Concurrency: Past and Present

Implications for Java Developers

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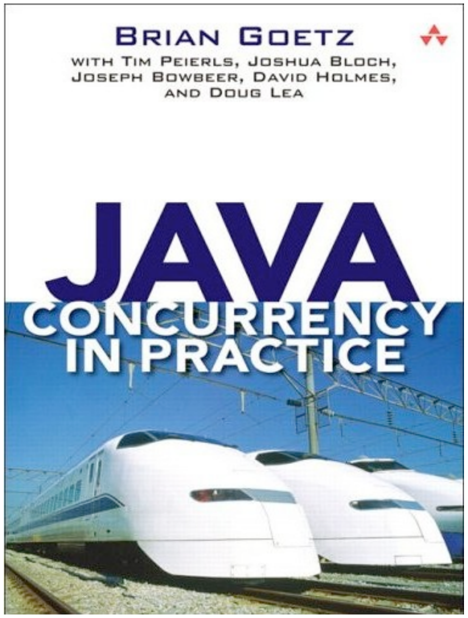
About the speaker

- Professional software developer for 20 years
  - > Sr. Staff Engineer at Sun Microsystems
- Author of *Java Concurrency in Practice*
  - > Author of over 75 articles on Java development
  - > See **`http://www.briangoetz.com/pubs.html`**
- Member of several JCP Expert Groups
- Frequent presenter at major conferences



What I think...

Concurrency is hard.

...but don't just take my word for it

- “Unnatural, error-prone, and untestable”
  > R.K. Treiber, *Coping with Parallelism*, 1986
- “Too hard for most programmers to use”
  > Osterhout, *Why Threads are a Bad Idea*, 1995
- “It is widely acknowledged that concurrent programming is difficult”
  > Edward Lee, *The Problem with Threads*, 2006

...but don't just take their word for it

- Adding concurrency control to objects can be harder than it looks
  - Let’s try it
  - We’ll develop a simple model, a bank account
- Basic concepts
  - A thread is a sequential process with its own program counter and call stack
  - Threads share VM-wide resources, such as memory, file handles, and security credentials
    - Upside: fine-grained data sharing between threads
    - Downside: fine-grained data sharing between threads
  - Threads execute concurrently (and with unpredictable relative timing) unless you use explicit locking to ensure that threads take turns accessing critical resources
  - Java has built-in locking via the **`synchronized`** keyword

Simple bank account model

```
public class Account {
    private int balance;

    public int getBalance() {
        return balance;
    }

    public void credit(int amount) {
        balance += amount;
    }

    public void debit(int amount) {
        balance -= amount;
    }
}
```

Problem: Incorrect synchronization

- The Rule: if mutable data is shared between threads, *all* accesses require synchronization
  - Failing to follow The Rule is called a *data race*
  - Computations involving data races have *exceptionally subtle semantics under the Java Language Specification*
    - (that's bad)
    - Code calling Account.credit() could write the wrong value
    - Code calling Account.getBalance() could read the wrong value
  - These hazards stem from the weak cache coherency guarantees offered by modern multiprocessor systems
    - Because stronger guarantees would be too expensive
    - So we let the programmer signal when stronger guarantees are needed by using **`synchronized`**

Adding synchronization

- Need thread safety? Just synchronize, right?
  - It's a good start, anyway

```
@ThreadSafe public class Account {
    @GuardedBy("this") private int balance;

    public synchronized int getBalance() {
        return balance;
    }

    public synchronized void credit(int amount) {
        balance += amount;
    }

    public synchronized void debit(int amount) {
        balance -= amount;
    }
}
```

Composing operations

- Say we want to transfer funds between accounts
  - > But only if there's enough money in the account
- We can create a *compound operation* over multiple Accounts

```
public class AccountManager {
    public static void transferMoney(Account from,
                                     Account to,
                                     int amount)
            throws InsufficientBalanceException {

        if (from.getBalance() < amount)
            throw new InsufficientBalanceException(...);
        from.debit(amount);
        to.credit(amount);
    }
}
```

Problem: race conditions

- A race condition is when the correctness of a computation depends on “lucky timing”
  - > Often caused by *atomicity failures*
- Atomicity failures occur when an operation should be atomic, but is not
  - > Typical pattern: Check-then-act

```
if (foo != null)        // Another thread could set
    foo.doSomething(); // foo to null
```

  - > Also: Read-modify-write

```
++numRequests;     // Really three separate actions
                   // (even if volatile)
```

Race Conditions

- All data in AccountManager is accessed with synchronization
  - > But still has a race condition!
    - > Can end up with negative balance with some unlucky timing
      - Initial balance = 100
      - Thread A: transferMoney(me, you, 100);
      - Thread B: transferMoney(me, you, 100);

```
public class AccountManager {
    public static void transferMoney(Account from,
                                     Account to,
                                     int amount)
            throws InsufficientBalanceException {

        // Unsafe check-then-act
        if (from.getBalance() < amount)
            throw new InsufficientBalanceException(...);
        from.debit(amount);
        to.credit(amount);
    }
}
```

