Software quality and formal methods: Hoare/Dijkstra approach

Dr. Ivan S. Zapreev

Neat Software Designs

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Global Outline:

- Software Quality
- Programming Languages
- Formal Verification
- Frama - C platform
- Verification in practice
- Concluding remarks

Software Quality

Software Quality: Outline

- Motivating examples
- Software Development
- Software Verification

Motivating examples: Therac-25

Years **1985–1987**: Radiation overdose

- Control software flaw:
  - Race conditions
- Death of 6 (six) cancer patients

Figure 1: Radiation therapy

Motivating examples: Ariane-5

Year **1996**: Missile crash

- Control software flaw:
  - 64-bit float to 16-bit integer conversion
- \$137 million Rocket + \$500 million cargo

Figure 2: Space flights

Motivating examples: Toyota

Year 2005: Sudden unintended acceleration

- Control software flaw:
  - Recursion causing stack overflow
- 89 deaths and 57 injuries
- $1.2 billion compensations

Figure 3: Toyota Camry

Motivating examples: Plenty More

The 12 Software Bugs That Caused Epic Failures: <link>

Software Development: V-model

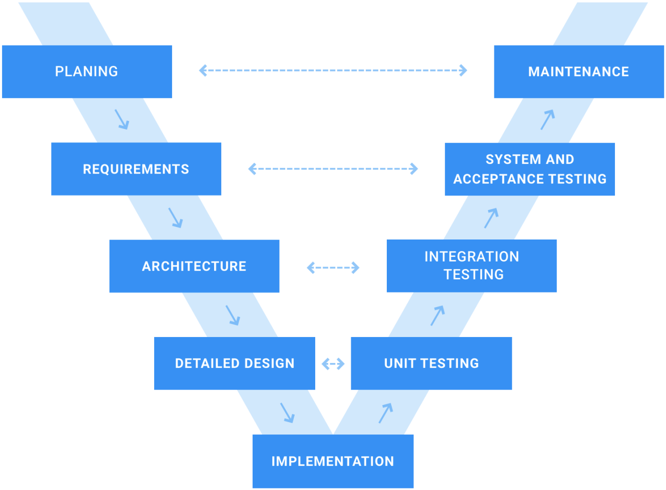

Figure 4: Software development process

Software Development: V & V

Software **Validation** and **Verification**.

Formally defined by the International Organization for Standardization, see `ISO-9000:2015`:

- **Verification** – *"Confirmation, through the provision of objective evidence, that specified requirements have been fulfilled."*
- **Validation** – *"Confirmation, through the provision of objective evidence, that the requirements for a specific intended use or application have been fulfilled."*

Software Development: Testing

- **Verification**:
  - Are we building the product right?
  - Does the system comply with its specification?
- **Validation**:
  - Are we building the right product?
  - Does the system meet the needs of the customer?

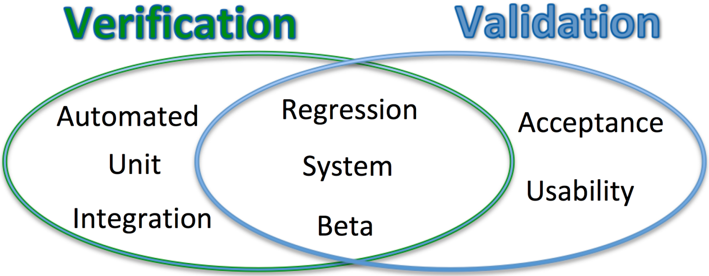

Figure 5: Types of testing

Software Verification: Goal

A *program* shall satisfy a formal specification of its *behavior*.

