17-423/723: Designing Large-scale Software Systems

Designing Interface Specifications

Feb 5, 2025

Logistics

- M1 due date changed to next Monday (Feb 10)
- HW1 returned later today

Leaning Goals

- Describe the role and importance of an interface specification
- Describe the structure and meaning of a specification
- Describe four different dimensions that must be considered while designing a specification

Examples & figures based on https://ocw.mit.edu/ans7870/6/6.005/s16/

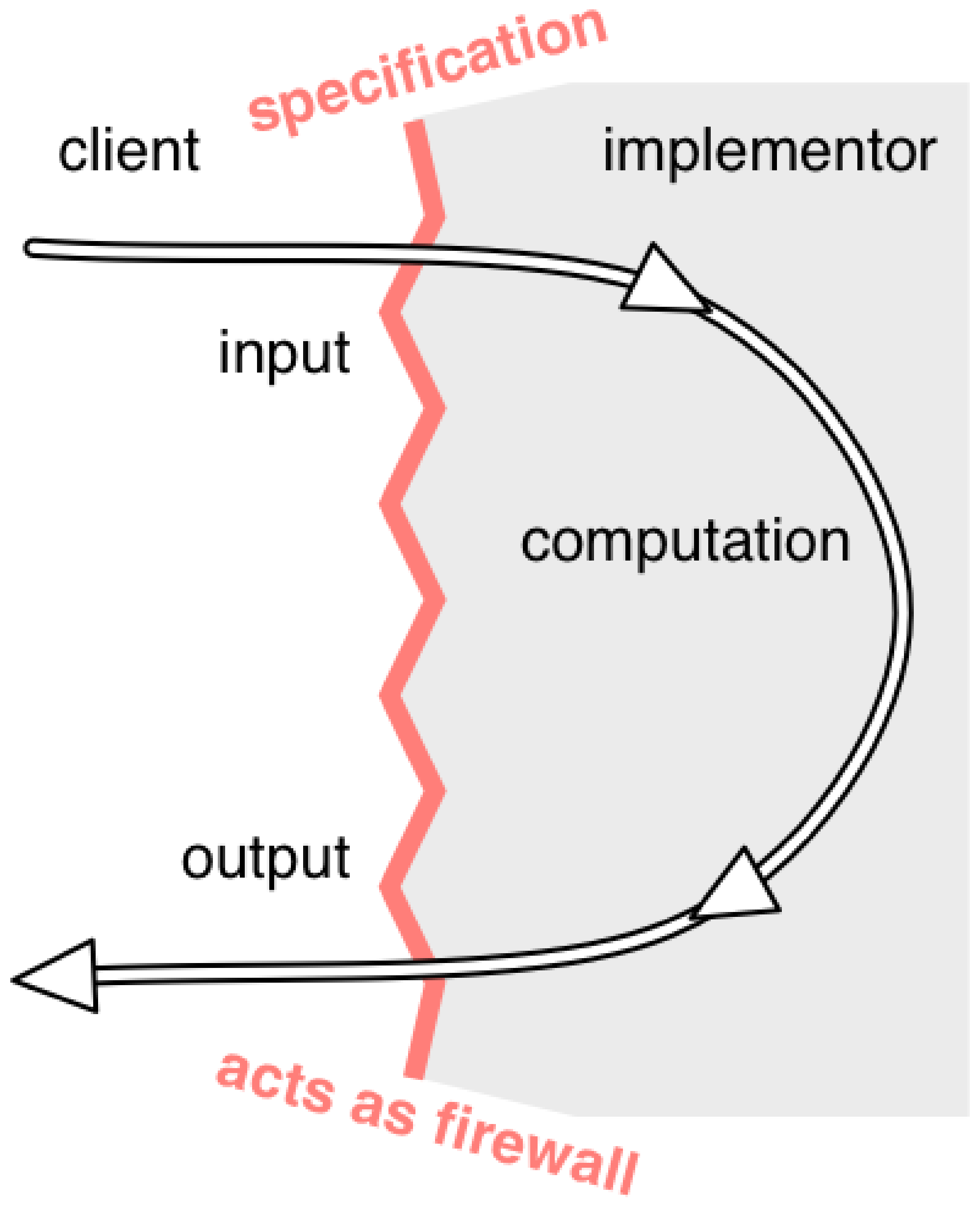
Interface Specifications

Specification

- A statement of a desired behavior or quality attribute of a software system
- Functional specification
  - “The scheduling system must provide a way for the patient to modify an existing appointment”
- Quality attribute specification
  - “The system must be able to handle additional 5000 users without a loss of latency” (scalability)
- **Interface specification**
  - Describes a piece of functionality or a service that a component is expected to deliver to its clients
  - **Today’s focus!**

