Principles of Software Construction: Objects, Design, and Concurrency

Concurrency Part III:

Structuring Applications

("Design Patterns for Parallel Computation")

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Learning Goals

- Reuse established libraries
- Apply common strategies to parallelize computations
- Use the Executor services to effectively schedule tasks

Administrivia

Last Tuesday

Guarded methods

- What to do on a method if the precondition is not fulfilled (e.g., transfer money from bank account with insufficient funds)
  - throw exception (**balking**)
  - wait until precondition is fulfilled (**guarded suspension**)
  - wait and timeout (combination of balking and guarded suspension)

Monitor Mechanics in Java (Recitation)

- Object.wait() – suspends the current thread's execution, releasing locks
- Object.wait(timeout) – suspends the current thread's execution for up to *timeout* milliseconds
- Object.notify() – resumes one of the waiting threads
- See documentation for exact semantics

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Monitor Example

```
class SimpleBoundedCounter {
  protected long count = MIN;
  public synchronized long count() { return count; }
  public synchronized void inc() throws InterruptedException {
        awaitUnderMax(); setCount(count + 1);
  }
  public synchronized void dec() throws InterruptedException {
        awaitOverMin(); setCount(count - 1);
  }
  protected void setCount(long newValue) { // PRE: lock held
        count = newValue;
        notifyAll(); // wake up any thread depending on new value
  }
  protected void awaitUnderMax() throws InterruptedException {
        while (count == MAX) wait();
  }
  protected void awaitOverMin() throws InterruptedException {
        while (count == MIN) wait();
  }
}
```

THREAD SAFETY: DESIGN TRADEOFFS

Synchronization

- **Thread-safe** objects vs **guarded**:
  - Thread-safe objects perform synchronization internally (clients can always call safely)
  - Guarded objects require clients to acquire lock for safe calls
- Thread-safe objects are easier to use (harder to misuse), but guarded objects can be more flexible

Designing Thread-Safe Objects

- Identify variables that represent the object's state
  - may be distributed across multiple objects
- Identify invariants that constraint the state variables
  - important to understand invariants to ensure atomicity of operations
- Establish a policy for managing concurrent access to state

Coarse-Grained Thread-Safety

- Synchronize all access to all state with the object

```
@ThreadSafe
public class PersonSet {
    @GuardedBy("this")
    private final Set<Person> mySet = new HashSet<Person>();

    @GuardedBy("this")
    private Person last = null;

    public synchronized void addPerson(Person p) {
        mySet.add(p);
    }

    public synchronized boolean containsPerson(Person p) {
        return mySet.contains(p);
    }

    public synchronized void setLast(Person p) {
        this.last = p;
    }
}
```

Fine-Grained Thread-Safety

- "Lock splitting": Separate state into independent regions with different locks

```
@ThreadSafe
public class PersonSet {
    @GuardedBy("myset")
    private final Set<Person> mySet = new HashSet<Person>();

    @GuardedBy("this")
    private Person last = null;

    public void addPerson(Person p) {
        synchronized (mySet) {
            mySet.add(p);
        }
    }

    public boolean containsPerson(Person p) {
        synchronized (mySet) {
            return mySet.contains(p);
        }
    }

    public synchronized void setLast(Person p) {
        this.last = p;
    }
}
```

Over vs Undersynchronization

- Undersynchronization -> safety hazard
- Oversynchronization -> liveness hazard and reduced performance

Tradeoffs

- Strategies:
  - Don't share the state variable across threads;
  - Make the state variable immutable; or
  - Use synchronization whenever accessing the state variable.
    - Thread-safe vs guarded
    - Coarse-grained vs fine-grained synchronization
- When to choose which strategy?
  - Avoid synchronization if possible
  - Choose simplicity over performance where possible

Today

- Design patterns for concurrency
- The Executor framework
- Concurrency libraries

THE PRODUCER-CONSUMER DESIGN PATTERN

Pattern Idea

- Decouple dependency of concurrent producer and consumer of some data
- Effects:
  - Removes code dependencies between producers and consumers
  - Decouples activities that may produce or consume data at different rates

Blocking Queues

- Provide blocking: `put` and `take` methods
  - If queue full, put blocks until space becomes available
  - If queue empty, take blocks until element is available

