Views: Object-Inspired Concurrency Control

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ABSTRACT
We present views, a new approach to controlling concurrency. Fine-grained locking is often necessary to increase concurrency. Correctly implementing fine-grained locking with today’s concurrency primitives can be challenging—race conditions often plague programs with sophisticated locking schemes. Views ease the task of implementing sophisticated locking schemes and provide static checks to automatically detect many data races.

Views consist of view declarations that describe which views of an object may be simultaneously held by different threads, which object fields may be accessed through a given view, and which methods can be called through a given view. A set of view annotations specify which code regions hold a view of an object. Our view compiler performs simple static checks which eliminate many data races.

We have ported three benchmark applications to use views: portions of Vuze, a BitTorrent client; Mailpuccino, a graphical e-mail client; and TupleSoup, a database. Our experience indicates that views are easy to use, make implementing sophisticated locking schemes simple, and can help eliminate concurrency bugs.

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1. INTRODUCTION
With the wide-scale deployment of multi-core processors, developers must write parallel software to realize the benefits of continued improvements in microprocessors. Using existing concurrency primitives such as locks can be difficult and error-prone, since these primitives force developers to specify implementation, not policy. Currently, developers must manually and painstakingly state how locking is to be implemented in a software system, not why locks exist.

This paper presents a new approach to concurrency control. Instead of providing low-level concurrency primitives, our approach raises the abstraction level of concurrency control to the level of object interfaces. A view specifies both a partial object interface and a list of incompatible object views. A partial object interface lists a subset of the object’s methods and fields; a thread must hold the given view to access the part of the object’s interface protected by the view. Additionally, the view mechanism provides concurrency control by enforcing incompatibility of views—two views are incompatible if two different threads cannot simultaneously hold the two views on the same object.

Views have two primary benefits. First, views enable developers to easily implement sophisticated concurrency control mechanisms which can maximize an application’s concurrency. Views accomplish this goal by providing a simple language mechanism which allows developers to protect subsets of an object’s fields and methods. They also provide a uniform mechanism which supports advanced concurrency primitives such as read-write locks. Second, views can statically detect many data races. Our view compiler can analyze view specifications and objects’ uses of views to detect and warn about possible race conditions and unprotected field and method accesses.

1.1 Contributions
This paper makes the following contributions:

• View Concept: It presents a new concurrency primitive that expresses concurrency control as acquisition of partial object interfaces, or views. Views provide a simple, natural abstraction that support a wide range of advanced locking approaches. Views make the connection between the concurrency primitive and the data it protects explicit.

• Automatic Lock Synthesis: It presents an algorithm that uses standard locks to implement views. Our compiler uses a greedy algorithm to synthesize an optimized implementation of views using locks.

• Static Checking: It presents several static checks that automatically detect possible concurrency bugs. These checks can detect view specifications that allow race conditions on data. These checks can also detect field and method accesses in which the developer neglected to acquire the proper object view.
Experience with Views: It presents our experience porting three significant benchmarks to use views. This experience indicates that it is relatively simple to use views, that views make supporting advanced locking straightforward, and that views can help to statically detect potential concurrency bugs.

The remainder of the paper is structured as follows. Section 2 presents an example to illustrate our approach. Section 3 presents the view extensions to Java. Section 4 describes how we compile views. Section 5 presents our experience using views with three existing applications. Section 6 discusses related work. Finally, Section 7 concludes.

2. EXAMPLE

We present an example that illustrates the use of views. Figure 1 presents a single-threaded implementation of the Vector class. This Vector class contains a set() method to set elements of the vector, a get() method which returns the current value of an element, and a resize() method which resizes the Vector. We omit remove() for space reasons; its implementation would mirror that of resize().

Views consist of two parts: view declarations, which identify the members of each view, and view annotations to Java source code, which acquire views as needed throughout the implementation. Figure 2 presents modifications to lines 28 through 31 of the existing Vector code to support views. Figure 3 presents view declarations for Vector.

