FormaliSE 2018. 2 June 2018. Gothenburg, Sweden

Formal verification of automotive embedded software

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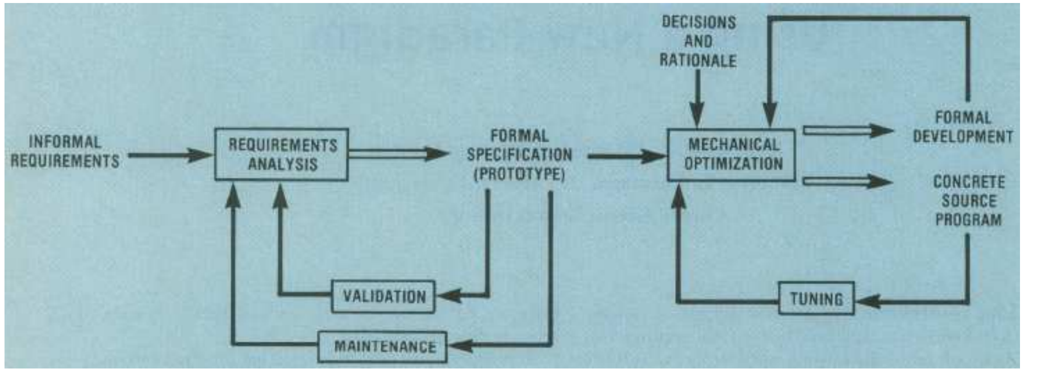
Need for safe advanced driver assistance systems ⇒ Formal methods?

Formal methods and software development process

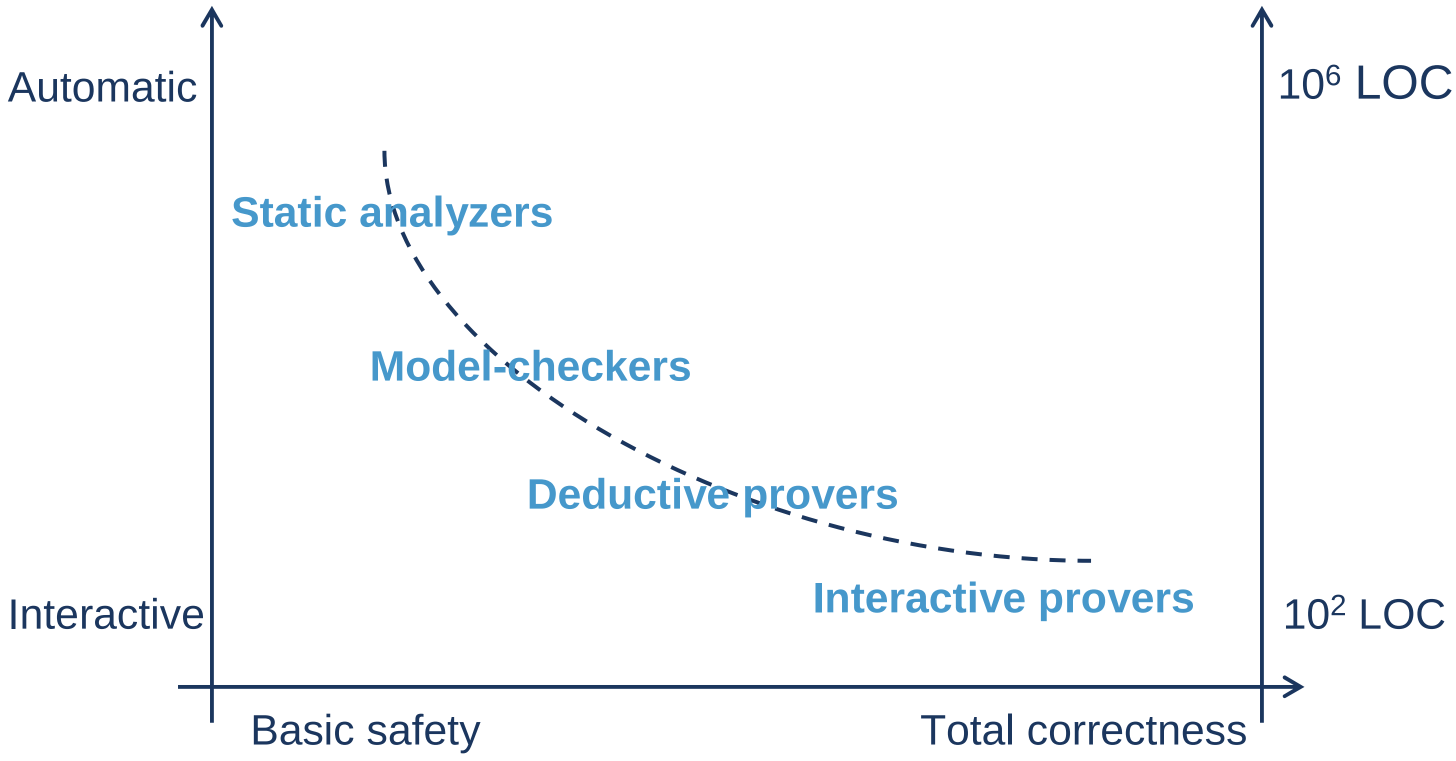
- Need for new software development process integrating formal methods
- 1983: Balzer* proposed for the first time such a process placing the formal methods in the heart of the development (link between requirements, prototype, implementation)



- 2018: there is still no standard process integrating formal methods: each company needs to create it
- Need to apply formal methods on automotive use cases to
  - identify the potential perimeter of their application
  - identify the impacts and difficulties to anticipate
  - verify which method could be integrated best in which part of the process

*Balzer, R., Jr. T. E. Cheatham, and C. Green. "Software Technology in the 1990's: Using a New Paradigm." Computer 16, no. 11 (November 1983): 39–45. doi:10.1109/MC.1983.1654237.

