CSE 331
Software Design & Implementation

Kevin Zatloukal

Summer 2017

Lecture 5 – Specifications

(Based on slides by Mike Ernst, Dan Grossman, David Notkin, Hal Perkins, Zach Tatlock)

Reminders

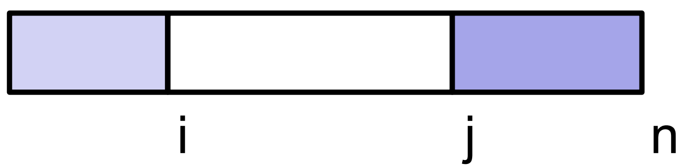
- HW2 is due tonight
- Quiz 2 is posted
  - due a week from Friday
- **Section tomorrow** on Git & HW3
  - HW3 will be posted shortly (should be easy)
  - you will need a CSE netid (if not, support@cs)
  - you should receive an email about your gitlab repo

Correctness & Termination

Example: Binary Search

Problem: Given a sorted array A and a number x, find index of x (or where it would be inserted) in A.

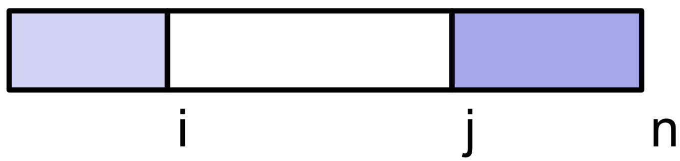
Idea: Look at A[n/2] to figure out if x is in A[0], A[1], ..., A[n/2] or in A[n/2+1], ..., A[n-1]. Narrow the search for x on each iteration.



Loop Invariant: A[0], ..., A[i-1] <= x < A[j], ..., A[n-1]

- insert point for x must lie in A[i], ..., A[j-1]
- A[i], ..., A[j-1] is the part where we don't know relation to x

Binary Search Code



Initialization:

- i = 0 and j = n
- white region is the whole array

Termination condition:

- i = j
- white region is empty
- if x is in the array, it is A[i-1]
  - if there are multiple copies of x, this returns the *last*

Binary Search Code

```
int i = 0;
int j = n;
{{ Inv: A[0], ..., A[i-1] <= x < A[j], ..., A[n-1] }}
while (i != j) {

    // need to bring i and j closer together...
    // (e.g., increase i or decrease j)

}
{{ A[0], ..., A[i-1] <= x < A[i], ..., A[n-1] }}
```

Binary Search Code

```
int i = 0;
int j = n;
```

{{ Inv: A[0], ..., A[i-1] <= x < A[j], ..., A[n-1] }}

```
while (i != j) {
  int m = (i + j) / 2;
  if (A[m] <= x) {
    i = m + 1;
  } else {
    j = m;
  }
}
```

{{ A[0], ..., A[i-1] <= x < A[i], ..., A[n-1] }}

Aside on Termination

- Most often correctness is harder work than termination
  - the latter follows from running time bound

- But also examples where termination is more interesting
  - (cases with variable progress toward termination condition)
  - quotient and remainder (Inv: q*y + r == x and r >= 0)
  - binary search
  - see 16su HW2 for a problem where correctness is trivial and the *only* difficult part is checking that it terminates

- Prove termination in these cases by showing that *every* iteration makes **progress** toward the termination condition

Binary Search in JavaScript

- Java has binary search in the standard library
- JavaScript does not
  - so you might actually need to implement it

- One new wrinkle: JavaScript numbers are all floats

Binary Search in JavaScript

```
var i = 0;
var j = n;
```

{{ Inv: A[0], ..., A[i-1] <= x < A[j], ..., A[n-1] }}

```
while (i != j) {
  var m = Math.round((i + j) / 2);
  if (A[m] <= x) {
    i = m + 1;
  } else {
    j = m;
  }
}
```

{{ A[0], ..., A[i-1] <= x < A[i], ..., A[n-1] }}

`(i+j)/2` may not be an integer but we can just round it to one

Binary Search in JavaScript

- Proof of correctness works exactly as before
  - all of our earlier reasoning still holds
  - (we didn't use any info about m's value)

- Let's work through termination though...
  - loop terminates when i = j
  - to make **progress**, every iteration should bring i & j closer
    - since i <= j, either increase i or decrease j

Binary Search in JavaScript

```
var i = 0;
var j = n;
```

{{ Inv: A[0], ..., A[i-1] <= x < A[j], ..., A[n-1] }}

```
while (i != j) {
  var m = Math.round((i + j) / 2);
  if (A[m] <= x) {
    i = m + 1;
  } else {
    j = m;
  }
}
```

increases i if m >= i

decreases j if m < j

{{ A[0], ..., A[i-1] <= x < A[i], ..., A[n-1] }}

Binary Search in JavaScript

- Need to have i <= m < j or else we loop forever

- Suppose that i + 1 = j
  – still not equal, so the loop body will execute

- Then (i + j) / 2 = (i + i + 1) / 2 = (2i + 1) / 2 = i + 0.5
- So Math.round((i + j) / 2) = Math.round(i + 0.5) = i + 1 = j
  – we get m = j, not m < j, and go into an infinite loop

- Java code was only correct because of truncating division

- Moral: correctness issues are often subtle
  – you need to reason through the code *carefully*
  – don't forget to check termination when it's not obvious

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. Modular
   – coping with scale

Specifications

To prove correctness of our method, we need

- precondition
- postcondition

Without these, we can't say whether the code is correct
These tell us what it means to be correct

They are (part of) the *specification* for the method

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**…

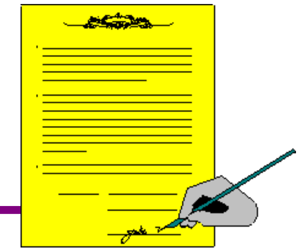
A discipline of modularity

- Two ways to view a program:
  - the implementer's view (how to build it)
  - the 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
  - 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 clients:

```
public class MyList extends 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;
 }
```

Why are you better off with a specification?

