T2 : Automated Testing Tool for Java
User Manual

(for T2 version 2.1)

`http://www.cs.uu.nl/wiki/WP/T2Framework`

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T2 : Automated Testing Tool for Java, User Manual

Contents

Chapter 1

Quick Start

1.1 What is T2?

- T2 is an *automatic* unit testing tool for Java. Use it to test your class.
- It is easy to use. It integrates with Junit, and any IDE supporting Junit.
- Write your specifications directly in Java! And yes, you can express quite sophisticated specifications with just plain Java.
- T2 supports multiple test automation strategies. It supports model based testing too.
- Lots of options!

1.2 Screen shots

See Chapter 7.

1.3 Installation

Download T2 jar, and put it somewhere. That's it. Just include this jar in your class path whenever you want to use T2.

1.4 Using T2

T2 can be used in several ways:

1. as a stand alone console application
2. as an API that can be called from another Java class.
3. used from within Junit framework.

For now I will just explain the first use (so, as a console application). The other uses will be explained later in this Manual.

To use T2 from the console, basically you just call the main tool `Sequenic.T2.Main`, passing to it the name of the target class you want to test; e.g. like this:

```
java  -ea  -cp TT.jar  Sequenic.T2.Main  java.awt.Point
```

This will unleash T2 to test the class `Point` from the `java.awt` package. A couple of things to note here:

1. You need to supply a fully qualified name of the target class.
2. The *must* turn on the `-ea` flag! This enables assertion checking. Else T2 will skip off your specifications.
3. Include the path to your TT jar in the `-cp` (class path) argument.

If T2 finds an error, it will report it. You probably won't find any error in the class `Point`. To see how T2 reports an error let's try to run it on one of the example classes included in T2 jar. Try this:

```
java  -ea  -cp TT.jar  Sequenic.T2.Main  Examples.SimpleSortedList
```

This will test the class `SimpleSortedList` from the package `Examples`. As the name suggest, the class is a simple implementation of a sorted list. It contains an error, and see how T2 finds it. The code of this class is in Figure 3.1.

Options

T2 allows you to specify options to influence its behavior. Options are listed after the name of the target class (the class to test). By default T2 will stop after trying 500 steps, or after finding the first violation. Using the option `--violmax` we can make T2 to search for more violations. For example to make it find up to 3 violations in `SimpleSortedList` we do:

```
java  -ea  -cp TT.jar  Sequenic.T2.Main  Examples.SimpleSortedList --violmax=3
```

There is no guarantee however that T2 will find three different errors; its strategy to generate tests is basically random-based. Anyway, we have seen an example of how to pass an option to T2.

The main tool (`Sequenic.T2.Main`) it self is actually a bundle of several tools. It contains at least T2's random-based test generator tool and a replay (regression) tool. Each tool plugged into `Main` can be called by passing the right selector, with the exception the the test generator tool, which is the default tool. It requires no selector to pass (which is why we don't see it in the examples above). Calling `Main` with no argument:

```
java -cp TT.jar  Sequenic.T2.Main
```

will show the general use of `Main`, and available tool selector. This:

```
java -cp TT.jar  Sequenic.T2.Main -E --help
java -cp TT.jar  Sequenic.T2.Main -R --help
```

will show the general use of the test generator tool respectively the replay tool, and short descriptions of available options.

T2 has lots of options. See Chapter 8.

Replay tool

The typical work cycle when using T2 is:

1. Write your class. Code in your specifications as needed.
2. Run a test with T2. Ask T2 to save test sequences, including violating ones.
3. Repair bugs.

4. Replay the saved sequences to see if the bugs disappear.
5. Repeat the cycle write-run-repair-replay until you are happy.

As an example consider this very trivial class:

```
public class Trivial{
   int x=0 ;
   public void inc(){ x++ ; assert x>0 ; }
   public int ouch() { x=0/0; return x ; }
}
```

The method `inc` simply increases `x`. The `assert` statement there express our specification for this method. The method `ouch` contains the obvious error of doing 0/0, but let us pretend we don't see this.

So after writing the class, and adding the specification we arrive at the above code, and at this point we want to test with T2. So we do:

```
java -ea -cp TT.jar  Sequenic.T2.Main  Trivial
```

T2 will generate random sequences of method calls to (objects of) the class `Trivial`. The odd is very good that one of the sequence calls `ouch`, and thus discovers a violation. The sequence producing this violation will be automatically saved, so that you can replay it latter to retest `Trivial` after you fix it. However, you may want to save more violating sequences, and even some of the non-violating sequences. So let us do this:

```
java -ea -cp TT.jar  Sequenic.T2.Main  Trivial  --violmax=3  --savegoodtr=3
```

This will save 3 violating sequences, and 3 good (non-violating) sequences. The sequences are saved in the file `Trivial.tr`. The extension `.tr` comes from 'traces' which is how we used to call 'sequences' in older T2s.

Now let's fix `Trivial`:

```
public class Trivial{
   int x=0 ;
   public void inc(){ x++ ; assert x>0 ; }
   public int ouch() { x=0; return x ; }
}
```

Using the replay tool we can reload saved sequences and test them again. Note that this only works if you do not change the signature of the methods of your target class. We can do the replay test as follows:

```
java -ea -cp TT.jar Sequenic.T2.Main -R Trivial.tr
```

You have to set the `-R` selector. Unlike the test generator, for the replay tool you need to pass the name of the save file (where the sequences are saved); in this case it is `Trivial.tr`.

In principle replay test is the same as *regression test*. However in practice 'regression test' usually means re-doing lots of tests at the system level. Because T2 replay test is at the unit testing level, it tends to be much smaller. Still, we can in principle do large regression with the replay tool if we want to.

Limitation

Some testing problems are beyond T2 ability. E.g. T2 cannot handle a non-deterministic class (e.g. if it uses random or multi threading). For more information, see Section 2.2.

Chapter 2

Overview

2.1 Features

- T2 is a automatic unit testing tool. Using it requires little effort and it is almost interactive; depending on the complexity of your class it can respond in less than a second, in which time it can inject thousands of tests!
- T2 checks for internal errors, run time exceptions, method specifications, and class invariant. It can even check temporal properties. Unlike other testing tools, T2 reads specifications written in plain java! They are usually placed in the class we want to specify. Specifications written in the same language as the programming language (in this case Java) are called *in-code specifications*. Though not as fancy as Z or JML, these plain java specifications do posse other charasteristic attributes of specifications: unambigous, declarative, formal, and powerful. Because they are in-code, their maintenance is also minimum.
- Unlike other testing tools T2 does not check individual methods in isolation. T2 does not generate Junit test classes; it performs the test directly (also called 'on the fly'). This is much faster, because there is no generation and compilation of Junit classes in between. We may add Junit generation in the future, if people really want it; but at the moment our position is that you simply don't need it.
- T2 on-the-fly testing is very fast, perhaps even giving the feel that it is interactive. Internally it generates tests in the form of *sequences of field updates and method calls*; each will be checked. Using sequences has the effect that methods are basically checking each other. That is, in e.g. a sequence $m_1(), m_2(), m_3()$ the call to m_1 will checked against its own specification (as far as one exists). However, even if this fails to detect a fault (because the specification is only partial), the fault may cause an error further down the sequence. That is, it can be caught as the specification of m_2 or m_3. The situation is then reversed when we generate another sequence with a different order, e.g. $m_3(), m_2(), m_1()$. This will check m_3 against the specs of other methods.
- Using sequences methods are essentially checking each other. This is called *reflexive testing*. The huge benefit of this is that it can still find errors and generates less meaningless sequences even if the specifications provided are individually very partial, whereas other testing tools would typically require fairly complete specifications. The catch is that the actual cause of an error (the 'fault') may not be in the same method that raises the error. You will have to analyze the execution report produced by T2 to locate the fault. This can be a problem is you have a very long sequence. Fortunately you can control how long the sequences are. The default is 5.
- By default T2 will generate the sequences *randomly*. This means that T2 randomly select which method to call or which field to update at each step, and randomly construct its

parameters. When a parameter is needed, it may construct a fresh object of the right type, or choose to pass on an old object (to simulate side effects). The decision is also random. The are options to control the probability of various decisions, and there are also options to specify which methods and fields are to be included into the testing scope.

- The basic mode to generate the test sequences is random. Currently two extra modes are supported. In the 'search mode' a trace that violates a pre-condition is not dropped, but retried with a different variation. The the 'combinatorial mode' the engines tries to generate all possible combinations of sequences (modulo the parameters passed to them).

- There are situations when methods of a target class have to be called in a certain order (e.g. perhaps a class implementing a door requires that the method `open` can only be called after `close`). T2 can accept an '*application model*', with which we can specify what valid orders are.

- Out of the box, it is a *unit testing tool*. The 'unit' in T2 is 'class' (and not method!). So, in principle T2 tests a given target class as a whole. This is simply the consequence of using sequences. However, when desired it is possible to configure T2 to tests individual methods. On paper it is also possible to set up T2 to do system testing. However, because a system is not a class, this requires a 'proxy class' to be hand crafted to provide an interface between T2 and the system.

- Violating sequences are reported, and can be saved. But we can also ask T2 to save non-violating sequences as well. Saved sequences are very useful for retesting. After fixing bugs, or after modifying the target class we will want to replay the same tests to see e.g. if the the violations now disappear. T2 provides a tool to reload and replay saved sequences.

- T2 uses real execution to test; this is in contrast to approaches that test on models or alternate representations. It follows that by definition T2 is *sound and complete*: it never produces a false positive nor a false negative. A sequence is a *false positive* if it is reported as violating by T2, but actually does not violate any non-assumptive assertions of the target class, nor throws an unexpected exception. It is a *false negative* if T2 sees it as non-violating, but actually it does violate some non-assumptive assertion or throws an unexpected exception.

- Although T2 generates the sequences randomly it does take pre-conditions and application models, if provided, into account. They filter out meaningless sequences. That is, a sequence is droped as soon as it is identified as meaningless. It is possible that some pre-conditions are too complicated to be met by purely random values generation; this means that T2 may be unable to generate sufficient number of meaningful sequences. T2 does provide hooks to allow custom value generators to be plugged-in.

- As a final note, being just a hunble a random-based tool T2 is not a substitute for cleverly hand crafted tests. It can however give you structural coverage with just a push of a button. The best way to use it is to use it is to complement manual testing. Though this appears to double the cost of unit testing, the combination is also more powerful. In the end we save a lot by leaking less faults to the latter development stages, where the cost of fixing them would multiply.

2.2 Limitations

- T2 cannot check a class that contains non-deterministic behavior. The following is typically a source of non-determinism:

  1. Use of random generator.
  2. Multi threading.

3. Interaction with user.
4. Interaction with other concurrent programs.

All those cases are beyond the reach of T2. The reason that T2 cannot handle non-determinsm, is that it prevents T2 from replaying exacting the same execution that originally produce the error. Even T2 reporting relies on replayability.

- T2 crucially assumes that the test sequences it generates does not interfere with each other. This assumption can be broken in several situation:

  1. If a target class can changes a static field at the runtime, this will break the assumption, because the previous sequence may alter the static field, and thus influencing the next sequence.
  2. If the target class uses a persistent object (like a file or a database), the state of this object persists over multiple sequences. So this too breaks the assumption.

  This problem can still be circumvented by forcing the target class and all the persistent objects it uses to be reinnitialized at the start of each sequence. The hook to do this in T2 is by rewriting the method `reset` of the class `Pool`; this can be done by writing your own subclass of `Pool`. The method `reset` is always called at the beginning of every sequence.

- T2 cannot completely handles type parameters (generics). When T2 needs to generate objects during a test, it does so based on the type of the object. This type is obtained through reflection. However Java compiler currently erases information on type parameters (type erasure), so reflection cannot recover it. Current solution (of T2) is to allow a global option where the tester can specify the type of the elements of e.g. collection like objects. This option applies globally in the sense that during a full run of the test engine it will use this option for all collections it has to generate. This is a very ad-hoc solution and works very limitedly. A general solution will probably have to wait until Java comes with a compiler with an option that supresses type erasure.

