CSE 331
Software Design & Implementation

James Wilcox

Autumn 2021

Lecture 5 – Specifications

Goals

We want our code to be:

1. Correct
   – everything else is secondary
2. Easy to change
   – most code written is changing existing systems
3. Easy to understand
   – corollary of previous two
4. Easy to scale
   – modular

Specifications

To prove correctness of our method, need

- precondition
- postcondition

Correctness =
Validity of
{{ P }} `S` {{ Q }}

Without these, we can't say whether the code is correct

These tell us what it means to be correct

They are the *specification* for the method

Importance of Specifications

Specifications are essential to **correctness**

They are also essential to **changeability**

- need to know what changes will break code using it

They are also essential to **understandability**

- need to tell readers what it is supposed to do

They are also essential to **modularity**…

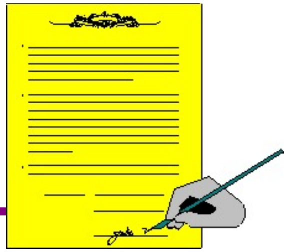
A discipline of modularity

- Two ways to view a program:
  - the implementer's view (how to build it)
  - the user's / client's view (how to use it)

- It helps to apply these views to program parts:
  - while implementing one part, consider yourself a client of any other parts it depends on
  - try *not* to look at other parts through implementer's eyes
  - helps dampen interactions between parts

- Formalized through the idea of a *specification*

A specification is a contract



- A set of requirements agreed to by the user and the manufacturer of the product
  - describes their expectations of each other

- Facilitates simplicity via *two-way* isolation (modularity)
  - isolate client from implementation details
  - isolate implementer from how the part is used
  - discourages implicit, unwritten expectations

- Facilitates change
  - reduces the “Medusa effect”: the specification, rather than the code, gets “turned to stone” by client dependencies

Isn’t the interface sufficient?

The interface defines the boundary between implementers and users:

```
public class MyList implements List<E> {
    public E get(int x) { return null; }
    public void set(int x, E y){}
    public void add(E elem) {}
    public void add(int index, E elem){}
    …
    public static <T> boolean isSub(List<T> a, List<T> b){
       return false;
    }
}
```

Interface provides the *syntax and types*

But nothing about the *behavior and effects*

- Provides **too little** information to clients

Why not just read code?

```
static <T> boolean ???(List<T> src, List<T> part) {
    int part_index = 0;
    for (T elt : src) {
        if (elt.equals(part.get(part_index))) {
            part_index++;
            if (part_index == part.size()) {
                return true;
            }
        } else {
            part_index = 0;
        }
    }
    return false;
}
```

How long does it take you to figure out what this does?

Recall the sublist example

```
static <T> boolean sub(List<T> src, List<T> part) {
    int part_index = 0;
    for (T elt : src) {
        if (elt.equals(part.get(part_index))) {
            part_index++;
            if (part_index == part.size()) {
                return true;
            }
        } else {
            part_index = 0;
        }
    }
    return false;
}
```

Code is complicated

- Code gives more detail than needed by client

- Understanding or even reading every line of code is an excessive burden
  - suppose you had to read source code of Java libraries to use them
  - same applies to developers of different parts of the libraries
  - would make it impossible to build million-line programs

- Client cares only about *what* the code does, not *how* it does it

Code is ambiguous

- Code seems unambiguous and concrete
  - but which details of code's behavior are essential, and which are incidental?

- Code invariably gets rewritten
  - client needs to know what they can rely on
    - what properties will be maintained over time?
    - what properties might be changed by future optimization, improved algorithms, or bug fixes?
  - implementer needs to know what features the client depends on, and which can be changed

Comments are essential

Most comments convey only an informal, general idea of what that the code does:

```
// This method checks if "part" appears as a
// subsequence in "src"
static <T> boolean sub(List<T> src, List<T> part){
   ...
}
```

Problem: ambiguity remains

- should be True if **`part`** is empty and False if **`src`** is empty
- what if **`src`** and **`part`** are both empty?