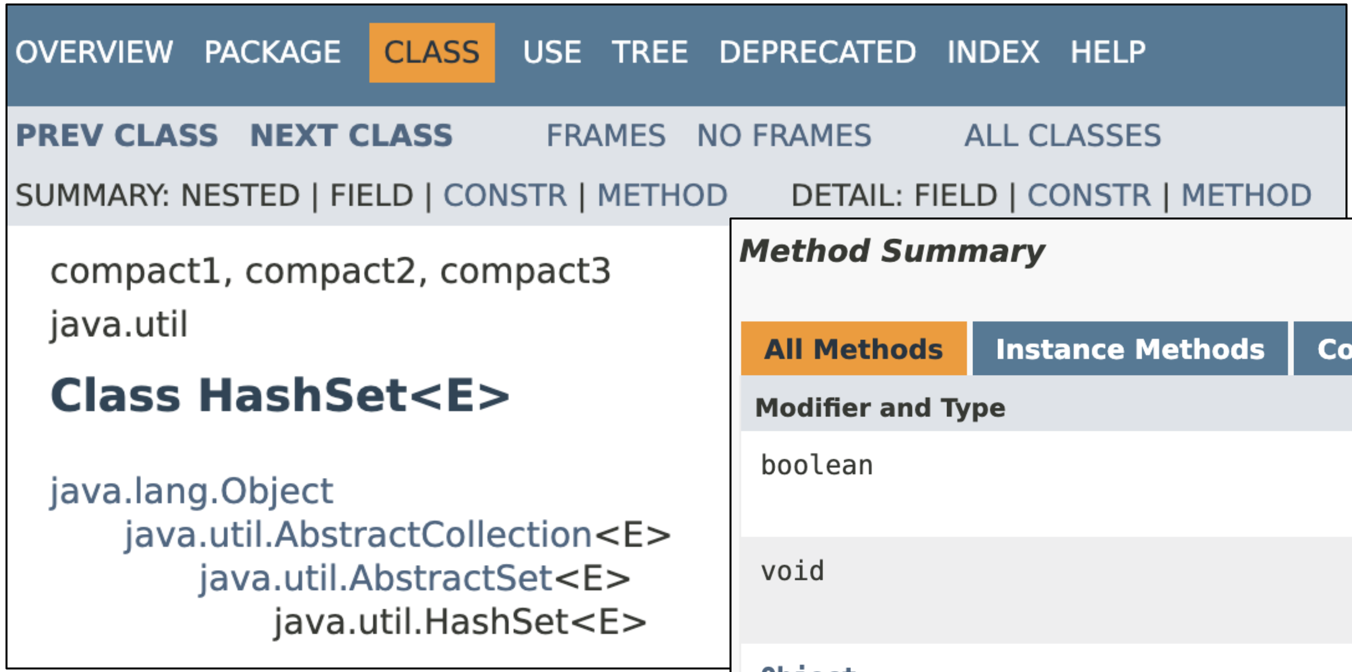
Interface Specification

- **Contract** between a client and a component
- For **clients**:
  - Describes what a client needs to know to use the component
  - Describes what is expected as the output, given an input
  - Hides implementation details (secrets!)
- For **implementors**:
  - Describes implementation tasks to be fulfilled by developers (or LLMs)
  - Hides possible uses of the component by clients (**Q. Why is this good?)**



Interface Specifications in Practice

Java Collections API



OVERVIEW PACKAGE CLASS USE TREE DEPRECATED INDEX HELP

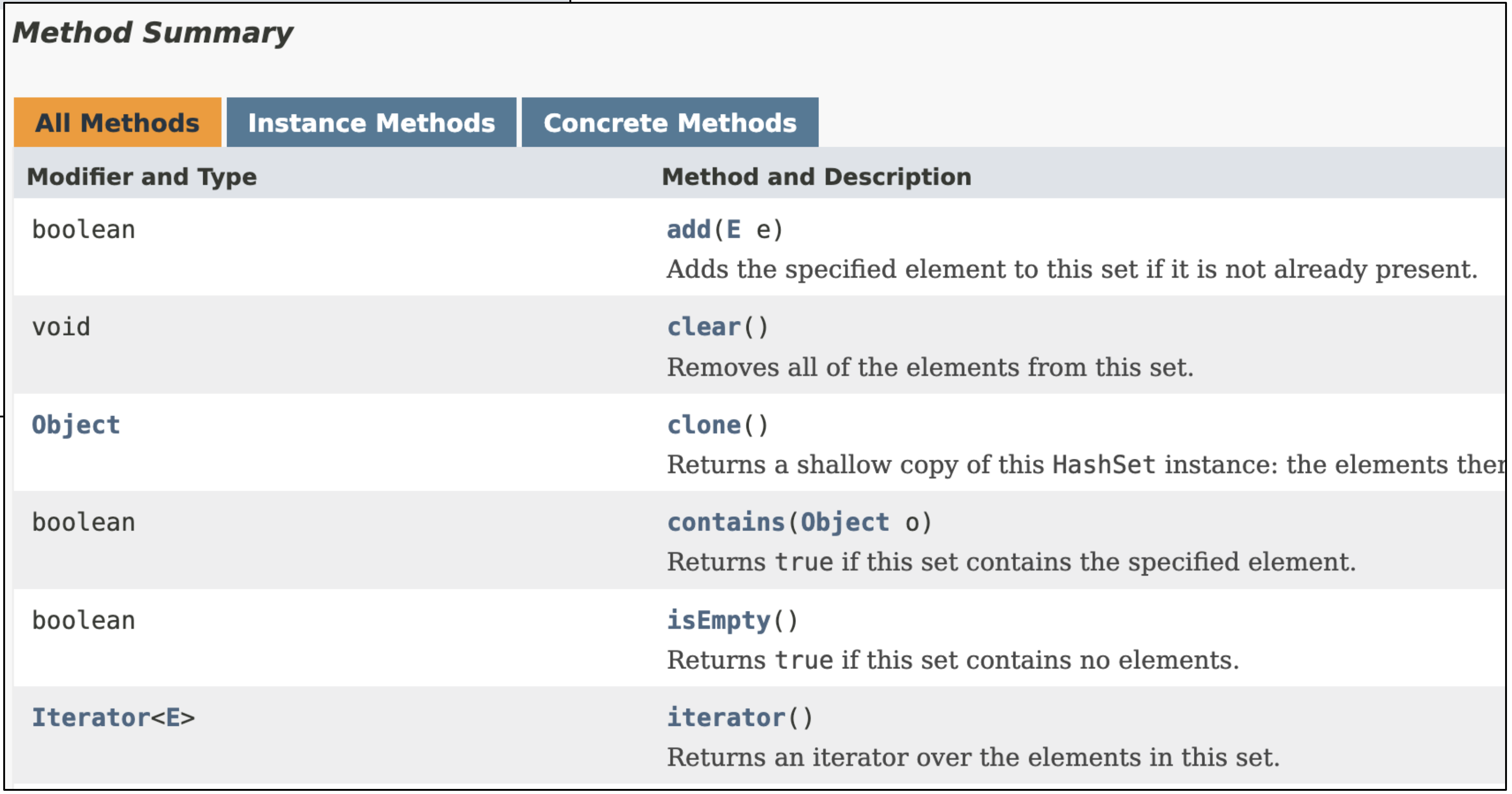
PREV CLASS NEXT CLASS FRAMES NO FRAMES ALL CLASSES

SUMMARY: NESTED | FIELD | CONSTR | METHOD DETAIL: FIELD | CONSTR | METHOD

compact1, compact2, compact3
java.util

Class HashSet<E>

```
java.lang.Object
    java.util.AbstractCollection<E>
        java.util.AbstractSet<E>
            java.util.HashSet<E>
```

