FORMAL SYNTHESIS OF FILTER COMPONENTS FOR USE IN SECURITY-ENHANCING ARCHITECTURAL TRANSFORMATIONS

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DISCLAIMER

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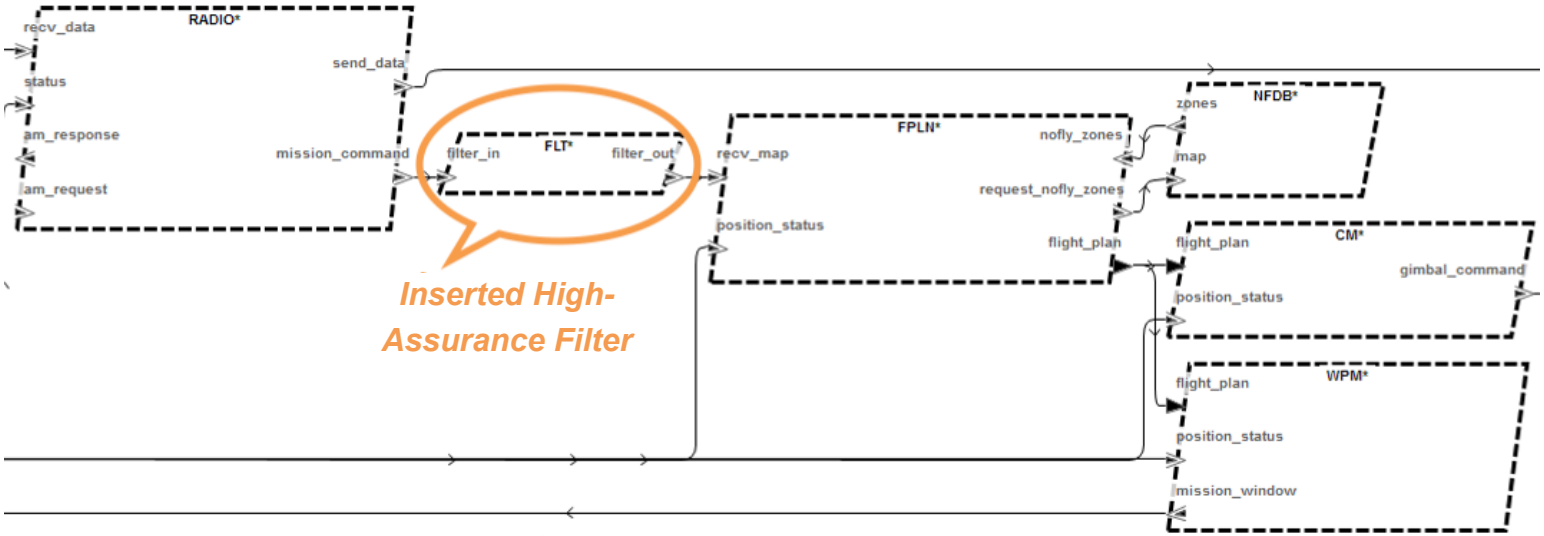
DARPA CASE

- The goal of the DARPA Cyber-Assured Systems Engineering (CASE) program is to “develop the necessary design, analysis and verification tools to allow system engineers to design-in cyber resiliency”
- Architecture models in the DARPA CASE program are expressed in the SAE standard Architectural Analysis and Design Language (AADL)
- The CASE Cyber Requirements tools examine the AADL model for the system, identifying potential cyber vulnerabilities
- The CASE user then identifies *security-enhancing architectural transformations* to be applied to the model to address the vulnerabilities
- Let’s say the need for an input well-formedness filter was identified:
  - The CASE user adds the filter to the model, and specifies the high-level filter behavior, e.g. using a regular expression
  - The CASE tools then automatically synthesize the filter and produce a proof of filter correctness all the way down to the binary level
  - This filter is hosted on a high-integrity operating system, e.g. seL4

DARPA CASE: SIMPLE UAV USE CASE



CASE FORMAL MESSAGE SPECIFICATIONS

- We concur with the LangSec tenet that “the only path to trustworthy software that takes untrusted inputs is treating all valid or expected inputs as a formal language.”
  - Our work differs somewhat from many LangSec efforts in that we focus on providing standalone high-assurance message filter and monitor components
  - This is due to the fact that part of our mission statement on DARPA CASE is to provide security-enhancing components for existing systems, whose legacy components may not be able to be readily modified to introduce a LangSec-based parser as part of its codebase
- We have investigated three different formal message specification/synthesis approaches:
  - Regular Expressions
  - Context-Free Grammars
  - Contiguity Types
- We will examine each of these in turn

