Q: A Sound Verification Framework for Statecharts and Their Implementations

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Formal Techniques for Safety-Critical Systems, 7 December 2022, Auckland, NZ
Introduction

Architecture

Refinement

Coq Formalization

Conclusion
Motivation

- Sandia National Labs is a US government research & development center
- Sandia develops software for high-consequence embedded control systems
- The cost for errors is very high
- Good use-case for formal methods
- Design features:
  - Asynchronous interacting components (e.g., across a bus)
  - Requirements documents in English and informal diagrams
  - Modeled in MATLAB Stateflow as an abstract model
  - Implemented in C
- From these, we require proofs of system-level properties.
Sandia has the fortune of strong control over structure of C programs, hardware interface, and interaction with software developers and system engineers.

Long history of verification of models (e.g., TLA, SMV) and of implementations directly (e.g., SLAM [3]).

However, existing research does not support compositional reasoning of state machines while also providing refinement proofs into C.

We developed Q Framework to address this gap and provide (mostly) automated refinement proofs.
Structure of This Presentation

1. Provide overview of Q Framework, piece by piece
   - Use a running example of a “secure coffee maker”
2. Describe our refinement argument between temporal properties of state charts and Frama-C [4] proof obligations
3. Give overview of our formalization of Q Framework in Coq
4. Related work, future work, conclusion
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Overview

- LTL, CTL Properties
- Stateflow Models
- C Source
  - QFact
  - Annot. C
  - ACSL
  - Frama-C (+ back-ends)
- QLang
- Stateflow Test Case
- Counter-example
- QSpec
- QSpeckler
- ACSL
- NuSMV
- SMV

Blue text
- Sandia-developed

Double-struck
- require manual writing or enforcement

- Annot. C
- specify UB
- obeys style
- Proof?
- SAT?

- QFact
- require manual writing or enforcement

- NuSMV
- require manual writing or enforcement

- SMV
- require manual writing or enforcement

- ACSL
- require manual writing or enforcement

- QSpec
- require manual writing or enforcement

- QSpeckler
- require manual writing or enforcement

- LTL, CTL Properties
- Stateflow Models
- C Source

Frama-C (+ back-ends)
Stateflow Models

- LTL, CTL Properties
- Stateflow Test Case
- C Source
- QSpec
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- SAT?
- SMV
- QLM
Coffee Maker in Stateflow

System

Brewer

Ready

[coin]

[~confirmed]

Confirm

[confirmed]

/ (brew = 0;)

[~confirmed... 
& & brew < 2]

Brewing

[brew < 2]

/ (brew = brew + 1;)

[brew == 2]

/ (brew = 0;)

Payment

Idle

[confirmed]

Paid

[coin]
Coffee Maker in Stateflow (Zoomed)
Coffee Maker State Machine

- Coffee maker with confirm and cancel buttons
- “payment” system which continuously pays and presses “confirm.”
LTL/CTL

LTL, CTL Properties

Stateflow Models → QSpeckler → QSpec → Counter-example

obeys style

C Source

QLang → QFact → ACSL

specify UB

Annot. C

Frama-C (+ back-ends) → Proof?

NuSMV → SAT?
LTL/CTL

- Write properties based on requirements docs
- Example safety condition in CTL:
  - AG !(state = confirm & brew = 2)
  - The coffee maker should not be “confirmed” after coffee is done brewing
- We support LTL and CTL because NuSMV does
QSpec and QSpeckler

- QSpec inspired by SCXML
- QSpec files (right) aren’t written by hand
- QSpeckler translates from Stateflow into QSpec
- QSpeckler understands MATLAB
  - Can generate a Stateflow test case from an SMV counterexample
  - QLang handles the translation into an SMV model

```xml
<?xml version="1.0" encoding="UTF-8"?>
<qspec> <!-- initialization -->
  <state id="System">
    <parallel>
      <sequential>
        <initial> <!-- ... --> </initial>
        <state id="Brewing">
          <transition label="Brewing_Brewing"
                      target="Brewing">
            <guard name="check_brewing"
                   predicate="(< brew 2)="/>
            <assign location="brew"
                     expr="(+ brew 1)="/>
            </transition>
          <!-- ... more states -->
        </state>
      </sequential>
    </parallel>
  </state>
</qspec>
```
C Implementation

