Cryptographic Module Design with Domain Specific Languages

NIST Workshop on Cryptography for Emerging Technologies and Applications

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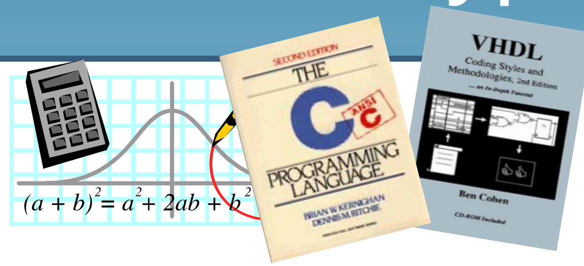
Crypto Verification & Validation



Creating a crypto algorithm requires skills in math AND programming

Variety of target architectures

Validation is complex and tedious

Variety of requirements

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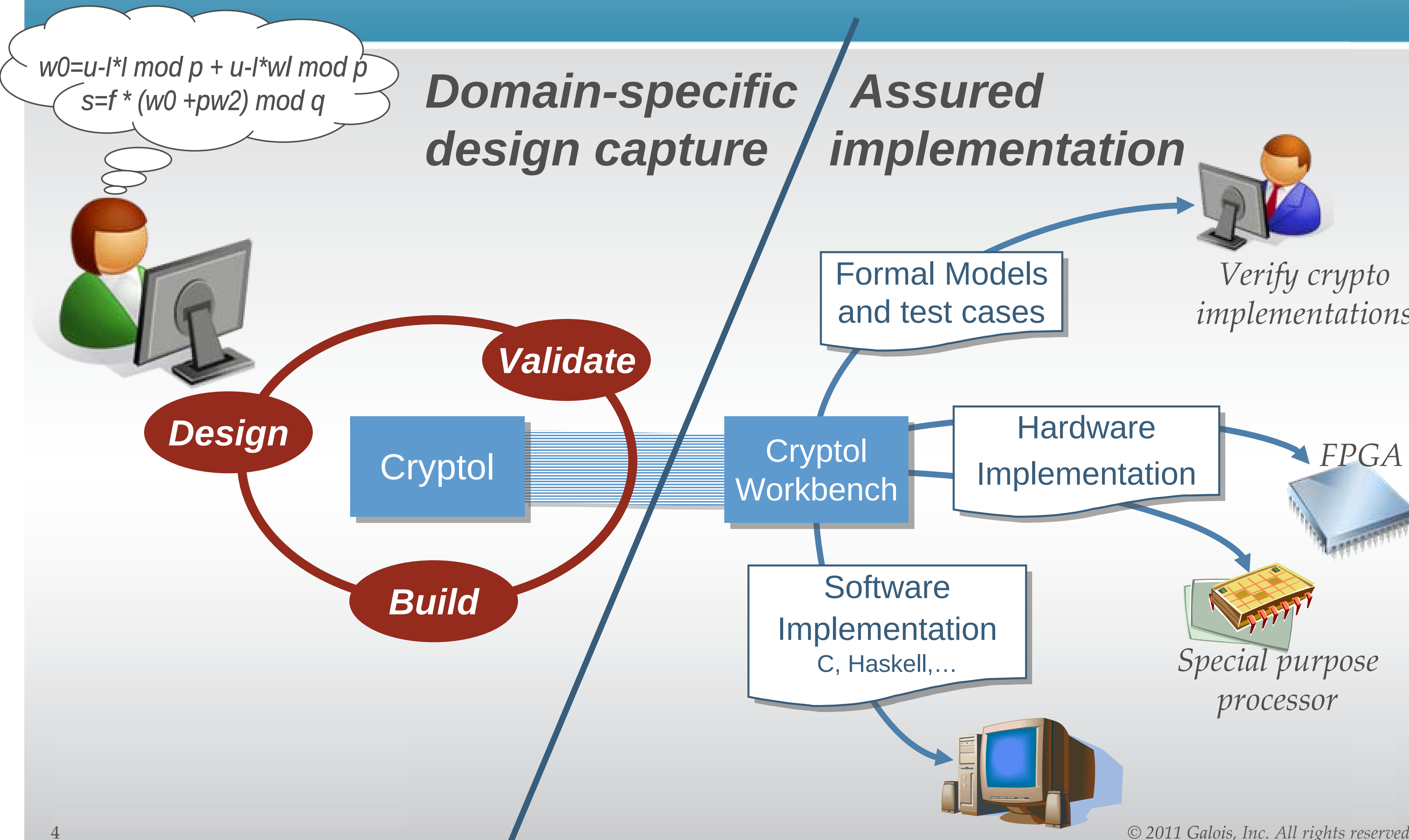
Requirements for a Crypto Domain-Specific Language