From vague comments to specifications

- Roles of a specification:
  - client agrees to rely *only* on information in the description in their use of the part
  - implementer of the part promises to support everything in the description
    - otherwise is perfectly at liberty

- Sadly, much code lacks a specification
  - clients often work out what a method/class does in ambiguous cases by running it and depending on the results
  - leads to bugs and programs with unclear dependencies, reducing simplicity and flexibility

A more careful description of **`sub`**

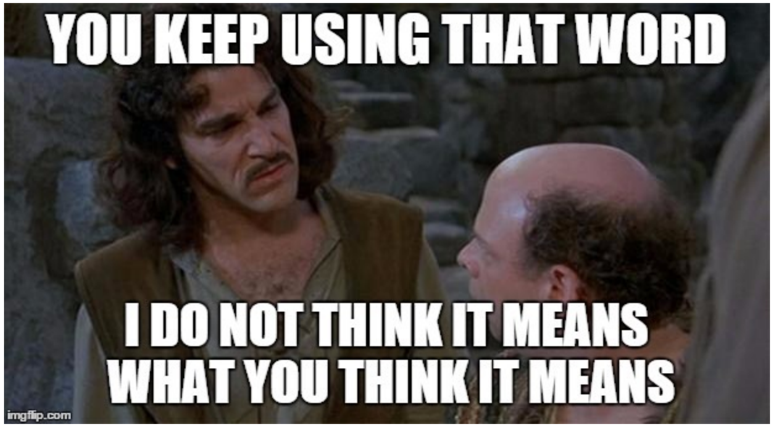
```
// Check whether "part" appears as a subsequence in "src"
```

needs to be given some caveats:

```
// * src and part cannot be null
// * If src is empty list, always returns false
```

Recall the sublist example

```
static <T> boolean sub(List<T> src, List<T> part) {
    int part_index = 0;
    for (T elt : src) {
        if (elt.equals(part.get(part_index))) {
            part_index++;
            if (part_index == part.size()) {
                return true;
            }
        } else {
            part_index = 0;
        }
    }
    return false;
}
```



A more careful description of **`sub`**

```
// Check whether "part" appears as a subsequence in "src"
```

needs to be given some caveats:

```
// * src and part cannot be null
// * If src is empty list, always returns false
// * Results may be unexpected if partial matches
//   can happen right before a real match; e.g.,
//   list (1,2,1,3) will not be identified as a
//   sub sequence of (1,2,1,2,1,3).
```

or replaced with a more detailed description:

```
// This method scans the "src" list from beginning
// to end, building up a match for "part", and
// resetting that match every time that...
```

A better approach

It's better to simplify than to describe complexity!

Complicated description suggests poor design

– rewrite **sub** to be more sensible, and easier to describe

```
// Returns true iff there exist sequences A and B (possibly
// empty) such that src = A + part + B, where + means concat
static <T> boolean sub(List<T> src, List<T> part) {
```

- Mathematical flavour not always necessary, but avoids ambiguity
- "Declarative" style is important: avoids reciting or depending on operational/implementation details

Sneaky fringe benefit of specs

- The discipline of writing specifications changes the incentive structure of coding
  - rewards code that is easy to describe and **understand**
  - punishes code that is hard to describe and **understand**
    - (even if it is shorter or easier to write)

- If you find yourself writing complicated specifications, it is an incentive to redesign
  - in **`sub`**, code that does exactly the right thing may be slightly slower than a hack that assumes no partial matches before true matches, but cost of forcing client to understand the details is too high

Writing specifications with Javadoc

- Javadoc
  - Sometimes can be daunting; get used to using it
  - Very important feature of Java (copied by others)

- Javadoc convention for writing specifications
  - Method signature
  - Text description of method
  - **`@param`**: description of what gets passed in
  - **`@return`**: description of what gets returned
  - **`@throws`**: exceptions that may occur

Example: Javadoc for `String.contains`

```
public boolean contains(CharSequence s)
```

Returns true if and only if this string contains the specified sequence of char values.

Parameters:

s- the sequence to search for

Returns:

true if this string contains s, false otherwise

Throws:

NullPointerException - if s is null

Since:

1.5

CSE 331 specifications

Note: these are abbreviated. In your code, it must be `@spec.requires`, `@spec.modifies`, etc.

