Effective Concurrency for the Java™ Platform

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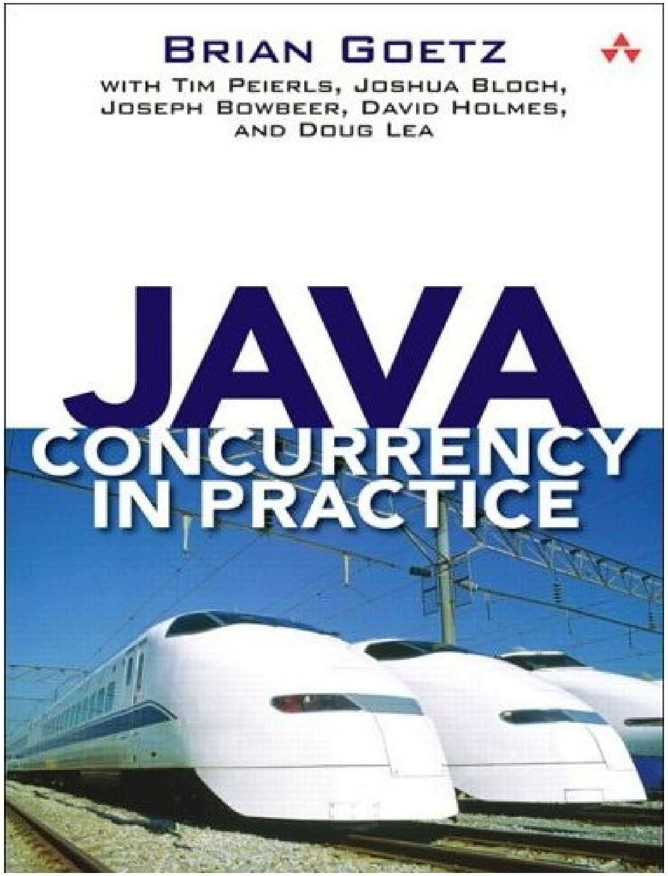
The Big Picture

Writing correct concurrent code is difficult, but not impossible

Using good object-oriented design techniques can make it easier

About the Speaker

- Brian Goetz has been a professional software developer for 20 years
- Author of ***Java Concurrency in Practice***
- Author of over 75 articles on Java™ platform development
  - **See** `http://www.briangoetz.com/pubs.html`
- Member of Java Community Process℠ (JCP℠) expert groups for JSRs 166 (Concurrency), 107 (Caching), and 305 (Safety annotations)
- Regular presenter at the JavaOne℠ conference, SDWest, OOPSLA, JavaPolis, and No Fluff, Just Stuff



JSR = Java Specification Request

Agenda

- Introduction
- Rules for Writing Thread-Safe Code
  - Document Thread-Safety Intent and Implementation
  - Encapsulate Data and Synchronization
  - Prefer Immutable Objects
  - Exploit Effective Immutability
- Rules for Structuring Concurrent Applications
  - Think Tasks, Not Threads
  - Build Resource-Management Into Your Architecture
  - Decouple Identification of Work from Execution
- Rules for Improving Scalability
  - Find and Eliminate the Serialization

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Rules for Improving Scalability

- Find and Eliminate the Serialization

Introduction

- This talk is about identifying patterns for concurrent code that are ***less fragile***
  - Conveniently, many are the good practices we already know
  - Though sometimes we forget the basics
- Feel free to break (almost) all the rules here
  - But be prepared to pay for it at maintenance time
  - Remember the core language value:
    Reading code is more important than writing code

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Document Thread-Safety

- One of the easiest way to write thread-safe classes is to build on existing thread-safe classes
  - But how do you know if a class is thread-safe?
    - The documentation ***should say***, but frequently doesn't
  - Can be dangerous to guess
    - Should assume not thread-safe unless otherwise specified
- Document thread-safety design intent
  - Class annotations: **`@ThreadSafe`**, **`@NotThreadSafe`**

```
@ThreadSafe
public class ConcurrentHashMap { .... }
```

