哈爾濱工業大學
HARBIN INSTITUTE OF TECHNOLOGY

Chapter 7: Software Construction for Robustness

7.3 Assertions and Defensive Programming

Ming Liu

April 17, 2019

Outline

- **Recall: Designing an ADT**
- **Assertions**
  - What to Assert and What not to?
  - Guidelines for Using Assertions
- **Defensive Programming**
  - Techniques for defensive programming
- **Summary**

1 Recall: Designing an ADT

First Defense: Make Bugs Impossible

- **The best defense against bugs is to make them impossible by design.**
  - **Static checking**: eliminates many bugs by catching them at compile time.
  - **Dynamic checking**: Java makes array overflow bugs impossible by catching them dynamically. If you try to use an index outside the bounds of an array or a List, then Java automatically produces an error.
  - **Immutability** (immunity from change): An immutable type is a type whose values can never change once they have been created.
  - **Immutable references**: by `final`

Second Defense: Localize Bugs

- If we can’t prevent bugs, we can try to localize them to a small part of the program, so that we don’t have to look too hard to find the cause of a bug.
- When localized to a single method or small module, bugs may be found simply by studying the program text.
- **Fail fast**: the earlier a problem is observed (the closer to its cause), the easier it is to fix.

```
/**
 * @param x  requires x >= 0
 * @return approximation to square root of x
 */
public double sqrt(double x) {
    if (! (x >= 0)) throw new AssertionError();
    ...
}
```

Second Defense: Localize Bugs

- **Assertions: When the precondition is not satisfied, this code terminates the program by throwing an `AssertionError` exception. The effects of the caller's bug are prevented from propagating.**

- **Checking preconditions is an example of defensive programming. Real programs are rarely bug-free. Defensive programming offers a way to mitigate the effects of bugs even if you don't know where they are.**

2 Assertions

哈爾濱工業大學
HARBIN INSTITUTE OF TECHNOLOGY

(1) What and Why Assertions?

What is assertion?

- **An assertion is code that's used during development that allows a program to check itself as it runs, i.e.,** to *test your assumptions* about your program logic (such as pre-conditions, post-conditions, and invariants).
  - When an assertion is true, that means everything is operating as expected.
  - When it's false, that means it has detected an unexpected error in the code.
- **An example**

```
public class AssertionTest {
   public static void main(String[] args) {
      int number = -5;    // assumed number is not negative
      // This assert also serve as documentation
      assert (number >= 0) : "number is negative: " + number;
      // do something
      System.out.println("The number is " + number);
   }
}
```

What is assertion?

- **Each assertion contains a `boolean` expression that you believe will be true when the program executes.**
- **If it is not true, the JVM will throw an `AssertionError`.**
- **This error signals you that you have an invalid assumption that needs to be fixed.**
- **Assertion is much better than using `if-else` statements, as it serves as proper documentation on your assumptions, and it does not carry performance liability in the production environment.**

What is assertion?

- **An assertion usually takes two arguments**
  - **a boolean expression** that describes the assumption supposed to be true
  - **a message** to display if it isn't.
- **The Java language has a keyword `assert`. There are two forms:**
  - `assert condition;`
  - `assert condition : expression;`
  - Both statements evaluate the condition and throw an `AssertionError` if the boolean expression evaluates to false.
  - In the second statement, the expression is passed to the constructor of the `AssertionError` object and turned into a message string. The description is printed in an error message when the assertion fails, so it can be used to provide additional details to the programmer about the cause of the failure.

Assertion in Java

- To assert that `x` is non-negative, you can simply use the statement

```
assert x >= 0;
```

- Or pass the actual value of `x` into the `AssertionError` object, so that it gets displayed later:

```
assert x >= 0 : “x is ” + x;
```

- If `x == -1`, then this assertion fails with the error message

```
x is -1
```

- This information is often enough to get started in finding the bug.

Assertion Example

```
public class AssertionSwitchTest {
   public static void main(String[] args) {
      // assumed either '+', '-', '*', '/' only
      char operator = '%';
      int operand1 = 5, operand2 = 6, result = 0;
      switch (operator) {
         case '+': result = operand1 + operand2; break;
         case '-': result = operand1 - operand2; break;
         case '*': result = operand1 * operand2; break;
         case '/': result = operand1 / operand2; break;
         default: assert false : "Unknown operator: " + operator;
      }
      System.out.println(operand1 + " " + operator + " "
               + operand2 + " = " + result);
   }
}
```

Why use assertions?