- Let u, v be objects; v is a *subobject* of u if v is reachable by following pointers inside u. We say u owns v if all access to v has to go through u. Ownership is often implicitly assumed. Unfortunately it is not statically checked by Java.

  T2 does not check ownership relations. More precisely, it does not check if a target class C respects ownership assumptions made by other classes it uses. Furthermore, if an instance u of C contains a subobject v of class D, and C does not claim ownership over v, T2 does not simulate calls to v's methods (another way to see it is that T2 simply assumes that v own all its subobjects).

- T2 does not attempt to avoid generating isomorphic objects. Future work.

- T2 does not generate mock objects for external resources (e.g. files, database). Use other tools to make your mocks (or write them manually). In addition you will still have to write wrappers over the methods you want to test, so that they interact with the mocks instead.

- T2 can detect potential non-termination (simply by using timer), but it cannot report the exact source of the non-termination (e.g. line number). It may still be able to identify the method that causes the problem. Future work.

Chapter 3

Examples

Figure3.1 shows a simple class. It is a simplistic implementation of sorted lists. Each `SortedList` object represents a sorted list. The list is maintained internally in the variable `s`, and can hold instances of `Comparable`. The method `insert` inserts a new element into the list, and the method `get` retrieves the greatest element from the list. Both are supposed to maintain the list sorted.

```
public class SortedList {

    private LinkedList<Comparable> s ;
    private Comparable max ;

    public SortedList() { s = new LinkedList<Comparable>() ; }

    public void insert(Comparable x) {
        int i = 0 ;
        for (Comparable y : s) {
            if (y.compareTo(x) > 0) break ;
            i++ ; }
        s.add(i,x) ;
        if (max==null || x.compareTo(max) < 0) max = x ;
    }

    public Comparable get() {
        Comparable x = max ;
        s.remove(max) ;
        max =  s.getLast() ;
        return x ;
    }
}
```

Figure 3.1: A simple class with an error.

The class has a single constructor, which just produces an empty list. We additionally maintain a variable `max` to point to one of the greatest elements in the list (if the list is not empty).

There are indeed some faults in the class, but let us pretend we are unaware of them. We'll proceed to testing the class. So far you don't have any specification. Still, you can test `SortedList` with T2. Just do:

```
java  -ea  -cp .;TT.jar  Sequenic.T2.Main  SortedList
```

It will probably report some errors, e.g. that the call to `getLast` in the body of `get` throws a `NoSuchElementException`.

Without a specification T2 can still check for internal error and unexpected runtime exception. T2 defines *internal error* as an instance of `Error` (which means that it can also be an instance of a subclass of `Error`) thrown by the target class. An *unexpected runtime exception* is an instance of `RuntimeException` thrown by the target class. Both kinds are considered as violation by T2.

3.1 How Does T2 Test a Class?

When given a *target class* C to test, T2 randomly generates tests for C. Each test is generated and executed on the fly. This is unlike other tools that first generate Junit code, which need to be compiled first before we can run it. On the fly testing is much faster. Depending on the complexity of your class, T2 can inject thousands of tests and report back in less than a second.

Each *test* is a *sequence* of step, and each step is either a call to a method of C, or an update to one of its field. By default T2 considers all non-private methods and fields, but this can be customized with options. See Subsection 2.2 for more information about the default testing scope of T2. After each step, the C's class invariant, if specified, will be checked. If a method is called in a step, and its specification exists, it will be checked as well.

To be more precise, each test starts with the creation of so-called *target object*, which is an instance of C. When a step updates a field, it will be a field of the target object. When a step calls a method, it will be either a method that takes the target object as the receiver, or takes the target object as an ordinary parameter. So, each step potentially affects the target object.

Note that unlike many other tools, T2 does not test each individual method in isolation (though it can do that, via some options). Instead it may call various methods in a single test sequence. The approach is called *sequence-based testing*.

The problem with testing each method in isolation is that we usually need a quite complete specification both to generate meaningful receiver objects for the method and as an oracle for catching faults. Though this problem does not completely disappear in sequence-based testing, it is much less acute.

A very beneficial side effect of using sequences as tests is that in a sequence, methods are basically checking each other (called *reflexive testing*). E.g. in a sequence $m1(); m2()$ we do not just check $m1()$ against its own specification, but also against $m2()$'s and m_3's specifications, and whatever fault detection mechanisms built into those methods. So, in sequence based testing we essentially check C against the conjunction of all specifications of its methods, plus the fault detection built in Java, and the fault detection built into the class by the programmer himself. Together they make a pretty strong correctness criterion, even if each individual specification is weak.

3.2 Adding Specifications

Before we fix the class `SortedList`, let us first add some simple specifications. We don't need JML, OCL, Z, etc to write specifications. We'll just use plain Java. Specifications written in the same language as the used programming language are called *in-code specifications*. Though not as fancy as Z or JML, in-code specifications are nevertheless non-ambigous, declarative, and powerful.

They are usually written in the target class that you want to specify. Java compiler itself will make sure that they are syntactically consistent with the class they specify, so their maintenance is also minimum.

Let us begin by specifying a class invariant. T2 defines a *class invariant* of a class C as a predicate that holds after an instance of C is created, and after each call to a method of C. Now, to specify a class invariant we write a boolean method called `classinv`, as shown in the example below:

```
public class SortedList {

    private LinkedList<Comparable> s ;
    private Comparable max ;

    ...

    private boolean classinv() { return s.isEmpty() || s.contains(max) ; }
}
```

It just says that if `s` is not empty, then `max` should be an element of `s`. This is indeed a very weak invariant (it does not even mention that `s` is kept sorted). But it is okay for now; we don't have to start with a complete specification. We can start with just simple specifications like the one above. We can check it with T2. It may already expose faults. If not, we may decide to add more details, thus making it stronger. A stronger specification has a better chance of catching faults. In this way we can develop our specifications incrementally.

The method `classinv` should takes no argument and return a boolean. It has to be non-static and private[1], and should not declare as throwing exceptions. See the above example. If it throws something other than an `AssertionError`, it is considered as false (violation to the invariant).

Next, we can specify each method individually. There are two ways to do it. First we'll just write the specification in the method itself. We do this by adding assertions. For example we can add these assertions to the method `get`:

```
    public Comparable get() {

        assert !s.isEmpty() : "PRE" ;

        Comparable x = max ;
        s.remove(max) ;
        max =  s.getLast() ;

        assert s.isEmpty() || x.compareTo(s.getLast()) >= 0 : "POST" ;

        return x ;
    }
```

The specification will impose that `s` is non-empty as the pre-condition of `get`, and some other condition as its post-condition.

It is important to mark a pre-condition with the marker `"PRE"`. A pre-condition is treated as an assumption. When a test is about to call a method m, and it violates its pre-condition the test is considered as meaningless, and is discarded by T2. Violating other assertions does count as violations.

You can put as many assertions as you want in a method, and in any place (so not only in in the post-condition position). This includes placing a `PRE`-marked assertion in the middle (rather

[1] T2 still accepts a `classinv` which is not private. The problem with this is as follows. Suppose that the target class C is a subclass of D. We may want to check if C also repects D's `classinv`. To do this T2 needs to call the latter from an instance of D. However, let `u` be an instance of C, Java's dynamic binding will refuse to associate a call `u.classinv()` to D's `classinv` (even if we first cast `u` to D). Making all `classinv`s private is a trick to get around this.

than at the beginning) of a method. The only thing you have to remember is the special treatment of `PRE` marking as explained above.

Another way to specify a method m is by writting a method named m_spec with *exactly the same header* as m, lists *the same exceptions*, and is given *the same access modifier*. The method m_spec should call m, and pass on the value returned by m. We put our assertions in m_spec, for example:

```
public Comparable get_spec() {
     assert !s.isEmpty() : "PRE" ;
     Comparable ret = get() ;
     assert s.isEmpty() || ret.compareTo(s.getLast()) >= 0 : "POST" ;
     return ret ;
 }
```

The advantage of this approach is that we don't clutter m with assertions. Furthermore, we can specify the post-conditions when m throws an exception. On the other hand, we won't be able to specify e.g. a loop invariant.

During the testing T2 will check if m_spec exists. If it does, it will be used instead of m.

To summerize, here is then the code of `SortedList`, along with the specifications we come up so far:

```
public class SortedList {

    private LinkedList<Comparable> s ;
    private Comparable max ;

    public SortedList() { s = new LinkedList<Comparable>() ; }

    private boolean classinv() {
        return s.isEmpty() || s.contains(max) ;
    }
    public void insert(Comparable x) {
        int i = 0 ;
        for (Comparable y : s) {
            if (y.compareTo(x) > 0) break ;
            i++ ; }
        s.add(i,x) ;
        if (max==null || x.compareTo(max) < 0) max = x ;
    }
    public Comparable get() {
        Comparable x = max ;
        s.remove(max) ;
        max =  s.getLast() ;
        return x ;
    }
    public Comparable get_spec() {
        assert !s.isEmpty() : "PRE" ;
        Comparable ret = get() ;
        assert s.isEmpty() || ret.compareTo(s.getLast()) >= 0 : "POST" ;
        return ret ;
    }
}
```

There is a mistake in the last line of `insert`. Rather than setting `max` = `x` when `x.compareTo(max)` < `0` (when `x` is less than `max`), we have to do it when `x` is greater than `max`.

If we are to test `insert` in isolation, the testing tool won't discover this, because `insert` doesn't even have a specification. The tool will also generate lots of meaningless inputs, since the class invariant we have does not mention that we should only consider instances of `SortedList` whose `s` is sorted.

However, this sequence:

```
u = new SortedList() ;
u.insert(0) ;
u.insert(1) ;
u.get()
```

will expose the fault, as we now get a violation to `get`'s specification. This demonstrates the strength of sequence-based testing.

Try to test `SortedList` with T2:

```
java -ea -cp .;TT.jar Sequenic.T2.Main SortedList
```

3.3 Handling type variable (generic)

Consider the class below; it implements linked lists. We omit most parts of the code —the full listing is provided at the end of this section. The most important thing to note here is that this class has a type parameter.

```
public class MyList<T>  {  // note the type variable

    ...

    public void insert(T i) { ... }

    public void remove(T x) { ... }

    public void remove_spec(T x) { ... } // specification of remove
}
```

When during a test T2 generates a class to a method m, it also has to generate parameters for m. To do this T2 needs to know the types of those parameters; it can then search for e.g. matching constructors, or for matching objets in its pool of old objects. T2 relies on reflection to inquiry the types of the parameters of m.

When the type of m contains type variables (aka type parameters aka generics), e.g. as the methods of `MyList` above, this poses a problem. When we compile a Java program the compiler checks the syntax, including the typing of the program (if it is type-correct). Type variables have to follow certain typing rules too; these are checked by the compiler. However, once this check is passed Java compiler erases the type variables from the byte code. This is for the reason of compatibility with order versions of Java that do not know the concept of type variable. In the place where a type variable `T` should occur, it is then replaced by an ordinary class. Usually (but not always; you may want to check out Java's tutorial on generics) it is the `Object`. So, the method `insert` and `remove` above appears to be of the following type:

```
public void insert(Object i) { ... }

public void remove(Object x) { ... }
```

T2 obtains typing information using reflection, which works on the byte code. So, it only sees the typing information as the compiler places it in the byte code. It means that T2 won't see the original type variables; it will see e.g. `insert` and `remove` to have the types as above. What we still can do is to give T2 a little hint, though this only works limitedly. As long as Java compiler still erases types, we will have no general way to solve the problem.

Suppose now we want to test `MyList` above using `java.awt.Point` for `T`. We can tell this to T2 using the `--elemty` option:

```
java -ea -cp .;TT.jar Sequenic.T2.Main MyList --elemty=java.awt.Point
```

This option forces T2 to do the following. Whenever it has to generate an instance of class `Object`, it tries to generate an instance of `java.awt.Point` instead. Effectively, we replace parameters of type `Object` with type `Point`.

If we pass no `elemty` option, T2 will default it to the class `Sequenic.T2.OBJECT` which is just this minimalistic class:

```
public class OBJECT {}
```

So it has not fields nor methods. The only interesting thing we can do with it is to compare whether two references (of type `OBJECT`) are the same (pointing to the same `OBJECT` instance) or not.

