Program Verification
Automated Test Case Generation, Part I

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Now we can formally specify program behavior. How to make use of it?
Introduction

Now we can formally specify program behavior. How to make use of it?

**Automated Test Case Generation (ATCG)**

- ✔ tool support for creating test cases
- ✔ ensuring test case coverage methodically
Now we can formally specify program behavior. How to make use of it?

Automated Test Case Generation (ATCG)

- tool support for creating test cases
- ensuring test case coverage methodically

View JML-annotated code as formal description of all anticipated runs

ATCG Principle

- Specialize contract/code to representative selection of concrete runs
- Turn these program runs into executable test cases
Ideas common to systematic (automated) test generation

- **Formal** analysis of specification and/or code yields enough information to produce test cases
- Systematic algorithms give certain **coverage** guarantees
- Post conditions can be turned readily into test **oracles**
- **Mechanic reasoning** technologies achieve automation: constraint solving, deduction, symbolic execution, model finding
Automated Test Generation Framework: Unit Tests

Test a single method or function, the implementation under test (IUT)

Create test case for popular JAVA unit test framework: JUNIT

Test Cases in Unit Testing

- Initialisation of test data (test fixture/preamble): create program state from which IUT is started
- Invoke IUT
- Inspection of result: test oracle: tell whether test succeeded: PASS or FAIL
Black box vs White Box Testing

Black box testing

The IUT is unknown, test data generated from spec, randomly, etc.
Black box vs White Box Testing

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**White box testing**
The IUT is analyzed to generate test data for it
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White box testing
The IUT is analyzed to generate test data for it

Specific Pros and Cons
- ✔ White box testing can use additional information from code
- ❌ White box testing does require source code
Black box vs White Box Testing

**Black box testing**
The IUT is unknown, test data generated from spec, randomly, etc.

**White box testing**
The IUT is analyzed to generate test data for it

**Specific Pros and Cons**
- ✔ White box testing can use additional information from code
- ✗ White box testing does require source code
- ✔ Black box testing does not require source code
- ✗ Black box testing can be irrelevant/insufficient for IUT
Reminder

A given program state $S$ makes a boolean JML expression true or false.

Example

Assume that int[] arr has value $\{1,2\}$ in $S$.

Then “arr.length==2 && search(arr, 1)==0” is true in $S$. 
A desired program state can be reached by suitable test case preamble.
Program States and Test Cases

A desired program state can be reached by suitable test case preamble.

Example
Assume that `int [] arr` has value `{1,2}` in `S`.
This state can be reached by the following preamble:

```cpp
int [] arr = {1,2};
```
A desired program state can be reached by suitable test case preamble.

Example

Assume that \texttt{int[]} \texttt{arr} has value \{1, 2\} in \texttt{S}.
This state can be reached by the following preamble:

\begin{verbatim}
int [] arr = \{1, 2\};
\end{verbatim}

Assume we can compute such initialization code automatically.
Specification-Based Test Generation

Generate test cases from analysing formal specification or formal model of IUT

- Black box technology with according pros and cons
- Many tools, commercial as well as academic: JMLUnit, BZ-TT, JML-TT, UniTesK, JTest, TestEra, Cow_Suite, UTJML, ...
- Various specification languages: B, Z, Statecharts, JML, ...
- Detailed formal specification/system model required
Test Generation Principle

View JML contract as formal description of all anticipated runs

Specification-Based Test Generation Principle

- Specialize JML contract to representative selection of concrete runs
- Turn these program runs into executable test cases
Contracts and Test Cases

/\*\@ public normal_behavior
  @ requires Pre;
  @ ensures Post;
  @*/

    public void m() { ... };

All prerequisites for intended behavior contained in requires clause

Unless doing robustness testing, consider unintended behavior irrelevant
Contracts and Test Cases

```java
/*@ public normal_behavior
   @ requires Pre;
   @ ensures Post;
   @*/
   
   public void m() { ... };
```

All prerequisites for intended behavior contained in `requires` clause

Unless doing robustness testing, consider unintended behavior irrelevant

**Test Generation Principle 1**

Test data must make required precondition true
Multi-Part Contracts and Test Cases

```java
/**
 * public normal_behavior
 * @ requires Pre; 
 * @ ensures Post;
 * @ also
 * @ ...
 * @ also
 * @ public normal_behavior
 * @ requires Pre;
 * @ ensures Post;
 */
public void m() { ... };
```