2.1 View Annotations

Our system allows threads to acquire views in two ways: 1) a thread may explicitly acquire a view using the acquire statement, and 2) a thread may implicitly acquire a view by calling a preferred method.

The statement acquire(this@resize) in Figure 2 causes the thread to acquire the resize view of the object referenced by this before executing lines 29–30 and then to release this view in line 31. Note how acquire generalizes Java’s synchronized construct. The relevant view declaration (see below) explains what the view protects.

When a thread makes a call to a preferred method, such as get() for the read view, without already holding a view that provides access to that method, the thread will automatically acquire the appropriate view and then execute the method. A non-preferred method is only callable by threads that already hold a view that contains the method.

2.2 View Declarations

Figure 3 declares five views: read, write, xclRead, resize and capacity. Each view, except resize and xclRead, corresponds to a method of Vector, and states the fields and methods required to execute that method. The views xclRead and resize support the resize() operation’s two phases—an exclusive-read phase, in which resize() copies the Vector’s contents, followed by the resize phase, which atomically writes to the Vector.

View declarations include a view’s name and its body. Figure 3 begins with the read view. A view body first lists views that are incompatible with the current view. For example, line 2 declares that the read view is incompatible with the write and resize views: no thread may acquire an object’s read view while any other thread holds the write or resize views of that object.

The view’s body also contains the view’s field and method declarations. A field declaration begins with a comma-separated list of fields followed by an access description. Field access descriptions are one of none, readonly, or readwrite. Line 3 declares that threads holding the read view of a Vector object may read its size, capacity, and array fields. Note that the readonly declaration ensures read-only access to the field in the same sense as the Java final modifier: it does not prevent line 18 of Vector from writing to the Vector’s underlying array object, but only prevents writes of the array field itself. A method declaration gives the method’s name and the types of its parameters, optionally followed by the keyword preferred. Line 4 declares that the read view contains the get() method with an integer parameter as a preferred member.
2.3 Checking Views

We have implemented an extension to the Polyglot extensible compiler framework [14] to support view annotations, prevent incorrect accesses to view-protected object interfaces, and generate executable code from the view-annotated sources. The compilation process proceeds in three steps. First, the compiler verifies that a program properly uses view declarations, as described below. Next, it uses the view declarations to synthesize a lock allocation: the acquisition of each view corresponds to the acquisition of a set of locks. Finally, it uses the lock allocation to generate code.

We next describe how our view compiler works on our Vector example on a method-by-method basis. The compiler grants constructors full access to objects. We expect developers to follow the standard practice of not exposing the object being constructed in the constructor.

The compiler next verifies that the get( ) and set( ) methods respect the view declaration. The compiler observes that the get( ) method accesses the size and array fields of the this object. Both of the fields have readonly view. Because the get( ) method belongs only to the read view, this must have the read view inside get( ), so the compiler accepts these reads of size and array. The fact that get( ) is a preferred method is irrelevant to checking the implementation of get( )—it only affects callers to get( ), which will automatically acquire the read view if they do not already possess it. The verification of set( ) proceeds similarly. However, the compiler also checks that the write view possesses write permissions for the size field. (Recall that set( ) does not require write permissions to array because it is not assigning to the array field itself, only to the array object.) Additionally, because set( ) calls the capacity( ) method, the compiler checks that the write view contains the capacity( ) method. All checks succeed in our example.

We finally discuss how the compiler verifies the resize( ) method. Note that we chose not to add the resize method to the resize view. Because resize( ) belongs to the xclRead view, the compiler permits the read of field array on line 26. The method then explicitly acquires the resize view on line 28 of the modified version of Vector, granting it permission to write to the array, capacity, and size fields. No other thread may execute any method of Vector in parallel with the resize view—a thread attempting to access the Vector must wait until the resize completes.

2.4 Code Generation

To generate code, the compiler must be able to reason about relationships between views, since these relationships determine the set of locks that it must create. It therefore starts by generating a view incompatibility graph. Figure 4 presents the incompatibility graph G for our running example. Graph vertices represent views, while edges between two views indicate that they are incompatible. Dotted lines represent cliques. The edge in G between the read vertex and the write vertex implies incompatibility of the read and write views.

