Program Verification
(6EC version only)

Erik Poll

Digital Security

Radboud University Nijmegen

TRU/e Master in Cyber Security

Overview

- Program Verification using Verification Condition Generators
- JML – a formal specification language for Java

  Used for the program verification exercise

Program verification

- Formally proving (in the mathematical/logical sense) that a program satisfies some property
  - eg that it does not crash, always terminates, never terminates, meets some functional specification, meets some security requirement, etc
  - *for all possible executions*: ie all possible inputs and all possible scheduling of parallel threads.
- NB in industry, the term verification is used for testing

  but testing provides only *weaker* guarantees
  - because testing will only try some executions
  - except in rare case where you can do exhaustive testing
- Formal verification provides the highest level of assurance that code is correct & secure
  - provided… you can formally verify what it means for the code to be secure

What do we need for program verification?

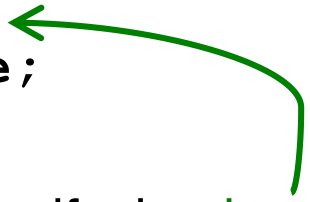
1. a formal semantics of the programming language
2. a specification language to express properties
3. a logic to reason about programs and specifications
   – aka a program logic
4. a verification tool to support all this

These topics are investigation in the field of field of formal methods

What to verify? Example

For the program

```
...
x[4] = false;
...
```



we might want to verify that here `x` is not null and `4` is within the array bounds (and that `x` is a Boolean array)

- Proving absence of runtime exceptions (or, in an unsafe language like C, memory-safety, or more generally, the absence of undefined behavior) is a great bottom-line specification to start verification!
- Typing is a simple form of program verification, for a limited and relatively weak class of properties, eg "`x` is a byte array"

  A type checker can be regarded as an automated program verifier for this class of properties.

How to specify what we want to verify?

A common way to write we want to verify is using assertions, ie properties that hold at specific program points

```
...
// assert x != NULL && x.length > 4;
x[4] = false;
...
```

Assertions written as annotations in code are also useful for testing, and for generating bug reports.

For methods or procedures, we can give pre- and post-conditions

How to verify?

Is the assertion below always true?

```
...
if (x < y) { int z; z = y; y = x; x = z;}
// assert y <= x
```

How do your verify this?

- You follow all paths in the control flow graph, and check that for each path the property holds using normal logical reasoning

Ways to formalize this reasoning process

- compute verification conditions using weakest precondition calculation (or strongest postcondition ~)
- use symbolic execution to obtain these verification conditions

Complication 1 : cycles

Is the assertion below always true?

```
...
int i = x-y;
while (i > 0) { y++;
                i--;
              }
// assert y >= x
```

We can't follow all paths through the control flow graph, as the graph contains a cycle.

We need a loop invariant.

Complication 1 : cycles

Is the assertion below always true?

```
...
int i = x-y; // so y+i == x
while (i > 0) { y++; // now y+i == x+1
                i--; // now y+i == x
              }
// now i <= 0 (because we exited the while loop)
// and y+i == x (because it is a loop invariant)
//   and therefore y >= x
```

Once we realise that **`y+i == x`** is a loop invariant, we can split the graph in a finite number of segments, and check that each segments meets the specification

Complication 2 : modularity & the heap

Programming languages offer procedures or methods for modularity. This complicates reasoning.

```
...
x = 5;
p();
// assert x == 5
```

Is the assertion always true?

Complication 2 : modularity & the heap

If **`x`** is on the stack, the assertion is always true

```
proc m() {
  int x;
  x = 5;
  p();
  // assert x == 5
}
```

because **`x`** is out of scope for **`p()`**

- *assuming that we are in a memory-safe language:*
  if p contains buffer overflows, pointer arithmetic, …
  all bets are off!

Complication 2 : modularity & the heap

If **`x`** is on the heap, things become tricky

- even in a safe programming language!

In Java, will the assertion below always hold?

```
x = 5;
o.p();
// assert x == 5
```

Complication 2 : modularity & the heap

```
class A {
   static int x = 12;  // ie a class field

   public void m() {
     x = 5;
     o.p();
     // assert x == 5
   }
   ...
```

Is the assertion below always true?

