Views: Specifying Locks by Policy, not Implementation

Patrick Lam
University of Waterloo
http://patricklam.ca

Joint work with Brian Demsky (UC Irvine)

Problem

Current locking mechanisms are hard to use.

Problems

- can’t express why locks exist;
- no way to express fine-grained locking;
- no guarantee that locks are consistently applied.

Goal

Raise abstraction level of concurrency control primitives.

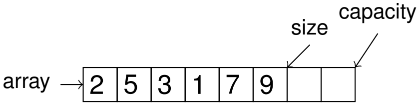
Subgoals

Support object-oriented design principles.

Support fine-grained locking at language level.

Support static checking to help catch concurrency bugs.

Array-Based Vector Implementation



Vector class definition

Vector
size : int
capacity : int
array : int[]

Rule: must hold owning lock to access "array".

Basic Approach: Compiler Checks

```
class Vector {
 public Object get(int i) {

   return array[i]; // must hold appropriate view!

 }

 // ...
}
```

Compiler reports error on attempt to read “array” without appropriate view.

Basic Approach: Compiler Checks

```
class Vector {
 public Object get(int i) {
  acquire (this@read) {
   return array[i];
  }
 }

 // ...
}
```

Acquiring the “read” view permits access to “array”.

Basic Approach: Code Generation

```
class Vector {
 public Object get(int i) {
  acquire (this@read) {
   return array[i];
  }
 }

 // ...
}
```

⇒

```
class Vector {
 public Object get(int i) {
  synchronized
     (this$lock0) {
   return array[i];
  }
 }

 // ...
}
```

Our compiler uses regular locks or read/write locks, as appropriate.

Interface of Vector Example

Our Vector provides the following methods:

- get()
- set()
- capacity(): queries current Vector capacity.
- resize(): changes Vector capacity, re-copying items.

Concrete Example: read view

```
view read {
     size, capacity, array: readonly;

     incompatible write, resize;

     get(int i) preferred;
     capacity();
}
```

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- Provides read-only access to fields “size”, “capacity” and “array”.

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- No thread can hold “read” view on an object while some other thread holds view “write” or “resize” on that object.

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- No thread can hold “read” view on an object while some other thread holds view “write” or “resize” on that object.
- Methods “get” and “capacity” belong to this view.

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    incompatible write, resize;

    get(int i) preferred;
    capacity();
}
```

- Provides read-only access to fields “size”, “capacity” and “array”.
- No thread can hold “read” view on an object while some other thread holds view “write” or “resize” on that object.
- Methods “get” and “capacity” belong to this view.
- Calling method “get” will auto-acquire this view.

Views for Vector Example

- capacity: provides read access to capacity field

All other views provide read access to Vector metadata (size, capacity) and:

- read: read access to Vector contents (“get”).
- write: write access to Vector contents (“set”).
- xclRead: read access to Vector contents; only one thread can hold xclRead.
- resize: write access to Vector contents and metadata.

Resizing the Vector

```
public void resize(int newcapacity) {
 Object[] newarray = new Object[newcapacity];
 for(int i=0; i < newcapacity && i < size; i++) {
  newarray[i] = array[i];
 }

 acquire (this@resize) {
  array = newarray; capacity = newcapacity;
  size = (size<newcapacity) ? size : newcapacity;
 }
}
```

1. Copy existing Vector's contents, holding xclRead view.
2. Switch over the Vector to point to the new copy, holding resize view.

Views Ensure Mutual Exclusion

Calling resize() auto-acquires xclRead view.

- No other thread may write while xclRead view held (xclRead incompatible with write, xclRead, resize).

During the critical switchover phase, no other thread may access the Vector: all views incompatible with resize view.

Ensuring Safe Access to Arrays

We enable developers to encapsulate arrays:

- permits local reasoning about array reads and writes.

In our solution:

- `readonly`, `readwrite` access don't allow array reference to escape (ensured by a static analysis).

Problem with Unencapsulated Arrays

Unencapsulated arrays have the following (aliasing-related) problem:

```
  Object[] escapeArray() { return array; }
// not protected by any views:
  escapeArray()[4] = null;
```

(Assume that `escapeArray()` has full rights to the `array`.)

Arrays: more details

We provide 5 access descriptions for arrays:

- `fieldreadonly`, `fieldreadwrite`: permit array references to escape;
- `readonly`: permits only reads of the array, e.g. `o.f[3]`, but no copies[1].
- `readwrite`: permits reads and writes, but no copies[2].
- `arraywrite`: enables mutation & unlimited reads of `o.f`.

[1] Actually, `Object r = o.f` is allowed, but `r` can't escape.
[2] Same exception as for read.

Sensible Defaults

Goal: minimize instrumentation overhead.

Base View: create a default base view (if not explicitly declared) and populate it with:

1. fields (with readwrite access) that belong to no other view;
2. methods that belong to no other view.

Constructors: have full access to the object being constructed.

Views and Inheritance

We permit views in subclasses to be (only) more permissive:

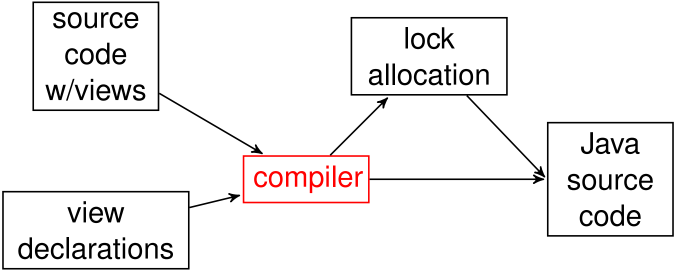
```
class Parent {
  int f;
  view v { f : readonly; }
}

class Child extends Parent {
  view v { f : readwrite; }
}
```

Developers may extend subclass behaviour without being constrained by superclass implementation.

Note: compiler allocates locks based on actual types, not declared types.

Views: Behind the scenes



Compiler Checks

We check:

- sanity for view declarations;
- adequacy of view acquisitions.

View Declaration Sanity

Recall: view declarations contain incompatibility declarations.
Assume v_1, v_2 incompatible and T_1 holds v_1.

- T_2 must wait for v_1 to be released before it may acquire v_2.

Read-Write Hazard Check: inspect view declarations, e.g.,

```
view v1 { f: readwrite; }
view v2 { f: readonly; }
```

Since v_1, v_2 are compatible, `f` may be subject to races.

General rule: for v_1, v_2 compatible, warn about any fields with write access in v_1 and read or write access in v_2.

Inheritance Check: views in subclasses may (only) be more permissive.

Compiler Checks: Assignments

We implemented a type system to check the following:

```
x = y;    // assignment to x
```

- Verify that `x` is not a method formal, nor declared with a view type (e.g. `Foo@v1 x`).
- (Can only assign to variables with view types at initial declarations, e.g. `Foo@v1 x = y;`, as long as types match.)

Compiler Checks: Field Accesses

```
x.f; // read field f
```

- Verify that all possible views of `x` allow reads of field `f`.

```
x.f = y; // write to field f
```

- Verify that all possible views of `x` allow writes to field `f`.

Compiler Checks: Method Calls

```
x.m(a1, ..., an); // method call
  // target: m(f1, ..., fn)
```

- Receiver check: Verify that all views of `x` contain *m*, or that *m* has a preferred view.
- Argument checks: Verify that each argument a_i at the call site matches view type of formal f_i (if applicable).

Static Analysis for Arrays (Escape Analysis Lite)

Must not expose arrays with `readonly`, `readwrite` access.

Intraprocedural analysis in two phases: 1) create constraints; 2) verify constraints are respected.

Analysis abstraction contains 3 flags per local variable:

- NO_ESCAPE: prohibits e.g. `return x;`
- NO_STORE: prohibits e.g. `o.f = x;`
- NO_WRITE_THRU: prohibits e.g. `o.f[i] = x;`

Analysis Example

```
// Assume: rw access to f, ro access on g,
// no constraints on p
Object[] x = foo(), y = o.g;

p.q = x;

x = o.f;

o.f[4] = y;
if (...)
  return x;
x[2] = new Object();
o.f = x;
```

Analysis Example

```
// Assume: rw access to f, ro access on g,
// no constraints on p
Object[] x = foo(), y = o.g;
  // y ∈ NO_ESCAPE, y ∈ NO_STORE, y ∈ NO_WRITE_THRU
p.q = x;
  // y ∈ NO_ESCAPE, y ∈ NO_STORE, y ∈ NO_WRITE_THRU (still)
x = o.f;
  // {x,y} ∈ NO_ESCAPE, {x,y} ∈ NO_STORE, y ∈ NO_WRITE_THRU
o.f[4] = y;
if (...)
  return x;
x[2] = new Object();
o.f = x;
  // {x,y} ∈ NO_ESCAPE, {x,y} ∈ NO_STORE, y ∈ NO_WRITE_THRU
```

Analysis Example

