1. Introduction
The Java language and runtime environment has had a profound worldwide impact on computer software since its introduction nearly two decades ago. It has enabled the creation of a rich ecosystem of libraries, frameworks, and tools that promises to deliver significant value for many years to come. Consequently, a wide range of Interactive Development Environments (IDEs) have emerged to increase the productivity of Java programmers. They vary in functionality based on the expertise level assumed for their target user base. The Eclipse Java Development Tools (JDT) project offers a rich set of power tools for experienced programmers, but can be harder for novice programmers to set up and use. In contrast, IDEs such as DrJava [2] and BlueJ [16] have been developed primarily for use in introductory programming courses.

In this tool demonstration paper, we summarize the DrHJ tool which will be demonstrated at the conference. In anticipation of the need for introducing parallelism earlier in the Computer Science curriculum, DrHJ extends DrJava with support for the pedagogic Habanero Java (HJ) parallel programming language that was derived from the earlier Java-based definition of the X10 language [4]. DrHJ builds on our past experiences at Rice with developing the DrJava IDE and the HJ language. DrJava is used by many universities world-wide, and has been downloaded over 1.1 million times since its inception in 2002.

The rest of the paper is organized as follows. Sections 2 and 3 summarize the DrJava IDE and the HJ language respectively. Section 4 describes how DrJava was extended to support HJ. In addition to implementing a plug-in extension for HJ in DrJava, DrHJ also includes a data race detection tool for a subset of the HJ language. Finally, Section 5 summarizes current status and future work items for DrHJ.

2. Overview of DrJava
DrJava is a free, open-source lightweight IDE for Java. It is designed primarily for students, providing an intuitive interface and the ability to interactively evaluate Java code in an Interactions Pane. It also includes powerful features for more advanced users, enabling (for example) the DrJava team to develop DrJava completely within DrJava.

The development of DrJava began in 2001, with the first release in Spring 2002 [2]. It was designed to support techniques popularized as “Extreme Programming” [10, 11], e.g., support for test-driven development using JUnit is fully incorporated into the IDE. From the beginning, DrJava supported Java programs that used generic types, which was a novel feature at the time. Later in the evolution of DrJava, support for Java generics was also added to the Interactions Pane.

DrJava’s Interactions Pane integrates well with the included source-level debugger and allows users to not only examine and modify variables when a breakpoint is hit, but also to invoke methods and execute complex programs in the Interactions Pane’s interpreter. After the addition of a project facility in 2004 and improved support for large projects in 2006, DrJava experienced a sharp increase in popularity.

In 2005, DrJava introduced support for a hierarchy of Java language levels, a pedagogic framework that helps beginners learn Java by partitioning the language into levels of increasing syntactic complexity [9]. The language levels are not mere subsets of Java. The levels restrict the use of some Java constructs, such as imperative loops, arrays, exceptions, but they also perform code augmentation by adding necessary modifiers to fields and methods; generating code for constructors; generating code for accessor methods; and generating code for to_string, equals, and hash_code methods. Recently, the language level facility has been simplified to provide a more flexible language level that combines the previous elementary and intermediate levels. We call this language level Functional Java because it disallows mutation and focuses on computation over immutable algebraic data types.

DrJava is a cross-platform application available for Windows, Mac OS and Linux. The IDE supports several different Java compilers, including Oracle/Sun’s JDK, OpenJDK, the Eclipse Java Compiler, as well as research compilers such as NextGen [17], Java Mint [20], and now HJ as well.

DrJava is still under active development by the JavaPLT group at Rice University. Since the inception of the DrJava project, it has been downloaded over 1.1 million times and is being used by many universities world-wide. DrJava has also been used as a teaching tool in books published by Pearson Education and Wiley Higher Education.

3. Habanero Java
The Habanero Java (HJ) language [8] was developed at Rice University during 2007-2010 as a pedagogic extension to the original Java-based definition of the X10 language [4]. In addition to its use as a research language in the Rice Habanero Multicore Software research project [7], HJ is used in a new sophomore-level course on

1 See http://x10-lang.org for the latest version of X10.
“Fundamentals of Parallel Programming” (COMP 322 [1]) which has become a required course for all Computer Science majors at Rice. The current HJ implementation supports Java v1.4 as its base language, though sequential2 code in Java 5/6/7 libraries and classes can be called from HJ programs. The HJ runtime system is fully compatible with the latest Java release, but the Polyglot-based [14] HJ front-end does not currently support generics; support for Java generics and annotations in the HJ front-end is currently in progress. The code generated by the HJ compiler consists of Java classes that can be executed on any standard JVM.

