CS 351
Design of Large Programs
Object Design: Safety and Liveness

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Software Assurance: Testing

Testing is an integral part of software development

- is a necessity at all levels
- is expensive
- can be simplified through the use of tools
- illuminates the existence of bugs
- fails to establish the absence of bugs
- is assisted by debugging tools and skills

Software Assurance: Testing

Concurrency make testing exceedingly difficult

- Program A
  - 10 boolean variables
  - 2^{10} possible states
- Program B
  - 10 boolean variables
  - 2^{10} possible states
- Concurrent execution
  - $2^{10} \times 2^{10}$ possible states
  - $2^{10} = 1024$
  - $2^{20} = 1048576$

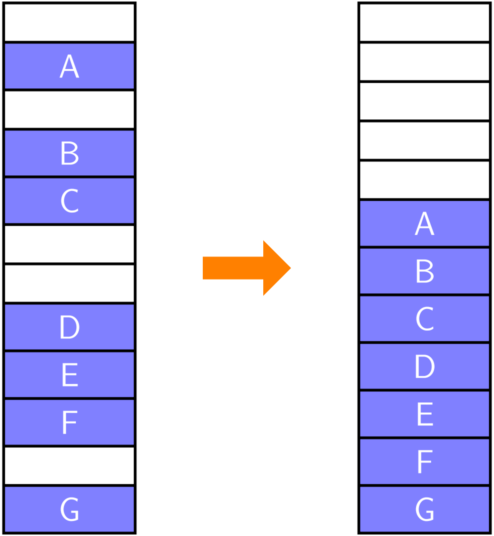
Software Assurance: Verification

- Formal verification
    - provides strong guarantees
    - is difficult to carry out
    - requires specialized knowledge and tools
- Good design facilitates both testing and verification

Key Concepts in Verification

- Safety – the program does nothing wrong
    - data integrity
    - absence of deadlock
- Liveness – the program does something
    - reaches a desired goal
    - terminates

Example: Memory Compaction



Specification

- Safety
  - the contents of each used memory block remains unchanged
  - the ordering of used memory blocks remains unaltered
  - the number of free space blocks remains unchanged
- Liveness
  - the protocol reaches a state in which all free space is contiguous located at the top

Safety Properties

- *Invariant* – a property that holds initially and forever
    - block A holds data XX
    - block A is above block C
- *Stable* – a property which, once established, holds forever
    - all blocks below k^{th} block are used blocks
    - all blocks above k^{th} block are free blocks

Liveness Properties

- *Leads to* – from a state S1 the Memory Compaction program eventually reaches a state S2
  - S1: any memory state
  - S2: all free space is at the top
- *Metric* – progress is measured by a decrease in some useful metric
  - sum of distances from the top of the memory to each free block
    - initial value: $0 + 2 + 5 + 6 + 10 = 23$
    - final value: $0 + 1 + 2 + 3 + 4 = 10$

Important Observations

- The protocol may be implemented as a sequential or concurrent program
- Concurrent threads should not interfere with each other
    - this is an important additional proof obligation
    - the proof may be highly complex
    - the program may be vulnerable to subtle errors
- It is desirable to ensure *correctness by design*
    - at least when it comes to non-interference (atomicity)

Design of Safe Objects

Conservative design strategies

- Immutability – avoiding state changes
- Synchronization – ensuring mutual exclusion
- Containment – structural restrictions ensuring exclusive access

Immutable Objects: Reliance on Constructors

- Fixed variables can be initialized in the constructor
- No methods to change the variable are provided

```
public class Leader {
  private final NodeId n;

  public Leader(NodeId n) {
    this.n = n;
  }
  // no setter for field!
}
```

Immutable Objects: Stateless Methods

- Methods that have no bearing on the state of the object
- Pure functions
  - return value depends only on the passed arguments
  - return value may also depend upon immutable variables

```
public class NumericalOps {
  public static int add(int a,
                        int b) {
    return a + b;
  }
}
```

```
public class Leader {
  private final NodeId n;
  //...
  public int rank(NodeId k) {
    if (k.id() < n.id()) {
      return n.id() - k.id();
    } else {
      return 0;
    }
  }
}
```

Immutable Objects: Copying Policy

- Making a local temporary copy and returning it as the result of the computation protects the original object
- Copy needs to be atomic in order to avoid destroying data integrity
- The object passed as argument needs to offer an atomic copy method

```
public int[] sort(int[] array) {
  int[] copy = new int[array.length];
  // place sorted elements in copy...
  return copy;
}
```

Synchronized Objects: Full Synchronization

- The goal is to ensure mutual exclusion among all the methods accessing the object
    - every method is synchronized
    - no public fields are present
- Access to other object can break encapsulation!
- Careful analysis and discipline is required

Display Room Lighting

- Assume that we have a display room with multiple light sources
- one and only one light is on at any one time
- a user can select a light to turn on
- a user can turn off the light, forcing some other light to be turned on

