Protean Code ltd
Process, Technology and Training for Critical Software

Industrial Applications of Static Verification

Roderick Chapman, 25th November 2016

Contents

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- Goals for Static Verification
- SPARK is… (and isn't…)
- Verification - what and how
- Projects…

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Goals…

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- “Design goals…hmmm…yes…you should definitely have some…”
  Guy L Steele Jr (ACM SIGPLAN 1994)

- SPARK has evolved over the years from its first definition in 1987 to the latest release in February 2016.

- BUT..we like to think that the design goals have persisted and have not been compromised.

General SV goals…

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- What would you really like from any SV tool?
- How about these “Big five” goals:

1. SOUND
   - No “False Negatives” please!
   - Sound tool says: “There are definitely no bugs”
   - Unsound tool says: “I’ve done my best and I can’t find any more bugs…”
   - The bad news: all general purpose SV tools for standard unsubsetted programming languages are unsound. See Coverity’s “Billion Lines of Code Later…” article in CACM, for example.

General SV goals…

2. COMPLETE

- Very few “False Positives” or “False Alarms” please.

- Very easy to write a tool that says “Warning: your program might have a bug…” all over the place…

- Very annoying for users. The number 1 cause of customer complaints!

- Zero false alarms is impossible for non-trivial program properties (See “Rice’s Theorem” for example).

General SV goals…

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3. FAST

- How long are you willing to wait for SV tool to run? It seems there are four important milestones:
  - "Now"
  - Coffee Break
  - Lunch
  - Overnight
- For non-trivial programs (e.g. 250kloc)
- Psychological driver: SV must be faster than "let's compile and test our program to see what it does…"

General SV goals…

4. MODULAR and CONSTRUCTIVE

- SV works on incomplete programs, during development.
- Modules can be verified in isolation. Integration of modules does not require re-verification of the “whole thing”.
- You never need to analyse the “whole program.”
  - nb…proper modularity has huge impact on analysis speed as well…
- A bit like “separate compilation” in most languages.

General SV goals…

5. DEEP

- Verification of non-trivial program properties, such as
  - “Type safety” and “Memory safety”
  - Absence of undefined behaviour
  - Partial correctness
  - Termination
  - Invariants
  - Application-specific safety- and/or security properties.

General SV goals…

- The “big five” goals
- The bad news: with any standard unsubsetted language (e.g. C, C++, Ada)…pick any 3.5!
  - Actually, you don’t get to pick…some tool vendor picks for you. Tough luck!
- The good news: there’s another way…

General SV goals…

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- Aside: Why is Soundness so hard to achieve?
- Technical reasons
  - Quiz time!
- Economic reasons

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SPARK isn't...

- SPARK ≠ Apache SPARK

and

- SPARK ≠ SPARC™

SPARK is…

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- …a programming language,
- a set of static verification tools,
- a discipline for high-integrity software development
- All of the above.

SPARK is…

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- SPARK design process:
  - Start with Ada (remember this all started in 1987…)
  - Soundness is #1 goal and non-negotiable.
  - Remove all undefined and unspecified behaviour by subsetting and introduction of "tighter" language rules. Aim for an unambiguous dynamic semantics.
    - Cool side effect: SPARK just works for all compilers and target machines.
- Remove language features that defy verification.
- Add contracts to enable both efficiency and modularity of analysis.
- Build tools…try to sell them…and use them…
- Do research…make language bigger…make tools more powerful…repeat…Adopt "good stuff" from Ada95, Ada2005, Ada2012…

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The most important language features that SPARK doesn't have?

- No "Access Types" – aka "pointers" !!!
- No Heap…
- No "malloc" or "free"
- No garbage collection.
- oh..and no runtime library to support any of the above…


Huh?!?!

No Pointers?!?!

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- Yes…but…
- Low-level programming *just works*… control of representation and data layout is easy in SPARK and Ada.
- Composite types are *first class* and we have high-level parameter passing modes.
  - Pass-by-reference *mechanism* is permitted for efficiency, but that’s OK and doesn’t break anything…

No Pointers?!?!

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- No heap -> predictable timing behaviour for real-time/embedded systems. (nb most coding standards for embedded/critical C say “no malloc”)

- Building linked data structures?
  - use arrays and array index values as “pointers” – works rather well!
  - or…we have formal, generic container libraries.

No Pointers?!?!

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- Implications for Verification…
- Massive simplification in modelling of variables and their values – no need to model “store” or “address” stuff…
- Calculation and verification of modsets is trivial.
- Aliasing analysis is trivial (and sound in P-time…)
- No need at all for a separation-logic. “Classic” Hoare logic worked all along…

Why contracts?

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- In C, consider, the following function prototype declaration:

```
int Sqrt (int x);
```

- What does this mean? What does the function promise to do? What is left un-stated?

Why contracts?