Given an incompatibility graph, the lock synthesis algorithm allocates locks by finding a clique covering of the graph: we will associate a lock with each clique. To acquire a view, a thread must acquire locks for all cliques that the view belongs to. The compiler uses read-write locks\(^1\). The compiler correctly displays an error message if resize( ) does not belong to any view granting access to array, as in an earlier version of this paper.

\(^1\)A read-write lock [12] can be held by any number of threads in read mode but by only one thread in write mode.
when a clique has exactly one view \( v \) which is compatible with itself. Such a situation indicates that \( v \) allows concurrent access to the resource being protected (corresponding to the read mode of the read-write lock), while any views \( v' \) in the same clique require exclusive access to the resource (write mode). If no views in a clique are compatible with themselves, the compiler uses an ordinary (exclusive) lock.

In our example, the three cliques \( C_1 = \{\text{read}, \text{write}, \text{resize}\} \), \( C_2 = \{\text{write}, \text{resize}, \text{xxlRead}\} \), and \( C_3 = \{\text{capacity}, \text{resize}\} \) cover the graph \( G \). The compiler therefore generates three locks, \( \ell_1 \), \( \ell_2 \), and \( \ell_3 \), one per clique. Cliques \( C_1 \) and \( C_3 \) contain exactly one view which is compatible with itself, so the compiler uses read-write locks for them. A thread may acquire the capacity view by acquiring \( \ell_3 \) in read mode, since capacity is compatible with itself; similarly, it may acquire read by acquiring \( \ell_1 \) in read mode. A thread may acquire write by acquiring \( \ell_1 \) in write mode (since write is incompatible with itself) as well as the ordinary lock \( \ell_2 \). To acquire the resize view, a thread must acquire write locks on both \( \ell_1 \) and \( \ell_3 \), plus \( \ell_2 \).

The compiler generates code by applying the lock allocation to the view acquisition statements. Intuitively, the compiler will translate a statement like acquire(this@resize) into a virtual call to a method on this which acquires the resize view by requesting the proper locks as per the lock allocation; the virtual call ensures that the thread gets the appropriate locks for the runtime type of this, in the presence of inheritance.

To handle preferred methods, the compiler generates a wrapper for the method which requests the view and delegates to the original implementation. In our example, the compiler renames the preferred method get() to get$view() and generates a new wrapper get(), which will hold the read view for the duration of the call to get$view(). Should a caller to get() already hold the read view, the compiler simply generates a call to the original method get$view() instead of calling the wrapper.

3. VIEW LANGUAGE EXTENSIONS

Figure 5 presents the grammar for view declarations, while Figure 6 presents the syntax extensions to Java for view annotations. As seen in Section 2, view declarations contain a list of incompatible views followed by a list of view members, which may be fields or methods. Field members have associated access descriptions (none, readonly or readwrite). Developers must unambiguously identify methods belonging to a view, and may optionally specify that a method is preferred for a view. We support two kinds of view annotations in Java code: 1) types may be decorated with views (i.e. Vector@get); and 2) our new acquire statement generalizes Java’s synchronized statement.

4. COMPILING VIEWS

We next describe in detail how we type check views, check consistent use of views, and automatically generate a locking strategy that enforces view incompatibility constraints.

4.1 View Types

We have extended the Java type system to support view types for method parameters and local variable declarations. A view type consists of a pair of a reference type and view. For example, the view type Vector@write indicates a reference to a Vector object for which the executing thread holds the write view. The type checker does not allow a local variable or a method parameter with a non-base view type to be re-assigned to reference a different object.

The type view of the this variable of a virtual method \( m \) is equal to the set of views that contain the method \( m \). The type checker must ensure that fields and methods accessed through the this variable are permitted by all views that declare the method.

Both the left and right hand sides of assignments to local variables or method formal parameters with view types must have the exact same view type. New views of an object can only be acquired through an explicit acquire or through an implicit acquisition via a call to a preferred method of a view. A method may not have a view type as its return type, nor may fields or arrays have view types. Collectively, these constraints ensure that threads cannot hold a view reference to an object after the release of a view acquired through an acquire statement or a preferred method.

