MIT
6.031: Software Construction
Max Goldman and Prof. Rob Miller revised Wednesday 4th December, 2019, 16:22

Solutions to Quiz 2 (December 3, 2019)

This quiz uses the same abstract data type as Quiz 1, *information board entries*. The description of the abstract values is reproduced on the rest of this page, unchanged from Quiz 1.

The problems in this quiz refer to the code for mutable `MutInfoEntry` and immutable `ImInfoEntry`, starting on page 11. **This code is different than the code in Quiz 1.** You may detach the code pages.

Train stations, airports, and other transit hubs often have displays that show upcoming departures or arrivals along with other information: a track or gate number, delays, cancellations, etc.

For this quiz, an *information board* is made of several *information board entries*. Each entry has limited space: 16 characters to display a *destination* and 12 characters for a *status*. Both are restricted to upper-case letters, digits, colons, and spaces. For example, a board with three entries:

```
WASHINGTON DC    11:05 AM
LONDON HEATHROW  11:55 AM
HONG KONG        DELAYED
```

In order to show more information, the board cycles each entry through a looping sequence of up to four statuses. For example, if WASHINGTON DC and LONDON HEATHROW have 2-status loops, and HONG KONG has a 3-status loop, then every few seconds the board will update:

```
WASHINGTON DC    ON TIME
LONDON HEATHROW  ON TIME
HONG KONG        NEW DEPRTURE
```

```
WASHINGTON DC    11:05 AM
LONDON HEATHROW  11:55 AM
HONG KONG         1:40 PM
```

```
WASHINGTON DC    ON TIME
LONDON HEATHROW  ON TIME
HONG KONG        DELAYED
```

```
WASHINGTON DC    11:05 AM
LONDON HEATHROW  11:55 AM
HONG KONG        NEW DEPRTURE
```

```
WASHINGTON DC    ON TIME
LONDON HEATHROW  ON TIME
HONG KONG         1:40 PM
```

. . . and so on.

Problem 1 (Thread Safety) (**26 points**).
Suppose a train station's information board system uses `MutInfoEntry` objects. The system is multi-threaded:

- one thread, the *display thread*, calls `nextStatus()` on all the `MutInfoEntry` objects every few seconds in order to display a cycling sequence of statuses to people in the station.
- other threads, the *update threads*, can call `setStatuses()` on any `MutInfoEntry` object when updated information about a train is received.

(a) Describe a race condition between the display thread and an update thread by showing an interleaving of operations that leads to a bad outcome, and state what the bad outcome is.

display thread	update thread

bad outcome:

Solution.

One bad interleaving is `statuses.clear()` on the update thread, immediately followed by `statuses.remove(0)` on the display thread, leading to throwing an `ArrayIndexOutOfBoundsException`, which violates the postcondition of `nextStatus()`.

Another bad interleaving is `statuses.remove(0)` on the display thread, immediately followed by `statuses.clear()` on the update thread, which eventually puts an out-of-date status back on the end of the just-updated statuses list, violating the postcondition of `setStatuses()`. If `setStatuses()` was called with a 4-element list, then this would also lead to breaking the rep invariant, since `statuses` now contains 5 statuses.

■

(b) Which objects involved in the rep of `MutInfoEntry` are in danger of having their rep invariants broken by concurrency? Circle either DANGER or SAFE, and explain why in at most one sentence.

`ArrayList` rep invariant
DANGER SAFE because:

`MutInfoEntry` rep invariant
DANGER SAFE because:

`String` rep invariant
DANGER SAFE because:

Solution.

`ArrayList` is SAFE because the only reference to it is inside a synchronized wrapper. The answer "SAFE because `ArrayList` is responsible for establishing and maintaining its own rep invariant" is not correct, because this question asked specifically about concurrency, and `ArrayList` does not guarantee to be threadsafe. The answer "DANGER because `ArrayList` is not threadsafe" is also not a sufficient answer, because it ignores the presence of the synchronized wrapper. The answer "DANGER" with an explanation that talks about dangers to the `MutInfoEntry` rep invariant, is also not correct, because the constraints on a `MutInfoEntry` rep aren't relevant to `ArrayList`'s rep invariant.

`MutInfoEntry` is in DANGER because interleaved calls to `setStatuses()` (between two update threads) or `nextStatus()` and `setStatuses()` (between the display thread and an update thread) could end up putting more than 4 statuses on the list.

`String` is SAFE because it is immutable.

■

(c) Suppose that we decide to use the *monitor pattern*. State in one sentence what changes we would make to `MutInfoEntry`.