The full code of `MyList` is shown in Figure 3.2 . It contains a fault in the method `remove`. Using either `Point` or `OBJECT` as `elemty` will expose this fault. So, the option works for this example.

However, the `elemty` option will fall short if we have more than one type variables, because both will then just be replaced with the `elemty` class. It is probably possible to have a more sophisticated type substitution scheme, but no such thing is currently implemented.

```
public class MyList<T>  {

public Link list ;

private class Link {
T item ;
Link next ;
Link(T i) { item = i ; next = null ; }
}

/**
 * A method for inserting an element at the head of the list.
 */
public void insert(T i) {
Link u = new Link(i) ;
u.next = list ;
list = u ;
}

/**
 * A method for deleting all occurences of x from the list. This
 * method has an error: it will miss removing x if it
 * occurs as the first element in the list.
 */
public void remove(T x) {
if (list==null) return ;
Link p = list ;
while (p!=null) {
if (p.next!=null && x == p.next.item) p.next = p.next.next ;
            p = p.next ;
}
}

/**
 * The specification of remove; it requires that after the removal
 * x does not appear in the list.
 */
public void remove_spec(T x) {
remove(x) ;
Link p = list ;
boolean ok = true ;
while (p != null && ok) { ok = p.item != x ; p=p.next ; }
        assert ok : "POST" ;
}
}
```

Figure 3.2: An example of a class with type variables.

Chapter 4

T2 Report

The report produced by T2 consists of several sections.

The first section reports the configuration of the test engine, e.g. the name of the target class, the maximum number of test steps that will be generated, the maximum length of each test, etc. Example:

```
** Invoked CONFIGURATION
   ** CUT = Examples.SimpleSortedList
   ** TYVAR0 = Sequenic.T2.OBJECT
   ** Pool = Sequenic.T2.Pool
   ** Base domain = Sequenic.T2.BaseDomainSmall
   ** Interface map = Sequenic.T2.InterfaceMap0
   ** Time-out = 20000
   ** Max. number of steps = 500
   ** Max. execution depth = 4
   ** Max. number of violations to look = 1
   ** Max. object depth (on creation) = 4
   ** Max. show depth = 5
   ** Max. array/collection size = 4
   ** Incl. Private = false
   ** Incl. Default = true
   ** Incl. Protected = true
   ** Incl. Static = true
   ** Incl. superclass members = true
   ** Incl. superclass classinvs = false
   ** Field update enabled = true
   ** Prob. of updating field = 0.1
   ** Prob. to generate NULL = 0.1
   ** Prob. to pass targetobj as param = 0.4
   ** Prob. of trying pool before constuctor = 0.7
**
```

The next section contains reports on violating executions, if any is found. After that there comes a section giving a summary of the testing result, mentioning e.g. the number of violations found before T2 halts, number of test steps generated, elapse time, etc:

```
** VIOLATIONS FOUND: 1
     1 assertion violations.
** number of irrelevant checks     : 3.
     3 PRE violations.
** total number of traces : 5
** total execution steps  : 16
** average trace lenght   : 3.0
```

```
** time                    : 172ms.
** average time per step   : 10.0ms.
...
** Saving 1 traces...
```

Note that it also mentions how many sequences are saved. Found violating sequences are always saved; but we can also ask T2 to save a number of non-violating sequences.

So, in the middle section T2 reports the violating sequences it encounters. Usually T2 will stop after the first violation, but we can ask it to search for more. For each violating sequence T2 prints the state of the target object after each step, which field is updated by a step, or which method is called, and what are the parameters passed to it. And finally, T2 informs what kind of violation the test commits, and when possible it also prints the stack trace, from where we can read the line number that causes the violation. Here is an example of such a report (of a single violating sequence):

```
** Begin test sequence.
** STEP 0: creating target object.
** Calling constructor Examples.SimpleSortedList
  ** Resulting target object:
     (Examples.SimpleSortedList) @ 0
     s (LinkedList)  @  1
     max NULL
** STEP 1.
** Calling method insert with:
  ** Receiver: target-obj
  ** Arg [0:]
     (Integer) : 2
  ** State of target object now:
     (Examples.SimpleSortedList) @ 0
     s (LinkedList)  @  1
       [0] (Integer) : 2
     max (Integer) : 2
** STEP 2.
** Calling method insert with:
  ** Receiver: target-obj
  ** Arg [0:]
     (Integer) : -3
  ** State of target object now:
     (Examples.SimpleSortedList) @ 0
     s (LinkedList)  @  1
       [0] (Integer) : -3
       [1] (Integer) : 2
     max (Integer) : -3
** STEP 3.
** Calling method get_spec with:
  ** Receiver: target-obj
  ** State of target object now:
     (Examples.SimpleSortedList) @ 0
     s (LinkedList)  @  1
       [0] (Integer) : 2
     max (Integer) : 2
xx Assertion VIOLATED!
** Strack trace: java.lang.AssertionError: POST
   ...
** End test sequence
```

Objects involved in an executions are also given numbers (`@0`, `@1`, `@2`, etc), which are shown in the report. For example we can see that through out the sequence that the `s` field of the target object always points to an object numbered by `@1`; which implies that `s` always point to the same object through out the sequence.

Values from primitive types (e.g. `int` and their corresponding boxing classes (e.g. `Integer`) cannot be numbered. The reason is technical.

Chapter 5

Replaying Tests (Regression)

T2 always saves violating tests. The default is that T2 stops after the first violation, so it will only save that one test that causes the violation. However we can ask T2 to keep on searching for more violations:

```
java -ea -cp .;TT.jar Sequenic.T2.Main MyClass --violmax=10
```

Now T2 will stop after 10 violations instead of 1; all the 10 violating tests are then saved. We can also ask T2 to also save random non-violating tests as well:

```
java -ea -cp .;TT.jar Sequenic.T2.Main MyClass --violmax=10 --savegoodtr=10
```

This will additionally save 10 non-violating tests. However, in both cases T2 will also stop if the maximum of total number of steps is exceeded (recall that each sequence is made of steps). The default is 500. This default can be changed with the `--nmax` option. We can also change the length of the sequences with the `--lenexec` option. The default is 4.

By default, the tests are saved in a file named `MyClass.tr` (to be more precise, the fully qualified name of the target class, appended with `.tr`).

After fixing `MyClass` you would want to replay the saved sequences, to see if the errors found now disappear, and hopefully no new error emerges. This is also called *regression test*. It is very easy to do it with T2:

```
java -ea -cp .;TT.jar Sequenic.T2.Main -R MyClass.tr
```

This will load the test sequences saved in `MyClass.tr` and rerun them.

The assumption here is that you don't change the types of the members of `MyClass`. If you do, the tests may fail to reload.

By default T2 will replay all reloaded sequences, but there are options to make it just choose randomly, or to only replay sequences which were violating –see Chapter 8.

Chapter 6

More on T2 Algorithm

Section 3.1 explains globally how T2 works. This explanation is probably sufficient to figure out how to use T2 to test simple classes. When you have a complicated class, you may want to configure T2 is specific ways. T2 offers lots of options. See Chapter 8 It is a powerful tool that let you configure it in many different ways. However advanced configurations may require you to understand a bit more about T2's algorithm.

T2 main loop is essentially quite simple. This is as explained in Section 3.1. Given a target class C to test, T2 will generate a whole bunch of tests for it. Each test σ is a sequence; it starts by creating an instance of C, which becomes the *target object* for the sequence. In the subsequent steps of σ, each step is either an update to a field of the target object, or a call to a method from C, that takes the target object as a parameter.

As T2 executes a test sequence, it will need to generate objects needed as parameters e.g. for the methods called in the sequence. The algorithm for generating objects is more complicated.

6.1 How T2 generates objects

One option is to keep generating fresh objects when we need them. However, this would not be realistic as it prevents methods to side effect each other through common objects. In practice this pattern occurs a lot, so we definitely do not want to exclude it from out testing scope. So, rather than keep creating fresh objects, we will also allow old objects to be passed on.

To facilitate the reuse of old objects, T2 maintains an *object pool*, implemented by the class `Pool`. Whenever objects are created during an execution, they are put in the pool. When an execution needs an object, T2 can decide to just pick one (of the right type) from the pool rather than creating a fresh one. Each object in the pool receives a unique integer ID. This ID is very important. Each test keeps track of the IDs of the pooled objects it uses. This allows us to later on replay exactly the same execution as the original execution of a sequence. This features is essential for T2 replay/regression functionality.

Note that the pool essentially holds the part of the JVM state that can be affected by a sequence.

T2 crucially assumes that sequences do not interfere with each other. That is, a test sequence is assumed to have no side effect on another sequence. Without this assumption an error in a sequence can be caused by some fault in a previously generated sequence. This forces us to analyze not just the violating sequence, but all its preceeding sequences. Obviouly this is not practical.

To make sure that sequences do not interfere with each other, T2 will reset its object pool whenever it starts a new sequence. This is done by calling the method `reset`() from the class `Pool`. By default it will just clear the pool (making it empty). Mostly this is sufficient. However there are cases where this is not sufficient. For example when the target class update some static variables, or when it uses persistent elements (e.g. files or databases). We have to reset these

elements too. This can be done by implementing a custom pool, overiding the method `reset` accordingly. We can pass a custom pool to T2 as an option.

Another reason to write a custom pool is if we want to have a pool with some pre-population.

In the sequel, when we say an object "*u to be of class D*", we mean that the actual class of u is either D or a subclass of D. When we say "*u is an instance of D*", we mean that the actual class of u is exactly D.

In addition to a object pool, the object generation algorithm also uses two more data structures. We list them, including the pool, below. We also explain some notation which we will use later to describe the algorithm itself.

1. An *object pool* (as explained above).

   If P is an object pool, and E is a class, let $E \in P$ means that the pool contains an object of class E; $P.get(E)$ will then deliver us such an object (randomly chosen).

2. An *interface map*; this is an instance of the class `InterfaceMap`. It is a mapping from class to class.

   If $Imap$ is an interface map, let $E \in Imap$ means that the class E is in the domain of $Imap$; $Imap.get(E)$ will deliver a class F to which E is mapped to.

   $Imap$ should make sure that F is a subclass of E.

3. A *base domain*; this is an instance of the class `BaseDomain`.

   If Dom is a base domain, $E \in Dom$ means that the base domain can deliver an instance of E; $Dom.get(E)$ will then deliver us such an instance.

The object generation algorithm is described by the program `META_mkObject` below. It takes a class E as a parameter, and uses $Pool$, $Imap$, and Dom, which are an object pool, an interface map, and a base domain repectively, as global variables. T2 uses certain defaults for these data structures, but they are fully configurable —see Chapter 8.

`META_mkObject(E)` =

1. Consult the interface map $Imap$

   If $E \in Imap$, and let $F = Imap.get(E)$, then return an instance of F instead. So, we do this:

   ```
   return META_mkObject(F)
   ```

   This mechanism is primarily used to deal with the situation when E is an interface or an abstract class. We cannot directly make an instance of such an E. The interface map can direct T2 to a concrete implementation of E.

   However, this mechanism can also be used to reroute T2 to generate instances of E through a custom generator (e.g. to implement a certain statistical distribution or to generate structures which are too difficult to generate randomly). We can do this by implementing the custom generator as a subclass of E and register it to $Imap$.

2. **Else** (so, if $E \notin Imap$), consult the base domain Dom.

   If $E \in Dom$, then ask Dom to deliver an instance x of E. To be precise, we do not actually use x, but a *clone* of x. So, we do:

   ```
   return clone(Dom.get(E))
   ```

   T2 uses deep cloning. The reason for cloning is to make sure that the base domain is protected from the side effect of the sequences. Dropping this protection will complicate

the analysis of violating sequence; we will then need to take the internal states of the base domain into account. We also already have a mechanism for exposing side effects, namely the pool.

A base domain is primarily used to generate values of primitive types (e.g. `int`) or their boxing counterparts (e.g. `Integer`), and strings. However it can also be used to implement custom generation of instances of any class F.

The only constraint is that F must implement serialization (thus allowing deep cloning).

