Automatic Verification&Testing

Programming with Contracts

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Programming with Contracts

Contract

A (formal) agreement between

Method M (callee)		**Callers of M**	
Rights	Responsabilities	Rights	Responsabilities

Example

Contract

Compute square root of a real number

Method (callee): get-square-root		Caller get-fibonaci-number	
Expects non negative numbers	Return the square root	Invoke method with non negative numbers	Obtain the square root

Programming with Contracts

- **Contract**: Agreement between parts
  - In this case: method and user method
- The method pre & postconditions defines an agreement between caller and callee.
  - The client (caller) must **ensure the precondition** and **assume the postcondition**
  - The method (callee) may **assume the precondition**, but it must **ensure the postcondition**

	Responsabilities	Rights
Caller	Pre_Callee	Post_Callee
Callee	Post_Callee	Pre_Callee

Specifying contracts in components

- A component implements some entity or important element for our solution
  - Component = set of classes
  - Class = set of methods

- Contracts
  - At method level: **Requires**, **Ensures**
  - At class level: object/class **invariants**
  - At component level: ownerships + invariantes among different objects

Weak vs. Strong specifications

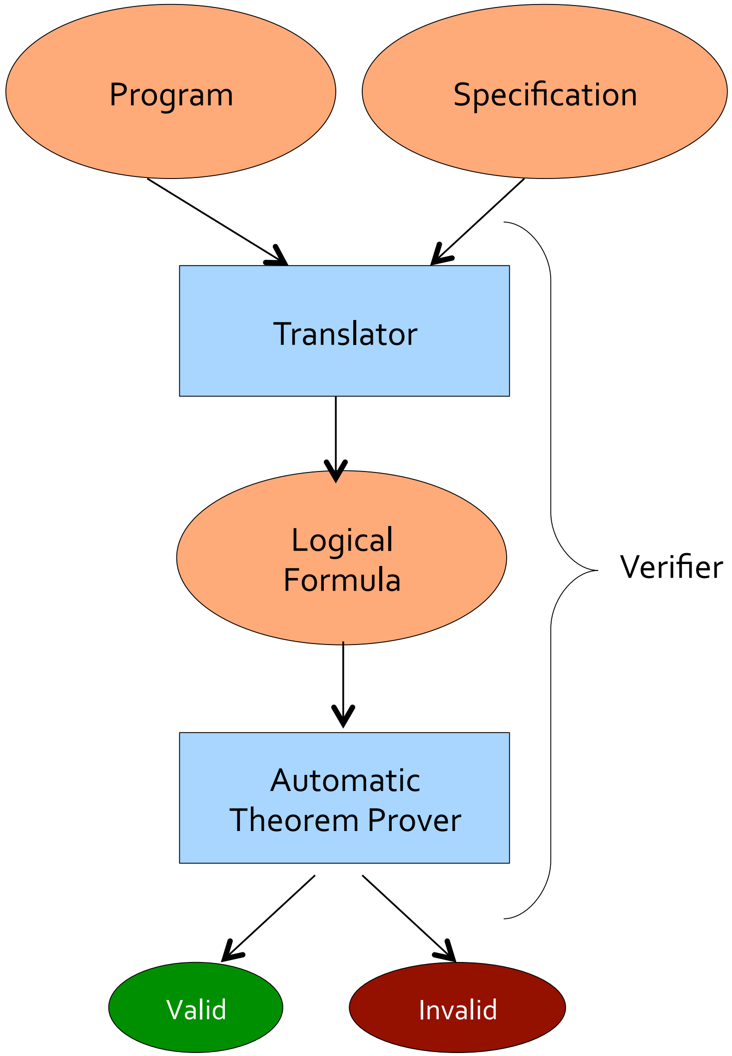
- Dataflow analysis and typestate checking are very effective for dealing with "weak" specifications
  - Very simple correction properties
  - Null pointers, zero division, API usage, etc.
- They are inadequate for dealing with complex/complete specifications ("strong" specifications)
  - This functions computes an invoice for a customer
  - The candidate declared as winner is the one who has more votes
- Can we write several weak specifications to express a strong specification?