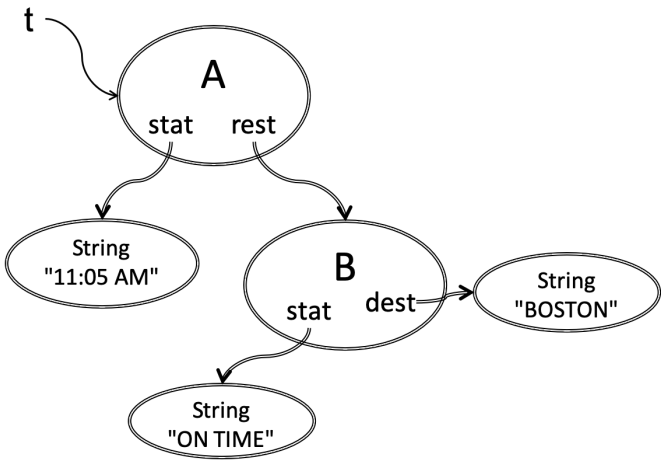
Solution.

Use the keyword `synchronized` on every public instance method of `MutInfoEntry`.

Other ways of using `synchronized` (e.g. only on the methods that touch `statuses`, or using the lock on the `statuses` object rather than `this`) may indeed solve the race condition in part (a), but they are not the monitor pattern. ■

Problem 2 (Recursive Datatypes) (**26 points**).
Suppose we want to implement `ImInfoEntry` (an *immutable* information board entry) as a recursive data type with two variants. The two variants are called A and B.

The snapshot diagram below shows how the datatype represents an information board entry `t` with destination "BOSTON" and two statuses "11:05 AM" and "ON TIME", whose current status is "11:05 AM".



(a) Write a datatype definition that corresponds to the snapshot diagram and implements `ImInfoEntry`.

ImInfoEntry =

Solution.

```
A(stat:String, rest:ImInfoEntry) + B(stat:String, dest:String)
```

■

(b) Fill in the blanks to implement `destination()`, `status()`, and `size()` for variants A and B:

```
public class A implements ImInfoEntry {
  ...
  public String destination() { return ____________________________________________ ; }

  public String status()      { return ____________________________________________ ; }

  public int size()           { return ____________________________________________ ; }
```

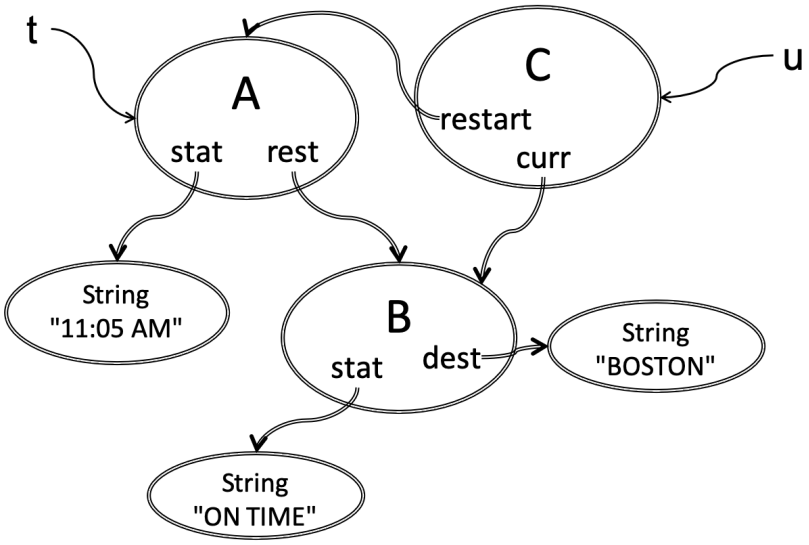
```
}

public class B implements ImInfoEntry {
  ...
  public String destination() { return ____________________________________________ ; }


  public String status()      { return ____________________________________________ ; }


  public int size()           { return ____________________________________________ ; }
}
```

Solution.

```
public class A implements ImInfoEntry {
  ...
  public String destination() { return this.rest.destination(); }


  public String status()      { return this.stat; }


  public int size()           { return 1 + this.rest.size(); }
}

public class B implements ImInfoEntry {
  ...
  public String destination() { return this.dest; }


  public String status()      { return this.stat; }


  public int size()           { return 1; }
}
```

■

To help implement the `nextEntry` operation, we add one more variant `C`.
The result of `u = t.nextEntry()` is shown in the snapshot diagram below.