Furthermore, because the base domain is always checked first before we fall back to using constructors to generate an instance (see below), we can also use it to limit the range of the instances of a certain class. For example, if the only intergers in the base domain are -1 and 1, then these will be the only integers T2 generates whevener it needs one (and alternatively, we can of course choose to use a base domain that supplies a random integer from the entire range of int values).

3. **Else** (when 1 and 2 fail), then randomly (based on a certain probability) decide to first check the pool.

   If we decide to check *pool*, and $E \in pool$, then ask *pool* to deliver us an instance; so we do:

   ```
   return pool.get(E)
   ```

4. **Else** (when 1,2,3 fail) then randomly chooses whether to just deliver a null (because it is also an instance of E), or to create a fresh instance x using a randomly chosen constructor of E.

   If this constructor needs a parameter of class E', then generate its instance by recursively calling `META_mkObject(E')`.

   Because x is a fresh object, we also add it to *pool*.

6.2 Testing Scope

As explained before (Section 3.1) T2 does not test a single method[1]. Rather it tests a whole class by exposing it to test sequences, each is a sequence of field updates and method calls. But which fields and methods are included in the tests?

The set of constructors, fields, and methods that are included in the tests is called the *testing scope*. T2 defines a *default scope*, but it also allows you to define a custom testing scope, as long as it is still a subset of its *maximum scope*. So if you want to do this you probably need to know what this maximum scope is. Even if you just stick with T2 default scope, at some point you may need to know which members are exactly included in the default scope.

Roughly the maximum scope consists of all declared and inherited members of the target class, and the default scope consists of all non-private members from the maximum scope. The precise definitions are however more complicated and contain several subtle points.

Let in the sequel C be the target object.

Maximum scope

Consists of the following members:

- All declared constructors of C, including private ones, except those which are marked with the `T2annotation.exclude` annotation.
- All declared and inherited fields of C, except:

[1] Although it can, if you configure it so.

1. Static fields.
2. Final fields.
3. Abstract fields.
4. Hidden fields.
5. Fields inherited from `Object`.
6. Fields whose name start with `AUX_`. T2 considers these fields
7. Fields that are marked with the `T2annotation.exclude` annotation.

- All declared and inherited methods of C, except:

1. Abstract methods.
2. Hidden and overriden methods.
3. Methods inherited from `Object`.
4. Methods whose name is `classinv`.
5. Methods whose name end with `_spec`. They are considered as specifications.
6. The `static public void main(String[])` method.
7. Methods that are marked with the `T2annotation.exclude` annotation.

T2 default testing scope

T2 default scope consists of all non-private members of the maximum scope. However only static methods that can accept the an instance of C as a parameter. This is reasonable because a (static) method that cannot accept an instance of C can be thought as unable to update instances of C (this is not completely true however), and from this perspective is irrelevant to be included in the testing of C.

Class invariants of super classes

Let C be our target class (the class we want to test). Obviously, C has to satisfy its own class invariant. But should we also check it against the class invariant of its superclass D? Afterall, every instance of C is also an instance of D. T2 leaves this decision to the tester. By default it won't check against the class invariant of the superclasses of C; but we can enable this checking by setting on the `--inclsuperinv` option.

Checking the m_spec specifications

Recall (Section 3.2) that when T2 decides to call a method m is a test step, then it will first search if a method named *m_spec* with the same signature exists. If it exists, it will be called instead of m. T2 assumes that *m_spec* will simply pass its arguments to m, but additionally it may assert some specifications.

Due to inheritence, there may be more than one *m_spec* with the same signature (just as there may be more than one m with the same signature). T2 will only take the *m_spec* which is declared in the same class as the class that declares m. This is always safe: you won't accidentally check m against an old specification intended for another m from a superclass.

However, this also means that you can't m against the *m_spec* of its superclass. You probably don't want to do this anyway. The fact that you have define a new m to override or to hide an old one usually means that your new m has a different specification. So it is a bit strange to check it against an old specification.

6.3 Search Mode

When T2 generates the test sequences, and it discovers that the current sequence violates a pre-condition or other assumption-like conditions, T2's default reaction is to drop the sequence and start a completely new sequence. Note that the violation will be at the last step in this current sequence. In principle, this violation happens because we pass wrong arguments to the step. So we may consider retrying the same sequence, but trying different arguments for its last step.

T2's rational is that we can just as well try the whole sequence anew. Of course this is not always smart. It may be the case that the state of the target object just before the last step is an interesting state but one that is difficult to reach. In such a case dropping the sequence that reaches it is indeed not smart. Consider this artificial example:

```
static public class Example {

    private int status = 0 ;

    public Example() {}

    public void m1() {
       assert status==0 : "PRE" ;
       status=1 ;
   }

   public void m2(){
      assert status==1 : "PRE" ;
      status=2 ;
   }

   public void m3(){
      assert status==2 : "PRE" ;
      status=3 ;
   }

   public void m4(){
      assert status==3 : "PRE" ;
      status=4 ;
   }

   public void m5(){
      assert status==4 : "PRE" ;
      assert false ;
   }
}
```

To reach the error in `m5` T2 will have to generate the sequence:

```
m1(); m2(); m3(); m4(); m5()
```

As you can imagine generating this exact sequence is quite hard (the chance is 1/3125).

We can solve this by enabling T2's *search mode*. In this mode, the current sequence will not be dropped when a pre-condition is violated. It will be retried up to the step before the last one. T2 will randomly choose a new last step; after that it continues as usual.

The search mode can be enabled by the option:

```
--searchmode=n
```

where n is a non-negative number. This will be the maximum number of times the current sequence will be retried if it continues to fail a pre-condition.

6.4 Combinatoric Testing

As explained before (Section 3.1) T2 generates the test sequences by default randomly. However, we also implement a combinatoric-based strategy.

Suppose C is our target class. Let U be the set of C's constructors which are within our testing scope, and V be the set of fields and methods in our testing scope, with the additional restriction that only non-static methods are included (so, we know that we can always pass the target object as the methods' receiver).

Given a trace length k (≥ 2) our combinatoric strategy will generate in principle all possible sequences of length k modulo the arguments (that is, if we do not count the arguments passed to the steps in the sequences).

The arguments for the sequences are still generated randomly. We can also specify the number d of duplicates (default is 2). Every sequence will then be duplicated d times, but for each duplicate the arguments are generated freshly and randomly. So we basically generate d random test per sequence combination.

Here is an artificial example to demonstrate the strategy:

```
public class Example {

   private int[] order = {-1,-1,-1} ;
   private int k = 0 ;

   void m1() { order[k]=1 ;k++ ; }
   void m2() { order[k]=2 ;k++ ; }
   void m3() { order[k]=3 ;k++ ; }
   void m4() { order[k]=4 ;k++ ; }
   void ouch() {
      order[k]=5 ;
      // This will only throw an error if we can generate
      // the sequence Example();m3();m1();ouch():
      assert !(order[0]==3 && order[1]==1 && order[2]==5) ;
     }
  }
```

Note that only the sequence:

```
new Example(); m3(); m1(); ouch()
```

will throw an assertion error. This is pretty hard to generate randomly. An exhaustive approach will do better in this case. To fire T2's combinatoric engine we use the `-C` tool selector. The rest of the options work the same as with its default engine. So we do:

```
java -ea -cp TT.jar Sequenic.T2.Main -C Example --lenexec=4
```

This will find the violation.

Since the total number of possible sequences can be huge; the option `--nmax` always gives a hard limit to the number of test steps generated. If that limit is reached, T2 will stop generating sequences.

Chapter 7

Integration with Junit and IDE

7.1 Calling T2 from your own Java class

So far we only use T2 as a console (command line) application. But we can also directly call T2 from your Java class. Suppose you have a class called `MyClass`, and you want to test it using a test class `MyClassTest`. You can use T2 to do test, which you can call from inside `MyClassTest`. We can write `MyClassTest` as follows:

```
public class MyClassTest {

   static public void main(String[] args) {
      String T2options = "" ; // specify your T2 options here
      Sequenic.T2.Main.main(MyClass.class.getName() + " " + T2options) ;
   }
}
```

Running `MyClassTest` will then call T2 with the options as you specify in the code above.

7.2 Integration with Junit

If you use Junit as your testing framework, you can easily integrate T2 into it. When using Junit you just write the above tester class `MyClassTest` a bit differently. We can furthermore mix automatic test with T2 with usual hand written tests with Junit:

```
import org.junit.Test ;
import static org.junit.Assert ;

public class MyClassTest {

   @Test  // Test with T2
   public void test1() {
      String T2options = "" ; // specify your T2 options here
      Sequenic.T2.Main.Junit(MyClass.class.getName() + " " + T2options) ;
   }

   @Test  // A hand crafted test
   public void test1() {
      MyClass u = new MyClass() ;
      assertTrue(u.checkme) ;
   }
}
```

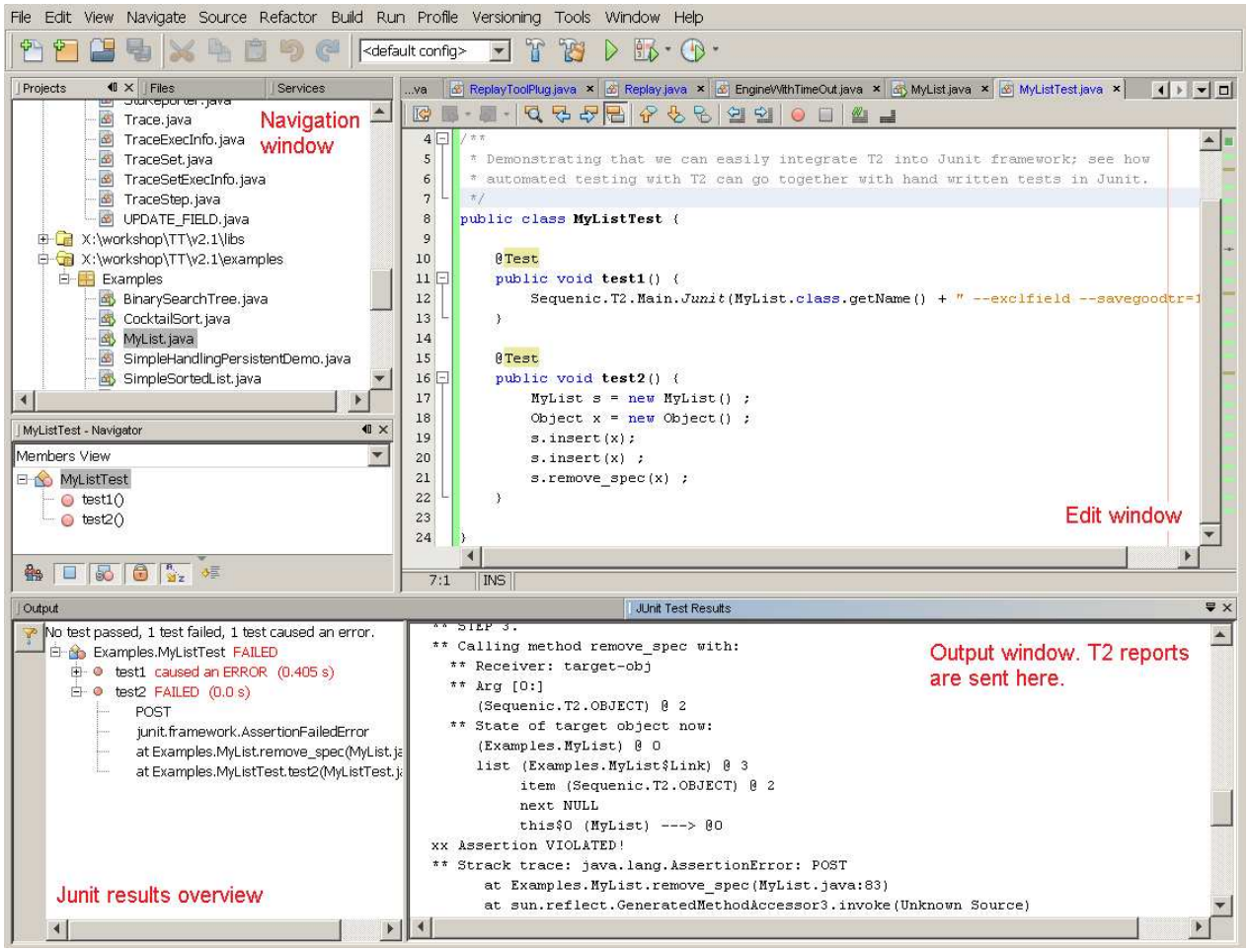


Figure 7.1: Integration with Netbeans.