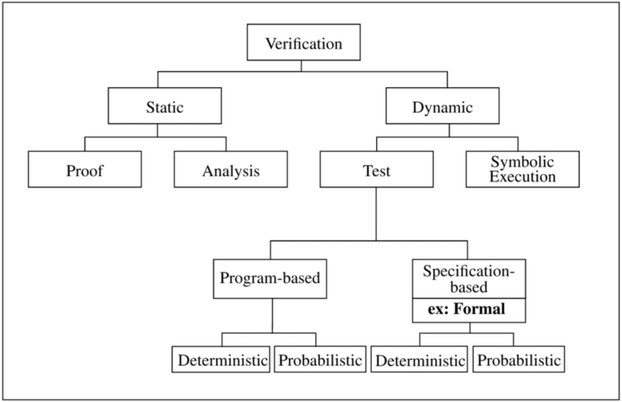

Figure 6: Verification methods

Software Verification: In formal

Formal verification[1]:

> *"Is the act of proving or disproving the correctness of intended algorithms underlying a system with respect to a certain formal specification or property, using formal methods of mathematics."*

Formal methods[2]:

> *"Formal methods are techniques used to model complex systems as mathematical entities."*

> *"By building a rigorous model of a complex system, it is possible to verify the system's properties in a more thorough fashion than empirical testing."*

[1] "Formal Verification" on Wikipedia

[2] "Formal Methods", Michael Collins, CMU

Programming Languages

Programming Languages: Outline

- Language generations
- Declarative vs. Imperative
- What is ANSI-C?

Language generations

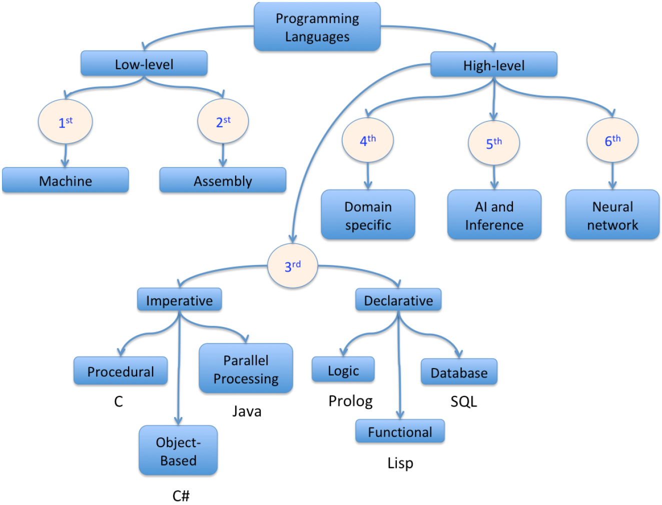

Figure 7: Generations of Programming languages

Declarative vs. Imperative: Main

Consider the problem of multiplying all array elements by 2:

- **Declarative** – Specifies **what** to achieve:

```
//Declarative `JavaScript`
var arr_dbl = arr.map((x) => x * 2)
```

- **Imperative** – Defines the **how** steps:

```
//Imperative `JavaScript`
var arr_dbl = []
for (let i = 0; i < arr.length; i++) {
  arr_dbl.push(arr[i] * 2)
}
```

Declarative vs. Imperative: Test

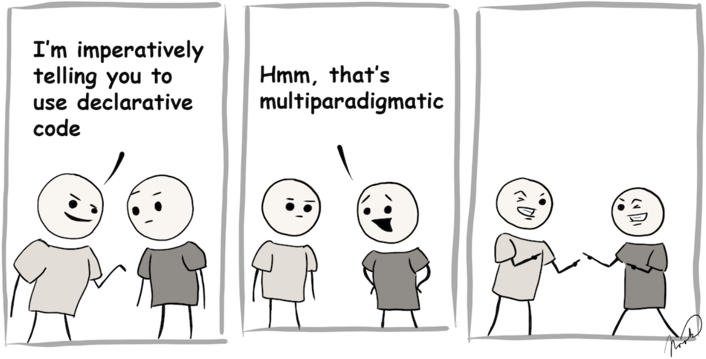

Figure 8: If you laugh, it means you've passed

What is ANSI-C: Old C

`C` language:

`C` is an *imperative procedural* language.