4.2 Static Checks

Compilation begins with several static checks on the view specifications, field accesses, and method calls. Our compiler performs the following checks on the view declarations:

- **Read/Write Hazards on Fields**: For each pair of compatible views \( (v_1, v_2) \) and each field \( f \), the com-
pilier flags the field \( f \) if \( v_1 \) has write access to the field \( f \) and \( v_2 \) has read or write access to \( f \). If a view is compatible with itself, this check flags all fields that are declared readwrite. Uncontrolled access to flagged fields may lead to race conditions. However, we anticipate that developers may choose to use external locks or other mechanisms to protect such fields. The compiler therefore only produces warning messages for the read/write hazards that it detects.

- **Field Read Checks:** For each field read \( x.f \), the compiler checks that all possible views of the receiver expression \( x \) allow reads of field \( f \).

- **Field Write Checks:** For each field write \( x.f = y \), the compiler checks that all possible views of the receiver expression \( x \) allow writes of field \( f \).

- **Method Call Checks:** For each method call site \( x.m(a_1, \ldots, a_N) \) to method \( m(f_1, \ldots, f_N) \), the compiler checks that each argument \( a_i \) at the call site matches the view type of the corresponding method formal parameter \( f_i \), if \( f_i \) has a view type. The compiler also checks that the view of the reference to the receiver object \( x \) contains \( m \) or that \( m \) has a preferred view.

- **Assignments:** The compiler checks that the program does not make assignments to local variables or method formal parameters with view types other than their initial declarations.

- **Field Inheritance Check:** The compiler ensure that an object’s fields cannot be accessed through upcasts, in violation of view constraints. To ensure field access safety, the compiler checks that if a field \( f \) is declared in a super class of \( C \) and is a member of a view \( v \) in the super class, then field \( f \) must be a member of view \( v \) in class \( C \), with at least as permissive access.

- **Method Inheritance Check:** The compiler must ensure that methods cannot be accessed through upcasts in violation of view constraints. To ensure method invocation safety, the compiler checks that if a method \( m \) is declared in a super class of \( C \) and is a member of a view \( v \) in the super class, then method \( m \) must also be a member of view \( v \) in class \( C \), with at least as permissive access. We make an exception to this check when \( v \) is the base view, if \( m \) has a preferred view in class \( C \). Note that if a method \( m \) is declared in an interface that class \( C \) implements, the method \( m \) must either be in the base view of class \( C \) or have a preferred view in class \( C \).

It is possible that a call to method \( o.m() \) may occur such that the declared type of \( o \) would require acquiring a preferred view to call \( m() \), but the run-time type of \( o \) indicates that the executing thread must already hold the appropriate view. In this case, a dynamic check would avoid needlessly acquiring the preferred view.

### 4.3 Lock Synthesis

We next describe how we synthesize a locking strategy that enforces the view incompatibility specification. For each class, the lock synthesis algorithm begins by constructing an undirected view incompatibility graph \( G \). The graph \( G \) contains a vertex \( v \) for each view in \( C \). For each pair of views \( v_1 \) and \( v_2 \), if \( v_1 \) lists \( v_2 \) as incompatible, or \( v_1 \) lists \( v_2 \) as incompatible, \( G \) contains an edge between \( v_1 \) and \( v_2 \).

Consider a subgraph \( G_C \) of \( G \) that is a clique—that is, \( G_C \) contains edges between every pair of vertices in \( G_C \). One lock can enforce all of the view incompatibility constraints between views in \( G_C \). Because views can be incompatible with themselves, self-edges may occur in the view incompatibility graph. We handle self-edges by using different kinds of locks. If all views but one in the clique have self-edges, we use an implementation of a reentrant read-write lock for the clique; we identify the read mode of the read-write lock with the view with no self-edges, and the write mode with all other views in the clique. This corresponds to the situation where any number of threads may hold view \( v \) with no self-edges, but only one thread may hold a view \( v' \) with self-edges or any of the views \( v'' \) that are incompatible with \( v' \). If all views in the clique contain self-edges, then we use the normal reentrant lock class from java.util.concurrent.locks. If more than one view in the same clique lacks a self-edge (which we expect to be rare in practice—views without self-edges typically only read data, so two views without self-edges should typically not conflict with each other), we would use a generalized implementation of a read-write lock which would permit multiple mutually-incompatible read locks and a single write lock.

