Embedded Contract Languages

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ABSTRACT

Specifying application interfaces (APIs) with information that goes beyond method argument and return types is a long-standing quest of programming language researchers and practitioners. The number of type system extensions or specification languages is a testament to that. Unfortunately, the number of such systems is also roughly equal to the number of tools that consume them. In other words, every tool comes with its own specification language.

In this paper we argue that for modern object-oriented languages, using an *embedding* of contracts as code is a better approach. We exemplify our embedding of Code Contracts on the Microsoft managed execution platform (.NET) using the C# programming language. The embedding works as well in Visual Basic. We discuss the numerous advantages of our approach and the technical challenges, as well as the status of tools that consume the embedded contracts.

Categories and Subject Descriptors

D.2.4 [**Software Engineering**]: Software/Program Verification—*Programming by contract*; D.2.1 [**Software Engineering**]: Requirements/Specifications—*Methodologies, Tools*; F.3.1 [**Logics and Meanings of Programs**]: Specifying and Verifying and Reasoning about Programs—*Assertions, Invariants, Pre- and post-conditions, Specification techniques*

General Terms

Design, Languages, Reliability, Verification

Keywords

C#, .NET, CodeContracts

1. SPECIFICATIONS AND CONTRACTS

Writing specifications for programs and verifying these specifications against the actual code (either dynamically or statically) has a long tradition in the research community. Specifications and their corresponding checkers take on a multitude of forms, from simple extensions to type systems [6, 7, 17], dependent types [19], monitors [1, 5], to full fledged logical specification and verification [16, 12, 2, 4, 20, 3].

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```
string Compute(string str, int index, Collection c, out int len)
{
  Contract.Requires( str == null ||
                     0 <= index && index < str.Length);
  Contract.Ensures( str == null ||
                     ! String.IsNullOrEmpty(Contract.Result())
                     && c.Count > Contract.OldValue(c.Count));
  Contract.Ensures(Contract.ValueAtReturn(out len) >= 0 );
  Contract.Ensures( str == null || Contract.ForAll(
                     0, Contract.ValueAtReturn(out len),
                     i => Contract.Result()[i] == s[i]) );
}
```

Figure 1: Example of embedded contracts

One of the recurring issues with specification languages is that they are either very specialized and limit the expressiveness of what properties can be expressed (often towards the goal of static checking), or they are general specification languages either with their own specialized programming language [16, 2, 4, 20, 3], or augmenting an existing language via structured comments [12]. In either case, these approaches require entire compiler infrastructures to support tools consuming the specifications. Specialized languages are difficult to get into general usage, as the compilers and support tools are usually not on par with commercial product quality. Often such infrastructures need to track the evolution of some original language (Spec# vs. C# and JML vs. Java), which means they either don't support the same language, or lag several years behind the features of the main language. Comment- and annotation-based approaches have additional problems that we discuss in the next section.

To avoid all these issues, we propose a novel approach based on embedding contract specifications in a programming language without any change to the programming language and taking full advantage of the existing language, compiler, and its supporting IDE and tools.

2. EMBEDDED CONTRACTS

The idea of embedding contracts in an existing programming language is to

1. express specification conditions as expression in the programming language itself, to
2. leverage the existing language compiler to perform name and overloading resolution, type checking, and code generation, and to

3. extract contract conditions from the compiled target code for use in contract related tools.

Figure 1 shows our embedding of contracts for C#. The method Compute specifies a precondition using a boolean expression that is the argument to the Contract.Requires method. It also specifies several postconditions using boolean expressions as the argument to the Contract.Ensures method.

In this embedding, contract specifications appear as method calls at the beginning of methods, where the specification conditions are simply the boolean expressions appearing as arguments to these methods. In .NET we are using static void methods defined in a static class called Contract. Other approaches are possible using global objects and methods.

Using an embedded approach for writing specifications provides numerous benefits to the programmer:

- The language of conditions is just the language of expressions in the programming language used.
- The existing editor and IDE can not only be used to author the contracts, the IDE actually supports writing proper contract expressions by providing highlighting, completion, intellisense, and early feedback on erroneous expressions (due to the fact that the existing language will background check the expressions as normal code).
- Refactoring tools work properly on contracts as well, e.g., renaming a parameter will rename any parameter use inside specifications as well. Contrast this to having specifications in attributes or special comments.

Thus, programmers don't have to learn a new language, a new compiler, or a new IDE, and the authoring of contracts feels like writing code.

Embedding is also beneficial to writers of tools such as dynamic and static contract checkers:

- Since the specifications are compiled by the existing compiler, the tool writer has no need to duplicate the full compiler infrastructure, such as the parser, type checker, name and overloading resolution, etc., or extend the IDE to recognize specifications in non-standard positions, such as attribute strings or comments.
- Extracting the specifications from the compiled target code as opposed to the source code allows the tool writer to deal with a smaller and usually better specified language than the original source language. In our example, consider the difference in complexity between the full C# language and the relative simplicity of the target MSIL intermediate language of .NET.
- The semantics of the expressions appearing in the specifications are unambigous. Consider operator overloading and other special language constructs. Working at the source level of expressions would require tool writers to duplicate the knowledge of how such operators are translated. Working in the target language obviates this need.
- The tool writer can typically reuse existing well tested infrastructure to manipulate/analyze the target code, such as .NET binary reader/writers, or similarly Java byte code infrastructures.