**Test Generation Principle 2**

There must be at least one test case for each operation contract
Example

public class Traffic {
    private /*@ spec_public @*/ boolean red, green, yellow;
    private /*@ spec_public @*/ boolean drive, brake, halt;

    /*@ public normal_behavior
        @ requires red || yellow || green;
        @ ensures \old(red) ==> halt &&
            @ \old(yellow) ==> brake;
    */

    public boolean setAction() {
        // implementation
    }
}

Which test cases should be generated?
Data-Driven Test Case Generation

Generate a test case for each possible value of each input variable

- Combinatorial explosion (already $2^5$ cases for our simple example)
- Infinitely many test cases for unbounded data structures
- Test cases unrelated to specification or IUT
Data-Driven Test Case Generation

Generate a test case for each possible value of each input variable

❌ Combinatorial explosion (already $2^5$ cases for our simple example)
❌ Infinitely many test cases for unbounded data structures
❌ Test cases unrelated to specification or IUT

Restriction to test cases that satisfy precondition?
Generate a test case for each possible value of each input variable

- Combinatorial explosion (already $2^5$ cases for our simple example)
- Infinitely many test cases for unbounded data structures
- Test cases unrelated to specification or IUT

Restriction to test cases that satisfy precondition?

Insufficient (still too many), but gives the right clue!
Disjunctive Partitioning

/*@ public normal_behavior
   @ requires red || yellow || green;
   @ ensures \old(red) ==> halt &&
   @ \old(yellow) ==> brake;
@*/

Disjunctive analysis suggests at least three test cases related to precondition
Disjunctive Normal Form

Disjunctive Normal Form (DNF)

Assume the requires clause has the form

\[ C_1 \lor C_2 \lor \cdots \lor C_n \]

where each \( C_i \) does not contain an explicit or implicit disjunction.
Disjunctive Normal Form

Disjunctive Normal Form (DNF)

Assume the requires clause has the form

\[ C_1 \lor C_2 \lor \cdots \lor C_n \]

where each \( C_i \) does not contain an explicit or implicit disjunction.

Test Generation Principle 3

For each disjunct of precondition in DNF create test case making it true
Disjunctive Normal Form

Disjunctive Normal Form (DNF)
Assume the requires clause has the form

\[ C_1 \ || \ C_2 \ || \ \cdots \ || \ C_n \]

where each \( C_i \) does not contain an explicit or implicit disjunction.

Test Generation Principle 3
For each disjunct of precondition in DNF create test case making it true

Example

\textbf{requires} red \ || \ yellow \ || \ green;

Gives rise to three test cases \texttt{red=true; yellow=green=false;}, etc.
Disjunctive Normal Form

Disjunctive Normal Form (DNF)
Assume the requires clause has the form

\[ C_1 \lor C_2 \lor \cdots \lor C_n \]

where each \( C_i \) does not contain an explicit or implicit disjunction.

Test Generation Principle 3
For each disjunct of precondition in DNF create test case making it true

Importance of Establishing DNF
Implicit disjunctions must be made explicit by computing DNF:
Replace \( A \implies B \) with \( \neg A \lor B \), etc.
**Test Coverage Criteria**

**Example**

```java
requires red || yellow || green;
```

is true even for `red=yellow=green=true;`
Test Coverage Criteria

Example

```java
requires red || yellow || green;
```

is true even for `red=yellow=green=true`;

Possible to generate a test case for each state making precondition true
Test Coverage Criteria

Example

requires red || yellow || green;

is true even for red=yellow=green=true;

Possible to generate a test case for each state making precondition true

(Specification-based) Test Coverage Criterion

How many different test cases to create that make precondition true?