Demarcating atomic operations

- Programmer must specify *atomicity requirements*
  - We could lock both accounts while we do the transfer
    - (Provided we know the locking strategy for Account)

```
public class AccountManager {
    public static void transferMoney(Account from,
                                     Account to,
                                     int amount)
            throws InsufficientBalanceException {

        synchronized (from) {
            synchronized (to) {
                if (from.getBalance() < amount)
                    throw new InsufficientBalanceException(...);
                from.debit(amount);
                to.credit(amount);
            }
        }
    }
}
```

Problem: Deadlock

- Deadlock can occur when multiple threads each acquire multiple locks in different orders
  - Thread A: transferMoney(me, you, 100);
  - Thread B: transferMoney(you, me, 50);

```
public class AccountManager {
    public static void transferMoney(Account from,
                                     Account to,
                                     int amount)
            throws InsufficientBalanceException {

        synchronized (from) {
            synchronized (to) {
                if (from.getBalance() < amount)
                    throw new  InsufficientBalanceException(...);
                from.debit(amount);
                to.credit(amount);
            }
        }
    }
}
```

Avoiding Deadlock

- We can avoid deadlock by *inducing a lock ordering*

```
public class AccountManager {
    public static void transferMoney(Account from,
                                     Account to,
                                     int amount)
            throws InsufficientBalanceException {

        Account first, second;
        if (from.getAccountNumber() < to.getAccountNumber()) {
            first = from; second = to;
        }
        else {
            first = to; second = from;
        }

        synchronized (first) {
            synchronized (second) {
                if (from.getBalance() < amount)
                    throw new  InsufficientBalanceException(...);
                from.debit(amount);
                to.credit(amount);
            }
        }
    }
}
```

That was hard!

- We started with a very simple account class
  > At every step, the “obvious” attempts at making it thread-safe had some sort of problem

  > Some of these problems were subtle and nonobvious

    > Reasonable-looking code was wrong

    > And this was a trivial class!

  > Tools didn't help us

  > Runtime didn't help us

Why was that so hard?

- There is a fundamental tension between object oriented design and lock-based concurrency control
- OO encourages you to hide implementation details
- Good OO design encourages composition
  - > But composing thread-safe objects requires knowing how they implement locking
    - > So that you can participate in their locking protocols
    - > So you can avoid deadlock
    - > Language hides these as implementation details
- Threads graft concurrent functionality onto a fundamentally sequential execution model
  - > Threads == sequential processes with shared state

Why was that so hard?

- Threads *seem* like a straightforward adaptation of the sequential model to concurrent systems
  - > But in reality they introduce significant complexity
    - > Harder to reason about program behavior
    - > Loss of determinism
    - > Requires greater care
- Like going from  to 

Development to watch: Software Transactional Memory (STM)

- Most promising approach for integrating with Java
  - > Not here yet, waiting for research improvements
- Replace explicit locks with transaction boundaries

```
atomic {
    from.credit(amount);
    to.debit(amount);
}
```

  - > Explicit locking causes problems if locking granularity doesn't match data access granularity
  - > Let platform figure out what state is accessed and choose the locking strategy
  - > No deadlock risk
    - > Conflicts can be detected and rolled back
  - > Transactions compose naturally!

Asynchrony, before threads

- Concurrency used to refer to *asynchrony*
  - > Signal handlers, interrupt handlers
  - > Handler interrupts program, finishes quickly, and resumes control
  - > Handlers might run in a restricted execution environment
    - > Might not be able to allocate memory or call some library code
- Primary motivation was to support asynchronous IO
  - > Multiple IOs meant multiple interrupts – hard to write!
  - > Data accessed by both interrupt handlers and foreground program required careful coordination

Asynchrony, before threads

- Consider an *asynchronous* account interface
  - Provides asynchronous get- and set-balance operations
  - (code sketch using Java syntax)

```
public class Accounts {
    public class AccountResult {
        public Account account;
        public int balance;
    }

    public interface GetBalCallback {
        public void callback(Object context, AccountResult result);
    }

    public interface SetBalCallback {
        public void callback(Object context, AccountResult result);
    }

    public static void getBalance(Account acct,
                                  Object context,
                                  GetBalCallback callback) { ... }

    public static void setBalance(Account acct, int balance,
                                  Object context,
                                  SetBalCallback callback) { ... }
}
```