```
[ContractClass(typeof(IContracts))]
interface I {
  int Foo(string s);
}

[ContractClassFor(typeof(I))]
class IContracts : I {
  int Foo(string s) {
    Contract.Requires( s != null );
    Contract.Requires( s.Length > 5);
    Contract.Ensures( Contract.Result() > 0 );

    return default(int); // dummy body
  }
}
```

Figure 2: Contracts on interface methods

Embedding a contract language also presents some challenges over alternative approaches. We examine these challenges in the next sections and provide solutions for them.

2.1 Common Specification Encodings

While reusing the existing language for expressions appearing in specifications is great, it also poses a problem in that specification languages usually require a few extra constructs not typically among the expressions of standard programming languages.

2.1.1 Method Result Expression

Postconditions often need to refer to the method result value. Languages typically don't have an expression form for this result value. To work around this issue, we use a dummy nullary method whose result stands for the result value of the method:

```
static T Result<T>();
```

The type parameter T stands for the method return type. Some languages can infer this type, but often programmers will need to specify it. An example use appears in Figure 1, where the postcondition ensures that the result string is neither null, nor empty.

2.1.2 Prestate Values

It is convenient to mention the *old value* of an expression in a postcondition, meaning the value of the expression on entry to the method. This is typically used to related the pre and the post state, e.g., to express that a count was incremented, an element was added, etc.

Again, standard programming languages don't have syntax for such a construct and we make use of a unary dummy function with the following signature:

```
static T OldValue<T>(T oldExpression);
```

2.1.3 Contracts on Interfaces

Writing contracts on interface declarations is very desirable, but not straightforward. Since we use code in method bodies to express contract conditions and interface methods don't typically allow writing method bodies, we have to find a way to write the contracts separately from the interface declaration and link the two.

To annotate an interface I with contracts, we use a *buddy* contract class, typically named IContracts that implements the interface and for each method contains the contracts and a dummy body (Figure 2). The interface type and its contract class are linked in our C# embedding using attributes. An alternative mechanism could use naming conventions.

2.1.4 Quantifiers

Specifications often require universal or existential quantifiers which are not typically available in mainstream programming languages. Fortunately, modern languages now provide support for closures, making it possible to express quantifiers as helper methods in ordinary expressions. Figure 1 contains a postcondition using a universal quantification over the range 0..len. The bound variable and universally quantified boolean expression is represented in C# as a lambda expression