The Verifying Compiler

- The Verifying Compiler
  - automatically checks that a program conforms to its specification
  - The correction can be specified using types, assertions or any other redudant annotation to the program
- **The Verifying Compiler: A Grand Challenge for Computing Research** [Hoare, 2004]
- First Proposal: 1969

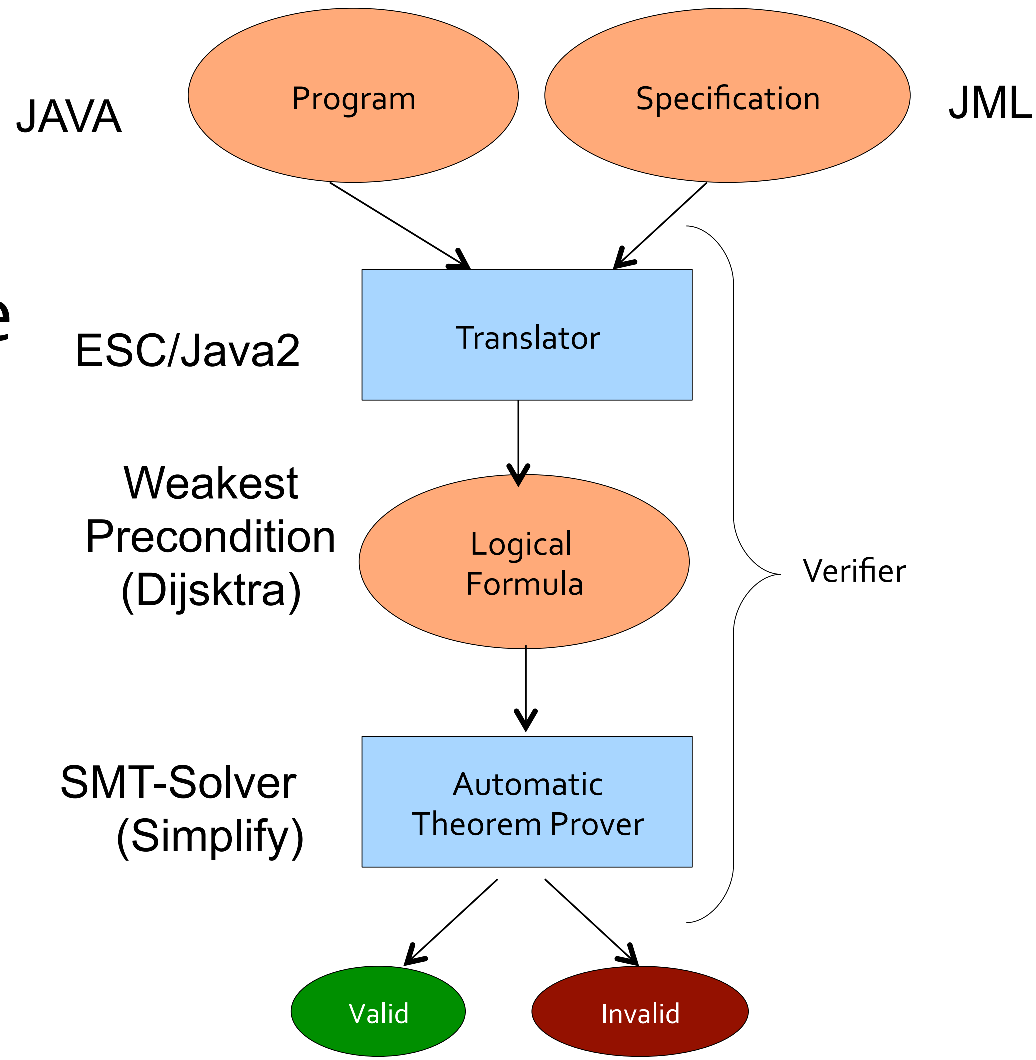
The Verifying Compiler

- *Soundness*:
  - If the formula is true, then the program satisfies the specification