Asynchrony, before threads

- How to build a balance-transfer operation?
  - > A compound operation with four steps
    - > Get from-balance, get to-balance, decrease from-balance, increase to-balance
  - > Each step is an asynchronous operation
    - > The callback of the first step stashes the result for later use
      - – And then initiates the second step
      - – And so on
      - – Callback of the last step triggers callback for the compound operation

```
public class AccountTransfer {
    public interface TransferCallback {
        public void callback(Object context, TransferResult result);
    }

    public void transfer(Account from, Account to, int amount,
                         Object context, TransferCallback callback) {...}
}
```

Asynchrony, before threads

- The code for the transfer operation in C could be 200 lines of hard-to-read code!
  - > 95% is “plumbing” for the async stuff
  - > Error-prone coding approach
    - > Coding errors show up as operations that never complete
    - > Prone to memory leaks
    - > Prone to cut and paste errors
  - > Hard to read – logic strewn all over the program
  - > Hard to debug
  - > Error handling made things even harder

Threads to the “rescue”

- Threads promised to turn these complex asynchronous program flows into synchronous ones
  - Now the whole control flow can be in one place
    - Code got much smaller, easier to read, less error-prone
  - A huge step forward – mostly
    - Except for that pesky shared-state problem

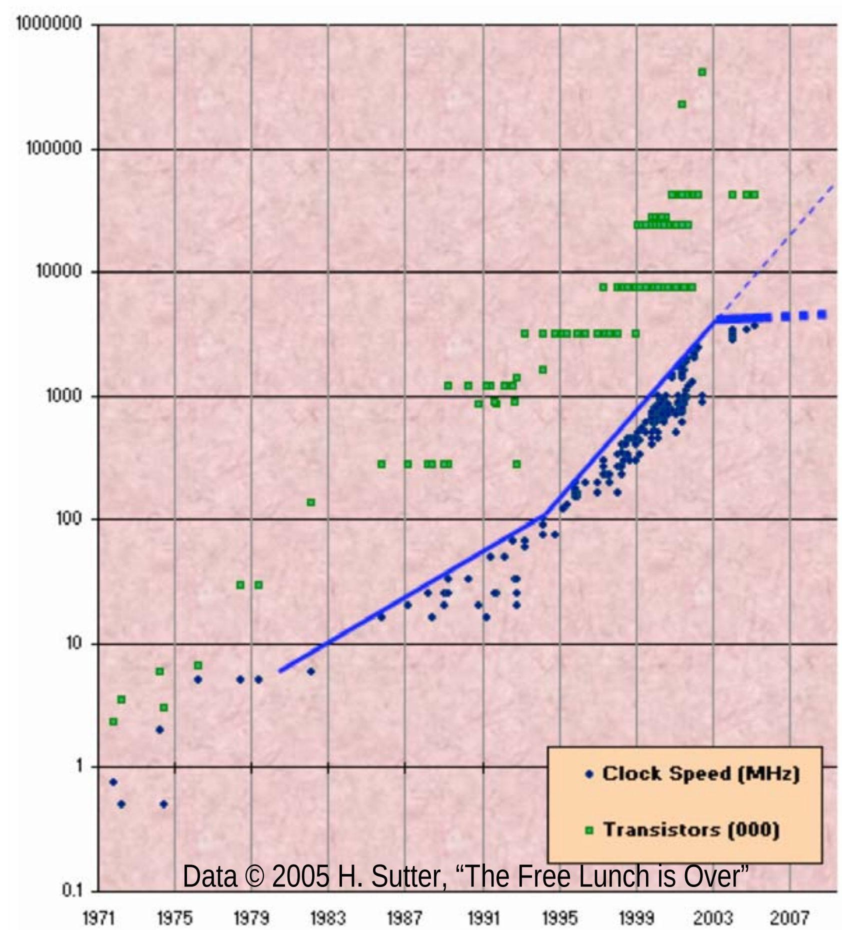
```
public class Accounts {
    // blue indicates blocking operations
    public static int getBalance(Account acct) { ... }
    public static void setBalance(Account acct, int balance) { ... }

    public void transfer(Account from, Account to, int amount) {
        int fromBal = getBalance(from);
        int toBal = getBalance(to);
        setBalance(from, fromBal - amount);
        setBalance(to, toBal + amount);
    }
}
```

Threads for parallelism

- Threads were originally used to simplify asynchrony
  - > MP machines were rare and expensive
- But threads also offer a promising means to exploit hardware parallelism
  - > Important, because parallelism is everywhere today
  - > On a 100-CPU box, a sequential program sees only 1% of the CPU cycles

Hardware trends

- Clock speeds maxed out in 2003
- But Moore's Law continues
  - > Giving us more cores instead of faster cores
- Result: many more programmers become concurrent programmers (maybe reluctantly)



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What are the alternatives?