(c) Fill in the blanks to implement `nextEntry()` for all three variants.

```
public class A implements ImInfoEntry {
  ...
  public ImInfoEntry nextEntry() {
      return new C(this, rest);
  }
}

public class B implements ImInfoEntry {
  ...
  public ImInfoEntry nextEntry() {

      return ____________________________________________________________ ;

  }
}

public class C implements ImInfoEntry {
  ...
  public ImInfoEntry nextEntry() {
    if (this.curr.size() == 1) { // curr has reached the end of the list

      return ____________________________________________________________ ;

    } else {

      return ____________________________________________________________ ;
    }
  }
}
```

Solution.

From the example and code shown for `A.nextEntry()`, the datatype definition is now:

```
ImInfoEntry = A(stat:String, rest:ImInfoEntry)
            + B(stat:String, dest:String)
            + C(restart:ImInfoEntry, curr:ImInfoEntry)
```

The `C` variant represents an information entry whose current status is `curr.status()` (i.e., possibly advanced farther down the list), and whose future statuses follow the `rest` pointers from `curr` until the end of the list (a `B` variant), and then loop back to `restart`.

So the given code for `A.nextEntry()` constructs a `C` whose `restart` is the `A` object and whose current status is the successor of the `A` object:

```
public class A implements ImInfoEntry {
  ...
  public ImInfoEntry nextEntry() {
      return new C(this, rest);
  }
}
```

Here is the simplest answer for `B.nextEntry()`:

```
public class B implements ImInfoEntry {
  ...
  public ImInfoEntry nextEntry() {
      return this;
  }
}
```

...because `B` represents an entry with only 1 status, so it immediately loops back to itself. Another possible answer is `new C(this, this)`.

Here is the simplest answer for `B.nextEntry()`:

```
public class C implements ImInfoEntry {
  ...
  public ImInfoEntry nextEntry() {
    if (this.curr.size() == 1) { // curr has reached the end of the list

      return this.restart;

    } else {

      return new C(this.restart, this.curr.nextEntry());
    }
  }
}
```

As before, `new C(this.restart, this.restart)` would also work for the first return statement.

Note that `C` is an immutable object, so it's necessary to create a fresh `C` here rather than, say, reassigning `this.curr = this.curr.nextEntry()`.

Note also that `this.curr.rest` is not correct, because `this.curr` might refer to any `ImInfoEntry` variant – A, B, or even C. `this.curr` doesn't necessarily point to a B object, and so the `rest` instance variable doesn't necessarily exist on that object.

■

Problem 3 (Grammars) (**22 points**).

(a) Which of these regular expressions accept (fully match) every legal status and destination string, and reject (fail to fully match) at least one illegal string? Circle YES or NO.

```
[A-Z0-9: ]+
        matches every legal string?              YES      NO

        rejects at least one illegal string?     YES      NO
```

Solution.

NO to matching every legal string – it does not match the empty string, which is a legal status.

YES to rejecting at least one illegal string – for example, it rejects the illegal string `","`.

■

```
([A-Z]*|[0-9]*|:*| *)+
        matches every legal string?              YES      NO

        rejects at least one illegal string?     YES      NO
```

Solution.

YES to matching every legal string. The parenthesized regex can match any legal character, and can also match the empty string. The parenthesized regex must then match at least once, because of the `+` operator applied to it, but because the parenthesized regex can match the empty string, this means that the overall regex can also match the empty string.

YES to rejecting at least one illegal string – for example, it rejects the illegal string `","`.

■

```
[A-Z]*[0-9]*[:]*[ ]*
        matches every legal string?              YES      NO

        rejects at least one illegal string?     YES      NO
```

Solution.

NO to matching every legal string – it does not match `"11:05 AM"`, for example, because once the colon has matched `[:]*`, there is no way to match the remaining digits and letters in the string.

YES to rejecting at least one illegal string – for example, it rejects the illegal string `","`.

■

```
.*[A-Z0-9: ]*
        matches every legal string?              YES      NO

        rejects at least one illegal string?     YES      NO
```

Solution.

YES to matching every legal string, because `.*` can match the empty string at the start, and then `[A-Z0-9: ]*` can match the rest of a legal string.

NO to rejecting at least one illegal string, because this regex actually matches all possible strings – `.*` can match the entire string first, and then `[A-Z0-9: ]*` can be satisfied by matching the empty string at the end.