Then you can run this test with Junit in the usual way. When T2 finds violations, it will signal Junit; so Junit will see that the test above fails.

Currently we can't yet pass on detailed information about the violations as Junit failures descriptions. So if you have an IDE that relies on Junit descriptions to make its own reporting then we cannot yet passed on T2 information to the IDE. It means that you will have to inspect T2 reports directly without the help of the IDE's post processing.

7.3 Integration with IDE

Because T2 fully integrates with Junit (though as commented above the integration can still be improved), it can be used with any IDE that supports Junit. All you need to do is to include T2-jar in your IDE.

For example I use Netbeans. It comes with a support for Junit, and you can additionally add a code coverage plugin that will also integrate with Junit. Figure 7.1 shows a screen shot of Netbeans. The edit window shows the source of a test class very much like the one in the above example. It has two Junit tests, one with T2, and another an ordinary hand crafted Junit test.

After compiling the test class (F9) we can run it (Shift-F6). Netbeans will implicitly call Junit. It will produce an overview of the result (botton left), where we can which Junit tests succeed and which ones fail. T2 will furthermore send its detailed violations report to the output window at

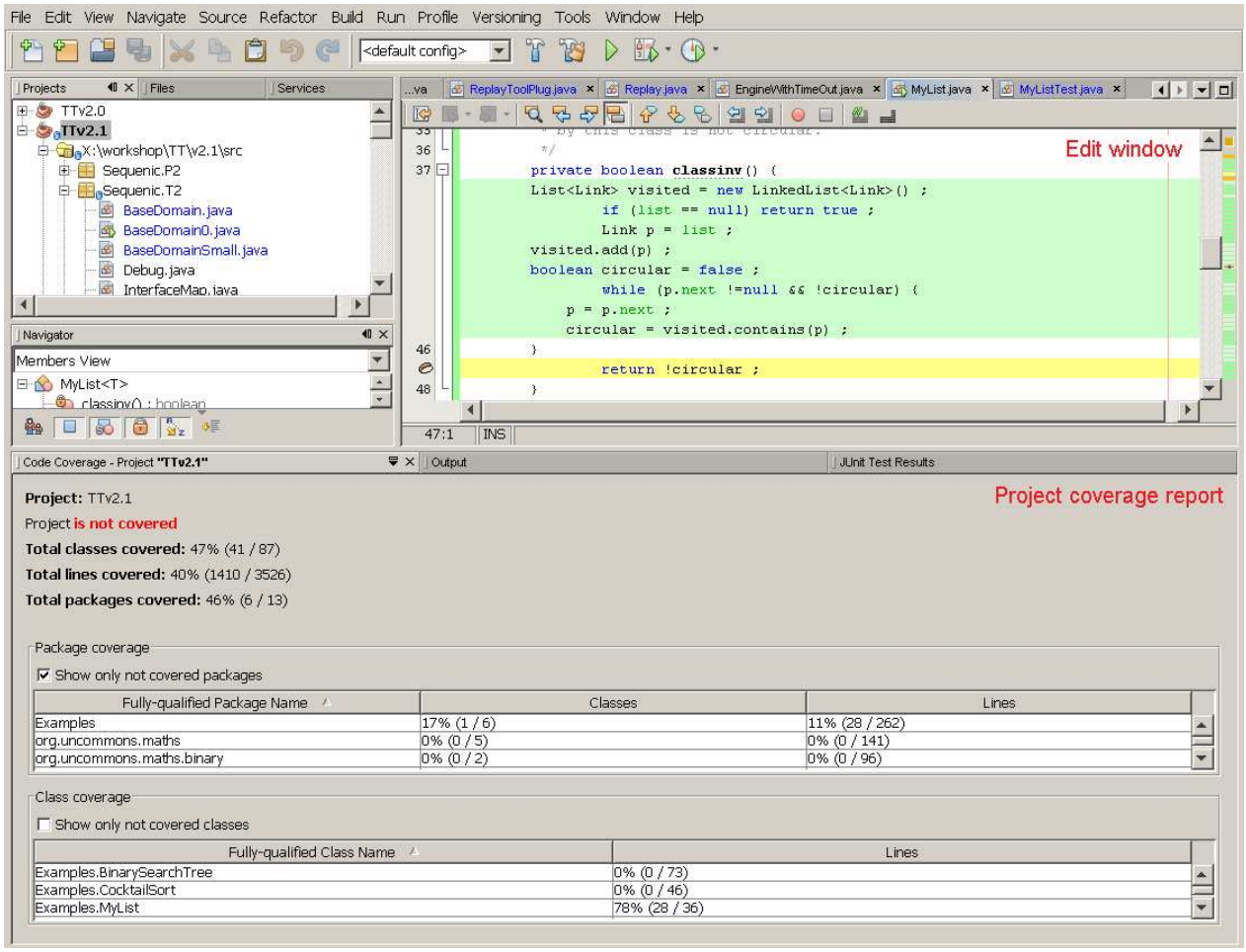


Figure 7.2: Integration with Netbeans also enables us to do coverage evaluation.

the bottom right.

With the coverage plugin (can be downloaded from inside Netbeans itself) we can subsequently evaluate the coverage of our tests. See the screen shot in Figure 7.2. The bottom window show the global coverage report window. It shows us the overall coverage statistics for the entire project, per package, and per class.

Furthermore, when you view the source code in the edit window, we can see in details which parts of the code are not yet covered. Netbeans color fully covered lines with green, uncovered lines with red, and partially covered ones with yellow (so there is one still partially covered line in Figure 7.2).

Chapter 8

Usage and Options

Recall that regardless how we use T2 (e.g. from a console, or from Junit) we always use it through the class `Sequenic.T2.Main`. This class is actually more a *tool box* rather than single tool. We can plugin tools into `Main`. For example by default it contains T2's automated testing tool and T2's replay tool. In the future we may plugin more tools to `Main`. `Main` provides a single entry to all tools provided by T2.

The general use of this `Main` tool box is:

`java -ea -cp` *TT-jar* `Sequenic.T2.Main [`*selector*`]` *Parameters*

TT-jar is the name of your TT jar (e.g. `TT.jar`), possibly prefixed by the path leading to it. A *selector* is used to select a tool. *Paramaters* typically specify a target for the selected tool, plus other options. Parameters are passed to the selected tool. If no selector is given then the default tool will be selected, which is the automatic random testing tool. Available selectors:

1. `-E` to select the random testing tool. This selector can be omitted.
2. `-R` to select the replay tool.
3. `-C` to select the combinatoric testing tool. This combinatorically generates the sequences. See Section 6.4.

The syntax for using T2 as APIs is basically analogous; see Section 8.3.

Printing short help

The following will print a help screen on T2 general use:

`java -cp` *TT-jar* `Sequenic.T2.Main --help`

The following will list available options for the selected tool, along with a short description of each option:

`java -cp` *TT-jar* `Sequenic.T2.Main` *selector* `--help`

8.1 Using the Default Testing Tool

T2's default testing tool is the random testing tool. We can use it through `Main`. The general use is (from console):

`java -ea -cp` *TT-jar* `Sequenic.T2.Main [-E]` *target-class option*`*`

This will apply automated random-based testing on the specified target class. The selector `-E` can be omitted.

The syntax for using T2 as APIs is basically analogous; see Section Section 8.3.

The *target-class* is the name of the target class. The name has to be in Java fully qualified format. E.g. to test the class `Point` from the `java.awt` package you have to pass `java.awt.Point` as *target-class*.

Available options are explained below. Also, rather than passing the options directly to `Main` as above, we can also specify options as annotations in the target class. This is useful because we do not have to keep rembering and retyping a long sequence of options. See Subsection 8.1.10.

8.1.1 Options for controling the main iteration

- `-n` *int* or `--nmax=`*int*

  Set a maximum on the total number of steps (total length) of all test sequences generated by T2. The default is 500.

- `-v` *int* or `--violmax=`*int*

  Set a maximum on the number of violations that T2 will search. When this number is reached, T2 will stop. The default is 1.

  T2 will stop too if `nmax` is reached (see above).

- `--elemty=`*name*

  name is a fully qualified name of a class. Supposed this class is D. Whenever T2 has to supply an instance of the class `Object`, it will now try to generate an instance of D instead.

  Note that if the target class has a method `m(Collection<T> U)`, after the type erasure the type of the parameter `U` becomes `Collection<Object>`. With this option on, T2 will then treat it as if it has the type `Collection<D>`, and will thus try to create a collection of `D`-objects as the parameter for m, when it is needed by a test.

  The default for `elemty` is `Sequenic.T2.OBJECT`, which is a simple class with no field and no method.

- `-l` *int* or `--lenexec=`*int*

  The length of each test sequence. The default is 4.

  All non-violating sequences (except perhaps the last one) will have this length. A violating sequence may be shorter, as T2 will stop the sequence after the violation.

- `--searchmode=`*int*

  Turn on the search mode. See Section 6.3 for more explanation.

  The integer parameter has to be non-negative. It specifies the maximum number of times the current sequence will be retried if it continues to fail a pre-condition.

  Currently the search mode does not work in combination with combinatorial mode.

- `-d` *int* or `--depthobj=`*int*

  When T2 needs to generate a fresh object of class D (so when it cannot or chooses not to take it from the base domain or from the pool), it generates it by calling a construtor of D. If this constructor has parameters, it in turn requires more objects to be generated. So, to generate an object T2 may generate a tree of calls to constructors. The above option set a maximum on the depth of this tree. The default is 4.

- `--maxarraylen=`*int*

  When T2 needs to generate an array, this option sets a maximum of the length of the generated array. If the array has multiple dimentions, the maximum applies to each dimension. The default is 4.

- `--savegoodtr=`*int*

  T2 always save violating sequences. This option will cause T2 to additionaly search up to the specified number of non-violating traces to be saved as well. The default is 0.

- `--savefile=`*name*

  If there are test sequences to be saved, they will now be saved in the specified file. The default savefile is *C*`.tr`.",

- `--timeout=`*int*

  When it is run, T2 will also set an internal timer. When it expires, it will interrupt the test engine and tries to stop it. This is useful to break from a non-terminating method in the target class. Using this option we can manualy set how long this time out is. The default is 20 seconds.

  Setting it to 0 or a negative value will disable the timer.

8.1.2 Options related to reporting

- `--outfile=`*name*

  This will cause the report to be sent to the specified file rather than the console.

- `--silent`

  When set, T2 will not report the execution of violating sequences. It still reports the global statistics.

- `--showdepth=`*int*

  When reporting a violating test, T2 prints the state of the target object after each step, and also the state of the objects passed as parameters to each step. If an object has subobjects, the state of the subobjects will also be printed. This goes on recursively (but T2 can detect cycles), up to the maximum depth set by the above option. The default is 5.

- `--hideintermstep`

  When reporting a violating sequence T2 will normally report every step in the sequence. However, when this option is set intermediate steps will not be reported. Only the creation step, the first step, and the last step in the sequence will be reported.

8.1.3 Options for controling testing scope

- `--ownclassonly`

  If set the T2 will include members of a target class *C* which are really declared in *C* in the testing scope. Inherited members (members of *C*'s superclasses) are excluded.

- `--inclprivate`

  If set T2 will include private members in its scope (so it will also generate calls to private methods and updates to private fields of the target class).

- `--excldefault`

  If set T2 will exclude members with the default access modifier from its scope.

- `--exclprotected`

  If set T2 will exclude members with the protected access modifier from its scope.

- `--pubonly`

  If set T2 will only check public members of the target class. This option overrides `--inclprivate`.

- `--exclstatic`

  If set T2 will exclude static methods from its scope.

- `--exclfield`

  If set T2 will exclude fields from its scope; so, it won't directly update any field (but of course it can still update a field through a method call).