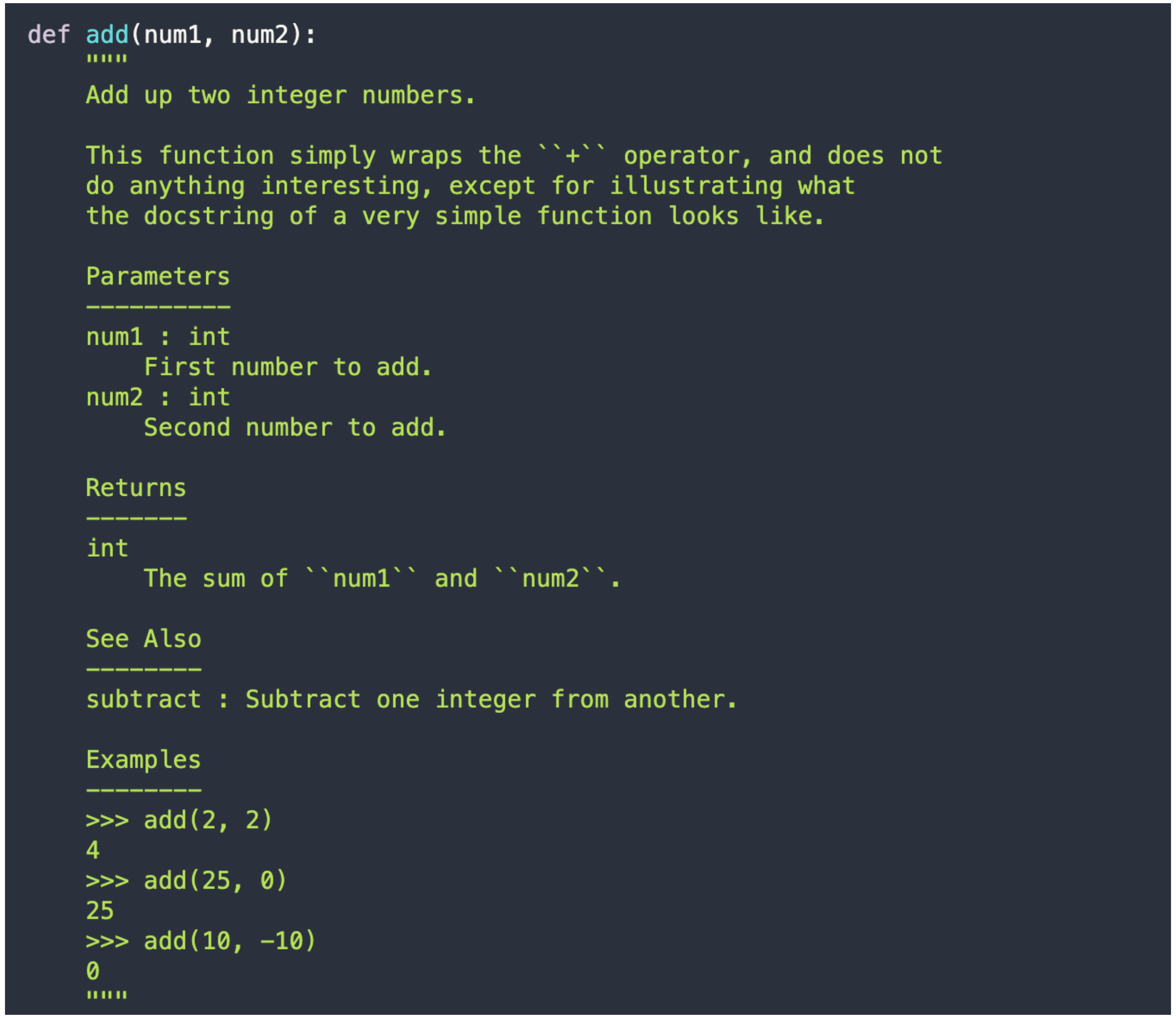


Method Summary

All Methods | Instance Methods | Concrete Methods

Modifier and Type	Method and Description
`boolean`	`add(E e)` Adds the specified element to this set if it is not already present.
`void`	`clear()` Removes all of the elements from this set.
`Object`	`clone()` Returns a shallow copy of this `HashSet` instance: the elements the
`boolean`	`contains(Object o)` Returns `true` if this set contains the specified element.
`boolean`	`isEmpty()` Returns `true` if this set contains no elements.
`Iterator<E>`	`iterator()` Returns an iterator over the elements in this set.

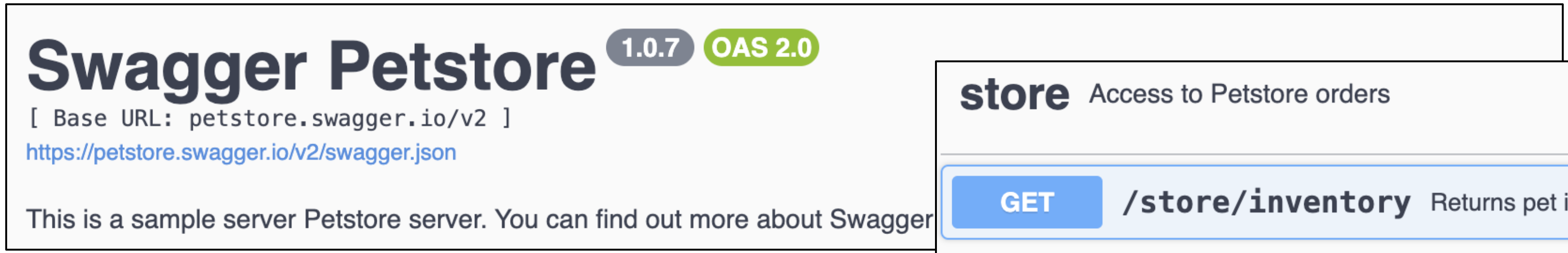
Interface Specifications in Practice



```python
def add(num1, num2):
    """
    Add up two integer numbers.

    This function simply wraps the ``+`` operator, and does not
    do anything interesting, except for illustrating what
    the docstring of a very simple function looks like.

    Parameters
    ----------
    num1 : int
        First number to add.
    num2 : int
        Second number to add.

    Returns
    -------
    int
        The sum of ``num1`` and ``num2``.

    See Also
    --------
    subtract : Subtract one integer from another.

    Examples
    --------
    >>> add(2, 2)
    4
    >>> add(25, 0)
    25
    >>> add(10, -10)
    0
    """
```