```
i => <expression over i>
```

where i is a bound variable and <expression over i> is the lambda body.

In our C# embedding, we provide several overloads of ForAll and Exists that work over integer ranges and collections. In the example, we use the following:

```
delegate bool Predicate<T>(T value);
bool ForAll(int lb, int ub, Predicate<int> condition);
```

Unbounded quantification can be expressed as well, but poses obvious problems for runtime checking.

2.1.5 Object Invariants

Object invariants are conditions on object state that should hold on all public method boundaries. Such invariants need to be specified at the type level, but languages again don't provide a way to associate code directly with types. Instead, we embed object invariants by defining additional instance methods on types and marking them as object invariants as shown below in our C# embedding:

```
[ObjectInvariantMethod]
void ObjectInvariant() {
  Contract.Invariant( this.field >= 0 );
}
```

These invariant methods take no parameters and return no result. The body consists of a sequence of Contract.Invariant method calls specifying the invariant conditions.

2.1.6 Language Workarounds

Programming language rules may get in the way of certain embedding usages, namely due to the fact that postconditions appear at the beginning of the method rather than where they are evaluated. E.g., C# supports *out-parameters* which are parameters passed by reference that need not be initialized on entry, but the method is guaranteed to assign them. C# enforces the rule that such parameters are not read before being assigned. A postcondition referencing an out-parameter will be flagged by the compiler as a use-before-assignment. To work around this and related issues in constructors, we provide a helper method whose meaning is that the location is read in the post state.

