Concurrency, the Java Memory Model and You

Preface

- What‘s in here:
  - Basics of how the JVM handles memory access in the context of concurrency
- What‘s not (yet) in here:
  - All things Garbage Collector
  - Details on JSR-166 (`java.util.concurrent`)

TOC

- Why a memory model?
- Theory
- Practice
- What does this mean for the working programmer?

Why a memory model?

- Provides rules for access to the main memory by threads
- Provides guarantees to the programmer about runtime behaviour
  - Rules about memory access can be reasoned about to debug or validate concurrent code.

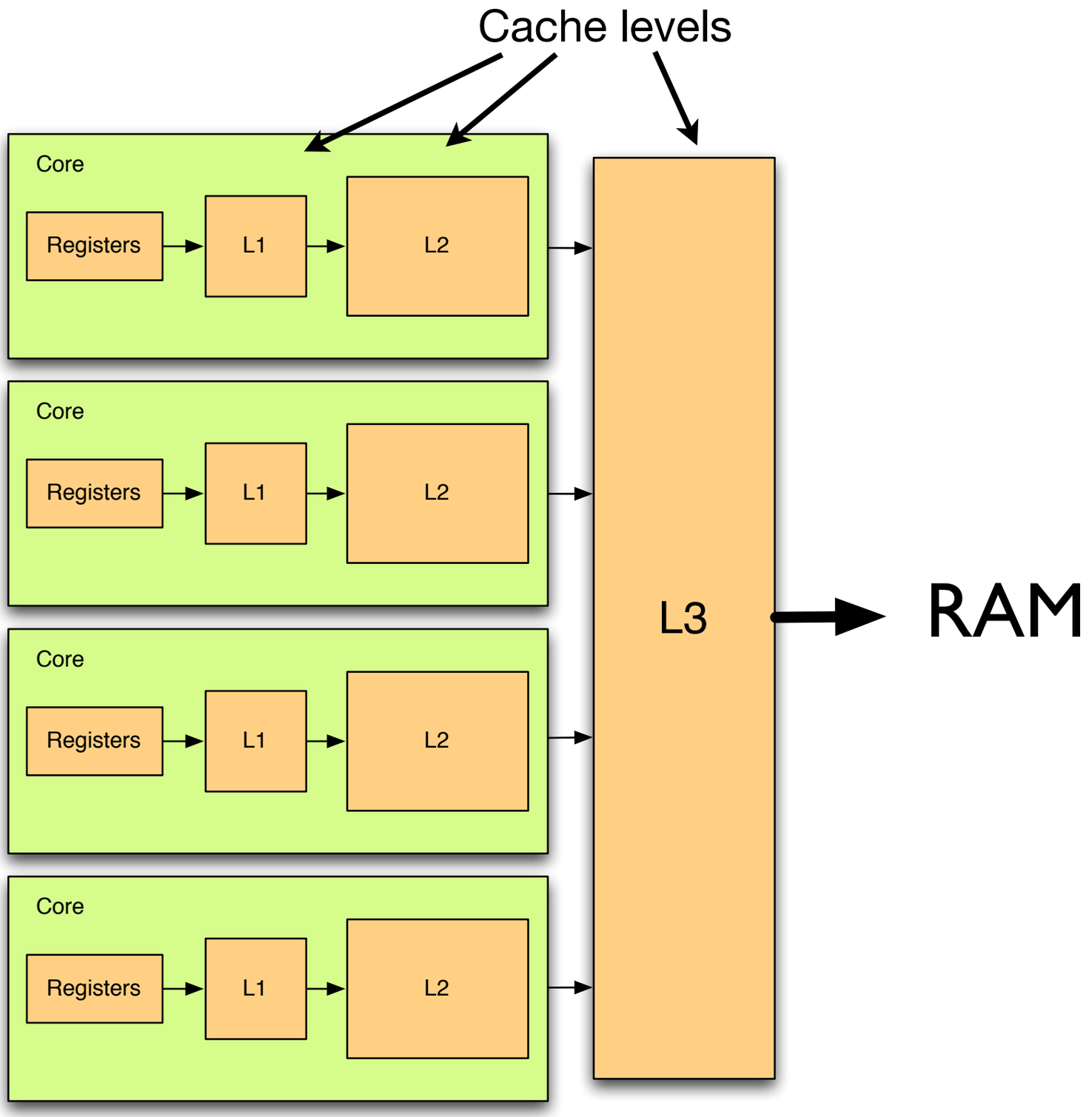
The Basics

- Working memory per thread
  - thread-confined variables not visible from the outside
  - need to synchronize shared variables between shared and thread memory

The Basics

- If synchronization is not made clear to the compiler, you end up with surprising results.
- Compiler optimizations may change code in several ways:
  - Statement Reordering
  - Forward substitution of variables
- CPU might further change things
  - Out-of-order execution
  - Microcode optimizations

Why does this make sense?