- **Document & test programmer's assumptions, e.g., invariants;**
- **Verify programmer’s understanding**
- **Quickly uncover bugs**
- **Increase confidence that program is bug-free**
- **Asserts turn black box tests into white box tests**

Assertion vs. Exception?

- **Assertions generally cover correctness issues of program.**
- **Exceptions generally cover robustness issues of program.**
- **Assertions are especially useful in large, complicated programs and in high reliability programs.**
  - They enable programmers to more quickly flush out mismatched interface assumptions, errors that creep in when code is modified, and so on.

- **Recall:** `CheckRep()` **in Chapter 2 ADT for Rep Invariants.**

(2) What to Assert and What not to?

What to Assert?

- **Method argument requirements**
- **Method return value requirements**
  - This kind of assertion is sometimes called a ***self check*** .

```
public double sqrt(double x) {
    assert x >= 0;
    double r;
    ... // compute result r
    assert Math.abs(r*r - x) < .0001;
    return r;
}
```

- **Covering all**
  - If a conditional statement or switch does not cover all the possible cases, it is good practice to use an assertion to block the illegal cases.

```
switch (vowel) {
    case 'a':
    case 'e':
    case 'i':
    case 'o':
    case 'u': return "A";
    default: assert false;
}
```

When to use assertions?

- **Normally, you don't want users to see assertion messages in production code; assertions are primarily for use during development and maintenance.**
- **Assertions are normally compiled into the code at development time and compiled out of the code for production. During development, assertions flush out contradictory assumptions, unexpected conditions, bad values passed to routines, and so on.**
- **During production, they are compiled out of the code so that the assertions don't degrade system performance.**
- **When should you write runtime assertions? As you write the code, not after the fact. When you're writing the code, you have the invariants in mind. If you postpone writing assertions, you're less likely to do it, and you're liable to omit some important invariants.**

What Not to Assert?

- **Runtime assertions are not free. They can clutter the code, so they must be used judiciously.**
  - Avoid trivial assertions, just as you would avoid uninformative comments.

```
// don't do this:
x = y + 1;
assert x == y+1;
```

  - This assertion doesn't find bugs in your code.
  - It finds bugs in the compiler or Java virtual machine, which are components that you should trust until you have good reason to doubt them.
  - If an assertion is obvious from its local context, leave it out.

Don’t Assert External Conditions

- **Never use assertions to test conditions that are external to your program.**
  - Such as the existence of files, the availability of the network, or the correctness of input typed by a human user.
  - Assertions test the internal state of your program to ensure that it is within the bounds of its specification.
  - When an assertion fails, it indicates that the program has run off the rails in some sense, into a state in which it was not designed to function properly. Assertion failures therefore indicate bugs.
  - External failures are not bugs, and there is no change you can make to your program in advance that will prevent them from happening.
  - External failures should be handled using exceptions instead. Avoid trivial assertions, just as you would avoid uninformative comments.

Turn on/off Assert in different phases

- **Many assertion mechanisms are designed so that assertions are executed only during testing and debugging, and turned off when the program is released to users.**
- **Java's assert statement behaves this way. (however, assertions are off by default)**
- **The advantage of this approach is that you can write very expensive assertions that would otherwise seriously degrade the performance of your program.**
  - For example, a procedure that searches an array using binary search has a requirement that the array be sorted.
  - Asserting this requirement requires scanning through the entire array, however, turning an operation that should run in logarithmic time into one that takes linear time.
  - You should be willing to pay this cost during testing, since it makes debugging much easier, but not after the program is released to users.

Suggestion: always enable assertions

- **However, disabling assertions in release has a serious disadvantage.**
- **With assertions disabled, a program has far less error checking when it needs it most.**
- **Novice programmers are usually much more concerned about the performance impact of assertions than they should be.**
- **Most assertions are cheap, so they should not be disabled in the official release.**

Enable & Disable assertions in Java

- **Enable assertions**
  - Running the program with the `-enableassertions` or `-ea` option:
    - `java -enableassertions MyApp`
  - The option -ea... turns on assertions in all classes of the default package.
    - `java -ea:MyClass -ea:com.mycompany.mylib... MyApp`
- **Disable assertions**
  - Running the program with the `-disableassertions` or `-da` option:
    - `java -ea:... -da:MyClass MyApp`
- **By default, assertions are disabled.**
- **Enable assertions in Eclipse:**
  - In preferences, go to Java → Installed JREs . Click “Java SE 8”, click “Edit…”, and in the “Default VM arguments” box enter: `-ea`