- High-level domain-specific language for design capture and exploration
- Specifications guide and document implementations
- Neutral to implementation platform
- Language should be high-level, yet detailed
  - Can talk about the bits, but in a platform-independent way

One Specification - Many Uses



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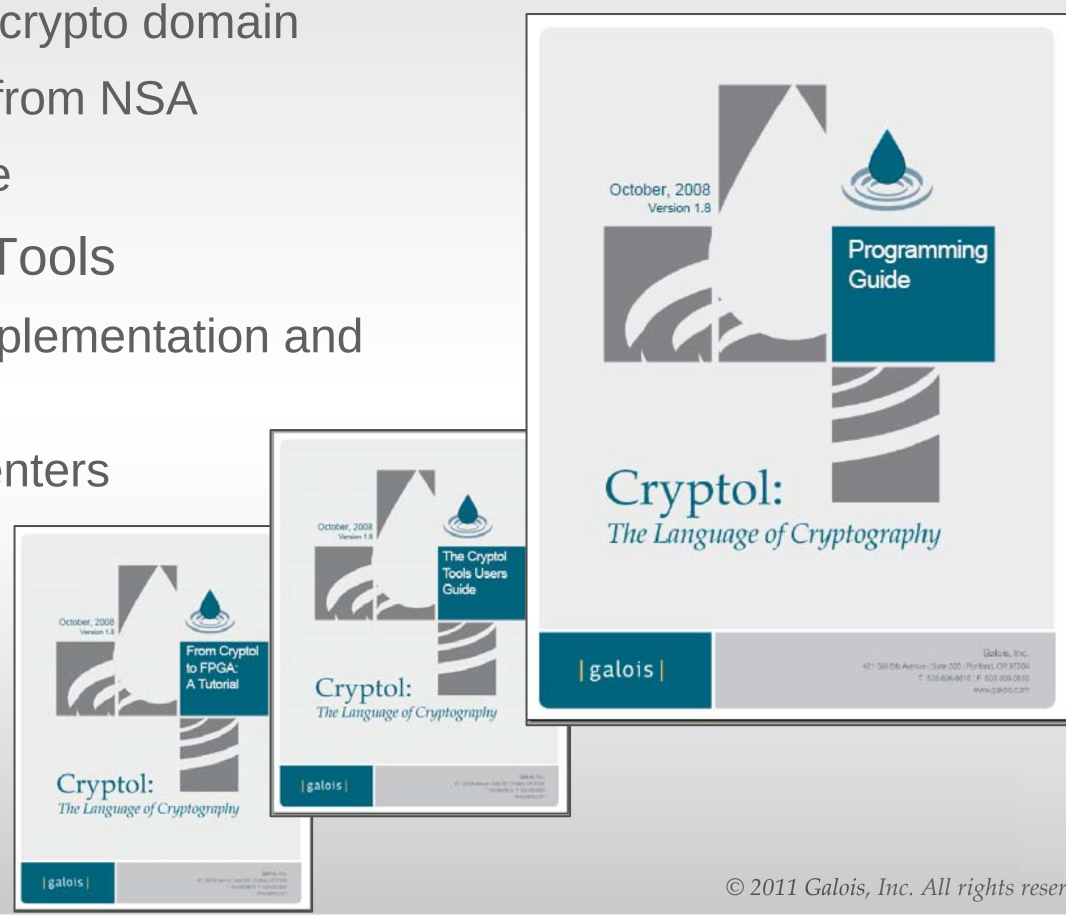
Cryptol: Specifications and Formal Tools