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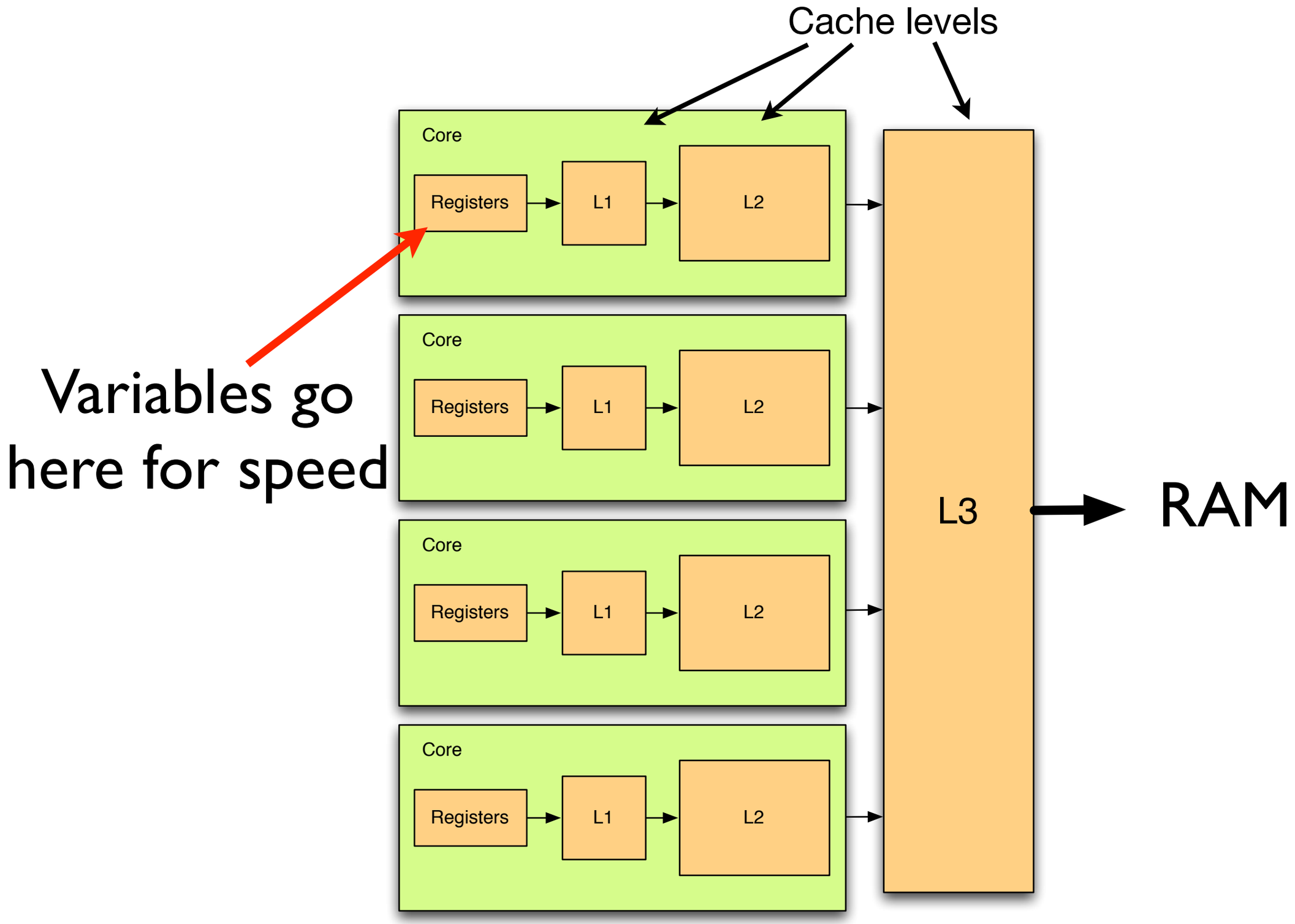


