# Program logics: reasoning principles for high-assurance software

Introduction

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# How to make sure that software behaves correctly?

# Conventional methods

## Test

- Run the program on well-chosen inputs.
- Compare observed behaviors with expected behaviors.

## Review

- Carefully proofread the code, the tests, the design documents, …

## Analysis

- Mathematical study of some aspects of the program: numerical precision, time or space complexity, etc.
- Pencil and paper, or with machine assistance (static analysis tools).

# Limitations of testing

*Testing shows the presence, not the absence of bugs.*

(E. W. Dijkstra, 1969)

We test a small number of all possible behaviors of the program.

Some bugs trigger very rarely!

**Example (carry propagation in a cryptographic library)**

Add `2 * ta * tb` to `c2:c1:c0` while "optimizing" carry propagation.

```
BN_UMULT_LOHI(t0,t1,ta,tb);
t2 = t1+t1; c2 += (t2<t1)?1:0;
t1 = t0+t0; t2 += (t1<t0)?1:0;
c0 += t1; t2 += (c0<t1)?1:0;
c1 += t2; c2 += (c1<t2)?1:0;
```

# Limitations of code review

*Given enough eyeballs, all bugs are shallow.*

(Eric Raymond, 1999)

Reviewers are tired or distracted.

Some codes such as hot fixes are not reviewed much.

**Example (the `goto fail` bug)**

```
if ((err=SSLHashSHA1.update(&hashCtx,&signedParams)) != 0)
    goto fail;
    goto fail;
if ...
...
fail: return err;
```

# Limitations of code analysis

*Beware of bugs in the above code;*
*I have only proved it correct, not tried it.*
(Donald E. Knuth, 1977)

Risk of errors in pencil-and-paper analyses
and of unsoundness in static analysis tools.

Possible gap between the analysis and the actual program or its actual execution context.

**Example (Ariane 501)**

Overflow in a conversion 64-bit FP number $\to$ 16-bit integer.

An analysis conducted in the context of Ariane 4 proved that the converted quantity, called BH, always fits in 16 bits. The analysis was invalid in the context of Ariane 5.

# Deductive verification (also called program proof)

Logical reasoning that establishes properties that hold for *all* possible executions of the program.

Unlike other “formal methods”, the properties established go all the way up to full functional correctness w.r.t. a specification.

Practical interest:

- Obtaining guarantees stronger than those we can get using testing and review.
- Finding bugs we cannot find by other means.

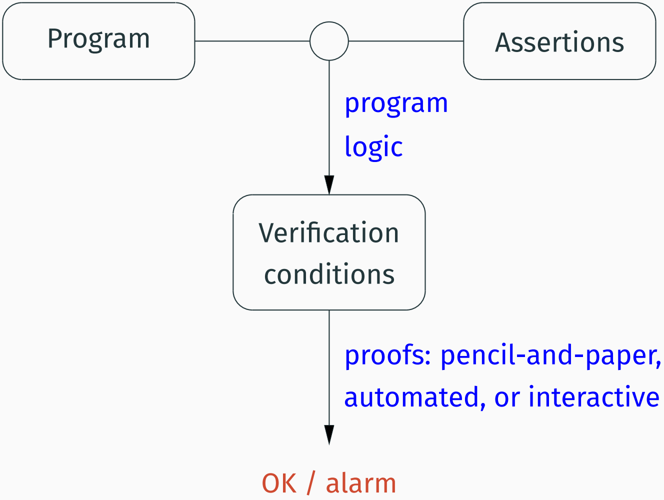
# Program logics

A program logic provides us with a specification langage and reasoning principles to reason about program behaviors.

Specifications generally consist in logical assertions about the program:

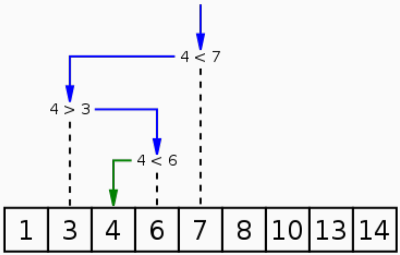
- preconditions: hypotheses on inputs
  (function parameters; initial values of variables)
- postconditions: guarantees on outputs
  (function results; final values of variables)
- invariants: guarantees on the states at a program point
  (loop invariants, data structure invariants, ...)

# Program logics and deductive verification



# Hunting for bugs:
# the example of binary search

# Binary search




```
l = 0; h = a.length - 1;
while (l <= h) {
  m = (l + h) / 2;
  if (a[m] == v) return m;
  if (a[m] < v) h = m - 1; else l = m + 1;
}
return -1;
```

# A long history

```
l = 0; h = a.length - 1;
while (l <= h) {
  m = (l + h) / 2;
  if (a[m] == v) return m;
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}
return -1;
```

1946 John Mauchly, *Moore School Lectures*

1960 Derrick H. Lehmer publishes the modern algorithm

1986 Jon Bentley, *Programming pearls*, chapter 4

2004 Bug report: `java.util.Arrays.binarySearch()` *will throw an* `ArrayIndexOutOfBoundsException` *if the array is large.*

2006 Joshua Bloch, *Nearly All Binary Searches and Mergesorts are Broken.*

# The source of the bug: an arithmetic overflow

```
m = (l + h) / 2;
```

We have $0 \le \texttt{l} \le \texttt{h} < \texttt{a.length}$.

`l + h` can overflow if `a.length` is large enough.

In Java, `l + h` becomes negative, as well as `m`, hence `a[m]` raises an "out of bounds" exception.

In C, we have a so-called undefined behavior. Often, the program continues with the wrong value of `m`. Worse things can happen.

A simple fix: `m = l + (h - l) / 2;`

# A bug that is hard to find

**Test:**

- We rarely test on very big inputs.
- A 64-bit machine and several Gb of RAM are required to trigger this bug.

**Review:**

- The formula $(l + h)/2$ is so familiar as to raise no suspicion.
- Reviewers are likely to suggest "optimizing" $l + (h - l)/2$ as $(l + h)/2$.

**Analyses:**

- A variation interval analysis can detect the problem.

# Demo

Deductive verification of binary search
using the Frama-C WP tool.

# The course and the seminar

# Objectives for the course

Understand the principles of program logics and the recent developments in this area.

*Leitmotiv*: which logics for which features of programming languages?

(variables, pointers, concurrency, higher-order, etc)

# Objectives for the seminar

Demonstrate implementations of program logics in industrial-strength verification tools.

Discuss new verification problems and new ideas to tackle them.

# Course outline

1. The birth of program logics
2. Variables and loops: Hoare logic
3. Pointers and data structures: separation logic
4. Shared-memory concurrency: concurrent separation logic
5. Extensions of separation logic: fractional permissions, ghost state, stored locks, …
6. Logics for weakly-consistent shared memory
7. Logics for functional, higher-order languages

# The seminar

11/03 Loïc Correnson (CEA).
*Les logiques de programmes à l'épreuve du réel: tours et détours avec Frama-C/WP*

18/03 Yannick Moy (Adacore).
*Preuve auto-active de programmes en SPARK*

25/03 Bart Jacobs (K. U. Leuven).
VeriFast: Semi-automated modular verification of concurrent C and Java programs using separation logic

01/04 François Pottier (Inria).
*Raisonner à propos du temps en logique de séparation*

08/04 Jacques-Henri Jourdan (CNRS).
*Protocoles personnalisés en logique de séparation: ressources fantômes et invariants dans la logique Iris*

15/04 Philippa Gardner (Imperial College London).
Gillian: Compositional Symbolic Testing and Verification