Foundational Program verification using VST

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deep spec

Verified Software Toolchain

IBM Programming Languages Day 2017

T.J. Watson Research Center
Monday, December 4th 2017
https://ibm.biz/plday2017

Styles of program verification

IDE-embedded verification tool

- annotation-enriched code
- verification carried out on intermediate form, using SAT/SMT
- assertions: expressions from the target programming language
- first-order quantification
- multitude of verification/modeling styles, encoded e.g. as ghost state
- automated verification for correct annotations
- relationship to compiler’s view of language unclear (soundness?)

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VST: realization in interactive proof assistant (Coq)

- loop-invariants proof-embedded; function specs separate
- verification carried out on AST of source language
- assertions: mathematics (Gallina, dependent type theory)
- higher-order quantification
- specs can link to domain-specific theories (eg crypto, see below)
- interactive verification, enhanced by tactics + other automation
- formal soundness proof (“model”) links to compiler (CompCert)

Formal **Program** Correctness **Verification**

"Prove"?

"Correct"?

Prove that your
C program is *correct*.

Prove in Coq that your
C program *satisfies* its
functional specification.

Q: How to express a functional spec?
A: Write a **functional** program!

Corollaries:
- safety, incl. memory safety: no buffer overruns etc.
- information-flow guarantees captured in functional model

Provides the expected functionality

Prove your **C** program
functionally correct ***in Coq***.

Not covered: intensional properties
- execution time, power consumption, cache behavior
- information flow via these side channels

Further refinements:

- **"prove": in Coq, semi-automatically**
- **"program": fragment (modularity)**
- **"satisfies": program logic with interpretation & soundness proof w.r.t. operational semantics**
- **"program": proof for C, guarantee for ASM via compiler correctness (CompCert)**
- **assumptions: Coq kernel, ASM model,…**

Gallina

The pure functional language inside Coq's logic has a nice clean proof theory. **This enables us to write specs that are easy to reason about, for students, practitioners,....**

Gallina is **executable** inside Coq, so specifications can be **tested**.

Many kinds of applications are best **programmed** in a safe, garbage-collected functional programming language. Gallina is **extractable** to OCaml so can be integrated into existing software infrastructures.

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Verified
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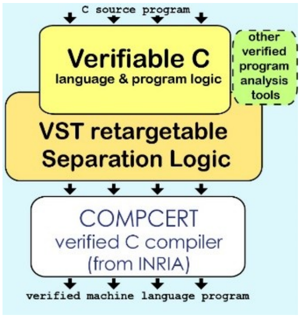

Concurrency (Dijkstra-Hoare + fine-grained), impredicative quantification, …

Floyd: forward-symbolic analysis, partial solution of side conditions using Ltac or verified decision procedures.

Clight, as formalized in CompCert

Expressive, modular, foundational, semi-automatic program logic for C and beyond.

Separation logic

Soundness proof for step-indexed model formalized w.r.t. operational semantics in Coq.

Partial correctness + safety + limited information flow.

X86-32/64, Arm, PowerPC, RiscV, RTL, …

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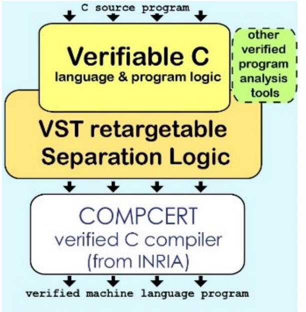