Procedural language:

Is an imperative language in which the program is built from one or more subroutines commonly known as `functions`.

Defining ANSI-C:

`ANSI-C` is a common name for two equivalent standards:

- `C89` – American National Standards Institute (ANSI)
- `C90` – International Organization for Standardization (ISO)

Formal Verification

Formal Verification: Outline

- Verification goal
- Hoare Approach
- Dijkstra Extension

Verification goal

Mathematically prove conformance to formal specifications.

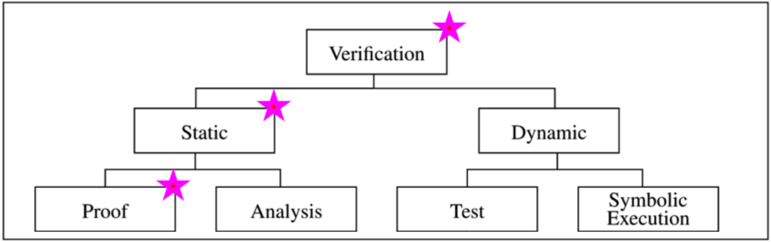

Figure 9: Formal correctness proving

Consider:

Hoare/Dijkstra approach for proving correctness of *imperative programs*.

Hoare Approach[3]

Hoare triples: $\{P\}\, C\, \{Q\}$

C - code; P - pre-condition; Q - post-condition;

Axioms, e.g. *Skip* and *Assign*:

$$\frac{-}{\{P\}skip\{P\}} \text{ and } \frac{-}{\{P[E/V]\}V{:=}E\{P\}}$$

Where E is any expression and V is any variable.

Inference rules, e.g. *Composition* and *Conditional*:

$$\frac{\{P\}S_1\{R\},\ \{R\}S_2\{Q\}}{\{P\}S_1;\ S_2\{Q\}} \text{ and } \frac{\{B \wedge P\}S\{Q\},\ \{\neg B \wedge P\}T\{Q\}}{\{P\}\ \textbf{if}\ B\ \textbf{then}\ S\ \textbf{else}\ T\ \textbf{elseif}\ \{Q\}}$$

Partial correctness: If P holds before executing C then Q holds afterwards, ONLY if C terminates.

[3] "An Axiomatic Basis for Computer Programming", Tony Hoare, 1969.

Dijkstra Extension[4]

The *weakest precondition calculus* for

- A predicate transform semantics to mechanize the proofs.
- Explains how C transforms P into Q.

Backward reasoning:

- Based on Q and C calculate the *weakest pre-condition* $\widehat{P}$
- If $P \implies \widehat{P}$, then the proof is complete

Forward reasoning:

- Based on P and C calculate the *strongest post-condition* $\widehat{Q}$
- If $\widehat{Q} \implies Q$, then the proof is complete

[4] "Guarded commands, non-determinacy and formal derivation of programs", Edsger Dijkstra, 1975

Frama - C platform

Frama - C platform: Outline

- Platform description
- Plugins overview
- What is ACSL?

Platform description

Frama-C is a:

- Plug-in-based
- Open-source
- Cross-platform

framework for ANSI-C source-code analysis:

- Browse unfamiliar code
- Static code analysis
- Dynamic code analysis
- Code transformations
- Certification of critical software

You can easily build upon the existing plug-ins to implement your own analysis.

Plugins overview: Main

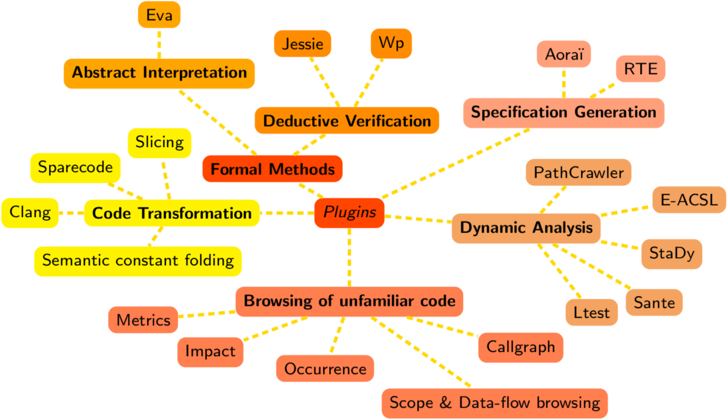

Figure 10: Frama-C plugins

Plugins overview: WP

WP – *weakest precondition* for ACSL specs of ANSI-C programs.