The Verifying Compiler

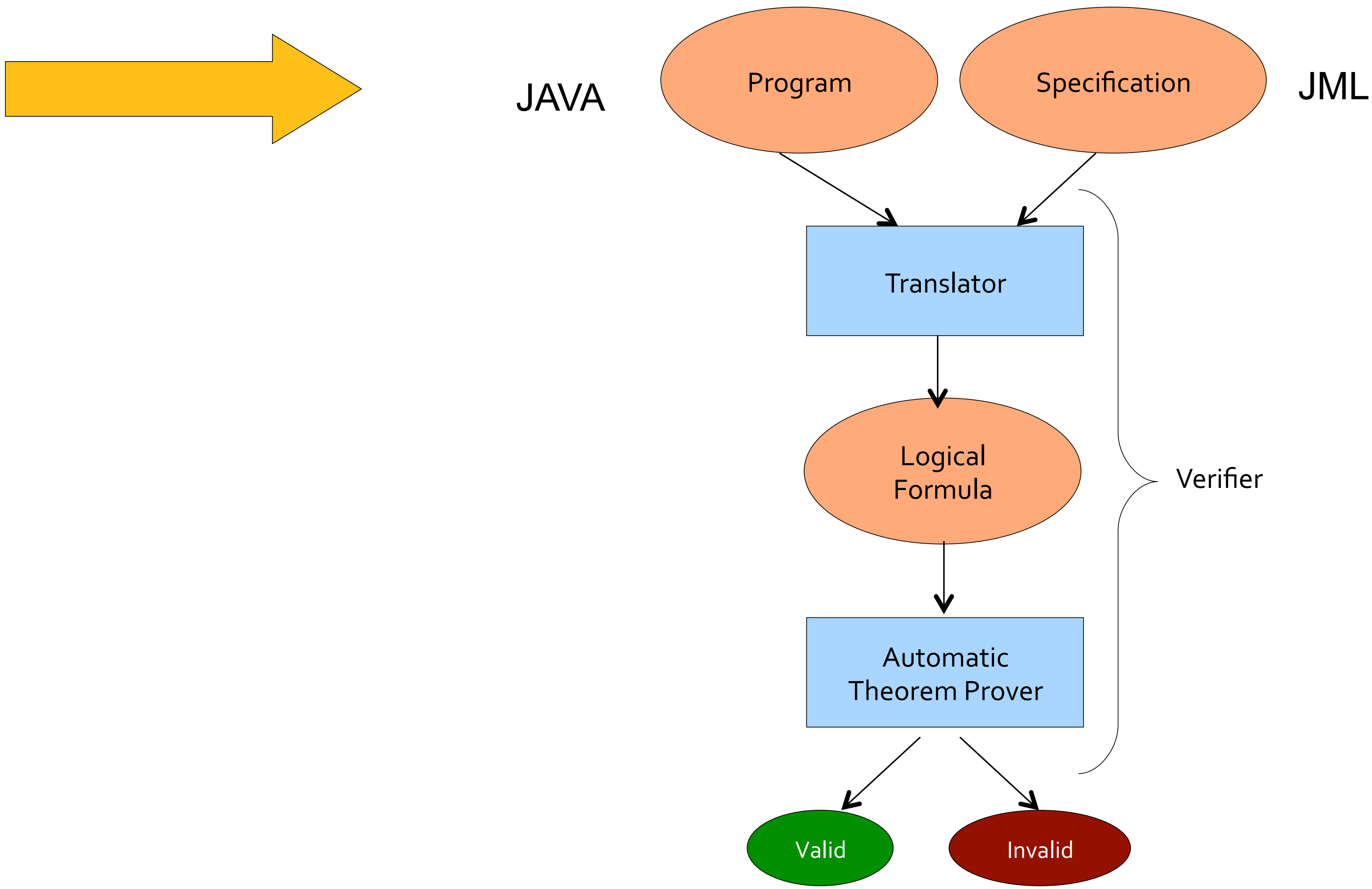
- Programming Language
- Specification Language
- Logical representation of the program
- Automatic Decision Procedure



Desired properties of a Verifying Compiler

- **Soundness**
  - If the verifier reports no failure, then the program does not fail
- **Completeness**
  - If the verifier reports a failure, then the program fails
- **Termination**
  - Given any program P, the verifier finishes the analysis of P (even with an unknown result)

The Specification Language



JML: Java Modeling Language

- Formal specification language for Java
- Objective: Design a specification language easy to use for most of the programmers
- Origin: runtime assertion checking
- Inspiration: Eiffel language (Design by Contract™)
- For C#: Spec#, CodeContracts™

JML Annotations

- Within comments in the Java code using /*@…@*/, or after //@ ….