Python Docstrings

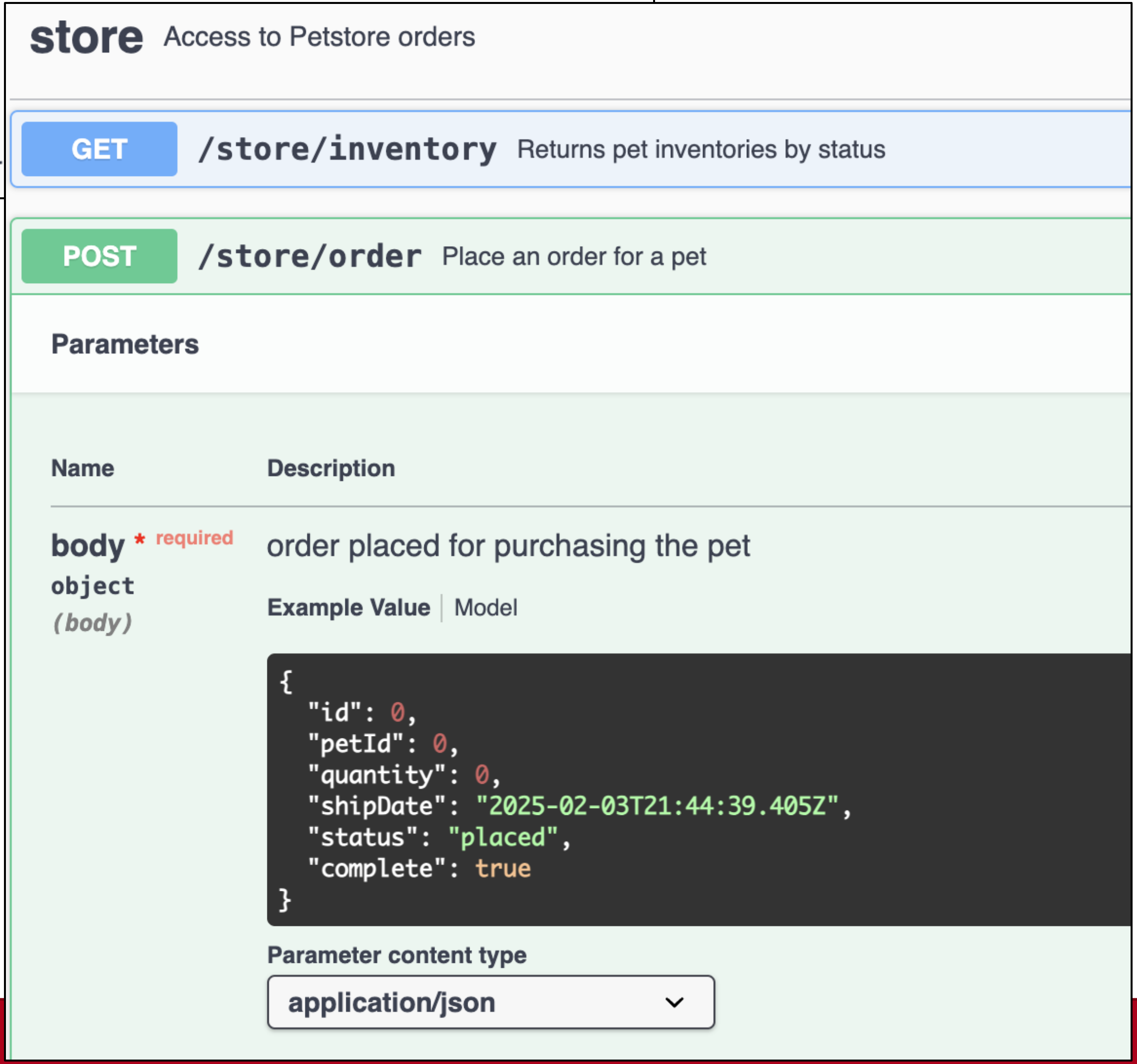
Interface Specifications in Practice


Swagger Petstore 1.0.7 OAS 2.0

[Base URL: petstore.swagger.io/v2]

https://petstore.swagger.io/v2/swagger.json

This is a sample server Petstore server. You can find out more about Swagger


store Access to Petstore orders

GET **/store/inventory** Returns pet inventories by status

POST **/store/order** Place an order for a pet

Parameters

Name	Description
body * required object *(body)*	order placed for purchasing the pet **Example Value** | Model

```
{
  "id": 0,
  "petId": 0,
  "quantity": 0,
  "shipDate": "2025-02-03T21:44:39.405Z",
  "status": "placed",
  "complete": true
}
```