- [`--meth=`*name*]+

  This option can be specified multiple times. It will cause T2 to only test methods whose names are as specified by this option. This option takes options like `--inclprivate` and `--pubonly` into account. So, if m is private, to set T2 to only test it we have to use the combined options:

  ```
  --meth=m  --inclprivate
  ```

  Furthermore, if `--meth` option is present, it will exlcude field updates.

- [`--xmeth=`*name*]+

  This option can be specified multiple times. Methods whose names are as specified by this option will be exlucded from the scope, regardless option like `--inclprivate` or `--meth`.

- `--inclsuperinv`

  Will cause T2 to also check the class invariants of C's superclasses (except `OBject`).

8.1.4 Options for controlling probabilities

The following options control the probabilities with which T2 random test generator takes various decisions, e.g. to generate a null. A probability is specified as a floating number. The probability of a certain decision to be taken is by default uniformly distributed between 0.0 and 1.0; probability 1.0 means that the decision in question will always be taken, probability 0.0 or negative means that it will never be taken.

Although internally we can implement different distributions (e.g. normal instead of uniform), currently we provide no option to let users configure this.

Also please note that options that takes e.g. floating numbers are subject to JVM's default `Locale` setting. E.g. in some Locale 0.99 has to be written as 0,99.

Another thing to keep in mind is the following. We can set e.g. the probability that T2 generates null when it needs to generate an object (e.g. as a parameter to a method call) with the option `nullprob`. E.g. to set this probability to 0.3 we do:

```
java -ea -cp .;TT.jar Sequenic.T2.Main MyClass --nullprob=0.3
```

However, this is not the real probability of generating `null`. At some point internally T2 uses this probability to make a decision as to whether or not it will generate null. However, there may be other points in T2 algorithm where a null can be generated (in fact there are). However, it is still true that sliding `--nullprob` towards 0 would make null rare, and sliding it towards 1 would make it more common.

Now, the list of available probability options:

- `--nullprob=`*float*

  When T2 needs to generate an fresh object, and it does not get it from the base domain, and it decides not to pick it from the pool, then it may choose between generating a fresh object, or generating `null`. This option sets the probability for choosing `null`. Use a negative value to surpress it.

  The default is 0.1.

- `--pickpoolprob=`*float*

  When T2 needs to generate a object, and it does not get it from the base domain, it may either choose to try to take one from the pool, or to generate a fresh object. This option sets the probability to choose for trying the pool. Use negative value surpress it.

  The default is 0.7.

- `--fupdateprob=`*float*

  When T2 generates a test step, it can either choose to update a field (of the target class C), or to call one of C's methods. This option sets the probability to choose field update. Use negative value to surpress it.

  The default is 0.1.

- `--tobjasparam=`*float*

  When T2 generates a test step where it chooses to call a method (of the target class C). If a non-static method is chosen, we can always pass the target object as its receiver. However, sometimes it is also possible to pass the target object as an ordinary parameter of a method. This option sets the probability for choosing a method of the second kind. Use negative value to surpress.

  The default is 0.4.

8.1.5 Using Custom Interface Map

Recall that T2 uses an 'interface map' to map interfaces to their concrete implementations. In general T2 cannot on its own generate instances of an interface of an abstract class, because they have no constructor. The the help of an interface map is needed, to direct T2 to an implementation that does provide a constructor. Furthermore, an interface map can also be used to direct T2 to a custom generator for object generator. See also the explanation in Chapter 6. T2's default interface map is rather minimalistic, but usually sufficient for most purposes. You will have to write your map if you want a more sophisticated one, and pass this to T2.

Changing the interface map

When you need to pass your own custom interface map, set this option:

`--imap=`*name*

where *name* is a fully qualified Java name of the class of your custom interface.

T2 default interface map

The default map is `Sequenic.T2.InterfaceMap0`; it maintains the following mapping:

```
java.lang.Comparable  →  java.lang.Integer
java.util.Collection  →  java.util.LinkedList
java.util.List        →  java.util.LinkedList
java.util.Queue       →  java.util.LinkedList
java.util.Set         →  java.util.HashSet
java.util.Map         →  java.util.HashMap
```

The class implementing this default is `Sequenic.T2.InterfaceMap0`.

Writing a custom interface map

To write a custom interface map you need to subclass the class `InterfaceMap` and provide/overide these members:

1. A public constructor with no parameter.
2. The method `getImplementation` of this type:

   ```
   Class getImplementation(Class I)
   ```

   Given an interface `I` this method should return a concrete class (so, not abstract class) implementing `I`. You can also use an interface map to map a normal class E to its subclass E'. This allows us to implement a custom generator for E in the form of a subclass E'.

8.1.6 Using Custom Base Domain

Recall that T2 uses base domain for generating primitive values and strings. It means that you can also use a base domain to e.g. limit the range of primitive values. You can also use the base domain to hook in a custom object generator, See also the explanation in Chapter 6.

T2 comes with a default base domain; its behavior is explained below. But you can pass your own base domain.

Changing base domain

Use this option to change the base domain:

`--bdomain=`*name*

where *name* is the fully qualified Java name of the class of your base domain.

Default base domain

T2's default base domain is `Sequenic.T2.BaseDomainSmall`; it has the following behavior:

- If an instance of an enumeration type is requested, one will be picked randomly.
- If an instance of a `boolean` or `Boolean` is requested, than true or false will be chosen randomly.
- If an instance of a int-like numeric type (primitive or its wrapper) is requested, a value between -3 upto (and exclusive) $range - 1$ will be picked randomly. The default of *range* is 7.
- If an instance of a float-like numeric type (primitive or its wrapper) is requested, a value between -3 upto (and inclusive) $range - 1$ will be picked randomly.
- If an instance of a `char` or `Character` is requested, one of the following will be chosen randomly: `a`, `A`, , `\n` , `\u0000`, `\uFFFF`.
- If an instance of a `String` is requested, one of the following will be chosen randomly: `""`, `"croco"`, `"TiGeR"`, `"1"`, `"line1 \n line2"`, `"\n \t"`, `"~!@#$%^&*()_-+<>?,.:;'[]{}‘"`, `"\"quote me\""`, `"\""`.
- If a value of a primitive type is requested, this base domain always return a value of its wrapper type.
- The default base domain never returns a null.

Writing a custom base domain

To write a custom base domain you need to subclass the class `Sequenic.T2.BaseDomain` and provide/override these members:

1. A public constructor with no parameter.

2. The method `get` of this type:

   ```
   Object[] get(Class C)
   ```

   This method returns a singleton array (array of size 1) containing an instance of `C`, if `C` is within the scope of your base domain. Else it returns a null. T2 interprets this null to mean that no instance of `C` can be found in your base domain, and thus it will try other means to generate it. Keep in mind that you should only include serializable classes in your base domain.

8.1.7 Using Custom Object Pool

Recall that whenever T2 create a new test sequence, it keeps track of objects it created starting from the creation of the sequence up to the current step of the sequence. The objects are kept in an 'object pool'. When T2 generates the next step, e.g. a method call, it may decide to reuse objects from the pool to pass as parameters to the method.

T2's default pool behaves basically just as a set of objects. It is implemented by the class `Sequenic.T2.Pool`. Customizing it should not be necessary, but there are two situations where you want to do it:

1. T2 requires that sequences do not influence each other. If you target class writes to some static fields or some persistent elements (e.g. a file or a database), then this assumption is broken. A way around it is to reset them before starting a sequence. Since T2 calls the `reset` method of the pool, we can hook in a custom reset by overriding this `reset` method; thus we need to write a custom pool.

2. You want the pool to have some pre-population.

Changing the pool

To change the pool use this option:

```
--pool=name
```

where *name* is the fully qualified Java name of the class of your custom pool.

Writing a custom pool

To write a custom pool you need to subclass the class `Sequenic.T2.Pool`, and provide/override these members:

1. A public constructor with no parameter.

2. The method `void reset()` (whose default behavior is just to emtpy the pool).

8.1.8 Model based testing

By default T2 generates the test sequences purely randomly. However this may not be what we want. T2 can also accept an 'application model'. Such a model provide more direction, as it can specify which next steps are allowed in a particular state. There are two ways to specify an application model: predicative and imperative. Predicative model is more abstract, but in can be expensive in terms of computation. Imperative model is fast, but requires more effort to write. For examples, see Section 9.2.

Models, either predicative or imperative, are written in the target class. However, to use an imperative application model, you also need to tell T2 so. Just turn on this option:

```
--customtracedir
```

8.1.9 Other options

- `--debug`

  Will turn on assertion checking inside T2 itself. Only useful for T2 developers.

8.1.10 Specifying Options as Annotations

Options can also be specified as an annotation on the target class. The name of the annotation is `@T2annotation.option` from the package `Sequenic.T2`. In the exampe below we specify `--pubonly` and `--bdomain` options as an annotation:

```
import Sequenic.T2.* ;

@T2annotation.option("--pubonly --bdomain=MyPackage.BD0")
public class MyClass {

   ...
}
```

Options passed through `@T2annotation.option` will be appended to the options passed from the console.

You can use the annotation `T2annotation.exclude` to specifically exclude one or more members from your testing scope. In the example below, the first constructor will be excluded by T2:

```
import Sequenic.T2.* ;

public class MyClass {

   @T2annotation.exclude
   public MyClass() ...

   public MyClass(int x) ...

   ...
}
```

Members with the `T2annotation.exclude` will be excluded regardless options such as `--inclprivate`.

8.2 Using the replay/regression tool

The replay tool is used to replay saved test sequences. We can call the tool through `Main`; the general use is (from console):

`java -ea -cp` *TT-jar* `Sequenic.T2.Main -R` *save-file option**

The syntax for using it as APIs is basically analogous; see Section Section 8.3.

The *save-file* is the name file in which the test sequences were saved. The file usually has a `.tr` extension.

Available options are listed below.

- `--tmax=`*int*

  Will only replay up to the specified number of sequences. When negative it poses no constraint.

- `--randomtr`

  When set will cause T2 to chose random sequences (from the saved sequences) and replay them. Up to `tmax` number will be selected.

  This option is ignored if `onlyviol` is set.

- `--onlyviol`

  If set, it will cause T2 to only replay sequences which were marked as violating (they were marked so when they were saved).

- `--timeout=`*int*

  Will set a timeout to the specified number (in ms). When this timeout expires T2 will try to kill the test. This mechanism is useful to exit from a possibly non-terminating method in the target class.

- `--showdepth=`*int*

  When reporting a violating test, T2 prints the state of the target object after each step, and also the state of the objects passed as parameters to each step. If an object has subobjects, the state of the subobjects will also be printed. This goes on recursively (but T2 can detect cycles), up to the maximum depth set by the above option. The default is 5.

- `--silent`

  When set, T2 will not report the execution of violating sequences. It still reports the global statistics.

- `--hideintermstep`

  When reporting a violating sequence T2 will normally report every step in the sequence. However, when this option is set intermediate steps will not be reported. Only the creation step, the first step, and the last step in the sequence will be reported.

- `--outfile=`*name*

  This will cause the report to be sent to the specified file rather than the console.

8.3 Using T2 from Java (as API)

So far in this chapter we explained of T2 from console. But we can also use T2 as an API. That is, we want to call T2 from a Java class. This includes calling T2 from your Junit test class. See also the examples in Chapter 7.

The use is completely analogous with the console use. The only thing that is different is that you now need an explicit API to call. There two; both are method of the class `Sequenic.T2.Main`:

1. `static public void main(String parameters)`
2. `static public void Junit(String parameters)`

Both do essentially the same as calling `Sequenic.T2.Main` from a console. Use the `Junit` API to call T2 from inside a Junit test class.

Both APIs above expect a single string. This string is just the arguments that you would otherwise pass to T2 when you use it from console. The sytax of those arguments is exactly the same. So, e.g. if you do this from console:

```
java -ea -cp .;TT.jar Sequenic.T2.Main MyClass --violmax=10
```

Then this is how you call the API `Junit` from your Junit test class:

```
public class myJUnitTest {
   ...
   @Test
   void test1(){
      ...
      Sequenic.T2.Main.Junit(MyClass.class.getName() + " --violmax=10") ;
   }
}
```

Also keep in mind that T2 requires the JVM flag `-ea` to be turned-on. So when you run Junit to execute the above class, you also need to turn on the `-ea` flag.