```
static T ValueAtReturn<T>(out T location);
```

Figure 1 contains a postcondition stating that the value upon return of the out-parameter len is non-negative.

2.2 Other Specification Encodings

There are a number of specification language features that we have not yet attempted to support in our encodings and tools. We list them here and provide ideas for how to encode them.

Model Fields are data members or properties of data structures that are typically only referred to from specifications rather than real code. They can be expressed as ordinary virtual properties, tagged with special attributes. Concrete implementations then act as the representation formuala.

Modifies Clauses describe the set of locations potentially modified by a method. A set of dummy methods, similar to ValueAtReturn, can be used to express classes of such locations.

Data Groups [13] are typically used to abstract over sets of locations, including recursively defined sets in order to express which parts of the machine state are (un)modified. We envision that such groups can be encoded with extra attributes.

Finally, specification languages often use *Model Types*, i.e., mathematical structures such as sets and sequences to express properties of implementation data structures. Spec# supports such model types as actual .NET implementations of functional data structures. The same approach can be used in an embedded setting.

3. CONTRACT EXTRACTION

Contract extraction consists of separating the code generated for contract conditions (preconditions and postconditions) inside a method from the code making up the body of the method.

For ordinary methods, code extraction is relatively simple. It consists of finding the last use of a contract method (Requires or Ensures) and then splitting up all code from the beginning of the method to that point into individual pre- and postconditions. This process must ensure certain well-formedness conditions in order to guarantee that the contracts and code can be properly separated:

- Each individual pre- and postcondition must post-dominate the entry point of the method. This guarantees that the contracts actually appear at method entry and are not control-flow dependent.
- Local variables initialized inside contracts must not be used inside the method body. This guarantees that contracts can be separated from the method body without having to perform detailed dependency analysis and to duplicate local initializations.
- No references to contract helper methods should appear in the main method body. This guarantees that the special meaning of contract helper methods only needs to be recognized as part of the contracts themselves.
- Preconditions can only mention types and members that are visible to all callers of the method. This guarantees that callers can understand the contract they are held to and avoids having meaningless preconditions, e.g., on private object state.
- Postconditions of virtual methods can only mention types and members that are visible to all potential im-

plementers of the method. This guarantees that overrides and implementations of the method can understand the postcondition they are held to.

- Contract helper methods such as `OldValue`, `Result`, and `ValueAtReturn` should only be referenced from within postconditions. Furthermore, the type instantiation of the `Result` method should agree with the method return type.

- Contract inheritance of preconditions should be checked to guarantee that methods don't strengthen preconditions. A simple way to enforce this without needing to determine arbitary logical implications is to simply disallow overriding methods from declaring their own preconditions and further guaranteeing that methods only have one base method (base class or interface) from which they inherit contracts.

- Any methods called from within contract expressions should be pure methods (or referentially transparent) to avoid issues of contract semantics and changing the behavior of the program depending on whether contract assertions are evaluated at runtime or not. We advocate requiring a purity annotation on methods called from contracts such as `[Pure]` to 1) document the intention of the method's purity and thus capturing it in the code, and 2) enable a separate analysis to discharge the purity obligation of such annotated methods.

  Additionally, methods used in contracts should be well-founded to avoid ill-defined specifications. Checking methods for purity and well-foundedness is non-trivial and beyond the scope of discussion for this paper.

Contracts need to be cleanly separated from ordinary code in order to enable manipulating the code for various runtime checking scenarios, such as removing all contract code, inheriting contract code to overridden methods, and inserting contract checking code at call-sites of methods.

3.1 Challenges

The basic extraction of contracts from methods is fairly simple as described above. Challenges arise when the code generated by the compiler is substantially more complicated than the source due to expansion of certain language features.

3.1.1 Constructors

Extraction from constructor methods is more complicated than for ordinary methods due to two issues: 1) base or delegated constructor calls, and 2) field initialization. Depending on the language, field initialization may appear before or after the base/delegated constructor call (e.g., C# puts field initialization before, Visual Basic puts them after). This makes recognizing the beginning of contracts more difficult, as they will appear after all the field initializations and base constructor call.

Another complication with constructors is that even though preconditions physically appear after the base/deferred constructor call, logically, the preconditions must be evaluated prior to the base/deferred constructor call. Prior to that call, the object being constructed is not yet accessible (fields may be written but not read and the object may not escape). As a result, preconditions in constructors must be checked to contain no references to the object under construction.

3.1.2 Closures

Most modern object oriented languages now support closures (or anonymous delegates) in one form or another. If the underlying target language does not support this feature directly, the compiler will emit helper types and methods to implement the feature, complicating the contract extraction. E.g., if a closure is used inside a contract, then the method code will contain closure object initialization code. Such code needs to be part of the contract code, but may also need to be part of the ordinary method body, since compilers will try to share the closure object between the two sections. As a result, such closure construction code has to be specially recognized and considered to be part of both the contract section and the normal method body.

3.1.3 Iterator Methods

Languages like C# and Visual Basic support iterator methods, i.e., methods producing an enumeration of values that can be written in the form of a coroutine using `yield` statements to yield individual values.

Compilers turn such iterator methods into iterator closure classes that implement enumeration interfaces. The code transformations are quite substantial, causing the embedded contracts to end up inside a different compiler generated method body for advancing to the next element of the iteration. To extract contracts properly from iterators, the extraction process must essentially recognize such iterators and partially decompile them.

4. MODULARITY

Before discussing tools built on top of embedded contracts, we need to discuss the issue of how to handle separate compilation and contracts of third-party components.

We view every component (be it a .NET assembly, or a Java class file, or other packaging granularity) as having a set of declared contracts. Tools working on a component A referencing a component B, typically need to obtain the contracts of component B, independently of whether B is instrumented with runtime checks or not. We therefore introduce the notion of a *Contract Reference Component* (CRC), such that for every component A there is a CRC called *A.Contracts* containing only contracts, no method bodies. One way to think about a CRC is as a rich header file giving detailed contract information beyond the typical type signatures.

Note that a CRC is a persisted form of the contracts in the source. The format of this persisted form is already given by whatever compiler target language we are employing, e.g., .NET or JVM. This again simplifies the contract story, as contracts in component reference assemblies have the same fixed semantics we have already assigned to the target language.

CRCs simplify dealing with multiple components and also permit writing contracts for components separately if the component does not originally contain contracts. It simplifies the description of tools acting on components. For the remainder of the paper, we assume that we can compile a component in such a way that it contains no contracts, to yield the uninstrumented pristine compiled component A. For C# and Visual Basic, we use the `Conditional("Contracts")` compilation attribute on all the Contract methods which causes the compilers to omit any calls to these methods when the compilation is performed without defining the symbol "Contracts".

Note that this approach permits authoring contracts on components, while guaranteeing that the non-contract code can easily be compiled into pristine form (i.e., containing just the non-contract code) with the standard compilers without any other tool in the process. This ability is important for adoption by product teams if they don't trust other tools to modify their code before shipping.

We can thus view the standard language compilers as our first tool in the contract toolbox. The next tools we need is the CRC generator, generating a contract reference component.

5. TOOLS

5.1 CRC Generation

Generating a contract reference component is simple: Compile the original code with contracts and then rewrite this component A to strip the method bodies and persist only the contracts as $A.Contracts$.

It is useful to perform an extra step in CRC generation, namely to persist the original source string of any contract conditions as part of the method calls to Contract.Requires, Contract.Ensures, and Contract.Invariant. Effectively, what this step does is it turns any code of the form