- With class-level thread-safety annotations:
  - Clients will know whether the class is thread-safe
  - Maintainers will know what promises must be kept
  - Tools can help identify common mistakes

Document Thread-Safety

- Should also document ***how*** a class gets its thread-safety
  - This is your ***synchronization policy***
- The Rule:
  - When writing a variable that might next be read by another thread, or reading a variable that might last have been written by another thread, ***both*** threads must synchronize using a common lock
- Leads to design rules of the form ***hold lock L when accessing variable V***
  - We say ***V is guarded by L***
- *These rules form **protocols** for coordinating access to data*
  - *Such as “Only the one holding the conch shell can speak”*
- *Only work if **all** participants follow the protocol*
  - *If one party cheats, everyone loses*

Document Thread-Safety

- Use **`@GuardedBy`** to document your locking protocols
- Annotating a field with **`@GuardedBy("this")`** means:
- *Only access the field when holding the lock on "this"*

```
@ThreadSafe
public class PositiveInteger {
    // INVARIANT: value > 0
    @GuardedBy("this") private int value = 1;

    public synchronized int getValue() { return value; }

    public void setValue(int value) {
        if (value <= 0)
            throw new IllegalArgumentException(....);
        synchronized (this) {
            this.value = value;
        }
    }
}
```

- Simplifies maintenance and avoids common mistakes
- Like adding a new code path and forgetting to synchronize
- Improper maintenance is a big source of concurrency bugs

Document Thread-Safety

- *For primitive variables, @GuardedBy is straightforward*
- *But what about*

```
@GuardedBy("this") Set<Rock> knownRocks = new HashSet<Rock>();
```

- There are three different types of potentially mutable state
  - The **`knownRocks`** reference
  - The internal data structures in the **`HashSet`**
  - The elements of the collection
- Which types of state are we talking about? All of them?
- It varies, but we can often tell from context
  - Are the elements owned by the class, or by clients?
  - Are the elements thread-safe?
  - Is the reference to the collection mutable?

```
@GuardedBy("this") final Set<Rock> knownRocks = ....
```

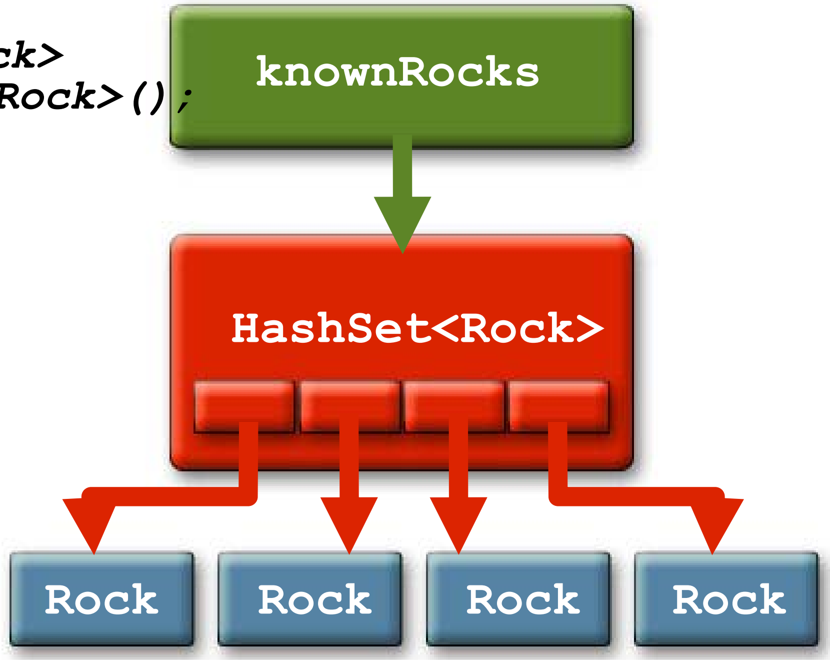
Document Thread-Safety

- *For complicated data structures, draw a diagram identifying ownership and synchronization policies*
  - *Color each state domain with its synchronization policy*

```
@ThreadSafe public class Rock { .... }

@GuardedBy("this") final Set<Rock>
        knownRocks = new HashSet<Rock>();
```