No, because **`o.p()`** might change **`A.x`**

Complication 2 : modularity & the heap

```
class A {
   int x = 12;

   public void m() {
     x = 5;
     o.p();
     // assert x == 5
   }
   ...
```

Assertion is not guaranteed to hold, because

- `o` might be aliased to `this` and `o.p()` could change `x`
- `o` might have a reference to `this` and then change `x`, via the reference if x `x` is not private, or by invoking a method
- ...

Complication 3

```
...
x = 5;
// assert x == 5
```

Is the assertion always true?

Complication 3: concurrency & the heap

```
...
x = 5;
// assert x == 5
```

Is the assertion always true?

No, not if there is another thread running that may also be accessing **`x`**

The problem, and possible solutions, are very similar to the problem of modular reasoning about procedures/methods.

Solutions include separation logic, implicit dynamic frames, or ownership

Newer programming languages such as Rust might be better suited for reasoning about concurrency

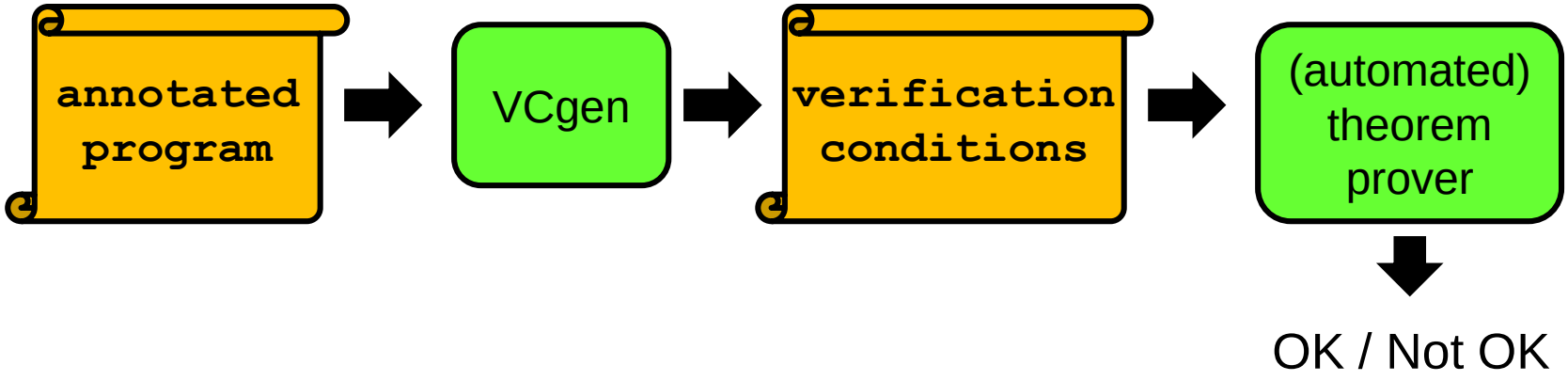
Program Verification
using
Verification Condition Generation

Program Verification using VCGen

One of the standard approaches for program verification:

using Verification Condition Generator (VCGen):

1. Program is annotated with properties (the specification)
2. Verification Condition Generator produces a set of logical properties, the so-called verification conditions
3. If these verification conditions are true, the annotations are correct – ie the program satisfies the specification



Example verification using VCGen

```
//@ requires true;
//@ ensures \result > 5;
public int example(int j)
{
  if (j < 8) {
    int i = 2;
    while (j < 6*i){
      j = j + i;
    }
  }
  return j;
}
```