REGULAR EXPRESSIONS

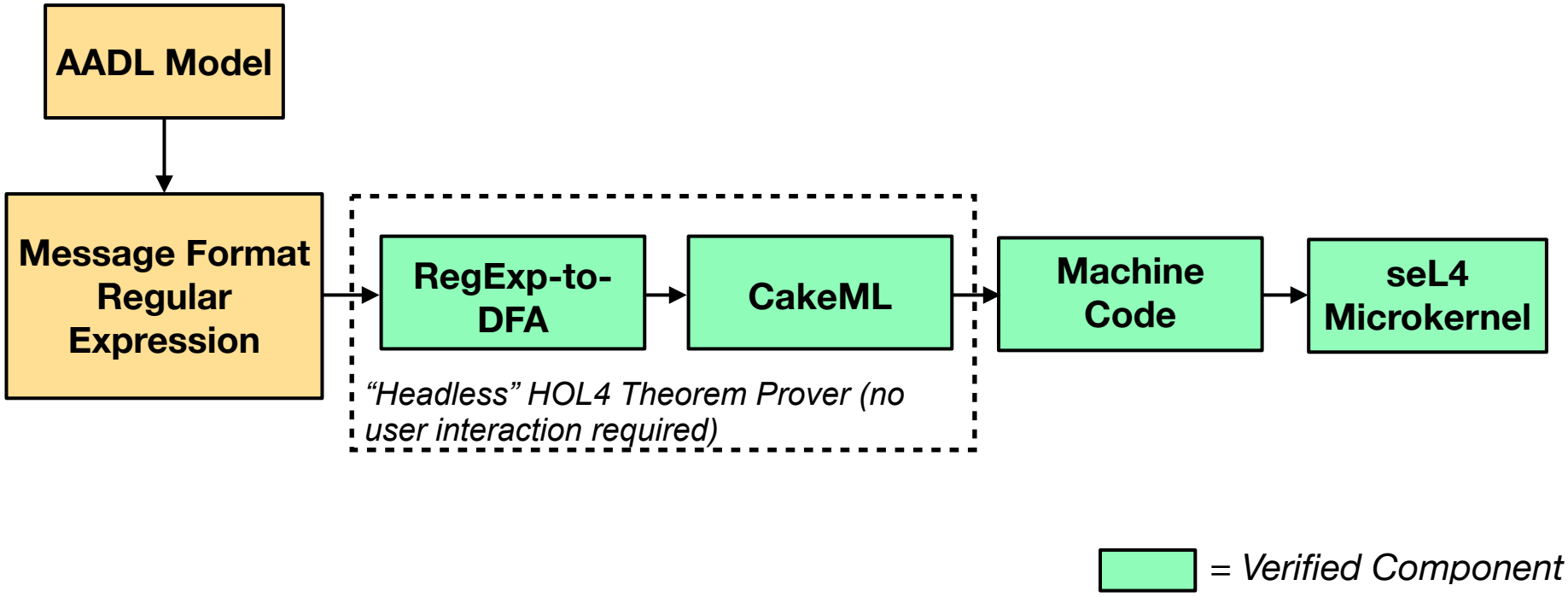
MESSAGE FORMATS FROM AADL MODELS

- Our AADL models feature assume/guarantee contracts expressed in the AGREE AADL annex
- We have built a translation of AGREE component input contracts to regular expressions, and provide proof tools for verifying semantical properties of the generated regular expressions.
- We call this tool SPLAT (Semantic Properties for Language and Automata Theory), since it combines formal language theory with specifications on the interpretation of the flat strings comprising a message format
- SPLAT also provides automated synthesis of message handling binary code using the facilities of the CakeML verified compiler

FAST REGULAR EXPRESSION PATTERN MATCHING

- Brzozowski (1964) presents a method for compiling a regular expression to a Deterministic Finite-state Automaton (DFA), which is subsequently run on candidate strings
  - Thus, regular expression matching becomes quite fast
- We have performed a correctness proof for regular expression compilation to DFAs, and contributed it to the HOL4 theorem prover source distribution
  - In **`examples/formal-languages/regular`**
- Thus, we can utilize a verified compiler toolchain to create a verified regular expression pattern matcher down to the binary level
  - The matcher is, in essence, a simple DFA state traverser function

CASE VERIFIED FILTER SYNTHESIS TOOL FLOW (REGEX)



CONTEXT-FREE GRAMMARS

EXAMPLE: JSON MESSAGE FORMAT

- Use case: a UAV air-ground communications system employs JSON (JavaScript Object Notation) to encode certain messages sent between the ground-based control station and the UAV