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

- What if **`src`** and **`part`** are both empty lists?
- When does the function return **`true`**?

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 at liberty to do whatever they want

- 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

Recall the sublist example

```
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;
}
```

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 sub-sequence in "src"
```

needs to be given some caveats (why?):

```
// * 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 flavor not always necessary, but often helps avoid ambiguity
- "Declarative" style is important: avoids reciting or depending on operational/implementation details

Sneaky fringe benefit of specs #1

- 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

- 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
  - **`@return`**: describes return value (Javadoc uses this too)
  - **`@throws`**: lists possible exceptions and conditions under which they are thrown (Javadoc uses this too)

(Outside of 331 this info is often hidden in the text, @return, and @param's.)

Example 1

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

requires	lst, oldelt, and newelt are non-null
modifies	lst
effects	change the first occurrence of oldelt in lst to newelt (& makes 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 change(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));
  }
}
```

Example 4 (Watch out for bugs!)

static void uniquify(List<Integer> lst)

requires	???
	???
modifies	???
effects	???
returns	???

```
static void uniquify(List<Integer> lst) {
   for (int i=0; i < lst.size()-1; i++)
       if (lst.get(i) == lst.get(i+1))
           lst.remove(i);
}
```

Should requires clause be checked?

- If the client calls a method without meeting the precondition, the code is free to do *anything*
  - including pass corrupted data back
  - it is polite, nevertheless, to *fail fast*: to provide an immediate error, rather than permitting mysterious bad behavior
- Preconditions are common in "helper" methods/classes
  - Example: binary search would normally impose a pre-condition rather than simply failing if list is not sorted. Why?
- 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
- In public libraries, it's necessary to deal with all possible inputs

Satisfaction of a specification

Let M be an implementation and S a specification

M satisfies S if and only if

- every behavior of M is permitted by S
- i.e., 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 program than the spec

Sneaky fringe benefit of specs #2

- Specification means that client doesn't need to look at implementation
  - so the code may not even exist yet!

- Write specifications first, make sure system will fit together, and then assign separate implementers to different modules
  - allows teamwork and parallel development
  - also helps with testing (future topic)

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 talk about *stronger* and *weaker* specifications
  - stronger specification provides more information about what states can be produced by the implementation
  - as a result, it is harder for implementations to satisfy

Stronger vs Weaker Specifications

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

- 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

- Two specifications may be *incomparable*
  - neither is weaker/stronger than the other
  - *some* implementations might still satisfy them both

Stronger vs Weaker Specifications

- A procedure satisfying a stronger specification can be used anywhere that a weaker specification is required
  - can substitute a procedure satisfying a stronger spec

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

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

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;
}
```

- 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;
}
```

- 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;
}
```

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

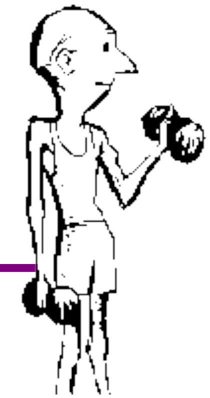
- Specification C
  - returns: **`i`** such that **`a[i]`** = **`value`**, or **`-1`** if value is not in **`a`**

Stronger vs Weaker Summary

- A stronger specification is
  - harder to satisfy (more constraints on the implementation)
  - easier to use (more guarantees, more predictable, client can make more assumptions)

- A weaker specification is
  - easier to satisfy (easier to implement, more implementations satisfy it)
  - harder to use (makes fewer guarantees)

Strengthening a specification



- Strengthen a specification by:
  - Promising more (stronger postcondition):
    - effects clause harder to satisfy
    - returns 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)

“Strange” case: @throws

Compare:

S1:

@throws FooException if x<0

@return x+3

S2:

@return x+3

- Both are *stronger* than @requires x>=0; @return x+3
- These are *incomparable* because they promise different, incomparable things when x<0

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"

More formal stronger/weaker

- A specification is a logical formula
  - S_2 stronger than S_1 if satisfies S_2 implies satisfies S_1
  - from implication all things follows:
    - example: S_2 stronger if requires is weaker
    - example: S_2 stronger if returns is stronger

- As in all logic (cf. CSE311), two rigorous ways to check implication
  - convert entire specifications to logical formulas and use logic rules to check implication
  - check every *behavior* described by stronger also described by the other
    - CSE311: truth tables
    - CSE331: *transition relations*

Transition relations

- There is a program state before a method call and after
  – all memory, values of all parameters/result, whether exception happened, etc.

- A specification "means" a set of pairs of program states
  – the legal pre/post-states
  – this is the transition relation defined by the spec
    - could be infinite
    - could be multiple legal outputs for same input

- Stronger specification means the transition relation is a subset

- Note: transition relations often are infinite in size