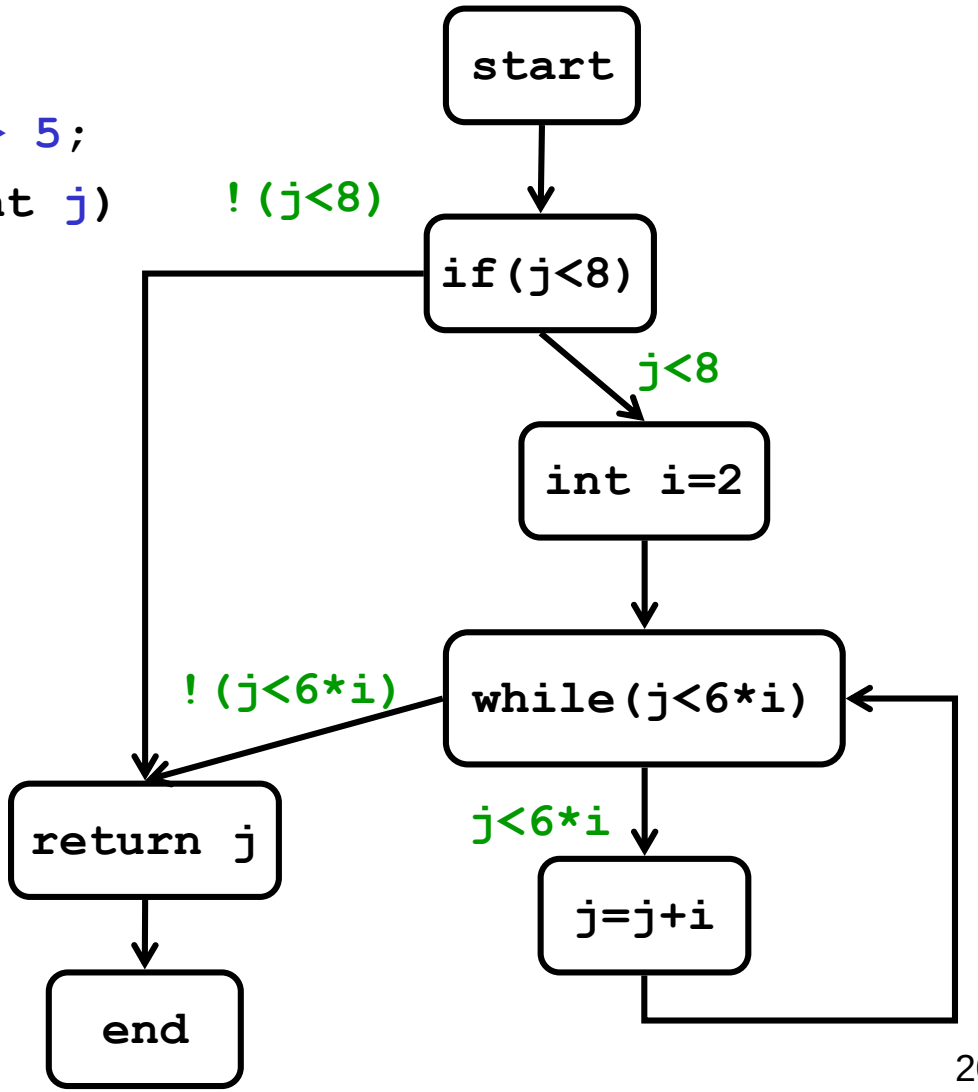
These annotations give a pre- and postcondition that form the specification:

on any input, this method will return a result greater than 5

- is this specification always met?
- how do you know this?
- could an automated tool reproduce your reasoning?