```
Contract.Requires( expr );
```

into

```
Contract.Requires( expr, "expr");
```

and similarly for Ensures and Invariant.

In order to perform this rewriting, we assume (or emit) binary forms of the contract methods that take an additional string argument after the boolean condition. Persisting the original source of the condition in this manner permits downstream tools to emit better error messages that can display the original condition that fails without the need to decompile a low-level target language into readable source.

The source extraction is done by using source debugging file information on the compiled target to help locate the correct source file and text extent.

5.2 Runtime Contract Checking

A principal use of contracts is to instrument contract checks as runtime assertions into the target code. Runtime checking increases test effectiveness as the extra assertions provide expected outcomes (oracles) and provide more ways to fail the code under test. Runtime contract checking is particularly effective in conjunction with automated testing, such as fuzzing [11, 8], and automated white-box testing [10, 9, 18].

Runtime checking can be instrumented on a component basis (or finer grained if desired). To instrument a component A, we need the pristine form of A, along with its CRC $A.Contracts$, as well as any CRCs $B.Contracts$, for any component B referenced by A.

Instrumentation can support different levels by including/omitting certain kinds of checks. Here we describe how our implementation instruments all contracts.

We view instrumentation as a rewriting of component A into A', where A' contains runtime assertions for contracts, but is otherwise identical to A. In particular, the actual name of the instrumented component does not change, but we use the primed version to simplify the explanation.

Rewriting proceeds on a per class basis, in an order where base classes (in the same component) are visited prior to derived classes.

5.2.1 Runtime Failure Behavior

Runtime failure of contracts should be customizable, as different scenarios require different behaviors. E.g., standard interactive debugging scenarios may want contract failure to pop-up a dialog box with the option to enter the debugger. Automated testing environments usually need failure in the form of a thrown exception, while deploying instrumented code scenarios may require the component to abort or to log failures in a file or over the network.

We therefore don't advocate any particular failure behavior, but leave that up to the instrumentation tool and the user's choice. All we assume is that the runtime failure operation has access to the source string representing the original contract condition in order to provide a meaningful level of detail about the failed contract.

5.2.2 Invariants

The various object invariant methods declared on a type are consolidated into a new method with a fixed name that does not clash with user defined method names, e.g., $invariant$. This $invariant$ method is a protected instance method containing all Contract.Invariant checks of all contract invariant methods. In addition, if the base class contains a $invariant$ method, then this means that the base class is instrumented and we can chain the invariant checking by calling this base method.

At the end of selected methods (e.g., all public methods), calls to this generated $invariant$ method can be inserted to validate the object invariant.

5.2.3 Preconditions

If contracts are well-formed (Section 3), a method only has one source of preconditions, either the method itself, or if it overrides/implements a base method, the base method's preconditions.

Instrumenting a precondition declared on the method itself is trivial, as the precondition can simply be copied in its existing form to the beginning of the method.

When inheriting a precondition, complications arise. The base class could be generic, and thus the base contract must be instantiated with the same instantiation used by the base type declaration. In target languages where generic code is compiled away (JVM), such instantiation is trivial, as it does not require changing the inherited code for the precondition. In target languages where generics are explicit however, such as .NET, the inherited code has to be properly instantiated before being emitted, or the runtime will reject the code.

5.2.4 Postconditions

Runtime checking of postconditions is more complicated due to the presence of the special Contract methods such as Result, OldValue, and ValueAtReturn. The simplest of the three is ValueAtReturn, which can simply be replaced by a dereference operation of the by-ref location.

Return values: To handle Result, we first replace all return points in the method with assignments to a new $result$ local and a branch to a common method exit point where the post conditions will be checked. Any calls to Contract.Result in the postcondition code can then be replaced with uses of the $result$ local variable.

Old-expressions: Dealing with OldValue requires evaluating the expression serving as the argument to OldValue in the prestate of the method and storing the result away in a fresh local variable. Each occurrence of a call to OldValue in the postconditions is then replaced with the corresponding local variable.

Due to shortcut evaluation constructs such as ||, &&, and conditional expressions present in most languages, OldValue expressions may not and should not be evaluated unconditionally. E.g., consider the postcondition:

```
int M(C c)
{
  Contract.Ensures( c == null ||
                 Contract.Result() < Contract.OldValue(c.Count) );
  ...
}
```

If the parameter c is non-null, then the method guarantees that the return value is less than the value of c.Count on entry to the method. Note that if c == **null** the method contract does not require evaluating the old value of c.Count. In fact, evaluating c.Count would throw a null reference failure in most languages. Essentially, the evaluation of the old value of c.Count is *guarded* by the condition c != **null** in this case, and instrumentation should be careful to only evaluate the old expression under that condition. As an alternative to determine the dominating guards of an old-expression, instrumentation can be emitted that masks all failures of old-expression evaluation, but that is in practice less desirable as it degrades the debugging experience.

Also note that guards must be meaningful in the pre-state of a method. If a guard were dependent on the post-state of a method, the evaluation is not well defined.

Parameters: Many imperative programming languages permit parameter values to be modified within the body of a method, essentially treating parameters as local variables. In such languages, the initial value parameters that are modified by a method body and referenced in postconditions must be stored away in auxiliary locals and used in place of the final value of a parameter in postconditions. Effectively, referring to a paramter p in a postcondition has the meaning OldValue(p), as it isn't meaningful to callers to express postconditions mentioning the final value of a local parameter.

5.2.5 Call-Site Checks

A useful feature a runtime contract checker can provide is the option of evaluating preconditions and or postconditions at call-sites to methods. Such a feature is useful in scenarios where a component B is being developed against another component A that ships without runtime contract checking enabled (possibly for efficiency reasons), but for which a contract reference component $A.Contracts$ is available. In that case, the developer of B can get the benefit of runtime precondition checks on methods in A at all call sites from B into A. The resulting development experience is as if the component A had precondition checks instrumented.

Checking postconditions at call-sites provides additional guarantees that the called component upholds the contract of the interface, even if the component isn't instrumented itself. Call-site postcondition checking poses an additional challenge: postconditions may mention members that are not accessible in the calling context (e.g., private base class fields, or component internal members). Instrumenting such checks into the calling context would thus produce invalid code. The postconditions need thus be filtered by removing all postconditions containing references to members that are inaccessible in the calling context