The lock synthesis algorithm computes a clique cover of \( G \). Minimizing the number of cliques in the cover minimizes the number of locks we must generate and the number of locks that must be acquired in a view. However, finding a minimum clique covering for a graph is an NP-complete problem [10]. We therefore use a greedy algorithm to compute a non-minimal clique covering in polynomial time. Our greedy algorithm selects an uncovered edge to cover to start the clique and adds vertices that will cover other uncovered edges. We expect that, in practice, many view incompatibility specifications will be simple enough that our greedy algorithm will generate a minimal covering.

### 4.4 Acquiring Views

We next describe how the compiled application acquires and releases views at runtime. For each view, the compiler generates three view acquisition methods: the tryacquireView method tries to acquire the view, the acquireView method acquires the view, and the releaseView method releases the view.

To acquire view \( v \), a thread must acquire all of the locks for \( v \). If \( v \) has a self edge in the incompatibility graph, the thread must acquire all readwrite locks in write mode and lock the normal reentrant locks. If \( v \) does not have a self edge, the thread must acquire all locks, which will be readwrite locks, in read mode. The tryacquireView method tries to acquire each lock. If it successfully acquires all locks, it returns true. If it fails to acquire any of the locks, it releases the locks it has already acquired, and returns false.

The acquireView method must block until it can ac-
public void acquireView() {
    int startindex = 0;
    while (true) {
        // Block on the first lock
        switch (startindex) {
            case 0:
                lock0.lock();
                break;
            ...
            case n-1:
                lock(n-1).lock();
                break;
        }
        // Try to acquire the rest of the locks
        int i;
        for (i=0; i<n; i++) {
            if (!lock0.trylock()) {
                break loop;
                break;
            }
            if (!lock(n-1).trylock()) {
                break loop;
                break;
            }
        }
        // Return if we hold all locks
        if (i == n)
            return;
        // Release locks if we failed to get one
        int unlockindex = startindex;
        for (; i>0; i--) {
            if ((--unlockindex) < 0)
                unlockindex = n-1;
            switch (unlockindex) {
                case 0:
                    lock0.unlock();
                    break;
                case n-1:
                    lock(n-1).unlock();
                    break;
            }
            // Repeat, trying to first blocking-acquire
            // the lock that we failed to get this time.
        }
    }
}

Figure 7: Locking Code to Acquire A View.

Releasing views is straightforward: the releaseView methods simply releases all locks corresponding to a view.

4.5 Simultaneously Acquiring Multiple Views

Our language supports simultaneously acquiring multiple views. We expect that developers will find this mechanism useful for locking multiple shared data structures while avoiding the possibility of deadlock. The generated code for acquiring multiple views would use the same basic strategy as the code in Figure 7 does on component locks, but instead uses this strategy on views.

4.6 Defaults

We have carefully designed the defaults for views to minimize instrumentation overhead. Our compiler automatically generates the base view if the developer does not explicitly declare a base view, according to the following rules:

1. A field is present in the base view with readwrite access if no other view declares that field.
2. A method is present in the base view if no other view declares that method.

Object constructors often write to many object fields that would be protected by views and call methods that require access to views. If treated like other methods, object constructors would have to acquire a number of views to access these fields. However, it is relatively rare for object constructors to make the object being constructed accessible to other threads before the constructor exits. Our implementation therefore allows the constructor to access fields and methods of the object being constructed without holding the necessary views. We believe that this is a reasonable tradeoff between usability and detecting possible races.

5. EXPERIENCE

We next discuss our experience adding views to several applications: Vuze, a file-sharing (BitTorrent) client; Mailpucino, a graphical e-mail client; and TupleSoup, a database.