- At least one (Decision Coverage)
- ...
- All (Multiple Condition Coverage)
Consistent Test Cases

Example (Class invariant specified in JML)

```java
public class Traffic {
    /*@ public invariant */ (red ==> !green && !yellow) &&
    (yellow ==> !green && !red) &&
    (green ==> !yellow && !red);
    /*@ */

    private /*@ spec_public */ boolean red, green, yellow;

    /*@ public normal_behavior */
    @ requires red || yellow || green;
    @ ... 

    The program state red=yellow=green=true; violates the class invariant
```
Consistent Test Cases

Example (Class invariant specified in JML)

```java
public class Traffic {
    /** @public invariant (red ==> !green && !yellow) &&
     * (yellow ==> !green && !red) &&
     * (green ==> !yellow && !red);
    */

    private /*@ spec_public @*/ boolean red, green, yellow;

    /** @public normal_behavior
     * @requires red || yellow || green;
     * ...
    */

    The program state red=yellow=green=true; violates the class invariant
```

If the class invariant always holds when a method is called, there is no point to generate test cases from program states violating it.
Consistent Test Cases

Example (Class invariant specified in JML)

```java
public class Traffic {
    /*@ public invariant */
    (red ==> !green && !yellow) &&
    @
    (yellow ==> !green && !red) &&
    @
    (green ==> !yellow && !red);
    @*/

    private /*@ spec_public */
    boolean red, green, yellow;

    /*@ public normal_behavior */
    @ requires red || yellow || green;
    @ ... 

    The program state red=yellow=green=true; violates the class invariant
```

Test Generation Principle 4

Generate test cases from states that do not violate the class invariant
Dealing with Large Datatypes (First-Order Logic)

Example (Square root)

```java
/*@ public normal_behavior
   @ requires (\exists \text{int } r; \ r \geq 0 \&\& \ r*r == n);
   @ ensures \text{result } * \text{result} == n;
   @*/

public static final int sqrt(int n) { ... }
```
Dealing with Large Datatypes (First-Order Logic)

Example (Square root)

```java
/*@ public normal_behavior
  @ requires (\exists int r; r >= 0 && r*r == n);
  @ ensures \result * \result == n;
@*/

public static final int sqrt(int n) { ... }
```

Where is the disjunction?
Dealing with Large Datatypes (First-Order Logic)

**Example (Square root)**

```java
/*@ public normal_behavior
   requires (\exists int r; r >= 0 && r*r == n);
   ensures \result * \result == n;
@*/

public static final int sqrt(int n) { ... }
```

**Existential quantifier as disjunction**

- Existentially quantified expression (\exists int r; P(r))
- Rewrite as: P(MIN_VALUE) || ... || P(0) || ... || P(MAX_VALUE)
- Get rid of those P(i) that are false: P(0) || ... || P(MAX_VALUE)
Equivalence Classes on Input Domains

Example (Square root)

```java
/*@ public normal_behavior
  @ requires (\exists int r; r >= 0 && r*r == n);
  @ ensures \result * \result == n;
  @*/

public static final int sqrt(int n) { ... }
```
Equivalence Classes on Input Domains

Example (Square root)

/*@ public normal_behavior
  @ requires (∃ int r; r >= 0 && r*r == n);
  @ ensures \result * \result == n;
  @*/

public static final int sqrt(int n) { ... }

Too many test cases from existential quantifier!

n = 0*0;, n = 1*1;, ..., n = MAX_VALUE*MAX_VALUE;
### Equivalence Classes on Input Domains

**Example (Square root)**

```java
/*@ public normal_behavior
  @ requires (\exists int r; r >= 0 && r*r == n);
  @ ensures \result * \result == n;
  @*/

public static final int sqrt(int n) { ... }
```

### Partition large/infinite domains in finitely many equivalence classes

<table>
<thead>
<tr>
<th>MIN_VALUE</th>
<th>negative values</th>
<th>0</th>
<th>positive values</th>
<th>MAX_VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>−2^{31}</td>
<td>−17</td>
<td>0</td>
<td>42</td>
<td>2^{31} − 1</td>
</tr>
</tbody>
</table>

... and create test case for only one representative of each
Boundary Values

Example (Square root)

```java
/*@ public normal_behavior
   @ requires (\exists int r; r >= 0 && r*r == n);
   @ ensures \result * \result == n;
   @*/

   public static final int sqrt(int n) { ... }

Choice of r=MAX_VALUE exhibits defective spec for overflow
```
Boundary Values

Example (Square root)

```java
/*@ public normal_behavior
    @ requires \exists int r; r >= 0 && r*r == n);
    @ ensures \result * \result == n;
    @*/

    public static final int sqrt(int n) { ... }

Choice of r=MAX_VALUE exhibits defective spec for overflow

Test Generation Principle 5
Include boundary values of ordered domains as class representatives
Boundary Values

Example (Square root)