```
interface IDictionary<K,V> {
  [Pure]
  bool ContainsKey(K key);
  [Pure]
  bool TryGetValue(K key, out V value);
   ensures Contract.Result()==ContainsKey(key);
}

class MyDict : IDictionary<int,int> {
  bool ContainsKey(int key) {
    int dummy;
    return this.TryGetValue(key, out dummy);
  }

  bool TryGetValue(int key, out int value) {
     ...
  }
}
```

Figure 3: Non-termination Example for Runtime Checking

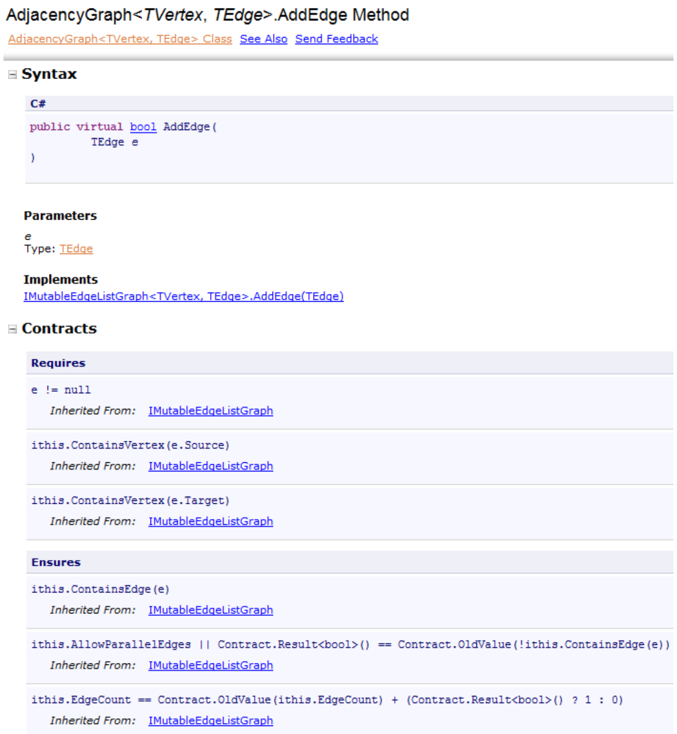
5.2.6 Recursion Guards

Since contracts may call pure methods, which in turn may call other pure methods, it is possible that instrumenting code with contracts may introduce non-terminating recursion into programs. This is particularly unforseeable when inheriting contracts. The runtime instrumentation of contract checks should therefore introduce recursion guards for all contract evaluations. An easy way to implement such guards is to use a thread-local variable inContract that is tested prior to evaluating any contracts and set upon entrance of a contract evaluation.

Figure 3 shows a scenario where recursion guards are necessary. The Dictionary interface specifies that the return value of TryGetValue is the same as the return value from ContainsKey for the same key. This postcondition is instrumented into every implementation of TryGetValue, and in particular into MyDict. The implementor of MyDict decided to implement ContainsKey by calling TryGetValue, which is perfectly reasonable. Naive instrumentation would generate an infinite recursion between the two methods in the postcondition evaluation of TryGetValue. With recursion guards, we prevent this problem. Note that the contracts are still well-formed and that memoizing of pure methods would also solve the problem.

5.3 Documentation Generation

Contracts enable programmers to document design decisions for future reference. These design decision may be about methods internal to a component, or public APIs. Contracts on component internal methods come in handy during code maintenance, which is often done by programmers



AdjacencyGraph<*TVertex*, *TEdge*>.AddEdge Method

AdjacencyGraph<TVertex, TEdge> Class See Also Send Feedback

Syntax

C#

