Refactoring Using Type Constraints

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Type constraints express subtype relationships between the types of program expressions, for example, those relationships that are required for type correctness. Type constraints were originally proposed as a convenient framework for solving type checking and type inference problems. This paper shows how type constraints can be used as the basis for practical refactoring tools. In our approach, a set of type constraints is derived from a type-correct program P. The main insight behind our work is the fact that P constitutes just one solution to this constraint system, and that alternative solutions may exist that correspond to refactored versions of P. We show how a number of refactorings for manipulating types and class hierarchies can be expressed naturally using type constraints. Several refactorings in the standard distribution of Eclipse are based on our work.

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1. INTRODUCTION

Refactoring is the process of applying behavior-preserving transformations (called "refactorings") to a program's source code with the objective of improving the program's design. Common reasons for refactoring include eliminating duplicated code, making

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existing program components reusable in new contexts, and breaking up monolithic systems into components. Refactoring was pioneered in the early 1990s by Opdyke et al. [Opdyke 1992; Opdyke and Johnson 1993] and by Griswold et al. [Griswold 1991; Griswold and Notkin 1993]. The profile of refactoring received a major boost with the emergence of code-centric design methodologies such as extreme programming [Beck 2000] that advocate continuous improvement of code quality. Fowler [1999] and Kerievsky [2004] authored popular books that classify many widely used refactorings, and Mens and Tourwé [2004] surveyed the field.

Refactoring is usually presented as an interactive process where the programmer first chooses a point in the program where a specific transformation should be applied. Then, the programmer must verify whether a number of specified preconditions hold, and, if so, apply a number of prescribed editing steps. Checking the preconditions may involve nontrivial analysis, and the number of editing steps may be significant. Therefore automated tool support for refactoring is highly desirable and has become a standard feature of modern development environments such as Eclipse[1] and IntelliJ IDEA.[2]

The main observation of this paper is that, for an important category of refactorings related to the manipulation of class hierarchies and types, the checking of preconditions and computation of required source code modifications can be expressed by a system of type constraints. Type constraints [Palsberg and Schwartzbach 1993] are a formalism for expressing subtype relationships between the types of program elements that must be satisfied in order for a program construct to be type-correct. They were originally proposed as a means for expressing type checking and type inference problems. In our work, we derive a set of type constraints from a program P and observe that, while the types and class hierarchy of P constitute one solution to the constraint system, alternative solutions may exist that correspond to refactored versions of P. This paper shows how several refactorings for manipulating class hierarchies and types can be expressed in terms of type constraints. This includes refactorings that: (i) introduce interfaces and supertypes, move members up and down in the class hierarchy, and change the declared type of variables, (ii) introduce generics, and (iii) replace deprecated classes with ones that are functionally equivalent.

In each case, a system of type constraints is constructed over the original program, with the types of certain entities left fixed, while others are allowed to vary. The solution to the constraint system, if one exists, asserts the safety of the proposed transformation, and indicates (in many cases) any additional changes that must be made in order to preserve behavior. The fixed-type entities include, among others, those that the user explicitly indicated should be changed by the refactoring, which represent the state of the source program after the refactoring is applied.

The type constraints considered in this paper do not express the complete set of correctness constraints for arbitrary transformations of Java code (say, those involving code motion, such as EXTRACT LOCAL VARIABLE). Rather, the type constraints described in the following have been carefully constructed to protect aspects of program behavior that the type-related refactorings described herein could possibly affect. As a particular example, type constraints cannot prevent a change in program behavior due to replacing an integer literal value 3 by 17; however, none of the type-related refactorings described below perform such changes.

[1]www.eclipse.org
[2]www.jetbrains.com/idea

1.1. Scope and Assumptions

The project reported on in this article was initiated in 2002 when one of the authors (A. Kieżun) was a member of the Eclipse development team. At this time, there was a desire to implement the EXTRACT INTERFACE refactoring in Eclipse. After devising a practical solution based on type constraints [Tip et al. 2003], we quickly realized that this type constraint model could be extended to serve as the basis for several other refactorings. From the outset, our goal has been to handle the entire Java programming language and to create realistic implementations that could be contributed to the Eclipse platform. Currently, several refactorings[3] in the Eclipse distribution are based on the research presented in this article.[4]

Our work makes a number of assumptions that are customary for refactoring tools. We assume that all the source code that needs to be refactored is available for analysis. The formalization in this paper omits several Java constructs including exceptions, auto-boxing, overloading, and annotations. Handling each of these language features requires minor extensions to the type constraint system. For example, in the presence of method overloading, refactorings such as EXTRACT INTERFACE that change the types of method parameters must take care not to change overload resolution, and this can be achieved by generating additional type constraints that force the signatures of overloaded methods to remain unchanged. Exceptions raise multiple issues, including the fact that changes to the class hierarchy may change the stack traces associated with exceptions that are thrown at runtime; in our opinion, programmers are unlikely to care about the precise content of stack traces. A somewhat more serious issue associated with exceptions is that care must be taken when attempting to generalize the type in `catch` clauses, in order to avoid situations where applying a refactoring results in associating a different handler with a given exception type. This problem, too, can be avoided by generating additional type constraints. A specific thorny issue that we do not address in this article is reasoning about how the correctness of refactorings may require, or be affected by, changes to access control modifiers (see the discussion of recent work by Steimann et al. in Section 7).

While the present paper does not exhaustively enumerate the type constraint generation rules required for all language constructs in Java, in principle, our techniques are capable of handling the full Java programming language. Furthermore, we expect that they could be adapted to handle other statically typed object-oriented languages such as C++, Eiffel, C#, and Scala with varying degrees of effort. Our implementations were successfully applied to large Java applications (see Section 6), and in our experiments, we determined that program behavior was preserved by compiling and running the refactored programs where possible to ensure that program behavior was preserved.

That said, our implementations have some known shortcomings and limitations. As with all refactoring tools, we cannot guarantee that behavior is preserved if applications use reflection, native code, or dynamic loading. Moreover, we assume that implementations of `clone()` are well behaved in the sense that the returned object has the same type as the receiver expression. Finally, the REPLACE CLASS refactoring presented in Section 5 relies on a static points-to and escape analysis. While any static points-to or escape analysis can be used, the precision of the particular analysis affects the effectiveness of the refactoring.

[3]These include the EXTRACT INTERFACE, GENERALIZE DECLARED TYPE, PULL UP MEMBERS, and INFER GENERIC TYPE ARGUMENTS refactorings presented in this article, and others.
[4]The implementations of these refactorings as they currently occur in the Eclipse distribution differ substantially from the ones that were evaluated in Section 6. In particular, the current Eclipse implementation uses a more efficient representation of type constraints, and relies on a different constraint solver.

$M, M', \cdots$	methods	$I, I', \cdots$	interfaces
$F, F', \cdots$	fields	$T, T', \cdots$	types (classes or interfaces)
$C, C', \cdots$	classes	$E, E', \cdots$	expressions (subscripts will be used as needed)
$NumParams(M)$	the number of formal parameters of method M		
$Param(M, i)$	the i^{th} formal parameter of method M		

(a) notation

α	$::=$	T	a type constant
		$[E]$	the type of E
		$[M]$	the declared return type of M
		$[F]$	the declared type of F
		$Dcl(M)$	the type in which M is declared
		$Dcl(F)$	the type in which F is declared

(b) constraint variables

$\alpha = \alpha'$	type α is the same as type α'
$\alpha < \alpha'$	type α is a proper subtype of type α'
$\alpha \leq \alpha'$	type α is the same as, or a subtype of, type α'
$\alpha \leq \alpha_1$ **or** $\cdots$ **or** $\alpha \leq \alpha_k$	$\alpha \leq \alpha_i$ holds for at least one i, $(1 \leq i \leq k)$

(c) type constraints (α, α' denote constraint variables)

Let M be a method. Define:
$$RootDefs(M) = \{\ M' |\ M \text{ overrides } M', \text{ and there exists no } M''\ (M'' \neq M') \text{ such that } M' \text{ overrides } M''\ \}$$

(d) auxiliary function *RootDefs*

Fig. 1. Syntax of type constraints.

Our previous papers [Tip et al. 2003; De Sutter et al. 2004; Fuhrer et al. 2005; Balaban et al. 2005; Kieżun et al. 2007; Tip 2007] presented a range of different refactorings in detail, along with extensive experimental evaluations. The purpose of this paper is to present a comprehensive overview of our research and to show how these different refactorings can all be handled using variations on a common type constraint framework, using variations on a single running example.

1.2. Organization of this Article

The remainder of this article is organized as follows. Section 2 presents the basic type constraint formalism that will be used as the basis for the refactorings presented in this paper. Section 3 shows how several refactorings related to generalization can be expressed using the basic type constraint model. Section 4 extends the basic type constraint model to accommodate the inference of generics, and presents two refactorings for introducing generics into Java programs. In Section 5, we present a refactoring for replacing deprecated classes with functionally equivalent ones, based on some further extensions to the type constraint model. Section 6 summarizes experiments that measure the effectiveness of the refactorings presented in Sections 4 and 5. Finally, Section 7 discusses related work, and Section 8 presents conclusions and directions for future work.

2. TYPE CONSTRAINTS

Type constraints [Palsberg and Schwartzbach 1993] are a formalism for expressing subtype relationships between the types of declarations and expressions. Figure 1 shows the syntax for type constraints used in this article, which relies on the following two concepts.

$$\frac{\text{assignment } E_1 = E_2}{[E_2] \leq [E_1]} \quad (1) \qquad \frac{\text{access } E \equiv E_0.f \text{ to field } F}{\begin{array}{lr}[E] = [F] & (2)\\ [E_0] \leq \mathit{Dcl}(F) & (3)\end{array}}$$

$$\frac{\begin{array}{c}\text{call } E \equiv E_0.m(E_1, \cdots, E_n) \text{ to method } M\\ \mathit{RootDefs}(M) = \{M_1, \cdots, M_k\},\ E'_i \equiv \mathit{Param}(M, i),\ 1 \leq i \leq n\end{array}}{\begin{array}{lr}[E] = [M] & (4)\\ [E_i] \leq [E'_i] & (5)\\ [E_0] \leq \mathit{Dcl}(M_1) \textbf{ or } \cdots \textbf{ or } [E_0] \leq \mathit{Dcl}(M_k) & (6)\end{array}}$$

$$\frac{\text{constructor call } E \equiv \texttt{new } C(E_1, \cdots, E_n) \text{ to constructor } M,\ E'_i \equiv \mathit{Param}(M, i),\ 1 \leq i \leq n}{\begin{array}{lr}[E] = C & (7)\\ [E_i] \leq [E'_i] & (8)\end{array}}$$

$$\frac{\begin{array}{c}M' \text{ overrides } M,\ M' \neq M,\ 1 \leq i \leq \mathit{NumParams}(M')\\ E_i \equiv \mathit{Param}(M, i),\ E'_i \equiv \mathit{Param}(M', i)\end{array}}{\begin{array}{lr}[E'_i] = [E_i] & (9)\\ [M'] \leq [M] & (10)\\ \mathit{Dcl}(M') < \mathit{Dcl}(M) & (11)\end{array}}$$

$$\frac{F' \text{ hides } F}{\mathit{Dcl}(F') < \mathit{Dcl}(F)} \quad (12) \qquad \frac{\texttt{return } E \text{ in method } M}{[E] \leq [M]} \quad (13)$$

$$\frac{\text{cast } (T)E}{[(T)E] = T} \quad (14) \qquad \frac{\text{downcast } (T)E}{[(T)E] \leq [E]} \quad (15) \qquad \frac{\text{upcast } (T)E}{[E] \leq [(T)E]} \quad (16)$$

$$\frac{\text{type } T}{\begin{array}{lr}T \leq \texttt{java.lang.Object} & (17)\\ [\texttt{null}] \leq T & (18)\end{array}} \qquad \frac{\text{use of } \texttt{this} \text{ in method } M}{[\texttt{this}] = \mathit{Dcl}(M)} \quad (19)$$

Fig. 2. Type constraints for a set of core Java language features.

—A *constraint variable* represents the type of a program construct. For example, a constraint variable $[E]$ represents "the type of expression E."

—A *type constraint* constrains the relationship between two or more constraint variables. For example, a type constraint $\alpha \leq \alpha'$ states that the type represented by constraint variable α must be the same as, or a subtype of, the type represented by constraint variable α'.

Type constraints are generated from a program's abstract syntax tree in a syntax-directed manner, and encode relationships between the types of declarations and expressions that must be satisfied in order to preserve type correctness or program behavior. Figure 2 shows rules that generate constraints from a representative set of program constructs. In Section 3, we will use these rules as the basis for refactorings for generalization. Section 4 and 5 will discuss how these rules need to be changed and generalized in order to support refactorings that introduce generics and refactorings for replacing functionally equivalent classes, respectively.

Most of the programs used in the experiments discussed in Section 6 use reflection, but we have checked that the type constraints that we generate are sufficient to preserve behavior.

In order to simplify the presentation of the refactorings in this article, we will assume that (i) programs do not use overloading, meaning that there are no methods with the same name but different formal parameter types, and (ii) that if two classes C_1 and C_2 declare a method with the same signature, then C_1 is a subtype of C_2 or C_2 is a subtype of C_1. Any program that does not meet these requirements can be transformed into an equivalent program that does via one or more renamings. These assumptions help us avoid a number of problems, such as the accidental creation or deletion of overriding relationships.

We will now discuss the rules of Figure 2. Rule (1) states that, for an assignment $E_1 = E_2$, a constraint $[E_2] \leq [E_1]$ is generated. Intuitively, this captures the requirement that the type of the right-hand side E_2 be a subtype of the type of the left-hand side E_1 because the assignment would not be type-correct otherwise.

Rules (2) and (3) state the type constraints induced by field access operations. For a field access $E_0.f$ that refers to a field F, Rule (2) states that the type of the entire expression $E_0.f$ is defined to be the same as the declared type of field F. Rule (3) states that the type of expression E_0 must be a subtype of the type in which field F is declared.

We say that a call $E_0.m(E_1, \cdots, E_k)$ is to a method M if, at runtime, the call will be dispatched to M or to some method that overrides M. Statically-dispatched, or direct, calls are handled by similar rules not shown here. Rule (4) defines the type of the call expression to be the same as M's return type.[5] Furthermore, the type $[E_i]$ of each actual parameter E_i must be the same as, or a subtype of, the type $[Param(M, i)]$ of the corresponding formal parameter $Param(M, i)$ (Rule (5)), and a method with the same signature as M must be declared in $[E_0]$ or one of its supertypes (Rule (6)). Note that Rule (6) relies on Definition 2.1 and the auxiliary notion *RootDefs* that is defined in Figure 2 to determine a set of methods $M_1, \ldots, M_k$ overridden by M, and requires $[E_0]$ to be a subtype of one or more of $Dcl(M_1), \cdots, Dcl(M_k)$.

Definition 2.1 (*Overriding*). A method declared in type C overrides itself and other methods defined in supertypes of C with the same name and the same sequence of parameter types.

The "overrides itself" part of Definition 2.1 ensures that *RootDefs* is not empty.

Example 2.2. Let us assume that we have a class hierarchy in which `C` is a subclass of `B`, where `C` also implements an interface `I`, and where a method `f()` is declared in `I` and `B`, but not in `C`. Then, we have that *RootDefs*(`C.f()`) = {`B.f()`, `I.f()`}.

Rules (7)–(8) are concerned with calls to constructor methods, and are analogous to the previously presented Rules (4)–(5).

Changing a formal parameter's type may affect method overriding and thereby virtual dispatch (and program) behavior, even if it does not affect type correctness. Hence, we require that the overriding relationships remain the same as they were in the original program: corresponding parameters of overriding methods were identical according to Definition 2.1 and must remain so (Rule (9)). For Java 5.0 and later, Rule (10) allows return types in overriding methods to be covariant. Rule (11) disallows solutions to the system of type constraints where two methods with the same signature end up in the same class by moving them up or down the type hierarchy. Similarly, Rule (12) creates type constraints that are needed in order to avoid changes to hiding (shadowing) relationships between fields with the same name.[6] In Java, a field F in a class C is said to *hide* a field F' in a superclass of C if F and F' have the same name. The purpose of Rule (12) has to do with the fact that refactorings such as PULL UP MEMBERS may *move* a field from the class where it is currently declared into the superclass of that class. Rule (12) serves to prevent refactorings from moving a field F into a class that already declares another field hidden by F.

[5]Rules (2), (4), (7), and (19) define the type of certain kinds of expressions. While not very interesting by themselves, these rules are essential for defining the relationships between the types of expressions and declared entities.
[6]This rule is sufficient to preserve hiding behavior for the refactorings under consideration in this article. However, additional constraint rules are needed if refactorings are considered that push members down from supertypes into subtypes.

Rule (13) states that for a statement `return` E that occurs within the body of a method M, the type of expression E must be a subtype of method M's declared return type, $[M]$.

Rules (14)–(16) generate type constraints that have the effect of preserving the behavior of cast expressions.[7] We define the type of a cast expression $(T)E$ to be type T (Rule (14)). Then, there are two cases: Rule (15) applies to downcasts in the original program and Rule (16) applies to upcasts. A cast is $(T)E$ is a *downcast* if T is a subtype of the type of E in the original program. Otherwise, if T is equal to, or a supertype of the type of E, it is an *upcast*. In each case, we generate a constraint that preserves the "direction" of the cast, ensuring that downcasts remain downcasts (or become no-ops), and upcasts remain upcasts.[8]

In general, each refactoring must preserve the exceptional behavior of casts, that is, the situations in which executing a cast results in a `ClassCastException`. For the refactorings presented in Section 3 and 4, this does not require additional rules because these refactorings do not affect the runtime type of objects created by the program. However, the refactoring of Section 5 may change the type of allocated objects and therefore requires additional rules for preserving cast behavior.

Rules (15) and (16) use "$[(T)E]$" instead of just "T" to accommodate different definitions of $[(T)E]$ than that in Rule (14) later on. For example, rules ($R14_a$) and ($R14_b$) in Figure 26(a) provide an alternative definition of $[(T)E]$ that enables the migration of legacy types.

Rules (17) and (18) state that `Object` is a supertype of any type T, and that the type of the `null` expression is a subtype of any type T, respectively. Rule (19) defines the type of a `this` expression to be the class that declares the associated method.

Thus far, we have shown how type constraints are generated from a variety of program constructs. These constraints will be used in subsequent sections for checking preconditions of refactorings, and for computing source code modifications that are to be applied by refactorings. In general, each constraint may play both of these roles. For example, we shall see how constraint Rule (6) will be used to compute source code modifications for the EXTRACT INTERFACE refactoring in Section 3.1, and for checking the preconditions for the PULL UP MEMBERS refactoring in Section 3.3.

3. REFACTORINGS FOR GENERALIZATION

Figure 3 shows a Java program that was designed to illustrate the issues posed by several different refactorings. The program declares a class `Stack` representing a stack, with methods `push()`, `pop()`, `isEmpty()`, and `contains()` with the expected behaviors, methods `moveFrom()` and `moveTo()` for moving an element from one stack to another, and a static method `print()` for printing a stack's contents. Also shown is a class `Client` that creates a stack, pushes the integers `1`, `2` and `3` onto it, and then creates another stack onto which it pushes the floating point value `4.4`. Two elements of the first stack are then moved to the second, the contents of the second stack are printed, and the elements of the first stack are transferred into a `Vector` whose contents are displayed in a tree. Hence, executing the program creates a graphical representation of a tree with a single node containing the value 1.

[7]The constraints for casts as shown in the figure are slightly more strict than what is necessary. In the presence of interface inheritance, casting between types that are neither subtypes nor supertypes of each other is allowed. Our implementation correctly handles this case.