```java
/*@ public normal_behavior
   @ requires (\exists \text{int } r; r >= 0 \&\& r*r == n)
   @        \&\& n <= \text{MAX\_VALUE};
   @ ensures \text{\_result} * \text{\_result} == n;
   @*/

    public static final int sqrt(int n) { ... } 
```

Choosing exact boundary value for $n$ amounts to computing result
Computing exact boundary values can be difficult or impossible!

Test Generation Principle 5

Include boundary values of ordered domains as class representatives
Example (Binary search, target not found)

```java
/*@ public normal_behavior
  @ requires (\forall int i; 0 < i && i < array.length
  @            ==> array[i-1] <= array[i]);
  @            (\forall int i; 0 <= i && i < array.length
  @            ==> array[i] != target);
  @ ensures \result == -1;
@*/

int search(int array[], int target ) { ... }
```
Implicit Disjunctions, Part I

Example (Binary search, target not found)

```java
/*@ public normal_behavior
   @ requires (\forall int i; 0 < i && i < array.length => array[i-1] <= array[i]);
   @ (\forall int i; 0 <= i && i < array.length
       => array[i] != target);
   @ ensures \result == -1;
   @*/

int search( int array[], int target ) { ... }
```

No disjunction in precondition!?
Example (Binary search, target not found)

/*@ public normal_behavior
   @ requires (\forall int i; 0 < i && i < array.length
   @                ==> array[i-1] <= array[i]);
   @                (\forall int i; 0 <= i && i < array.length
   @                ==> array[i] != target);
   @ ensures \result == -1;
   @*/

int search( int array[], int target ) { ... }

We can freely choose array in precondition!
Test Generation Principle 6

Values of variables without explicit quantification can be freely chosen
Data Generation Principles

Test Generation Principle 6
Values of variables without explicit quantification can be freely chosen

Systematic enumeration of values by data generation principle
Assume declaration: `int[] ar;`, then the array `ar` is

1. either the null array: `int[] ar = null;`
2. or the empty array of type `int`: `int[] ar = new int[0];`
3. or an `int` array with one element
   3.a `int[] ar = { MIN_VALUE };`
   3.b ...
   3.ω `int[] ar = { MAX_VALUE };`
4. or an `int` array with two elements ...
5. or an `int` array with `n` elements ...

ProgVer: ATCG I
Combining the Test Generation Principles

Example (Binary search, target found)

```
requires (\exists \text{ int } i; \ 0 \leq i \&\& i < \text{array}.\text{length} \\
\&\& \text{array}[i] == \text{target} ) \&\& \\
(\forall \text{ int } i; \ 0 < i \&\& i < \text{array}.\text{length} \\
\implies \text{array}[i-1] \leq \text{array}[i] );
```

Apply test generation principles

- Use data generation principle for int arrays
- Choose equivalence classes and representatives of int, int[]:
  - int[] empty array, singleton, two elements
  - int 0, 1
- Generate all test cases that make precondition true
Combining the Test Generation Principles

Example (Binary search, target found)

```java
requires (\exists \text{ int } i; \ 0 \leq i && i < \text{array}.length \\
    && \text{array}[i] == \text{target}) \\
(\forall \text{ int } i; \ 0 < i && i < \text{array}.length \\
    ==> \text{array}[i-1] \leq \text{array}[i]);
```

- empty array: precondition cannot be made true, no test case
- singleton array, target must be only array element
  ```java
  array = { 0 }; target = 0;
  array = { 1 }; target = 1;
  ```
- two-element sorted array, target occurs in array, four tests
  ```java
  array = { 0,0 }; target = 0;
  array = { 0,1 }; target = 0;
  etc.
  ```
Example (Copy)

```java
/*@ public normal_behavior
  @ requires src != null && dst != null;
  @ ensures ... 
  @*/

static void java.util.Collections.copy (List src,List dst)
```
Implicit Disjunctions, Part II

Example (Copy)

```java
/*@ public normal_behavior
  @ requires src != null && dst != null;
  @ ensures ...
  @*/
static void java.util.Collections.copy (List src,List dst)
```

Aliasing and Exceptions

In Java object references src, dst can be aliased, i.e., src==dst

- Admission of aliasing often unintended in contract

Forgotten protection against runtime exceptions

```java
src.length <= dst.length
```
Implicit Disjunctions, Part II

Example (Copy)