Synchronized Object: Display Room Lighting

```
public class LightControl {
  private List<Light> lights;
  private Light onLight;
  private Random rand;
  // initialize fields...

  public synchronized void on(Light light) {
    if (onLight != null) onLight.turnOff();
    onLight = light;
    onLight.turnOn();
  }

  public synchronized void off() {
    if (onLight != null) onLight.turnOff();
    onLight = lights.get(rand.nextInt(lights.size()));
    onLight.turnOn();
  }
}
```

Static Field Complications

- Synchronization assures mutual exclusion among methods of the same object
- Methods of different objects can interfere with each other if they access static fields
- Options:
  - allow only static synchronized methods to access static fields
  - use block synchronization with a lock on that class – getClass()

Protecting Static Fields: File Users Counter

```java
public class FileUsers {
  private static int userCount = 0; // never access directly

  protected void beginUsing() {
    synchronized (getClass()) {
      ++userCount;
    }
  }

  protected void endUsing() {
    synchronized (getClass()) {
      --userCount;
    }
  }

  public static synchronized int numberUsing() {
    return userCount;
  }
}
```

Partial Synchronization

- Only methods that can interfere with each other are declared as synchronized
- Only sections of code where interference can occur are protected by a synchronization block

```
synchronized(this) {
  // code here...
}
```

Partial Synchronization: Linked List

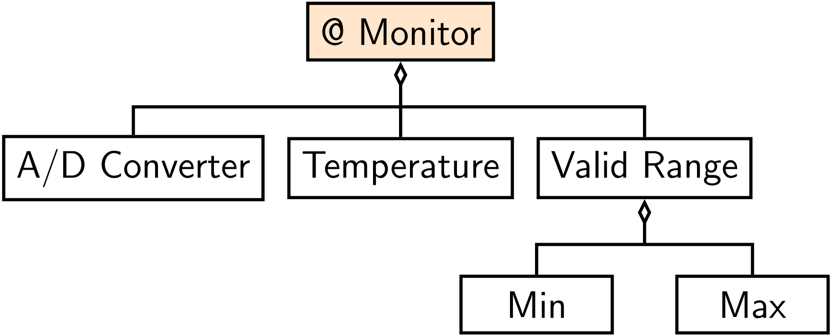
```java
public class LinkedCell {
  protected double value;
  protected final LinkedCell next;

  public LinkedCell (double value, LinkedCell next) {
    this.value = value;
    this.next = next;
  }

  public synchronized double getValue() { return value; }

  public synchronized void setValue(double value) {
    this.value = value;
  }

  public LinkedCell getNext() { return next; }

  public double sum() { // add up element values
    double v = getValue(); // get value via synchronized accessor
    if (next() != null) { v += next().sum(); }
    return v;
  }
}
```

Contained Objects: Exclusive Ownership

The outer object

- ensures that only one thread executes at a time (synchronized methods)
- subordinate objects are locally created
- references to the subordinate objects are not leaked
    - not passed as arguments
    - not passed as returned values

Exclusive Ownership Example



@ Monitor

A/D Converter

Temperature

Valid Range

Min

Max

Contained Objects: Managed Ownership

- It is often the case that ownership of a resource may change over time
- Invariant: *only one accessible reference exists in the system at any one time*
- Ownership transfer operations must be subject to defined policies enforced by design

Liveness: Failure Modes

- Reliance on timing properties
  - proofs of concurrent programs are meant to show that under all possible interleaving of events the execution is correct
- Contention on the CPU leading to starvation
  - proofs of concurrent programs assume that no thread is denied service by the OS
- Dormancy – a suspended thread never becomes schedulable again
  - suspend/resume and wait/notify pairing errors
- Premature termination
- Deadlock

Deadlock Prevention

- Every thread locks the resources it needs in the same order
- The locking order is not always readily visible
- Complications arise when locks are deep inside the object nesting structure

```
public class Document {
  private Document otherPart;
  public synchronized void print() {
    // print this part of the document
  }
  public synchronized void printAll() {
    otherPart.print();
    print();
  }
}
```

Deadlock Illustration

Thread 1	**Thread 2**

Deadlock Illustration

Thread 1

letter.printAll

letter is locked

Thread 2

enclosure.printAll

enclosure is locked

Deadlock Illustration

Thread 1

letter.printAll

letter is locked

letter.otherPart.print

blocked

waiting for enclosure

Thread 2

enclosure.printAll

enclosure is locked

enclosure.otherPart.print

blocked

waiting for letter

Additional Failure Modes

- Data integrity violations
  - synchronized methods do not always guarantee atomicity
  - data inconsistencies lead to incorrect decisions
- Lack of progress
  - progress made by one thread is undone by another
- Livelock
  - threads take turns yielding to each other

Livelock Illustration

Thread 1	**Thread 2**
resource requested	resource requested

Livelock Illustration

Thread 1

resource requested

contention on resource?

Thread 2

resource requested

contention on resource?

Livelock Illustration

Thread 1	**Thread 2**
resource requested	resource requested
contention on resource?	contention on resource?
Yes!	Yes!