- Boolean Java expressions extended with some new operators
  - (\old, \forall, \result,\sum…)

- Several kinds of annotations
  - Modifiers: pure, non_null, nullable…
  - Method level: requires, ensures, signals,
  - Class level: invariant

JML: pre-, post-conditions (1)

```
/*@ requires amount>=0;
  @ ensures balance == \old(balance)-amount;
  @ ensures \result == balance
  @*/
 public int debit(int amount) {...}
```

- **\old**(...) returns the value of the expression before the execution of the method
- **\result** refers to the return value of the method

JML: pre-, post-conditions (2)

```
/*@ requires amount>=0;
  @ ensures \result == balance
  @*/
 public int debit(int amount) {...}
```

- JML specifications can be as weak (or strong) as we want them to be.
- This specification is stronger or weaker then the previous one?

JML: exception handling

```
/*@ requires amount>=0;
  @ ensures true;
  @ signals (BankException e)
  @                     amount > balance &&
  @                     balance==\old(balance) &&
  @                     e.getReason().equals(...)
  @*/
public int debit(int amount) throws BankException {...}
```

- If the program signals an exception of type BankException, then the predicate holds

JML: exceptions handling

- All exceptions are allowed by default (ensures only applies to normal termination).
- To change this:
  - Forbid all exceptions

```
/*@ normal_behaviour
  @ requires …
  @ ensures …
  @*/
```

JML: exceptions handling

- All exceptions are allowed by default (ensures only applies to normal termination).
- To change this:
  - Forbid all exceptions
  - Forbid one exception type E

```
//@ signals (E) false;
```

JML: exceptions handling

- All exceptions are allowed by default (ensures only applies to normal termination).
- To change this:
  - Forbid all exceptions
  - Forbid one exception type E
  - Allow only some exceptions types E1,…,En

```
//@ signals_only E1,...,En;
```

JML: exceptional behavior

```
//@ signals (Ex e) P(e);
```

- This means: if an exception e of type Ex is thrown, then P(e) holds
- Can we say: if this precondition holds, then the exception Ex is thrown?

JML: exceptional_behavior

```
/*@ normal_behavior
  @     requires amount<=this.balance;
  @ also
  @ exceptional_behavior
  @     requires amount>this.balance;
  @     signals (BankException e) e.getReason().equals(...);
  @*/
public int debit(int amount) throws BankException {...}
```

- **normal_behavior** implicitly includes a clause:
  - **signals** (Exception ex) false;

JML: assert (1)

- An assertion specifies a property that holds at a given program point

```
if (i<=0 || j<0) {
  ...
} else if (j<5) {
  //@ assert i>0 && 0<j && j<5;
  ...
}
```

JML: assert (2)

- JML assertions have more expressive power since we can include JML operators

```
for (n=0; n<a.length; n++) {
  if (a[n]==null) break;
  //@ assert (\forall int i; 0<=i && i<n; a[i]!=null);
  ...
}
```

JML: assume

- Like JML assertions, but we restrict ourselves to traces where the condition is true

```
//@ assume b!=null && b.length>0;
b[0]=2;
```

- Useful during development
  - We can document assumptions
  - They “help” the automatic theorem prover

JML: frame conditions

- A frame conditions constraints the side-effects of a given method

```
/*@ requires amount>0;
  @ assignable this.balance
  @ ensures this.balance==\old(this.balance) – amount;
  @*/
public int debit(int amount) {…}
```

- Can we constraint side-effects by adding postconditions?

- By default: //@ modifies \everything

JML: frame conditions

- A method with no side-effects is called "pure".

```
Public /*@ pure @*/  int getBalance() {…}
```

- The pure annotation is equivalent to

```
//@ assignable \nothing;
```

- Only pure methods can be used in specifications

```
//@ requires this.getBalance()>0;
```

JML: frame conditions (3)

- Problem: dealing with assignable annotations can be VERY ANNOYING.

```
public class Timer{

  int time_hrs, time_mins, time_secs;
  int alarm_hrs, alarm_mins, alarm_secs;

  //@ assignable time_hrs, time_mins, time_secs;
  public void tick() {...}

  //@ assignable alarm_hrs, alarm_mins, alarm_secs;
  public void setAlarm(int hrs, int mins, int secs){...}
```