- Can also be bounded: throttle activities that threaten to produce more work than can be handled

- See https://docs.oracle.com/javase/7/docs/api/java/util/concurrent/BlockingQueue.html

Example: Desktop Search (1)

```
public class FileCrawler implements Runnable {
    private final BlockingQueue<File> fileQueue;
    private final FileFilter fileFilter;
    private final File root;

    ...
    public void run() {
        try {
            crawl(root);
        } catch (InterruptedException e) {
            Thread.currentThread().interrupt();
        }
    }

    private void crawl(File root) throws InterruptedException {
        File[] entries = root.listFiles(fileFilter);
        if (entries != null) {
            for (File entry : entries)
                if (entry.isDirectory())
                    crawl(entry);
                else if (!alreadyIndexed(entry))
                    fileQueue.put(entry);
        }
    }
}
```

The producer

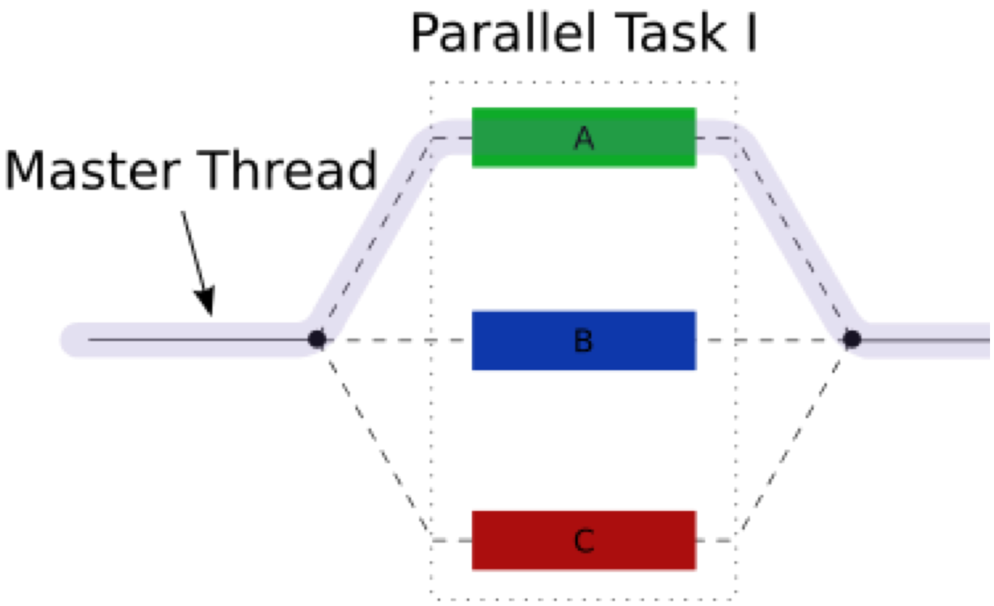
Example: Desktop Search (2)

```
public class Indexer implements Runnable {
    private final BlockingQueue<File> queue;

    public Indexer(BlockingQueue<File> queue) {
        this.queue = queue;
    }

    public void run() {
        try {
            while (true)
                indexFile(queue.take());
        } catch (InterruptedException e) {
            Thread.currentThread().interrupt();
        }
    }

    public void indexFile(File file) {
        // Index the file...
    };
}
```

The consumer

THE FORK-JOIN DESIGN PATTERN

Pattern Idea



- Pseudocode (parallel version of the divide and conquer paradigm)

```
if (my portion of the work is small enough)
    do the work directly
else
    split my work into two pieces
    invoke the two pieces and wait for the results
```

THE MEMBRANE DESIGN PATTERN

Pattern Idea

Multiple rounds of fork-join that need to wait for previous round to complete.