[8]These rules are slightly more strict than what is necessary for preserving behavior for most refactorings we consider in this paper, but having this distinction between downcasts and upcasts makes the presentation of the type constraint systems used for different refactorings more uniform.

```
1:   class Client {
2:     public static void main(String[] args){
3:       Stack s1 = new Stack();
4:       s1.push(new Integer(1));
5:       s1.push(new Integer(2));
6:       s1.push(new Integer(3));
7:       Stack s2 = new Stack();
8:       s2.push(new Float(4.4));
9:       s2.moveFrom(s1);
10:      s1.moveTo(s2);
11:      Stack.print(s2);
12:      Vector v1 = new Vector(); /* A1 */
13:      while (!s1.isEmpty()){
14:        Integer n = (Integer)s1.pop();
15:        v1.add(n);
16:      }
17:      JFrame frame = new JFrame();
18:      frame.setTitle("Example");
19:      frame.setSize(300, 100);
20:      JTree tree = new JTree(v1);
21:      frame.add(tree, BorderLayout.CENTER);
22:      frame.setVisible(true);
23:    }
24:  }
25:  class Stack {
26:    private Vector v2;
27:    public Stack(){
28:      v2 = new Vector(); /* A2 */
29:    }
30:    public void push(Object o1){
31:      v2.addElement(o1);
32:    }
33:    public Object pop(){
34:      return v2.remove(v2.size()-1);
35:    }
36:    public void moveFrom(Stack s3){
37:      this.push(s3.pop());
38:    }
39:    public void moveTo(Stack s4){
40:      s4.push(this.pop());
41:    }
42:    public boolean isEmpty(){
43:      return v2.isEmpty();
44:    }
45:    public boolean contains(Object o2){
46:      return v2.contains(o2);
47:    }
48:    public static void print(Stack s5){
49:      Enumeration e = s5.v2.elements();
50:      while (e.hasMoreElements())
51:        System.out.println(e.nextElement());
52:    }
53:  }
```

Fig. 3. Example program P_1. The allocation sites for the two Vectors created by this program have been labeled A1 and A2 to ease the discussion of the Replace Class refactoring in Section 5.

3.1. Extract Interface

One possible criticism of the code in Figure 3 is that class Client explicitly refers to class Stack. Such explicit dependences on concrete data structures are generally frowned upon because they make code less flexible. The Extract Interface refactoring addresses this issue by (i) introducing an interface that declares a subset of the instance methods in a class and (ii) updating references in client code to refer to the interface instead of the class wherever possible. This change would enable the programmer to vary the implementation of the stack without having to change any reference that uses the interface type.

As an example, let us assume that the programmer has decided that it would be desirable to create an interface IStack that declares all of Stack's instance methods,[9] and to update references to Stack to refer to IStack instead. In the resulting code in Figure 4, the code fragments changed by the application of Extract Interface are underlined. Observe that s1, s3, and s4 are the only variables for which the type has been changed to IStack. Changing the type of s2 or s5 to IStack would result in type errors. In particular, changing s5's type to IStack results in an error because field v2, which is not declared in IStack, is accessed from s5 on line 49.

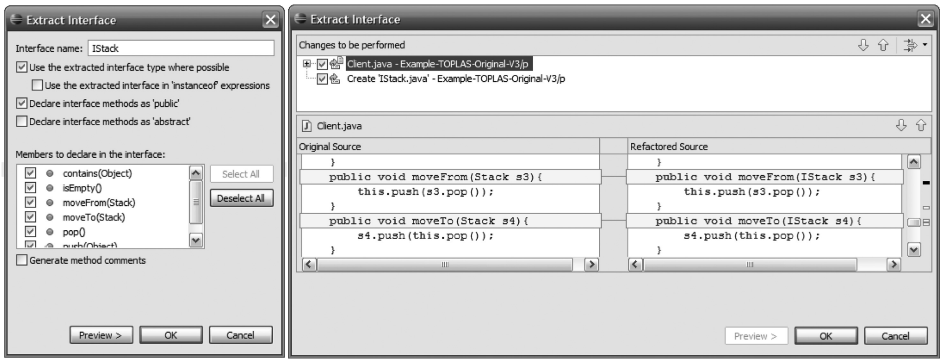
Using type constraints, it is straightforward to compute the declarations that can be updated to refer to IStack instead of Stack. In this case of the Extract Interface refactoring, we are looking for a way of assigning types to constraint variables that would maximize the use of the extracted interface while preserving type correctness. Furthermore, Extract Interface should not change the location of fields and methods in the class hierarchy. The latter requirement is enforced by the rules of Figure 6, which express that all constraint variables of the forms $Dcl(F)$ and $Dcl(M)$ should be bound to the type that originally declared the member under consideration.

[9]We assume that the programmer wants the static method print() to remain in class Stack.

```
class Client {
  public static void main(String[] args){
    IStack s1 = new Stack();
    s1.push(new Integer(1));
    s1.push(new Integer(2));
    s1.push(new Integer(3));
    Stack s2 = new Stack();
    s2.push(new Float(4.4));
    s2.moveFrom(s1);
    s1.moveTo(s2);
    Stack.print(s2);
    Vector v1 = new Vector();
    while (!s1.isEmpty()){
      Integer n = (Integer)s1.pop();
      v1.add(n);
    }
    JFrame frame = new JFrame();
    frame.setTitle("Example");
    frame.setSize(300, 100);
    Component tree = new JTree(v1);
    frame.add(tree, BorderLayout.CENTER);
    frame.setVisible(true);
  }
}
interface IStack {
  public void push(Object o1);
  public Object pop();
  public void moveFrom(IStack s3);
  public void moveTo(IStack s4);
  public boolean isEmpty();
  public boolean contains(Object o2);
}
```

```
class Stack implements IStack {
   private Vector v2;
   public Stack(){
     v2 = new Vector();
   }
   public void push(Object o1){
     v2.addElement(o1);
   }
   public Object pop(){
     return v2.remove(v2.size()-1);
   }
   public void moveFrom(IStack s3){
     this.push(s3.pop());
   }
   public void moveTo(IStack s4){
     s4.push(this.pop());
   }
   public boolean isEmpty(){
     return v2.isEmpty();
   }
   public boolean contains(Object o2){
     return v2.contains(o2);
   }
   public static void print(Stack s5){
     Enumeration e = s5.v2.elements();
     while (e.hasMoreElements())
       System.out.println(e.nextElement());
   }
}
```

Fig. 4. The example program of Figure 3 after applying Extract Interface to class `Stack` (code fragments affected by this step are underlined), and applying Generalize Declared Type to variable `tree` (the affected code fragment is shown boxed).


Extract Interface

Interface name: IStack

[✓] Use the extracted interface type where possible

[ ] Use the extracted interface in 'instanceof' expressions

[✓] Declare interface methods as 'public'

[ ] Declare interface methods as 'abstract'

Members to declare in the interface:

[✓] contains(Object)
[✓] isEmpty()
[✓] moveFrom(Stack)
[✓] moveTo(Stack)
[✓] pop()
[✓] push(Object)

[ ] Generate method comments

Extract Interface

Changes to be performed

[✓] Client.java - Example-TOPLAS-Original-V3/p
[✓] Create 'IStack.java' - Example-TOPLAS-Original-V3/p

Client.java

Original Source
```
    }
    public void moveFrom(Stack s3){
        this.push(s3.pop());
    }
    public void moveTo(Stack s4){
        s4.push(this.pop());
    }
```

Refactored Source
```
    }
    public void moveFrom(IStack s3){
        this.push(s3.pop());
    }
    public void moveTo(IStack s4){
        s4.push(this.pop());
    }
```

Fig. 5. Screenshots of the Extract Interface refactoring in Eclipse.

Figure 5 shows some screenshots of the user-interface for the Extract Interface refactoring in Eclipse. The window shown on the left appears when a programmer selects a class, and then activates the `Refactor->Extract Interface...` menu entry. In this window, the programmer has to select the methods that should be declared in the extracted interface. After pressing the `Preview` button, the tool computes the set of variables that can be given type `IStack` using the previously described algorithm, and displays the corresponding source code modifications in a separate window. The programmer can then confirm the proposed changes by pressing the `OK` button. All

program construct	**implied type constraint**	
declaration of method M (declared in type T)	$\mathit{Dcl}(M) = T$	(EI20)
declaration of field F (declared in type T)	$\mathit{Dcl}(F) = T$	(EI21)

Fig. 6. Additional constraint generation rules for Extract Interface.

line	**constraint**	**rule**
3	`Stack`≤[`s1`]	(7) (1)
4,5,6	[`s1`]≤*Dcl*(`IStack.push()`)	(6)
7	`Stack`≤[`s2`]	(7) (1)
8	[`s2`]≤*Dcl*(`IStack.push()`)	(6)
9	[`s2`]≤*Dcl*(`IStack.moveFrom()`)	(6)
9 36	[`s1`]≤[`s3`]	(5)
10	[`s1`]≤*Dcl*(`IStack.moveTo()`)	(6)
10 39	[`s2`]≤[`s4`]	(5)
11 48	[`s2`]≤[`s5`]	(5)
13	[`s1`]≤*Dcl*(`IStack.isEmpty()`)	(6)

line	**constraint**	**rule**
14	[`s1`]≤*Dcl*(`IStack.pop()`)	(6)
37	[`s3`]≤*Dcl*(`IStack.pop()`)	(6)
40	[`s4`]≤*Dcl*(`IStack.push()`)	(6)
49	[`s5`]≤*Dcl*(`Stack.v2`)	(3)
26	*Dcl*(`Stack.v2`)=`Stack`	(EI21)
30	*Dcl*(`Stack.push()`)=`Stack`	(EI20)
33	*Dcl*(`Stack.pop()`)=`Stack`	(EI20)
36	*Dcl*(`Stack.moveFrom()`)=`Stack`	(EI20)
39	*Dcl*(`Stack.moveTo()`)=`Stack`	(EI20)
42	*Dcl*(`Stack.isEmpty()`)=`Stack`	(EI20)
45	*Dcl*(`Stack.contains()`)=`Stack`	(EI20)
—	*Dcl*(`IStack.push()`)=`IStack`	(EI20)
—	*Dcl*(`IStack.pop()`)=`IStack`	(EI20)
—	*Dcl*(`IStack.moveFrom()`)=`IStack`	(EI20)
—	*Dcl*(`IStack.moveTo()`)=`IStack`	(EI20)
—	*Dcl*(`IStack.isEmpty()`)=`IStack`	(EI20)
—	*Dcl*(`IStack.contains()`)=`IStack`	(EI20)

Fig. 7. Type constraints generated for the application of the Extract Interface refactoring to the program of Figure 3 after creating an interface `IStack` that is implemented by class `Stack`, which declares all of `Stack`'s instance methods (only nontrivial constraints related to variables `s1`–`s5` are shown).

methods except `print()` were selected in the left window of Figure 5, which resulted in the suggested code modifications as shown in the right window in Figure 5.

We will now explain how the refactoring tool of Figure 5 automatically determines how the source code should be transformed. Consider Figure 7, which shows the relevant type constraints generated for declarations and expressions of type `Stack` in the program of Figure 3, according to the rules of Figures 2 and 6. Note that these constraints were generated after adding interface `IStack` to the class hierarchy.

Now, from the constraints of Figure 7, it is easy to see that:

$$\texttt{Stack} \leq [\texttt{s2}] \leq [\texttt{s5}] \leq \mathit{Dcl}(\texttt{Stack.v2}) = \texttt{Stack},$$

and hence that the types of `s2` and `s5` have to remain `Stack`. However, the types of `s1` and `s3` are less constrained:

$$\begin{array}{c}
[\texttt{s1}] \leq \mathit{Dcl}(\texttt{IStack.push()}) = \texttt{IStack} \\
[\texttt{s1}] \leq \mathit{Dcl}(\texttt{IStack.moveTo()}) = \texttt{IStack} \\
[\texttt{s1}] \leq \mathit{Dcl}(\texttt{IStack.isEmpty()}) = \texttt{IStack} \\
[\texttt{s1}] \leq \mathit{Dcl}(\texttt{IStack.pop()}) = \texttt{IStack} \\
[\texttt{s1}] \leq [\texttt{s3}] \leq \mathit{Dcl}(\texttt{IStack.pop()}) = \texttt{IStack},
\end{array}$$

implying that type `IStack` may be used for these variables. Note that, in general, the types of variables cannot be changed independently. For example, changing `s1`'s type to `IStack` but leaving `s3`'s type unchanged results in a type-incorrect program; this fact is captured by Rule (5).

Our algorithm for computing the set of declarations that can be updated is based on the above observations. In presenting the algorithm, the term *declared entity* will be used to refer to local variables, parameters in static, instance, and constructor methods, fields, method return types, and to type references in cast expressions. Moreover, $\mathit{All}(P, C)$ denotes the set of all declared entities of type C in program P.

Example 3.1. For the program P_1 of Figure 3, we have:

$$All(P_1, \texttt{Stack}) = \{\texttt{s1}, \texttt{s2}, \texttt{s3}, \texttt{s4}, \texttt{s5}\}.$$

Definition 3.2 ($\mathrm{TC}_{\mathrm{EI}}(P)$). Let P be a program, containing an interface I that has been extracted from a class C such that I declares a subset of C's instance methods. Then $\mathrm{TC}_{\mathrm{EI}}(P)$ denotes the set of type constraints inferred for program P according to Rules (1)–(19) of Figure 2 and Rules (EI20)–(EI21) of Figure 6.

Example 3.3. Let P_1' be the program of Figure 3 after adding an interface `IStack`, implemented by class `Stack`, that declares all of `Stack`'s instance methods. Figure 7 shows the constraints in $\mathrm{TC}_{\mathrm{EI}}(P_1')$ that pertain to expressions of type `Stack`.

Definition 3.4 defines the set of declarations of type C whose type cannot be updated to refer to an interface I. This is accomplished by first identifying those declared entities in program P for which changing the type to the new interface would violate a constraint in $\mathrm{TC}_{\mathrm{EI}}(P)$. Then, additional declared entities are identified as *non-updatable* because they are involved in constraints with declared entities that were previously identified as *non-updatable*. Note that the solution of the constraint system here is strictly symbolic. In particular, no constraints need be evaluated (or constraint variables be assigned values) to arrive at a solution.

Definition 3.4. (*Non-Updatable* Declared Entities). Let P be a program, let C be a class in P, and let I be an interface in P such that C is the only class that implements I and I does not have any supertypes other than `Object`. Define:

$$
\begin{array}{lr}
\multicolumn{2}{l}{NonUpdatable(P, C, I) = \{\, E \mid E \in All(P, C),\ \text{and}} \\
\quad (\ (\text{“}[E] \le T_1\ \textbf{or}\ \cdots\ \textbf{or}\ [E] \le T_k\text{”} \in \mathrm{TC}_{\mathrm{EI}}(P), I \not\le T_1, \cdots, I \not\le T_k, k \ge 1) & \textbf{(a)} \\
\quad\quad \text{or} & \\
\quad\quad \text{“}[E] = C\text{”} \in \mathrm{TC}_{\mathrm{EI}}(P) & \textbf{(b)} \\
\quad\quad \text{or} & \\
\quad\quad (\text{“}[E] \le [E']\text{”} \in \mathrm{TC}_{\mathrm{EI}}(P), E' \notin All(P, C), I \not\le [E']) & \textbf{(c)} \\
\quad\quad \text{or} & \\
\quad\quad (\text{“}[E] = [E']\text{”} \in \mathrm{TC}_{\mathrm{EI}}(P)\ \text{or} & \textbf{(d)} \\
\quad\quad\ \ \text{“}[E] \le [E']\text{”} \in \mathrm{TC}_{\mathrm{EI}}(P)\ \text{or} & \\
\quad\quad\ \ \text{“}[E] < [E']\text{”} \in \mathrm{TC}_{\mathrm{EI}}(P),\ E' \in NonUpdatable(P, C, I)))\}. &
\end{array}
$$

Part (a) of Definition 3.4 is concerned with constraints that are due to a method call $E.m(\cdots)$, and reflects situations where E cannot be given type I because a declaration of $m(\cdots)$ does not occur in (a supertype of) I. Part (b) reflects situations where the type of a declared entity is constrained to be exactly C. Such constraints may be generated due to several program constructs, including object allocation, and also due to the rules presented in Figure 6. Part (c) of Definition 3.4 deals with constraints $[E] \le [E']$ due to assignments and parameter passing, and states that E cannot be given type I if the declared type of E' is not C, and I is not equal to or a subtype of E''s type. The latter condition is needed for situations where a declared entity of type C is assigned to a declared entity of type `Object`. Part (d) handles the propagation of *non-updatability* due to overriding, assignments, and parameter passing.

Example 3.5. For example program P_1 of Figure 3, we find that:

$$NonUpdatable(P_1\texttt{Stack}, \texttt{IStack}) = \{\texttt{s2}, \texttt{s5}\}$$

This implies that the type of variables `s1`, `s3`, and `s4` can be updated to `IStack`. The corresponding changes to the source code were shown earlier in Figure 4.

line	constraint	rule applied
20	JTree≤[tree]	(7),(1)
21	[tree]≤java.awt.Component	(8)
12	Vector≤[v1]	(7),(1)
15	[v1]≤*Dcl*(java.util.Collection.add())	(6)
20	[v1]≤Vector	(8)
28	Vector≤[v2]	(7),(1)
31	[v2]≤*Dcl*(java.util.Vector.addElement())	(6)
34	[v2]≤*Dcl*(java.util.Collection.remove())	(6)
43	[v2]≤*Dcl*(java.util.Collection.isEmpty())	(6)
46	[v2]≤*Dcl*(java.util.Collection.contains())	(6)
49	[v2]≤*Dcl*(java.util.Vector.elements())	(6)
—	*Dcl*(java.util.Collection.add()) = java.util.Collection	(EI20)
—	*Dcl*(java.util.Vector.addElement()) = java.util.Vector	(EI20)
—	*Dcl*(java.util.Collection.remove()) = java.util.Collection	(EI20)
—	*Dcl*(java.util.Collection.isEmpty()) = java.util.Collection	(EI20)
—	*Dcl*(java.util.Collection.contains()) = java.util.Collection	(EI20)
—	*Dcl*(java.util.Vector.elements()) = java.util.Vector	(EI20)

Fig. 8. Type constraints used for the application of GENERALIZE DECLARED TYPE (only constraints related to variables `tree`, `v1`, and `v2` are shown). Line numbers refer to Figure 3, and rule numbers to rules of Figures 2 and 6.

3.2. GENERALIZE DECLARED TYPE

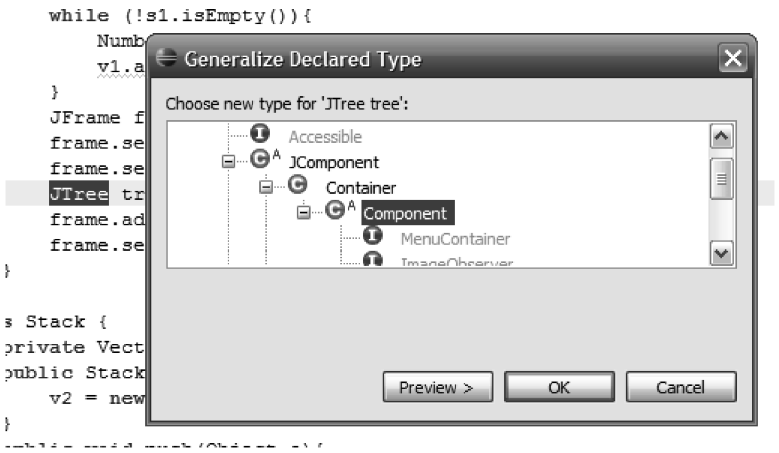
Another possible criticism of the program of Figure 3 is the fact that the declared types of some variables are overly specific. This is considered undesirable because it reduces flexibility. The GENERALIZE DECLARED TYPE refactoring in Eclipse lets a programmer select a declaration, and determines whether its type can be generalized without introducing type errors or behavioral changes. If so, the programmer may choose from the alternative permissible types. Using this refactoring, the type of variable `tree` can be updated to refer to `java.awt.Component` instead of `javax.swing.JTree` without affecting type correctness or program behavior, as is indicated by a box in Figure 4. This, in turn, would enable one to vary the implementation to use, say, a `JList` instead of a `JTree` in `Client.main()`.