```java
/*@ public normal_behavior
   @ requires src != null && dst != null;
   @ ensures ... 
@*/

static void java.util.Collections.copy (List src,List dst)
```

Test Generation Principle 7
Generate separate test cases that enforce aliasing and raising exceptions
The Postcondition as Test Oracle

Oracle Problem in Automated Testing
How to determine automatically whether a test run succeeded?
The Postcondition as Test Oracle

Oracle Problem in Automated Testing
How to determine automatically whether a test run succeeded?

The “ensures” clause of a JML contract tells exactly this provided that “requires” clause is true for given test case.
The Postcondition as Test Oracle

Oracle Problem in Automated Testing
How to determine automatically whether a test run succeeded?

The “ensures” clause of a JML contract tells exactly this provided that “requires” clause is true for given test case

Test Generation Principle 1
Test data must make required precondition true

Test Generation Principle 8
Use “ensures” clauses (postconditions) of JML contracts as test oracles
Executable JML Expressions

How to determine whether a JML expression is true in a program state?
Executable JML Expressions

How to determine whether a JML expression is true in a program state?

Example

\exists \text{int } i; \ 0 \leq i \land i < \text{ar.length} \land \text{ar}[i] = \text{target}

is of the form

\exists \text{int } i; \ \text{guard}(i) \land \text{test}(i)

- \text{guard}() \text{ is JAVA guard expression with fixed upper/lower bound}
- \text{test}() \text{ is executable JAVA expression}
Executable JML Expressions

How to determine whether a JML expression is true in a program state?

Example

$$\exists \text{int } i; 0 \leq i \land i < \text{ar.length} \land \text{ar}[i] = target$$

is of the form

$$\exists \text{int } i; \text{guard}(i) \land \text{test}(i)$$

- guard() is JAVA guard expression with fixed upper/lower bound
- test() is executable JAVA expression

Guarded existential JML quantifiers as Java (Example)

```java
for (int i = 0; 0 <= i && i < ar.length; i++) {
    if (ar[i] == target) {
        return true;
    }
} return false;
```
Executable JML Expressions

How to determine whether a JML expression is true in a program state?

Example

\( \exists \text{int } i; \ 0 \leq i \land i < \text{ar.length} \land \text{ar}[i] = \text{target} \)

is of the form

\( \exists \text{int } i; \ \text{guard}(i) \land \text{test}(i) \)

- \text{guard()} is JAVA guard expression with fixed upper/lower bound
- \text{test()} is executable JAVA expression

Guarded existential JML quantifiers as Java (General)

```java
for (int i = lowerBound; guard(i); i++) {
    if (test(i)) { return true; }
} return false;
```
Executable JML Expressions

How to determine whether a JML expression is true in a program state?

Example

\( \exists \text{int } i; \ 0 \leq i \land i < \text{ar.length} \land \text{ar}[i] = \text{target} \)

is of the form

\( \exists \text{int } i; \ \text{guard}(i) \land \text{test}(i) \)

- \text{guard()} \) is JAVA guard expression with fixed upper/lower bound
- \text{test()} \) is executable JAVA expression

Guarded JML quantifiers as Java

- Universal quantifiers treated similarly (exercise)
- Alternative JML syntax for quantifiers ok as well:
  \( \exists \text{int } i; \ \text{guard}(i) \land \text{test}(i) \)
Summary

- **Black box vs White box testing**
- Black box testing $\sim$ **Specification-based Test Generation**
- Systematic test case generation from JML contracts guided by **Test Generation Principles**
- Only generate test cases that make **precondition true**
- Each operation contract and each **disjunction** in precondition gives rise to a separate test case
- **Coverage** criteria, decision coverage
- Large/infinite datatypes represented by **class representatives**
- Values of free variables supplied by **Data Generation Principle**
- Create separate test cases for potential **aliases** and **exceptions**
- Postconditions of contract provide **test oracle**
- Turn pre- and postconditions into **executable JAVA code**
What Next?

Remaining Problems of ATCG

1. How to automate specification-based test generation?
2. Generated test cases have no relation to implementation
Remaining Problems of ATCG

1. How to automate specification-based test generation?
2. Generated test cases have no relation to implementation

1. Tools jml–junit and jtest discussed in Exercises
2. Code-based test generation that uses symbolic execution of IUT