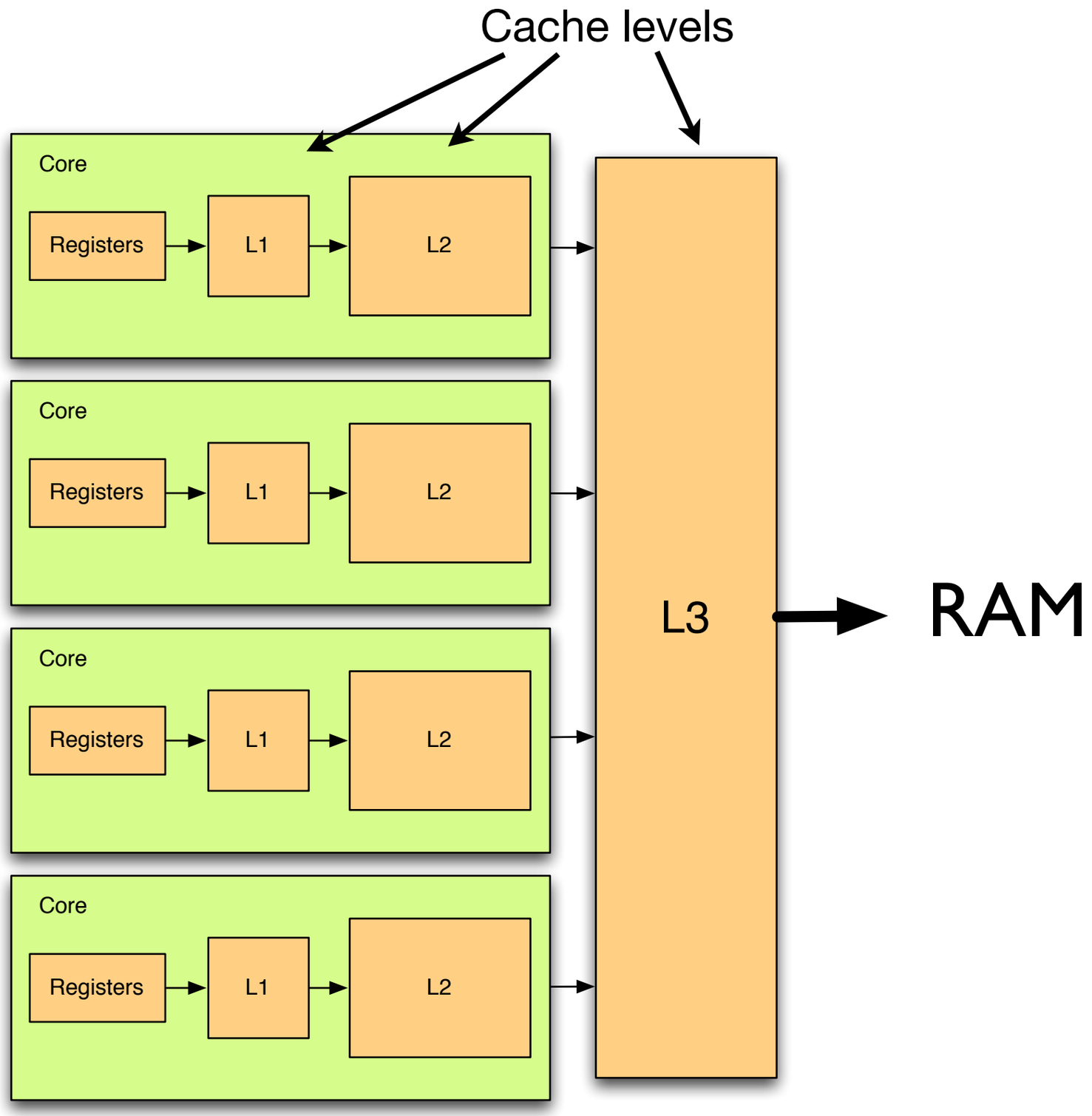
Why does this make sense?

Thread 1

Thread 2

Thread 3

Thread 4



Why does this make sense?

- Variables stay in Registers longer
  - minimizes memory access
- Need for a write back before accessing variable from another core
  - Memory fences

How does Java model this?