- For example, a UAV coordinate could be encoded in JSON as:

```
{"lat":42.008, "long":-91.644, "alt":5000}
```

- In order to create such a well-formedness filter for JSON, we need to perform both *lexical* and *syntactic* level analysis on any candidate JSON message, to ensure that it is legal JSON

LEXICAL ANALYSIS

- We describe the lexical tokens, or *lexemes*, of JSON by way of regular expressions

- JSON lexemes include:
  - true, false, null, string, float, and integer values
  - `{`, `}`, `[`, `]`, `:`, `,`

- A lexical analyzer generator accepts these regex token specifications, and produces a lexer that takes an input candidate JSON message, and produces a list of JSON tokens
  - We combine the individual regular expressions for our JSON tokens to create an overall DFA table for the lexer

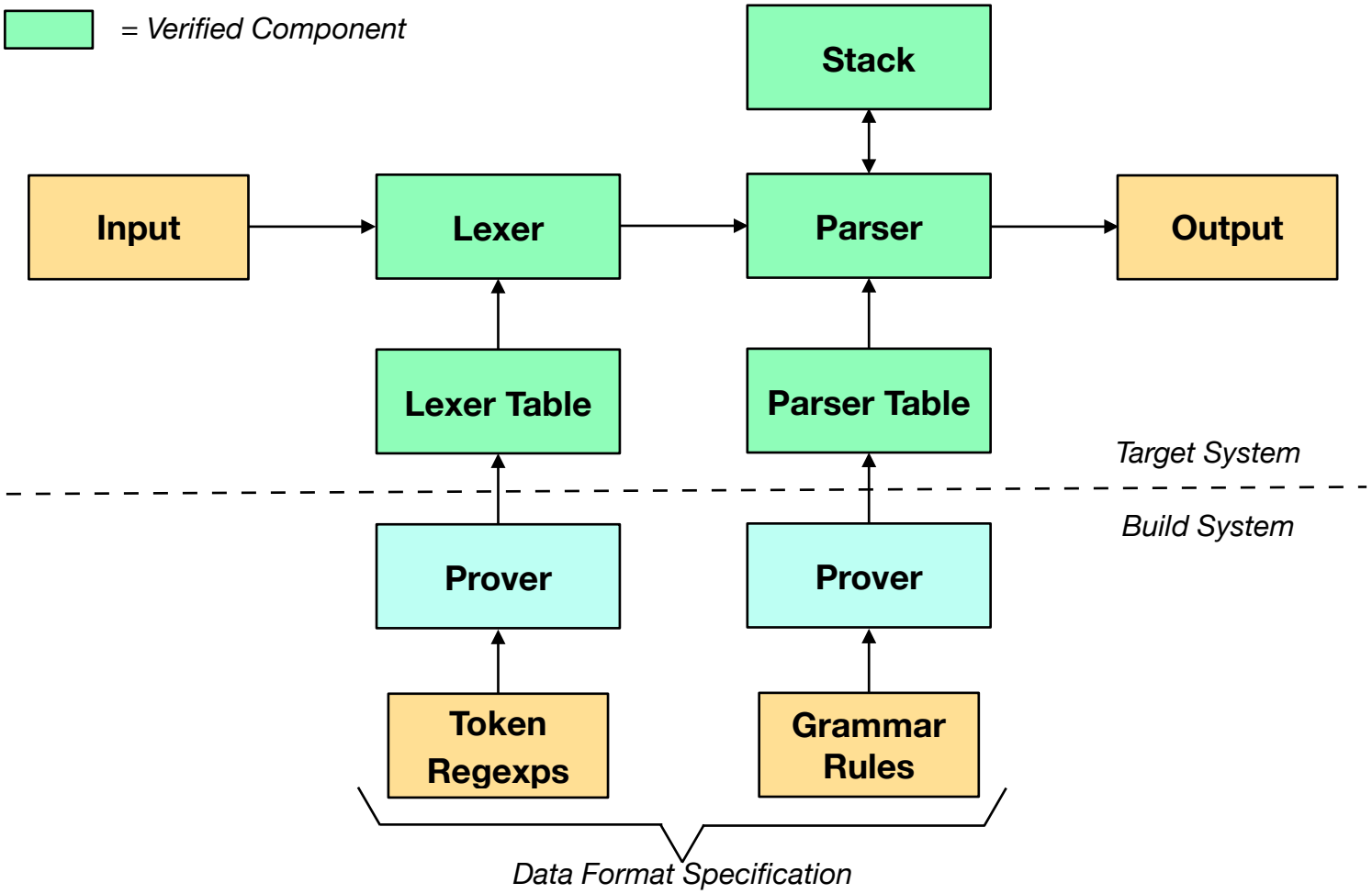
SYNTACTIC ANALYSIS

- We utilize a verified parser generator to create a verified parser table for JSON
  - In particular, we employ the Vermillion verified LL(1) parser generator (Lasser *et al.* 2019)
    - We present a set of grammar rules for legal JSON messages to Vermillion;
    - extract the verified parser table from Vermillion;
    - then transfer the verified parser table to our target system
- By generating both the lexer table and parser table in formally verified fashion, we enable *verified data* to be transferred from host-based provers to the target system
- The parser function is a bit more complex than the lexer, in that it requires a rule stack; otherwise, it is also a fairly straightforward table traverser

HARDWARE/SOFTWARE CO-DESIGN AND CO-ASSURANCE FOR THE JSON FILTER