Verification using VCGen
(i) program as graph

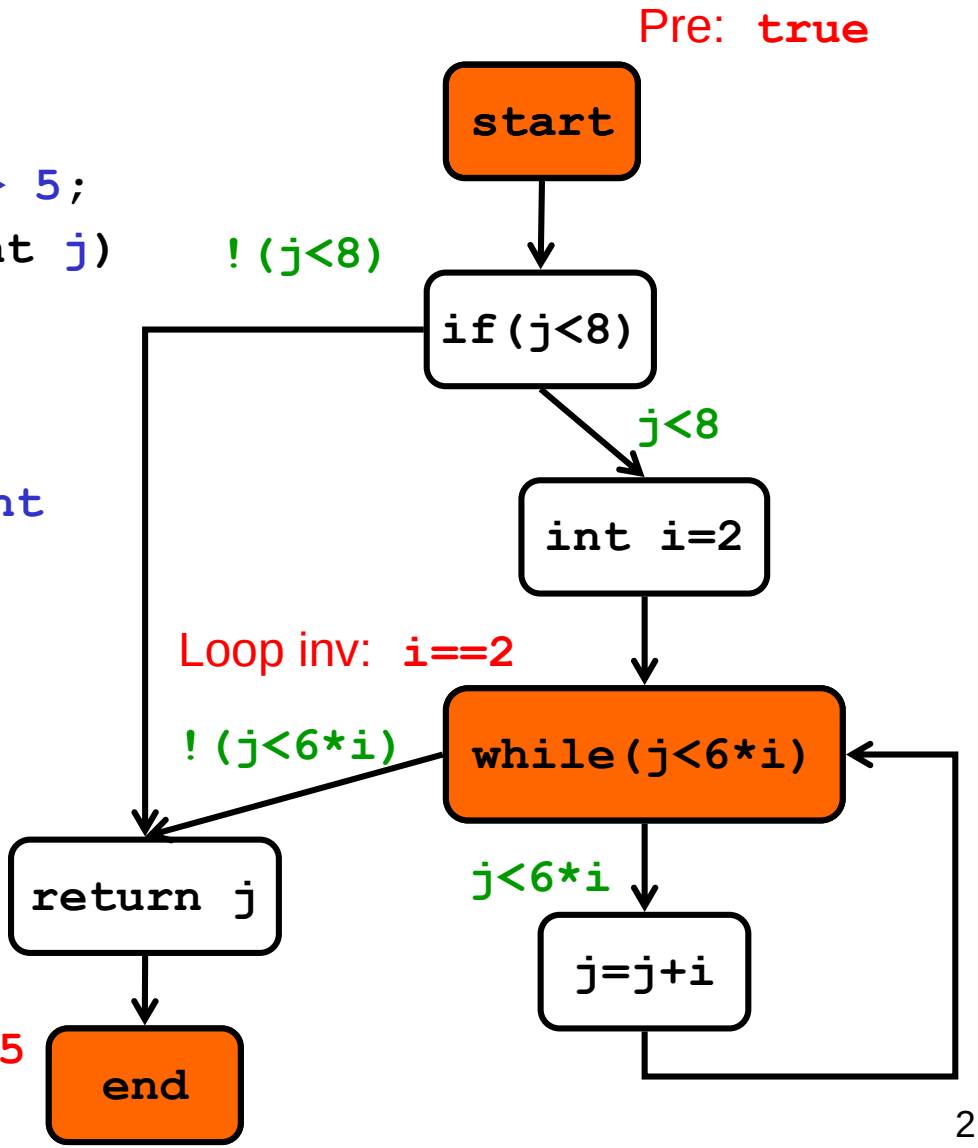
```
//@ ensures \result > 5;
public int example(int j)
{
  if (j < 8) {
     int i = 2;
     while (j < 6*i){
       j = j + i;
     }
  }
  return j;
}
```