The HJ extensions to Java are primarily focused on task parallelism. Similar extensions to C and Scala are being pursued in the Habanero C and Habanero Scala projects at Rice. A brief summary of the most commonly-used HJ constructs is included below. (A notable omission due to space limitation is places [4, 21], which is used to teach students about data locality and task affinity.) Additional details on HJ can be found in [3] and [1].

1) async: Async is a construct for creating a new asynchronous task. The statement async stmt causes the parent task to create a new child task to execute stmt logically in parallel with the parent task. stmt is permitted to read/write any data in the heap and to read (but not write) any local variable belonging to the parent task’s lexical environment.

HJ also includes support for async tasks with return values in the form of futures. The statement “final future<T> f = async<Expr>” creates a new child task to evaluate Expr that is ready to execute immediately. In this case, f contains a “future handle” to the newly created task and the operation f.get() (also known as a force operation) can be performed to obtain the result of the future task. If the future task has not completed as yet, the task performing the f.get() operation blocks until the result of Expr becomes available. Future tasks are especially well-suited for introducing parallelism in the context of Functional Java.

2) finish: The statement finish stmt causes the parent task to execute stmt and then wait until all sub-tasks created within stmt have terminated (including transitively spawned tasks). Operationally, each statement executed in an HJ task has a unique Immediately Enclosing Finish (IEF) statement instance [18].

3) isolated: The isolated construct isolated stmt enables execution of a statement stmt in isolation (mutual exclusion) relative to all other instances of isolated statements. As advocated by Larus and Rajwar [12], we use the isolated keyword instead of atomic to make explicit the fact that the construct supports weak isolation rather than strong atomicity. Commutative operations, such as updates to histogram tables or insertions into a shared data structure, are a natural fit for isolated blocks executed by multiple tasks in deterministic parallel programs. Towards the end of the COMP 322 course, the students are taught how certain patterns of isolated statements can be replaced by calls to java.util.concurrent (j.u.c.) libraries for atomic variables and concurrent collections.

4) phasers: The phaser construct [18] integrates collective and point-to-point synchronization by giving each task the option of registering with a phaser in signal-only/wait-only mode for producer/consumer synchronization or signal-wait mode for barrier synchronization. These properties, along with the generality of dynamic parallelism, phase-ordering and deadlock-freedom safety properties, distinguish phasers from synchronization constructs in past work including barriers [6] and X10’s clocks [4]. The latest release of j.u.c in Java 7 includes Phaser synchronizer objects, which are derived in part [13] from the phaser construct in HJ.

```java
finish {
    phaser[] ph = new phaser[n+2];
    for (int j = 0; j< n+1; j++) ph[j] = new phaser();
    for (int j = 1; j< n; j++)
            for (iter = 0; iter < NUM_ITERS; iter++) {
                temp = newA; newA = oldA; oldA = temp;
                next;
            }
        }
    }
```

Figure 1. One-Dimensional Iterative Averaging using Phasors for Point-to-Point Synchronization

(The j.u.c Phaser class only supports a subset of the functionality available in HJ phasers.)

In general, a task may be registered on multiple phasers, and a phaser may have multiple tasks registered on it. Three key phaser operations are:

• new: When a task A, performs a new phaser() operation, it results in the creation of a new phaser ph such that A is registered with ph in the signal-wait mode (by default).

• registration: The statement, async phased (ph1(model1), ph2(model2), ...) (stmt), creates a child task that is registered on phaser ph1 with model1, phaser ph2 with model2, etc. The child task’s registrations must be subset of the parent task’s registrations.

• next: The next operation has the effect of advancing each phaser on which the invoking task A, is registered on to its next phase, thereby synchronizing all tasks registered on the same phaser. In addition, a next statement for phasers can optionally include a single statement, next (stmt2). This guarantees that the statement (stmt2) is executed exactly once during the phase transition [18, 22].

Figure 1 shows an iterative averaging example to illustrate the power of using phasors for point-to-point synchronization. The forasync pattern creates a parallel loop in which each j-iteration executes a separate task. Phasers are used to orchestrate interactions among those tasks. In this example, task Ti is registered on three phasers — ph[j] in signal-only mode and ph[j-1] & ph[j+1] in wait-only mode. Note that phasers gracefully handle boundary conditions that often arise in point-to-point synchronization. For example, the wait operations on ph[0] ph[n+1] by task Ti-m becomes a no-op, because there is no task registered on ph[0] ph[n+1] with signal capability.