However, in some situations, the type of a variable cannot be generalized. For example, changing the type of `v2` to `Collection` or to any other supertype of `Vector` would result in a type error because line 31 invokes the method `addElement()`, which is not declared in any supertype of `Vector`. Furthermore, the type of `v1` cannot be generalized because line 20 passes `v1` as an argument to the constructor `JTree(Vector)`. `JTree` is part of the standard Java libraries for which we cannot change the source code, and the fact that its constructor expects a `Vector` implies that a more general type cannot be used.

Figure 8 shows the constraints generated from the constraint rules of Figures 2 and 6 and the example program of Figure 3 for variables `tree`, `v1`, and `v2`. Note that, for parameters of methods in external classes such as the constructor of `JTree`, we must include constraints that constrain these parameters to have their originally declared type, because the source code in class libraries cannot be changed. Therefore, we have that:

$$\begin{gathered}\texttt{JTree} \leq [\texttt{tree}] \leq \texttt{java.awt.Component}\\ \texttt{Vector} \leq [\texttt{v1}] \leq \texttt{Vector}\\ \texttt{Vector} \leq [\texttt{v2}] \leq \texttt{Vector}.\end{gathered}$$

In other words, the types of `v1` and `v2` must be exactly `Vector`, but for `tree` we may choose any supertype of `JTree` that is a subtype of `java.awt.Component`: `javax.swing.JComponent`, `java.awt.Container`, or `java.awt.Component`. Note that, unlike in the case of EXTRACT INTERFACE where we computed the solution using a



```
    while (!s1.isEmpty()){
        Numb
        v1.a
    }
    JFrame f
    frame.se
    frame.se
    JTree tr
    frame.ad
    frame.se
}

s Stack {
private Vect
public Stack
    v2 = new
}
```

Generalize Declared Type

Choose new type for 'JTree tree':

- Accessible
- JComponent
  - Container
    - Component
      - MenuContainer
      - ImageObserver

Fig. 9. Screenshot of the GENERALIZE DECLARED TYPE refactoring in Eclipse.

```
1:   class BasicStack {
2:     public BasicStack(){
3:       v2 = new Vector();
4:     }
5:     public void push(Object o){
6:       v2.addElement(o);
7:     }
8:     public Object pop(){
9:       return v2.remove(v2.size()-1);
10:    }
11:    public boolean isEmpty(){
12:      return v2.isEmpty();
13:    }
14:    protected Vector v2;
15:  }
16:  class FullStack extends BasicStack {
17:    public FullStack(){
18:      super();
19:    }
20:    public FullStack moveFrom(FullStack s3){
21:      this.push(s3.pop());
22:      return this;
23:    }
24:    public void print(){
25:      Enumeration e = v2.elements();
26:      while (e.hasMoreElements())
27:        this.printElement(e);
28:    }
29:    private void printElement(Enumeration e){
30:      System.out.println(e.nextElement());
31:    }
32:  }
```

Fig. 10. Example program P_2.

symbolic analysis of the constraints, computing the set of permissible types requires solving the constraints.

The user-interface of GENERALIZE DECLARED TYPE in Eclipse includes a tree view of the class hierarchy, in which the names of permissible types are shown in black, and where nonpermissible types are "grayed out", as is shown in Figure 9. Figure 4 shows the refactored code after selecting `java.awt.Component`, which is the most general of the three permissible types.

3.3. PULL UP MEMBERS

PULL UP MEMBERS is a refactoring for moving fields and methods from a class to its immediate superclass. Unlike the previously discussed refactorings, PULL UP MEMBERS does not affect the declared types of variables, method parameters, and fields, nor does it affect method return types. We will illustrate this refactoring using the example program of Figure 10, which is a variation on the example program of Figure 3. In particular, we now have a class `BasicStack` that declares the methods `push()`, `pop()`, and `isEmpty()`, and a subclass `FullStack` of `BasicStack` that declares methods `moveFrom()` and `print()`. Note that `moveFrom()` has been changed to return `this` in order to enable the chaining of method calls, and `print()` has been changed to an instance method.

program construct	implied type constraint	
explicit declaration of variable or method parameter $T\ v$	$[v] = T$	(PM22)
declaration of method M with return type T	$[M] = T$	(PM23)
declaration of field F with type T	$[F] = T$	(PM24)

Fig. 11. Additional constraint generation rules for PULL UP MEMBERS.

line	constraint	rule applied
20	$[$`FullStack.moveFrom()`$] =$ `FullStack`	(PM23)
22	$[$`this`$] \leq [$`FullStack.moveFrom()`$]$	(13)
22	$[$`this`$] = Dcl($`FullStack.moveFrom()`$)$	(19)
27	$[$`this`$] \leq Dcl($`FullStack.printElement()`$)$	(6)
27	$[$`this`$] = Dcl($`FullStack.print()`$)$	(19)

Fig. 12. Type constraints used for applications of PULL UP MEMBERS to the example program P_2 of Figure 10 (only constraints related to method declarations are shown). Line numbers refer to Figure 10, and rule numbers to rules of Figures 2 and 11.

Now suppose that the programmer has decided that it would be desirable to migrate the `moveFrom()` method from `FullStack` to `BasicStack`. Does moving this method from `FullStack` to `BasicStack` preserve type correctness? In general, moving members from a type to its supertype may result in type errors because the type of the special variable `this` is defined as the class in which the surrounding method is declared. Moving a method from a type to its supertype *changes* the type of `this`, which may result in type errors if the type of `this` is otherwise constrained (e.g., when `this` is used in the method body as the receiver of a method call, as the target of a field access, or as a return value).

To answer the specific question of whether the `moveFrom()` method can be pulled up into class `BasicStack` without introducing type errors, we need a slightly different set of type constraints than we used previously. This is because we need to permit changing the locations of members in the class hierarchy while leaving the declared types of members unchanged. To accomplish this, we add type constraint rules that require the types of declarations and fields, and method return types to remain the same as in the original program (see Figure 11). As mentioned in Section 2, these constraints embody the refactoring's preconditions. If the constraint system possesses a solution, the refactoring preserves the type-correctness of the original program. Definition 3.6 below defines $\text{TC}_{\text{PM}}(P)$ to be the set of all type constraints generated for a program P, according to the rules of Figures 2 and 11.

Definition 3.6 ($\text{TC}_{\text{PM}}(P)$). Let P be a program. Then $\text{TC}_{\text{PM}}(P)$ denotes the set of type constraints inferred for program P according to Rules (1)–(19) of Figure 2 and Rules (PM22)–(PM23) of Figure 11.

Figure 12 shows the set of type constraints $\text{TC}_{\text{PM}}(P_2)$ that was generated for the example program P_2 of Figure 10. From these constraints, it can be seen that:

$$Dcl(\texttt{FullStack.moveFrom()}) = [\texttt{this}] \leq [\texttt{FullStack.moveFrom()}] = \texttt{FullStack}.$$

In other words, the method `moveFrom()` must remain declared in `FullStack` or a subtype of `FullStack`, of which there are none in this example. Any attempt to move `moveFrom()` into class `BasicStack` would render the return statement `return this` on line 22 type-incorrect, and applying the PULL UP MEMBERS refactoring to `moveFrom()` produces an error message indicating that the refactoring cannot be performed safely.

From the constraints in Figure 12, it can also be seen that:

$$\mathit{Dcl}(\texttt{FullStack.print()}) = [\texttt{this}] \leq \mathit{Dcl}(\texttt{FullStack.printElement()}),$$

indicating that `printElement()` must be declared in a supertype of the type in which `print()` is declared. In other words, applying PULL UP MEMBERS to method `print()` by itself results in a type-incorrect program, and is therefore not allowed. However, applying PULL UP MEMBERS to the methods `print()` and `printElement()` simultaneously is permitted.

So far, we have only discussed how to ensure that PULL UP MEMBERS preserves type-correctness. However, in some cases, moving a method from a given class to its superclass may affect method dispatch behavior. For example, the program P_3 below:

```
class A {
  public String toString(){ return "A"; }
}
class B extends A {
  // no definition of toString() in class B
}
class C extends B {
  public String toString(){ return "C"; }
}
public class Example {
  public static void main(String[] args){
    System.out.println((new B()).toString());
  }
}
```

prints "`A`". While pulling up method `C.toString()` into class `B` does not affect type-correctness, it results in the program printing "`C`" instead. In order to avoid such changes in program behavior, we impose the following additional precondition on PULL UP MEMBERS.

$$\forall\, C \leq \mathit{super}(\mathit{Decl}_P(M)) : \quad \mathit{staticLookup}(P, C, \mathit{Sig}(M)) <_P \mathit{super}(\mathit{Decl}_P(M)).$$

Here, $\mathit{Decl}_P(M)$ denotes the class in which M is declared in the original program P, $\mathit{super}()$ is a function that maps a class to its superclass, and $\mathit{staticLookup}(P, C, S)$ is a function that, for a given program P and class C, determines the nearest superclass of C that declares a method with signature S.

The precondition prevents changes in dispatch behavior by ensuring that, if a method with signature $\mathit{Sig}(M)$ is called on a subtype of $\mathit{super}(\mathit{Decl}_P(M))$ then the call should resolve to a proper subtype of $\mathit{super}(\mathit{Decl}_P(M))$. The application of PULL UP MEMBERS to method `C.toString()` in program P_3 does not satisfy the precondition because for type `B` we have that:

$$\texttt{A} = \mathit{staticLookup}(P_3, \texttt{B}, \texttt{toString()}) \not<_{P_3} \mathit{super}(\mathit{Decl}_{P_3}(\texttt{C.toString()})) = \texttt{B}.$$

3.4. Other Refactorings for Generalization

It is clear that `moveFrom()` can be pulled up in Figure 10 if its return type and the type of its parameter are changed to `BasicStack`, and this can be deduced from the constraints. In practice, this refactoring can be decomposed into an application of the GENERALIZE DECLARED TYPE refactoring, followed by an application of PULL UP MEMBERS. For the simple code of Figure 10 it therefore seems straightforward to combine both into one automated refactoring. However, such a combined refactoring can become quite complex when overridden methods or interface inheritance are present. Implementing refactorings correctly for a language as large as Java is already quite challenging, and it is therefore our preference to keep individual refactorings as simple as possible, and to express complex refactorings as sequences of more simple ones.

Two more simple refactorings related to generalization have also been implemented. The EXTRACT SUPERCLASS refactoring for extracting a superclass from a class is similar to EXTRACT INTERFACE in the sense that updatable declarations must be computed. The USE SUPERTYPE WHERE POSSIBLE refactoring enables programmers to replace references to a type with references to a supertype of that type. The EXTRACT SUPERCLASS and USE SUPERTYPE WHERE POSSIBLE refactorings both rewrite multiple declarations to use a single new type and require the same analysis as the one we presented for EXTRACT INTERFACE. By contrast, GENERALIZE DECLARED TYPE rewrites one declaration in isolation, but considers all possible types that can be given to that declaration, so for those reasons it requires a different analysis.

4. REFACTORINGS THAT INTRODUCE GENERICS

Generics were introduced in Java 5.0 to enable the creation of reusable class libraries with compiler-enforced type-safe usage. For example, an application that instantiates `Vector<E>` with, say, `String`, obtaining `Vector<String>`, can only add and retrieve `String`s. In the previous, nongeneric version of this class, `Vector.get()` is declared to return `Object` and therefore downcasts to `String` are needed to recover the type of retrieved elements. When a programmer makes a mistake, such downcasts fail at run time, with `ClassCastException`s.

Java's generics have been designed with backward compatibility in mind. To this end, programmers are allowed to refer to a parameterized class without explicitly specifying the type arguments that are bound to the formal type parameters of that class. This feature, commonly referred to as "raw types," essentially amounts to having the compiler instantiate each formal type parameter with its bound. For example, if a class `Cell`$\langle T$ `extends Number`$\rangle$ is referred to as simply `Cell`, the reference is treated as though an explicit type argument `Number` were supplied. This technique enables existing applications to work without modification, even after library classes upon which they depend have become parameterized.

Donovan et al. [2004] identified two refactoring problems related to the introduction of generics. The *parameterization problem* consists of adding type parameters to an existing class definition so that it can be used in different contexts without the loss of type information. For instance, parameterization converts the declaration of `Vector` into `Vector<E>`. Once a class has been parameterized, the *instantiation problem* is the task of determining the type arguments that should be given to instances of the generic class in client code. For instance, instantiation may convert a use of `Vector` into `Vector<String>`. The former problem subsumes the latter, because the introduction of type parameters often requires the instantiation of generic classes. Section 4.2 presents the INFER GENERIC TYPE ARGUMENTS refactoring that solves the instantiation problem [Fuhrer et al. 2005]. Section 4.3 presents the INTRODUCE TYPE PARAMETER refactoring that solves the parameterization problem [Kieżun et al. 2007], given the programmer's selection of a declaration whose type is to be replaced with a new formal type parameter. As we shall see shortly, this may involve nontrivial changes to other declarations (e.g., by introducing wildcard types [Torgersen et al. 2004]).

4.1. Motivating Example

Figure 13 shows the class `Stack` of Figure 3 after applying both INTRODUCE TYPE PARAMETER and INFER GENERIC TYPE ARGUMENTS. Applying INTRODUCE TYPE PARAMETER to the formal parameter of method `Stack.push()` causes the changes in the right column. For the purposes of this example, it is assumed that class `Stack` is analyzed in isolation. As can be seen in the figure, a new type parameter `T1` was added to

```
class Client {
  public static void main(String[] args){
    Stack<Integer> s1 = new Stack<Integer>();
    s1.push(new Integer(1));
    s1.push(new Integer(2));
    s1.push(new Integer(3));
    Stack<Number> s2 = new Stack<Number>();
    s2.push(new Float(4.4));
    s2.moveFrom(s1);
    s1.moveTo(s2);
    Stack.print(s2);
    Vector<Integer> v1 = new Vector<Integer>();
    while (!s1.isEmpty()){
      Integer n = ~~(Integer)~~ s1.pop();
      v1.add(n);
    }
    JFrame frame = new JFrame();
    frame.setTitle("Example");
    frame.setSize(300, 100);
    JTree tree = new JTree(v1);
    frame.add(tree, BorderLayout.CENTER);
    frame.setVisible(true);
  }
}
```

```
class Stack<T1> {
  private Vector<T1> v2;
  public Stack(){
    v2 = new Vector<T1>();
  }
  public void push(T1 o1){
    v2.addElement(o1);
  }
  public T1 pop(){
    return v2.remove(v2.size()-1);
  }
  public void moveFrom(Stack<? extends T1> s3){
    this.push(s3.pop());
  }
  public void moveTo(Stack<? super T1> s4){
    s4.push(this.pop());
  }
  public boolean isEmpty(){
    return v2.isEmpty();
  }
  public boolean contains(Object o2){
    return v2.contains(o2);
  }
  public static void print(Stack<?> s5){
    Enumeration<?> e = s5.v2.elements();
    while (e.hasMoreElements())
      System.out.println(e.nextElement());
  }
}
```

Fig. 13. The example program of Figure 3 after refactorings to introduce generics. Underlining and strikethroughs indicate changes. Application of INTRODUCE TYPE PARAMETER to the formal parameter of `Stack.push()` caused the changes in the right-hand column. Then, application of INFER GENERIC TYPE ARGUMENTS to the entire program caused the changes in the left-hand column.

class `Stack`[10], and `T1` is used as the type for field `v2`, the parameter of `Stack.push()`, and the return type of `Stack.pop()`. A more interesting change can be seen in the `moveFrom()`, `moveTo()`, and `print()` methods: their parameters now have wildcard types `Stack<? extends T1>`, `Stack<? super T1>`, and `Stack<?>`, respectively. To understand what this means, consider, for example, a call to `moveFrom()`. Its signature `Stack<T1>.moveFrom(Stack<? extends T1>)` implies that the type of the elements of the stack that is passed as an argument in the call must be a subtype of the type of the elements of the stack that is the receiver in that call. As we shall see in the next paragraph, this allows for greater flexibility when refactoring class `Client` because it enables the transfer of elements between the two stacks without the loss of precision in the declared types of the stacks. Note also that the type of parameter `o2` of method `Stack.contains()` has remained `Object`. This is generally considered good Java style and is followed in the standard class libraries available with the Java Development Kit (JDK). It allows clients to call `contains()` with an argument of any type. The solution in which the type of `o2` is `T1`, while perhaps more intuitive, is actually overly restrictive. To see this, consider for example a call `s1.contains(o)` where the type of variable `o` is `Object`; This call would make it impossible to instantiate `s1` as `Stack<Number>`.

The left column of Figure 13 shows the result of applying INFER GENERIC TYPE ARGUMENTS to the example program after the parameterization of `Stack`. The types of `s1` and `s2` are now `Stack<Integer>` and `Stack<Number>`, respectively. The downcast on line 14 that was present originally has been removed, which was enabled by the introduction of wildcard types in `Stack.moveFrom()` and `Stack.moveTo()`. If the formal parameters of these methods had been changed to `Stack<T1>` instead, Java's typing

[10]Our current implementation chooses names `T1`, `T2`, $\cdots$ for newly introduced type parameters.

$\mathit{TParam}(T, x)$	the type that is bound to formal type parameter T in the type of x

Fig. 14. Typeparam constraint variable used for solving the instantiation problem, in addition to the variables of Figure 1.

$$\frac{\begin{array}{c}\text{call } E \equiv E_0.m(E_1, \cdots, E_k) \text{ to method } M,\\ \mathit{RootDefs}(M) = \{M_1, \cdots, M_k\},\ E'_i \equiv \mathit{Param}(M, i),\ 1 \leq i \leq n,\\ C = \mathit{Dcl}(M),\ \neg\mathit{IsParameterizedType}(C)\end{array}}{\begin{array}{c}[E] = [M]\\ [E_i] \leq [E'_i]\end{array}} \quad \begin{array}{c}(\text{I4}_a)\\ (\text{I5}_a)\end{array}$$

$$\frac{\begin{array}{c}M' \text{ overrides } M,\ M' \neq M,\ 1 \leq i \leq \mathit{NumParams}(M'),\\ E_i \equiv \mathit{Param}(M, i),\ E'_i \equiv \mathit{Param}(M', i),\\ C = \mathit{Dcl}(M),\ \neg\mathit{IsParameterizedType}(C)\end{array}}{\begin{array}{c}[E_i] = [E'_i]\\ [M'] \leq [M]\\ \mathit{Dcl}(M') < \mathit{Dcl}(M)\end{array}} \quad \begin{array}{c}(\text{I9})\\ (\text{I10})\\ (\text{I11})\end{array}$$

Fig. 15. Updated type constraint rules for method calls and for method overriding. Changes from Figure 2 are shaded. Rules prefixed by a letter replace the previous versions. Subscripted rules are partial replacements; in this case, Figure 18 defines Rules (I4_b) and (I5_b). Omitted rules, such as Rule (6), are retained without change.

rules would have required `Stack<Number>` for the types of both `s1` and `s2`, thus making it impossible to remove the downcast.

4.2. Infer Generic Type Arguments

The Infer Generic Type Arguments refactoring requires extensions and changes to the type constraint formalism of Section 2. Most significantly, we need a new kind of constraint variable in order to reason about type parameters, as is shown in Figure 14. These *typeparam* constraint variables are of the form $\mathit{TParam}(T, x)$, representing the type that is bound to formal type parameter T in the type of x. For example, if we have a parameterized class `Vector<E>` and a variable v of type `Vector<String>`, then $\mathit{TParam}($`E`$, v) =$ `String`.

Furthermore, the generation of type constraints for method calls now depends on whether or not the invoked method is declared in a parameterized class. This requires two changes. First, the rules of Figure 2 that govern method calls are restricted to methods declared in nonparameterized classes, using a predicate $\mathit{IsParameterizedType}(C)$, which returns true if and only if class C is a parameterized class. Figure 15 shows the updated rules for method calls and for overriding. The rules for constructor calls are updated similarly. Second, we introduce a new set of rules for generating constraints for calls to methods in parameterized classes. Section 4.2.1 presents some motivating examples, and Section 4.2.2 presents the definition of these rules.