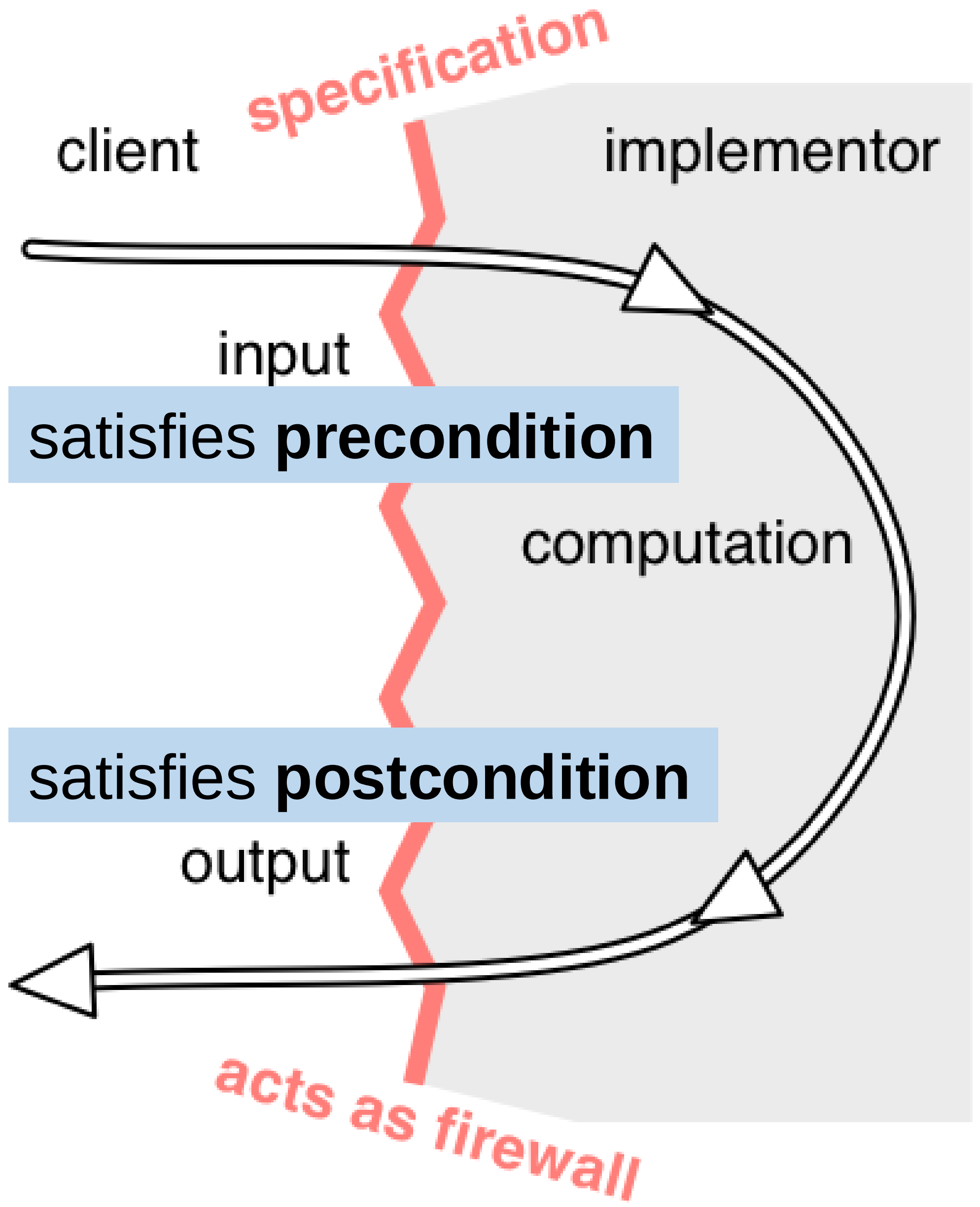
Parameter content type

application/json

REST API Doc

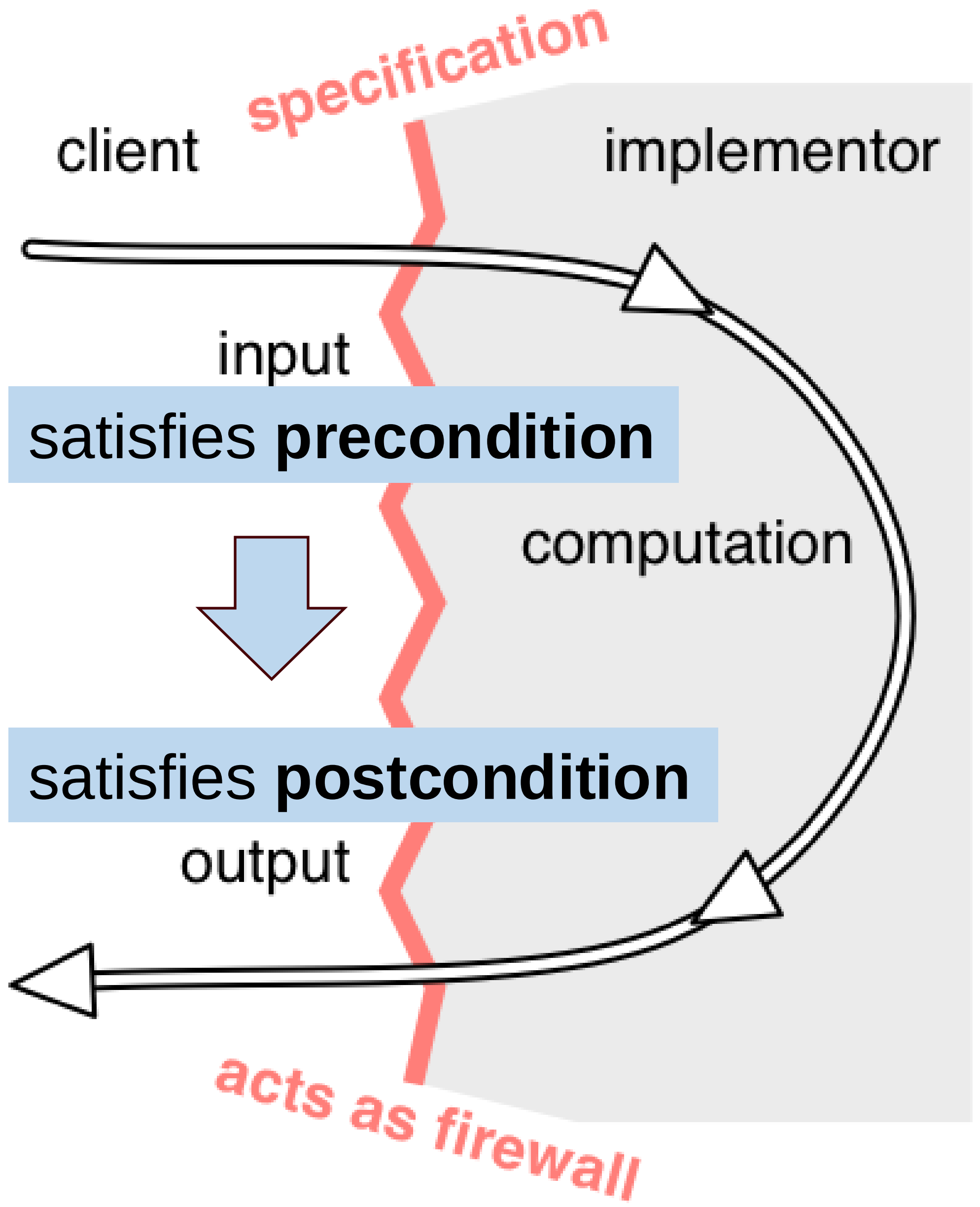
Specification: Elements

- Each specification of a function is associated with **pre-** & **post-conditions**
- **Pre-condition**
  - What the component **expects from the client**, expressed as a condition over the function input and/or component state
- **Post-condition**
  - What the component **promises to deliver**, as a condition over the function output and/or component state