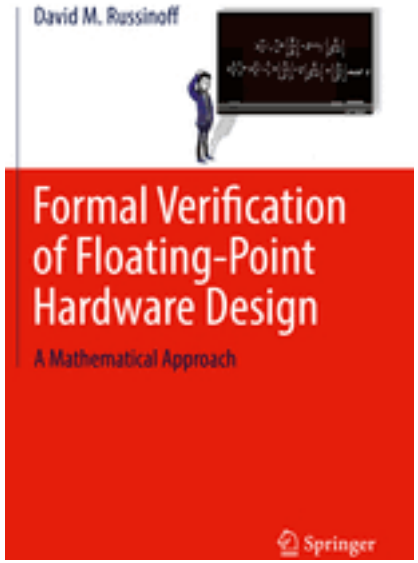
- We wish to create a lexical/syntactic filter for JSON using hardware/software co-design and co-assurance techniques
- We utilize the verified lexer generation and verified parser generation capabilities described earlier to create the lexer table and parser table for JSON (“verified data”)
- The table traversal code is written by hand in the hardware/software co-design language
  - In the future, this code will be automatically generated
- For the parser rule stack, we utilize a previously verified fixed-size stack component written in the hardware/software co-design language

JSON FILTER BUILT FROM HARDWARE/ SOFTWARE CO-ASSURANCE COMPONENTS



THE RUSSINOFF-O'LEARY APPROACH TO HARDWARE/SOFTWARE VERIFICATION

- The hardware/software verification approach we employ was developed by David Russinoff and John O'Leary, while both were at Intel
  - The approach was initially based on SystemC, and was called MASC
  - Russinoff changed the source language from SystemC to Algorithmic C after he moved to Arm, made several enhancements, and renamed the system RAC (Restricted Algorithmic C)



- RAC is extensively documented in Russinoff's 2018 book, *Formal Verification of Floating-Point Hardware Design: A Mathematical Approach*, wherein RAC is applied to the verification of realistic Arm floating-point designs
  - RAC, and the verifications described in the book, are all available in the standard ACL2 thereom prover distribution

ALGORITHMIC C

- The Algorithmic C datatypes “provide a basis for writing bit-accurate algorithms to be synthesized into hardware”