■

(b) Suppose an information board entry is represented as a string of text as in this example:

```
WASHINGTON|NEW DEPRTURE,TRACK 2,11:35AM
```

Complete the grammar below so that it can be used to parse an information board entry, with starting nonterminal `infoentry`. Your grammar must use the `destination` and `status` nonterminals shown, which you can assume have been defined with a correct answer from part (a).

For the purpose of this grammar, assume that statuses and destinations have **no maximum length**, and an information board entry has **no maximum number of statuses**.

destination ::= *a correct regular expression from part (a)*
status ::= *a correct regular expression from part (a)*

infoentry ::=

Solution.

```
infoentry ::= destination '|' status ( ',' status )*
```

Here is another solution that avoids using the repetition operator `*` by introducing a new nonterminal:

```
infoentry ::= destination '|' statuses
statuses ::= status   |   status ( ',' status )*
```

And here is a solution that enforces the maximum number of statuses (which was not required by the instructions):

```
infoentry ::= destination '|' statuses
statuses ::= status
           | status ',' status
           | status ',' status ',' status
           | status ',' status ',' status ',' status
```

■

Problem 4 (Map/Filter and Callbacks) (**26 points**)**.**
Suppose we add `map` and `filter` operations to `ImInfoEntry`, to transform the (cyclic) stream of status messages that an information board entry displays:

```
map: ImInfoEntry x (String -> String) -> ImInfoEntry
filter: ImInfoEntry x (String -> Boolean) -> ImInfoEntry
```

These operations affect only the statuses of an `ImInfoEntry`, not its destination.

(a) Of the four kinds of ADT operations, what kind(s) of operations is `ImInfoEntry.map`? Leave extra boxes blank:

Solution.

Producer.

■

(b) Use `map` to replace every English status message found in the `translations` map below with its corresponding French translation.

```
Map<String, String> translations = Map.of("ON TIME",   "A LHEURE",
                                          "CANCELED", "SUPPRIME");

ImInfoEntry train1 = ImInfoEntry.parse("MONTREAL|ON TIME,11:05 AM");
// train1 has statuses "ON TIME", "11:05 AM"

ImInfoEntry train2 = train1.map(...MAP...);
// train2 has statuses "A LHEURE", "11:05 AM"
```

Write a Java lambda expression for **`...MAP...`** in the code above:

Solution.

```
status -> map.getOrDefault(status, status)
```

Alternatively:

```
status -> {
    if (map.containsKey(status)) {
        return map.get(status);
    } else {
        return status;
    }
}
```

■

(c) Write a Java lambda expression that, if passed to **`filter`** (not `map`), would transform the stream of status messages in a way that cannot be a legal abstract value of the `ImInfoEntry` type.

Solution.

This filter function would fail to match all possible status messages, which is illegal because an information entry must have at least one status:

```
status -> false
```

■

Now suppose that a mutable information board entry `MutInfoEntry` also has a `map` operation:

```
map: MutInfoEntry x (String -> String) -> void
```

`MutInfoEntry.map` transforms all statuses subsequently returned by the entry, as shown in this example:

```
1 Function<String, String> toFrench = ...MAP...; // a correct answer to part (b) above
2 MutInfoEntry train = new MutInfoEntry("MONTREAL");
3 train.nextStatus();  // returns ""
4 train.map(toFrench);
5 train.setStatuses(List.of("ON TIME","11:05 AM"));
6 train.nextStatus();  // returns "A LHEURE"
7 train.nextStatus();  // returns "11:05 AM"
8 train.setStatuses(List.of("CANCELED"));
9 train.nextStatus(); // returns "SUPPRIME"
```

(d) What kind(s) of operation is `MutInfoEntry.map`? Leave extra boxes blank:

Solution.

Mutator.

Note that "observer" is not a good answer here, because the `map` operation by itself returns no information to the client, and doesn't even necessarily call the client's transform function with any statuses (yet).

■

To implement `map`, the rep of `MutInfoEntry` now has a third field:

```
private Function<String, String> f;
```

and its abstraction function is (only relevant parts shown):

> AF(`destination`, `statuses`, `f`) = the info board entry with current status `f(statuses[0])` and looping through future statuses `f(statuses[1])`, ..., `f(statuses[statuses.length-1])`, `f(status[0])`, and so on... [rest of AF elided]

The `MutInfoEntry` methods are implemented to obey this AF and behave as shown in the code above.

(e) Write a Java lambda expression for the initial value of `f` for a new `MutInfoEntry` object.

Solution.

It should be the identity function, e.g.:

```
status -> status
```

■

(f) During which of the numbered lines in the example code above is the `toFrench` function called? List all line numbers that apply, or write NEVER if `toFrench` is never called. Note that this question is asking about **`toFrench`**.