- All actions in a program are governed by a partial ordering.
- If the `happens_before` relation from action A to B is valid, A is guaranteed to happen before B.
- If two write accesses to a variable don‘t have a `happens_before` relationship you have a data race.

Actions

- Non-volatile Read/Write
- Synchronized:
  - Volatile Read/Write
  - Locking/Unlocking a monitor
  - Create/Join of a thread
  - External actions
  - Thread divergence (infinite loop)

happens_before ordering

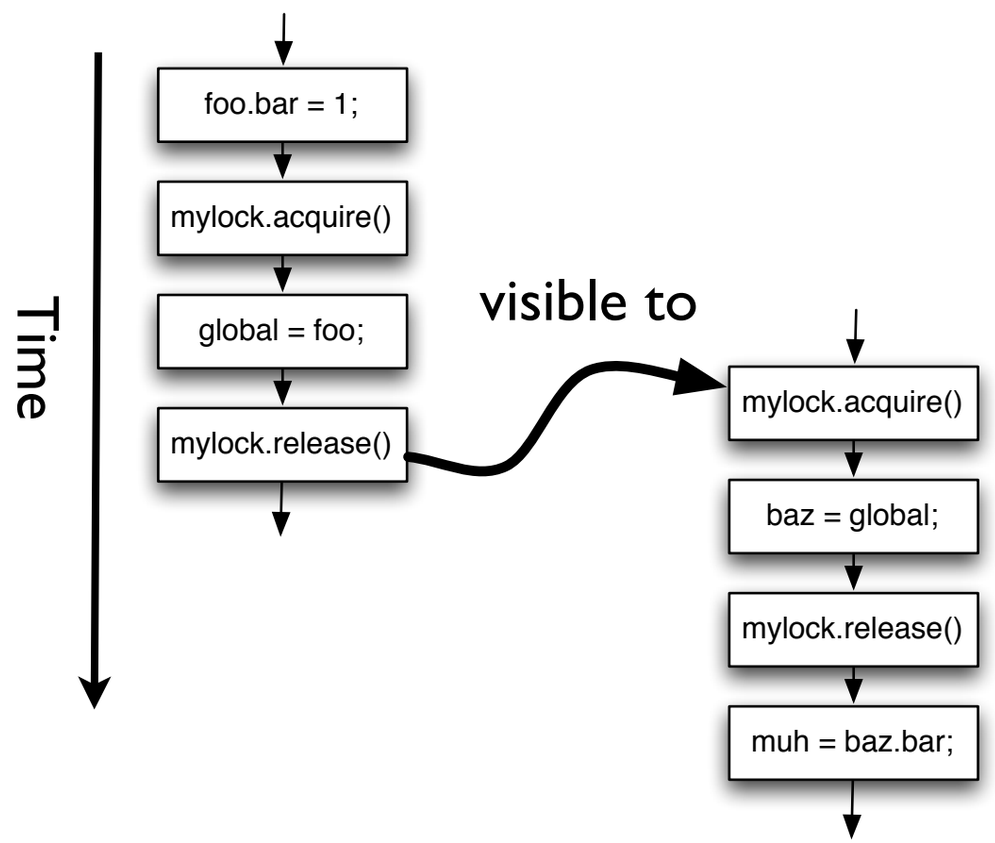
- Let x, y be actions.
  - If x and y are in the same thread and x comes before y then x `happens_before` y.
  - The end of construction for an object `happens_before` the start of the its finalizer.
  - An unlock of a monitor `happens_before` any subsequent lock on that monitor.
  - A write to a volatile field `happens_before` any subsequent read from that field.
  - A call to a threads start() method `happens_before` any actions inside the started thread.
  - The last action in a thread `happens_before` any other thread successfully returns from a call to join() on that thread.