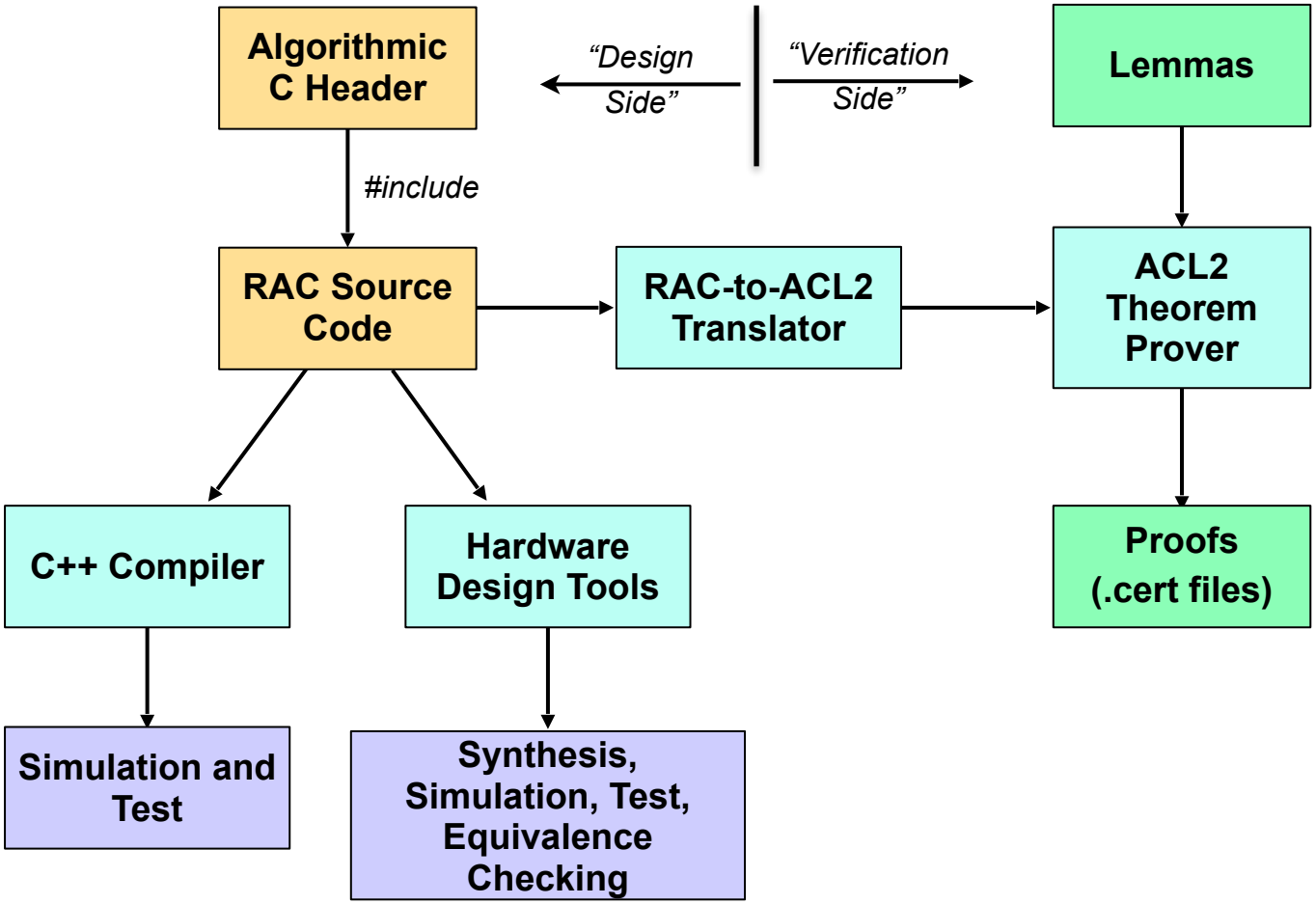
- Example use:
  - `typedef ac_int<112,false> ui112;`

  declares an unsigned 112-bit type used in floating-point hardware datapaths

- Supported by Mentor hardware synthesis tools, e.g. Catapult; for details, see **`https://hlslibs.org`**

- Restricted Algorithmic C (RAC) further restricts Algorithmic C to facilitate proof; see Chapter 15 of Russinoff’s book for details

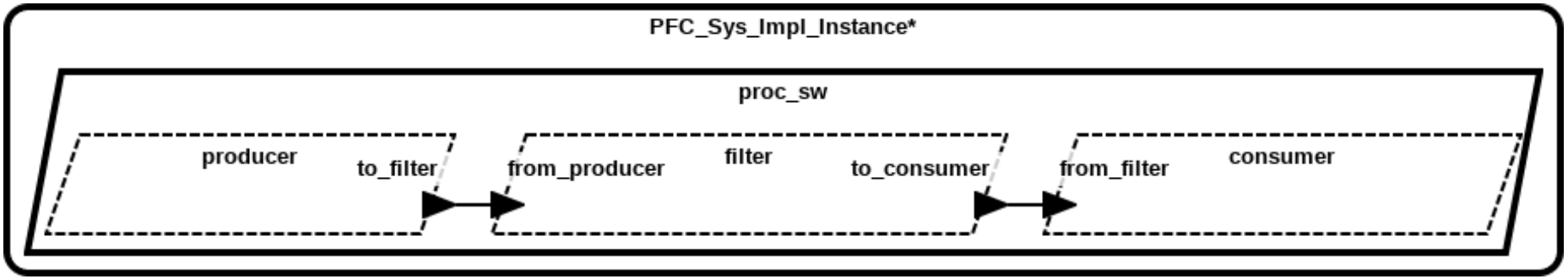
RESTRICTED ALGORITHMIC C TOOLCHAIN



HARDWARE/SOFTWARE CO-SYNTHESIS FROM AADL MODELS (KANSAS STATE UNIVERSITY)