- Domain-specific declarative specification language
  - Language tailored to the crypto domain
  - Designed with feedback from NSA
  - Non-proprietary language
- Execution and Validation Tools
  - Tool suite for different implementation and verification applications
  - In use by crypto-implementers



Key Ideas in Cryptol

- Domain-specific data and control abstractions
  - Sequences
  - Recurrence relations (not for-loops)
- Powerful data transformations
  - Data may be viewed in many ways
  - Machine independent
- Algorithms parameterized on size
  - Size constraints are explicit in many specs
  - Number of iterations may depend on size
  - A sized type system captures and maintains size constraints

Choosing what to leave out is critical

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Cryptol Programs

- File of mathematical definitions
  - Two kinds of definitions: values and functions
  - Definitions may be accompanied by a type declarations (a signature)
- Definitions are computationally neutral
  - Cryptol tools provide the computational content (interpreters, compilers, code generators, verifiers)

```
x : [4][32];
x = [23 13 1 0];

F : ([16],[16]) -> [16];
F (x, x') = 2 * x + x';
```

Cryptol: Specify interfaces unambiguously

From the Advanced Encryption Standard definition†

3.1 Inputs and Outputs

The **input** and **output** for the AES algorithm each consist of **sequences of 128 bits** (digits with values of 0 or 1). These sequences will sometimes be referred to as **blocks** and the number of bits they contain will be referred to as their length. The **Cipher Key** for the AES algorithm is a **sequence of 128, 192 or 256 bits**. Other input, output and Cipher Key lengths are not permitted by this standard.

```
blockEncrypt : {k} (k >= 2, 4 >= k) => ([128], [64*k]) -> [128]
```

- **For all k**
- **...between 2 and 4**
- **First input is a sequence of 128 bits**
- **Second input is a sequence of 128, 192, or 256 bits**
- **Output is a sequence of 128 bits**

†http://csrc.nist.gov/publications/fips197/fips-197.pdf

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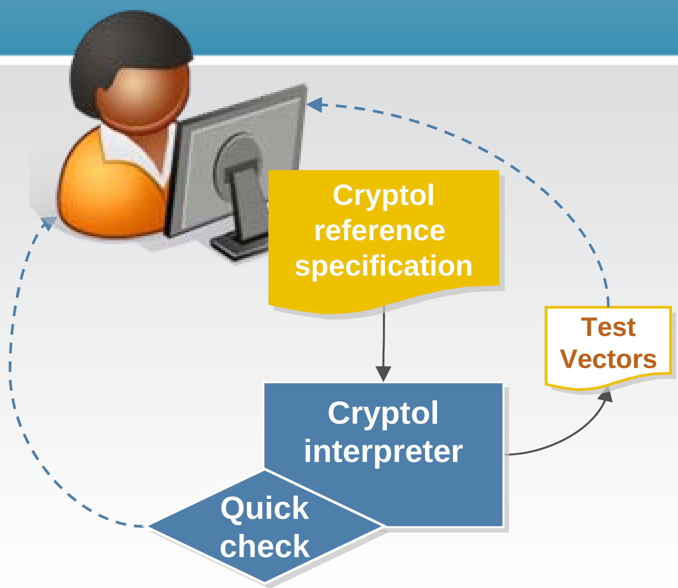
Basic Cryptol Use Case