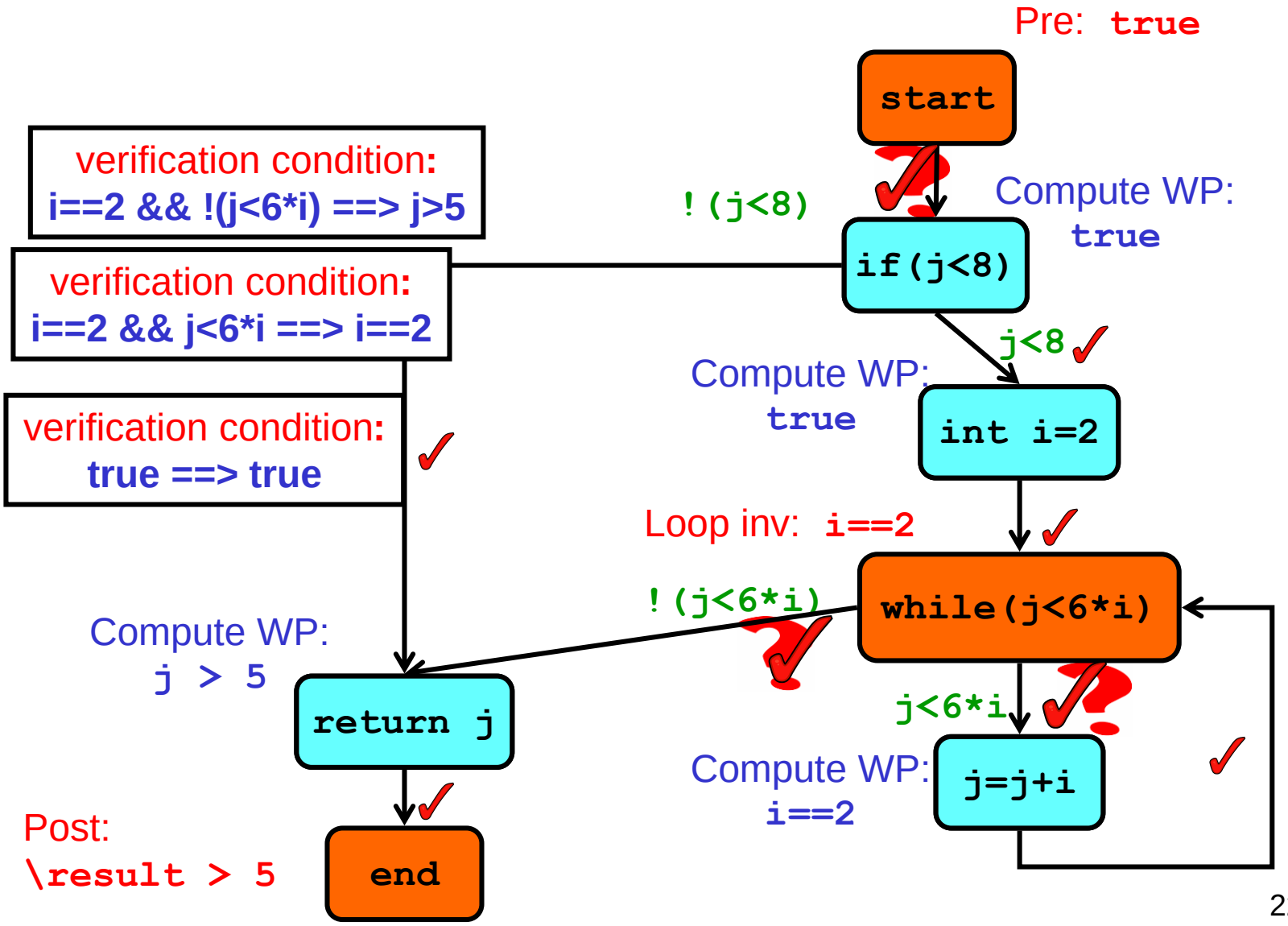
Verification using VCGen
(ii) add assertions

```
//@ ensures \result > 5;
public int example(int j)
{
  if (j < 8) {
     int i = 2;
     /*@ loop_invariant
           i==2;
     @*/
     while (j < 6*i){
       j = j + i;
     }
  }
  return j;
}
```

Post: `\result > 5`



Verification using VCGen
(iii) compute VCs & check



Verification condition generation

Given a postcondition and loop invariants

- compute a assertion P_s for every state s

  based on assertions $P_{s'}$ of the states s' reachable from s
  - key idea: P_s is the weakest predicate such that if it hold in state s, and the program goes to state s' then $P_{s'}$ will hold in that state s'
- all that remains to be verified
  - $Pre \Rightarrow P_0$

    the precondition specified in the program implies the assertion computed for the initial state
  - $Loop_s \Rightarrow P_s$

    each loop assertion specified in the program implies the assertion computed for that state

“Opposite” approach: forward instead of backwards

Instead of working backwards from the postcondition of the final state, you can work forward from the precondition in the initial state:

you then compute strongest postconditions

instead of weakest preconditions

This is very similar to symbolic execution of a program.

Tricky issues in program verification

Whatever the approach, the bottlenecks in program verification remain…

1. pointers / references & the heap

   Reasoning about data on the heap is difficult.

   Even in a language with automatic memory management, such as Java or C#, we still have the complication of aliasing

2. concurrency aka multi-threading

Examples of program verification for security

- Verification of Microsoft Hyper-V Hypervisor using the VCC program verifier for C [2009]

  the motivation to verify this is… security!

  - Info on VCC

    http://research.microsoft.com/en-us/projects/vcc/

  - Video presentation on VCC

    http://channel9.msdn.com/posts/Peli/Michal-Moskal-and-The-Verified-C-Compiler/

- Verification of seL4 microkernel in L4.verified project at NICTA

  http://ts.data61.csiro.au/projects/TS/l4.verified/

- Fully verified TLS implementation miTLS

  https://mitls.org

JML
Formal specification for Java

JML

- Formal specification language for Java

  Properties can be specified in Design-By-Contract style, using pre/postconditions and object invariants

  NB by default, in JML invariants are *object* invariants, not *loop* invariants.