Demo: Synthesize Hardware for CASE-generated filter

AADL Model:

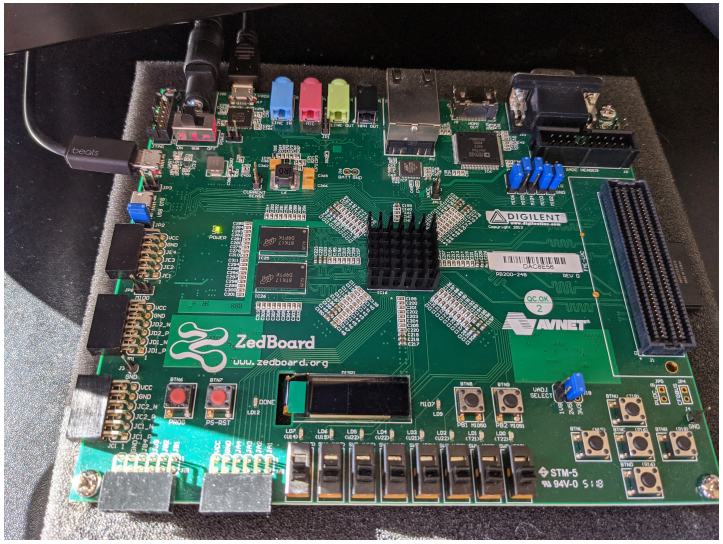


…mapped to
Linux software process

…mapped to
Linux process with FPGA hardware driver
to access hardware-based filter implementation

…mapped to
Linux software process

TESTING ON FPGA DEVELOPMENT BOARD




```
root@os:~# Consumer_proc_sw_consumer_App &
[1] 818
Art: Registered component: PFC_Sys_Impl_Instance_proc_sw_producer (periodic: 1000)
Art: - Registered port: PFC_Sys_Impl_Instance_proc_sw_producer_to_filter (data out)
Art: Registered component: PFC_Sys_Impl_Instance_proc_sw_filter (periodic: 1000)
Art: - Registered port: PFC_Sys_Impl_Instance_proc_sw_filter_from_producer (data in)
Art: - Registered port: PFC_Sys_Impl_Instance_proc_sw_filter_to_consumer (data out)
Art: Registered component: PFC_Sys_Impl_Instance_proc_sw_consumer (periodic: 1000)
Art: - Registered port: PFC_Sys_Impl_Instance_proc_sw_consumer_from_filter (data in)
Art: Connected ports: PFC_Sys_Impl_Instance_proc_sw_producer_to_filter -> PFC_Sys_Impl_Instance_proc_sw_filter_from_producer
Art: Connected ports: PFC_Sys_Impl_Instance_proc_sw_filter_to_consumer -> PFC_Sys_Impl_Instance_proc_sw_consumer_from_filter
root@os:~# Producer_proc_sw_producer_App &
[2] 819
Art: Registered component: PFC_Sys_Impl_Instance_proc_sw_producer (periodic: 1000)
Art: - Registered port: PFC_Sys_Impl_Instance_proc_sw_producer_to_filter (data out)
Art: Registered component: PFC_Sys_Impl_Instance_proc_sw_filter (periodic: 1000)
Art: - Registered port: PFC_Sys_Impl_Instance_proc_sw_filter_from_producer (data in)
Art: - Registered port: PFC_Sys_Impl_Instance_proc_sw_filter_to_consumer (data out)
Art: Registered component: PFC_Sys_Impl_Instance_proc_sw_consumer (periodic: 1000)
Art: - Registered port: PFC_Sys_Impl_Instance_proc_sw_consumer_from_filter (data in)
Art: Connected ports: PFC_Sys_Impl_Instance_proc_sw_producer_to_filter -> PFC_Sys_Impl_Instance_proc_sw_filter_from_producer
Art: Connected ports: PFC_Sys_Impl_Instance_proc_sw_filter_to_consumer -> PFC_Sys_Impl_Instance_proc_sw_consumer_from_filter
root@os:~# Filter_proc_sw_filter_App &
[3] 820
Art: Registered component: PFC_Sys_Impl_Instance_proc_sw_producer (periodic: 1000)
Art: - Registered port: PFC_Sys_Impl_Instance_proc_sw_producer_to_filter (data out)
Art: Registered component: PFC_Sys_Impl_Instance_proc_sw_filter (periodic: 1000)
Art: - Registered port: PFC_Sys_Impl_Instance_proc_sw_filter_from_producer (data in)
Art: - Registered port: PFC_Sys_Impl_Instance_proc_sw_filter_to_consumer (data out)
Art: Registered component: PFC_Sys_Impl_Instance_proc_sw_consumer (periodic: 1000)
Art: - Registered port: PFC_Sys_Impl_Instance_proc_sw_consumer_from_filter (data in)
Art: Connected ports: PFC_Sys_Impl_Instance_proc_sw_producer_to_filter -> PFC_Sys_Impl_Instance_proc_sw_filter_from_producer
Art: Connected ports: PFC_Sys_Impl_Instance_proc_sw_filter_to_consumer -> PFC_Sys_Impl_Instance_proc_sw_consumer_from_filter
root@os:~# Main
root@os:~# Main
root@os:~# Consumer_proc_sw_consumer_App starting ...
```

```
…
Consumer_proc_sw_consumer_App starting ...
Producer_proc_sw_producer_App starting ...
PFC_Sys_Impl_Instance_proc_sw_producer: Sending [00, 00, 00, 00, 00, 00, 00, 00, 00, 3A,
00, 00]
Filter_proc_sw_filter_App starting ...
PFC_Sys_Impl_Instance_proc_sw_filter: Payload approved - MissionData([00, 00, 00, 00, 00,
00, 00, 00, 00, 3A, 00, 00])
PFC_Sys_Impl_Instance_proc_sw_consumer: Received MissionData([00, 00, 00, 00, 00, 00, 00,
00, 00, 3A, 00, 00])
PFC_Sys_Impl_Instance_proc_sw_producer: Sending [00, 6F, 6F, 6F, 00, 00, 00, 00, 00, 3A,
00, 00]
PFC_Sys_Impl_Instance_proc_sw_filter: Payload rejected - MissionData([00, 6F, 6F, 6F, 00,
00, 00, 00, 00, 3A, 00, 00])
```