`assert` vs. `assertXXX()`... in JUnit

- **The Java assert statement is a different mechanism from the JUnit methods** `assertTrue()`, `assertEquals()`, **etc.**
- **They all assert a predicate about your code, but are designed for use in different contexts.**
- **The** `assert` **statement should be used in implementation code, for defensive checks inside the implementation.**
- **JUnit** `assertXXX()` **methods should be used in JUnit tests, to check the result of a test.**
- **The** `assert` **statements don't run without** `-ea`, **but the JUnit** `assertXXX()` **methods always run.**

(3) Guidelines for Using Assertions

Assertions vs. exceptions

- **Use error handling code (exception) for conditions you expect to occur;**
- **Use assertions for conditions that should never occur**
  - **Assertions check for conditions that should never occur**. **Error handling code checks for off-nominal circumstances that might not occur very often**, but that have been anticipated by the programmer who wrote the code and that need to be handled by the production code. Error-handling typically checks for bad input data; assertions check for bugs in the code.
  - If error handling code is used to address an anomalous condition, the error handling will enable the program to respond to the error gracefully.
  - If an assertion is fired for an anomalous condition, the corrective action is not merely to handle an error gracefully—the corrective action is to change the program's source code, recompile, and release a new version of the software.

Avoid putting executable code in assertions

- **Since assertions may be disabled, the correctness of your program should never depend on whether or not the assertion expressions are executed.**
- **In particular, asserted expressions should not have *side-effects* .**
  - For example, if you want to assert that an element removed from a list was actually found in the list, don't write it like this:
- **If assertions are disabled, the entire expression is skipped, and x is never removed from the list. Write it like this instead:**

```
// don't do this:
assert list.remove(x);
```

```
// do this:
boolean found = list.remove(x);
assert found;
```

Use Assertions for pre-/post- conditions

- **Preconditions and postconditions are part of an approach to program design and development known as "design by contract".**
  - When preconditions and postconditions are used, each routine or class forms a contract with the rest of the program.
  - **Preconditions are the properties that the client code of a routine or class promises will be true before it calls the routine or instantiates the object.** Preconditions are the client code's obligations to the code it calls.
  - **Postconditions are the properties that the routine or class promises will be true when it concludes executing.** Postconditions are the routine or class's obligations to the code that uses it.
- **Assertions are a useful tool for documenting preconditions and postconditions.**
  - Comments could be used to document preconditions and postconditions, but assertions can check dynamically whether the preconditions and postconditions are true.

Use Assertions for pre-/post- conditions

- **If the variables latitude, longitude, and elevation were coming from an external source, invalid values should be checked and handled by error handling code rather than assertions.**
- **If the variables are coming from a trusted, internal source, however, and the routine's design is based on the assumption that these values will be within their valid ranges, then assertions are appropriate.**

```
float latitude;
float longitude;
float elevation;

//Preconditions
assert latitude>=-90 && latitude<=90;
assert longitude>=0 && longitude<360;
assert elevation>=-500 && elevation<=75000;
……
//Postconditions
assert Velocity>=0 && Velocity <= 600

//return value
return Velocity;
```

Combine assert and error handling for robustness

- **Both assertions and error handling code might be used to address the same error.**
- **In the source code for Microsoft Word, for example, conditions that should always be true are asserted, but such errors are also handled by error-handling code in case the assertion fails.**
- **For extremely large, complex, long-lived applications like Word, assertions are valuable because they help to flush out as many development-time errors as possible.**
- **But the application is so complex (million of lines of code) and has gone through so many generations of modification that it isn't realistic to assume that every conceivable error will be detected and corrected before the software ships, and so errors must be handled in the production version of the system as well.**

3 Defensive Programming

What is defensive programming?

- **Defensive programming is a form of defensive design intended to ensure the continuing function of a piece of software under unforeseen circumstances.**
  - Defensive programming practices are often used where high availability, safety or security is needed.
- In defensive programming, **the main idea is that if a method is passed bad data, it won't be hurt, even if the bad data is another routine's fault.**
  - More generally, it's the recognition that programs will have problems and modifications, and that a smart programmer will develop code accordingly.