- The *precondition*: constraints that hold before the method is called (if not, all bets are off)
  - **`@requires`**: spells out any obligations on client

- The *postcondition*: constraints that hold after the method is called (if the precondition held)
  - **`@modifies`**: lists objects that may be affected by method; any object not listed is guaranteed to be untouched
  - **`@effects`**: gives guarantees on final state of modified objects
  - **`@throws`**: lists possible exceptions and conditions under which they are thrown (Javadoc uses this too)
  - **`@return`**: describes return value (Javadoc uses this too)

Example 1

static <**T**> int changeFirst(List<T> lst, T oldelt, T newelt)

requires lst is non-null

modifies lst

effects change the first occurrence of oldelt in lst to newelt (making no other changes to lst)

returns the position of the element in lst that was oldelt and is now newelt or -1 if not in oldelt

---

```
static <T> int changeFirst(
    List<T> lst, T oldelt, T newelt) {
   int i = 0;
   for (T curr : lst) {
       if (curr == oldelt) {
           lst.set(newelt, i);
           return i;
       }
      i = i + 1;
   }
   return -1;
}
```

Example 2

static List<Integer> zipSum(List<Integer> lst1, List<Integer> lst2)

requires lst1 and lst2 are non-null.
lst1 and lst2 are the same size.

modifies none
effects none

returns a list of same size where the ith element is the sum of the ith elements of lst1 and lst2

```
static List<Integer> zipSum(
    List<Integer> lst1, List<Integer> lst2) {
  List<Integer> res = new ArrayList<Integer>();
  for(int i = 0; i < lst1.size(); i++) {
    res.add(lst1.get(i) + lst2.get(i));
  }
  return res;
}
```

Example 3

static void listAdd(List<Integer> lst1, List<Integer> lst2)

requires lst1 and lst2 are non-null.
lst1 and lst2 are the same size.

modifies lst1

effects ith element of lst2 is added to the ith element of lst1

returns none

```
static void listAdd(
    List<Integer> lst1, List<Integer> lst2) {
  for(int i = 0; i < lst1.size(); i++) {
      lst1.set(i, lst1.get(i) + lst2.get(i));
  }
}
```

Should requires clause be checked?

- Preconditions are common in ordinary classes
  - in public libraries, necessary to deal with all possible inputs
- If the client calls a method without meeting the precondition, the code is free to do *anything*
  - including pass corrupted data back
  - it is a good idea to *fail fast*: to provide an immediate error, rather than permitting mysterious bad behavior
- Rule of thumb: Check if cheap to do so
  - Example: list has to be non-null → check
  - Example: list has to be sorted → skip
  - Be judicious if private / only called from your code

Comparing specifications

- Occasionally, we need to compare different specification:
  - comparing potential specifications of a new class
  - comparing new version of a specification with old
    - recall: most work is making changes to existing code

- For that, we often consider *stronger* and *weaker* specifications...

Satisfaction of a specification

Let M be an implementation and S a specification

M satisfies S if and only if

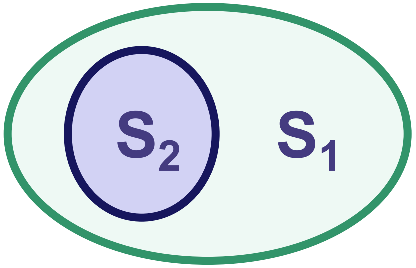
- for every input allowed by the spec precondition,
  M produces an output allowed by the spec postcondition

If M does not satisfy S, either M or S (or both!) could be "wrong"

- *"one person's feature is another person's bug."*
- usually better to change the implementation than the spec

Stronger vs Weaker Specifications

- **Definition 1**: specification S_2 is stronger than S_1 iff
  - for any implementation M: M satisfies S_2 => M satisfies S_1
  - i.e., S_2 is harder to satisfy

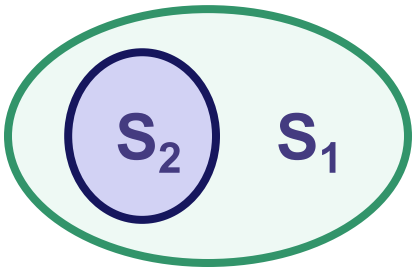


(satisfying **implementations**)

- Two specifications may be *incomparable*
  - but we are usually choosing between stronger vs weaker

Stronger vs Weaker Specifications

- An implementation satisfying a stronger specification can be **used anywhere** that a weaker specification is required
  - can **use** a method satisfying S_2 anywhere S_1 is expected



Making changes to a specification...

- changing from S_1 to S_2 should not break clients
  - but it could break implementation
- changing from S_2 to S_1 should not break implementation
  - but it could break clients!