CONTIGUITY TYPES

SELF-DESCRIBING MESSAGE APPROACHES

- Any successful message format description language must deal with self-describing message formats
- The self-describing aspect, unfortunately, defeats the use of standard lexer and parser technology
- Regular languages are insufficient, and context-free grammars can't capture the dependency of one field (or collection of fields) on another
- Context-sensitive grammars are a possibility, but there is little tool support
- Parser combinators allow hand-rolled parsers to be very quickly constructed, and can be adapted to support the accumulation and propagation of the necessary dependency information
- Chlipala and others have done work in this area using dependent types in Coq

- We have decided to take a Formal Language Theory approach since there is a strong connection between messages (flat strings of bits/bytes) and the strings of formal language theory

CONTIGUITY TYPES

- Contiguity Types attempt to bridge the gap between standard data structures (base types, arrays, records) and Formal Language Theory
- We start with a collection of base types and close under making records, arrays, and unions:

- $base ::= bool \mid char \mid u8 \mid u16 \mid u32 \mid u64 \mid i16 \mid i32 \mid i64 \mid float \mid double$

  $\tau ::= base \mid \textbf{\textit{Recd}}\ (f_1 : \tau_1)\ \ldots (f_n : \tau_n) \mid \textbf{\textit{Array}}\ \tau\ \text{exp} \mid \textbf{\textit{Union}}\ (bexp_1 : \tau_1)\ \ldots (bexp_n : \tau_n)$

- The Array construct uses arithmetic expressions to describe the number of elements in the array
- The Union construct uses boolean expressions to decide which choice to take
- In both cases the expressions can refer to earlier elements in the message
- L-values and R-values provide a comprehensive notation for such references.
  - L-values can occur on the left-hand side of an assignment, R-values on the right, e.g., A[0].foo := bar.B[i] + z;

EXAMPLE CONTIGUITY TYPES

- Record type, variable-length array of floats, variable-length 2D array of bytes:

```
{ A : Char
  B : Float
  C : Double
  D : i64
  E : u32 [1024]
 }
```

```
{ len : u16
  elts : Float [len]
}
```

```
{ Dims : { rows : u32
           cols : u32
         }
  Image : u8 [Dims.rows * Dims.cols]
}
```

- Two versions of a GPS coordinate, selected by a Release field:

```
{Release : u8
 contents : Union {
     (Release <= 14 --> {lat : Double, lon : Double, alt : u32})
     (Release >  14  --> {lat : Double, lon : Double, alt : u32,
                          altTy : AltitudeType, status : Bool})}
}
```

ASSERTIONS ON MESSAGES

- Contiguity types can express in-message assertions:
- $\boldsymbol{Assert}\ bexp = \boldsymbol{Union}\ (bexp,\ \boldsymbol{SKIP})\ (\neg bexp,\ \boldsymbol{VOID})$
- $\boldsymbol{SKIP} = \boldsymbol{Recd}\ [\ ]$
- $\boldsymbol{VOID} = \boldsymbol{Union}\ (\boldsymbol{false},\ u8)$