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- In C, consider, the following function prototype declaration:

```
int Sqrt (int x);
```

- Answer: not much. There is enough info here for the compiler to know how to call Sqrt, but not much else!

- Moral: Don’t let compiler-writers design programming languages! This trend has crippled program verification for decades…

Why contracts?

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- In SPARK 2014…

```
subtype Sqrt_Domain is Natural range 0 .. 1_000_000;

subtype Sqrt_Range  is Natural range 0 .. 1_000;
```

```
procedure Sqrt (X : in     Sqrt_Domain;
                Y :    out Sqrt_Range)
with
   Global => (In_Out => Call_Count);
```

Why contracts?

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- In SPARK 2014…going further…

```
subtype Sqrt_Domain is Natural range 0 .. 1_000_000;

subtype Sqrt_Range  is Natural range 0 .. 1_000;
```

```
procedure Sqrt (X : in     Sqrt_Domain;
                Y :    out Sqrt_Range)
with
   Global => (In_Out => Call_Count),
   Post   => (Y * Y) <= X and
             (Y + 1) * (Y + 1) > X;
```

Why contracts?

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- Summary

- Contracts tell the verification system exactly what is needed on the specification of a unit, not the body.

- They say what a unit does and doesn’t do.

- Contracts are the key to modularity, efficiency and abstraction in verification.

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Verification

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- SPARK is designed to be amenable to many forms of verification
- Static
  - Subset and “type checking”
  - Data- and Information-flow analysis (essential to get rid of uninitialised variables before “proof” can start).
  - “Proof” - by generation verification conditions and then using a theorem-prover.
  - Worst-case memory-usage analysis.
  - Worst-case execution-time analysis.

Verification

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- SPARK is designed to be amenable to many forms of verification

- Dynamic
  - Testing, based on contracts. (like in Eiffel)
  - Structural coverage analysis.

- Note - in SPARK 2014, contracts can be used statically (for proof), dynamically (for test) or both. Allows “mixed language” development and verification.

Verification

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- **What can be “proven”???**
- “Type safety” - this really means:
  - No undefined behaviour.
  - No invalid data read or generated.
  - No “exceptions” - i.e. buffer overflow, arithmetic overflow, division by zero etc.
  - Program “never crashes” for any input data and state.

Verification

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- **What can be “proven”???**
- User-defined Assertions - anything you like!
  - Partial correctness against Pre- and Post-conditions.
  - Invariants (for types or package state)
  - Top-level safety and/or security properties. (Really just an assertion at the “main loop” level in your program.)

Verification - How

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- Under the hood - SPARK 2014

- SPARK 2014 is a complete reboot of the language design and tooling, based on Ada2012…

- Tools are structured like a compiler, but with a very different “back end.”

- “Front-end” is GNAT Pro Ada Compiler (GCC) and AdaCore’s GPS IDE.

Verification - How

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- “Middle-end”
  - Expands language constructs - e.g. generics.
  - Subset checking and extended legality rules.
  - Information-flow analysis, based on Program Dependence Graphs (PDGs).
  - Translation to “Why3ML” language for proof.

Verification - How

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- “Back-end”
  - Why3 VC Generator
    - Multiple “proof engines”, using SMTLib format
      - CVC4, Alt-Ergo, Z3 provers…
      - More to come…
- Oh…it’s all “FLOSS” (Freely Licensed/Open Source).

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Projects

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- Not an exhaustive list, but a selection of significant projects, with data where available…

The first big industrial SPARK project…

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SHOLIS - 1995ish

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SHOLIS - 1995ish

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LM-130J - 1996-

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Tokeneer - 2003-

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- NSA-funded demonstrator for high-security software engineering.
- Developed by Praxis (now Altran UK) in Bath.
- Fully formal “Correctness by Construction” development.
- Delivered about 10kloc SPARK. Zero bugs found by customer until 2008.
- 2008 - Unprecedented open-source release of the entire project archive.
- Only 4 or 5 bugs ever found since…