Stronger vs Weaker Specifications

- **Definition 2**: specification S_2 is stronger than S_1 iff
  - postcondition of S_2 is stronger than that of S_1 (on all inputs allowed by both)
  - precondition of S_2 is weaker than that of S_1

- A **stronger** specification:
  - is harder to satisfy
  - gives more guarantees to the caller

- A **weaker** specification:
  - is easier to satisfy
  - gives more freedom to the implementer

Example 1 (stronger postcondition)

```
int find(int[] a, int value) {
    for (int i=0; i<a.length; i++) {
        if (a[i]==value)
          return i;
    }
    return -1;
}
```

Which is stronger?

- Specification A
  - requires: value occurs in **a**
  - returns: **i** such that **a[i]** = **value**
- Specification B
  - requires: value occurs in **a**
  - returns: *smallest* **i** such that **a[i]** = **value**

Example 2 (weaker precondition)

```
int find(int[] a, int value) {
    for (int i=0; i<a.length; i++) {
        if (a[i]==value)
          return i;
    }
    return -1;
}
```

Which is stronger?

- Specification A
  - requires: value occurs in **a**
  - returns: **i** such that **a[i]** = **value**

- Specification C
  - returns: **i** such that **a[i]** = **value**, or **-1** if value is not in **a**

Example 3

```
int find(int[] a, int value) {
    for (int i=0; i<a.length; i++) {
        if (a[i]==value)
          return i;
    }
    return -1;
}
```

Which is stronger?

- Specification B
  - requires: value occurs in **`a`**
  - returns: *smallest* **`i`** such that **`a[i]`** = **`value`**

- Specification C
  - returns: **`i`** such that **`a[i]`** = **`value`**, or **`-1`** if value is not in **`a`**

“Strange” case: @throws

Compare:

S1:

@throws FooException if x<0

@return x+3

S2:

@return x+3

S3:

@requires x >= 0

@return x+3

- S1 & S2 are *stronger* than S3
- S1 & S2 are *incomparable* because they promise different, incomparable things when x<0

Strengthening a specification

- Strengthen a specification by:
  - Promising more (stronger postcondition):
    - returns clause harder to satisfy
    - effects clause harder to satisfy
    - fewer objects in modifies clause
    - more specific exceptions (subclasses)
  - Asking less of client (weaker precondition)
    - requires clause easier to satisfy
- Weaken a specification by:
  - (Opposite of everything above)

Which is better?

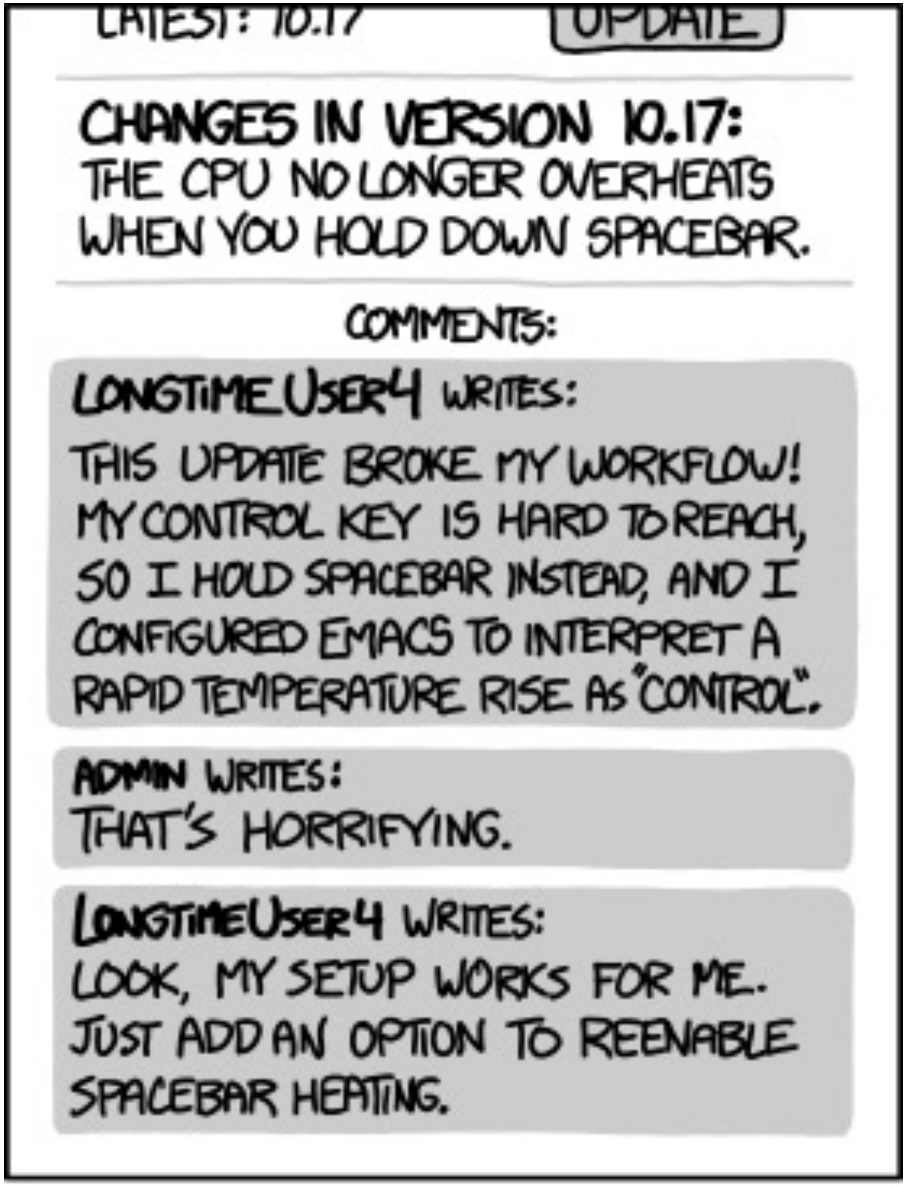
- Stronger does not always mean better!
- Weaker does not always mean better!
- Strength of specification trades off:
  - usefulness to client
  - ease of simple, efficient, correct implementation
  - promotion of reuse and modularity
  - clarity of specification itself
- “It depends”

