A Layered Certifying Compiler Architecture

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How do you structure the verification of a compiler?

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    - Target fixed, well-understood languages
- Many compilers and languages are:
    - Implementated in language not suitable for verification
    - Community-developed, open-source: in constant flux
- Instead of proving the compiler code correct, prove individual runs correct (translation validation)

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- Tool checks if each pass was performed correctly
- The tool should produce some checkable evidence

Layered Architecture

- For each compiler pass, develop four layers:
    1. Specification layer
    2. Interface layer
    3. Automation layer
    4. Verification layer
- Implemented in a proof assistant (here Coq)
- Each layer gradually improves the trustworthiness of the overall system

Language: STLC

$$
\begin{array}{rcl}
t & ::= & x \\
  & | & \lambda x.\ t \\
  & | & t\ t \\
  & | & \texttt{let}\ x = t\ \texttt{in}\ t
\end{array}
$$

Inlining

Inliner behaviour

“pre-term”

```
let x = 3
in ... (2 * x) ... x ...
```

Inlining

Inliner behaviour

“pre-term” $\mapsto$ “post-term”

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let x = 3
in ... (2 * x) ... x ...
```

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let x = 3
in ... (2 * 3) ... x ...
```

Inliner: specification layer

Specification layer (translation relation)

$$\boxed{\Gamma \vdash s \triangleright t}$$

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$$\frac{\Gamma(x) = t}{\Gamma \vdash x \triangleright t}\ \textsc{Inline-Var}_1 \qquad \frac{}{\Gamma \vdash x \triangleright x}\ \textsc{Inline-Var}_2$$

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$$\frac{\Gamma \vdash s \triangleright s' \qquad \Gamma \vdash t \triangleright t'}{\Gamma \vdash s\ t \triangleright s'\ t'}\ \textsc{Inline-App}$$

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$$\frac{\Gamma \vdash s \rhd s' \qquad \Gamma \vdash t \rhd t'}{\Gamma \vdash s\ t \rhd s'\ t'}\ \textsc{Inline-App}$$

$$\frac{x, \Gamma \vdash t \rhd t'}{\Gamma \vdash \lambda x.\ t \rhd \lambda x.\ t'}\ \textsc{Inline-Lam}$$

Specification layer

$$\Gamma \vdash s \triangleright t$$

- Serves as a *formal reference* for compiler implementors
- This relation does not prescribe *what* inlining strategy to use
- It captures all possible inlining strategies

Formalize in proof assistant

```
Inductive inline : list (string * binder_info) -> term -> term -> Prop
  | inline_Var_1 : forall G x t t',
    lookup x G = let_bound t ->
    inline G t t' ->
    inline G (Var x) t
  | inline_Var_2 : forall G x,
    inline G (Var x) (Var x)
  | inline_Let : forall G x s t s' t',
    inline G s s' ->
    inline (let_bound x s :: G) t t' ->
    inline G (Let x s t) (Let x s' t')
  | inline_Lam : forall G x t t',
    inline (lam_bound x :: G) t t' ->
    inline G (Lam x t) (Lam x t')
  | inline_App : forall G s t s' t',
    inline G s s' ->
    inline G t t' ->
    inline G (App s t) (App s' t').
```

Inliner: interface layer

2. Interface Layer

- Bridges the gap between the compiler and the proof assistant
- Modify the compiler: dump intermediate ASTs (gray-box)
- Parse in the proof assistant

```
Definition p1 := Let "x" (App (Lambda ...
Definition p2 := Let "x" (App (Lambda ...

Theorem valid : inline [] p1 p2.
```

Infrastructure to formulate and prove that a pass was performed *according to specification*.

Inliner: automation layer

3. Automation Layer

- Writing proofs by hand gets tedious: large proof objects, proof search becomes slower
- Instead: prove specification decidable (reflection)

```
Fixpoint dec_inline :
  list binder_info -> AST -> AST -> bool.
...

Theorem iff_dec_inline : forall G p q,
  dec_inline G p q = true <-> inline G p q.
```

Inliner: verification layer

4. Verification Layer

- Prove that a specification is correct: related programs should be semantically equivalent
- Choose appropriate semantics, notion of program equivalence

```
Theorem correct : forall p q,
  inline [] p q -> p ≃ q.
```

Scaling up: the Plutus compiler

Plutus Compiler

Plutus is an optimizing compiler, used for compiling smart contracts on the Cardano blockchain.