What is defensive programming?

- **Defensive programming** DOESN'T MEAN being defensive about your programming—"It does so work!"
- The idea is based on defensive driving.
  - In defensive driving, you adopt the mind-set that you're never sure what the other drivers are going to do.
  - That way, you make sure that if they do something dangerous you won't be hurt.
  - You take responsibility for protecting yourself even when it might be the other driver's fault.

Techniques for defensive programming

Techniques for defensive programming

- **Protecting programs from invalid inputs**
- **Assertions**
- **Exceptions**
- **Specific error handling techniques**
- **Barricade**
- **Debugging aids**

- **The best form of defensive coding is not inserting errors in the first place.**
- **You can use defensive programming in combination with the other techniques.**

(1) Protecting Programs From Invalid Inputs

- **“Garbage in, garbage out.”**
  - That expression is essentially software development’s version of caveat emptor: let the user beware.
- **For production software, garbage in, garbage out isn’t good enough.**
- **A good program never puts out garbage, regardless of what it takes in.**
  - “garbage in, nothing out”
  - “garbage in, error message out”
  - “no garbage allowed in”
- **“Garbage in, garbage out” is the mark of a sloppy, non-secure program.**

Protecting Programs From Invalid Inputs

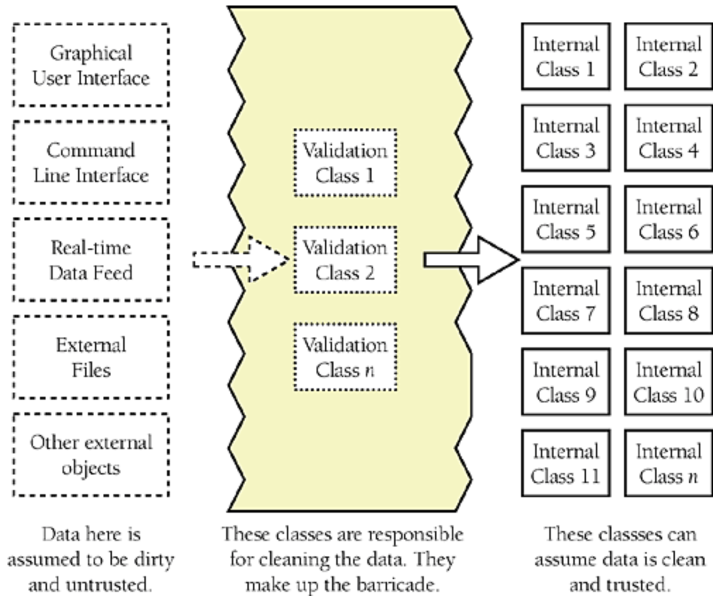
- **Check the values of all data from external sources**
  - When getting data from a file, a user, the network, or some other external interface, check to be sure that the data falls within the allowable range.
- **Examples:**
  - Make sure that numeric values are within tolerances and that strings are short enough to handle.
  - If a string is intended to represent a restricted range of values (such as a financial transaction ID or something similar), be sure that the string is valid for its intended purpose; otherwise reject it.
  - If you're working on a secure application, be especially leery of data that might attack your system: attempted buffer overflows, injected SQL commands, injected html or XML code, integer overflows, and so on.

Protecting Programs From Invalid Inputs

- **Check the values of all routine input parameters**
  - Checking the values of routine input parameters is essentially the same as checking data that comes from an external source.
- **Decide how to handle bad inputs**
  - Once you've detected an invalid parameter, what do you do with it? Depending on the situation, you might choose any of a dozen different approaches, which are described in detail later in this chapter.

(2) Barricade

- **Barricades are a damage-containment strategy.**
  - The reason is similar to that for having isolated compartments in the hull of a ship and firewalls in a building.
- **One way to barricade for defensive programming purposes is to designate certain interfaces as boundaries to "safe" areas. Check data crossing the boundaries of a safe area for validity and respond sensibly if the data isn't valid.**



Defining some parts of the software that work with dirty data and some that work with clean can be an effective way to relieve the majority of the code of the responsibility for checking for bad data.