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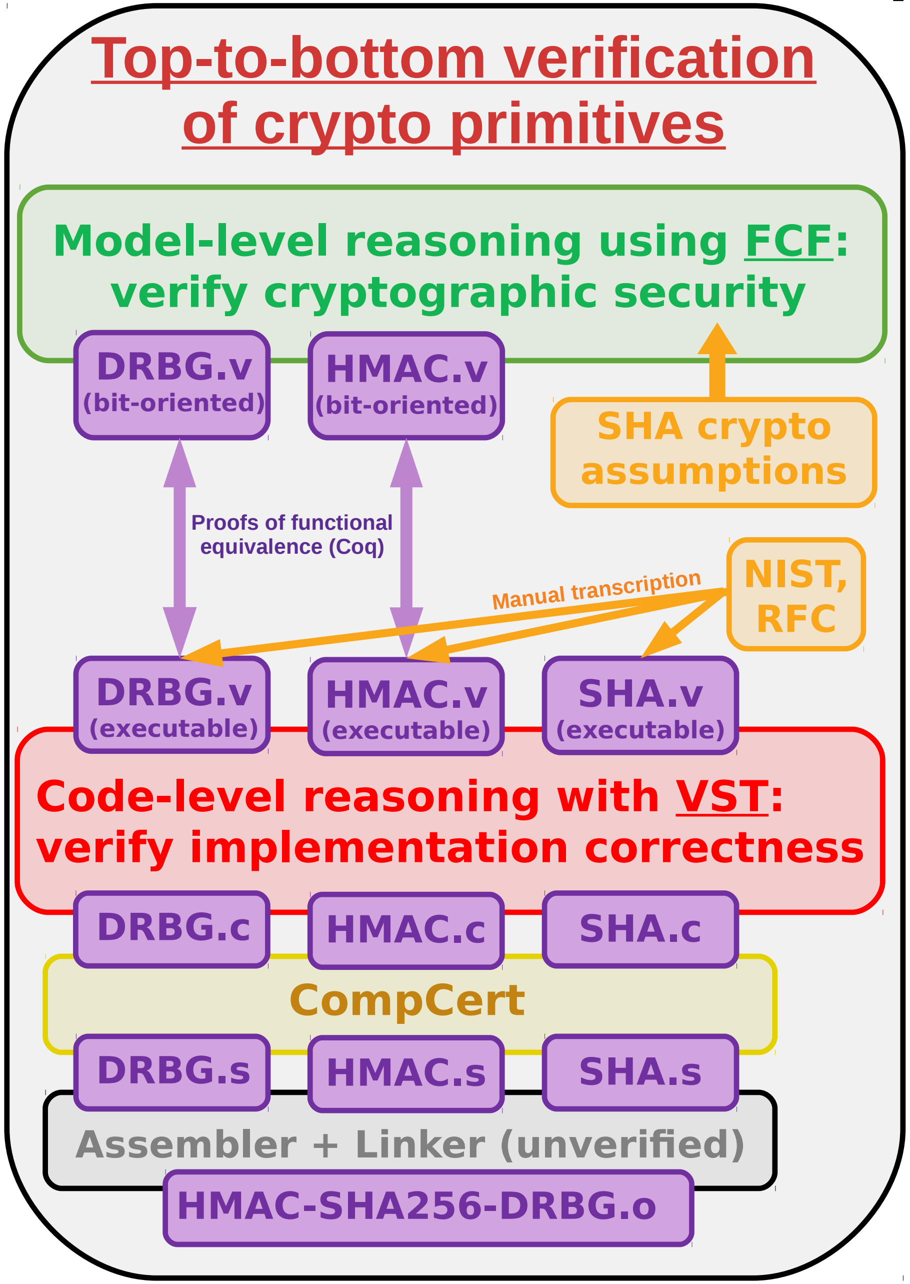
Typical use: exploit convenience of Gallina:

1. write a (functional) **model program** **p** in Gallina
2. structure of **p**: one function **f** for each C function **c**
3. Function spec for **c** refers to specification function **f**

```
Fixpoint app (al bl: list Z) : list Z :=
 match al with
 | nil => bl
 | a::al' => a :: app al' bl
 end.
```