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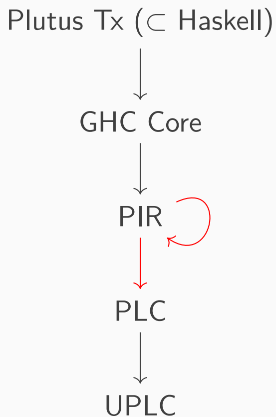
- These programs have to be extremely well-behaved (DAO vulnerability: $\sim$ \$50 million)
- Is the compiler correct?

The Plutus compiler pipeline

The Plutus compiler



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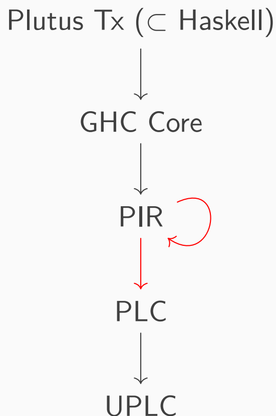

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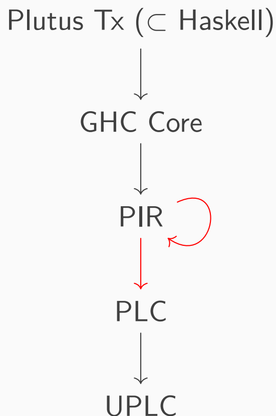

- PIR = System F^{μ}_{ω} + `let(rec)` + ADTs
- PLC = System F^{μ}_{ω}

Plutus pass: dead code elimination

1. Specification Layer (Dead Code elimination)

$$\frac{}{\texttt{let } x = t; bs \texttt{ in } s \rhd} \text{DCE-ELIM}$$

$$\frac{}{\texttt{let } x = t; bs \texttt{ in } s \rhd} \text{DCE-KEEP}$$

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$$\frac{s \rhd t \qquad t \rhd t'}{s\ t \rhd s'\ t'}\ \textsc{DCE-Apply} \qquad \frac{t \ \rhd\ t'}{\lambda x : \tau.\ t \rhd \lambda x : \tau.\ t'}\ \textsc{DCE-Lambda} \qquad \ldots$$

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$$\frac{x \notin \mathrm{FV}(\texttt{let rec } bs'_0 \texttt{ in } s') \qquad t \in value \qquad \texttt{let rec } bs \texttt{ in } s \rhd_{rec} \texttt{let rec } bs' \texttt{ in } s' \mid bs'_0}{\texttt{let rec } x = t; bs \texttt{ in } s \ \rhd_{rec} \ \texttt{let rec } bs' \texttt{ in } s' \mid bs'_0} \ \textsc{DCE-Elim-Rec}$$

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- Composite pass: inliner includes dead code elimination

$$t \rhd t' := \exists t_1.\ t \rhd_{inl} t_1 \ \wedge \ t_1 \rhd_{dce} t'$$

2. Interface Layer

- Plutus implementation and process are open-source: fork + pull request on Github
- Dump the intermediate ASTs (and sometimes pass-specific information)

Decision procedure dead-code elimination:

```
Fixpoint dec_dce : AST -> AST -> bool.

Theorem iff_dec_dce : forall p q,
  dec_dce p q = true <-> dce p q.
```

3. Automation Layer

Composite pass: Inlining + Dead Code Elimination

$$t \triangleright t' := \exists t_1.\ t \triangleright_{inl} t_1 \ \wedge\ t_1 \triangleright_{dce} t'$$

Intermediate term t_1 is not dumped by the compiler...

...But we can reconstruct it!

```
Fixpoint make_intermediate :
    list Var -> AST -> AST -> option AST.
...
```

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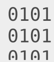
- Step-indexed logical relation that implies contextual equivalence
- Correctness of translation relation

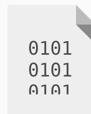
$$s \triangleright t \ \wedge \ \Delta; \Gamma \vdash s : \tau \ \Rightarrow \ \Delta; \Gamma \vdash s \simeq_{ctx} t : \tau$$