Barricade

- **The class's public methods assume the data is unsafe, and they are responsible for checking the data and sanitizing it.**
- **Once the data has been accepted by the class's public methods, the class's private methods can assume the data is safe.**
- **Another way of thinking about this approach is as an operating-room technique.**
  - Data is sterilized before it's allowed to enter the operating room. Anything that's in the operating room is assumed to be safe.
  - The key design decision is deciding what to put in the operating room, what to keep out, and where to put the doors—which routines are considered to be inside the safety zone, which are outside, and which sanitize the data.
  - The easiest way to do this is usually by sanitizing external data as it arrives, but data often needs to be sanitized at more than one level, so multiple levels of sterilization are sometimes required.

Relationship between Barricades and Assertions

- **The use of barricades makes the distinction between assertions and error handling clean cut.**
  - Routines that are outside the barricade should use error handling because it isn't safe to make any assumptions about the data.
  - Routines inside the barricade should use assertions, because the data passed to them is supposed to be sanitized before it's passed across the barricade. If one of the routines inside the barricade detects bad data, that's an error in the program rather than an error in the data.

- **The use of barricades also illustrates the value of deciding at the architectural level how to handle errors. Deciding which code is inside and which is outside the barricade is an architecture-level decision.**

(3) Debugging Aids

- **Debugging aids is a key aspect of defensive programming for quickly detecting errors. (See 7.4 debugging)**
- **Don't Automatically Apply Production Constraints to the Development Version.**
  - A common programmer blind spot is the assumption that limitations of the production software apply to the development version.

production version	development version
has to run fast	might be able to run slow
has to be stingy with resources	might be allowed to use resources extravagantly
shouldn't expose dangerous operations to the user	can have extra operations that you can use without a safety net

  - Be willing to trade speed and resource usage during development in exchange for built-in tools that can make development go more smoothly.

Debugging Aids: Use Offensive Programming

- **Some ways you can program offensively:**
  - Make sure asserts abort the program. Don't allow programmers to get into the habit of just hitting the ENTER key to bypass a known problem. Make the problem painful enough that it will be fixed.
  - Completely fill any memory allocated so that you can detect memory allocation errors.
  - Completely fill any files or streams allocated to flush out any file-format errors.
  - Be sure the code in each case statement's else clause fails hard (aborts the program) or is otherwise impossible to overlook.
  - Fill an object with junk data just before it's deleted
- **Sometimes the best defense is a good offense.**
- **Fail hard during development so that you can fail softer during production.**

Debugging Aids: Plan to Remove Debugging Aids

- **In commercial software, leaving all the debugging code in the program will cause that the performance penalty in size and speed can be prohibitive. Plan to avoid shuffling debugging code in and out of a program.**
  - Use version control and build tools like make
    - Version-control tools(like ant, make…) can build different versions of a program from the same source files.
    - In development mode, you can set the build tool to include all the debug code.
    - In production mode, you can set it to exclude any debug code you don't want in the commercial version.
  - Use a built-in preprocessor
    - If your programming environment has a preprocessor—as C++ does, for example—you can include or exclude debug code at the flick of a compiler switch.
    - You can use the preprocessor directly or by writing a macro that works with preprocessor definitions.

Debugging Aids: Plan to Remove Debugging Aids

- **Use debugging stubs使用调试存根**
  - In many instances, you can call a routine to do debugging checks.
  - During development, the routine might perform several operations before control returns to the caller.
  - For production code, you can replace the complicated routine with a stub routine that merely returns control immediately to the caller or performs only a couple of quick operations before returning control.
  - This approach incurs only a small performance penalty, and it's a quicker solution than writing your own preprocessor. Keep both the development and production versions of the routines so that you can switch back and forth during future development and production.

```
// check object passed in during development
void checkObject(someClass XXX){
   …//check whether null
   …//check data format
   …
   …//check data integrality  }
```

```
// check object passed in during production
void checkObject(someClass XXX){
// no code; just return to caller
}
```

Determining How Much Defensive Programming to Leave in Production Code?

