5]. Fig. 2 presents the architecture of Falcon. For completeness, the dashed rectangle at the top left shows the development of the Java subject system although this is not part of Falcon.

The major elements of the architecture are:

- **Custom Java parser**. Entirely separate from the compiler used to build the subject system, Falcon includes a Java parser that produces a symbol table and an abstract syntax tree for the subject software. This parser ensures that Falcon does not depend upon any of the toolsets being used in system development.
- **Synthesizers**. The synthesizers help the user develop the real-world type system for a given subject system. They process the development materials in various ways including: (a) parsing identifiers in the software using grammars derived from typical naming conventions, (b)

application of elementary natural language processing, (c) consultation of lexical/ontological databases, (d) real-world type inference, and (e) user review of synthesized type materials.

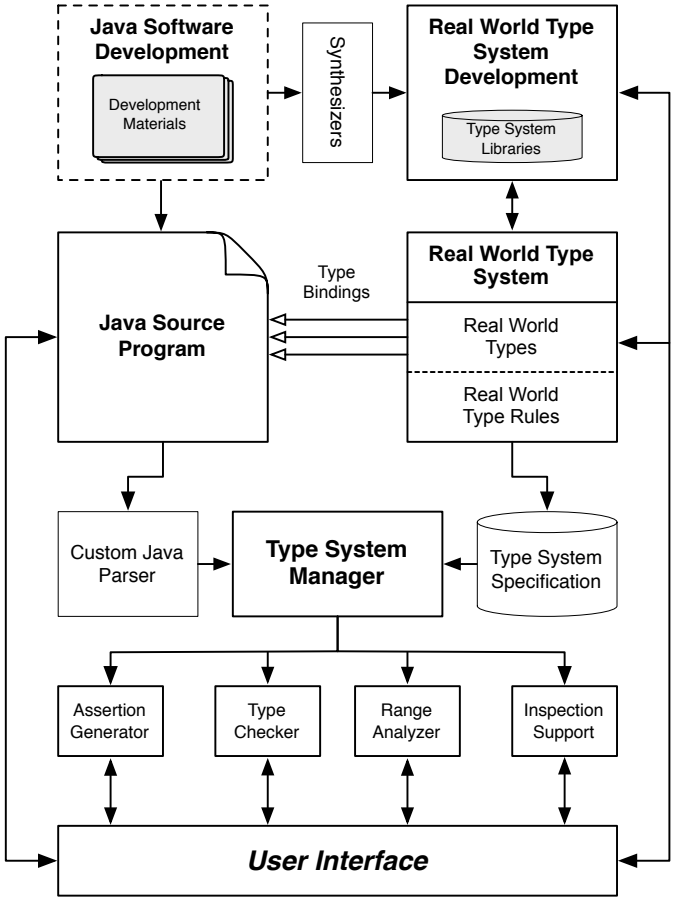

Fig. 2. Architecture of the Falcon toolset

- **Type system manager**. The type system manager is a control mechanism that determines the materials needed for the various analysis mechanisms and supplies it as needed to the analysis components of the toolset.
- **Analysis engines**. Presently, Falcon provides four different forms of analysis. Each of the analyses is implemented by a different engine. The architecture is designed to support additional analyses as they become available.
- **Type system libraries**. Libraries of real-world types enable reuse of type definitions across applications. Some type definitions derive from real-world constraints and rarely change. Others derive from application-specific concepts and constraints (units and frames of reference for example), and are more likely to be suitable for reuse on an individual type basis. Support for reuse of individual types and type collections (what we are calling type systems) is implemented by a simple catalog and search mechanism.

Falcon is implemented through a Java class hierarchy and a simple set of file types that ensure flexibility and support for future growth.

The current implementation of Falcon supports the use of real-world types for most Java program elements. In particular, the Java entities that can be bound to real-world types are: (a) local variables, (b) fields in classes, (c) method parameters, (d) method return values, and (e) class instances. In order to make the development of the prototype toolset tractable, the current version imposes some restrictions on the use of real-world types in Java, specifically:

- **Fields**. Fields in classes are assumed to be monomorphic, i.e., a field in a class is assumed to have the same corresponding real-world entity in all class instances. Fields are associated with real-world specifications inside the class declaration body.
- **Class instances**. Different instances of a class might have different real-world meanings and so the real-world type is of the instance, not the class. For example, suppose a class `Point` has three fields `x`, `y`, `z`. Further, suppose that `pt1` and `pt2` are both instances of `Point` but are from different coordinate systems. Writing a statement that involves both `pt1.x` and `pt2.x` such as `pt1.x + pt2.x` might be a fault and so the two instances need to be distinguished.
- **Method return value**. Each function with a return value is associated with a real-world type. If a particular method does not have a real-world type, the analysis treats the method as polymorphic. For a polymorphic method, at each invocation site, all the expressions in the method declaration body are examined to determine the real-world type of the return statement. That ultimately will be the real-world type of the method invocation. If the method contains multiple return statements, the real-world type for the return value will be the one with no faults. Also, if real-world types for return statements are inconsistent, a warning message is issued.
- **Arrays**. All elements of an array are assumed to have the same real-world type.
- **Constants**. Variables are associated with real-world types at the point of declaration, but constants are used as needed. Constants are dealt with simply by associating each one with a hidden variable and binding a real-world type to that variable.
- **Compound objects**. Class instances introduce the possibility of nesting of real-world typed entities because the class might have a real-world type and the fields within the class might have real-world types. In that case, the real-world specification of a qualified name is the union of the specifications of all the elements in the path to a specific item of interest in an expression. This same rule applies to method invocation where fields are retrieved such as `cs2.get_x();`

V. Validation

We assessed the performance of the Falcon toolset as part of two case studies on open-source software systems that

implement various mapping/geographic services. The systems used in the case studies were: (1) the Kelpie Flight Planner (13,884 lines of code) [8], and (2) OpenMap (157,858 lines) [11].

In the Kelpie flight planner study, seven faults were located by real-world type checking and 12 faults by reasonable range analysis [12]. In the OpenMap case study, 24 faults were located by real-world type checking and 12 faults by reasonable range analysis [14]. Our informal assessment of the toolset is that it provided comprehensive support for defining and manipulating real-world types and for using them to analyze subject software.

The toolset was also effective in assisting in the development of real-world type systems by synthesis. On average, the toolset: (1) synthesized candidate real-world types that were used to produce 60% of the real-world types needed, (2) produced candidate real-world type rules that covered all real-world type rules needed, and (3) synthesized 50% of the real-world type bindings required. In addition, the real-world types and type rules created for the Kelpie Flight Planner software were fully reused in the case study of the OpenMap software.

Again informally, from our experience with the toolset and with the underlying technology of real-world type systems, our initial assessment is that Falcon meets the six goals outlined in Section II, namely: *analysis support*, *immutable code*, *ease of use*, *incremental adoption*, *reuse*, and *type system management*.

VI. Related Work

The toolset introduced in this paper implements the idea of real-world type systems for documenting, in a mechanically checkable form, the intended real-world interpretations of otherwise purely logical software constructs. Other researchers have developed many enhancements to the type systems of industrial programming languages in order to support additional checking capabilities. The distinguishing characteristic of our approach is its emphasis on explicitly representing and checking consistency of code with an interpretation that defines the intended *correspondence of code with the real world*. By contrast, most work on type systems aims to improve the ability to express and check constraints internal to the software logic (e.g., constraints on aliasing).

Pluggable type systems [4] enhance built-in type systems in applicable formal languages and provide support for additional type checking. The Checker framework [2] is a toolset that implements the idea of pluggable type system for Java. Falcon is, in a sense, a pluggable type system for an existing industrial programming language (Java), distinguished, again, by its aim to establish and check machine-world-to-real-world correspondences.

Dependent type systems, such as Coq [3] and Agda [1] provide higher-order logics for defining data, function, and proposition types and values. In future work, we aim to explore the use of such notations for defining real-world types.

Some research tools support units checking and dimensional analysis [6], [7]. They permit adding annotations or type qualifiers to the source programs to denote units and enforce unit consistency. These tools focus on units and dimensional analyses, and thus support only narrow special cases of our broader conception of real-world types and associated analyses.

Falcon is also distinguished from much preceding work by its strong emphasis on ease of use and practical application. Compared with much previous work, Falcon emphasizes the separation of the development of source code from real-world type systems, comprehensive user interfaces, and synthesis mechanisms. It is meant for, and we have validated as, a useful tool for practical applications in real engineering environments.

VII. Conclusion

In this paper, we have introduced the Falcon toolset; a toolset designed and implemented to support real-world type systems. The toolset enables analysis using constraints derived from properties of the real world. The toolset provides all the necessary capabilities to develop and apply real-world type systems to Java software and to analyze the result.

The toolset has been applied to modern software system as part of two case studies. In the case studies, the analyses made possible by the toolset detected a significant number of faults.

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