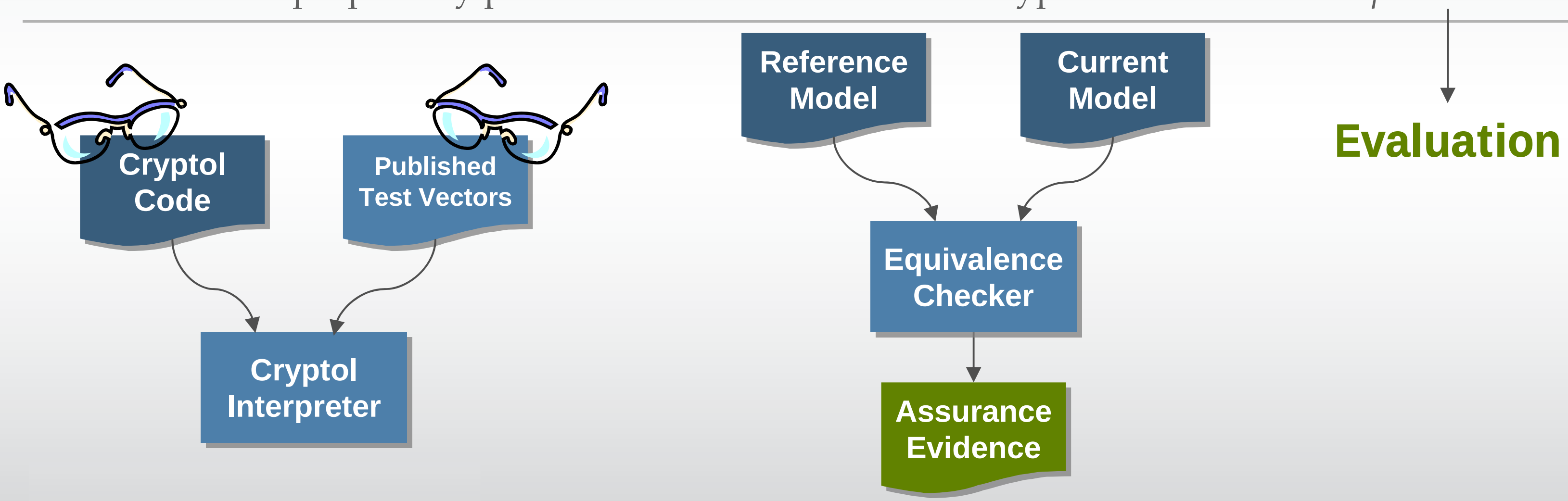
- Create a Cryptol reference specification
- Execute the specification, including assertion checks
- Generate test vectors with Quickcheck to bundle with the reference specification

Benefits:

- A clear and unambiguous model
  - E.g. bit-order and endian-ness
- Natural notation
  - Simplifies expression, inspection, and re-use
- Specification can be validated
  - Validate any part of algorithm
- Re-usable models
  - Validate, re-use many times
  - Specification for both hardware and software implementations
- Specifications can easily be re-factored

Case Study: Cryptol in the development process

Description/Purpose	Language	Artifact
Eg: NIST / NSA spec, technical paper	Pseudo-code/Mathematics	*Conventional specification*
Test understanding of specification	Cryptol	*Reference model*
Capture structure of implementation	Cryptol	*Implementation model*
Capture semantics of code fragments	Cryptol	*Fragment models*
Create code for proprietary platform	Microcode with Cryptol annotations	*Implementation*



User Experience

- *“The Cryptol specification removes ambiguities that are inevitable in the English-language descriptions and removes platform dependencies (like word-size) that creep into the C snippets.”*
- *“...an experienced Cryptol programmer given a new crypto program specification and a soft copy of test vectors can be expected to learn the algorithm and have a fully functional and verified Cryptol model in a few days to a week.”*

Alan Newman, General Dynamics C4 Systems

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The SHA-3 Candidates in Cryptol