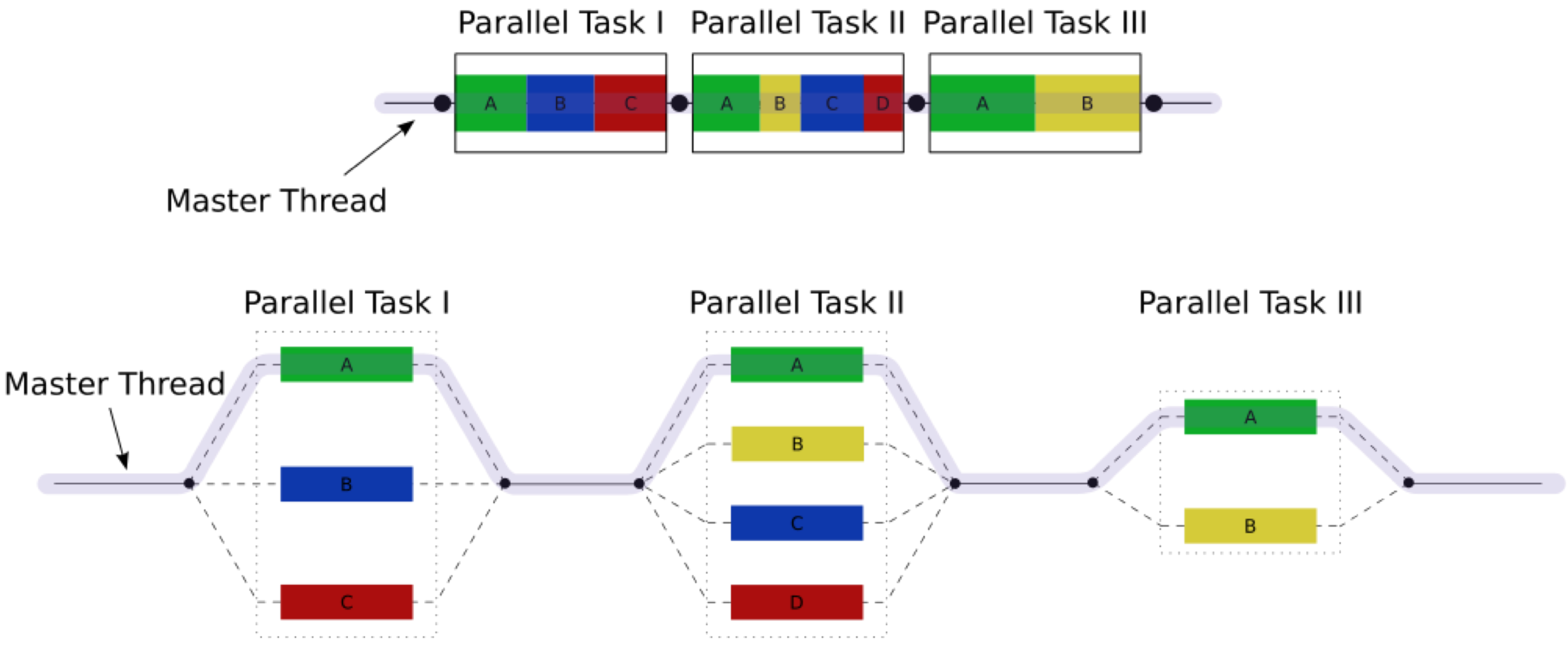


Image from: Wikipedia

TASKS AND THREADS

Executing tasks in threads

- Common abstraction for server applications
  - Typical requirements:
    - Good throughput
    - Good responsiveness
    - Graceful degradation
- Organize program around task execution
  - Identify *task boundaries*; ideally, tasks are *independent*
    - Natural choice of task boundary: individual client requests
  - Set a sensible *task execution policy*

Example: Server executing tasks sequentially

```
public class SingleThreadWebServer {
    public static void main(String[] args) throws IOException {
        ServerSocket socket = new ServerSocket(80);
        while (true) {
            Socket connection = socket.accept();
            handleRequest(connection);
        }
    }

    private static void handleRequest(Socket connection) {
        // request-handling logic here
    }
}
```

- Can only handle one request at a time
- Main thread alternates between accepting connections and processing the requests

Better: Explicitly creating threads for tasks

```
public class ThreadPerTaskWebServer {
    public static void main(String[] args) throws IOException {
        ServerSocket socket = new ServerSocket(80);
        while (true) {
            final Socket connection = socket.accept();
            Runnable task = new Runnable() {
                public void run() { handleRequest(connection); }
            };
            new Thread(task).start();
        }
    }
    private static void handleRequest(Socket connection) {
        // request-handling logic here
    }
}
```