5.1 Methodology

We have developed a prototype implementation of views as an extension to the Polyglot extensible compiler infrastructure [14]. The source code for our extension is available at http://demsy.eecs.uci.edu/views/.

5.2 Vuze Buddy Plugin

Our first benchmark is a subsystem of the open-source Vuze file-sharing client. The source distribution of Vuze is available at http://azureus.sourceforge.net. While Vuze contains 194,000 lines of code in all, we chose to concentrate on the buddy plugin of Vuze, which consists of 13,500 lines of code. This plugin is implemented in the com.aelitis.azureus.plugins.net.buddy package.

Parts of the buddy plugin contain a rich locking structure. After inspecting the code, we chose to annotate the BuddyPluginTracker and BuddyPlugin classes. The
other classes in the plugin use locking solely to protect data structure accesses: before an access to a non-thread-safe data structure (typically a Map or List), Vuze acquires the lock on that data structure. Views interoperate smoothly with ordinary Java synchronized statements implementing such simple locking strategies.

**BuddyPlugin annotations.**

We added 4 views to BuddyPlugin: general read and write views `read_state` and `write_state`, for mutable fields previously protected by the lock on the BuddyPlugin object itself (i.e., `synchronized(this)`), as well as views to protect the `pd_queue` and `publish_write_contacts` data structures. Our compiler found a few field reads that were inconsistently unprotected in the original code. Our change preserves the existing lock structure and also provides static guarantees that the program doesn’t attempt to access protected state without the protecting lock.

**BuddyPluginTracker annotations.**

We found that the `track.BuddyPluginTracker` class contained the most interesting locking structure in the buddy plugin. This class contains 5 different locks: `online_buddies`, `actively_tracking`, `tracked_downloads`, `buddy_peers`, and on the object itself. We carefully studied the fields that the class accessed under each lock and encoded this information in our view declarations.

Figure 9 presents the view declarations for the `track.BuddyPluginTracker` class. We converted the 5 locks into 6 views, splitting accesses to this into read-only and read-write views `read_internal_state` and `write_internal_state`, respectively, and changing the other locks into views.

The `actively_tracking` view protects access to the `actively_tracking` Set. Its access pattern is similar to that of the other data structures in the buddy plugin.

The `online_buddies` view protects two correlated data structures: the `online_buddies` Set and the `online_buddy_ips` Map. Our view annotations therefore express the formerly-implicit connection between the `online_buddies` lock and the `online_buddy_ips` data structure and statically ensure that the program always follows the proper locking discipline.

The `tracked_downloads` field protects six related fields, including two sets and two maps. In the original version of the BuddyPluginTracker, the application always acquired the `tracked_downloads` lock before accessing any of these fields.

Finally, the three views `read_internal_state`, `write_internal_state` and `buddy_peers` all protect miscellaneous internal state of the `BuddyPluginTracker`. Both the `write_internal_state` and `buddy_peers` views provide write access to different parts of the tracker. The `read_internal_state` view is not incompatible with itself, so multiple threads may simultaneously read internal state. Each of the `write_views` is incompatible with itself and with the `read_internal_state` view.

We found that views enable developers to confidently use fine-grained concurrency patterns. Using the view declarations, our compiler statically verifies that the code always acquires the appropriate locks.

### 5.3 Mailpuccino

Mailpuccino is an open-source graphical mail client written in Java that supports the POP3 and IMAP protocols. Mailpuccino is available at http://www.kingkongs.org/mailpuccino/. It contains over 14,000 lines of code.

Mailpuccino maintains separate cache data structures for the message headers, message flags, message parts, and the message structure. The locking for the original cache objects used synchronized methods. The original coarse-grained locking structure only allowed one thread to read from the message cache at a time.

Figure 10 presents the views that we wrote for Mailpuccino’s `Cache` object. We created four views in all, belonging to two sets of two views each.