```
// Assume: rw access to f, ro access on g,
// no constraints on p
Object[] x = foo(), y = o.g;
  // y ∈ NO_ESCAPE, y ∈ NO_STORE, y ∈ NO_WRITE_THRU
p.q = x; // OK, no constraints on x or p
  // y ∈ NO_ESCAPE, y ∈ NO_STORE, y ∈ NO_WRITE_THRU (still)
x = o.f; // OK, have read access on f
  // {x,y} ∈ NO_ESCAPE, {x,y} ∈ NO_STORE, y ∈ NO_WRITE_THRU
o.f[4] = y; // violates y ∈ NO_WRITE_THRU
if (...)
  return x; // violates y ∈ NO_ESCAPE
x[2] = new Object(); // OK (x = o.f was rw)
o.f = x;    // violates x ∈ NO_STORE
  // {x,y} ∈ NO_ESCAPE, {x,y} ∈ NO_STORE, y ∈ NO_WRITE_THRU
```

1. Creating constraints

Constraints propagate forward, and arise as follows:

`o.f = x; // assume readonly/rw access to f`
creates `x.NO_ESCAPE`, `x.NO_STORE`.

`Object[] x = o.f;`
creates `x.NO_ESCAPE`, `x.NO_STORE`
(for `readonly` access to `f`), creates `x.NO_WRITE_THRU`.

`return x; // or other statements escaping x`
creates `x.NO_STORE`

`y = x;`
creates `x.NO_STORE`, `y.NO_STORE`.

We also have rules for `System.arraycopy`.

2. Checking constraints

`o.f = x;`

verify `!x.NO_ESCAPE`, and if `f` rw, `!x.NO_STORE`

`Object[] x = o.f;`

verify read-only access on `f`

`return x; // or other statements escaping x`

verify `!x.NO_ESCAPE`

`y = x;`

verify `!x.NO_ESCAPE`

`x[i] = ...;`

verify `!x.NO_WRITE_THRU`

View Inference

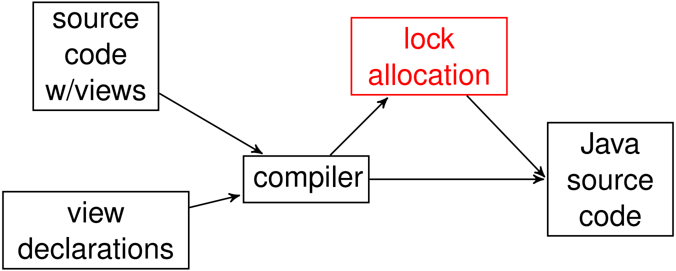
Implemented: infer view incompatibility based on hazards.

- If v_1, v_2 contain field `f`, with v_1 granting readwrite
  $\Longrightarrow v_1, v_2$ incompatible.

Current work: unsound view inference algorithm, mirroring manual approach.

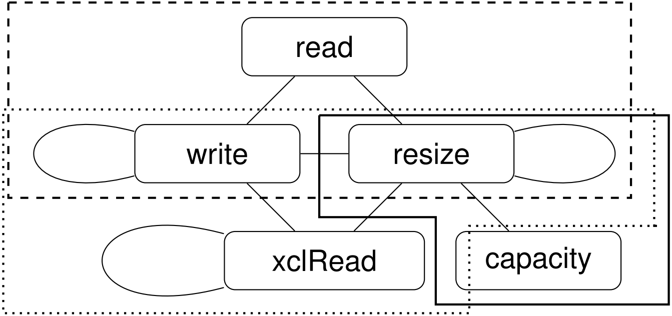
- Record field reads and writes in `synchronized()` blocks.
- Create view definitions based on accessed fields.
- Convert `synchronized()` blocks into `acquire()` blocks.

Views: Behind the scenes



Lock Allocation Example

Compile incompatibility graph (vertices = views, incompatibility = edges, boxes = cliques) into lock allocation.



Use greedy algorithm to approximate clique cover.

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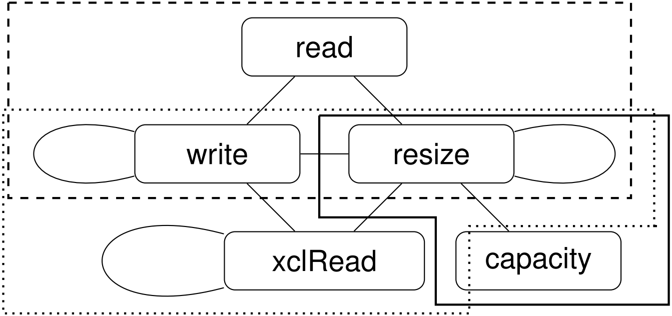

One lock per clique.
No self-compatible views in clique = normal lock.

Lock Allocation Example

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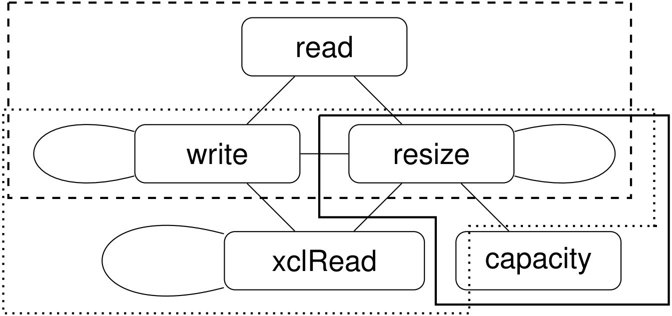


Exactly one self-compatible view in clique = read/write lock.

Acquiring a View