4.2.1. Examples.

We now give a few examples to illustrate what constraints are needed in the presence of calls to parameterized classes. In giving these examples, we assume that class `Stack` has already been parameterized as in the right column of Figure 13. This can be done either manually, or automatically using the Introduce Type Parameter refactoring that will be presented in Section 4.3.

Example 1. Consider the method call `s1.push(new Integer(1))` on line 4 in Figure 3. This call refers to the method `void Stack<T1>.push(T1 o1)`. If `s1` is of a parameterized type, say, `Stack<`C`>`, then this call can only be type-correct if `Integer` $\leq C$. This requirement is expressed by Rule (GEN-I25) in Figure 16.

program construct	constraints	
method call E_1`.push(`E_2`)` to `void Stack<T1>.push(T1)`	$[E_2] \leq \mathit{TParam}(\texttt{T1}, E_1)$	(GEN-I25)
method call E.pop() to `T1 Stack<T1>.pop()`	$[E.\texttt{pop}()] = \mathit{TParam}(\texttt{T1}, E)$	(GEN-I26)
method call E_1`.moveFrom(`E_2`)` to `void Stack<T1>. moveFrom(Stack<? extends T1>)`	$\mathit{TParam}(\texttt{T1}, E_2) \leq \mathit{TParam}(\texttt{T1}, E_1)$	(GEN-I27)
method call E_1`.moveTo(`E_2`)` to `void Stack<T1>. moveTo(Stack<? super T1>)`	$\mathit{TParam}(\texttt{T1}, E_1) \leq \mathit{TParam}(\texttt{T1}, E_2)$	(GEN-I28)
method call E_1`.add(`E_2`)` to `boolean Vector<E>.add(E)`	$[E_2] \leq \mathit{TParam}(\texttt{E}, E_1)$	(GEN-I29)

Fig. 16. Additional constraint generation rules needed for the Infer Generic Type Arguments refactoring. Only constraints for methods used in the example program are shown. The constraint generation rules (GEN-I25)–(GEN-I29) are not built into the refactoring as with all other constraint generaton rules in this paper. Rather, they are specific to the program of Figure 3 and were automatically derived from method signatures using the rules of Figure 18.

line	constraint	rule
4,5,6	$\texttt{Integer} \leq \mathit{TParam}(\texttt{T1}, \texttt{s1})$	(7),(GEN-I25)
8	$\texttt{Float} \leq \mathit{TParam}(\texttt{T1}, \texttt{s2})$	(7),(GEN-I25)
9	$\mathit{TParam}(\texttt{T1}, \texttt{s1}) \leq \mathit{TParam}(\texttt{T1}, \texttt{s2})$	(GEN-I27)
10	$\mathit{TParam}(\texttt{T1}, \texttt{s1}) \leq \mathit{TParam}(\texttt{T1}, \texttt{s2})$	(GEN-I28)
14	$[\texttt{s1.pop()}] = \mathit{TParam}(\texttt{T1}, \texttt{s1})$	(GEN-I26)
15	$\texttt{Integer} \leq \mathit{TParam}(\texttt{E}, \texttt{v1})$	(GEN-I29)

Fig. 17. Type constraints generated for the example program using the rules of (a). Only nontrivial constraints relevant to the inference of type parameters in uses of `Stack` and `Vector` are shown. Line numbers refer to Figure 3, and rule numbers refer to Figures 16 and 2.

Example 2. Similarly, the call `s1.pop()` on line 14 refers to method `T1 Stack<T1>.pop()`. If `s1` is of some parametric type, say `Stack<`C`>`, then $[\texttt{s1.pop()}] = C$. This requirement is expressed by Rule (GEN-I26).

Example 3. Consider the call `s2.moveFrom(s1)` on line 9. If we assume that `s1` and `s2` are of parameterized types `Stack<`C_1`>` and `Stack<`C_2`>`, respectively, for some C_1, C_2, then the call is type-correct if $C_1 \leq C_2$. This requirement is expressed by Rule (GEN-I27).

Figure 17 shows the constraints generated for the example of Figure 3 according to the rules of Figure 16. From these constraints, it follows that $\texttt{Integer} \leq \mathit{TParam}(\texttt{T1}, \texttt{s1})$, $\texttt{Float} \leq \mathit{TParam}(\texttt{T1}, \texttt{s2})$, and $\mathit{TParam}(\texttt{T1}, \texttt{s1}) \leq \mathit{TParam}(\texttt{T1}, \texttt{s2})$, and hence that $\texttt{Integer} \leq \mathit{TParam}(\texttt{T1}, \texttt{s2})$. Since `Number` is a supertype of both `Integer` and `Float`, a possible solution to this constraint system is:

$$\mathit{TParam}(\texttt{T1}, \texttt{s1}) \leftarrow \texttt{Integer},\ \mathit{TParam}(\texttt{T1}, \texttt{s2}) \leftarrow \texttt{Number}.$$

Generating the refactored source code that was shown in the left column of Figure 13 is now straightforward. The type of variable `s1` in the example program, for which we inferred $\mathit{TParam}(\texttt{T1}, \texttt{s1}) = \texttt{Integer}$, is rewritten to `Stack<Integer>`. Similarly, the type of `s2` is rewritten to `Stack<Number>`, and that of `v1` is rewritten to `Vector<Integer>`. Furthermore, all downcasts are removed for which the type of the expression being cast is a subtype of the target type. For example, for the downcast `(Integer)s1.pop()` on line 14, we inferred $[\texttt{s1.pop()}] = \texttt{Integer}$ enabling us to remove the cast.

4.2.2. Constraint Generation. As can be seen from Figure 16, the rules for generating constraints have a regular structure, in which occurrences of type parameters in method

$$\begin{array}{c} \text{call } E \equiv\ E_0.m(E_1,\ldots,E_k) \text{ to method } M, 1 \le i \le k \\ \dfrac{C = \mathit{Dcl}(M), \mathit{IsParameterizedType}(C)}{\mathit{CGen}([E],\ =,\ [M]_{\mathcal{P}},\ E_0) \cup} \qquad (\mathrm{I4}_b) \\ \mathit{CGen}([E_i],\ \le,\ [\mathit{Param}(M,i)]_{\mathcal{P}},\ E_0) \qquad (\mathrm{I5}_b) \end{array}$$

(a) constraints for generic method calls

$$\mathit{CGen}(\mathtt{act}, op, \mathtt{fml}, \mathtt{rcvr}) = \begin{cases} \{\mathtt{act}\ op\ C\} & \text{when } \mathtt{fml} \equiv\ C & \text{(c1)} \\ \{\mathtt{act}\ op\ \mathit{TParam}(T_i, \mathtt{rcvr})\} & \text{when } \mathtt{fml} \equiv\ T_i & \text{(c2)} \\ \mathit{CGen}(\mathtt{act}, \le, \tau, \mathtt{rcvr}) & \text{when } \mathtt{fml} \equiv ?\ \mathit{extends}\ \tau & \text{(c3)} \\ \mathit{CGen}(\mathtt{act}, \ge, \tau, \mathtt{rcvr}) & \text{when } \mathtt{fml} \equiv ?\ \mathit{super}\ \tau & \text{(c4)} \\ \{\mathtt{act}\ op\ C\} \cup & \text{when } \mathtt{fml} \equiv C\langle \tau_1, \ldots, \tau_m\rangle & \text{(c5)} \\ \mathit{CGen}(\mathit{TParam}(W_i, \mathtt{act}), =, \tau_i, \mathtt{rcvr}) & \text{and } C \text{ is declared as} & \\ & C\langle W_1, \ldots, W_m\rangle, 1 \le i \le m & \end{cases}$$

(b) recursive constraint-generation function ***CGen***

$$\dfrac{\begin{array}{c}\alpha_1 \le \alpha_2 \\ \mathit{TParam}(T_1, \alpha_1) \text{ or } \mathit{TParam}(T_1, \alpha_2) \text{ exists}\end{array}}{\mathit{TParam}(T_1, \alpha_1) = \mathit{TParam}(T_1, \alpha_2)}\ (\mathrm{I30}) \qquad \dfrac{\begin{array}{c}\mathit{TParam}(T_1, \alpha) \text{ exists} \\ C_1\langle T_1\rangle \ \mathtt{extends/implements}\ C_2\langle T\rangle \\ C_2 \text{ is declared as } C_2\langle T_2\rangle\end{array}}{\mathit{TParam}(T_2, \alpha) = \mathit{TParam}(T, \alpha)}\ (\mathrm{I31})$$

(c) closure rules

Fig. 18. Extensions to the type constraint formalism of Figure 2 required by the INFER GENERIC TYPE ARGUMENTS refactoring, together with Figure 15. Part (a) shows how rules (4) and (5) of Figure 2 for method calls are adapted to handle calls to generic methods. These rules make use of an auxiliary function $CGen$ that is shown in Part (b). Part (c) shows closure rules that impose constraints on actual type parameters due to language constructs such as assignments. In the rules of part (c), α, α_1, and α_2 denote constraint variables that are not type constants.

signatures give rise to different forms of constraints, depending on where these references occur in the method signature and on whether or not wildcards are used. While such rules can be written by the programmer, this is tedious and error-prone. As before, our approach will be to generate type constraints directly from language constructs in the subject program. To this end, we generalize the constraint generation rules of Figure 2, as discussed below. Conceptually, these generalized rules embody the same case analysis on where type parameters occur in method signatures as the one that was used to construct the rules needed for INFER GENERIC TYPE ARGUMENTS in Figure 16. However, we skip the intermediate step of generating these rules but instead generate the constraints directly.

Figure 18(a) shows how the previously shown Rules (4) and (5) of Figure 2 are adapted to handle calls to methods in generic classes.[11] For a given call, Rule ($\mathrm{I4}_b$) creates constraints that define the type of the method call expression, and Rule ($\mathrm{I5}_b$) creates constraints that require the type of actual parameters to be equal to or a subtype of the corresponding formal parameters. A recursive helper function *CGen*(`act`, *op*, `fml`, `rcvr`), shown in Figure 18(b), generates the appropriate constraints. *CGen* takes 4 parameters: `act`, representing the method call's actual argument (or return) type; *op*, identifying a type constraint operator; `fml`, representing the declared type of the call target's formal argument (or return value); and `rcvr`, representing the method call's receiver.

CGen is defined by case analysis on the structure of its third argument, `fml`. `fml` can take one of 5 possible forms: a simple nongeneric type, for example, `String`, a type

[11]In fact, these augmented constraint generation rules could be used with the refactorings of Section 3 to permit the generalization of type arguments.

parameter of `rcvr`'s type, an upper- or lower-bounded wildcard type, or a generic type. The cases in *CGen* handle each form in turn. Case (c1) applies when `fml` is a nongeneric class. Case (c2) applies when `fml` is a type parameter. In these cases, *CGen* generates a single type constraint using the given constraint operator. The remaining 3 cases involve formal types with substructure; accordingly, *CGen* operates recursively. Cases (c3) and (c4) apply when `fml` is an upper or lower-bounded wildcard type, respectively. In these two cases, `act` is constrained by the $\leq$ or $\geq$ operator, respectively, according to whether the wildcard type is bound from above or below. Finally, case (c5) applies when `fml` is a generic type. In this last case, the recursive call to *CGen* specifies the $=$ operator in constraining the type arguments, in accordance with Java 5's invariant-subtyping rule for type arguments. (See also the discussion of Rule (I30) in Section 4.2.3.) *CGen*'s correctness can be established straightforwardly from the completeness of its case analysis, along with its adherence to the Java 5 typing rules relevant to each case.

We will now give a few examples that show how the rules of Figure 18 are used to generate type constraints such as those shown in Figure 17.

Example 1. Let us again consider the call `s1.push(new Integer(1))` on line 4 in Figure 3. Applying Rule ($I4_b$) of Figure 18 yields *CGen*([`s1.push(new Integer(1))`], =, `void`, `s1`), and applying case (c1) of the definition of *CGen* produces {[`s1.push(new Integer(1))`] = `void`}. Likewise, applying Rule ($I5_b$) yields *CGen*([`new Integer(1)`], $\leq$, `T1`, `s1`), and applying case (c2) and Rule (7) produces {`Integer` $\leq$ *TParam*(`T1`, `s1`)}. This result is shown on the first line of Figure 17.

Example 2. Consider the call `s2.moveFrom(s1)` to method `void Stack<T1>.moveFrom(Stack<? extends T1>)` on line 9. Applying Rule ($I4_b$) of Figure 18 yields *CGen*([`s2.moveFrom(s1)`], =, `void`, `s2`), and applying case (c1) of the definition of *CGen* produces {[`s2.moveFrom(s1)`] = `void`}. Furthermore, applying Rule ($I5_b$) produces *CGen*([`s1`], $\leq$, `Stack<? extends T1>`, `s2`), and an application of case (c5) produces {[`s1`] $\leq$ `Stack`} $\cup$ *CGen*(*TParam*(`T1`, `s1`), =, `? extends T1`, `s2`). The second part of this term evaluates to *CGen*(*TParam*(`T1`, `s1`), $\leq$, `T1`, `s2`) using an application of case (c3), and then to {*TParam*(`T1`, `s1`) $\leq$ *TParam*(`T1`, `s2`)} using case (c2). This result is shown in Figure 17. In summary, for the call to `moveFrom()` on line 9, the following set of constraints is generated: {[`s2.moveFrom(s1)`] = `void`, [`s1`] $\leq$ `Stack`, *TParam*(`T1`, `s1`) $\leq$ *TParam*(`T1`, `s2`)}.

4.2.3. Closure Rules. Thus far, we introduced additional typeparam constraint variables such as *TParam*(T, E) to represent the actual type parameter bound to T in E's type, and we described how calls to methods in generic libraries give rise to constraints on typeparam variables. However, we have not yet discussed how types inferred for actual type parameters are constrained by language constructs such as assignments and parameter passing. For example, consider an assignment `a = b`, where `a` and `b` are both declared of type `Vector<E>`. The invariant subtyping on Java generics[12] implies that *TParam*(`E`, `a`) = *TParam*(`E`, `b`). The situation becomes more complicated in the presence of inheritance relations between generic classes. Consider a situation involving class declarations[13] such as:

```
interface List<E_l> { ... }
class Vector<E_v> implements List<E_v> { ... }
```

[12] In the presence of wildcard types, Java uses the more relaxed "containment" subtyping [Gosling et al. 2005]: `? extends Number` is *contained* in `? extends Object` and therefore `Set<? extends Number>` is a subtype of `Set<? extends Object>`). In this paper and in our implementation, we conservatively assume invariant subtyping even with wildcard types.

[13] In the Java collections library, the type formal parameters of both `Vector` and `List` have the same name, `E`. In this section, for disambiguation, we subscript them with v and l, respectively.

and two variables, `c` of type `List` and `d` of type `Vector`, and an assignment `c = d`. This assignment can only be type-correct if the same type is used to instantiate $\texttt{E}_l$ in the type of `c` and $\texttt{E}_v$ in the type of `d`. In other words, we need a constraint $\mathit{TParam}(\texttt{E}_l, \texttt{c}) = \mathit{TParam}(\texttt{E}_v, \texttt{d})$. The situation becomes yet more complicated if generic library classes are assigned to variables of non-generic supertypes such as `Object`. Consider the program fragment:

```
Vector v1 = new Vector();
v1.add("abc");
Object o = v1;
Vector v2 = (Vector)o;
```

Here, we would like to infer $\mathit{TParam}(\texttt{E}_v, \texttt{v1}) = \mathit{TParam}(\texttt{E}_v, \texttt{v2}) = \texttt{String}$, which would require tracking the flow of actual type parameters through variable `o`.[14]

The required constraints are generated by the closure rules of Figure 18(c). These rules infer, from an existing system of constraints, a set of additional constraints that unify the actual type parameters as outlined in the examples above. Rule (I30) states that, if a subtype constraint $\alpha_1 \leq \alpha_2$ exists, and another constraint implies that the type of α_1 or α_2 has formal type parameter T_1, then the types of α_1 and α_2 must have the same actual type parameter T_1.[15] This rule thus expresses the invariant subtyping among generic types. Observe that this has the effect of associating type parameters with variables of nongeneric types, in order to ensure that the appropriate unification occurs in the presence of assignments to variables of nongeneric types. For the example code fragment, a constraint variable $\mathit{TParam}(\texttt{E}_v, \texttt{o})$ is created by applying Rule (I30). Values computed for variables that denote type arguments of nongeneric classes (such as `Object` in this example) are discarded at the end of constraint solution.

Rule (I31) is concerned with subtype relationships among generic library classes such as the one discussed above between classes `Vector` and `List`. The rule states that if a variable $\mathit{TParam}(T_1, \alpha)$ exists, then constraints are created to relate $\mathit{TParam}(T_1, \alpha)$ to the types of actual type parameters of its superclasses. For example, if we have two variables, `c` of type `List` and `d` of type `Vector`, and an initial system of constraints $[\texttt{d}] \leq [\texttt{c}]$ and $\texttt{String} \leq \mathit{TParam}(\texttt{E}_v, \texttt{d})$, then using the rules of Figure 18(c), we obtain the additional constraints $\mathit{TParam}(\texttt{E}_v, \texttt{d}) = \mathit{TParam}(\texttt{E}_v, \texttt{c})$, $\mathit{TParam}(\texttt{E}_l, \texttt{d}) = \mathit{TParam}(\texttt{E}_v, \texttt{d})$, $\mathit{TParam}(\texttt{E}_l, \texttt{c}) = \mathit{TParam}(\texttt{E}_l, \texttt{d})$, and $\mathit{TParam}(\texttt{E}_l, \texttt{c}) = \mathit{TParam}(\texttt{E}_v, \texttt{d})$.

Note that we require that the constraint variables α, α_1, and α_2 in Rules (I30) and (I31) are not type constants. This requirement is necessary to ensure that different occurrences of a parameterized type can be instantiated differently. Type constants may arise due to several program constructs such as casts, method calls, and field accesses.

4.2.4. Pragmatic Issues. Several pragmatic issues needed to be addressed in our implementation of INFER GENERIC TYPE ARGUMENTS.

The constraint system is typically underconstrained, and there is usually more than one legal type associated with each constraint variable. For instance, the constraints shown in Figure 17 also allow the following uninteresting solution:

$$\mathit{TParam}(\texttt{T1}, \texttt{s1}) \leftarrow \texttt{Object},\ \mathit{TParam}(\texttt{T1}, \texttt{s2}) \leftarrow \texttt{Object}.$$

[14]In general, a cast to a parameterized type cannot be performed in a dynamically safe manner because type arguments are erased at run time. In this case, however, our analysis is capable of determining that the resulting cast to `Vector<String>` would always succeed.

[15]That is, unless wildcard types are inferred, which we do not consider in this section.

When faced with a choice, our solver relies on heuristics to guide it towards preferred solutions. The two most significant of these heuristics are preferring more specific types over less specific ones, and avoiding marker interfaces such as `Serializable`.

In some cases, the actual type parameter inferred by our algorithm is equal to the bound of the corresponding formal type parameter, which typically is `Object`. Since this does not provide any benefits over the existing situation (no additional casts can be removed), our algorithm leaves raw any declarations and allocation sites for which this result is inferred. The opposite situation, where the actual type parameter of an expression is completely unconstrained, may also happen, in particular for incomplete programs. In principle, any type can be used to instantiate the actual type parameter, but since each choice is arbitrary, our algorithm leaves such types raw as well.