Warnings on Specifications

Specifications are also the products of human design, so...

- They will contain **bugs**
  - (recall the central dogma of this course)
  - harder to fix the more people that have seen it
    - "turns to stone" a bit more with each viewer

XKCD 1172



EVERY CHANGE BREAKS SOMEONE'S WORKFLOW.

Warnings on Specifications

Specifications are also the products of human design, so...

- They will contain **bugs**
  - (recall the central dogma of this course)
  - harder to fix the more people that have seen it
    - “turns to stone” a bit more with each viewer

- Creating them requires **judgement**
  - no “turn the crank” way to produce good specs (or invariants)
  - harder but good for job security

Back to Correctness…

Correctness Toolkit

- Learned forward and backward reasoning for
  - assignment
  - if statement
  - while loop

- One missing element: function calls
  - we needed specifications for that
  - now we have them

Reasoning about Function Calls

```
static int f(int a, int b) { … }
```

requires P(a,b) -- some assertion about a & b

returns R(a,b,c) -- some assertion about a, b, & c (returned)

Forward

{{ P1 }}

```
c = f(a, b);
```

Reasoning about Function Calls

```
static int f(int a, int b) { … }
```

requires P(a,b) -- some assertion about a & b

returns R(a,b,c) -- some assertion about a, b, & c (returned)

Forward

{{ P1 }}

```
c = f(a, b);
```

{{ P1 and R(a,b,c) }}

if P1 implies P(a,b)

Reasoning about Function Calls

```
static int f(int a, int b) { … }
```

requires P(a,b) -- some assertion about a & b

returns R(a,b,c) -- some assertion about a, b, & c (returned)

Backward

```
 c = f(a, b);
```

{{ Q }}

Reasoning about Function Calls

```
static int f(int a, int b) { … }
```

requires P(a,b) -- some assertion about a & b
returns R(a,b,c) -- some assertion about a, b, & c (returned)

Backward

solve R(a,b,c) for c
substitute c appears in Q

{{ Q[c / f(a,b)] and P(a,b) }}
```
c = f(a, b);
```
{{ Q }}

What about Recursion?

- As with loops, this does not prove termination
  - infinite recursion (like infinite loops) could occur

- Separate argument to bound the running time

Toolkit for functional languages

- This is a toolkit for “imperative” languages
  - ones with assignments and loops
- (Pure) functional languages lack those
  - recursion used instead of loops
- Correctness for these languages is covered in CSE 311
  - simple programming language consisting of
    - recursively defined functions
    - recursively defined data types
  - same ideas apply to other functional languages