The first set of views includes the `lookup` view and `modify` view for the Mailpuccino cache. The `lookup` view provides read-only access, enabling methods to safely read the cache, while the `modify` view provides read-write access, allowing methods to safely modify the cache. Multiple threads may simultaneously read from `Cache` objects, so the `lookup` view is compatible with itself. However, while any thread is modifying the `Cache` object, no other threads can safely access that `Cache` object at the same time. Therefore, the `modify` view is incompatible with both itself and the `lookup` view. Note that our set of views enables the `Cache` object to potentially support multiple simultaneous lookup operations.

The second set of views includes the `file` and `indexfile` views. Each cache is backed by two files: the `DataFile` file and its index, `IndexFile`. Cache misses are served from these files. While the `lookup` view conceptually protects these accesses and prevents simultaneous writes, Java’s `RandomAccessFile` object does not support atomic reads from a specific file offset, so Mailpuccino performs a seek followed by a read. We must therefore ensure
Figure 9: Views for BuddyPluginTracker class.

that no other thread accesses the file object between the seek and the read operations. To do so, we created two more views to protect the file objects. Only threads which have acquired these self-incompatible views may access the fields that reference the corresponding files. This ensures that only one thread may seek and read from a file at a time. While we have described our changes to Cache, we also modified the MsgPartsCache class in a similar fashion.

We next modified the synchronized methods in the MonitorInputStream class to use views. This class contained two synchronized methods: the mark method and the reset method. The “synchronized” annotations led us to believe, at first, that the class was designed to be safely shared between threads. The mark and reset methods access only two fields: MarkedBytesRead and BytesRead. We wrote a view that allowed access to these fields and added the mark and reset methods to the view.

At this point, we believed that we had distilled MonitorInputStream’s old synchronization pattern into views. We therefore attempted to compile the modified class. Surprisingly, the compiler threw error messages warn-

Figure 10: Mailpuccino Cache Views

ing that MonitorInputStream’s read method accesses the ByteRead field without holding an appropriate view. However, the read method contained no synchronization! Closer examination revealed that the MonitorInputStream class is not thread safe and its mark and reset methods are never called. We modified the class to remove these methods and added comments to make it clear that the class is not thread safe.

5.4 TupleSoup

TupleSoup is an open-source database library written in Java. TupleSoup is available at http://sourceforge.net/projects/tuplesoup/. TupleSoup contains over 6,600 lines of code. We rewrote all of the synchronization in TupleSoup to use views.

TupleSoup contains three index classes: a MemoryIndex class, a PageIndex class, and a FlatIndex class. The original index classes only permitted one thread to search the index at a time. We created two views per index class: an access view and a modifying view. Multiple threads can simultaneously hold the access view. If one thread holds the modifying view of an index, no other thread can hold the modifying or access views of the index.

The DualFileTable class implements a cached table backed by two separate files. The original version of DualFileTable contained four separate locks: one lock for each of the two data files, a lock for the cache, and a lock for the statistics counters. We first examined the code to see if we could modify the class to allow multiple simultaneous calls to the getCacheEntry cache lookup method. Unfortunately, this method actually mutates a list of least-recently-used cache entries that is used to determine which entries to evict. Therefore, it is not safe to allow multiple
threads to simultaneously call the `getCacheEntry` method.

We finally used a straightforward translation to views, shown in Figure 11, which replaces each lock with a corresponding view, and synchronized methods with preferred views for methods. Such a translation is quite straightforward to carry out and enables developers to explicitly express the correlations between fields that the locking structure implicitly encoded. In other words, the views explicitly label the data that each lock protects, and our view compiler provides static assurances that the code never accesses protected fields without holding an appropriate view.

5.5 Discussion

We used the following process for annotating an existing class with views. First, we studied an existing class’s locking structure. Next, we proposed a view structure which would protect a related group of fields and methods, typically with a read-only view for accessing state and a read-write view for updating state. We fed this view structure to our compiler, which guaranteed that accesses to protected fields and methods only occur when holding appropriate views.

We found that it was straightforward to replace the traditional Java locking structure with view acquisitions; it sufficed to replace `synchronized(x)` with `acquire(x@v)` and synchronized methods with preferred view methods. Each benchmark took a couple of hours to annotate; the crux was in understanding the existing locking structures.