There are several cases where raw types must be retained to ensure that program behavior is preserved. When an application passes an object o of a generic library class to an external library,[16] nothing prevents that library from writing values into o's fields (either directly, or by calling methods on o). In such cases, we cannot be sure what actual type parameter should be inferred for o, and therefore generate an additional constraint that equates the actual type parameter of o to be the bound of the corresponding formal type parameter, which has the effect of leaving o's type raw. Finally, Java does not allow creation of arrays of generic types [Bracha et al. 2004]. For example, `new Vector<String>[10]` is not allowed. Our algorithm generates constraints that equate the actual type parameter to the bound of the corresponding formal type parameter, which has the effect of preserving rawness. Section 6 presents a summary of results obtained with our implementation of INFER GENERIC TYPE ARGUMENTS on a suite of Java programs.

A final minor matter is the introduction of an additional constraint generation rule in order to handle Java 5's "enhanced for" loops to constrain the type of the loop induction variable:

$$\frac{\text{for-loop } \texttt{for}(T\ \ v : E)\ S \qquad E \ \texttt{extends Iterable}\langle T' \rangle}{[v] \leq \mathit{TParam}(T', E)}$$

A similar rule handles the case where the expression E is of an array type, rather than `Iterable`.

4.3. INTRODUCE TYPE PARAMETER

The INTRODUCE TYPE PARAMETER refactoring requires a further adaptation of the type constraint formalism of Section 4.2. This adaptation includes replacing the *typeparam* constraint variables of Section 4.2 with the more general notion of a *context* constraint variable, the introduction of a new form of constraint variable called *wildcard variables*, changes to the constraint generation rules, and a specialized constraint solver. This section discusses these extensions and illustrates them on the class `Stack` of Figure 3. The preferred parameterization of this class was previously shown in the right column of Figure 13.

4.3.1. Extensions to the Type Constraints Model. Figure 19 shows how the formalism of Figure 1 is extended with two new kinds of constraint variables, *context variables* and *wildcard variables*, in order to accommodate the INTRODUCE TYPE PARAMETER refactoring. Note that we use the *typeparam* variables that were introduced in Section 4.2 in this

[16]The situation where an application receives an object of a generic library type from an external library is analogous.

α	$::=$	α_{nw}	non-wildcard variable
		? extends α_{nw}	wildcard type upper-bounded by α_{nw}
		? super α_{nw}	wildcard type lower-bounded by α_{nw}
α_{nw}	$::=$	α_{ctxt}	contexts
		T	type parameter
		$\mathcal{I}_{\alpha_{ctxt}}(\alpha)$	α, interpreted in context α_{ctxt}
α_{ctxt}	$::=$	$[E]$	type of expression E
		$[M]$	return type of method M
		$[\mathit{Param}(M, i)]$	type of i^{th} formal parameter of method M
		C	monomorphic type constant

Fig. 19. Constraint variables used for the INTRODUCE TYPE PARAMETER refactoring.

section only for references to already parameterized classes (see Section 4.3.5 for an example).

A *context variable* is of the form $\mathcal{I}_{\alpha'}(\alpha)$ and represents the *interpretation* of a constraint variable α in a *context* given by another constraint variable, α'. We give the intuition behind this new form of constraint variables by examples.

Example 4.1. Consider the JDK class `List<E>`. References to its type parameter `E` make sense only within the definition of `List`. In the context of an instance of `List<String>`, the interpretation of `E` is `String`, while in the context of an instance of `List<Number>`, the interpretation of `E` is `Number`.

Example 4.2. Consider the type `Stack<T1>` declared in Figure 13. For a variable `x` of type `Stack<Number>`, the interpretation of `T1` in the context of the type of `x` is `Number`. We will denote this fact by $\mathcal{I}_{[\texttt{x}]}(\texttt{T1}) = \texttt{Number}$. Here, $\mathcal{I}_{[\texttt{x}]}$ is an *interpretation function*. An interpretation function is subscripted by a constraint variable that corresponds to a program entity of a parameterized type, and maps each of the formal type parameters of that parameterized type to the types with which they are instantiated. For the example being considered, $\mathcal{I}_{[\texttt{x}]}$ maps the formal type parameter[17] `T1` of `Stack` to the type, `Number`, with which it is instantiated in type [`x`].

Example 4.3. Consider the method call `s1.push(new Integer(1))` on line 4 of Figure 3. For this call to be type-correct, the type `Integer` of actual parameter `new Integer(1)` must be a subtype of the formal parameter `o1` of `Stack.push()` *in the context of the type of* `s1`. This is expressed by the constraint $\texttt{Integer} \leq \mathcal{I}_{[\texttt{s1}]}([\texttt{o1}])$. It would be incorrect to simply require that $\texttt{Integer} \leq [\texttt{o1}]$ because when `Stack` becomes a parameterized class `Stack<T1>`, and the type of `o1` becomes `T1`, then `T1` is out of scope at the call site. In addition, `Integer` is not a subtype of `T1`.

In some cases, a context α_{ctxt} is irrelevant. For example, $\mathcal{I}_{\alpha_{ctxt}}(\texttt{String})$ always resolves to `String`, regardless of the context α_{ctxt} in which it is interpreted.

Context variables can be viewed as a generalization of the typeparam variables that were introduced in Section 4.2. Recall that, in Section 4.2, a typeparam variable $\mathit{TParam}(\texttt{E}, \texttt{x})$ was used for expressions `x` whose type was an instantiation of a parameterized class such as `Vector<E>`, where it denoted the type with which the formal type parameter `E` was instantiated. For example, if `x` is declared as `Vector<String>`, then $\mathit{TParam}(\texttt{E}, \texttt{x}) = \texttt{String}$. Context variables take this idea one step further and are concerned with situations where we are trying to *infer* a new type parameter for class `Vector`. The interpretation function $\mathcal{I}_{[\texttt{x}]}$ is a variable in our constraint system

[17]For parameterized types with multiple type parameters such as `HashMap`, the interpretation function provides a binding for each of them [Kieżun et al. 2007].

for which our solver will attempt to find a suitable value: a mapping from formal type parameters to the types with which they are instantiated. When such a mapping can be found, generating a name for such a new type parameter is trivial.

A *wildcard variable* has the form `? extends` α or `? super` α (where α is another constraint variable), and is used in cases where Java's typing rules *require* the use of wildcard types. Consider the following class that extends the library class `java.util.Vector<E>`.

```
class SubVector extends Vector {
  @Override
  public boolean addAll(Collection c){ ··· }
}
```

In this example, `SubVector.addAll()` overrides `java.util.Vector.addAll()`. If `SubVector` becomes a generic class with formal type parameter `T`, then preserving this overriding relationship requires the formal parameter `c` of `SubVector.addAll()` to have the same type as that of `Vector.addAll()`, which is declared in the Java standard libraries as `Vector.addAll(Collection<? extends E>)`. Three parts of our algorithm work together to accomplish this: (i) the type of `c` is represented, using a context variable, as `Collection<`$\mathcal{I}_{[\texttt{c}]}$`(E)>`, (ii) type constraint generation produces $\mathcal{I}_{[\texttt{c}]}(\texttt{E}) = \texttt{? extends } \mathcal{I}_{\texttt{SubVector}}(\texttt{E})$, which uses a wildcard variable, and (iii) constraint solution resolves $\mathcal{I}_{\texttt{SubVector}}(\texttt{E})$ to `T`.

In addition to the above cases, where wildcard types are required by Java's typing rules, our algorithm heuristically introduces wildcard types in one other case: when doing so yields a more flexible typing for a given entity. Further details appear in the example of Section 4.3.5, and in Section 4.3.7, which describes the heuristics used by our algorithm to select the most useful solution, when a choice exists.

4.3.2. Type Constraint Generation. Figure 20 shows the changes to the constraint generation rules necessary for the INTRODUCE TYPE PARAMETER refactoring. Rules (P4) and (P5) in part (a) of the figure generate the appropriate constraints for method calls, and are adaptations of the corresponding rules in Figures 15 and 18. Rule (P4) states that the type of the method call expression is the same as the return type of the method (in the context of the receiver). Rule (P5) relates the actual and formal type parameters of the call. The $\mathit{TargetClasses}$ set is a user-supplied input to the parameterization algorithm that indicates which classes should be refactored by adding type parameters. For example, in Figure 3, class `Stack` is in $\mathit{TargetClasses}$. The auxiliary function CGen, defined in Figure 20(b), actually generates constraints.

Java's type rules impose certain restrictions on parametric types. Closure rules such as (P30) and (P31) in Figure 20(c) enforce those restrictions. Rule (P30) enforces invariant subtyping of parametric types: $C\langle\tau\rangle$ is a subtype of $C\langle\tau'\rangle$ iff $\tau = \tau'$ (see discussion in footnote 12). Rule (P31) requires that, given two formal type parameters[18] T_1 and T_2 such that $T_1 \leq T_2$ and any context α in which either actual type parameter $\mathcal{I}_\alpha(T_1)$ or $\mathcal{I}_\alpha(T_2)$ exists, the subtyping relationship $\mathcal{I}_\alpha(T_1) \leq \mathcal{I}_\alpha(T_2)$ must also hold. To illustrate this rule, consider a class `C<T1, T2 extends T1>` and any instantiation `C<C1, C2>`. Then, `C2` $\leq$ `C1` must hold, implying that, for instance, `C<Number, Integer>` is legal but that `C<Integer, Number>` is not.

The type bound on any newly introduced type parameter is defined by our algorithm to be the corresponding type in the original program, in order to preserve the program's type erasure. By doing so, we ensure that the refactoring can be safely applied to library

[18]These can also be constraint variables that could become formal type parameters.

$$\frac{\begin{array}{c}\text{call } E \equiv E_0.m(E_1,\ldots,E_k) \text{ to method } M\\ inScope \equiv \mathit{Dcl}(M) \in TargetClasses, 1 \le i \le k\end{array}}{\begin{array}{c}CGen([E], =, [M], [E_0], inScope) \cup \\ CGen([E_i], \le, [\mathbf{Param}(M,i)], [E_0], inScope)\end{array}} \qquad \begin{array}{c}(P4)\\(P5)\end{array}$$

(a)

$$CGen(\texttt{act}, op, \texttt{fml}, \texttt{rcvr}, inScope) =$$
$$\begin{cases} \{\texttt{act}\ op\ C\} & \text{when } \texttt{fml}_{\mathcal{P}} \equiv C \text{ and } inScope \equiv false & (c1') \\ \{\texttt{act}\ op\ \mathcal{I}_{\texttt{rcvr}}(\texttt{fml})\} & \text{when } \texttt{fml}_{\mathcal{P}} \equiv C \text{ and } inScope \equiv true & (c1'') \\ \{\texttt{act}\ op\ \mathcal{I}_{\texttt{rcvr}}(T)\} & \text{when } \texttt{fml}_{\mathcal{P}} \equiv T & (c2') \\ CGen(\texttt{act}, \le, [\tau'], \texttt{rcvr}, inScope) & \text{when } \texttt{fml}_{\mathcal{P}} \equiv \texttt{? extends } \tau' & (c3') \\ CGen(\texttt{act}, \ge, [\tau'], \texttt{rcvr}, inScope) & \text{when } \texttt{fml}_{\mathcal{P}} \equiv \texttt{? super } \tau' & (c4') \\ \{\texttt{act}\ op\ C\} \cup & & \\ \bigcup_{1 \le i \le m} CGen(\mathcal{I}_{\texttt{act}}(W_i), =, [\tau_i], \texttt{rcvr}, inScope) & \text{when } \texttt{fml}_{\mathcal{P}} \equiv C\langle \tau_1,\ldots,\tau_m\rangle \text{ and } C \text{ is declared as } C\langle W_1,\ldots,W_m\rangle & (c5') \end{cases}$$

(b)

$$\frac{\alpha_1 \le \alpha_2 \qquad \mathcal{I}_{\alpha_1}(\alpha) \text{ or } \mathcal{I}_{\alpha_2}(\alpha) \text{ exists}}{\mathcal{I}_{\alpha_1}(\alpha) = \mathcal{I}_{\alpha_2}(\alpha)} \qquad (P30)$$

$$\frac{\alpha_1 \le \alpha_2 \qquad \mathcal{I}_{\alpha'}(\alpha_1) \text{ or } \mathcal{I}_{\alpha'}(\alpha_2) \text{ exists}}{\mathcal{I}_{\alpha'}(\alpha_1) \le \mathcal{I}_{\alpha'}(\alpha_2)} \qquad (P31)$$

(c)

Fig. 20. Extensions to the type constraint formalism required by the INTRODUCE TYPE PARAMETER refactoring. Part (a) shows (P4) and (P5) that generalize the corresponding rules ($I4_a$), ($I4_b$), ($I5_a$), and ($I5_b$) of Figures 15 and 18(a). Here, *TargetClasses* is a set of classes that should be parameterized by adding type parameters. Part (b) shows a generalized version of the function *CGen* of Figure 18(b), which has been extended to handle context variables, and by taking an additional parameter *inScope*. Here, $\alpha_{\mathcal{P}}$ denotes the type of the program construct corresponding to α in the original program $\mathcal{P}$. Part (c) presents closure rules (P30) and (P31) that generalize the corresponding rules of Figure 18(c).

classes without making a "closed-world" assumption, which would require access to all clients of the classes being parameterized.

4.3.3. Algorithm. A solution to the system of type constraints is computed using the iterative worklist algorithm of Figure 21. During solving, each variable α has an associated type estimate *Est*(α). An estimate is a set of types. Each estimate is initialized to the set of all possible nonparametric types and shrinks monotonically as the algorithm progresses. When the algorithm terminates, each estimate consists of exactly one type. Because type estimates do not contain parametric types, they are finite sets, and algebraic operations such as intersection can be performed directly. As an optimization, our implementation uses a symbolic representation for type estimates.

The algorithm begins by initializing the type estimate for each constraint variable, at lines 2 and 15–22 in Figure 21. A workset P is used to contain those constraint variables that it has decided shall become type parameters, but for which that decision has yet to be executed. The set P is initially seeded with the constraint variable that corresponds to the declaration that is selected either by a heuristic or by the user on line 3. The inner loop of parameterize() on lines 5–11 repeatedly removes an element from P and sets its estimate to a singleton type parameter. For new type parameters, the upper bound is the declared type in the original (unparameterized) program.

Whenever a type estimate changes, those changes must be propagated through the type constraints, possibly reducing the type estimates of other variables as well. The propagate() subroutine performs this operation, ensuring that the estimates on both sides of a type constraint contain only types that are consistent with the relation.

Notation:

$Est(\alpha)$	a set of types, the type estimate of constraint variable α
$\alpha_{\mathcal{P}}$	type of constraint variable α in the original program
$\boldsymbol{Sub}(\tau)$	set of all non-wildcard subtypes of τ
$Wild(X)$	set of wildcard types (both lower- and upper-bounded) for all types in type estimate X
$\boldsymbol{U}_E^S$	universe of all types, including all wildcard types (i.e., both <u>s</u>uper and <u>e</u>xtends wildcards)

```
1  Subroutine parameterize():
2    initialize()
     // $P$ is a set of variables known to be type parameters
3    $P \longleftarrow$ {automatically- or user-selected variable}
4    repeat until all variables have single-type estimates
5      while $P$ is not empty do
6        $\alpha_{tp} \longleftarrow$ remove element from $P$
7        if $Est(\alpha_{tp})$ contains a type parameter then
8          $Est(\alpha_{tp}) \longleftarrow$ {type parameter from $Est(\alpha_{tp})$}
9        else
10         $Est(\alpha_{tp}) \longleftarrow$ {create new type parameter}
11       propagate()
12     if $\exists \alpha . |Est(\alpha)| > 1$ then
13       $Est(\alpha) \longleftarrow$ {select a type from $Est(\alpha)$}
14       propagate()

   // Set initial type estimate for each constraint variable
15 Subroutine initialize():
16   foreach non-context variable $\alpha$ do
17     if $\alpha$ cannot have wildcard type then
18       $Est(\alpha) = \boldsymbol{Sub}(\alpha_{\mathcal{P}})$
19     else
20       $Est(\alpha) = \boldsymbol{Sub}(\alpha_{\mathcal{P}}) \cup Wild(\boldsymbol{Sub}(\alpha_{\mathcal{P}}))$
21   foreach context variable $\mathcal{I}_{\alpha'}(\alpha)$ do
22     $Est(\mathcal{I}_{\alpha'}(\alpha)) = \boldsymbol{U}_E^S$

   // Reconcile the left and right sides of each type inequality
23 Subroutine propagate():
24   repeat until fixed point (i.e., until estimates stop changing)
25     foreach constraint $\alpha \leq \alpha'$ do
26       Remove from $Est(\alpha)$ all types that are not a subtype of a type in $Est(\alpha')$
27       Remove from $Est(\alpha')$ all types that are not a supertype of a type in $Est(\alpha)$
28       if $Est(\alpha)$ or $Est(\alpha')$ is empty then
29         stop: "No solution"
30   foreach context variable $\mathcal{I}_{\alpha'}(\alpha)$ do
31     if $Est(\mathcal{I}_{\alpha'}(\alpha))$ is a singleton set with type parameter $T$ and $Est(\alpha)$ does not
       contain $T$ then
32       add $\alpha$ to $P$
```

Fig. 21. Pseudocode for the constraint solving algorithm.

Whenever a context variable $\mathcal{I}_{\alpha'}(\alpha)$ gets resolved to a type parameter, α must also get resolved to a type parameter on line 30. To see why, suppose that α gets resolved to a nontype parameter type, C. In that case, the context is irrelevant, and thus $\mathcal{I}_{\alpha'}(\alpha)$ also must get resolved to C (i.e., *not* a type parameter). This is a contradiction. Section 4.3.6 discusses an example that illustrates this situation.

line	constraint	
31	$[\texttt{o1}] \leq \mathit{TParam}(E, v2)$	(i)
34	$\mathit{TParam}(E, v2) \leq [\texttt{Stack.pop()}]$	(ii)
37	$\mathcal{I}_{[\texttt{s3}]}([\texttt{Stack.pop()}]) \leq [\texttt{o1}]$	(iii)
40	$[\texttt{Stack.pop()}] \leq \mathcal{I}_{[\texttt{s4}]}([\texttt{o1}])$	(iv)
46	$[\texttt{o2}] \leq \texttt{Object}$	(v)

(a)

constraint variable	inferred type
[o1]	T1
$\mathit{TParam}(E, v2)$	T1
[Stack.pop()]	T1
$\mathcal{I}_{[\texttt{s3}]}([\texttt{Stack.pop()}])$	? extends T1
$\mathcal{I}_{[\texttt{s4}]}([\texttt{o1}])$	? super T1
[o2]	Object

(b)

Fig. 22. (a) Type constraints generated for class Stack of Figure 3 when applying INTRODUCE TYPE PARAMETER. (b) Solution to the constraints computed by our algorithm.

4.3.4. Correctness. An informal justification of the solver's correctness follows from several key observations. First, the set of constraint variables is fixed and finite, as is the size of the initial estimates (established in initialize(), lines 18 and 20). Second, the estimate set of each constraint variable monotonically decreases in size as the algorithm progresses (see propagate(), lines 26 and 27). Moreover, propagate() removes types from a constraint variable's estimate set only if that type cannot possibly satisfy a constraint in which the given variable is involved. In other words, the algorithm never removes a viable type from an estimate set. Third, the algorithm terminates either when some estimate collapses to empty (indicating that no solution to the constraint system is possible), or when all estimate sets are singletons, in which case a concrete solution has been found. Finally, propagate() binds an entity's type to a new type parameter (at line 32) only when there is no other possible choice. That is, making α a type parameter is necessary because a generic type (e.g., T) cannot be obtained from a source that is not able to store them. Nevertheless, such a decision can never violate a constraint that would otherwise be satisfiable. In short, the algorithm's correctness rests on the correctness of the generated constraints. An argument similar to that in Section 4.2.2 establishes the validity of the constraints generated by the modified *CGen* function.