- In words: "If $bexp$ is true, continue without consuming any bytes, else fail"

- We can place assertions inside contiguity types that will be checked when the message handler runs

- Example: macro for variable-length arrays with bounds

```
BoundedArray contig bound =
   {len : u16
    len-check : Assert(len <= bound)
    elts : contig [len]
  }
```

ALGORITHMS FOR CONTIGUITY TYPES

- **Decoding**. A decoder breaks a sequence of bytes up and puts the pieces into a useful data structure, typically a parse tree.
- **Filtering**. Computes an answer to the question: “does a sequence of bytes meet the specification of a given contiguity type”. This is an instance of the language recognition problem in Formal Language Theory.
- **Serialization**. Given a contiguity type, synthesize a function that writes a compact binary version of a data structure to a message.
- **Test generation**. Given a contiguity type, generate byte sequences that do (or do not) meet its specification and feed the sequences to implementations in order to observe their behavior.
- **Learning**. Given training sets of message buffers that are accepted/rejected by an implementation, attempt to discover a contiguity type exactly capturing the entire set of messages.

- Thus far, we have implementations for decoders, filters, and test generation:
  - $\boldsymbol{decode} : \tau \rightarrow bytes \rightarrow parsetree$
  - $\boldsymbol{filter} : \tau \rightarrow bytes \rightarrow bool$
  - $\boldsymbol{testgen} : \tau \rightarrow bytes\ list$

SEMANTICS OF CONTIGUITY TYPES

- Contiguity types look like “normal” programming language types, but they are in fact formal languages
- Each base type is characterized by its width, and denotes all byte-strings of that width; thus the meaning of base type i64 is “all strings of length 8 bytes”
- The meaning of $\boldsymbol{Recd}\ (f_1 : \tau_1) \cdots (f_n : \tau_n)$ is the concatenation of the languages denoted by $\tau_1 \ldots \tau_n$. (*)
- The meaning of $\boldsymbol{Array}\ \tau\ exp$ is “evaluate exp to get a natural number n; the result is the n-ary concatenation of the language denoted by τ" . (*)
- The meaning of $\boldsymbol{Union}\ (bexp_1, \tau_1) \cdots (bexp_n, \tau_n)$ is “if there is exactly one $(bexp_k)$ that evaluates to true, return the language denoted by τ_k: else, return the empty language $\varnothing$”
- Expression evaluation (and Boolean expression evaluation) is done with respect to an environment that maps L-values to slices of the message

- (*) $\boldsymbol{Recd}$ and $\boldsymbol{Array}$ are accumulative: the meaning of later fields (or array elements) can depend on the values of earlier fields

FORMALIZATION

- We have defined contig-types and the matcher and filter functions over them in HOL4
- These have been proved to terminate
- The matcher function $\boldsymbol{match} : \tau \rightarrow bytes \rightarrow \theta\ option$ attempts to match the contig-type against the byte array
- If successful, match returns the built-up environment θ which binds locations specified by τ to segments of the byte array
- A simple version of the correctness of the matcher can be stated as

$$\boldsymbol{match}\ \tau\ bytes = \boldsymbol{Some}\ \theta \implies \theta(\tau) = bytes$$

- Also needed is a theorem relating the language of a contig-type with the matcher's behavior:

$$\left(\exists \theta .\ \ \boldsymbol{match}\ \tau\ bytes = \boldsymbol{Some}\ \theta\right) \iff bytes \in Lang(\tau)$$

- This proof effort is underway

CONCLUSION AND FUTURE WORK

- We have detailed a method and toolchain for the creation of formally verified critical system components developed for the DARPA CASE program
- We have demonstrated how this toolchain can be used to implement security-enhancing transformations on system architectures specified in AADL, with implementations automatically synthesized using the verified CakeML compiler
- We have described the use of regular expressions, context-free languages, as well as a novel contiguity type specification language, to formally describe message formats
- We have conducted formal synthesis for wellformedness checkers including verified DFA generation, table-driven lexer generation, and table-driven parser generation
- We have also described methods and tools for enhancing the safety and security of critical systems using a hardware/software co-design/co-assurance approach
- In future work, we will continue to enhance our verified synthesis tools for increasingly complex systems
- We will continue to evolve the contiguity type specification language, developing a compiler for contiguity type specifications, and bridging the gap with conventional parsing technology based on context-free grammars