- Threads are just one concurrency model
  - Threads == sequential processes that share memory
  - Any program state can change at any time
  - Programmer must prevent unwanted interactions
- There are other models too (Actors, CSP, BSP, staged programming, declarative concurrency, etc)
  - May limit *what* state can change
  - May limit *when* state can change
- Limiting the timing or scope of state changes reduces unpredictable interactions
- Can improve our code by learning from other models

What are the alternatives?

- With lock-based concurrency, the rules are
  - Hold locks when accessing shared, mutable state
  - Hold locks for duration of atomic operations
- Managing locking is difficult and error-prone
- The alternatives are
  - Don't mutate state
    - Eliminates need for coordination
  - Don't share state
    - Isolates effect of state changes
  - Share state only at well-defined points
    - Make the timing of concurrent modifications explicit

Prohibit mutation: functional languages

- Functional languages (e.g., Haskell, ML) outlaw mutable state
  - Variables are assigned values when they are declared, which never change
  - Expressions produce a value, but have no side effects
- No mutable state $\longrightarrow$ no need for synchronization!
  - No races, synchronization errors, atomicity failures
- No synchronization $\longrightarrow$ no deadlock!
- JOCaml == ML + Objects + Join Calculus

Applying it to Java: prefer immutability

- You can write immutable objects in Java
  - And you should!
  - Functional data structures can be efficient too
- Immutable objects are automatically thread-safe
  - And easier to reason about
  - And safer
  - And scale better
- Limit mutability as much as you can get away with
  - The less mutable state, the better
  - Enforce immutability if possible
    - Final is the new private!

Prohibit sharing: message passing

- Most parallel computation frameworks are based on message-passing
  - All mutable state is private to an activity
  - Interface to that activity is via messages
  - If you want to read it, ask them for the value
  - If you want to modify it, ask them to do it for you
- This makes the concurrency explicit
  - Apart from send/receive, all code behaves sequentially

Erlang: functional + message passing

- Everything is an Actor (analogous to a thread)
- Actors have an address, and can
  - > Send messages to other Actors
  - > Create new Actors
  - > Designate behavior for when a message is received
- Concurrency is explicit – send or receive messages
  - > Send primitive is “!”, received primitive is “receive”
  - > No shared state!
- Used in telephone switches
  - > 100KLoc, less than 3m/year downtime

Example: a simple counter in Erlang

- State in Erlang is local to an Actor
  - > Each counter is an Actor, who owns the count
  - > Clients send either “increment” or “get value” messages

```
increment(Counter) ->
    Counter ! increment.  %Send “increment” to Counter actor

value(Counter) ->
    Counter ! {self(),value}, %Send (my address, “value”) tuple
    receive                   %Wait for reply
        {Counter,Value} -> Value
    end.

%% The counter loop.
loop(Val) ->
    receive
        increment -> loop(Val + 1);
        {From,value} -> From ! {self(),Val}, loop(Val);
        Other -> loop(Val)  % All other messages
end.
```

- No shared or mutable state!

Actors in Scala

- Scala is an object-functional hybrid for the JVM
  - Similar in spirit to F# for .NET
  - Scala also supports an Actor model
    - Uses partial functions to select messages

```
case class Increment
case class Value

class Counter extends Actor {
   private var myValue = 0
   def act() {
      while (true) {
         receive {
            case Increment() => myValue += 1
            case (from: Actor, v: Value)
               => from ! (this, myValue)
            case _ =>
         }
      }
   }
}
```

Single mutation: the declarative model

- Functional languages have only bind, not assign
- The declarative concurrency model relaxes this somewhat to provide *dataflow variables*
  - Single-assignment (write-once) variables
    - Can either be unassigned or assigned
      - Only state transition is undefined → defined
    - Assigning more than once is an error
    - Reads to unassigned variables *block* until a value is assigned
- Nice: all possible executions with a given set of inputs have equivalent results
  - No races, locking, deadlocks
- Can be implemented in Java using Future classes

Responsible concurrency

- I don't expect people are going to ditch Java in favor of JOCaml, Erlang, or other models any time soon
- But we can try to restore predictability by limiting the nondeterminism of threads
  - Limit concurrent interactions to well-defined points
    - Encapsulate code that accesses shared state in frameworks
  - Limit shared data
    - Consider copying data instead of sharing it
  - Limit mutability
- Each of these reduces risk of unwanted interactions
  - Moves us closer to restoring determinism

Recommendations

- Concurrency is hard, so minimize the amount of code that has to deal with concurrency
  - Isolate concurrency in concurrent components such as blocking queues
  - Isolate code that accesses shared state in frameworks
- Use immutable objects wherever you can
  - Immutable objects are automatically thread safe
  - If you can't eliminate all mutable state, eliminate as much as you can
- Sometimes it's cheaper to share a non-thread-safe object by copying than to make it thread-safe

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