- Very effective for designing and reviewing code!
  - Frequently identifies gaps or inconsistencies in synchronization policies



Summary: Document Thread-Safety

- Document classes as **`@ThreadSafe`** or **`@NotThreadSafe`**
  - Saves your clients from guessing wrong
  - Puts maintainers on notice to preserve thread-safety
- Document synchronization policy with **`@GuardedBy`**
  - Helps you make sure you have a clear thread-safety strategy
  - Helps maintainers keep promises made to clients
  - Helps tools alert you to mistakes
- Use diagrams to verify thread-safety strategies for nontrivial data structures
- Inadequate documentation → fragility

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Encapsulate Data and Synchronization

- Encapsulation promotes clear, maintainable code
  - Reduces scope of effect of code changes
- Encapsulation similarly promotes thread safety
  - Reduces how much code can access a variable
  - And therefore how much be examined to ensure that synchronization protocols are followed
- Thread safety is about ***coordinating access to shared mutable data***
  - Shared—might be accessed by more than one thread
  - Mutable—might be modified by some thread
- Less code that accesses a variable means fewer opportunities for error

Encapsulate Data and Synchronization

- ***Encapsulation makes it sensible to talk about individual classes being thread-safe***
- ***A body of code is thread-safe if:***
  - ***It is correct in a single-threaded environment, and***
  - ***It continues to be correct when called from multiple threads***
    - Regardless of interleaving of execution by the runtime
    - Without additional coordination by callers
- *Correct means **conforms to its specification***
  - *Often framed in terms of **invariants and postconditions***
    - *These are statements about **state***
- *Can't say a body of code guarantees an invariant unless no other code can modify the underlying state*
  - *Thread-safety can only describe a body of code that manages all access to its mutable state*
  - *Without encapsulation, that's the **whole program***

Encapsulate Data and Synchronization

- ***Is this code correct? Is it thread-safe?***

```
public class PositiveInteger {
    // INVARIANT: value > 0
    @GuardedBy("this") public int value = 1;

    public synchronized int getValue() { return value; }

    public synchronized void setValue(int value) {
        if (value <= 0)
            throw new IllegalArgumentException(....);
        this.value = value;
    }
}
```

- We can't say unless we examine all the code that accesses `value`
  - Doesn't even enforce invariants in single-threaded case
  - Difficult to reason about invariants when data can change at any time
  - Can't ensure data is accessed with proper synchronization

Encapsulate Data and Synchronization

- *Without encapsulation, cannot determine thread-safety without reviewing the entire application*
  - *Much easier to analyze one class than a whole program*
  - *Harder to accidentally break thread safety if data and synchronization are encapsulated*
- We ***can*** build thread-safe code without encapsulation
  - But it's fragile
  - Requires code all over the program to follow the protocol

```
public final static Object lock = new Object();
@GuardedBy("lock")
public final static Set<String> users
     = new HashSet<String>();
```

- Imposing locking requirements on external code is asking for trouble
  - ***Fragility increases with the distance between declaration and use***

Encapsulate Data and Synchronization

- Sometimes we can push the encapsulation even deeper
  - Manage state using thread-safe objects or volatile variables
  - Even less fragile—can't forget to synchronize
  - ***But only if class imposes no additional invariants***
- *Can transform this*

```
public class Users {
        @GuardedBy("this")
        private final Set<User> users = new HashSet<User>();

        public synchronized void addUser(User u) { users.add(u); }
        ....
    }
```

- Into this

```
    public class Users {
        private final Set<User> users
            = Collections.synchronizedSet(new HashSet<User>());

        public void addUser(User u) { users.add(u); }
        ....
    }
```