8.4 Using the Combinatoric Testing Tool

The combinatoric testing tool can generate all possible the test sequences up to a certain length —see also Section 6.4. The tool can be called through `Main`; the general use is (from console):

`java -ea -cp` *TT-jar* `Sequenic.T2.Main -C` *target-class option*`*`

This will apply combinatoric-based testing on the specified target class.

The syntax for using it as APIs is basically analogous; see Section Section 8.3.

The *target-class* is the name of the target class. The name has to be in Java fully qualified format. This convention is the same as with the default testing tool. Available options are the same as with the default tool (Section 8.1), except the following.

The engine will try to generate all possible sequences of length as specified by the `--lenexec` option (or its default if it is not specified). It will however stop generating if the number of steps has reached tt –nmax (or its default if it is not specified).

As explained in Section 8.3, the arguments passed to the steps in the sequences are still generated randomly.

The engine will also duplicate each sequence `--dup` number of times (or its default, if it is not specified). For each duplicate, the arguments are generated randomly.

Chapter 9

More Advanced Specifications

9.1 Some useful specification patterns

Specifying collection-like structures

Suppose we have this class `Club`:

```
public class Club {

   Set<Member> members ;
   ...
   public boolean cleanup() { ... }
}
```

The method `cleanup` removes all 'inactive' members. Suppose we want to explicitly express this in a specification. This is how we can code the specification in Java:

```
public class Club {

   Set<Member> members ;
   ...

   public boolean cleanup() { ... }

   cleanup_spec() {
      // Call the specified method:
      boolean result = cleanup() ;
      // Specify that after cleanup there is no inactive members left:
      for (Member m : members) assert m.active ;
      return result ;
   }
}
```

Using freeze variables

Consider again the `Club` example above. Suppose now that as part of the post-condition we also want to say that `cleanup` returns true if it removed at least one member, and otherwise false. It is probably easier to express this specification as an assertion in the method `cleanup` itself. However, suppose that for some reason we do not want to do that. Expressing this in `cleanup_spec` requires a bit more effort. We need to know e.g. how many members were there before we call `cleanup`. However, in the post-condition we will lose this information. We can get around this by introducing local variables that 'freeze' the old values of our variables (before the call). For our example, this willl do:

```
   cleanup_spec() {
      // Freezing initial size of members:
      int oldsize = members.size() ;

      // Call the specified method:
      boolean result = cleanup() ;

      // Now, specify the post-condition:

      assert return = members.size() < oldsize ;
      for (Member m : members) assert m.active ;

      return result ;
   }
}
```

Variables like `oldsize` above, because of their role, are called *freeze variables*.

Specifying state after exception

Suppose the class `Club` also has a method `readFromFile`:

```
public class Club {

   Set<Member> members ;
   ...
   public void readFromFile(File f) throws IOException { ... }
}
```

This method `readFromFile` reads new members data from the specified file and add them to the `members` list. However it should only do so if it can successfully read the file. So, if an `IOException` is thrown, then `members` should not change. We can express this by the following specification:

```
   public void readFromFile_spec(File f) throws IOException {
        // Freeze the initial size of members:
        int oldsize = members.size() ;
```

```
        // Call the specified method:
        try { readFromFile(f) ; }
        catch(IOException e) {
            // Now specify what to expect when IOException is thrown:
            assert members.size == oldsize ;
            throw e ;
        }
    }
```

The specification is partial, because it doesn't really say that `members` does not change. It just says that its size does not change. We can express a more complete specification if we want to; I leave it to you as an exercise ☺.

9.2 Model-based Testing

By default T2 generates the sequences randomly. In many cases this works pretty well. But there are cases where we want to have more control. For example suppose we have a class `Buffer` with two methods `put` and `get`. Suppose we expect that any application that uses `Buffer` will only call its methods in this order:

`put`; `get`, `put`, `get`, ...

So, a sequence like `get`, `get` is not an allowed sequence. In practice an assumption like this is often left implicit, or if documented it is only informally documented.

In any case, when we want to generate specific patterns of sequence, pure random generation may not be the most efficient way to do it.

What we can do is to write a 'model' of the proper use of our class, and use this model to provide more direction in generating test sequences. This is also called *model based* testing. We will also call such a model an *application model*.

From T2 perspective you do not have to supply a complete application model (in other words you may give T2 an under specified model). T2 sees it simply as a mechanism that determines which members of the target class are in scope to be selected for the next test step.

You have two ways to specify an application model: predicatively, or imperatively.

9.2.1 Predicative Application Model

A predicative application model express the model as a predicate. T2 uses this predicate to filter the sequences it generate; thus dropping those sequences that do not satisfy the predicate. The advantage of this kind of model is that it is more abstract (than imperative models). The disadvantage is that this way of generating sequences can be inefficient (which is the case if the predicate is very hard to satisfy).

As an example, consider the following simple class:

```
public class Simple {

   public int x = 0 ;

   public void inc() { x++ ; }
   public void dec() { x-- ; }

   private boolean classinv() { return x>=0 ; }

}
```

The specification of this class is expressed by a simple class invariant requiring `x`$\geq$`0`. You can immediately see that this will be a problem. However, suppose we assume that an application using this class should not set the value of `x` to a negative value; nor should it call a method of `Simple` that can cause `x` to be negative. Under this assumption, the above specification makes sense.

Now to make T2 to take this assumption into account, we need to make it explicit and we need a mechanism to inform it to T2. We express such an assumption in an *application model*. That is, such a model express the proper way for an environment or an application of a target class to use the class. E.g. it may put constraints on the sequence of the methods to call, or constraints on parameters passed to them, etc.

A predicative application model is checked after each test step (including after the first step that creates the target object for the current sequence). Because T2 calls the method `classinv` after each test step, we can therefore insert our application model inside `classinv`. However, keep in mind that despite its placement inside `classinv`, an application model is *not* a class invariant. Anyway, to make this clearer here is now how we can express the above application model in `classinv`:

```
public class Simple {

   public int x = 0 ;

   public void inc() { x++ ; }
   public void dec() { x-- ; }

   private boolean classinv() {
      assert x>=0 : "APPMODEL" ; // a simple application model
      return return x>=0 ;
   }
}
```

Notice that `classinv` contains now contains an assertion `x`$\geq$`0`, tagged with the APPMODEL marker. This informs T2 that the assertion should be interpreted as an (predicative) application model. When T2 checks `classinv`, and discovers that its APPMODEL is violated, then it simply *drops* the current test sequence. Such a sequence violates our application model, and thus is not an allowed use of the target class. There is no point to test such a sequence.

The above application model will prevent T2 from generating test sequences on `Simple` that will make `x` to become negative.

Now let's try a bit more sophisticated application model. Suppose we want to enforce that T2 only generates alternating sequences of `inc`, `dec`, `inc`, ... So we want to write an application model that imposes this sequencing. We need an additional mechanism to do it; it is called *slot variable*.

A target class may declare one or more slot variables. These are private variables with some pre-defined names and types. T2 fills these variables with its run time information. One of the slot variable is `aux_laststep` of type `String`.

After each test step, T2 will put a string identifying this step in this variable. If the step was a method call, then the name of this method will be put; if it was a field update, then the name of the field will be put. The only exception is the creation step (the step that starts a sequence). A creation step is always a call to the constructor of the target class. T2 will then put the (fully qualified name) of the target class in `aux_laststep`.

So, by looking at the value of this variable the target class can infer what the last test step was in T2, and based on this information its application model can determine what the possible next steps are. Now consider this application model:

```
public class Simple {

   public int x = 0 ;

   public void inc() { x++ ; }
   public void dec() { x-- ; }

   private String aux_laststep ; // declaring a slot variable
   private int    aux_k = 0    ; // an auxilliary variable

   private boolean classinv() {
      if (aux_k == 1) assert aux_laststep.equals("inc") : "APPMODEL" ;
      if (aux_k == 2) assert aux_laststep.equals("dec") : "APPMODEL" ;
      if (aux_k < 2) aux_k++ ; else aux_k-- ;
      return x>=0 ;
   }
}
```

Another mechanism involved here is *auxilliary variable*. T2 will not mess with any variable/field whose name starts with `aux_`. These variables are considered to be part of some specifications.

The auxilliary variable `aux_k` above acts like an internal state of our application model. It has thus three states: 0,1,2. State 0 is used to identify the starting state. After that the model goes alternatingly between the state 1 and state 2. The model above imposes that when it is in state 1, then the test step that brings the model to this state should be `inc`, and otherwise it should be `dec`. Effectively this will filter the sequences generated by T2 so that only alternating sequences of the form `inc`, `dec`, `inc`, ... will be considered.

This works, but it can also be problematic. Suppose you have instructed T2 to create sequences of length 4 (it's the default btw). Under the hood T2 still generates the sequences randomly. It justs uses the application model to filter out meaningless sequences. However, the chance of sucessfully creating an alternating sequence `inc`, `dec`, `inc`, ... of length 4 is only 1/16, which is a bit small, but it still doable. However if you now request sequences of length 10, the odd will be very small (2/1024).

Specifying an application model using predicates (the APPMODEL assertions) as above is more abstract; but in terms of performance it can be quite bad.

9.2.2 Imperative Application Model

There is another way to write an application model: the imperative way. The idea is to explicitly specify which methods can be called in the next step. This must be programmed in this method in the target class:

```
private List < Method > customTraceDirector()
```

This method is also called *trace director*. When T2 is called with the `--customtracedir` option set, it will drop its own algorithm for generating sequences. Instead, it uses the trace director that you wrote. That is, whenever T2 wants to construct the next test step, it calls `customTraceDirector`. This returns a list of methods. One will then chosen randomly, and it is then taken as the next test step. So, the trace director now fully dictates the generation of the sequences. T2 still controls the generation of the parameters supplied to the methods in those sequences.

To write a trace director you also have to know a little meta programming in Java (programming with reflection).

As an example let's try to rewrite the application model from the previous subsection. It is the one that generates alternating sequences `inc`, `dec`, `inc`, ... for the class `Simple`. Let's now rewrite it in the imperative style:

```
import java.util.* ;
import java.lang.reflect.* ;

public class Simple {

   public int x = 0 ;

   public void inc() { x++ ; }
   public void dec() { x-- ; }

   public boolean classinv(){ return x>=0 ; }

   static private Method INC ; // Meta representation of the method 'inc'
   static private Method DEC ; // Meta representation of the method 'dec'

   {  // Setup INC and DEC:
       try {
           INC = ImperativeAppModelDemo.class.getDeclaredMethod("inc", new Class[0]) ;
           DEC = ImperativeAppModelDemo.class.getDeclaredMethod("dec", new Class[0]) ;
       }
       catch (Exception e) { }
   }

   private List<Method> aux_nextsteps = new LinkedList<Method>() ;
   private int aux_k = 0    ; // a help variable

   // The application model is here:

   private List<Method> customTraceDirector() {
      aux_nextsteps.clear() ;
      if (aux_k == 0) aux_nextsteps.add(INC) ; else aux_nextsteps.add(DEC) ;
      aux_k = (aux_k+1) % 2 ;
      return aux_nextsteps ;
   }
}
```

So we see above that `classinv` is restored to be as it was originally; we insert no boiler code there now.

However now we must specify an explicit trace director (in the method `customTraceDirector`). We use the variables `INC` and `DEC`; these are meta representations for the methods `inc` and `dec`. In the trace director we specify that at one time only `INC` is possible, and at the next time only `DEC`.

The obvious thing to notice above is that we have more boiler plates. But on the other hand it is very efficient. Unlike the predicative style, it will have no problem generating an alternating sequence of any length.

9.3 Specifying Temporal Properties

With a bit extra work we can also use T2 to check temporal properties. A temporal property is a property of an object over time. In many formal frameworks, temporal properties are often associated with concurrent systems. It is true that many interesting properties of concurrent systems are temporal. These would be beyond T2's power, since it can test concurrent threads. However, we can also express temporal properties of a sequential system. 'Temporal' simply means that they are time related.