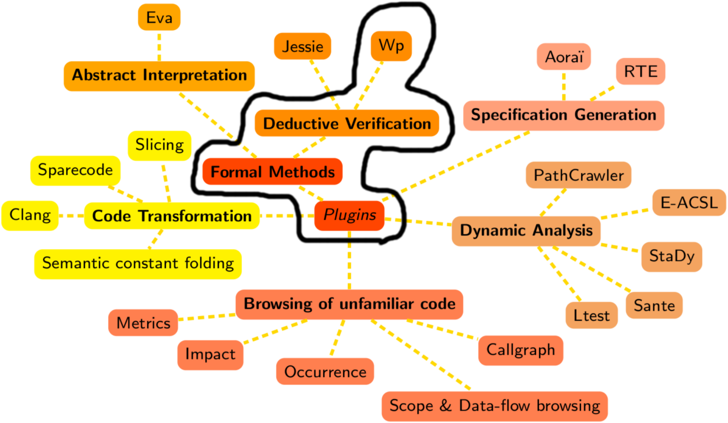

Figure 11: Frama-C WP plugin

What is ACSL: General

In short:

- ACSL – ANSI/ISO C Specification Language
- Allows to formally specify properties of C programs

It is all about function contracts:

```
/*@ ensures \result >= x && \result >= y;
    ensures \result == x || \result == y;
 */
int max (int x, int y) {
  return(x > y) ? x : y;
}
```

A function contract is a combination of:

- post-conditions - `ensures`
- pre-conditions - `requires`

What is ACSL: Pointers

ACSL allows to reason about, e.g.:

- Pointers
- Arrays
- Termination

Consider pointers:

```
/*@ requires \valid(x) && \valid(y);
    ensures *x <= *y;
 */
void max_ptr (int *x, int *y) {
  if(*x > *y) {
    int tmp = *x;
    *x = *y;
    *y = tmp;
  }
}
```

What is ACSL: Completeness

Is the following `max_ptr` implementation correct?

```
/*@ requires \valid(x) && \valid(y);
      ensures *x <= *y;
 */
void max_ptr (int *x, int *y) {
  *x = *y = 0;
}
```

We need to make our specification **complete**:

```
/*@ requires \valid(x) && \valid(y);
      ensures *x <= *y;
      ensures (*x == \old(*x) && *y == \old(*y)) ||
              (*x == \old(*y) && *y == \old(*x));
 */
void max_ptr(int *x, int *y);
```

What is ACSL: The whole spec.

The complete ACSL specification *v1.4* has 93 pages: https://frama-c.com/download/acsl_1.4.pdf

Figure 12: Feel free to explore

Verification in practice

Verification in practice: Outline

- Verification Examples
- Verification Outcomes
- Experience summary

Verification Examples: abs(.)

Consider a primitive integer absolute value computation:

```
/*@
    ensures \result >= 0;
 */
int abs(int val) {
  if(val < 0) return -val;
  return val;
}
```

The verification shall return **OK**, right?