Encapsulate Data and Synchronization

- If a class imposes invariants on its state, it must also provide its own synchronization to protect these invariants
  - Even if component classes are thread-safe!
- UserManager follows The Rule
  - But still might not be thread-safe!

```
public class UserManager {
    // Each known user is in exactly one of {active, inactive}
    private final Set<User> active
        = Collections.synchronizedSet(new HashSet<User>());
    private final Set<User> inactive
        = Collections.synchronizedSet(new HashSet<User>());

    // Constructor populates inactive set with known users

    public void activate(User u) {
        if (inactive.remove(u))
            active.add(u);
    }

    public boolean isKnownUser(User u) {
        return active.contains(u) || inactive.contains(u);
    }
}
```

Encapsulate Data and Synchronization

- In UserManager, all data is accessed with synchronization
  - But still possible to see a user as neither active nor inactive
    - Therefore not thread-safe—can violate its specification!
  - Need to make compound operations atomic with respect to one other
    - Solution: synchronize UserManager methods

```
public class UserManager {
    // Each known user is in exactly one of {active, inactive}
    private final Set<User> active = Collections.synchronizedSet(...);
    private final Set<User> inactive = Collections.synchronizedSet(...);

    public synchronized void activate(User u) {
        if (inactive.remove(u))
            active.add(u);
    }
    public synchronized boolean isKnownUser(User u) {
        return active.contains(u) || inactive.contains(u);
    }
    public Set<User> getActiveUsers() {
        return Collections.unmodifiableSet(active);
    }
}
```

Encapsulate Data and Synchronization

- The problem was that synchronization was specified ***at a different level than the invariants***
  - *Result: atomicity failures (race conditions)*
  - *Could fix with client-side locking, but is fragile*
  - *Instead,* ***encapsulate enforcement of invariants***
    - *All variables in an invariant should be guarded by same lock*
    - *Hold lock for duration of operation on related variables*
- Always provide synchronization at the same level as the invariants
  - *When composing operations on thread-safe objects, you may end up with multiple layers of synchronization*
  - *And that's OK!*

Summary: Encapsulation

- A thread-safe class encapsulates its data and any needed synchronization
  - Lack of encapsulation → fragility
- Without encapsulation, correctness and thread-safety can only describe the entire program, not a single class
- Wherever a class defines invariants on its state, it must provide synchronization to preserve those invariants
  - Even if this means multiple layers of synchronization
- Where should the synchronization go?
  - In the client—too fragile
  - In the component classes—may not preserve invariants
  - In the composite that defines invariants—just right

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- Find and Eliminate the Serialization

Prefer Immutable Objects

- An immutable object is one whose
  - State cannot be changed after construction
  - All fields are final
    - Not optional—critical for thread-safety of immutable objects
- ***Immutable objects are automatically thread-safe!***
- *Simpler*
  - Can only ever be in one state, controlled by the constructor
- *Safer*
  - Can be freely shared with unknown or malicious code, who cannot subvert their invariants
- *More scalable*
  - No synchronization required when sharing!
- (See Effective Java technology Item #13 for more)

Prefer Immutable Objects

- Most concurrency hazards stem from the need to coordinate access to mutable state
  - Race conditions and data races come from insufficient synchronization
  - Many other problems (e.g., deadlock) are consequences of strategies for proper coordination
- No mutable state → no need for coordination
  - No race conditions, data races, deadlocks, scalability bottlenecks
- Identify immutable objects with **`@Immutable`**
  - ***`@Immutable`*** *implies* ***`@ThreadSafe`***
- Don’t worry about the cost of object creation
  - Object lifecycle is generally cheap
  - Immutable objects have some performance benefits too

Prefer Immutable Objects

- Even if immutability is not an option, less mutable state can still mean less coordination
- Benefits of immutability apply to individual variables as well as objects
  - Final fields have special visibility guarantees
  - Final fields are simpler than mutable fields
- ***Final is the new private***
  - *Declare fields final wherever practical*
    - *Worth doing extra work to avoid making fields nonfinal*
  - *In synchronization policy diagrams, final variables provide a synchronization policy for references*
    - *But not the referred-to object*
- *If you can't get away with full immutability, seek to limit mutable state as much as possible*