Linear temporal properties are properties defined in terms of *sequences of states* that are observable during the execution of a system. For example we may want to express that if p holds on some state in a sequence, then q should hold on the next state. Since T2 also generates sequences, we may wonder if can use it to check linear temporal properties. To some extend we can.

We will need to fix the concept of 'sequences' over which we will interpret our temporal properties: our sequences are sequences of field updates and method calls. So, the kind of sequences generated by T2. More precisely, our temporal properties are interpreted over the sequences of observable states induced by T2 sequences. The states we consider *observable* are the states after each step in a test. In particular, the states of a target object during a method execution (that is, its states as we are still *inside* the method) are considered as not observable. Its states just before and after the call are observable.

Stringly speaking, temporal properties are properties over infinite sequences. In general they cannot be directly checked, because T2 cannot generate infinite sequences. However we can do a trick common in LTL (linear time temporal logic) model checking: we can convert it to an automaton (called *Buchi automaton*, also known as *never claim*) which can be checked over finite sequences.

Not all temporal properties require Buchi encoding though. Some can be translated quite easily to a class invariant. Here is a simple example. This class `Simple` maintains a private integer variable `x` and a private boolean variable `open`. The user of this class can call `inc` or `dec` on a `Simple` object to increase or decrease the value of its `x`. However, once he calls `close` the state of this object will freeze (it won't change anymore).

```
private int x = 0;
    private boolean open = true;

    public void inc() { if (open) x++; }
    public void dec() { if (open) x--; }

    public void close() { if (open) open=false ; }
}
```

Suppose we want to express the following temporal property. In LYL notation it would be expressed as follows:

$$\Box(\neg open \ \wedge \ (x = N) \quad \rightarrow \quad \circ(\neg open \ \wedge \ x = N))$$

for all N.

It says that once `open` becomes false, it will remain false, and furthermore the value of `x` will not change anymore.

The implicit quantification over N is a bit problem. The straight forward implementation of this will require us to to test the property for various N. Let's introduce new variables that will

record the 'previous value' of `open` and `x`. With these variables we can re-express the property as below. This time we have no quantification:

$$\Box(\neg open\_old \;\; \rightarrow \;\; (\neg open \;\wedge\; x = x\_old))$$

Furthermore, `open_old` should be initialized to true. Such a property can actually be directly encoded as a class invariant. We only need to additionally take care of the proper update of 'old' variables.

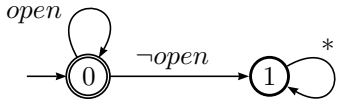
```
public class Simple {

    private int x = 0;
    private boolean open = true;

    public void inc() { if (open) x++; }
    public void dec() { if (open) x--; }

    public void close() { if (open) open=false ; }

    // Defining old-variables:
    private boolean aux_open_old;
    private int aux_x_old;

    // A check to temporal spec is encoded in the class invariant:

    private boolean classinv() {
        // Evaluate the property:
        boolean ok = aux_open_old || (!open && (x == aux_x_old)) ;
        // Update the old-vars:
        aux_open_old = open;
        aux_x_old = x;
        // Return the value of the property (true or not):
        return ok;
    }
}
```

Let's now try something more complicated. We want to check if our `Simple` class satisfies this property (in LTL):

$$\Diamond(\neg \texttt{open})$$

You can probably already see that this is not a valid property of `Simple`. But our concern now is more on how to express this property in Java.

Unlike the previous property, this one cannot be straight forwardly converted into a class invariant. For this property we need to convert it first to a Buchi automaton:



State 0 is marked as a so-called 'accepting' state. For us it is used as the state that would mark a violation; so the term 'error' state is perhaps better. However, the notion of violation in a Buchi automaton is that of ω-violation. That is, a sequence is a violating sequence if it visits the

error state infinitely many times. This implies that if we can detect a cycle that goes through an error state, then we have detected a violation.

Now, let us implement this checking in Java —see below. The implementation maintains the variable `aux_state` which keeps track in which state in the Buchi automaton above we are currently in. It maintains a history of the states of the target object. However, we do not actually store full images of the states; we just store their hashcode. This is very efficient, but incomplete due to hash collisions. Moreover, it also depends on the specific implementation of the method `hashCode()`. It uses this history to check cycle.

```
public class Simple{

    private int x = 0;
    private boolean open = true;

    public void inc() { if (open) x++; }
    public void dec() { if (open) x--; }

    public void close() { if (open) open=false ; }

    // Defining auxiliary variables
    private List<Integer> aux_history = new LinkedList<Integer>() ;
    private int aux_state = 0 ;
    static private final int ERROR_STATE = 0 ;

    private boolean classinv() {
        boolean violation = false ;
        // If we're in an error state, check cycle:
        if (aux_state == ERROR_STATE) violation = aux_history.contains(hashCode()) ;
        // Update Buchi state:
        if (aux_state==0 && !open) aux_state=1 ;
        // Update history:
        if (aux_state == ERROR_STATE) aux_history.add(hashCode()) ;
        // Returning the result of checking:
        return !violation ;
    }
}
```

Note that this approach requires you to first convert your temporal property to a Buchi automaton. The resulting automaton can be quite elaborate; so you may want to use a tool to automate the conversion. There are some tools out there that can do this; but probably there is none that can directly convert it to Java. Currently T2 also provides no support here. Future work :)

9.3.1 Stutter Insensitive Property

A temporal property ϕ is called stutter insentitive if it cannot be violated by a step that does nothing (skip). For example $(x{=}0) \rightarrow \circ(x{=}0 \vee y{=}0)$ is stutter insensitive, but $(x{=}0) \rightarrow \circ(x{=}1)$ is not.

You should only specify a temporal property which is stutter insentitive. Otherwise it does not make much sense, because it forces the environment of an object to do something that changes the object's state, whereas in general an object usually can't force its environment to make an action.

Chapter 10

Pluging Custom Object Generators

Consider the following class `Person` that uses the class `PhoneNumber`:

```
public class Person {
   String name ;
   Set<PhoneNumber> pnumbers ;

   ...

   addNewNumber(PhoneNumber n) {
      assert n.isValid : "PRE" ;
      pnumbers.add(n) ;
   }

   private boolean classinv() {
      for (PhoneNumber n: pnmubers) assert n.isValid() ;
      return true ;
   }
}

public class PhoneNumber {
   String nationCode ;
   String areaCode ;
   String nr ;

   public PhoneNumber(String number) {
      String[] parts = number.split("-") ;
      assert parts.length == 3 : "PRE" ;
      nationCode = parts[0] ; areaCode = parts[1] ; nr = parts[2] ;
   }

   public boolean isValid() ;
}
```

The class invariant of `Person` requires that all phone numbers in the set `pnumbers` are valid numbers. For this reason we have to guard the method `addNewNumber` with a pre-condition that the new number must be a valid number. This however creates a problem when testing the

class `Person`. Given the definition of the class `PhoneNumber` it is very hard for T2 random-based algorithm to generate valid phone numbers. It would have to do so via the constructor of `PhoneNumber`, for which T2 has to pass a single string. But it has to be a string in a certain format to make a valid phone number, of which T2 has totally no knowledge of.

This is a very typical problem in testing. T2 will need your help to solve this. You will have to come up with a custom `PhoneNumber` generator (either by writing it yourself or by using some library). You will also have to somehow hook this custom generator in T2. There are several ways to do this, I'll just explain here the easiest way to do it.

Just for the sake of example, let's now write a very simple `PhoneNumber` generator. The easiest way to hook this in to T2 is by implementing the generator as a subclass of `PhoneNumber`:

```
public class PhoneNumberGenerator extends PhoneNumber {

   static String[] data = { "031-20-334221", "021-62-111111", "001-06-112221" }

   @Sequenic.T2.T2annotation.exclude
   PhoneNumberGenerator(String number) { super(number) ; }

   public PhoneNumberGenerator(int pickone) {
      this(data[pickone % 3]) ;
   }
}
```

Assuming the phone numbers listed in `data` are valid numbers, the constructor of this generator always produces `PhoneNumber` objects satisfying the `isValid` predicate.

To actually plug this generator in T2 we still to take few more extra steps. When T2 has to generate an object of class D, recall that it first consults its interface map (Chapter 6). If the map maps D to E, then T2 proceed by trying to generate an object of class E instead. This is now the mechanism that we are going to use to reroute the generation of `PhoneNumber` to `PhoneNumberGenerator`. We need to add the mapping:

`PhoneNumber` $\mapsto$ `PhoneNumberGenerator`

to the interface map. However you not allowed to mess up with T2's internal state. Instead, the way to do it is to first define your own interface map, that includes the above mapping, and then pass this map as an option to T2. We'll do this by subclassing T2's default interface map, which is the class `InterfaceMap0`:

```
public class MyInterfaceMap extends InterfaceMap0 {

   public MyInterfaceMap() { super() ; }

   public Class getImplementation(Class D) {
     if (D == PhoneNumber.class) return PhoneNumberGenerator.class ;
     else return super.getImplementation(D) ;
   }
}
```

The custom interface map needs to implement a non-argument constructor, and the method `getImplementation`. Next we need to pass the above class `MyInterfaceMap` to T2 when we test our target class, which is `Person`. So, we do:

```
java -ea -cp TT.jar Sequenic.T2.Main Person --imap=MyInterfaceMap
```

Note: you may need to specify the fully qualified name of `Person` and `MyInterfaceMap` if they are part of some packages.

That's it. Now T2 will use your `PhoneNumberGenerator` for generating `PhoneNumber` objects.

Note however, that T2 does not look in its interface map when it wants to generate an instance of the target class. So, even if your interface map contains a mapping from `Person` to `PersonGenerator`, this generator will not be used. The rationale behind this is that when testing `Person` it would be part of the testing job to test whether its constructors produce 'valid' persons.

Chapter 11

Dealing with Persistent Components

A *persistent component* is a state carrying component of a program that remains to exists over multiple executions of the program. A file or a database are typical examples thereof.

There are a number of problems in testing a class that uses persistent components. The first problem is that of generation. If a method if our testing scope takes a file as an argument, T2 will have to generate a file when it calls the method in a test sequence. If the method expects e.g. a HTML file, a pure random generation ala T2 will be very ineffective.

An HTML file does not contain an arbitrary string, but a string with a very specific format. Fortunately, T2 allows you to plug in custom generators (Chapter 10). Of course this still means that someone has to provide those generators.

The second problem is specific T2. T2 assumes that test sequences do not interfere with each other. This is a very crucial assumption (Chapter 6). Using a persistent object may break this assumption. This happens e.g. when a sequence reads from a file, which has been updated by an earlier sequence.

In order not to break the assumption you must reset all the persistent components at the beginning of every sequence. Fortunately this can be done without having to hack into T2. When T2 is about to create a new sequence it always 'reset' its object pool. This is done by calling the method `reset()` of the pool. Since T2 allows us to replace its default pool with a custom pool, we can use this mechanism for reseting the persistent components.

Consider this simple class `Thermometer` below. It has a method `log` that will log the value of the temperature at that moment to some log file. This value will be *appended* to the file. Just to make it simple we hard-code the name of this file, which is `mylog`.

```
import java.io.* ;

public class Thermometer {
    int temperature ;
    FileWriter fw ;

    public Thermometer() {
        try { fw = new FileWriter("mylog",true) ; }
        catch (Exception e) { }
    }

    ... // other members

    public void log(){
```

```
        try { fw.write(":" + temperature) ; fw.flush() ; }
        catch (Exception e) { }
    }
}
```

Running T2 to test this class raises a problem. Values appended by a sequence to `mylog` will be carried over to the next sequence; thus breaking T2's non-inteference assumption.

This problem can be solved by reseting the content `mylog` to some fix value whenever we start a new sequence. This makes sure that a sequence won't influence the next ones through this file. We do this by subclassing `Pool`, and implement our reset procedure in its `reset` method:

```
public class MyPool {

   public MyPool() { super() ; }

   public void reset() {
      // This will do to empty the file:
      try { new FileWriter("mylog") ; }
      catch (Exception e) { }
      super.reset() ;
  }
}
```

Now we only need to pass the above class `MyPool` to T2 to test `Simple`, which we can do it like this:

```
java -ea -cp TT.jar Sequenic.T2.Main Thermometer --pool=MyPool
```