- LTL, CTL Properties
- Stateflow Models
- Stateflow Test Case
- QSpeckler
- Counter-example
- QSpec
- C Source
- QLang
- SMV
- NuSMV
- QFact
- Annot. C
- specify UB
- Frame-C (+ back-ends)
- Proof?
- SAT?
C Coding Standards

- Q Framework expects a restricted subset of C
- Must be able to map from Stateflow to C
- Separate all hardware access (memory-mapped I/O or volatile variables) into function calls
  - Axiomatize the hardware behavior
  - These specifications are written in Frama-C
- These are used for our soundness argument

```c
/*@ 
requires \valid(unsigned char volatile *v);
requires fgetC == v;
ensures obs_t == \old(obs_t) + 1;
ensures \result \in (0 .. 255);
ensures \result <=>
  fgetCObs(obs_at(\old(obs_t))); 
*/
uint8_t *volatile_load_uint8_t_(uint8_t *v);
```
QLang

- LTL, CTL Properties
- Stateflow Models
- C Source
- QFact
- Annot. C
- specify UB
- obey style
- Stateflow Test Case
- QSpeckler
- obeys style
- QSpec
- Counter-example
- QLang
- ACSL
- Frama-C (+ back-ends)
- Proof?
- SMV
- NuSMV
- SAT?
- obeys style
- specifiy UB
- QFact
- Annot. C
- specify UB
- obey style
QLang

- **Input**
  1. QSpec (including the desired temporal properties)
  2. C program written in a constrained style
  3. Simulation map between Stateflow and C variables

- **Output**
  1. “flattened” SMV model
  2. C header file with ANSI C Specification Language (ACSL) annotations
     - These are the proof obligations to be proven by Frama-C

- **QLang has several back-ends**
  - The most interesting being SMV, but also, e.g., one for visualization
A flattened state chart has no nesting or parallel composition

- Benefit: simple implementation
- Concern: Exponential increase in size of model
  - Can pass onto NuSMV; in practice this sometimes helps
  - Future work to address this (e.g., assume-guarantee reasoning)
QFact

- Clang tool which annotates a C program with its ACSL specification
- Why is this necessary?
QFact

- Clang tool which annotates a C program with its ACSL specification
- Why is this necessary?
- C semantics are complex
  - Lots of implementation-defined, unspecified, and undefined behavior
  - e.g., evaluation order of function arguments
- Our trick: Convert from C → Clight, then back to C
  - Fortunately, CompCert has such a forward translation; we modify it to do the reverse
QWorkflow

LTL, CTL Properties
Stateflow Models
C Source
QFact
Annot. C
specify UB

Stateflow Test Case
QSpeckler
obeys style

Counter-example
QSpec

QLang

ACSL

SMV

NuSMV

Proof?
SAT?

Frama-C (+ back-ends)
QWorkflow

- Orchestrate all the moving parts
- Provide:
  - Requirements documents (Microsoft Word, Visio)
  - Each requirement in the Word document has identifier
  - Stateflow model
  - C code
- Runs analysis, generates counterexample (if available), and links the status of each requirement to whether its proof completed in Frama-C and NuSMV
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The Goal of Q Framework, Restated

- Prove system-level temporal properties
  1. Prove the temporal properties hold for QSpecs
  2. Prove a given C program implements (refines) a component of the QSpec

- 1. is done by encoding QSpec model as SMV, then using NuSMV
- We next describe 2.
  - Generate ACSL function contracts
  - Use Frama-C to prove the C implements these contracts
  - Carefully chose our notions of refinement (model $\rightarrow$ C) and composition
  - With these, any properties we prove of the QSpec also hold for C implementation
Ghost State

- Observations *within* a function call may not be observable to Frama-C, but are observable behavior to C semantics
- Solve this with *ghost state*
- Frama-C annotation to describe whenever the ghost state changes

Frama-C specification:

```c
/*@ 
ghost int obs_t;
axiomatic model {
    type obs;
    logic obs obs_at(integer t);
    logic uint8_t fgetCObs(obs o);
} */
volatile uint8_t fgetCVal;
```