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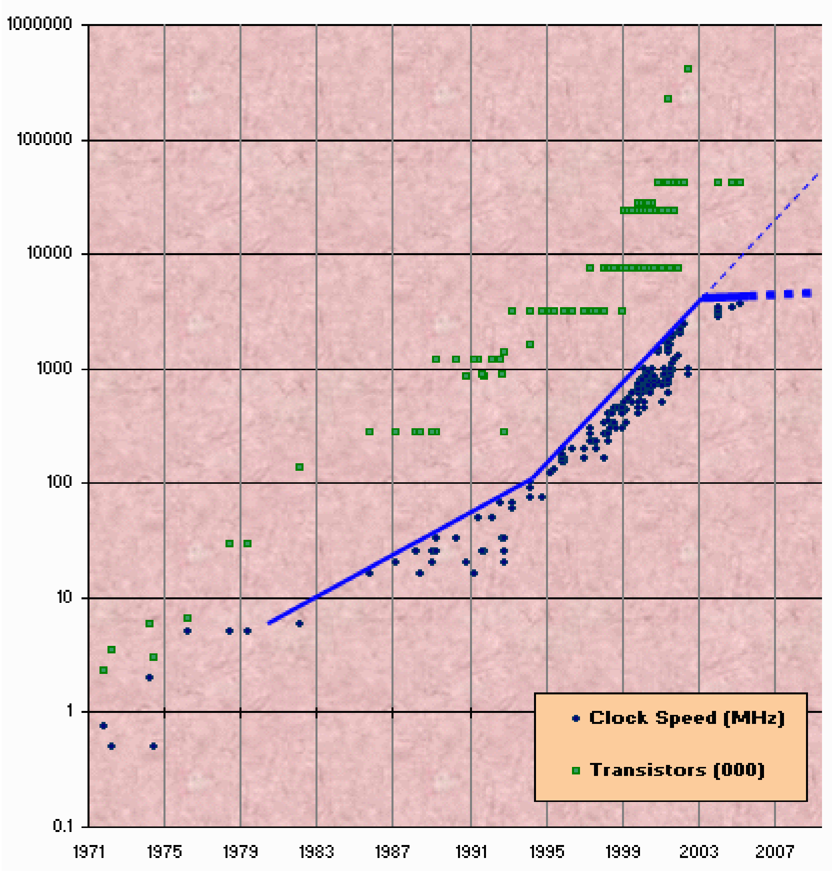
Find the Serialization

- Performance is a measure of ***how fast***
  - Learning to work faster increases your performance
- Scalability is a measure of ***how much more*** work could be done with more resources
  - Learning to delegate increases your scalability
- When problems get over a certain size, performance improvements won't get you there—you need to scale
- If a problem got ten times bigger, how much more resources would I need to solve it?
  - If you can just buy ten times as many CPUs (or memory or disks), then we say the problem scales ***linearly or perfectly***

Find the Serialization

- Processor speeds flattened out around 2003
  - Moore's law now gives us more cores, not faster ones
  - Increasing throughput means keeping more cores busy
- Can no longer just buy a faster box to get a speedup
  - Must write programs that take advantage of additional CPUs
  - Just adding more cores may not improve throughput
    - Tasks must be amenable to parallelization



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Find the Serialization

- System throughput is governed by ***Amdahl's Law***
  - Divides work into ***serial*** and ***parallel*** portions
    - Serial work cannot be sped up by adding resources
    - Parallelizable work can be
- Most tasks have a mix of serial and parallel work
  - Harvesting crops can be sped up with more workers
    - But additional workers will not make them grow any faster
- Amdahl's Law says: $\textbf{\textit{Speedup}} \leqslant \dfrac{1}{\left(F + \dfrac{(1-F)}{N}\right)}$
  - F is the fraction that must be executed serially
  - N is the number of available workers
- As N → infinity, speedup → 1/F
  - With 50% serialization, can only speed up by a factor of two
    - No matter how many processors