- Main thread still alternates bt accepting connections and dispatching requests
- But each request is processed in a separate thread (higher throughput)
- And new connections can be accepted before previous requests complete (higher responsiveness)

Still, what's wrong?

```
public class ThreadPerTaskWebServer {
    public static void main(String[] args) throws IOException {
        ServerSocket socket = new ServerSocket(80);
        while (true) {
            final Socket connection = socket.accept();
            Runnable task = new Runnable() {
                public void run() { handleRequest(connection); }
            };
            new Thread(task).start();
        }
    }
    private static void handleRequest(Socket connection) {
        // request-handling logic here
    }
}
```

Disadvantages of unbounded thread creation

- Thread lifecycle overhead
  - Thread creation and teardown are not free
- Resource consumption
  - When there are more runnable threads than available processors, threads sit idle
  - Many idle threads can tie up a lot of memory
- Stability
  - There is a limit to how many threads can be created (varies by platform)
    - `OutOfMemory` error

THE THREAD POOL DESIGN PATTERN

Pattern Idea

- A thread pool maintains multiple threads waiting for tasks to be allocated for concurrent execution by the supervising program
  - Tightly bound to a *work queue*
- Advantages:
  - Reusing an existing thread instead of creating a new one
    - Amortizes thread creation/teardown over multiple requests
    - Thread creation latency does not delay task execution
  - Tune size of thread pool
    - Enough threads to keep processors busy while not having too many to run out of memory

EXECUTOR SERVICES

The Executor framework

- Recall: *bounded queues* prevent an overloaded application from running out of memory
- *Thread pools* offer the same benefit for thread management
  - Thread pool implementation part of the `Executor` framework in `java.util.concurrent`
  - Primary abstraction is `Executor`, not Thread

```
public interface Executor {
    void execute(Runnable command);
}
```

  - Using an `Executor` is usually the easiest way to implement a *producer-consumer* design

`Executors` – your one-stop shop for executor services

- `Executors.newSingleThreadExecutor()`
  - A single background thread
- `newFixedThreadPool(int nThreads)`
  - A fixed number of background threads
- `Executors.newCachedThreadPool()`
  - Grows in response to demand

Web server using Executor

```
public class TaskExecutionWebServer {
    private static final int NTHREADS = 100;
    private static final Executor exec
            = Executors.newFixedThreadPool(NTHREADS);

    public static void main(String[] args) throws IOException {
        ServerSocket socket = new ServerSocket(80);
        while (true) {
            final Socket connection = socket.accept();
            Runnable task = new Runnable() {
                public void run() {
                    handleRequest(connection);
                }
            };
            exec.execute(task);
        }
    }

    private static void handleRequest(Socket connection) {
        // request-handling logic here
    }
}
```

Easy to specify / change execution policy

- Thread-per-task server:

```
public class ThreadPerTaskExecutor implements Executor {
    public void execute(Runnable r) {
        new Thread(r).start();
    };
}
```

- Single thread server:

```
public class WithinThreadExecutor implements Executor {
    public void execute(Runnable r) {
        r.run();
    };
}
```

Execution policies

- Decoupling submission from execution
- Specify:
  - In what thread will tasks be executed?
  - In what order (FIFO, LIFO, …)?
  - How many tasks may execute concurrently?
  - How many tasks may be queued pending execution?
  - …
- Notice the strategy/template method pattern: general mechanism but highly customizable

Design goals (and tradeoffs): Task granularity and structure

- Maximize parallelism
  - The smaller the task, the more opportunities for parallelism → better CPU utilization, load balancing, locality, scalability; greater throughput
- Minimize overhead
  - Intrinsically more costly to create and use task objects than stack-frames → coarse-grained tasks
- Minimize contention
  - Maintain as much independence as possible between tasks → ideally, no shared resources, global (static) variables, locks
  - Some synchronization is unavoidable in fork/join designs
- Maximize locality
  - When parallel tasks all access different parts of a data set (e.g., different regions of a matrix), use partitioning strategies that reduce the need to coordinate across

Finding exploitable parallelism

- `Executor` framework makes it easy to specify an execution policy if you can describe your task as a `Runnable`
  - A single client request is a natural task boundary in server applications
- Task boundaries are not always obvious (see next slide)