In Clight, use pointer `fgetC`:

```c
$1 = volatile_load_uint8_t_(fgetC);
```
Weak Simulation

\[ O_Q \xrightarrow{\rightarrow_Q} \mathcal{P}(S_Q \times S_Q) \]

\[ \hat{\varphi}_{[R_{OQ}]} \downarrow \subseteq \downarrow \hat{\varphi}_{[R_{S_Q}]} \]

\[ \mathcal{P}(\text{GhostState}) \xrightarrow{\rightarrow_{P_C}} \mathcal{P}(\text{ProgState} \times \text{ProgState}) \]

- \( Q \) is the abstract model (QSpec)
- \( P_C \) is the concrete implementation (C program)
- \( \hat{\varphi} \) is a JSON file relating Stateflow variables to predicates over C variables.
- \( \rightarrow_Q \) is a Galois connection between \( O_Q \) and \( \mathcal{P}(S_Q \times S_Q) \)
- This demonstrates a proof of weak simulation, provided we can think of \( P_C \) as a transition system: this is not trivial when considering C semantics
Weak Simulation

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Weak Simulation

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Weak Simulation

\[ O_Q \xrightarrow{\rightarrow_Q} \mathcal{P}(S_Q \times S_Q) \]

\[ \hat{\varphi}^{[RO_Q]} \downarrow \subseteq \downarrow \hat{\varphi}^{[RS_Q]} \]

\[ \mathcal{P}(\text{GhostState}) \xrightarrow{\rightarrow_{PC}} \mathcal{P}(\text{ProgState} \times \text{ProgState}) \]

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Weak Simulation

- $Q$ is the abstract model (QSpec)
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Weak Simulation

$O_Q \xrightarrow{\rightarrow_Q} \mathcal{P}(S_Q \times S_Q)$

$\hat{\varphi}^{[R_{OQ}]} \downarrow \subseteq \downarrow \hat{\varphi}^{[R_{S_Q}]}$

$\mathcal{P}(\text{GhostState}) \xrightarrow{\rightarrow_{P_C}} \mathcal{P}(\text{ProgState} \times \text{ProgState})$

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Refinement

Above: Composition in the model with an LTS with a single state 1

Below: Composition in the C program with an environment for volatiles
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Coq Formalization

- Have semantics of state charts in Coq
- Model of what we’ve implemented in Q Framework
- Also provide notion of refinement between two state charts

(* $S$ is State
  $E$ is environment (model vars) *)

Record Machine :=
{  m_initial : (S * E) -> Prop;
  m_terminal : (S * E) -> Prop;
  m_inner : S -> E -> E -> Prop;
  m_step : (S * E) -> (S * E) -> Prop
).

Inductive Chart :=
| Unit : Chart
| Par : Chart -> Chart -> Chart
| Nest : Machine ->
  (S -> Chart) -> Chart.
Example: Must Go

**Theorem** qspec_must_go_ind :
forall qchart qspec data
cfg1 cfg2 env1 env2,
qchart = semantics qspec data
-> chart_step
qchart
(cfg1, env1)
(cfg2, env2)
-> chart_step_pred
must_go_pred qchart
(cfg1, env1)
(cfg2, env2).

- Informally, if a top level state machine can step from $A \rightarrow B$, then it should guarantee that we cannot go from $A \rightarrow A$ as an inner step.
- Q Framework compositional over parallel composition, this states in which cases nested composition is compositional.
Related Work

- DeepSpec project and the Verified Software Toolchain (VST)
  - strongest assurance arguments
  - a full program logic for C
  - time-intensive

- Modeling with eventB [1], SMT, TLA+

- Trillium [5]: Coq proof of refinement between TLA+ specs and a DSL for specifying concurrent systems, AnerisLang
Future Work

- Add multiple observables per function call
- Size of flattened QSpec model causes scalability concerns
- Modularity of (Stateflow) design *should* allow some modular reasoning
  - Plan to add support for assume-guarantee, circular assume-guarantee reasoning for Q Framework
- We have Coq model of semantics and semantics of C, but not a formal proof of compilation between them
- Less restrictions on C code implementations
- Automatically generate some ACSL specs, especially for pure functions
  - To this effect, use Verified Software Toolchain’s (VST) [2] symbolic executor
Conclusion

- Q Framework allows us to build compositional reasoning, and provides evidence that a C implementation refines a given state machine model.
- Q has rather strict limitations on the structure of the C.
- Future work of “One Q.E.D.”
- Not open source, but examples can be found here: https://github.com/sampollard/q-supplement
References I