5) forall: The statement forall(point p : R) stmt supports parallel iteration over all the points in region R by launching each iteration as a separate async, and including an implicit finish to wait for all of the spawned asyncs to terminate. A point is an element of an n-dimensional Cartesian space (n ≥ 1) with integer-valued coordinates. A region is a set of points, and can be used to specify an array allocation or an iteration range as in the case of async.

Each dynamic instance of a forall statement includes an implicit phaser object (let us call it ph) that is set up so that all iterations in the forall are registered on ph in signal-wait mode3. Since the scope of ph is limited to the implicit finish in the forall, the parent task will drop its registration on ph after all the forall iterations are created.

4. DrHJ

DrHJ is an extension of the DrJava IDE developed at Rice University that supports the HJ language. It was used in laboratory

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2 Some concurrency constructs of Java can interfere with the HJ runtime system; however, we allow the use of non-blocking calls to the j.u.c. libraries, e.g. to ConcurrentHashMap and atomic variables.

3For readers familiar with the foreach statement in X10 and HJ, one way to relate forall to foreach is to think of forall (stmt) as syntactic sugar for “ph=new phaser(); finish foreach phased (ph) (stmt)”.

In DrHJ, we distinguish between the main JVM that executes the DrHJ IDE, and the "Interpreter JVM" that executes HJ applications. DrHJ’s main JVM communicates with the Interpreter JVM using Java’s Remote Method Invocation (RMI) API. When the user instructs DrHJ to run a program, an RMI invocation triggers the execution of the program in the Interpreter JVM. Any output produced by the Interpreter JVM is forwarded back to DrHJ to be displayed in the Interactions Pane. Decoupling program execution from DrHJ provides a better user experience by preventing critical errors such as out of memory conditions from impacting the IDE.

DrHJ also includes a tool to detect data races in HJ programs, based on the ESP-bags algorithm developed for HJ [15]. The ESP-bags algorithm is a generalization of the SP-bags algorithm developed for Cilk’s spawn and sync constructs [5]. Like SP-bags, ESP-bags works by following a depth-first execution of a sequentialized version of the parallel program. (The extensions in ESP-bags were necessary because the set of computation graphs generated by async-finish constructs in HJ is more general than the graphs generated by spawn-sync constructs in Cilk.) As a result, the DrHJ data race detector is that it uses the depth-first execution to report all potential races that may be encountered across all task schedules for a given input.

Figure 3 shows a screenshot of the DrHJ GUI for a simple program ArraySum.hj, that attempts to use two tasks to sum the elements of an array. The child async task in lines 50–54 computes the sum of elements $X[0...mid]$ in $X[0]$. The parent task computes the sum of elements $X[mid...n-1]$ in $X[mid]$ in parallel with the child task, and then adds $X[0]$ and $X[mid]$ in line 60 after the finish statement which ensures the completion of the child task. However, this code contains an error because $X[mid]$ is read by the child task, and is also read and written by the parent task. This error is detected as a data race by DrHJ, as shown in the Interactions Pane in Figure 3. The error report includes the source coordinates for the two conflicting accesses as well as the index of the array location on which the race occurs.

5. Current Status and Future Work

The DrHJ IDE currently supports the following features as extensions to DrJava:

- Selection of the HJ compiler, which can be either bundled in the same jar file or specified using the HJ_HOME environment variable.

- Editing of HJ source files with syntax highlighting for HJ constructs.

- Compilation of HJ source files.

- Execution of HJ programs in the Interactions Pane.

- Race detection option: when enabled, DrHJ compiles and runs HJ programs with data race detection turned on.

Topics for future work include:

- Supporting interpreted HJ constructs in the Interactions Pane. Currently, the Interactions Pane can invoke code (e.g., a method call) containing HJ constructs, but the HJ constructs cannot be interpreted directly in the Interactions Pane.

- Transferring HJ compilation error messages from the console pane to the error pane. DrJava typically displays compiler errors

4 Support for implementing hyperlinks from the source coordinates in this error message to the source locations in the Definitions Pane is in progress.
in an error pane, but HJ compilation errors are currently only printed in the console.

- Creating a dedicated Race Detection Pane to display data race errors in HJ programs.

In summary, the combination of the popular DrJava IDE and the high-level HJ parallel programming language enabled us to create a tool suitable for use by undergraduate sophomores in a new introductory parallel programming course at Rice University. The integration of a data-race detection tool with DrJava provides students with a powerful tool to create, edit, test, and debug parallel programs for laboratory and programming assignments in the course.

References