Livelock Illustration

Thread 1	**Thread 2**
resource requested	resource requested
contention on resource?	contention on resource?
Yes!	Yes!
withdraw request	withdraw request

Livelock Illustration

Thread 1	**Thread 2**
resource requested	resource requested
contention on resource?	contention on resource?
Yes!	Yes!
withdraw request	withdraw request
try later	try later

Livelock Illustration

Thread 1

resource requested

contention on resource?

- Yes!
- withdraw request
- try later

Thread 2

resource requested

contention on resource?

- Yes!
- withdraw request
- try later

How could we stop colliding?

Locking and Performance

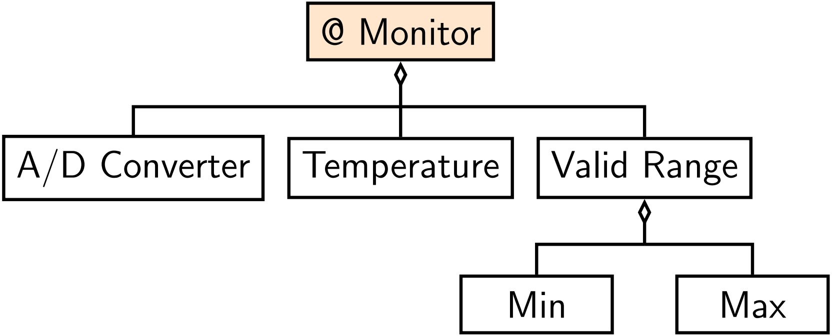
- Synchronized methods and locks may introduce performance penalties
    - correctness must come first
    - thoughtful analysis can ensure correctness and enhance performance
- Instant variable analysis helps determine where synchronization is or is not needed
- Proper design of object hierarchies may simplify analysis and reduce the need for synchronization

Interleaving Semantics

- Access and update methods are normally synchronized
- A very long update can delay reading of the data
- Two solutions:
  - employ synchronization blocks
  - let the access method be unsynchronized as long as it returns one of only two values:
    - the value *before* the update
    - the value *after* the update

A Conservative Design Revisited

- All methods of Monitor are synchronized
    - protection against any data inconsistencies
- Only one thread can use Monitor at a time



@ Monitor

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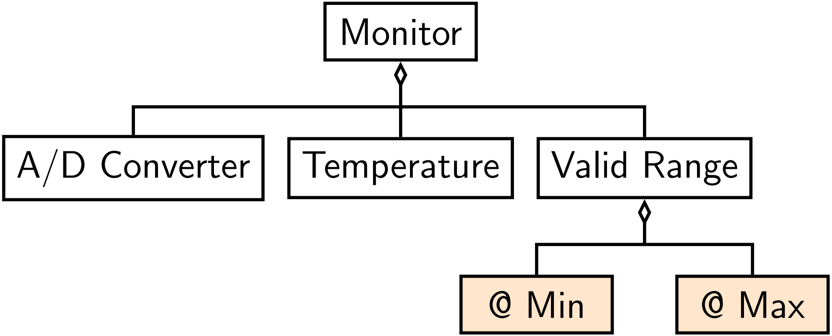
Class Splitting

- Monitor can be redesigned
    - by using synchronization only on contained objects that need it
- Multiple threads can use Monitor concurrently
- More generally, contained objects may be designed in order to achieve fine-grained synchronization and increased levels of concurrency

Class Splitting



Monitor

A/D Converter

Temperature

Valid Range

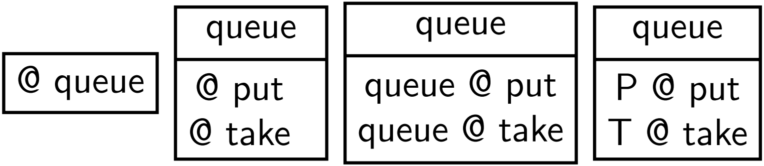
@ Min

@ Max

Lock Splitting

- Every Java Object can be a lock
- Synchronized methods use the object to which they belong as a lock
- Another object could be used to accomplish the same objective
- Using multiple locks allows subgroups of methods to be mutually exclusive
- Going one step further, locks can be selectively used in a state dependent manner

Sample Design Notation



@ queue

queue

@ put
@ take

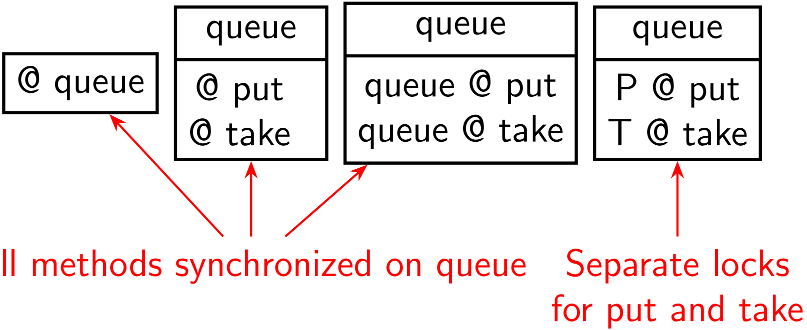
queue

queue @ put
queue @ take

queue

P @ put
T @ take

Sample Design Notation



All methods synchronized on queue

Separate locks for put and take