- Skein (Schneir et al.)
  - Galois verified two third-party VHDL implementations
- Blake (Aumasson et al., Switzerland)
  - Verification of third-party VHDL implementation in process
- CubeHash (Bernstein, USA)
- MD-6 (Rivest et al, since withdrawn from competition)
- SANDstorm (Sandia, since withdrawn from competition)
- Groestl (Knudsen et al, Denmark)
  - Students at U.Minho in Portugal generated a respectable FGPA implementation and verified it against the Cryptol specification
- Shabal (Misarsky, France)
  - Cryptol specification written at INRIA

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Examples of Other Cryptol Tools

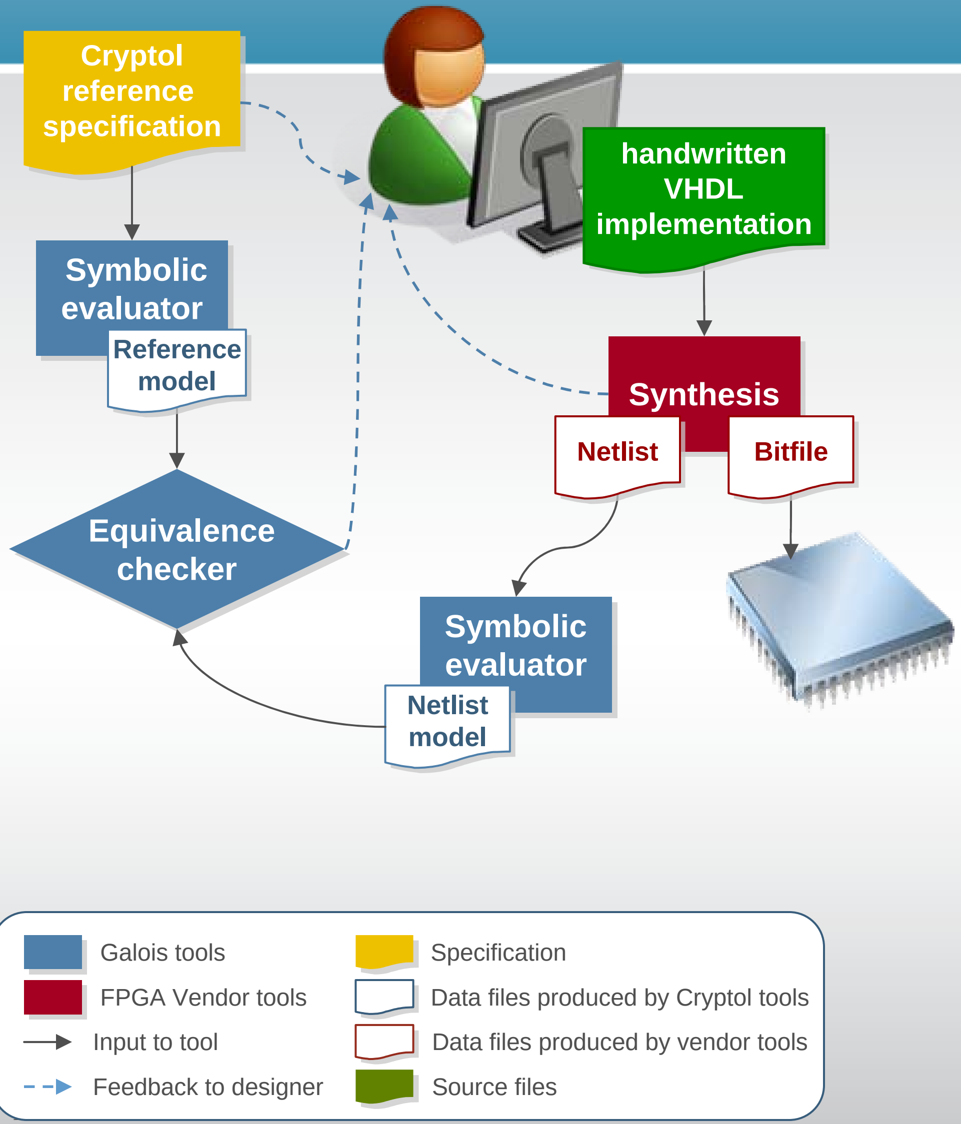
Cryptol Specification

A Domain Specific Specification Language
- Precise, Declarative Semantics
- High level design exploration