- Various tools to check JML specifications by eg
  - runtime checking
  - program verification

to make JML easy to use

- JML annotations are added as special Java comments, between `/*@ .. @*/` or after `//@`

- JML specs can be in .java files, or in separate .jml files

- Properties specified using Java syntax, extended with some operators

  `\old( ), \result, \forall, \exists, ==>`, ..

  and some keywords

  `requires, ensures, invariant, ....`

Example JML

```
public class ChipKnip{
  private int balance;
  //@ invariant 0 <= balance && balance < 500;

  //@ requires amount >= 0;
  //@ ensures balance <= \old(balance);
  //@ signals (BankException) balance == \old(balance);
  public debit(int amount) {
    if (amount > balance) {
          throw (new BankException("No way"));}
    balance = balance - amount;
 }
```

JML basics

- preconditions **`requires`**
- postconditions **`ensures`**
- exceptional postconditions **`signals`**
- (object) invariants **`invariant`**
  - must be established by constructors
  - must be preserved by methods
    - ie. assuming invariant holds in pre-state, it must hold in the post-state

Exceptional postconditions: signals

```
//@ requires ….
//@ ensures)…
//@ signals (BankException) balance == \old(balance);
 public debit(int amount) throws BankException {
   if (amount > balance) {
         throw (new BankException("No way"));}
   balance = balance – amount;
}
```

But you can ignore this for the practical exercise! There we will always prove that no exceptions can be thrown.

JML convention: a method may only throw exceptions that are explicitly listed in the throws clause. (Java allows implicit Runtime- excptions, eg Nullpointer- and ArrayIndexOutofBound; JML does not!)

non_null

- Lots of invariants and preconditions are about reference not being null, eg

```
int[] a; //@ invariant a != null;
```

- Therefore there is a shorthand

```
/*@ non_null @*/ int[] a;
```

- But, as most references are non-null, some JML tools adopt this as default, so that only *nullable* fields, arguments and return types need to be annotated, eg

```
/*@ nullable @*/ int[] b;
```

- We could also use JSR308 Java tags for this

```
@Nullable int[] b;
```

Defaults specs and joining specs

- Default pre- and postconditions

```
//@ requires true;
//@ ensures true;
```

can be omitted

-
```
//@ requires P
//@ requires Q
```

means the same as

```
//@ requires P && Q;
```

but the former may allow tools to give more precise feedback, namely on whether P or Q is not satisfied

What can you do with this?

- Documentation/specification
  - explicitly record detailed design decisions & document assumptions (and hence obligations!)
  - precise, unambiguous documentation
    - parsed & type checked
- Use tools for
  - runtime assertion checking
    - eg when testing code
  - compile time program analysis
    - up to full formal program verification

assert and loop_invariant

Inside method bodies, JML allows

- assertions

```
/*@ assert (\forall int i; 0<= i && i< a.length;
                           a[i] != null );
@*/
```

- loop invariants

```
/*@ loop_invariant 0<= n && n < a.length &
                    (\forall int i; 0<= i & i < n;
                                    a[i] != null );
@*/
```

- Program verification tools, such as ESC/Java2, KeY, Krakatoa, ... can do program verification of JML-annotated Java code

  There is a limit to what *fully automated* tools, such as ESC/Java2, can verify

  eg. they won't be able to prove Fermat's Last theorem

- So far, only really feasible for small(ish) programs
  - incl. realistic Java Card smart card applications

- In addition to doing the verification, which is a lot of work, a bottleneck is expressing the security property you want to verify

JML for security

JML can be used to specify for instance

1. which – if any - exceptions can be thrown
   incorrectly/not handling errors common source of security problems
2. security-critical invariants to be preserved
   even when exceptions occur
3. assumptions on input the application relies on
4. any property expressible by security automaton

Simply trying to verify that a program throws no exceptions – or just no Nullpointer-exceptions - will expose many (implicit) invariants and assumptions on input

Related work

- Spec# for C#
  by Rustan Leino & co at Microsoft Research

- SparkAda for Ada
  by Praxis High Integrity System

- ACSL for C
  used in the Frama-C toolset
  https://www.youtube.com/watch?v=J_xgbO5-32k

Some industrial usage, but esp. for *safety*-critical software (notably in avionics) rather than *security*-critical software