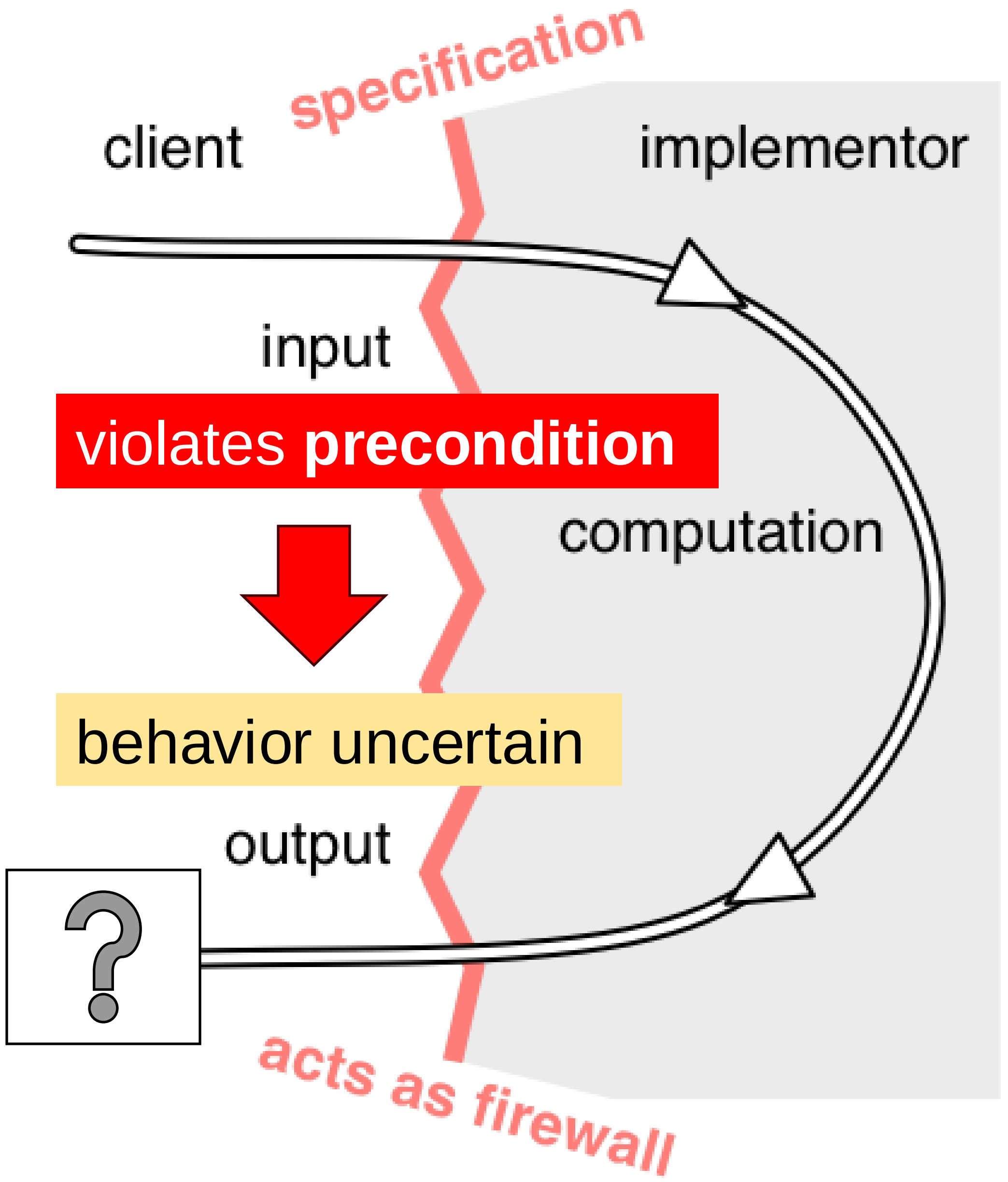
Specification: Meaning

- **Pre-condition ⇒ Post-condition** (i.e., logical implication)
- If the client satisfies the pre-condition, the component promises to satisfy post-condition



Specification: Meaning

- **Pre-condition ⇒ Post-condition** (i.e., logical implication)
- If the client satisfies the pre-condition, the component promises to satisfy post-condition
- But if the client violates the pre-condition, the component can behave in an arbitrary way!
  - Logically, “false implies anything”
  - **Q. Why is this reasonable?**



Example: Specifying Array Find

```
static int find(int[] arr, int val)
  requires: val occurs exactly once in arr
  effects: returns index i such that arr[i] = val
```

- A specification of a “find” function
- By convention, we will label pre- & post-conditions as **requires** and **effects**
- **Meaning**: If “val” occurs exactly once in “arr”, then it returns index “i” such that arr[i] = val
  - If “val” occurs zero times or more than once, then “find” may return anything

Specification as an Implementation Set

- Specification defines a **set of possible implementations**
- Given a pre- & post-condition, any implementation that fulfills the requirement “**pre-condition ⇒ post-condition”** is a valid implementation of the specification

Example: Implementing Array Find

```
static int find(int[] arr, int val) {
  for (int i = 0; i < arr.length; i++) {
    if (arr[i] == val) return i;
  }
  return arr.length;
}

static int find(int[] arr, int val) {
  for (int i = arr.length -1 ; i >= 0; i--) {
    if (arr[i] == val) return i;
  }
  return -1;
}
```