Automated Synthesis down to FPGA
- Algebraic rewrite-based compilation
- Traceability back to specification

Automated Verification
- AIG-based Equivalence Checking
- SAT Solver technology

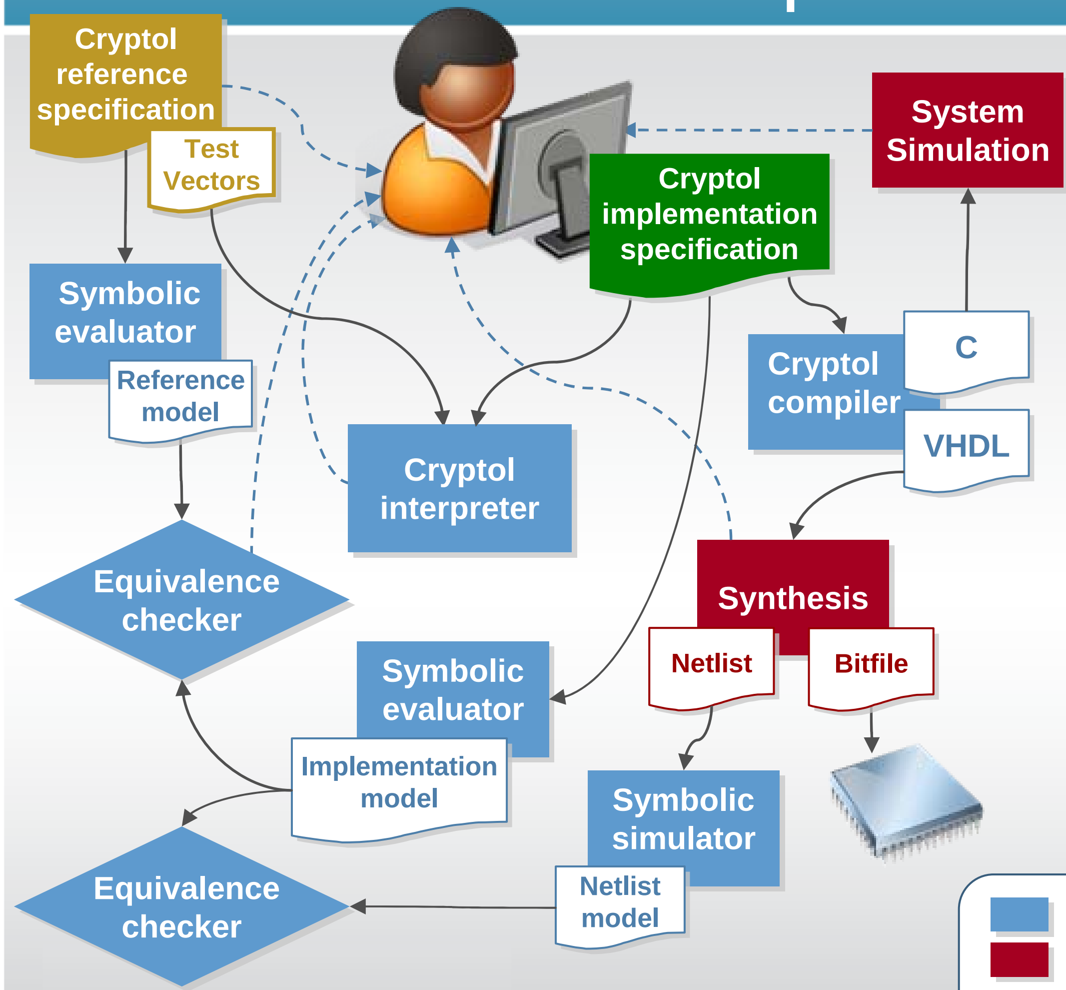
Cryptol in the VHDL Development Process



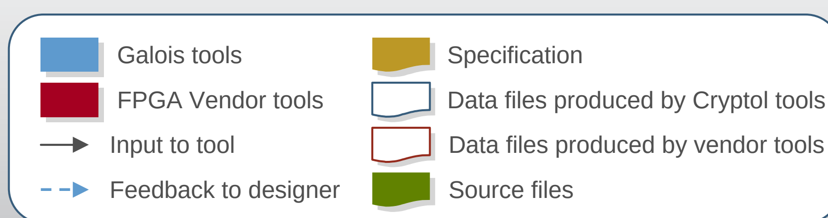
An FPGA engineer:

- Uses the reference specification to guide the VHDL implementation
- Produces intermediate specifications to reflect design decisions
- Generates test vectors to test portions of the VHDL
- Uses equivalence checkers to ensure that the implementation is correct