Certificates

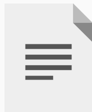
A Certificate



A Certificate



A Certificate



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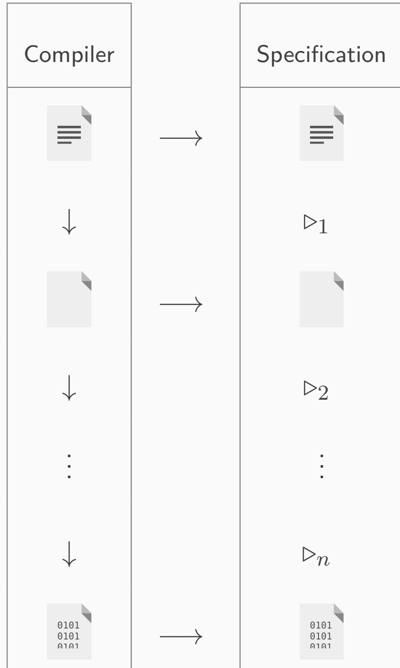
A Certificate

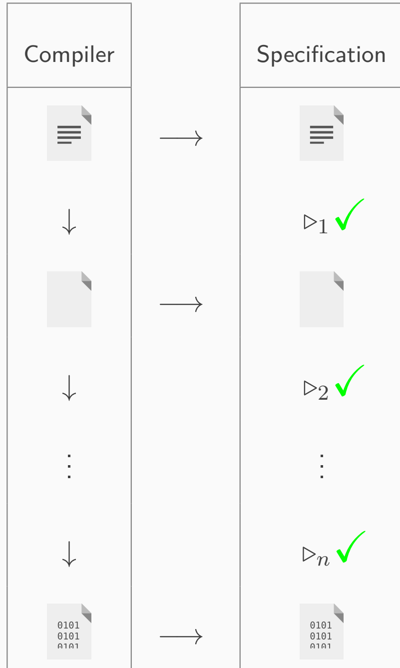
We want a *verifiable link* (certificate) that

1. Relates the source code to the compiled code
2. The compiler did not introduce any bugs

Compiler

Compiler


Compiler
Specification
$\triangleright_1$
$\triangleright_2$
$\triangleright_n$
0101
0101
0101
0101


Compiler
Specification
$\triangleright_1$ ✓
$\triangleright_2$ ✓
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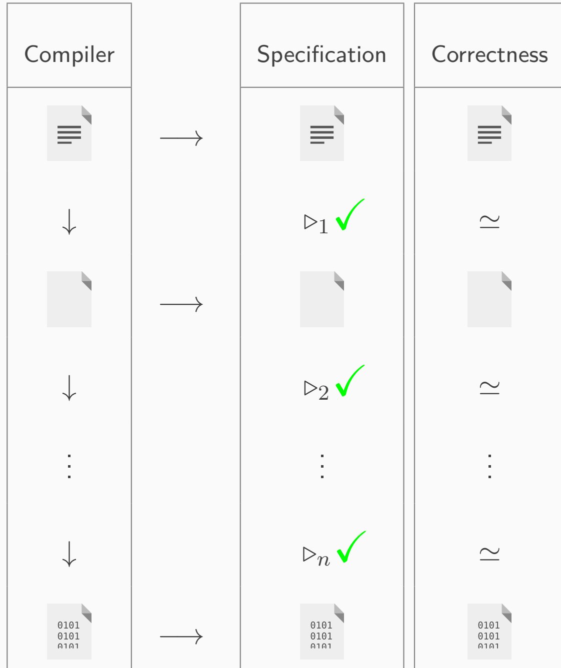
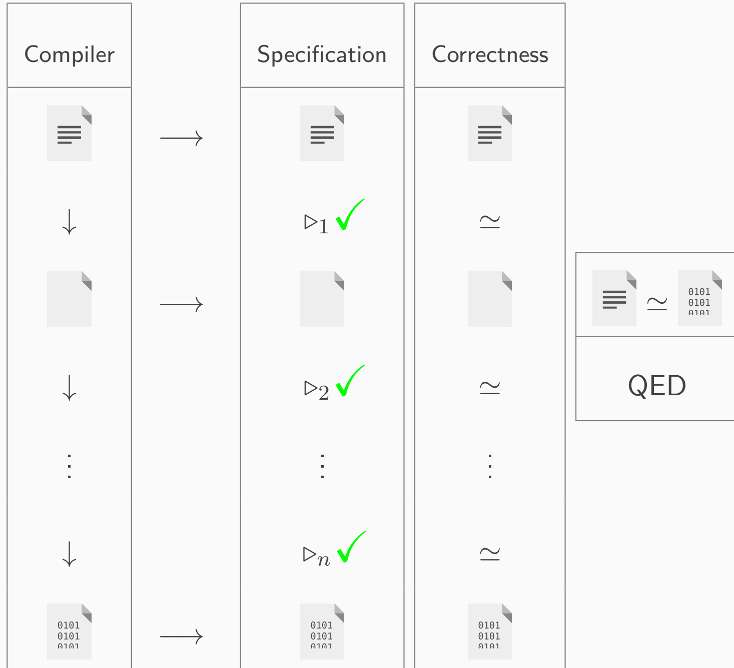
0101
0101