Q. Do these functions behave the same or differently?

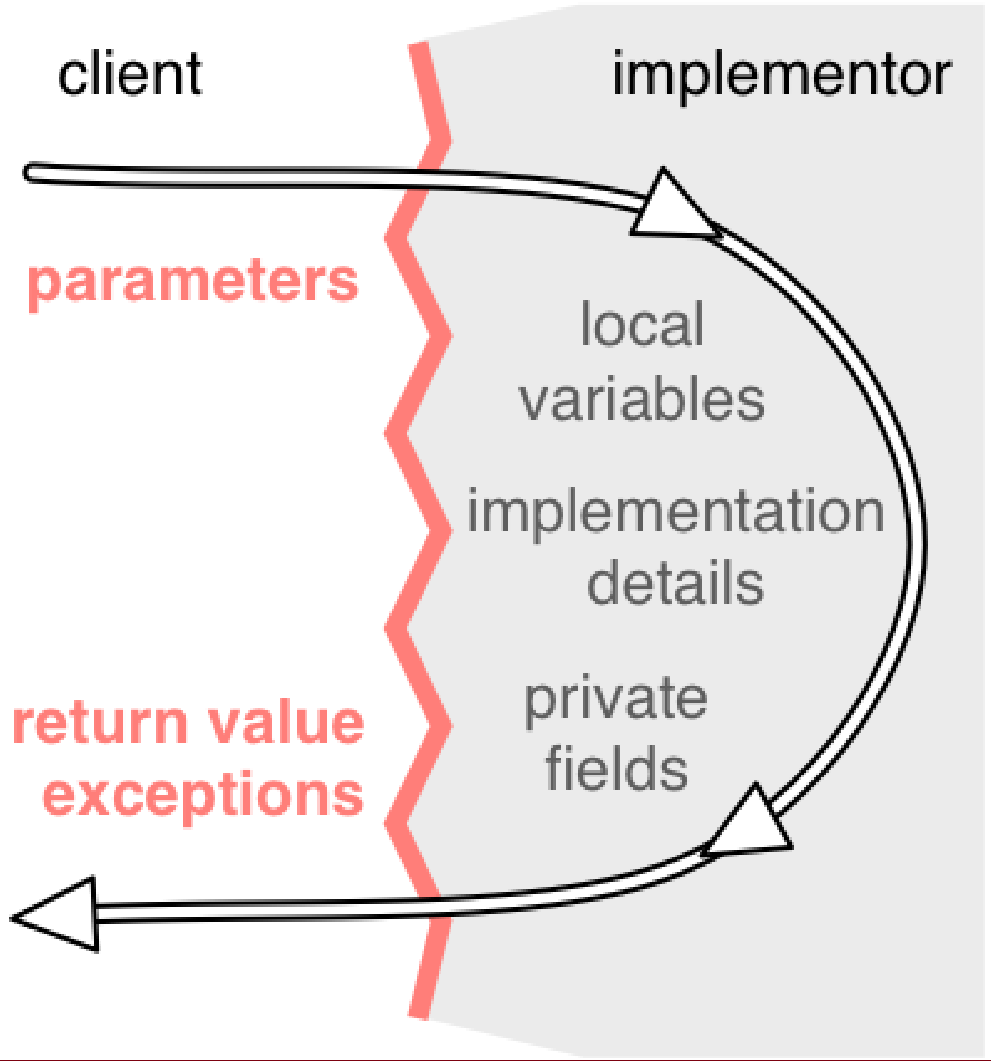
Example: Specifying Array Find

```
static int find(int[] arr, int val)
  requires: val occurs exactly once in arr
  effects: returns index i such that arr[i] = val
```

- A specification of the “find” function
- The two versions of “find” are both valid implementations of this specification!
  - As far as the client is concerned, they have the same behavior
  - One could be substituted with the other, without affecting the client’s code

Specification Must Hide Unnecessary Details

- What can appear inside the pre- & post-conditions?
- Recommended practice
  - Pre-conditions should only mention input parameters of a function (**Q. Why not output?**)
  - Post-conditions should only mention the input & output parameters
  - They should avoid mentioning hidden/private fields in the component (**Q. Why not?**)
    - If necessary, instead refer to publicly visible fields/functions



Specification Must Hide Unnecessary Details

```
public class Account {
  private String accountID;
  private int currBalance; // in cents

  public void deposit(int dollars)
      requires: nothing
      effects: increase currBalance by (dollars)*100
    { … // implementation }
}
```

- **Q. What’s undesirable about this specification of “deposit”?**
- **Q. How would you improve this?**

How do we design a “good” specification?

Factors in Designing Specifications

- Deterministic vs. under-determined
- Declarative vs. operational
- Strong vs. weak
- General vs. restrictive

Deterministic vs. Under-determined

- A specification of a function is **deterministic** if, for any given input, it allows exactly one possible output.
- A specification is **under-determined** if, for some input, it allows multiple possible outputs.

Recall: Specification of Find

```
static int find(int[] arr, int val)
  requires: val occurs exactly once in arr
  effects: returns index i such that arr[i] = val
```

- An example of a **deterministic** specification
  - Only one return value is possible for any given input

Recall: Specification of Find

```
static int find(int[] arr, int val)
  requires: val occurs exactly once in arr
  effects: returns index i such that arr[i] = val
```

Spec ver1

```
static int find(int[] arr, int val)
  requires: val occurs in arr
  effects: returns index i such that arr[i] = val
```

Spec ver2

- **Q. Is the second specification (ver2) deterministic or under-determined? Why?**

Recall: Implementations of Find

```
static int find(int[] arr, int val) {
  for (int i = 0; i < arr.length; i++) {
    if (arr[i] == val) return i;
  }
  return arr.length;
}

static int find(int[] arr, int val) {
  for (int i = arr.length -1 ; i >= 0; i--) {
    if (arr[i] == val) return i;
  }
  return -1;
}
```

These are both valid implementations of Spec ver1 & ver2!

Deterministic vs. Under-determined

- A specification of a function is **deterministic** if, for any given input, it allows exactly one possible output.
- A specification is **under-determined** if, for some input, it allows multiple possible outputs.
- An under-determined specification is ambiguous and can result in behaviors that are “surprising” to the client
  - The client can’t rely on what output the function will return
- In general, deterministic specifications are preferrable
  - **Design consideration**: For a given input, are multiple ouputs possible? If so, how do I modify the pre- or post-condition to make it deterministic?