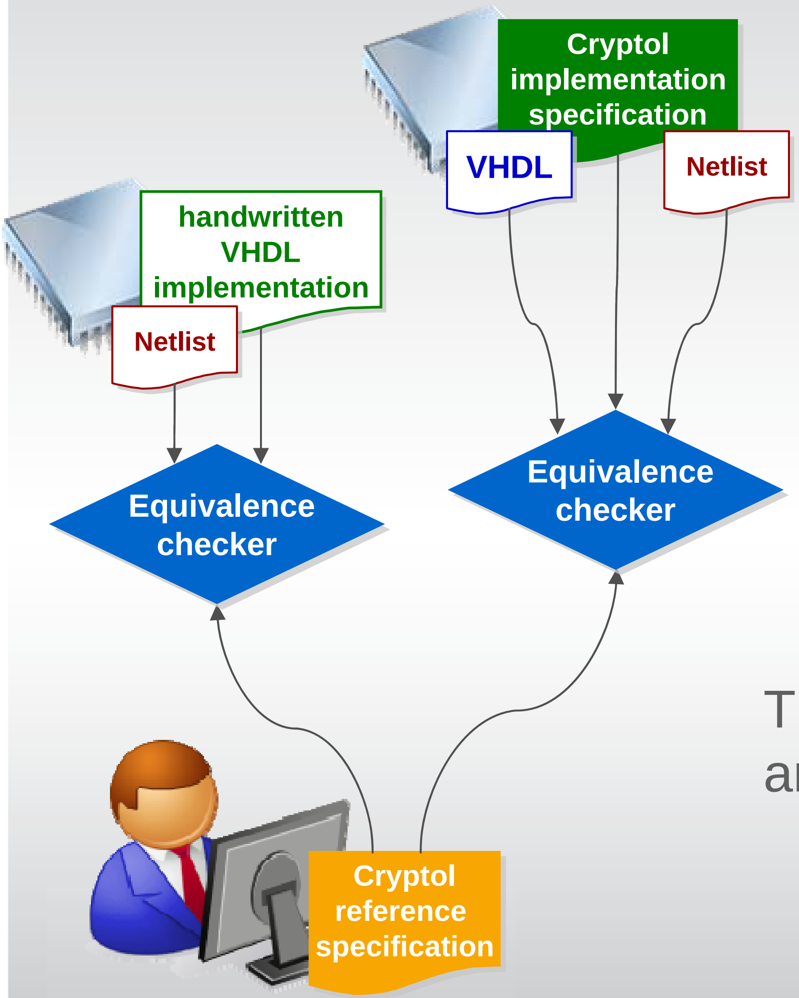
Cryptol in an FPGA Development Process: emphasis on high-level design



- It is easier to experiment with new micro-archtectures in a specification language like Cryptol than in VHDL



Cryptol in the evaluation process



A crypto-device evaluator:

- Creates a reference specification and associated formal model
- Checks the equivalence of the implementation models at several points in the tool

The process works for both hand-written and Cryptol-generated designs

Questions?

www.cryptol.net

- Language open
- Free download of interpreter
- Documentation