Find the Serialization

- Every task has some sources of serialization
  - You just have to know where to look
- The primary source of serialization is the ***exclusive lock***
  - The longer locks are held for, the worse it gets
- Even when tasks consist only of thread-local computation, there is still serialization inherent in task dispatching

```
while (!shutdownRequested) {
    Task t = taskQueue.take();   // potential serialization
    Result r = t.doTask();
    resultSet.add(result);       // potential serialization
}
```

- Accessing the task queue and the results container invariably involves serialization

Find the Serialization

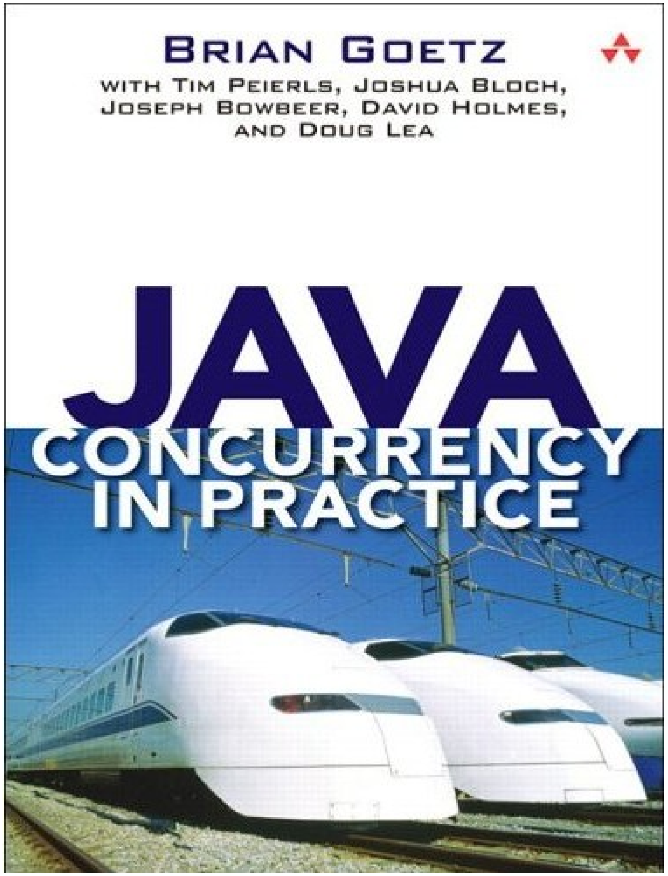
- To improve scalability, you have to find the serialization and break it up
- Can reduce lock-induced serialization in several ways
  - Hold locks for less time—“get in, get out”
    - Move thread-local computation out of synchronized blocks
      - But don’t make them so small as to split atomic operations
    - Replace synchronized counters with **`AtomicInteger`**
  - Use ***lock splitting or lock striping*** to reduce lock contention
    - Guards different state with different locks
    - Reduces likelihood of lock contention
    - Replace synchronized **`Map`** with **`ConcurrentHashMap`**

Find the Serialization

- Can eliminate locking entirely in some cases
  - Replace mutable objects with immutable ones
  - Replace shared objects with thread-local ones
  - Confine objects to a specific thread (as in Swing)
  - Consider **`ThreadLocal`** for heavyweight mutable objects that don't need to be shared (e.g., **`GregorianCalendar`**)
- Signs that a concurrent program is bound by locking and not by CPU resources
  - Total CPU utilization < 100%
  - High percentage of kernel CPU usage

For More Information

- Other sessions
  - TS-2220: Testing Concurrent Software
  - TS-2007: Improving Software Quality with Static Analysis
  - BOF-2864: Debugging Data Races
- Books
  - ***Java Concurrency in Practice*** (Goetz, et al)
    - See http://www.jcip.net
  - ***Concurrent Programming in Java*** (Lea)
  - ***Effective Java*** (Bloch)



Q&A

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