Example: HTML page renderer

```
void renderPage(CharSequence source) {
    renderText(source);

    List<ImageData> imageData = new ArrayList<ImageData>();

    for (ImageInfo imageInfo : scanForImageInfo(source))
        imageData.add(imageInfo.downloadImage());

    for (ImageData data : imageData)
        renderImage(data);
}
```

- Issues:
  - Underutilize CPU while waiting for I/O
  - User waits long time for page to finish loading

Result bearing tasks: `Callable` and `Future`

- `Runnable.run` cannot return value or throw checked exceptions (although it can have side effects)
- Many tasks are deferred computations (e.g., fetching a resource over a network) → `Callable` is a better abstraction
  - `Callable.call` will return a value and anticipates that it might throw an exception
- `Runnable` and `Callable` describe *abstract* computational tasks
- `Future` represents the *lifecycle* of a task (created, submitted, started, completed)

Callable and Future interfaces

```
public interface Callable<V> {
    V call() throws Exception;
}
```

```
public interface Future<V> {
    boolean cancel(boolean mayInterruptIfRunning);
    boolean isCancelled();
    boolean isDone();
    V get() throws InterruptedException,
        ExecutionException, CancellationException;
    V get(long timeout, TimeUnit unit)
        throws InterruptedException, ExecutionException,
        CancellationException, TimeoutException;
}
```

Creating a Future to describe a task

- `Process:`
  - `submit` a `Runnable` or `Callable` to an executor and get back a `Future` that can be used to retrieve the result or cancel the task
  - Or explicitly instantiate a FutureTask for a given `Runnable` or `Callable`

Example: Page renderer with Future

- Divide into two tasks
  - Render text (CPU-bound)
  - Download all images (I/O-bound)
- Steps (also go to recitation):
  1. – Create a `Callable` for download subtask
  2. – Submit `Callable` to `ExecutorService`
  3. – `ExecutorService` returns `Future` describing the task's execution
  4. – When main task reaches point where it needs the images, it waits for the result by calling `Future.get`
     - If lucky, images already downloaded
     - If not, at least we got a head start

Future renderer (1)

```
public abstract class FutureRenderer {
    private final ExecutorService executor = ...;

    void renderPage(CharSequence source) {
        final List<ImageInfo> imageInfos = scanForImageInfo(source);
        Callable<List<ImageData>> task =
            new Callable<List<ImageData>>() {
                public List<ImageData> call() {
                    List<ImageData> result = new ArrayList<ImageData>();
                    for (ImageInfo imageInfo : imageInfos)
                        result.add(imageInfo.downloadImage());
                    return result;
                }
            };

        Future<List<ImageData>> future = executor.submit(task);
        renderText(source);

    // Continued below
```

1 2 3

Future renderer (2)

```
public abstract class FutureRenderer {
       ...
        try {
            List<ImageData> imageData = future.get();
            for (ImageData data : imageData)
                renderImage(data);

        } catch (InterruptedException e) {
            // Re-assert the thread's interrupted status
            Thread.currentThread().interrupt();
            // We don't need the result, so cancel the task too
            future.cancel(true);
        } catch (ExecutionException e) {
            throw launderThrowable(e.getCause());
        }
    }
}
```

4

Future renderer analysis

- Allows text to be rendered concurrently with downloading data
- When all images are downloaded, they are rendered onto the page

- Can we do better?

Limitations of parallelizing heterogeneous tasks

- We tried to execute two different types of tasks in parallel—downloading images, rendering page
- Does not scale well
  - How can we use more than two threads?
  - Tasks may have disparate sizes
    - If rendering text is much faster than downloading images, performance is not much different from sequential version
- Lesson: real performance payoff of dividing a program's workload into tasks comes when there are many independent, *homogeneous* tasks that can be processed concurrently

Example: Page renderer with CompletionService

- `CompletionService` combines the functionality of an `Executor` and a `BlockingQueue`
  - `submit` `Callable` tasks to `CompletionService`
  - use queue-like methods `take` and `poll` to retrieve completed results, packaged as `Futures`, as they become available