JML: DataGroup

- DataGroups: allow us to specify a recurrent subset of assignable locations

```
public class Timer{
  JMLDataGroup time, alarm;
  int time_hrs, time_mins, time_secs; //@ in time;
  int alarm_hrs, alarm_mins, alarm_secs; //@ in alarm;

  //@ assignable time;
  public void tick() {…}

  //@ assignable alarm;
  public void setAlarm(int hrs, int mins, int secs){…}
```

JML: class invariants

- Class invariants are properties that must be preserved by all methods

```
public class Wallet {
  public static final short MAX_BAL = 1000;
  private short balance;
  /*@ invariant 0<=this.balance &&
    @           this.balance<=MAX_BAL;
    @*/
```

- They are implicitly included in all methods
- They must be preserved even in case of abnormal termination

JML spec_public

```
public class ArrayOps {
private /*@ spec_public @*/ Object[] a;
//@ public invariant  0 < a.length;
/*@ requires 0 < arr.length;
@ ensures this.a == arr;
@*/
public void init(Object[] arr) {
this.a = arr;
}
```

Private fields can be Used in the specification

Object invariant

Specification of method init

JML: non_null

- This modifier allows us to specify if a given field, argument or variable can be null
- By default: all fields (!), arguments, return types and quantified variables (\forall, \exists) have an implicit **non_null** modifier.
- The opposite annotation of **non_null** is **nullable**
- Example:
  - **/*@ nullable @*/** Integer i;
  - **/*@ non_null @*/** Object o;

Loop invariant

- A predicate describing how the program state changed by executing the loop.

- Part of the reasoning we do (our subconscious?) while writing a loop
  - Formal description:
    - What we assume before loop execution
    - How the program state evolved at the end of the iteration

- **For verification purposes they are foundamental** (unless we have a loop free program)

Loop invariants

```
int sumX (x: Int) {
//@   requires x >= 0;
//@   ensures \result == \sum(i: int; 0<=i<=x; i)
```

```
int sumX (int x) {
   int s = 0, i = 0;
   while (i < x) {
      // state s1
      i = i + 1;
      s = s + i;
     // state s2
   }
   return s;
}
```

i@s1	s@s1	i@s2	s@s2
0	0	1	1
1	1	2	3
2	3	3	6
3	6	4	10

Loop invariants

s == \sum(j: int; 0<=j<=i; j)
&& 0 <= i <= x

JML: loop annotations

- JML allows us to annotate a loop invariant and a variant function:

```
//@ loop_invariant product==m*i && i>=0 && i<=n && n>0;
//@ decreases n-i;
while (i < n) {...}
```

- **loop_invariant**: the loop invariant
- **decreases**: variant function

- Why do we need a variant function for?

JML: ghost fields

- A *ghost* field is a regular field, except for the fact that we can only refer to it from the specification
  - Example: **//@ ghost** Object F;
- JML provides the special statements **set** for updating the value of a *ghost* field
  - Instead of assigning a new value, the update is captured by using a <u>condition</u>.
  - Example: **//@ set** F==null;

JML: ghost fields

```
class Animal {
  //@ ghost Zoo owner;
  ....
}
```

```
Class Zoo {
 void add(Animal a) {
 ...
 //@ set a.owner==this;
 }

 //@ requires a.owner==this;
 void feed(Animal a) {...}
}
```

Reachability in JML: \reach(...)

- Returns the set of "reachable" objects

- \reach captures the reflexive-transitive closure of a binary relation
  - $R^* = \{\} \cup R \cup (R;R) \cup (R;R;R) \cup (R;R;R;R) \cup \ldots$

- The expression value is a JMLObjectSet (empty if only null is reachable)

Some \reach(…) flavours

- \reach(this.f)
  - All objects that are reachable by using any field in the reachable objects starting from this.f
- \reach(this.f, T, f2)
  - All objects that are reachable starting from this.f BUT
    - Only traversing field f2
    - Objects of type T