Compiler
Specification
Correctness
0101
0101
0101
0101
0101
0101


Compiler
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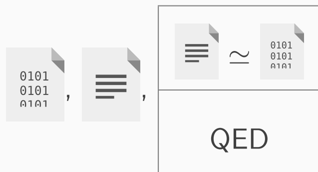
0101
0101
QED

Certifier



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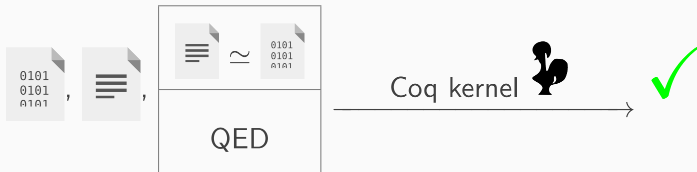

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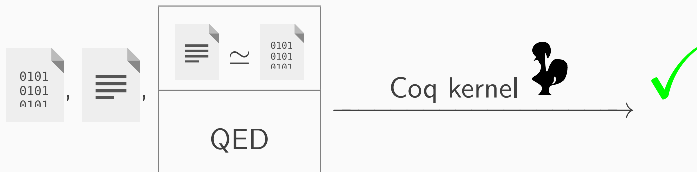
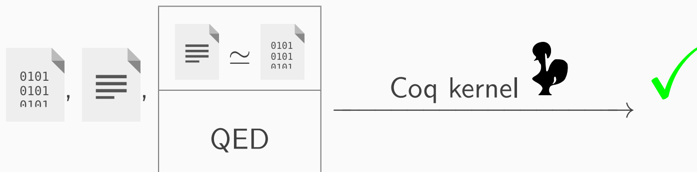


- Trusted computing base

Certifier



- Trusted computing base
    - Definition of $\simeq$

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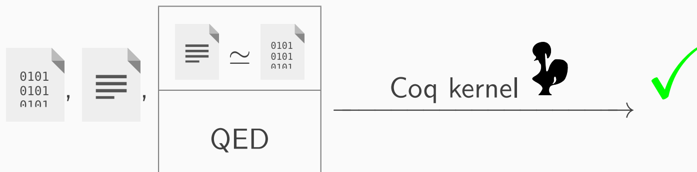

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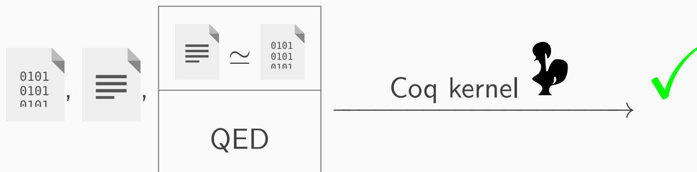

- Trusted computing base
  - Definition of $\simeq$
  - Coq Kernel
- Coq kernel: relatively small and well-studied code base

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  - Integrate decision procedures directly in the compiler
- Improved compiler testing
  - Plutus: existing test suite (example input/outputs)
  - Property-based testing
- Generate LaTeX from specification (Coq code)

Further work

- End-to-end verification
  - Plutus: Haskell $\rightarrow$ PIR $\rightarrow$ PLC
  - Alternative front-end: Gallina + CertiCoq
- Proof transportation?
  - Use equivalence proof
- Certifier implementation: Coq vs Agda?
- Hints for constructing typing derivation, instead of re-implementing type-checker

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- We don't have to reason about an implementation, only a high-level specification
- Robustness: certain changes in the compiler do not affect the verification at all.
- Separation of concerns: compiler writers do not have to be proof engineers