- **One of the paradoxes of defensive programming is that during development, you'd like an error to be noticeable.**
- **But during production, you'd rather have the error be as unobtrusive as possible, to have the program recover or fail gracefully.**
- **Some guidelines for deciding which defensive programming tools to leave in your production code and which to leave out:**

(1) Leave in code that checks for important errors

- **Decide which areas of the program can afford to have undetected errors and which areas cannot.**
- **E.g., in a spreadsheet program, undetected errors in the screen-update area of the program may be affordable, but undetected errors in the calculation engine is unaffordable.**

(2) Remove code that checks for trivial errors

- **If an error has truly trivial consequences, remove code that checks for it.**
- **In the previous example, you might remove the code that checks the spreadsheet screen update.**
- **"Remove" doesn't mean physically remove the code. It means use version control, precompiler switches, or some other technique to compile the program without that particular code.**
- **If space isn't a problem, you could leave in the error-checking code but have it log messages to an error-log file unobtrusively.**

(3) Remove code that results in hard crashes

- **If your program contains debugging code that could cause a loss of data, take it out of the production version.**
- **During development, when your program detects an error, you'd like the error to be as noticeable as possible so that you can fix it.**
  – Often, the best way to accomplish such a goal is to have the program print a debugging message and crash when it detects an error.
  – This is useful even for minor errors.
- **During production, your users need a chance to save their work before the program crashes and are probably willing to tolerate a few anomalies in exchange for keeping the program going long enough for them to do that.**
  – Users don't appreciate anything that results in the loss of their work, regardless of how much it helps debugging and ultimately improves the quality of the program.

(4) Leave in code that helps crash gracefully

- **If your program contains debugging code that detects potentially fatal errors, leave the code in that allows the program to crash gracefully.**
- **In the Mars Pathfinder, for example, engineers left some of the debug code in by design. An error occurred after the Pathfinder had landed.**
- **By using the debug aids that had been left in, engineers at JPL were able to diagnose the problem and upload revised code to the Pathfinder, and the Pathfinder completed its mission perfectly (March 1999).**

(5)(6) Log errors and friendly error messages

- **5. Log errors for your technical support personnel**
  - Consider leaving debugging aids in the production code but changing their behavior so that it's appropriate for the production version.
  - If you've loaded your code with assertions that halt the program during development, you might considering changing the assertion routine to log messages to a file during production rather than eliminating them altogether.
- **6. See that the error messages you leave in are friendly**
  - If you leave internal error messages in the program, verify that they're in language that's friendly to the user.
  - A common and effective approach is to notify the user of an "internal error" and list an email address or phone number the user can use to report it.

Being Defensive about Defensive Programming

- **Too much defensive programming creates problems of its own.**
  - Overly defensive programming however introduces unnecessary code for errors impossible to even happen, adds complexity to the software, thus wasting runtime and maintenance costs.
  - Code installed for defensive programming is not immune to defects, and you're just as likely to find a defect in defensive-programming code as in any other code.
  - There is also the risk that the code traps or prevents too many exceptions, potentially resulting in unnoticed, incorrect results.

- **Think about where you need to be defensive, and set your defensive-programming priorities accordingly.**

CHECKLIST: Defensive Programming

- **General**
  - Does the routine protect itself from bad input data?
  - Have you used assertions to document assumptions, including preconditions and postconditions?
  - Have assertions been used only to document conditions that should never occur?
  - Does the architecture or high-level design specify a specific set of error handling techniques?
  - Does the architecture or high-level design specify whether error handling should favor robustness or correctness?
  - Have barricades been created to contain the damaging effect of errors and reduce the amount of code that has to be concerned about error processing?

CHECKLIST: Defensive Programming

- **General**
  - Have debugging aids been used in the code?
  - Has information hiding been used to contain the effects of changes so that they won't affect code outside the routine or class that's changed?
  - Have debugging aids been installed in such a way that they can be activated or deactivated without a great deal of fuss?
  - Is the amount of defensive programming code appropriate—neither too much nor too little?
  - Have you used offensive programming techniques to make errors difficult to overlook during development?

CHECKLIST: Defensive Programming

- **Exceptions**
  - Has your project defined a standardized approach to exception handling?
  - Have you considered alternatives to using an exception?
  - Is the error handled locally rather than throwing a non-local exception if possible?
  - Does the code avoid throwing exceptions in constructors and destructors?
  - Are all exceptions at the appropriate levels of abstraction for the routines that throw them?
  - Does each exception include all relevant exception background information?
  - Is the code free of empty catch blocks? (Or if an empty catch block truly is appropriate, is it documented?)

CHECKLIST: Defensive Programming

- **Security Issues**
  - Does the code that checks for bad input data check for attempted buffer overflows, SQL injection, html injection, integer overflows, and other malicious inputs?
  - Are all error-return codes checked?
  - Are all exceptions caught?
  - Do error messages avoid providing information that would help an attacker break into the system?

The end

April 17, 2019