Verification Examples: Issue #1

NOP - the verification results are inconclusive:

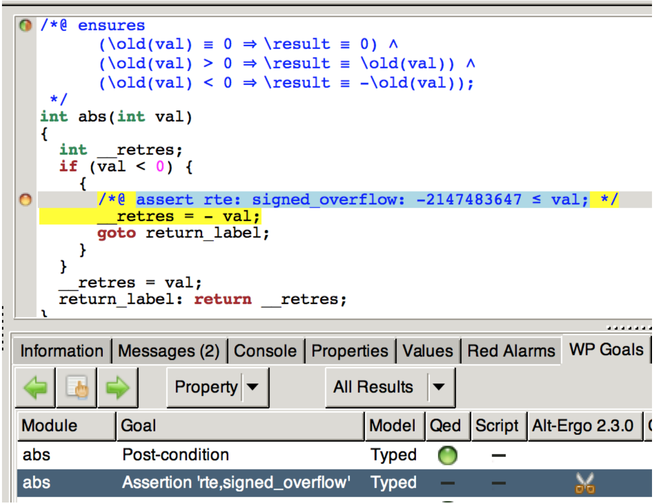

Figure 13: WP detects a possible overflow

Verification Examples: Issue #2

Extend the specification with a pre-condition:

```
/*@ requires INT_MIN < val;
    ensures \result >= 0;
 */
int abs(int val) {
  if(val < 0) return -val;
  return val;
}
```

The verification is **OK**, but the spec is lame:

```
/*@ requires INT_MIN < val;
    ensures \result >= 0;
 */
int abs(int val) {
  return 1;
}
```

Verification Examples: Final?

An explicit `\result` value specification makes it complete:

```
/*@ requires INT_MIN < val;
    ensures (val == 0 ==> \result == 0) &&
            (val > 0 ==> \result == val) &&
            (val < 0 ==> \result == -val);
 */
int abs(int val) {
  if(val < 0) return -val;
  return val;
}
```

What if the implementation was wrong?

Would we be able to identify the root-cause?

Verification Examples: Faulty

Consider a lengthy and potentially buggy implementation:

```
/*@ requires INT_MIN < val;
    ensures (val == 0 ==> \result == 0) &&
            (val > 0 ==> \result == val) &&
            (val < 0 ==> \result == -val);
 */
int abs(int val) {
  if(val == 0) {
    return 0;
  } else {
    if(val < 0) {
      return val;
    } else {
      return -val;
    }
  }
}
```

Verification Examples: Issue #3

The verification is inconclusive, the prover has failed!

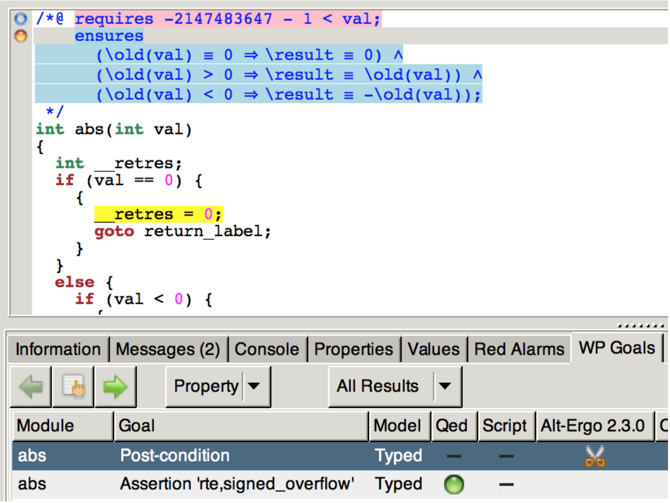

Figure 14: What is the actual reason?

Verification Examples: Split

What if we split the post-condition from:

```
/*@ requires INT_MIN < val;
    ensures (val == 0 ==> \result == 0) &&
            (val > 0 ==> \result == val) &&
            (val < 0 ==> \result == -val);
 */
```

into separate statements:

```
/*@ requires INT_MIN < val;
    ensures (val == 0 ==> \result == 0);
    ensures (val > 0 ==> \result == val);
    ensures (val < 0 ==> \result == -val);
 */
```

and then run verification again.