Page renderer with CompletionService
Download images in parallel (1)

```
public abstract class Renderer {
    private final ExecutorService executor;

    ...

    void renderPage(CharSequence source) {
        final List<ImageInfo> info = scanForImageInfo(source);

        CompletionService<ImageData> completionService =
                new ExecutorCompletionService<ImageData>(executor);

        for (final ImageInfo imageInfo : info)
            completionService.submit(new Callable<ImageData>() {
                public ImageData call() {
                    return imageInfo.downloadImage();
                }
            });

        renderText(source);
        // Continued below
```

Page renderer with CompletionService
Download images in parallel (2)

```
public abstract class Renderer {
        ...

        try {
            for (int t = 0, n = info.size(); t < n; t++) {
                Future<ImageData> f = completionService.take();
                ImageData imageData = f.get();
                renderImage(imageData);
            }

        } catch (InterruptedException e) {
            Thread.currentThread().interrupt();
        } catch (ExecutionException e) {
            throw launderThrowable(e.getCause());
        }
    }
}
```

Summary

- Structuring applications around the execution of tasks can simplify development and facilitate concurrency
- The Executor framework permits you to decouple task submission from execution policy
- To maximize benefit of decomposing an application into tasks, identify sensible task boundaries
  - Not always obvious

Recommended Readings

- Goetz et al. Java Concurrency In Practice. Pearson Education, 2006, Chapters 5 (Building blocks) and 6 (Task executions)
- Lea, Douglas. Concurrent programming in Java: design principles and patterns. Addison-Wesley Professional, 2000, Chapter 4.4 (Parallel decoposition)

REUSE RATHER THAN BUILD: KNOW THE LIBRARIES

Synchronized Collections

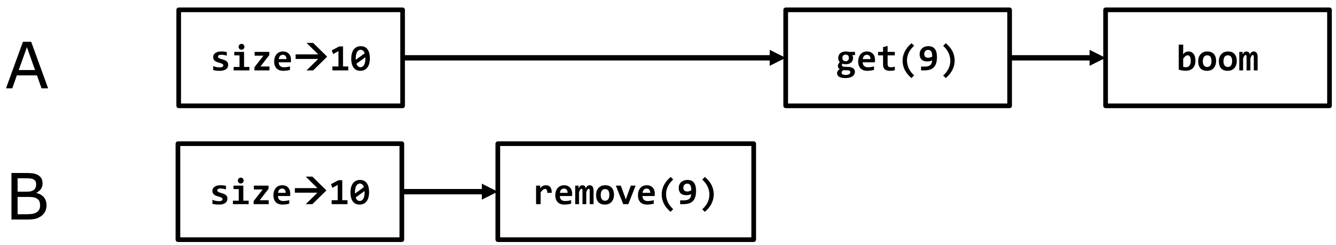
- Are thread safe:
  - Vector
  - Hashtable
  - Collections.synchronizedXXX
- But still require client-side locking to guard compound actions:
  - Iteration: repeatedly fetch elements until collection is exhausted
  - Navigation: find next element after this one according to some order
  - Conditional ops (put-if-absent)

Example

- Both methods are thread safe

```
public static Object getLast(Vector list) {
    int lastIndex = list.size() - 1;
    return list.get(lastIndex);
}

public static void deleteLast(Vector list) {
    int lastIndex = list.size() - 1;
    list.remove(lastIndex);
}
```

- Unlucky interleaving that throws `ArrayIndexOutOfBoundsException`



Solution: Compound actions on Vector using client-side locking

- Synchronized collections guard methods with the lock on the collection object itself

```
public static Object getLast(Vector list) {
    synchronized (list) {
        int lastIndex = list.size() - 1;
        return list.get(lastIndex);
    }
}

public static void deleteLast(Vector list) {
    synchronized (list) {
        int lastIndex = list.size() - 1;
        list.remove(lastIndex);
    }
}
```

Another Example

- The size of the list might change between a call to `size` and a corresponding call to `get`
  - Will throw `ArrayIndexOutOfBoundsException`

```
for (int i = 0; i < vector.size(); i++)
    doSomething(vector.get(i));
```

- Note: Vector is still thread safe:
  - State is valid
  - Exception conforms with specification