4.3.5. Example: Application of Algorithm to Class Stack*.* Figure 22(a) shows the relevant set of constraints that our algorithm generates for class Stack of Figure 3. Figure 22(b) shows the result that the algorithm computes for the constraints in Figure 22(a). Our tool lets the user select a type reference to parameterize; Figure 22(b) assumes that the user selected the type of o1 on line 30 of Figure 3. The solver works as follows. The solver creates a new type parameter T1 for o1 because the user selected the declaration of o1. Constraints (i) and (ii) in Figure 22 imply that *TParam*(E, v2) and [Stack.pop()] must each be a supertype of T1, and constraint (iii) implies that $\mathcal{I}_{[\texttt{s3}]}$([Stack.pop()]) must be a subtype of T1. The only possible choices for [Stack.pop()] are T1 and Object because wildcard types are not permitted on the return type of a method, and the algorithm selects T1 because choosing Object would lead to a violation of constraint (iii).

Taking into account constraint (ii), it follows that *TParam*(E, v2) = T1. Now, for $\mathcal{I}_{[\texttt{s3}]}$([Stack.pop()]), the algorithm may choose any subtype of T1, and it heuristically chooses ? extends T1.[19] Likewise, the algorithm selects the type ? super T1 for $\mathcal{I}_{[\texttt{s4}]}$([o1]).

The type of variable o2 is constrained only by Object according to constraint (v), and the solver therefore leaves the type unchanged. This is the required solution for the parameter of the contains() method, as argued in Section 4.1.

The type estimates created during the constraint solution algorithm are all non-parametric, even for constraint variables that represent program entities whose type

[19]Other possible choices include T1, or a new type parameter that is a subtype of T1. Kieżun et al. [2007] present more details on the use of heuristics.

was parametric, such as v2 in Figure 3, or will be parametric after refactoring, such as s3 in Figure 3. Assembling these results into parametric types is straightforward. Figure 22(b) indicates that the type of o1 and the return type of Stack.pop() become T1. Moreover, from *TParam*(E, v2) = T1, it follows that the type of v2 becomes Vector<T1>. The type of s3 is rewritten to Stack<? extends T1> because the return type of Stack.pop() is T1 and the type of $\mathcal{I}_{[\texttt{s3}]}$([Stack.pop()]) is ? extends T1. By a similar argument, the type of s4 is rewritten to Stack<? super T1>. The right column of Figure 13 shows the result.

A technical report [Kieżun et al. 2006] walks through a more detailed example of the solving algorithm.

4.3.6. Example: Application of Algorithm to Interdependent Classes. Often, parameterizing one class requires parameterizing other classes as well. For example, consider the code in Figure 13. Throughout Section 4.3 we assumed that the class Vector had been parameterized before (as part of the standard Java collections). However, had the class not been parameterized before, then to parameterize Stack, it would have been necessary to parameterize Vector as well.

The parameterization algorithm can parameterize multiple classes simultaneously. Lines 30–32 of the algorithm in Figure 21 handle propagating type parameters to interdependent classes. That part of the algorithm can be understood as follows. Whenever an estimate of a context variable is narrowed to a single type, that is, the solver finds a solution for the context variable on line 30, the variable to which the context refers must also be assigned a type parameter on line 32.

For example, consider the scenario in which Vector is *not* parameterized at the time when we run the algorithm for Stack. Here we discuss the crucial part of the algorithm that enables parameterizing both classes. To generate a constraint for line 34 in Figure 3, our algorithm uses the constraint generation Rule (c1”) from Figure 20 and generates $\mathcal{I}_{[\texttt{Vector.remove(int)}]}$([v2]) $\leq$ [Stack.pop()]. This constraint corresponds to constraint (ii) from Figure 22 that gets generated when class Vector had been already parameterized. During solving, the type estimate of [Stack.pop()] narrows down to T1, as shown in Figure 22. At that time, the addition on step 32 in the solving algorithm marks [Vector.remove(int)] as a variable to which a new type parameter will be assigned. Thus, parameterizing class Stack results in parameterizing class Vector, as is necessary. A more detailed example that illustrates the issues associated with parameterizing interdependent classes can be found in Kieżun et al. [2006].

4.3.7. Use of Heuristics in the Algorithm. The algorithm of Figure 21 makes an underconstrained choice on lines 3, 6, 12, and 13. (On line 8, there is only one possibility.) Any choice yields a correct (behavior-preserving and type-safe) result, but some results are more useful to clients, for example by permitting the elimination of more casts. Our implementation makes an arbitrary choice at lines 6 and 12, but uses heuristics at lines 3 and 13 to guide the algorithm to a useful result.

On line 3, our tool lets a user select a type to parameterize. Alternatively, the tool can apply the following heuristic.

(1) If a generic supertype exists, use the supertype’s signatures in the subtype. This is especially useful for customized container classes.
(2) Parameterize the return value of a “retrieval” method. A retrieval method’s result is downcasted by clients, or it has a name matching such strings as get and elementAt. Even classes that are not collections often have such retrieval methods [Donovan et al. 2004].
(3) Parameterize the formal parameter to an insertion method. An insertion method has a name matching such strings as add or put.

The heuristic further forbids selecting these uses of types.

(1) Type uses that are not in the public interface of the class.
(2) Parameters of overridden methods (such as `equals()`), unless their type in the overridden class is a type parameter. To preserve method overriding, types of such parameters must remain unchanged, and cannot be parameterized.
(3) Type uses in interfaces or abstract classes. Their uses tend to be underconstrained and can lead to suboptimal results.

On line 13, the algorithm uses a heuristic that minimizes the use of casts in client code, while preserving flexibility in cases where this does not affect type safety. It prefers (in this order):

(1) types that preserve type erasure over those that do not,
(2) wildcard types over nonwildcard types, and
(3) type parameters over other types, but only if such a choice enables inference of type parameters for return types of methods.

To justify the latter restriction, observe that assigning a type parameter or a parametric type to a method return type is beneficial, because doing so reduces the need for casts in clients of the class. Otherwise, introducing type parameters simply increases the apparent complexity of the class for clients.

4.3.8. Miscellaneous Issues. Some classes are not parameterizable by any tool [Kieżun et al. 2006]. If the presented algorithm is applied to such a class (e.g., `String`), then the algorithm either signals that parameterization is impossible (on line 28 in Figure 21) or else produces a result in which the type parameter is used in only one or two places. An implementation could issue a warning in this case. For example, consider the following class:

```
class C {
  public String getText() { return "hello"; }
}
```

If the return type of `getText` is selected for parameterization, the type parameter would have to have a concrete lower bound: `T super String`. Such type parameters are disallowed in Java. Line 28 in Figure 21 detects cases in which no solution can be found.

As noted before, lines 30–32 of Figure 21 handle inter-class dependencies. Interfaces and abstract classes are handled by the same mechanism, that is, our algorithm creates type constraints to preserve method overriding and treats `implements` and `extends` relationships as other interclass dependencies.

Our algorithm and implementation fully support parameterization in the presence of generic methods, for instance, those in `java.util.Collections`, but we have not yet implemented *adding* type parameters to methods.[20]

Native methods pose no special problems to our analysis, which can conservatively approximate the flow of objects between argument expressions and the return value, based on the native method's signature.

[20]Von Dincklage and Diwan [2004] used heuristics to handle generic methods; such heuristics may also be applicable to our work. In previous work, we used a context-sensitive version of the generic instantiation algorithm to parameterize methods [Fuhrer et al. 2005].

5. A REFACTORING FOR REPLACING CLASSES

As applications evolve, classes are occasionally deprecated in favor of others with roughly the same functionality. In Java's standard libraries, for example, class `Hashtable` has been superseded by `HashMap`, and `Iterator` is now preferred over `Enumeration`. In such cases it is often desirable to migrate client applications to make use of the new idioms, but manually making the required changes can be labor-intensive and error-prone. Another occasion at which people might want to replace source classes with target classes is when their focus in the development process of an application shifts from functional correctness to performance optimization. At that point they might, for example, want to replace the generic `HashMap` implementation by a `MyHashMap` tailored to the specific use of hash maps in their application. Several examples of such optimizations have been presented by De Sutter et al. [2004].

In what follows, we will use the term *migration* to refer to the process of replacing references to a *source class* with references to a *target class*. In the program of Figure 3, the type `Vector` is used for the declaration of variable `v1` on line 12, and for that of field `v2` on line 26. Class `ArrayList` was introduced in the standard libraries to replace `Vector`, and is considered preferable because its interface is minimal and matches the functionality of the `List` interface. `ArrayList` also provides unsynchronized access to a list's elements whereas all of `Vector`'s public methods are `synchronized`, which results in unnecessary overhead when `Vector`s are used by only one thread. The example program illustrates several factors that complicate the migration from `Vector` to `ArrayList`, which will be discussed next.

Example 5.1. Some methods in `Vector` are not supported by `ArrayList`. For example, the program of Figure 3 calls `Vector.addElement()` on line 31, a method not declared in `ArrayList`. In this case, the call can be replaced with a call to `ArrayList.add()` (see Figure 23), but other cases require the introduction of more complex expressions, or preclude migration altogether.

Example 5.2. Opportunities for migration may be limited when applications interact with class libraries and frameworks for which the source code is not under the programmer's control. For example, variable `v1` declared on line 12 serves as the actual parameter in a call to a constructor `JTree(Vector)` on line 20. Changing the type of `v1` to any supertype of `Vector` would render this call type-incorrect. Hence, the allocation site on line 12, labeled `A1`, cannot be migrated to `ArrayList`.

Example 5.3. Migration of one class may require the migration of another. Consider the call on line 49 to `Vector.elements()`, which returns an `Enumeration`. `ArrayList` does not declare this method, but its method `iterator()` returns an `Iterator`, an interface with similar functionality.[21] In this case, we can replace the call to `elements()` with a call to `iterator()`, *provided that* we replace the calls to `Enumeration.hasMoreElements()` and `Enumeration.nextElement()` on lines 50 and 51 with calls to `Iterator.hasNext()` and `Iterator.next()`, respectively.

If a `Vector` is accessed concurrently by multiple threads, then preservation of synchronization behavior is important. This is accomplished by introducing *synchronization wrappers*. This issue does not arise in the program of Figure 3 because it is single-threaded; Balaban et al. [2005] present an example.

We have developed a Replace Class refactoring that addresses all of these migration issues.

[21]The methods `hasNext()` and `next()` in `Iterator` correspond to `hasMoreElements()` and `nextElement()` in `Enumeration`, respectively. `Iterator` declares an additional method `remove()` for the safe removal of elements from the collection being iterated over.

```
(S1)  new Vector(), unsynchronized                  → new ArrayList()
(S2)  new Vector(), synchronized                    → Collections.synchronizedList(
                                                         new ArrayList())
(S3)  boolean Vector:receiver.add(Object:v)         → boolean receiver.add(v)
(S4)  void Vector:receiver.addElement(Object:v)     → boolean receiver.add(v)
(S5)  Object Vector:receiver.firstElement()         → Object receiver.get(0)
(S6)  Object Vector:receiver.remove(int:i)          → Object receiver.remove(i)
(S7)  int Vector:receiver.size()                    → int receiver.size()
(S8)  boolean Vector:receiver.contains(Object:o)    → boolean receiver.contains(o)
(S9)  boolean Vector:receiver.isEmpty()             → boolean receiver.isEmpty()
(S10) void Vector:receiver.copyInto(Object[]:array) → void Util.copyInto(receiver, array)
(S11) Enumeration Vector:receiver.elements()        → Iterator receiver.iterator()
(S12) boolean Enumeration:receiver.hasMoreElements() → boolean receiver.hasNext()
(S13) Object Enumeration:receiver.nextElement()     → Object receiver.next()
```

Fig. 23. Specification used for migrating the example program of Figure 3.

5.1. Migration Specifications

The Replace Class refactoring takes as input a program to be refactored, and a *migration specification*. The migration specification defines rules for rewriting all possible method calls, constructor calls, and field accesses of each source class, with equivalent constructs on a target class. In order to ensure termination of the refactoring algorithm, we restrict migration specifications such that for any rewrite rule of a migration specification, applying the rule to a method call, constructor call, or field access of a source class must result in an expression such that no rewrite rule is applicable to it nor to its subexpressions. In addition, in order to simplify the presentation, in the rest of this section we shall consider only programs in which migratable expressions are not nested within one another. This means that in a field access, method call, or constructor call of a source type, the constituent subexpressions are not candidates for rewriting. This imposes no practical restriction on the input program, since any nested expression can be refactored into an equivalent sequence of non-nested expressions by introducing local variables.

Figure 23 shows the fragments of the specification for performing the migration from `Vector` to `ArrayList` and from `Enumeration` to `Iterator` needed for the example program of Figure 3, plus some other rewriting rules. Balaban et al. [2005] provide a complete specification. Migration specifications have to be written only *once* for each pair of (source, target) classes.

For example, Rule (S3) states that migrating calls to method `Vector.add()` requires no modification, since `ArrayList` defines a syntactically and semantically identical method. If methods in the source class are not supported by the target class, rewriting method calls becomes more involved. For example, `Vector` supports a method `firstElement()` not defined in `ArrayList`. Rule (S5) states that a call `receiver.firstElement()`, where `receiver` is an expression of type `Vector`, should be transformed into `receiver.get(0)`. In cases where it is not possible to express the effect of a method call on the source class in terms of calls to methods on the target class, calls may be mapped to methods in user-defined classes. For example, `Vector` has a method `copyInto()` that copies the contents of a `Vector` into an array. Since `ArrayList` does not provide this functionality, Rule (S10) transforms `receiver.copyInto(array)` into a call to the static method `copyInto(receiver, array)` in the `Util` class shown in Figure 24. This strategy can also be used to migrate between methods that throw different types of exceptions. Specifically, a user-defined adapter method can be used to wrap a method in a target class in order translate between exception types. Finally, when an operation in a source class that is not supported by a target class cannot be modeled using an auxiliary class, migration may become impossible.

```
public class Util {
  public static void copyInto(ArrayList v, Object[] target) {
    if (target == null)
      throw new NullPointerException();
    for (int i = v.size() - 1; i >= 0; i--)
      target[i] = v.get(i);
  }
}
```

Fig. 24. Auxiliary class that contains a method used for migrating `Vector.copyInto()`.

$$\alpha_1 \in \{\alpha_2, \cdots, \alpha_n\}$$

$$\alpha_1 \not\leq \alpha_2$$

$$(\alpha_1 = T) \Rightarrow \alpha_2 \; \mathit{op} \; \alpha_3$$

Fig. 25. Additional forms of type constraints required by the REPLACE CLASS refactoring.

Rules (S1) and (S2) in Figure 23 are both concerned with rewriting allocation sites of the form `new Vector()`. The former applies in cases where thread-safety need not be preserved, and transforms the allocation site into an expression `new ArrayList()`. The latter applies in situations where thread-safety must be preserved, and transforms the allocation site into `Collections.synchronizedList(new ArrayList())` using a standard synchronization wrapper in the class `java.util.Collections`. Our tools rely on an escape analysis [Choi et al. 1999] to determine which of the two rules should be applied, and prefers (S1) over (S2) whenever possible. Section 5.3 explains how the escape analysis algorithm is integrated into the refactoring process.

The specification of Figure 23 describes how program fragments can be transformed, but it does not state when the transformation is allowed.

5.2. Extensions to the Type Constraints Formalism

To analyze when transformations can be applied, another adaptation of the type constraint formalism of Figure 2 is needed. However, the adaptation needed here differs significantly from the ones that were used for the refactorings for generalization, and for introducing generics. The refactorings for generalization in Section 3 have the effect of making types of declarations more general, and the refactorings for introducing generics in Section 4 can be seen as making declarations more specific (by replacing occurrences of type `Object` with type parameters). More formally, the refactorings from the previous sections move type declarations between partially ordered types S and T for which either $S \leq T$ or $T \leq S$. For the REPLACE CLASS refactoring, this is no longer the case. As a result, conjunctions of $\leq$-constraints cannot be used to constrain a declaration to the set of unordered types $\{S, T\}$.

To handle such situations, we will use constraints of the form $\alpha_1 \in \{\alpha_2, ..., \alpha_n\}$ indicating that α_1 must be equal to one of $\alpha_2, \cdots, \alpha_n$, as shown in Figure 25. Two other additional forms of constraints are shown in the figure. Constraints of the form $\alpha_1 \not\leq \alpha_2$ indicate that the type α_1 is not a subtype of the type α_2. In addition, we introduce *implication constraints* of the form $(\alpha_1 = T) \Rightarrow \alpha_2 \; \mathit{op} \; \alpha_3$, where *op* is one of the operators "=," "$\leq$," or "$\not\leq$." Intuitively, this means that the unconditional constraint $\alpha_2 \; \mathit{op} \; \alpha_3$ must hold if α_1 is bound to the type T.

$$\frac{\begin{array}{c}\text{call } E \equiv E_0.m(E_1,\cdots,E_n) \text{ to method } M\\ \mathit{Dcl}(\mathrm{M}) = \mathrm{C},\ C \notin \mathit{MigrationTypes}\\ \mathit{RootDefs}(M)=\{M_1,\cdots,M_k\},\ E_i' \equiv \mathit{Param}(M,i),\ 1\le i\le n\end{array}}{\begin{array}{cr}[E]=[M] & \text{(R4)}\\ [E_i]\le[E_i'] & (\text{R5}_a)\\ [E_0]\le \mathit{Dcl}(M_1)\ \textbf{or}\ \cdots\ \textbf{or}\ [E_0]\le \mathit{Dcl}(M_k) & \text{(R6)}\end{array}}$$

$$\frac{\begin{array}{c}\text{constructor call } E \equiv \texttt{new}\ C(\cdots)\\ C \notin \mathit{MigrationTypes}\end{array}}{[E]=C}\ (\text{R7}_a)$$

$$\frac{\begin{array}{c}\text{constructor call } E \equiv \texttt{new}\ C(E_1,\cdots,E_n)\\ E_i' \equiv \mathit{Param}(M,i),\ 1\le i\le n,\ C \notin \mathit{MigrationTypes}\end{array}}{[E_i]\le[E_i']}\ \text{(R8)}$$

$$\frac{\text{cast } (T)E,\ T \notin \mathit{MigrationTypes}}{[(T)E]=T}\ (\text{R14}_a) \qquad \frac{\text{cast } (T)E,\ T \in \mathit{MigrationTypes},\ T \mapsto_{\mathcal{C}} T'}{[(T)E]\in\{T,T'\}}\ (\text{R14}_b)$$

(a)

$$\frac{\begin{array}{c}\text{call } E = E_0.m(E_1,\cdots,E_n) \text{ to method } M,\ \mathit{Dcl}(M)\in \mathit{ExternalTypes}\\ [E_i]_{\mathcal{P}} = T_i,\ 1\le i\le n\end{array}}{[E_i]=T_i}\ (\text{R5}_b)$$

$$\frac{\begin{array}{c}\text{cast } (T)E,\ E' \in \mathit{PointsTo}(P,E)\\ [E']_{\mathcal{P}} \le [(T)E]_{\mathcal{P}}\end{array}}{[E']\le[(T)E]}\ \text{(R32)} \qquad \frac{\begin{array}{c}\text{cast } (T)E,\ E' \in \mathit{PointsTo}(P,E)\\ [E']_{\mathcal{P}} \not\le [(T)E]_{\mathcal{P}}\end{array}}{[E']\not\le[(T)E]}\ \text{(R33)}$$

(b)

$$\frac{\begin{array}{c}\text{constructor call } E \equiv \texttt{new}\ C(\cdots)\\ C \in \mathit{MigrationTypes},\ C \mapsto_{\mathcal{C}} C'\end{array}}{[E]\in\{C,C'\}}\ (\text{R7}_b)$$

$$\frac{\begin{array}{c}\text{constructor call } E \equiv \texttt{new}\ C(E_1,\cdots,E_n)\\ C \in \mathit{MigrationTypes},\ C \mapsto_{\mathcal{C}} C',\ E \mapsto_{\mathcal{E}} E',\ c \in \mathit{cons}(E),\ c' \in \mathit{cons}(E')\end{array}}{\begin{array}{cr}([E]=C)\Rightarrow c & \text{(R34)}\\ ([E]=C')\Rightarrow c' & \text{(R35)}\end{array}}$$

$$\frac{\begin{array}{c}\text{call } E \equiv E_0.m(E_1,\cdots,E_n) \text{ to method } M,\ \mathit{Dcl}(M)=C\\ C \in \mathit{MigrationTypes},\ C \mapsto_{\mathcal{C}} C',\ E \mapsto_{\mathcal{E}} E',\ c \in \mathit{cons}(E),\ c' \in \mathit{cons}(E')\end{array}}{\begin{array}{cr}([E]=C)\Rightarrow c & \text{(R36)}\\ ([E]=C')\Rightarrow c' & \text{(R37)}\end{array}}$$

(c)

Fig. 26. Constraint generation rules for Replace Class. Part (a) of the figure shows how some of the rules of Figure 2 are adapted to apply only to nonmigration types. Part (b) shows additional rules that are needed to ensure that program behavior is preserved. Part (c) shows additional rules that generate implication constraints. Changes from Figure 2 are shaded. For a given rule $E \mapsto_{\mathcal{E}} E'$ in a migration specification, $\mathit{cons}(E)$ denotes the set of constraints computed by the rules of parts (a) and (b) for the expression E and its subexpressions if no types are migration types, and $\mathit{cons}(E')$ denotes the set of constraints computed by the rules of parts (a) and (b) for the expression E' and its subexpressions if no types are migration types.