Exercise

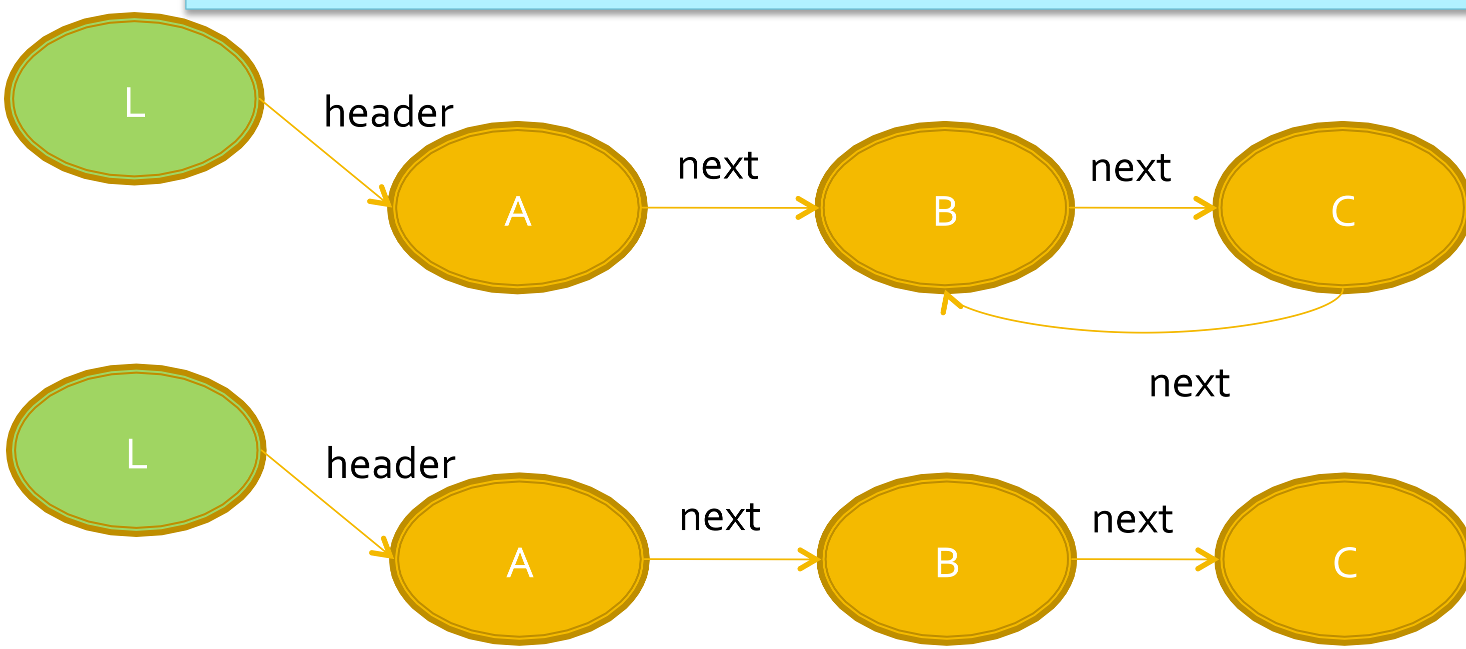
```
class List { Node header; }
 class Node { Node next; Object data; }
```

- Write an invariant for class List such that all reachable nodes form an **acyclic list**.

```
/*@
  @ invariant (\forall Node n;
  @    (\reach(this.header, Node, next)).has(n) ;
  @   !(\reach(n.next, Node, next)).has(n) ) ;
  @*/
```

The invariant in detail

```
/*@
  @ invariant (\forall Node n;
  @    (\reach(this.header, Node, next)).has(n) ;
  @   !(\reach(n.next, Node, next)).has(n) ) ;
  @*/
```



B ∈ {A, B,C}
&& B ∈ {C,B}

ForA,B y C:
A∉ { B,C}
B∉ {C}
C∉ {}

Example

- What is wrong in this class?

```
public class Counter {
  private /*@ spec_public @*/ int val;
  //@ modifies val;
  //@ ensures val == \old(val + y.val);
  //@ ensures y.val == \old(y.val);
  public void addInto(Counter y) {
    val += y.val; }
  }
}
```

Example

- What is wrong with this class?

```
public class Counter {
  private /*@ spec_public @*/ int val;
  //@ modifies val;
  //@ requires y!=this;
  //@ ensures val == \old(val + y.val);
  //@ ensures y.val == \old(y.val);
  public void addInto(Counter y){
   val += y.val; }
  }
}
```