Compiler translates view acquisition into lock acquisition.

To acquire a view v, acquire the lock corresponding to each clique that v belongs to.

- for a read/write lock, acquire in read mode if the view is self-compatible.

Results

No speedups.

1. Microbenchmarks: views are fast enough.
2. Case studies: views are useful.

Microbenchmarks

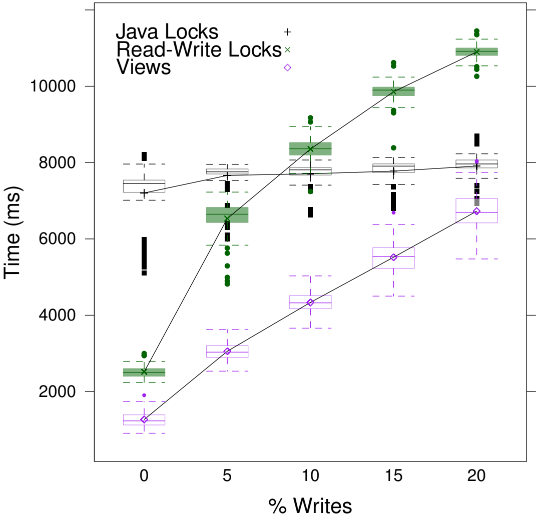
Investigate performance of views, compared to naïve locks and hand-coded implementations.

Two benchmarks:

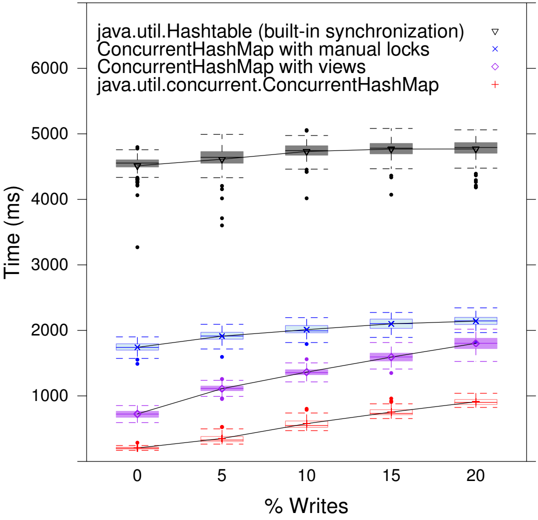
- Red-black tree
- Concurrent hash map

Hardware: dual-processor quad-core Intel Xeon E5520.

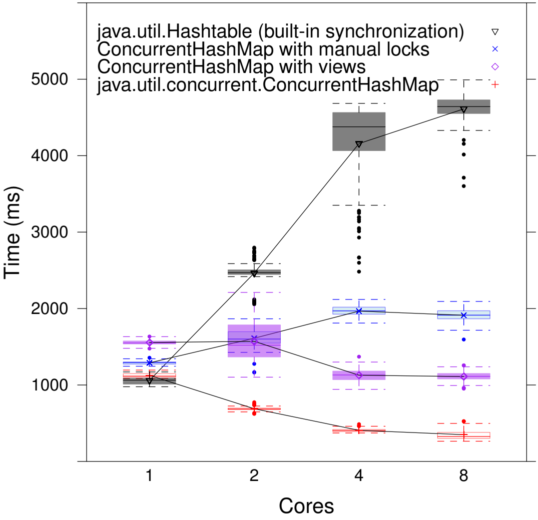
Red-black tree performance



Concurrent hash map performance (vs. % writes)



Concurrent hash map performance (vs. # cores)



Case study results

Implemented Views as a Polyglot (extensible compiler framework) extension.

Views compiler available for download at `http://demsky.eecs.uci.edu/software.php`.

Acquired and ported 4 multi-threaded Java applications:

- Vuze file-sharing client
- Mailpuccino mail client
- TupleSoup database library
- jPhoneLite voIP softphone

Vuze file-sharing client case study

194,000 lines of code total.

We modified the buddy plugin for Vuze, 13,500 lines of code.

Changed two classes:

- BuddyPlugin, 4 views
- BuddyTracker, 9 views

Vuze: BuddyPlugin class

Added 4 views:

- read_state: provides read access to 11 fields, incompatible with write_state
- write_state: provides write access to 11 field, incompatible with read_state and write_state
- pd_queue, publish_write_contents: lock-like, provide read/write access to 1 field, incompatible with self

Note how views protect part of the class's state and ensure appropriate locks are held.

Vuze: BuddyPluginTracker class

Most interesting locking structure in buddy plugin.

Converted 5 locks into 6 views:

- “this” lock maps to 2 views, “read_internal_state” and “write_internal_state”
- other locks generally map to 1 view

For instance:

- view “online_buddies” provides read/write access to fields “online_buddies”, “online_buddy_ips”.
- view “read_internal_state” provides read access to 12 fields, incompatible with “write_internal_state” and “buddy_peers”.

Mailpuccino graphical mail client

Contains 14,000 lines of code.

Ported the mail folder cache to use views, allowing multiple threads to simultaneously read the message cache.