Verification Examples: Insights

This gives us insights into what could be wrong:

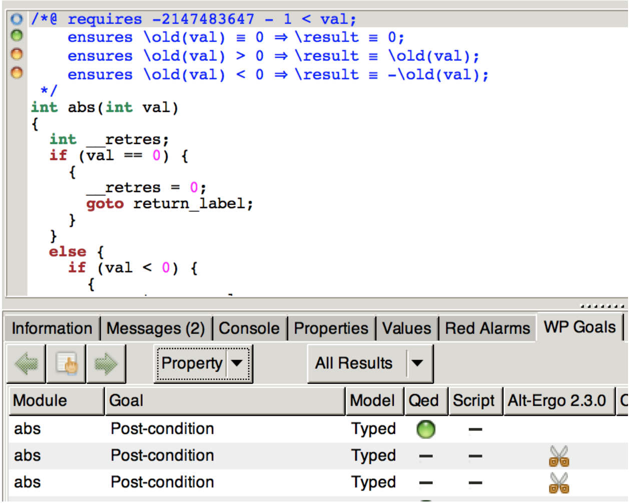

Figure 15: Finding the root-causes

Verification Examples: Bugs

Now we can now look into the code and identify bugs:

```
/*@ requires INT_MIN < val;
    ensures (val == 0 ==> \result == 0);
    ensures (val > 0 ==> \result == val);
    ensures (val < 0 ==> \result == -val);
 */
int abs(int val) {
  if(val == 0) {
    return 0;       //OK
  } else {
    if(val < 0) {
      return val;  //BUG #1, should return -val
    } else {
      return -val; //BUG #2, should return val
    }
  }
}
```

Verification Examples: Issue #4

Fixing BUG #1 turns the corresponding post-conditions green!

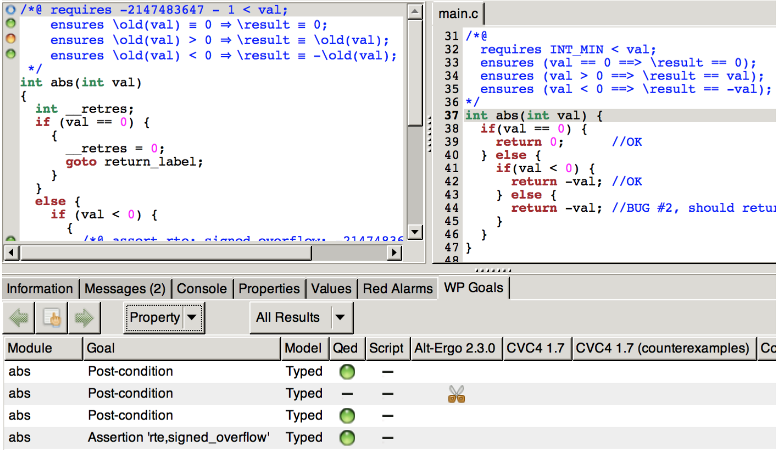

Figure 16: Sequential issue resolution

Verification Examples: Issue #5

Fixing BUG #2 yields an **OK** verification result!

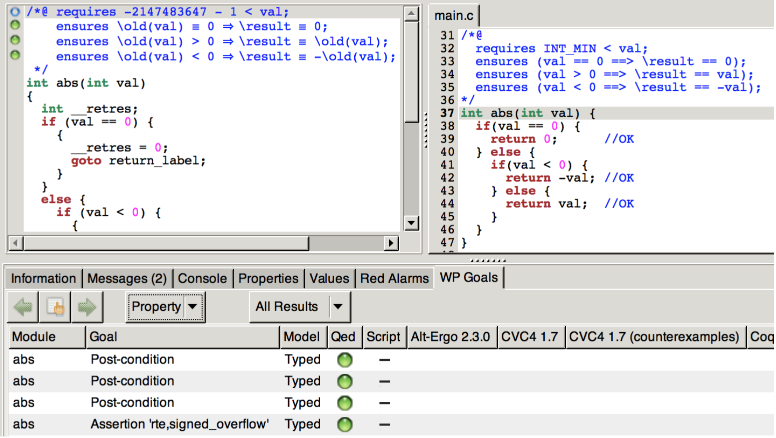

Figure 17: Now we are all fine

Verification Outcomes

If the verification result is **OK**:

- The program satisfies the specification
- *Is the specification correct/complete?*

If the verification result is **NOK**[5]:

- An *incorrect implementation*
  - Find counter-example via test generation;
- A *wrong specification*
  - Complete spec. and proof analysis;
  - Change/extend the specification;
- A *prover's failure*
  - Alternative provers;
  - Interactive proof assistants;

[5] This includes a failed verification attempt, e.g. a time out

Experience summary

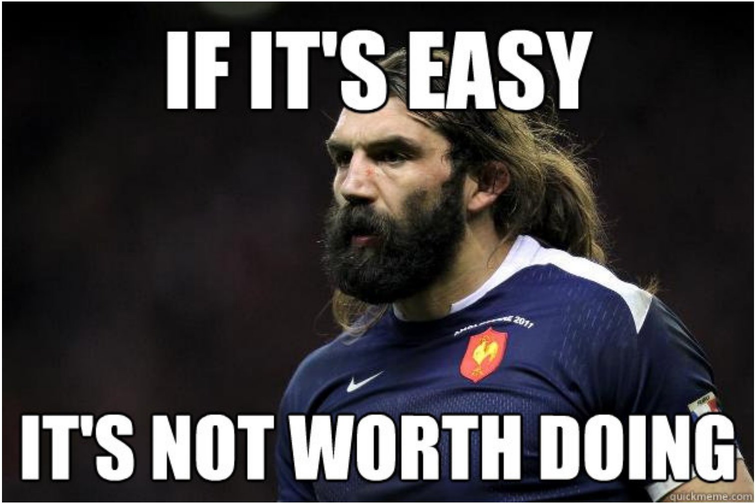

Figure 18: It is not so easy but . . .

Concluding remarks

Concluding remarks

We have looked into:

- Software quality and software engineering
- Programming language classification
- Formalization of software verification
- Hoare/Dijkstra approach to formal proving
- Frama-C a platform for ANSI-C code analysis
- Experienced practical program verification

We can conclude that:

- Formal software verification is useful
- It is not yet fully automated
- There is a lot more to learn about it!

Thank you and are there any questions?

I appreciate your time!

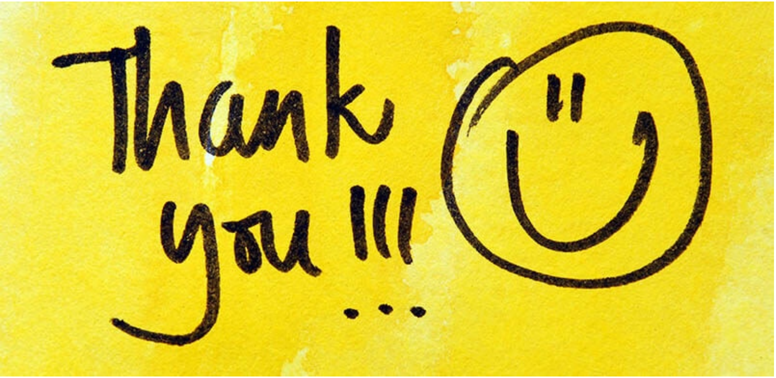

Figure 19: It was great to give you a talk!

More useful links:

- **ACSL Mini-Tutorial:** https://frama-c.com/download/acsl-tutorial.pdf
- **ACSL-tutorial:** https://frama-c.com/download/acsl-tutorial.pdf
- **ACSL-by-Example:** https://www.cs.umd.edu/class/spring2016/cmsc838G/frama-c/ACSL-by-Example-12.1.0.pdf
- **Frama-C website:** https://frama-c.com/
- **Frama-C v20.0 manual:** https://frama-c.com/download/user-manual-20.0-Calcium.pdf
- **Frama-C WP tutorial:** https://allan-blanchard.fr/publis/frama-c-wp-tutorial-en.pdf