Figure 26 shows how the constraint generation rules of Figure 2 are adapted and extended to accommodate the Replace Class refactoring. These rules fall into three categories: (a) adaptations of the basic type constraint generation rules of Figure 2 to take the migration of classes into account, (b) rules that generate additional constraints needed to preserve program behavior in the presence of migrations, and (c) additional rules that generate implication constraints for constructor calls and method calls that may be subject to migration. Below, we will discuss a representative sample of the rules in each of these categories. In these rules, the set *MigrationTypes* contains the source classes of migrations, and *ExternalTypes* is the set of external library classes. Furthermore, we will use the notation $C \mapsto_{\mathcal{C}} C'$ to denote the fact that class C is mapped to class C' in the migration specification, and $E \mapsto_{\mathcal{E}} E'$ indicates that an expression E is rewritten to an expression E' according to the migration specification.

5.2.1. Adapting Existing Type Constraint Rules. Figure 26(a) shows how some of the rules of Figure 2 are adapted to take class migrations into account.[22] The key idea is that different constraints are generated for migration types than for types that will not migrate. For migration types, part (c) of the Figure generates conditional constraints that account for two possibilities: either a given type is migrated or it is not.

Regarding the rules shown in Figure 26(a), assignments are modeled the same way as before so we simply reuse Rule (1) from Figure 2. For method calls, Rules (R4), (R5_a), and (R6) restrict the corresponding Rules (4)–(6) of Figure 2 to classes that are not in the set *MigrationTypes*.

For constructor calls $E \equiv$ `new` $C(E_1, \cdots, E_n)$, Rule (7) of Figure 2 is replaced by two Rules (R7_a) and (R7_b). Rule (R7_a) restricts the original Rule (7) of Figure 2 to classes that are not being migrated. For calls to constructors of migration classes, Rule (R7_b) constrains the type of the entire constructor call expression to be either the source class or the target class of the migration. The constraint solver will try to find a valid solution for all generated constraints in which the type of the constructor call expression is the target class of the migration. If it finds such a solution, the migration will be applied for the constructor call. Otherwise, the migration will not be applied, at least not for that constructor call. Rule (R8) restricts the original Rule (8) of Figure 2 to classes that are not in the set *MigrationTypes*.

Rules (R14_a) and (R$_b$) adapt the original Rule (14) of Figure 2 for casts of the form $(T)E$, restricting the original rule to classes that are not the source of a migration, and permitting the migration of casts to types that are subject to migration by constraining their type to either the source class or the target class of the migration.

5.2.2. Additional Rules for Preserving Program Behavior. Figure 26(b) shows rules that generate additional constraints that are needed for preserving program behavior. Here, $[E]_{\mathcal{P}}$ denotes the type of expression E in the original program P, and *ExternalTypes* is the set of external library classes.

As we discussed earlier, opportunities for migration may be limited when an application calls a method in an external class library. This is encoded by Rule (R5_b), which states that the type of an expression E_i that is used as an actual parameter in a call to a method in an external library must remain the same as in the original program.[23]

Rules (R32) and (R33) in Figure 26 are needed to preserve the runtime behavior of casts when classes are migrated. Consider, for example, an original program that contains a cast operation in an expression `((C)x).get(y)` in which `x` is declared as type `Object`. This cast is then a downcast from type `Object` to type `C`. Now assume that at some point during program execution, `x` is bound to an object of type `D`. If `D` is a subtype of `C`, then the cast will succeed in the original program. For a migration `C` $\mapsto_{\mathcal{C}}$ `C'` to respect program behavior, the corresponding execution of the downcast in the rewritten program should also succeed. However, when `C'` is not a subtype of `C`, this is not guaranteed by the existing constraint generation rules.

The additional Rule (R32) enforces such a successful casting where needed. Here, the notation PointsTo(P, E) refers to the set of objects (identified by their allocation expressions) that an expression E in program P can point to whenever the expression

[22]Figure 26(a) shows only the adapted counterparts for some of the rules of Figure 2. The remaining rules of that figure are adapted similarly.
[23]This rule is overly conservative in the sense that it prevents the type of E_i from being migrated to a subtype of its current type. It is possible to extend the rules to allow such migrations, but we have not yet experienced the need for migrations from a source class to one of its subtypes.

```
1:   class Example {
2:     public static
            void main(String[] args){
3:       Vector v = new Vector(); /* A1 */
4:       v.add("a"); v.add("b");
5:       Enumeration e = v.elements();
6:       External.print(e);
7:     }
8:   }
```

```
9:   class External {
10:    public static
            void print(Enumeration e){
11:      for ( ; e.hasMoreElements(); ){
12:        System.out.println(e.nextElement());
13:      }
14:    }
15:  }
```

(a)

line	constraint	rule	
3	$[\texttt{A1}] \leq [\texttt{v}]$	(1)	(i)
3	$[\texttt{A1}] \in \{\texttt{Vector}, \texttt{ArrayList}\}$	(R7$_b$)	(ii)
5	$[\texttt{v}] = \texttt{Vector} \Rightarrow [\texttt{v.elements()}] = \texttt{Enumeration}$	(R36), (R4)	(iii)
5	$[\texttt{v}] = \texttt{ArrayList} \Rightarrow [\texttt{v.elements()}] = \texttt{Iterator}$	(R37), (R4)	(iv)
5	$[\texttt{v.elements()}] \leq [\texttt{e}]$	(1)	(v)
6	$[\texttt{e}] = \texttt{Enumeration}$	(R5$_b$)	(vi)

(b)

Fig. 27. Example program that requires solver to backtrack. Part (a) contains the program, as well as the definition of an external dependency class class named `External`. Part (b) shows some of the constraints generated for the program.

is being evaluated during any possible execution of the program. This set is called the points-to set of E. Rule (R32) ensures that for each E' in the points-to set of E for which the cast succeeds in the original program, the cast will still succeed in P'. Any of several existing static, conservative algorithms [Hind and Pioli 2001; Ryder 2003] can be used to compute points-to sets. The term *conservative* in this context means that the computed points-to set of an expression includes at least all possible types to which the expression can point when it is being evaluated during any execution of the program. So for at least all successful casts executed during any execution of the original program, there will be a corresponding constraint generated by Rule (R32), enforcing a successful cast in the rewritten program. The computed points-to set for an expression can be overly conservative, in the sense that it also contains types to which the expression cannot ever point in practice. When this occurs for some expression, it results in additional constraints being generated. This can prohibit a valid migration from being applied, but it will never cause an invalid migration to be allowed. Rule (R33) generates similar constraints for failing casts. Together, these rules ensure that the behavior of casts is preserved after migration.

5.2.3. Rules for Generating Implication Constraints. Figure 26(c) shows rules that generate implication constraints for calls to methods and constructors of types that may be subject to migration. These rules are needed for calls to constructors or methods of source classes for which the corresponding constructor or method of the target class has different parameter types (or, in the case of method calls, a different return type). For such calls, the constraints to be placed on the types of the arguments depend on whether or not the migration is actually performed.

Consider the example code fragment in Figure 27(a). The method `main()` in class `Example` declares a local variable `v` of type `Vector`. The `Enumeration` resulting from a call to its `elements()` method is passed to the method `print()` of an external class `External` that cannot be rewritten. If the allocation site `A1` is migrated from `Vector` to `ArrayList` according to the migration specification of Figure 23, the type returned by the call to `elements()` would become `Iterator`. This is not valid, however, because the parameter type `Enumeration` of the external method `print()` cannot be changed. To prevent such problems, we need to generate constraints that make the migration of a call expression contingent on whether or not the receiver expression can be migrated.

To express this formally, we generate implication constraints of which the antecedents express whether a migration of a constructor or method call will take place, and of which the consequents constrain the parameter types and return types accordingly. Rules (R34) and (R35) are concerned with constructor calls of the form $E \equiv$ `new` $C(E_1, \cdots, E_n)$, where $C \mapsto_{\mathcal{C}} C'$ and $E \mapsto_{\mathcal{E}} E'$. As explained on the example, there are two cases for which constraints need to be generated.

(1) The migration will not take place, which will happen when other constraints constrain the type of E such that $[E] = C$. To generate constraints for this case, we first compute the constraints c that would be computed by the rules of Figure 26 parts (a) and (b) for the expression E and its subexpressions if C were not a migration type. For each such constraint, an implication constraint $([E] = C) \Rightarrow c$ is produced.
(2) The migration will take place, which will happen when $[E] = C'$ is a solution to the constraint system. For this case, we first compute the constraints c' that would be computed by the rules of Figure 26 parts (a) and (b) for the expression E' and its subexpressions. For each such constraint, an implication constraint $([E] = C') \Rightarrow c'$ is produced.

Constraints for both cases always have to be produced, because the decision of whether or not to migrate is taken after all constraints have been generated,

The generation of implication constraints for method calls by Rules R36 and R37 is analogous. For the code in Figure 27(a), constraints (iii) and (iv) of Figure 27(b) are generated.

5.2.4. Constraint Solving. In order to solve the non-implication constraints presented in this section, we employ a straightforward iterative algorithm similar to that shown in Figure 21. The algorithm in Figure 21 does not handle $\not\leq$ constraints, which we do support here (see Balaban et al. [2005] for details). Furthermore, the algorithm in Figure 21 does not handle $\in$-constraints. A practical solution to this problem is the insertion of two artificial types $C^\top$ and $C_\perp$ in the type hierarchy for each migration $C \mapsto_{\mathcal{C}} C'$. $C^\top$ is inserted as an immediate supertype of C and C', and $C_\perp$ as an immediate subtype. Each constraint of the form $[E] \in \{C, C'\}$ can then be replaced with the two constraints $[E] < C^\top$ and $C_\perp < [E]$.

Since the algorithm assigns a concrete type to a constraint variable on every iteration, it has a worst-case running time that is polynomial in the size of the program.

In order to deal with implication constraints, we extend the algorithm with backtracking as follows. When the solver heuristically assigns a concrete type to a variable as in line 13 in Figure 21, it checkpoints its progress thus far, and proceeds. Furthermore, whenever the antecedent of an implication constraint is detected as satisfied, the consequent is added to the constraint system. The newly introduced consequent constraint potentially makes the system unsatisfiable given the heuristic selections made by the solver up to that point. In such cases, the solver backtracks to the last heuristic variable assigment, and selects a different concrete type. For example, this occurs while solving the constraints of Figure 27(b) once the solver optimistically assigns the type `ArrayList` to [`v`]. Since the antecedent of implication constraint (iv) is now satisfied, the consequent [`v.elements()`] = `Iterator` is added to the constraint system. However, from constraints (v) and (vi) we have that [`v.elements()`] $\leq$ [`e`] = `Enumeration`. Thus the constraint system is unsatisfiable, and the solver backtracks and reassigns the type `Vector` to [`v`]. The backtracking algorithm is supported by our implementation, as presented in detail by Balaban et al. [2005].

line	constraint	rule	
12	$[\texttt{A1}] \leq [\texttt{v1}]$	(1)	(i)
12	$[\texttt{A1}] \in \{\texttt{Vector}, \texttt{ArrayList}\}$	(R7$_b$)	(ii)
20	$[\texttt{v1}] = \texttt{Vector}$	(R5$_b$)	(iii)
28	$[\texttt{A2}] \leq [\texttt{v2}]$	(1)	(iv)
28	$[\texttt{A2}] \in \{\texttt{Vector}, \texttt{ArrayList}\}$	(R7$_b$)	(v)
31	$[\texttt{v2}] = \texttt{Vector} \Rightarrow [\texttt{o1}] \leq \texttt{Object}$	(R36)	(vi)
31	$[\texttt{v2}] = \texttt{ArrayList} \Rightarrow [\texttt{o1}] \leq \texttt{Object}$	(R37)	(vii)
43	$[\texttt{v2}] = \texttt{Vector} \Rightarrow [\texttt{v2}] \leq \texttt{Collection}$	(R36)	(viii)
43	$[\texttt{v2}] = \texttt{ArrayList} \Rightarrow [\texttt{v2}] \leq \texttt{Collection}$	(R37)	(ix)
49	$[\texttt{s5.v2}] = \texttt{Vector} \Rightarrow [\texttt{s5.v2.elements()}] = \texttt{Enumeration}$	(R36)	(x)
49	$[\texttt{s5.v2}] = \texttt{ArrayList} \Rightarrow [\texttt{s5.v2.elements()}] = \texttt{Iterator}$	(R37)	(xi)

Fig. 28. Some of the type constraints generated for the application of the REPLACE CLASS refactoring to the program of Figure 3.

Due to backtracking, the worst-case running time of the solving algorithm is exponential in the program size. However, our solver applies a number of straightforward simplifications that either eliminate implication constraints or replace them with equivalent non-implication constraints. One example is replacing a pair of constraints, $c_1 \Rightarrow c_2$ and $\neg c_1 \Rightarrow c_2$, by simply c_2. Another example is removing an implication constraint if an equivalent unconditional constraint exists. Our subject programs have shown that as a result, the worst-case running time is rarely encountered in practice.

5.2.5. Example. Figure 28 shows some of the type constraints generated as a result of the application of REPLACE CLASS to the program of Figure 3.

Constraint (i) establishes the required subtype relationship between the type of variable `v1` and the allocation site labeled `A1`, using Rule (1). Constraint (ii) in Figure 28 is generated for the allocation site labeled `A1` on line 12 in Figure 3 by Rule (R7$_b$). Constraint (iii) is generated for the call to the constructor of the external class `JTree` in line 20, by Rule (R5$_b$). The generation of constraints (iv) and (v) is analogous to that of constraints (i) and (ii).

As a more interesting example, consider the call `s5.v2.elements()` on line 49 of Figure 3, which can be rewritten to an expression `s5.v2.iterator()` according to the migration specification of Figure 23. For this method call, we have that

$$[\texttt{s5.v2.elements()}] = \texttt{Enumeration} \in \mathit{cons}(\texttt{s5.v2.elements()})$$
$$[\texttt{s5.v2.iterator()}] = \texttt{Iterator} \in \mathit{cons}(\texttt{s5.v2.iterator()})$$

and therefore the implication constraints

$$[\texttt{s5.v2}]\texttt{=Vector} \Rightarrow [\texttt{s5.v2.elements()}]\texttt{=Enumeration}$$
$$[\texttt{s5.v2}]\texttt{=ArrayList} \Rightarrow [\texttt{s5.v2.elements()}]\texttt{=Iterator}$$

are generated. These constraints, shown as constraints (x) and (xi) in Figure 28, state that the type of the call expression `s5.v2.elements()` is `Enumeration` if the type of `v2` remains `Vector`, but becomes `Iterator` if the expression is rewritten to `s5.v2.iterator()`.

Similarly, consider the call `v2.isEmpty()` on line 43 in Figure 3. Rules (R36) and (R37) generate the constraints (viii) and (ix), both of which are conditional depending on whether the type of `v2` is migrated from `Vector` to `ArrayList`.

As an example of a simplification that reduces the need for backtracking, consider the call `v2.addElement(o1)` on line 31. If the type of `v2` remains `Vector`, `o1` must be a subtype of the formal parameter of `Vector.addElement()`, which is expressed by constraint (vi) in Figure 28:

$$[\texttt{v2}]\texttt{=Vector} \Rightarrow [\texttt{o1}] \leq \texttt{Object}.$$

Similarly, constraint (vii) in Figure 28 reflects the case in which the type of `v2` becomes `ArrayList`:

```
class Client {
  public static void main(String[] args){
    Stack s1 = new Stack();
    s1.push(new Integer(1));
    s1.push(new Integer(2));
    s1.push(new Integer(3));
    Stack s2 = new Stack();
    s2.push(new Float(4.4));
    s2.moveFrom(s1);
    s1.moveTo(s2);
    Stack.print(s2);
    Vector v1 = new Vector(); /* A1 */
    while (!s1.isEmpty()){
      Integer n = (Integer)s1.pop();
      v1.add(n);
    }
    JFrame frame = new JFrame();
    frame.setTitle("Example");
    frame.setSize(300, 100);
    JTree tree = new JTree(v1);
    frame.add(tree, BorderLayout.CENTER);
    frame.setVisible(true);
  }
}
```

```
class Stack {
  private ArrayList v2;
  public Stack(){
    v2 = new ArrayList(); /* A2 */
  }
  public void push(Object o1){
    v2.add(o1);
  }
  public void moveFrom(Stack s3){
    this.push(s3.pop());
  }
  public void moveTo(Stack s4){
    s4.push(this.pop());
  }
  public Object pop(){
    return v2.remove(v2.size() - 1);
  }
  public boolean isEmpty(){
    return v2.isEmpty();
  }
  public boolean contains(Object o2){
    return v2.contains(o2);
  }
  public static void print(Stack s5){
    Iterator e = s5.v2.iterator();
    while (e.hasNext())
      System.out.println(e.next());
  }
}
```

Fig. 29. The example program of Figure 3 after the application of REPLACE CLASS refactoring. The allocation site labeled A1 cannot be migrated.

$$[\texttt{v2}]=\texttt{ArrayList} \Rightarrow [\texttt{o1}]\leq\texttt{Object}.$$

These constraints can be combined into a single unconditional constraint [o1] ≤ Object.

From constraints (i) and (iii) in Figure 28, it follows that [A1]≤[v1]=Vector, implying that the type of A1 must remain Vector. However, the typing [A2] ← ArrayList, [v2] ← ArrayList satisfies the constraint system, indicating that allocation site A2 can be migrated to ArrayList.

5.3. Rewriting the Program

Once a solution to the constraints is obtained, the program is rewritten by inspecting each constraint variable and the type that has been assigned to it by the solver, and rewriting associated program elements as needed. If a constraint variable has been assigned a target type (and was originally a source type), then the corresponding program element (either a method call, a field access, or a constructor call) needs to be rewritten. This is done by selecting and applying a rule from the migration specification with a matching left side. For example, consider the method call e.hasMoreElements() in line 50 of the program of Figure 3. Since the variable e is being migrated from type Enumeration to type Iterator, we must rewrite e.hasMoreElements() to a method call of Iterator. To do this, we apply Rule (S12) of the migration specification (Figure 23), resulting in the expression e.hasNext(). The complete refactored source code for the example program is shown in Figure 29.

If the program element to be rewritten is a method call or a field access expression, the choice of rewrite rule is unambiguous, as we allow at most one rule for each method and field of a source class. However, if the program element is a constructor call, a migration specification may specify two rules, depending on whether thread safety needs to be explicitly preserved in the rewritten program. It is in this case that we rely on an escape analysis to determine whether objects allocated by the constructor call may escape their thread. If objects are potentially escaping, then a rule is chosen that introduces explicit synchronization such as (S2) in Figure 23. Otherwise, the program element is rewritten using a rule that does not introduce synchronization, such as (S1). In principle, our approach can be integrated with any escape analysis. In our experimental evaluation, we use a simple escape analysis that was described by Balaban et al. [2005].