Created 4 views in all: 2 sets of 2 views each.

1. lookup and modify views: protect the “KeyValues” field (which stores the cache) and its accessor methods.
2. file and indexfile views: protect the cache file and its index. Only one thread may access a file at a time.

Compiler synthesizes 3 locks: 2 normal plus 1 read/write lock.

Mailpuccino graphical mail client: bad code

Benchmark also contains a class MonitoredInputStream.

- Tried to replace two synchronized methods with views.
- Compiler warned that a third unsynchronized method accessed a view protected method.
- Discovery: MonitorInputStream was not thread safe and the synchronized methods were never actually called.

jPhoneLite VoIP softphone

Contains 20,000 lines of code.

Annotated the RTP and RTPChannel classes.

- readSamples, writeSamples: protect a circular buffer containing incoming data.
  readSamples writes to the buffer metadata.
- readHostPort, writeHostPort: protect destination information (remoteip, remoteport fields)

Compiler produces 1 read-write lock (host port) and 1 normal lock (samples) for RTP, plus 1 normal lock for RTPChannel.

Also kept the original lock on RTP to protect remaining state.

TupleSoup database library

Contains 6,000 lines of code.
Three index classes: MemoryIndex, PageIndex, FlatIndex.

Original implementation used one lock to protect all indexes.

Created 2 views per index class: access and modifying.

- multiple threads may hold an access view;
- only one thread may hold modifying view, and no other thread may access or modify concurrently.

Compiler uses read-write locks to implement these views.

Also converted a cached table (5 locks) to use views.

- one lock was unnecessary; views made this obvious.

Related Work

- Type systems to ensure absence of data races (Boyapati et al; Abadi et al; Bacon et al)
- Race detection tools (Eraser; Choi et al; Marino et al; RacerX; Warlock; Sema)
- Automatic generation of locking schemes for critical regions (Halpert et al; Emmi et al; Hicks et al; Zhang et al)

Conclusion

Presented the views concurrency control mechanism:

- raise the abstraction level of concurrency control; and,
- enable static checking that can help catch concurrency bugs.

Experience indicates that views are:

- simple to program with;
- support sophisticated fine-grained access control; and
- can detect concurrency bugs.