happens_before ordering

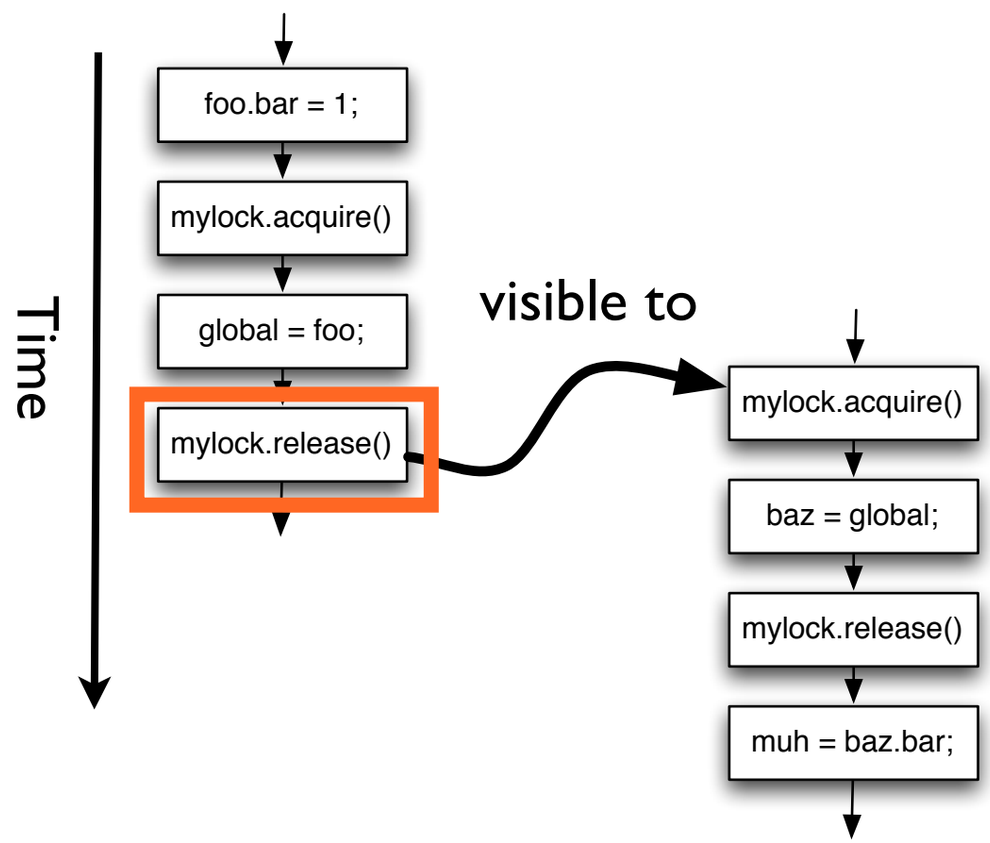
If this ordering holds over all conflicting accesses to a variable in a program, that program is said to be `correctly synchronized`.

It is a necessary, but not sufficient constraint on program consistency!