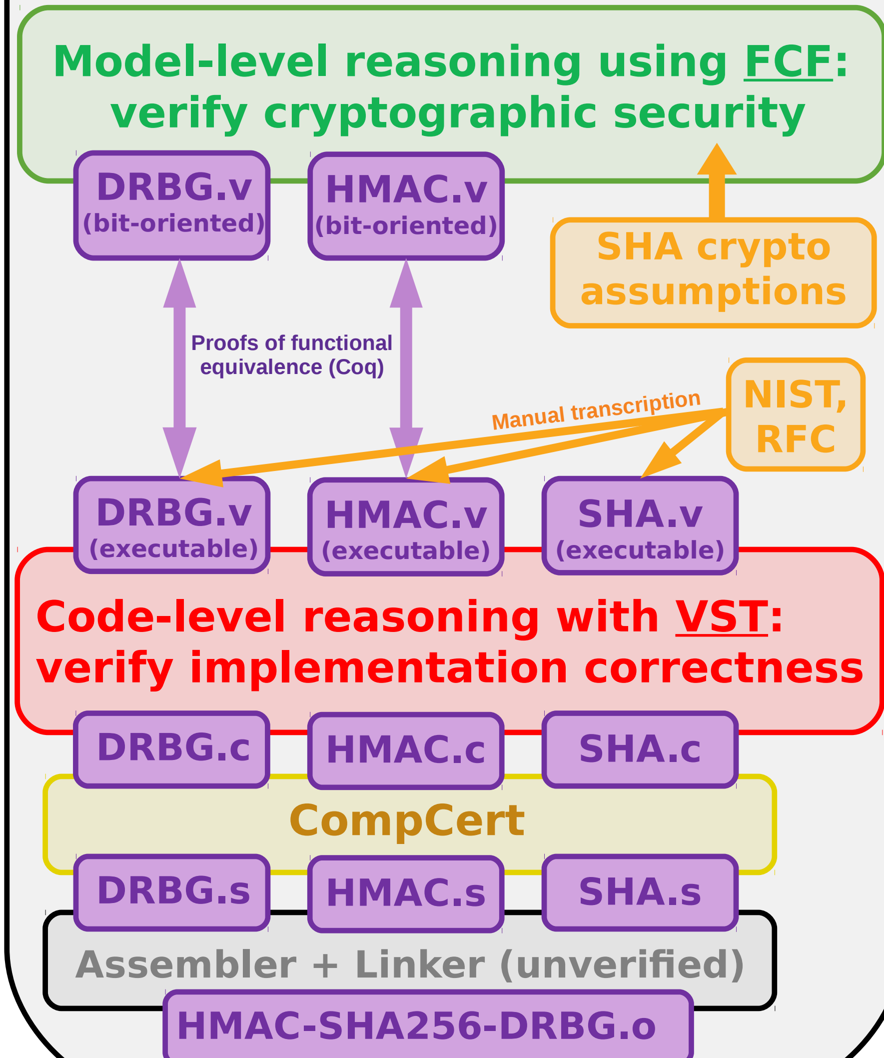
{ listseg α x **null** * listseg β y **null** } append(x,y) { listseg (app α β) retval **null** }