Panorama of the formal verification tools



Panorama proposed by Xavier Leroy, INRIA

Abstract interpretation

Context

- AUTOSAR application software, 300 K lines of C code
- Sound static analyzers were known to produce a big amount of false positives
- People using model-based design think there is no need to analyze the code because it is generated automatically and is thus correct

Experiments

- MathWorks Polyspace Code Prover R2016b
- AbsInt Astrée 17.04i

Results

- Reasonable number of alarms that could be analyzed by the engineers
- Not the same number of alarms for the two tools although they are sound
- Model-based design can produce runtime errors difficult/impossible to find by testing
- ISO 26262 (v2018) introduces abstract interpretation

What is a real bug?

```
typedef unsigned char u8;
void main (void)
{
   u8 a = 1;
   u8 b = ~a;
}
```

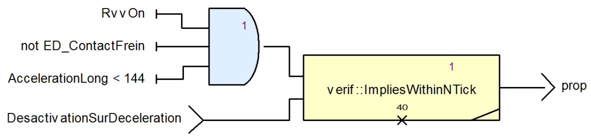
Table 7 — Methods for software unit verification

	Methods	ASIL A	ASIL B	ASIL C	ASIL D
1a	Walk-through [a]	++	+	o	o
1b	Pair-programming [a]	+	+	+	+
1c	Inspection [a]	+	++	++	++
1d	Semi-formal verification	+	+	++	++
1e	Formal verification	o	o	+	+
1f	Control flow analysis [b, c]	+	+	++	++
1g	Data flow analysis [b, c]	+	+	++	++
1h	Static code analysis [e]	++	++	++	++
1i	Static analyses based on abstract interpretation [e]	+	+	+	+
1j	Requirements-based test [f]	++	++	++	++
1k	Interface test [g]	++	++	++	++
1l	Fault injection test [h]	+	+	+	++
1m	Resource usage evaluation [i]	+	+	+	++
1n	Back-to-back comparison test between model and code, if applicable [j]	+	+	++	++

SAT/SMT-based model checking

- **Context**
  - Cruise Controller function allocated to body controller unit
  - 110 pages of textual requirements
- **Experiments**
  - Model all textual requirements in SCADE (formally defined language)
  - Transform the SCADE model in Lustre (via XSLT)
  - Compare the native Prover plugin with different Lustre model checkers (JKind, Kind2, GaTEL)
  - Prove the validity of the safety requirements about the Cruise controller deactivation
- **Example of property to prove**

  "In order to respect the safety objectives in the case the brake pedal sensor is not working, 2 seconds of deceleration under 144 without pressing the brake pedal shall turn off the function."



- **Results**
  - A bug previously found was confirmed only in few seconds
  - Certain properties like the previous one are not inductive and we need to explore all the states of the model ⇒ Problem : if we increase the time from 2s to 2min **none of the model checkers is able to prove it** within 24h
  - *PDR/IC3** is generating invariants starting from the property but in our case we needed to find an inductive relation between the variables of the property and the model. How can we find this relation automatically?
  - We need a better invariant generator and are working on its improvement

**Bradley, Aaron R., and Zohar Manna. "Property-Directed Incremental Invariant Generation." Formal Aspects of Computing 20, no. 4 (2008): 379–405*

Deductive proof

- Context
  - SQRT function using linear integer interpolation over 40 values
- Experiments
  - Annotate the code using ACSL specification language
  - Use Frama-C to prove the correctness for a given precision
  - Develop the same function in Ada
  - Use SPARK to prove the correctness for a given precision
- Results
  - SPARK succeeded with 40 values at once using a little hint: bit vectors are easy to handle by the SMT solvers
  - SPARK can return a counterexample when a contract fails
  - Frama-C proved the correctness for 8 values but when extending the table to 40 values it didn't scale
  - After submitting the problem to the developers of Frama-C we got a new version integrating the Colibri SMT solver which worked. The reason was that Colibri worked with modular arithmetic unlike the others

Conclusion and future work

- **Formal methods**
  - Our experiments showed that formal methods definitely bring more confidence in the software verification process finding bugs earlier and faster than testing
  - They also help thinking about and getting a better specification
  - They can be introduced incrementally
- **Formal tools**
  - Some are mature enough to be used in an industrial context
  - Tools are complex and may contain bugs $\Rightarrow$ use of more than one tool?
  - Problem: Using mathematical numbers (reals and infinite integers) while we want to prove programs using floating point numbers and bounded integers
  - Challenges: scalability, floating point numbers, nonlinear arithmetic, timers, counters, lookup tables
- **Future work**
  - Can we get 0 false alarm using abstract interpretation tools and what is the prerequisite?
  - Can we get a better confidence in the software development using a formally defined language for MBD?
  - Can we get better invariant generation using a different methodology (e.g. functionally typing the variables)?