```
public virtual bool AddEdge(
        TEdge e
)
```

Parameters

e
Type: TEdge

Implements

IMutableEdgeListGraph<TVertex, TEdge>.AddEdge(TEdge)

Contracts

Requires

`e != null`
Inherited From: IMutableEdgeListGraph

`ithis.ContainsVertex(e.Source)`
Inherited From: IMutableEdgeListGraph

`ithis.ContainsVertex(e.Target)`
Inherited From: IMutableEdgeListGraph

Ensures

`ithis.ContainsEdge(e)`
Inherited From: IMutableEdgeListGraph

`ithis.AllowParallelEdges || Contract.Result<bool>() == Contract.OldValue(!ithis.ContainsEdge(e))`
Inherited From: IMutableEdgeListGraph

`ithis.EdgeCount == Contract.OldValue(ithis.EdgeCount) + (Contract.Result<bool>() ? 1 : 0)`
Inherited From: IMutableEdgeListGraph

Figure 4: Generated Documentation with Contracts

other than the original author. For public APIs, contracts provide programmers with unambigous descriptions of the API they are trying to use, complementing any natural language documentation.

Thus, generating good documentation from the embedded contracts is a key scenario when using an embedded contract language. Most programming languages and platforms come with tools that generate API documentation (web pages and help files) from idiomatic comments in the code, such as JavaDocs and .NET XML doc comments.

We have prototyped an extension this documentation generation approach for .NET where we augment the XML documentation file of .NET assemblies with new elements for contracts based on the corresponding contract reference component and the original source text of preconditions, postconditions, and object invariants.

The resulting XML file can then be rendered into documentation with an existing tool such as Sandcastle (`http://www.codeplex.com/Sandcastle`), which only requires patching a few XSL transforms. An example of the generated documentation is presented in Figure 4.

As is visible in the example, a key feature of the generated documentation is that it includes inherited contracts on derived methods, thereby making it easier to discover contracts than if they were another hyperlink away.

5.4 Static Contract Checking

Various approaches can be used to attempt to validate contracts statically. ESC/Java and Spec# translate a method and its contracts into a logic verification condition that is then given to a theorem prover which either discharges it or produces a counterexample. Alternatively, special purpose static checkers can be written for subsets of specifications, e.g., those having to do with nullness of pointers.

Yet another approach is to use abstract interpretation to compute program invariants and then attempt to use these invariants to discharge the proof-obligations introduced by contracts. Abstract interpretation enables more automation than verification condition approaches due to its ability to infer loop-invariants and post-conditions. It also enables fine-tuning performance/precision trade-offs [15].

Whatever the mechanism used to prove contracts, all contracts can be viewed as `assert` or `assume` statements in the code to be analyzed. E.g., a precondition at a call-site turns into an assertion, as the precondition needs to be discharged there. The same precondition at the beginning of the method declaring or inheriting it turns into an assumption, a condition the rest of the method can assume and does not need to be proven. Similarly, postconditions on exit of a method must be treated as asserts, but on return from a method are treated as assumes. This rely-guarantee view of contracts enables modular static checking, where each method can be analyzed in isolation (if desired). Of course, checkers are free to inline methods, or determine stronger contracts than the declared ones, thereby performing more global analyses.

Our approach advocates performing the static contract checking on the target language of the compiler, as this is how we associate semantics with contract conditions. Note that contract conditions and ordinary code therefore use the same language and the analysis is thus simpler than if these were two distinct code representations. Furthermore, analyzing the target language of a compiler is often simpler, as it is usually smaller than a source language in terms of complexity and number of distinct language elements [14].

The presence of CRC's again provides the necessary access to contracts of components being called from a component A under analysis. To analyze A, we thus need $A.Contracts$, as well as $B.Contracts$ for all components B referenced from A.

6. CONCLUSION

This paper argues for embedding a contract language inside an existing, standard, production quality language instead of inventing custom contract annotations or comment conventions. Embedding contracts means expressing specifications as expressions in the existing programming language and making them machine discoverable through the use of marker methods such as `Contract.Requires`.

Advantages of embedding a contract language are that programmers need not learn a new specification language, and existing tools such as compilers and IDEs can be used without modification, making it easier for developers to adopt contract-based programming. Furthermore, the semantics of contract conditions is the same as the semantics of the existing program expressions. The target language provides an automatic persisted format for contracts.

Since contract expressions are compiled by the existing compiler, the typical problem of having the specifications and the code drift apart due to edits, refactoring, etc., is avoided.

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