Recent applications



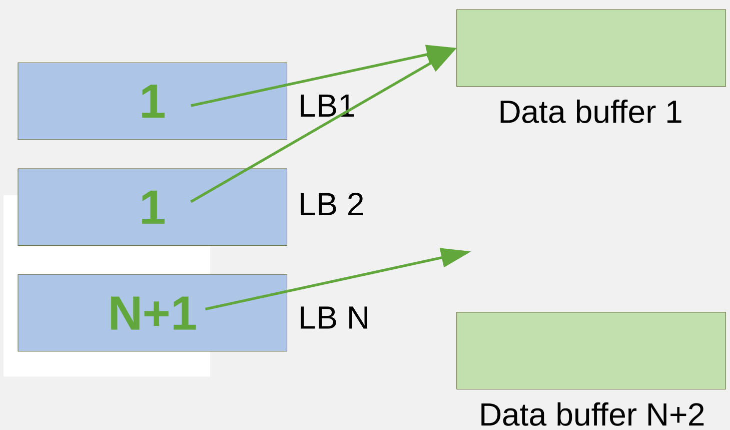
Recent applications

Top-to-bottom verification of crypto primitives



Nonblocking concurrency

N readers, 1 writer

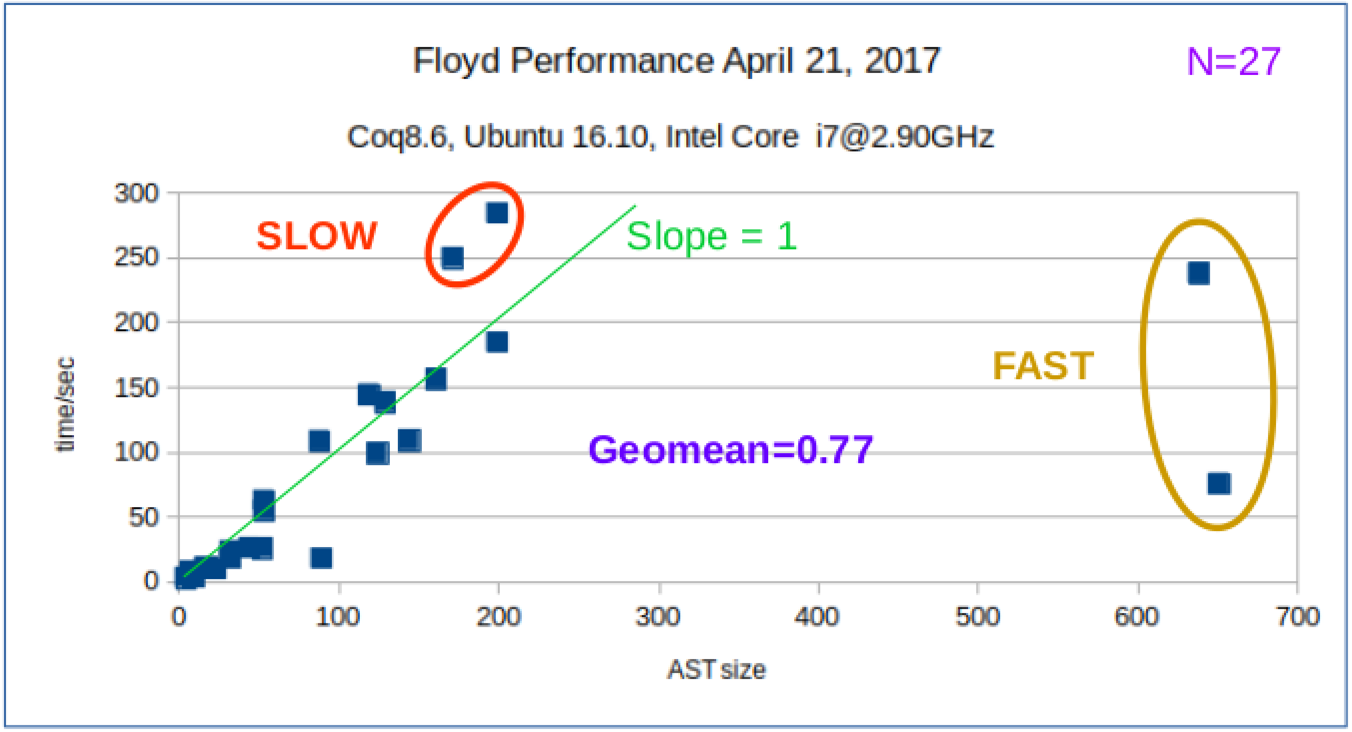


1) W selects free data buffer 0 < **b** < N+3 and writes data to **b**
2) W communicates **b** to all N readers using atomic exchanges to all LB’s
3) Reader **i** inspects LB**i** to find location of next data item
4) Reader **i** acknowledges receipt of **b** using atomic exchange “Empty” in Lb**i**
5) Accesses to data buffers use ordinary load/store operations

N+2: W can always find a free data buffer !

Automation & Performance

- assertions in **canonical form**: PROP (P) LOCAL (Q) SEP (R)
- SL proof rules for C complex! Many entailments!
- full employment theorem for tactics programmers
- horizontal frame, not vertical: **PROP (P) LOCAL (Q) SEP (R) FR (F)**



Current & Future Work

Concurrency:

- Semantic justification of concurrent ghost state a la Iris/GPS
- Derivation of proof rules for C11 atomics
- Application to nonblocking algorithms and data structures

DeepSpec (NSF):

- **crypto** primitives and protocols: integration with FiatCrypto's ECC, TLS 1.3, ...
- specification of **CertiKOS** system call API
- specification and verification of web server
- Interaction with **Vellum**, **CoreHaskell**, and **CertiCoq**

Try it yourself: **http://vst.cs.princeton.edu/download**