Solution: Client-side locking

- Hold the Vector lock for the duration of iteration:
  - No other threads can modify (+)
  - No other threads can access (-)

```
synchronized (vector) {
    for (int i = 0; i < vector.size(); i++)
        doSomething(vector.get(i));
}
```

Iterators and `ConcurrentModificationException`

- Iterators returned by the synchronized collections are not designed to deal with concurrent modification → *fail-fast*
- Implementation:
  - Each collection has a modification count
  - If it changes, `hasNext` or `next` throws `ConcurrentModificationException`
- Prevent by locking the collection:
  - Other threads that need to access the collection will block until iteration is complete → starvation
  - Risk factor for deadlock
  - Hurts scalability (remember lock contention in reading)

Alternative to locking the collection during iteration?

Yet Another Example: Is this safe?

```java
public class HiddenIterator {
    @GuardedBy("this")
    private final Set<Integer> set = new HashSet<Integer>();

    public synchronized void add(Integer i) { set.add(i); }

    public synchronized void remove(Integer i) { set.remove(i); }

    public void addTenThings() {
        Random r = new Random();
        for (int i = 0; i < 10; i++)
            add(r.nextInt());
        System.out.println("DEBUG: added ten elements to " + set);
    }
}
```

Hidden Iterator

- Locking can prevent `ConcurrentModificationException`
- But must remember to lock everywhere a shared collection might be iterated

```
public class HiddenIterator {
    @GuardedBy("this")
    private final Set<Integer> set = new HashSet<Integer>();

    public synchronized void add(Integer i) { set.add(i); }

    public synchronized void remove(Integer i) { set.remove(i); }

    public void addTenThings() {
        Random r = new Random();
        for (int i = 0; i < 10; i++)
            add(r.nextInt());
        System.out.println("DEBUG: added ten elements to " + set);
    }
}
```

Hidden Iterator

```
System.out.println("DEBUG: added ten elements to " + set);
```

- String concatenation
  - → `StringBuilder.append(Object)`
  - → `Set.toString()`
  - → Iterates the collection; calls `toString()` on each element
  - → `addTenThings()` may throw `ConcurrentModificationException`

- **Lesson: Just as encapsulating an object's state makes it easier to preserve its invariants, encapsulating its synchronization makes it easier to enforce its synchronization policy**

Concurrent Collections

- Synchronized collections: thread safety by serializing all access to state
  - Cost: poor concurrency
- Concurrent collections are designed for concurrent access from multiple threads
  - Dramatic scalability improvements

Unsynchronized	Concurrent
HashMap	ConcurrentHashMap
HashSet	ConcurrentHashSet
TreeMap	ConcurrentSkipListMap
TreeSet	ConcurrentSkipListSet

ConcurrentHashMap

- `HashMap.get`: traversing a hash bucket to find a specific object → calling `equals` on a number of candidate objects
  - Can take a long time if hash function is poor and elements are unevenly distributed
- `ConcurrentHashMap` uses ***lock striping*** (recall reading)
  - Arbitrarily many reading threads can access concurrently
  - Readers can access map concurrently with writers
  - Limited number of writers can modify concurrently
- Tradeoffs:
  - `size` only an estimate
  - Can't lock for exclusive access

You can't exclude concurrent activity from a concurrent collection

- This works for synchronized collections…

```
Map<String, String> syncMap =
    Collections.synchronizedMap(new HashMap<>());
synchronized(syncMap) {
    if (!syncMap.containsKey("foo"))
        syncMap.put("foo", "bar");
}
```

- But ***not*** for concurrent collections
  - They do their own internal synchronization
  - **Never synchronize on a concurrent collection!**

Concurrent collections have prepackaged read-modify-write methods

- V **putIfAbsent**(K key, V value)
- boolean **remove**,(Object key, Object value)
- V **replace**(K key, V value)
- boolean **replace**(K key, V oldValue, V newValue)
- V **compute**(K key, BiFunction<...> remappingFn);
- V **computeIfAbsent**(K key, Function<...> mappingFn)
- V **computeIfPresent**(K key, BiFunction<...> remapFn)
- V **merge**(K key, V value, BiFunction<...> remapFn)

Summary

- Design patterns for concurrency
- The Executor framework
- Concurrency libraries

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