Declarative vs. Operational

- An **operational** specification describes **how** a function achieves its post-condition through a series of steps
- A **declarative** specification describes **what** a function achieves without saying **how**

Declarative vs. Operational: Example

```
static int find(int[] arr, int val)
  requires: val occurs in arr
  effects: examines a[0],a[1],…, in turn and returns
                    the index of the 1st element equal to val
```

- An example of an operational specification
  - **Q. What is undesirable about this specification?**
  - Expose details about how the function is implemented internally
  - Unnecessarily constrains the set of possible implementations

Declarative vs. Operational: Example

```
static int find(int[] arr, int val)
  requires: val occurs in arr
  effects: examines a[0],a[1],…, in turn and returns
                     the index of the 1st element equal to val
```

Operational

```
static int find(int[] arr, int val)
  requires: val occurs in arr
  effects: returns index i such that arr[i] = val
```

Declarative

- Declarative specifications tend to:
  - Be shorter, easier to understand
  - Allow a larger set of implementations
  - Give more flexibility to the implementor!

Declarative vs. Operational

- An **operational** specification describes **how** a function achieves its post-condition through a series of steps
- A declarative specification describes **what** a function achieves without saying **how**
- Operational specifications tend to:
  - Expose details about how the function is implemented internally
  - Unnecessarily constrains the set of possible implementations
- Declarative specifications are preferrable
  - **Design consideration**: Is the specification describing “how” something is done? If so, can we rewrite it to say only “what” it does?

Strong vs. Weak

- Let S1 and S2 be specifications with the same pre-condition
- S1 is **stronger** than S2 if S1 provides more guarantees about the output than S2 does
  - (Mathematically, S1’s post-condition is **logically stronger** than S2’s post-condition)

Strong vs. Weak: Example

```
static int find(int[] a, int val)
  requires: val occurs at least once in a
  effects: returns index i such that a[i] = val
```

Spec ver1

```
static int find(int[] a, int val)
  requires: val occurs at least once in a
  effects: returns lowest index i such that a[i] = val
```

Spec ver2

- Spec ver2 is stronger than ver1, since it provides stronger guarantees about the output
- How strong is “strong enough”?
  - Depends on the client’s requirements
  - To fulfill their own tasks, does the client rely on the index being the lowest?

Strong vs. Weak: Example #2

```
static int find(int[] a, int val)
  requires: nothing
  effects: returns index i such that a[i] = val
```

Spec ver3

- **Q. What is wrong with ver3?**
    - The specification is too strong. In fact, there is no possible valid implementation for this specification!

Strong vs. Weak: Example #2

```
static int find(int[] a, int val)
  requires: nothing
  effects: returns index i such that a[i] = val
```

Spec ver3

```
static int find(int[] a, int val)
  requires: nothing
  effects: if val doesn't occur in a, returns -1
                      else returns index i such that a[i] = val
```

Spec ver4

- Specification should be as weak as possible
  - Stronger specifications allow a smaller set of implementations & are harder to implement
  - Weaker specifications give more flexibility to the implementor

Strong vs. Weak

- Let S1 and S2 be specifications with the same pre-condition
- S1 is **stronger** than S2 if S1 provides more guarantees about the output than S2 does
  - (Mathematically, S1's post-condition is **logically stronger** than S2's post-condition)
- A specification should be strong enough to support the needs of the client
- A specification should also be as weak as possible, to provide as flexibility to the implementor
  - **Design consideration**: Is the specification providing more guarantees than needed? If so, how much can we relax them without breaking the client's code?

General vs. Restrictive

- Let S1 and S2 be specifications with the same post-condition
- S1 is **more general** than S2 if S1 puts less restrictions on the input than S2 does
  - (Mathematically, S1’s pre-condition is **logically weaker** than S2’s pre-condition)

General vs. Restrictive: Example

```
static int find(int[] a, int val)
  requires: val occurs exactly once in a
  effects: returns index i such that a[i] = val
```

Spec ver1

```
static int find(int[] a, int val)
  requires: val occurs in a
  effects: returns index i such that a[i] = val
```

Spec ver2

- Spec ver2 is more general than ver1, since it accepts a larger set of inputs
  - In ver1, the client must ensure that “val” occurs exactly once; ver2 imposes less burden on the client

General vs. Restrictive: Example #2

```
static int find(int[] a, int val)
  requires: nothing
  effects: if val doesn’t occur in a, returns -1
                    else returns index i such that a[i] = val
```

- Spec ver3 is most general (for the given post-condition)
  - Accepts any inputs; no burden on the client!
- But also shifts the burden onto the component to check input
  - Sometimes, this is undesirable, due to complexity or performance issues (e.g., consider a very large input array)
- A restriction of the pre-condition is sometimes necessary

General vs. Restrictive

- Let S1 and S2 be specifications with the same post-condition
- S1 is **more general** than S2 if S1 puts less restrictions on the input than S2 does
    - (Mathematically, S1's pre-condition is **logically weaker** than S2's pre-condition)
- A specification should be as general as possible
    - A pre-condition places burden on the client to satisfy it
    - Less restrictive it is, more applicable the function is
- A specification should be restrictive when necessary
    - **Design consideration:** What needs to be checked about the input? If the check is too expensive, can we restrict the pre-condition to rule out bad inputs?

Factors in Designing Specifications

- Deterministic vs. under-determined
- Declarative vs. operational
- Strong vs. weak
- General vs. restrictive

Exercise: Are these good specifications?

```
static Set union(Set s1, Set s2)
  requires: “s1” and “s2” are non-empty
  effects: returns a new set that contains the
                         elements from both “s1” and “s2”
```

```
static List sort(List l)
  requires: nothing
  effects: returns a new list that results from
                     applying merge sort to “l”
```

```
static String read(String filepath)
  requires: filepath is not null
  effects: opens the file at “filepath” and returns
                     the content of the file as a string
```

Interface Specifications: Takeaway

- A specification defines a contract between a component and its clients
- A specification defines a set of valid possible implementations
- A specifications should be deterministic rather than under-determined
- A specification should be declarative rather than operational
- A specification should be sufficiently strong, while being as weak as possible
- A specification should be as general as possible, while being restrictive when necessary

Summary

- Exit ticket!