6. EXPERIMENTAL RESULTS

We previously presented detailed evaluations of the effectiveness of the INFER GENERIC TYPE ARGUMENTS [Fuhrer et al. 2005], INTRODUCE TYPE PARAMETER [Kieżun et al. 2007], and REPLACE CLASS [Balaban et al. 2005] refactorings. This section presents a summary of the experiments conducted and results obtained. For further detail, the reader is referred to our previous papers.

For all experiments discussed in this section, we ensured that no type errors were introduced by our implementations by checking that the program compiled properly after applying each refactoring. Furthermore, we determined that each program's runtime behavior was unchanged by running the applications and their test suites before and after performing each refactoring and comparing their behaviors.

The implementation of INTRODUCE GENERIC TYPE ARGUMENTS and INTRODUCE TYPE PARAMETER are quite efficient, and require seconds to a small number of minutes to process medium-sized applications. Concretely, in Fuhrer et al. [2005], we reported that applying INTRODUCE GENERIC TYPE ARGUMENTS to a 90KLOC application required 113.9 seconds, and in Kieżun et al. [2007] we reported a processing time of 301 seconds to apply INTRODUCE TYPE PARAMETER to a 9.9KLOC program. Our implementation of the REPLACE CLASS REFACTORING is currently much less efficient because it relies on a previous implementation of the type constraints model, and we reported a processing time of approximately 2 hours for a 50KLOC subject program. We expect that this latter result could be improved dramatically by adopting the newer, more space-efficient representation for type constraints that is currently used in Eclipse. For a more detailed discussion of these performance results, the reader is referred to our previous papers [Fuhrer et al. 2005; Kieżun et al. 2007; Balaban et al. 2005].

6.1. Evaluation of INTRODUCE GENERIC TYPE ARGUMENTS

One of the main benefits of INTRODUCE GENERIC TYPE ARGUMENTS is that it removes downcasts that have become unnecessary. To evaluate the effectiveness of the refactoring, we used INTRODUCE GENERIC TYPE ARGUMENTS to infer actual type parameters for declarations and allocation sites that refer to the unparameterized standard collections in a suite of moderate-sized Java programs named in column 1 of Table I.[24] We then measured the percentage of downcasts that could be removed, and the percentage of "unchecked warnings" that were eliminated.

Table I shows that an average of 49% of all casts could be removed from each program, and an average of 91% of all unchecked warnings were eliminated. When considering casts, the reader should note that the number of casts given in column (iv) of Table I includes casts that are not related to the use of generic types. However, a manual inspection of the results revealed that our tool removes the vast majority of generics-related casts, from roughly 75% to 100%. For example, we estimate that only one-fifth of *ANTLR*'s total number of casts relates to the use of collections, which is close to our tool's 19% removal rate.

[24]For more details, see: `www.junit.org`, `www.cs.princeton.edu/~appel/modern/java/JLex/`, `www.cs.princeton.edu/~appel/modern/java/CUP/`, `www.spec.org/osg/jvm98/`, `vpoker.sourceforge.net`, `telnetd.sourceforge.net`, `www.antlr.org`, `jbidwatcher.sourceforge.net`, `pmd.sourceforge.net`, `htmlparser.sourceforge.net`, and `www.ovmj.org/xtc/`.

Table I.
Experimental results for INFER GENERIC TYPE ARGUMENTS. Column (i) is the name of the program. The size of the application is measured in (ii) number of types, (iii) thousands of source lines, and (iv) number of casts. The generics-related metrics count the number of (v) allocation sites of generic types, (vi) generic-typed declarations, (vii) subtypes of generic types, and (viii) "unchecked warnings" issued by the compiler. Lastly, columns (ix) and (x) show the percentage of casts removed and unchecked warnings eliminated as a result of applying INFER GENERIC TYPE ARGUMENTS

	Size			Generics-Related Metrics				Removed	
Program	Types	KLOC	Casts	Allocs	dcls	Subt.	Warn.	Casts	Warn.
JUnit	59	5.3	54	24	48	0	27	44%	93%
V_poker	35	6.4	40	12	27	1	47	80%	100%
JLex	22	7.8	71	17	33	1	40	68%	85%
Db	32	8.6	78	14	36	1	652	51%	100%
JavaCup	36	11.1	595	19	62	0	55	82%	96%
TelnetD	52	11.2	46	16	28	0	22	83%	100%
Jess	184	18.2	156	47	64	1	692	53%	99%
JBidWatcher	264	38.6	383	76	184	1	195	54%	97%
ANTLR	207	47.7	443	46	106	3	84	19%	94%
PMD	395	38.2	774	75	286	1	183	20%	89%
HTMLParser	232	50.8	793	72	136	2	205	22%	97%
Jax	272	53.9	821	119	261	3	583	19%	48%
xtc	1,556	90.6	1,114	330	668	1	583	36%	88%
							average:	48.6%	91.2%

Table II.
Experimental results for INTRODUCE TYPE PARAMETER. From left to right, the columns of the table show: (i) the name of the library, (ii) the number of analyzed classes, including their nested classes, (iii) the number of lines of code, and (iv) the number of occurrences of a reference (non-primitive) type in the library; the latter is the maximal number of locations where a type parameter could be used instead. The "comparison to manual" columns (v)-(vii) indicate how our tool's output compares to the manual parameterization; the numbers count type uses, as in column (iv). These columns are empty for the last two libraries, which have not been manually parameterized by their authors.

	Parameterizable Classes			Comparison to Manual		
Library	Classes	LOC	Type Uses	Same	Better	Worse
concurrent	14	2715	415	353	37	25
apache	74	9904	1183	1011	116	56
jutil	9	305	80	65	15	0
jpaul	17	827	178	148	22	8
amadeus	8	604	129	125	1	3
dsa	9	791	162	158	4	0
antlr	10	601	140	n/a	n/a	n/a
eclipse	7	582	100	n/a	n/a	n/a
Total	148	16329	2387	1860	195	92

6.2. Evaluation of INTRODUCE TYPE PARAMETER

In order to evaluate the INTRODUCE TYPE PARAMETER refactoring, we inferred type parameters in a set of nonparameterized libraries. Our evaluation uses a combination of 6 libraries that have already been parameterized by their authors, and 2 libraries that have not yet been made generic. For already parameterized libraries, we first applied a tool that erased the formal and actual type parameters and added necessary type casts, and then compared the results produced by our implementation of INTRODUCE TYPE PARAMETER against the existing parameterization. In the case of the libraries for which no generic version was available, we asked the developers to examine every change proposed by our implementation and to give their opinion of the result.

The leftmost column of Table II lists the class libraries used in this experiment.[25] Not all classes in these libraries are amenable to parameterization; we selected a subset of the library classes that we considered likely to be parameterizable. The experiments processed the classes of the library in the following order: we first built a dependence graph of the classes, and then applied our tool to each strongly connected component, starting with those classes that depended on no other classes still to be parameterized. This is the same order a programmer faced with the problem would choose.

Given an existing manual parameterization and one computed by our refactoring tool, we used two criteria to decide which was more precise. The first, and more important, is which one allows more casts to be removed—in clients or in the library itself. The secondary criterion is which one more closely follows the style used in the JDK collections; they were developed and refined over many years by a large group of experts and can be reasonably considered models of style.[26] The two criteria are in close agreement.

Our results for the already parameterized libraries can be summarized as follows. For 87% of all type annotations, the output of our tool is identical to or equally good as the existing parameterization. For 4% of annotations, the output of our tool is worse than that created by the human. For 9% of annotations, the tool output is better than that created by the human. For the *eclipse* and *antlr* libraries, no existing parameterization was available. A developer of Eclipse concluded that the changes were "good and useful for code migration to Java 5.0." Out of 100 uses of types in the Eclipse classes we parameterized, he mentioned only 1 instance where the inferred result, while correct, could be improved. A developer of ANTLR stated that the changes made by our tool are "absolutely correct." Out of 140 uses of types in the parameterized classes, he mentioned 1 instance where the inferred result, while correct, could be improved.

From these results, it is clear that the parameterizations computed by our tool resemble the manually computed solutions very closely. Here are a few examples where the output of our tool was worse.

(1) In *concurrent*, our tool does not instantiate the field `next` in member type `LinkedBlockingQueue.Node` as `Node<E>`, but leaves it raw. Such a choice is safe, but it is less desirable than the manual parameterization.
(2) Our tool does not infer type parameters for methods; an example is *apache*'s `PredicatedCollection.decorate()`.
(3) Our tool inferred two separate type parameters for interface `Buffer` in the *apache* library. In this case, the manual parameterization had only one.

Here are a few examples where the output of our tool was better. In each case, the developers of the package agreed the inferred solution was better than their manual parameterization.

(1) Our tool adds a formal type parameter to member class `SynchronousQueue.Node` in *concurrent*. The parameter allows elimination of several casts inside `Synchronous-Queue`.

[25]Here, *concurrent* is the `java.util.concurrent` package from Sun JDK 1.5, *apache* is the Apache collections library (`larvalabs.com/collections/`), *jutil* is a Java Utility Library (`cscott.net/Projects/JUtil/`), *jpaul* is the Java Program Analysis Utility Library (`jpaul.sourceforge.net`), *amadeus* is a data structure library (`people.csail.mit.edu/adonovan/`), *dsa* is a collection of generic data structures(`www.cs.fiu.edu/~weiss/#dsaajava2`), *antlr* is a parser generator (`www.antlr.org`), and *eclipse* is a universal tooling platform (`www.eclipse.org`).
[26]When multiple styles appear in the JDK, we did not count differences in either the "better" or "worse" category.

Table III.
Experimental Results for REPLACE CLASS. From left to right, the columns of the table show: (i) the name of the program, (ii) the number of classes in the program, (iii) the number of lines of source code (in thousands), (iv) the migration source classes used in this program, where *V* denotes `Vector`, *HT* denotes `Hashtable`, and *E* denotes `Enumeration`. The last columns of the table show the experimental results: (v) the number of source declarations of legacy types that could be migrated and that had to be left unchanged, (vi) the number of allocation sites of legacy types that could be migrated and without synchronization wrappers, that could be migrated but needed synchronization wrappers, and that could not be migrated, and (vii) the number of legacy call sites that could be migrated and that could not be migrated.

Program	Types	KLOC	Migration Classes	Declarations (migr./	unchanged)	Alloc. Sites (migr. desync/	migr. wrap/	unchanged)	Call Sites (migr./	unchanged)
Hanoi	41	4.0	*V*	3	0	3	0	0	26	0
JUnit	100	5.3	*V*, *HT*, *E*	55	7	23	1	0	111	7
JLex	26	7.9	*V*, *HT*, *E*	29	10	12	0	4	167	18
JavaCup	36	10.6	*HT*, *E*	56	0	14	0	0	153	0
Cassowary	68	12.2	*V*, *HT*, *E*	121	18	44	0	2	692	36
Azureus	160	13.9	*V*	13	0	6	6	0	51	0
HTML Parser	115	17.1	*V*, *HT*	141	3	21	0	2	461	6
JBidWatcher	154	22.9	*V*, *HT*	67	4	32	1	3	291	3
SpecJBB	110	31.3	*V*, *HT*, *E*	22	6	13	0	2	78	10
Jax	309	53.1	*V*, *HT*, *E*	208	43	81	0	12	706	0

(2) In method `VerboseWorkSet.containsAll()` in *jpaul*, our tool inferred an upper-bounded type parameter wildcard for the `Collection` parameter. This permits more flexible use and fewer casts by clients, and also adheres to the standard collections style from the JDK.
(3) Our tool inferred `Object` as the type of the parameter of method `Canonical.getIndex()` in *amadeus*. This is more flexible than the developers' solution, with fewer casts, and follows the JDK style. A similar case occurred in *jpaul* in which our tool inferred `Object` for the parameter of `WorkSet.contains()`.

6.3. Evaluation of REPLACE CLASS

We evaluated our implementation of REPLACE CLASS on a number of Java applications of up to 53 KLOC that we migrated from `Vector` to `ArrayList`, from `Hashtable` to `HashMap`, and from `Enumeration` to `Iterator`. Table III states the essential characteristics for each program.

The results are shown in last three columns of the table. For example, for the *Cassowary* program we found that:

(1) 121 of the original 139 source class declarations were migrated, but 18 could not be migrated,
(2) 44 of the 46 source allocation sites could be migrated without inserting synchronization wrappers, and the remaining 2 source allocation sites could not be migrated at all, and
(3) 692 of the 728 source call sites could be migrated, and the remaining 36 call sites could not be migrated.

On average, 90% of source declarations and 97% of source call sites were migrated successfully. Furthermore, an average of 92% of all allocation sites can be migrated: 83% without the insertion of synchronization wrappers and 9% with the insertion of synchronization wrappers.

We now discuss a few cases out of the experiments that illustrate some interesting aspects of migration.

Nontrivial rewriting. *JBidWatcher*, *JUnit*, and *SpecJBB* contain calls to the previously discussed method `Vector.copyInto()` which requires nontrivial rewriting and introduction of an auxiliary class. In *JBidWatcher*, *JUnit*, *SpecJBB*, and *Jax*, the percentages of migrated call sites for which the method's name or signature was changed are 30%, 75%, 73%, and 47%, respectively. Clearly, manual migration of these applications would involve a significant amount of error-prone editing work.

Interaction with external libraries. In *JUnit*, one of the `Vectors` is passed to the constructor of the external *Swing* library class `JList`, whose formal parameter is of type `Vector`. This flow of objects is not immediately evident from the code, as the allocated `Vector` is assigned to a variable that is elsewhere passed to the constructor. Similar cases occur in *SpecJBB* where various `Vectors` are not migrated because they are stored in other `Vectors`. With more insight into the implementation of `Vector`, it is evident that concrete types of its elements are irrelevant, which could be utilized by a more precise analysis.[27]

Synchronization preservation. The migration of *JUnit* includes a synchronization-wrapped allocation site. It is detected as escaping since it is assigned to a field whose declaring class declares a `Runnable` that references the field. The `Runnable` object is passed to *Swing*, which would cause any escape analysis without access to the *Swing* code to declare it as escaping. In *Azureus*, escape analysis reports that synchronization wrappers need to be introduced for certain `ArrayLists`, but the program already performs explicit synchronizations. In principle, a more precise escape analysis could enable migration without synchronization wrappers in this case.

7. RELATED WORK

Opdyke [1992, page 27–28] identified some of the invariants that refactorings must preserve. One of these, *Compatible Signatures in Member Function Redefinition*, states that overriding methods must have corresponding argument types and return types, corresponding to our Rules (9) and (10). Opdyke writes the following about the *Type-Safe Assignments* invariant: "The type of each expression assigned to a variable must be an instance of the variable's defined type, or an instance of one of its subtypes. This applies both to assignment statements and function calls." This corresponds to our Rules (1), (5), and (8).

Fowler [1999] presents a comprehensive classification of a large number of refactorings, which includes step-by-step directions on how to perform each of these manually. Many of the thorny issues discussed in this article are not addressed by Fowler. For example, in the case of EXTRACT INTERFACE, Fowler only instructs one to "Adjust client type declarations to use the interface," ignoring the fact that not all declarations can be updated.

Tokuda and Batory [2001] discuss refactorings for manipulating design patterns including one called SUBSTITUTE that "generalizes a relationship by replacing a subclass reference to that of its superclass". Tokuda and Batory point out that "This refactoring must be highly constrained because it does not always work." Our model can be used to add the proper precondition checking.

Halloran and Scherlis [2002] present an informal algorithm for detecting over-specific variable declarations. This algorithm is similar in spirit to our GENERALIZE DECLARED TYPE refactoring by taking into account the members accessed from a variable, as well as the variables to which it is assigned.

The INFER TYPE refactoring by Steimann et al. [2006] lets a programmer select a given variable and determines or creates a minimal interface that can be used as the type

[27]Such information could be provided in the form of *stub* implementations that approximate the behavior of selected library methods.

for that variable. Steimann et al. present their type inference algorithm informally, but their constraints appear similar to those presented in Section 2. In more recent work, Steimann and Mayer [2007] observe that the repeated use of INFER TYPE may produce suboptimal results (e.g., the creation of many similar types). Their Type Access Analyzer performs a global analysis to create a lattice that can be used as the basis for extracting supertypes, changing the types of declarations, merging structurally identical supertypes, and similar transformations.

The KABA tool [Streckenbach and Snelting 2004; Snelting and Tip 2000] generates refactoring proposals for Java applications (e.g., indications that a class can be split, or that a member can be moved). In this work, type constraints record relationships between variables and members that must be preserved. From these type constraints, a binary relation between classes and members is constructed that encodes precisely the members that must be visible in each object. Concept analysis is used to generated a concept lattice from this relation, from which refactoring proposals are generated.

Duggan's approach for parameterizing classes [Duggan 1999] predates Java generics, and his PolyJava language is incompatible with Java in several respects (e.g., the treatment of raw types and arrays, no support for wildcards). Unlike our approach, Duggan's takes a class as its input and relies on usage information to generate constraints that relate the types of otherwise unrelated declarations. If usage information is incomplete or unavailable, too many type parameters may be inferred. To our knowledge, Duggan's work was never implemented.

Donovan and Ernst [2003] present solutions to both the parameterization and the instantiation problems. For parameterization, a dataflow analysis is applied to each class to infer as many type parameters as are needed to ensure type correctness. Then, type constraints are generated to infer how to instantiate occurrences of parameterized classes. Donovan and Ernst report that "often the class is over-generalized," that is, too many type parameters are inferred. Donovan and Ernst's work infers arrays of parameterized types, which are not allowed in Java but were permitted by the then-current proposal. Their work was only partially implemented before they turned to the work that follows.

Donovan et al. [2004] present a solution to the instantiation problem based on a context-sensitive pointer analysis. Their approach uses "guarded" constraints that are conditional on the rawness of a particular declaration, and that require a (limited) form of backtracking, similar to the implication constraints used in Section 5. Our solution is more scalable than Donovan's because it requires neither context-sensitive analysis nor backtracking, and more general because it is capable of inferring precise generic supertypes for subtypes of generic classes. Moreover, as Donovan's work predates Java 1.5, their refactoring tool does not consider wildcard types and supports arrays of generic types (now disallowed).

Von Dincklage and Diwan [2004] present a solution to both the parameterization problem and the instantiation problem based on type constraints. Their Ilwith tool initially creates one type parameter per declaration, and then uses heuristics to merge type parameters. While the successful parameterization of several classes from the Java standard collections is reported, some of the inferred method signatures differ from those in the Java 1.5 libraries. It also appears that program behavior may be changed because constraints for overriding relationships between methods are missing. As a practical matter, Ilwith does not actually rewrite source code, but merely prints method signatures without providing details on how method *bodies* should be transformed.

In recent work, Steimann and Thies [2009] investigate the correctness of several existing refactorings in the presence of access modifiers such as `public` and `private`. They identify situations where the application of existing refactorings such as MOVE CLASS causes unexpected changes to program behavior unless care is taken to adapt access modifiers. These behavioral changes occur when a refactoring causes references to methods or fields to be bound differently, resulting in changed virtual dispatch behavior (by changing method overriding), or by changing the resolution of overloaded methods. Steimann and Thies present a constraint-based solution to this problem where the constraints reflect relationships between the declared accessibility of an entity and the access modifier required to reference another entity from the first entity's location. These constraints are similar in spirit to the ones used in our work, but range over a different domain (access modifiers vs. types).

8. CONCLUSIONS

An important category of refactorings is concerned with manipulating types and class hierarchies. For these refactorings, type constraints are an excellent basis for checking preconditions and computing source code modifications. We have demonstrated how refactorings for generalization, for the introduction of generics, and for performing migrations between similar classes can be modeled using variations on a common type constraint formalism. All of our refactorings have been implemented in Eclipse, and several refactorings in the standard Eclipse distribution are based on our research. We demonstrated the practicality of the approach by applying several of the refactorings under consideration to a number of Java applications, and presented a summary of the experiments conducted and results obtained.

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