Solution.

Lines 6, 7, 9. `toFrench` must be called by every `nextStatus()` call after it is installed.

Line 3 is not correct because `toFrench` is not been called yet.

Line 4 is not correct because `toFrench` is passed just as a reference to the function, not a call.

Lines 5, and 8 are not correct because the abstraction function declares that `statuses` in the rep is a list of untransformed statuses. The map function should not be called when the statuses are stored, only when they are displayed. Calling `toFrench` during these lines is possible (perhaps by a fast-failing `checkRep()` method) but not necessary.

■

(g) What should `MutInfoEntry`'s rep invariant comment say about `f`? Note that this question is asking about **`f`**.

Solution.

`f` is a function that requires a valid status as input (the precondition) and returns a valid status (postcondition). Without this constraint, the `nextStatus()` operation is unable to satisfy its postcondition.

A statement that includes only the postcondition – e.g. "`f` returns only valid statuses" – is too strong, because it excludes many valid functions. For example, the identity function can return an invalid status if it is given an invalid status.

A statement that speaks only about the current state of the object – e.g. "`f(statuses[i])` is a valid status for all `i`" – is not strong enough. There may be some valid status `s` *not currently* in `statuses` where `f(s)` is invalid. `setStatuses()` would have to accept `s` as one of the new statuses, but this would break the rep.

A statement that repeats the type signature of `f`, e.g. "`f` is a function from strings to strings", is not strong enough, and is unnecessary to include in the rep invariant comment because the type declaration already states it.

■

You may detach this page. Write your username at the top, and hand in all pages when you leave.

```
/**
 *  An information board entry that shows a destination (e.g. "WASHINGTON DC")
 *  and cycles through a list of 1 to 4 statuses (e.g. [ "11:05 AM", "ON TIME" ],
 *  or [ "NOW BOARDING", "TRACK 3" ]).
 *
 *  A valid destination is up to 16 characters, consisting only of
 *  upper-case letters A-Z, digits, colons, or spaces.
 *
 *  A valid status is up to 12 characters, consisting only of
 *  upper-case letters A-Z, digits, colons, or spaces.
 */
public class MutInfoEntry {

    private final String destination;
```

```
    private List<String> statuses = Collections.synchronizedList(new ArrayList<String>());

    // Abstraction function:
    //   <elided>
    // Rep invariant:
    //   - destination is a valid destination (defined above)
    //   - statuses has 1-4 elements, each of which is a valid status (defined above)

    /** Create a new information board entry with the given destination and
     *  a single empty status.
     *  @param destination a valid destination (defined above) */
    public MutInfoEntry(String destination) {
        this.destination = destination;
        statuses.add("");
    }

    /**  @return the destination */
    public String destination() { return destination; }

    /** @return the next status to display, infinitely cycling through this
     *          info board entry's statuses in order  */
    public String nextStatus() {
        final String status = statuses.remove(0);
        statuses.add(status); // put it back on end so that statuses cycle forever
        return status;
    }

    /** Set the statuses. The first status in the list will be displayed next.
     *  @param statuses new statuses, a 1- to 4-item list of valid statuses */
    public void setStatuses(List<String> statuses) {
        this.statuses.clear();
        this.statuses.addAll(statuses);
    }
}
```

You may detach this page. Write your username at the top, and hand in all pages when you leave.

```
/**
 *  An information board entry that shows a destination (e.g. "WASHINGTON DC")
 *  and current status (e.g. "DELAYED") in a cycle of 1 to 4 statuses
 *  (e.g. [ "DELAYED", "NEW DEPRTURE", "11:55 AM" ]).
 *
 *  A valid destination is up to 16 characters, consisting only of
 *  upper-case letters A-Z, digits, colons, or spaces.
 *
 *  A valid status is up to 12 characters, consisting only of
 *  upper-case letters A-Z, digits, colons, or spaces.
 */
public interface ImInfoEntry {

    /** @return the destination */
```

```
    public String destination();

    /** @return the currently-shown status */
    public String status();

    /** @return the entry with the same destination and statuses,
     *          showing the next status in the cycle  */
    public ImInfoEntry nextEntry();

    /** @return number of statuses in the cycle, from 1 to 4 */
    public int size();

    /** @param entry information board entry represented as a string according
     *               to the grammar in Problem 3
     *  @return corresponding information board entry value */
    public static ImInfoEntry parse(String entry) { ... }

}
```