Our process typically results in an application with increased potential for concurrency. Many of our annotated benchmarks allow multiple threads to simultaneously read state, while ensuring that only one thread can write state.

6. RELATED WORK

We discuss three threads of work related to expressing Java concurrency patterns: type systems which ensure the absence of races; static and dynamic race detection tools; and automatic generation of locking schemes.

Many teams have developed different type systems which ensure that well-typed programs are free of data races. Boyapati, Lee and Rinard have developed type systems which ensure the absence of data races by tracking object ownership [3, 2]. Abadi, Flanagan and Freund have developed RaceFreeJava [7], where developers associate a lock with each shared field and express this information via the type system; the compiler infers additional type annotations and verifies that programs conform to the specified type-based discipline. Bacon, Strom and Tauraflar propose the Guava race-free dialect of Java [1], which forces all members of shared objects to synchronize. Views generalize RaceFreeJava by allowing developers to specify the locking policy for a set of related fields and methods, not just for one field at a time as in the RaceFreeJava case. That is, views allow developers to explicitly express, in one place, the state and methods protected by each lock. Moreover, unlike previous approaches, views are not limited to using simple Java locks to guarantee race-freedom; they can leverage read-write locks and other more sophisticated approaches to concurrency control. Views provide developers with a flexible mechanism that can be used to implement sophisticated approaches to concurrency control.

An alternate approach to statically ensuring that programs are free of races is to detect these races, either statically or dynamically. The Eraser dynamic race detection tool computes lock sets for memory locations and warns if a memory location is not protected by a lock [15]. Choi et al. have developed a runtime approach that records access events and uses several optimizations to minimize overheads [4]. Marino et al’s LiteRace tool uses sampling to minimize overheads [13]. Other dynamic approaches use static analysis to lower the instrumentation overhead [17]. While dynamic race detection is useful, it requires adequate test suites to detect bugs. RacerX instead uses interprocedural static analysis to detect race conditions and deadlocks [6]. Other static analysis include Warlock [16] and Sema [11]. Race detection tools are, in general, useful for detecting bugs in programs. However, they provide developers with little guidance about which fields need to be protected by locks. Any solution requires developers to formulate a suitable concurrency control policy for their system. Views enable developers to express concurrency control policies; the compiler then automatically compiles a mechanism for implementing the policy. Views therefore differ from race detection and race-free type systems approaches because those approaches only verify that implemented solutions are free of races.

Another technique related to ours is that of automatically generating locking schemes for critical regions [8, 5, 9]. Typically, such approaches allow developers to specify critical or atomic sections of their programs. Zhang et al. state a minimal lock assignment problem that is similar to the problem...
of lock synthesis for views, but differs in that it contains information about non-conflicting critical sections that are never executed concurrently and therefore can share locks without limiting concurrency [18]. This body of work must rely on static analysis to generate locks and therefore may generate overly conservative locking schemes. Furthermore, this work does not attempt to detect possible data races arising from accessing shared state outside of critical regions. Views instead start with a data-centric approach: developers declare certain fields (and methods) as belonging to a view, and specify when threads acquire views; the compiler then ensures that the program always acquires appropriate views, and synthesizes a locking strategy which respects the view annotations.

7. CONCLUSION

Views can be an effective tool for implementing sophisticated concurrency control and statically detecting possible concurrency bugs. A developer using views writes a set of view declarations and annotates code with view acquisitions. A view declaration describes which views of an object may be simultaneously held by different threads and the parts of the object interface that the view controls. The partial object interface specifies which fields can be read, which fields can be written, and which methods can be called through the view. Our compiler performs static checks of the view specifications and the program’s use of views to detect many concurrency bugs. Our compiler automatically synthesizes a locking scheme that enforces the view compatibility constraints. Our experience indicates that views are simple to program with, support sophisticated fine-grained access control, and can detect concurrency bugs. Our approach promises to ease the difficult task of implementing locking schemes for fine-grained concurrency.

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8. REFERENCES