NATS iFACTS 2006-now

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Before iFACTS…

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After iFACTS…

NATS iFACTS

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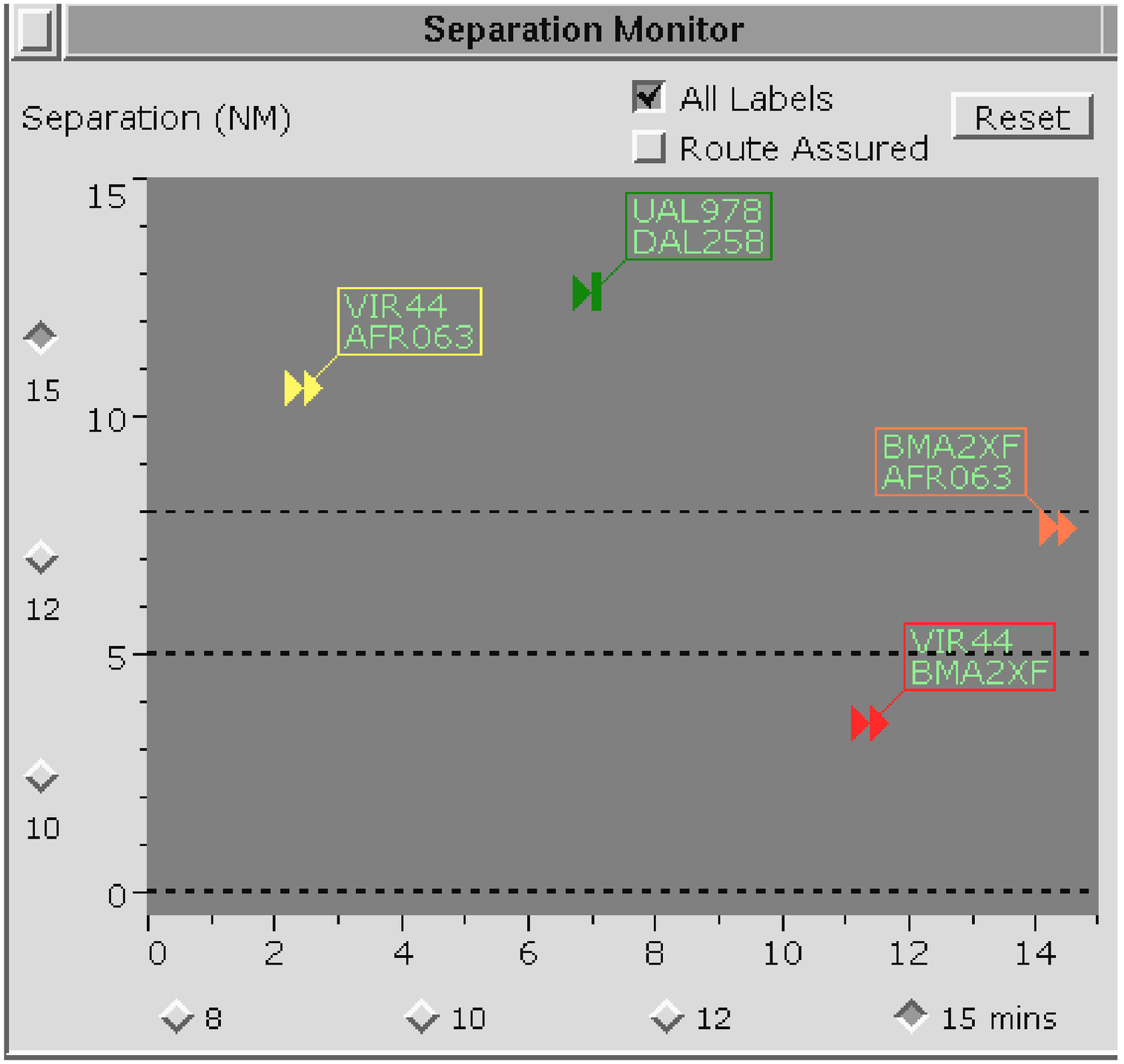

NATS iFACTS

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- In full operational service since December 2011.
- About 250kloc SPARK
- Proved “type safe” (i.e. crash proof etc.) *as a matter of course…*
- 152,000 VCs. 98.76% discharged automatically by tools. Remainder proved with user-defined lemmas, so 100% automation.
- Complete re-proof takes about 15 minutes on a standard PC, using distributed persistent proof caching. i.e. we’re down to “coffee break” for the whole system.
- Small changes are re-proved by developers before commit to CM system.

SPARKSKein - 2010

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- SPARK Reference Implementation of the “Skein” hash algorithm - one of the (then) contenders to become SHA-3.

- Implementation is: fast, formal, proven, portable, and (we think) readable.

- Debunks the myth that “formal is slow”.

- Released Open-Source.

- Also (en-passant) spotted a nasty corner-case overflow bug in the designer’s own (C) reference implementation.

Muen - 2013

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- Muen is a small separation kernel for x86_64 architecture.

- Proved type-safe and “crash proof”

- Open source

- Latest version now in SPARK 2014.

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To end…

- Static Verification really does work!
- A disciplined mindset can bring huge benefits.
- Soundness enables us to modify later verification activities (e.g. do less testing!). This can save lots of money.
- Many industrial projects do this for real, right now.

Homework…

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- Have a play…
- All the tools are GPL and freely available.
  - (Support for Professors, too… :-))
- Download Muen, SPARKSkein, or Tokeneer and see what you think.

Resources

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- SPARK 2014 - www.spark-2014.org (including language definition, blog, community projects page etc.)
- GPL tools: libre.adacore.com
- Tokeneer: www.adacore.com/tokeneer
- SPARKSkein: www.skein-hash.info
- Muen: muen.codelabs.ch
- Universities using SPARK: www.adacore.com/academia
- me: rod@proteancode.com
- SPARK Team in Bath: www.altran.co.uk