Visibility between threads

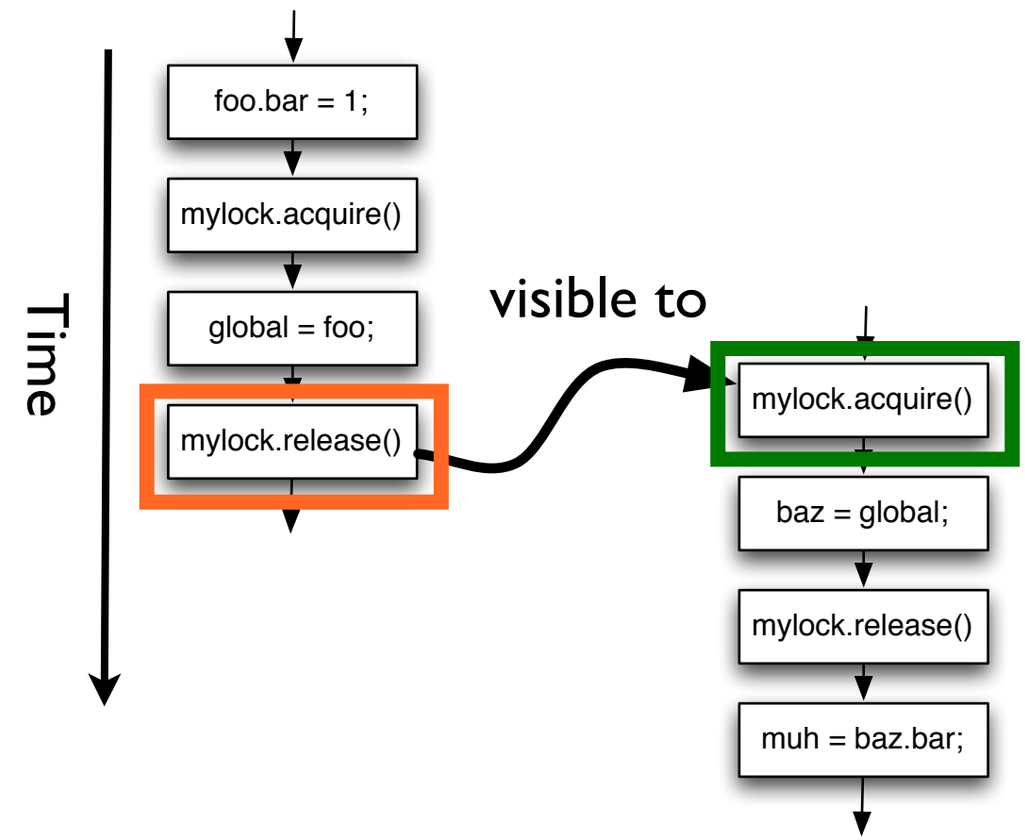


Visibility between threads



Everything before this unlock

Visibility between threads



Everything before this unlock
is visible to everything after this lock

Example

A == B == 0

Thread 1	Thread 2
B = 1;	A = 2;
r2 = A;	r1 = B;

happens_before consistent outcomes:

```
B = 1;
A = 2;
r2 = A;
r1 = B;
```

```
r2 = A;
r1 = B;
B = 1;
A = 2;
```

http://docs.oracle.com/javase/specs/jls/se7/html/jls-17.html#jls-17.4.5-table-1

What does this mean in practice?

```
import java.util.concurrent.TimeUnit;

public class StopThread {
    private static boolean stopRequested;

    public static void main(String[] args) throws InterruptedException {
        Thread backgroundThread = new Thread(new Runnable() {
                public void run() {
                    int i = 0;
                    while (!stopRequested) {
                        i++;
                    }
                    System.out.println(i);
                }
                });
        backgroundThread.start();
        TimeUnit.SECONDS.sleep(1);
        stopRequested = true;
}}
```

What does this mean in practice?

```
import java.util.concurrent.TimeUnit;

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            });
        backgroundThread.start();
        TimeUnit.SECONDS.sleep(1);
        stopRequested = true;
    }}
```

UNDEFINED BEHAVIOUR!

Corrected program

```
import java.util.concurrent.TimeUnit;

public class StopThread {
    private static volatile boolean stopRequested;

    public static void main(String[] args) throws InterruptedException {
        Thread backgroundThread = new Thread(new Runnable() {
                public void run() {
                    int i = 0;
                    while (!stopRequested) {
                        i++;
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                    System.out.println(i);
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        backgroundThread.start();
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}}
```

happens_before must remain valid!

A note on volatile

- volatile variables are always directly written to memory.
- access to volatile longs and doubles is atomic (access to non-volatile versions is NOT!)

The semantics of `final`

- Guarantee to the compiler about access to the `final` field
  - No writes means maximum reordering flexibility.
- No synchronization necessary when dealing with immutable objects

Safe publication

- An object is only in a consistent state once properly initialized.
- Publishing a reference to an object before construction is finished means doom! DOOM!

Safe publication

```
public class Holder {
  private int n;

  public Holder(int n) {this.n = n;}

  public void assertSanity() {
    if (n != n)
      throw new AssertionError("WTF");
  }
```

Safe Publication idioms

- To safely publish an object, proper construction must be assured.
  - Store it in a `volatile` field or `AtomicReference`
  - Store it in a `final` field
  - Guard the publication using a lock
  - Use a static initialization block

Primary Sources

B. Goetz, T. Peierls et al. - Java Concurrency in Practice: http://www.pearsonhighered.com/educator/product/Java-Concurrency-in-Practice/9780321349606.page

J. Bloch - Effective Java, 2nd Ed.: http://www.pearsonhighered.com/educator/product/Effective-Java/9780321356680.page

Java 7 SE Language Specification: http://docs.oracle.com/javase/specs/jls/se7/html/index.html

Java 7 Virtual Machine Specification: http://docs.oracle.com/javase/specs/jvms/se7/html/index.html

Java 5 Virtual Machine Specification: http://docs.oracle.com/javase/specs/jls/se5.0/html/j3TOC.html

William Pugh‘s page on the Java Memory Model: http://www.cs.umd.edu/~pugh/java/memoryModel/