ConCert: A Smart Contract Certification Framework in Coq

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CPP2020, January 21, 2020

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What are smart contracts?

- A concept of smart contracts was proposed by Nick Szabo in 90s.
- This is different from smart contracts *on blockchains*.

Fritz Henglein: smart contracts are neither (smart nor contracts).

They are

programs in a general-purpose language running "on a blockchain"

- Check conditions, change global state (account balances) and local state (user-defined contract state).
- Code and calls to contracts *from users* are recorded in blocks.
- Can call other contracts containing possibly malicious code.
- Each node executes the calls and maintains state.
- Contracts are not self-executing: someone has to call.

What is so special about smart contracts?

- They often manage money: auctions, crowdfunding campaigns, multi-signature wallets, DAOs.
- Once deployed, contract code cannot be changed.
- Code is Law.
- Flaws may result in huge financial losses:
  - The DAO $\sim$ \$50M — hacker attack.
  - Parity's multi-signature wallet $\sim$ \$280M — a bug in the library code.

Functional smart contract languages

- Contracts are programs in a functional language transforming the state:

  `contract : CallCtx * Msg * State -> State * Action list`
- But blockchains are stateful.
- Contracts are used as transition functions.
- A *scheduler* handles transfers and calls to other contracts in `Action list`.

Examples of such languages:

- Liquidity, LIGO (Tezos)
- Scilla (Zilliqa)
- **Acorn(Concordium)**

ACORN

- ACORN is a smart contract language for the Concordium blockchain.
- Explicitly typed System F_2, inductive types, general recursion.
- The Concordium blockchain interprets ACORN programs.
- That's what we are going to verify!

Our contributions

- Deep embedding (AST + semantics): for meta-theory.
- Shallow embedding (Coq functions): for convenient reasoning about programs.

- Combine deep and shallow embeddings.
- λ_{smart}: explicitly typed System F + ADT + structural recursion ($\sim$ $\textsc{Acorn}$, or a pure subset of ML-like functional language).
- Shallow embedding of λ_{smart} programs through meta-programming facilities of MetaCoq.
- Soundness using the formalisation of Coq's meta-theory in Coq.
- Integration of the shallow embedding with the execution model (scheduler).

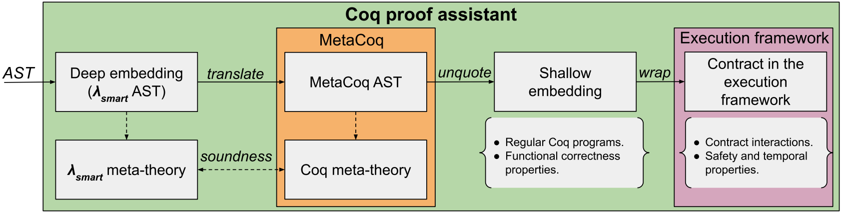
The MetaCoq project

MetaCoq: Metaprogramming in Coq

Consists of several subprojects. Relevant for our project:

- Template Coq — adds meta-programming facilities to Coq:
  - quote: from Coq's definitions to AST as an inductive data type.
  - **unquote**: from AST to back to a Coq definition.
- PCUIC — formalisation of Coq's meta-theory.

ConCert: A Smart Contract Certification Framework



- "translate": a compiler from λ_{smart} (System F + inductives) into PCUIC.
- A bit of λ_{smart} meta-theory: a "fueled" definitional interpreter.

$$\texttt{eval} : \mathbb{N} \to \texttt{global\_env} \to \texttt{env} \to \texttt{expr} \to \texttt{res val}$$

Embedding ACORN code into Coq

Code in ACORN

```
definition foldr a b (f :: a → b → b) (initVal :: b) =
    letrec go (xs :: List a) :: b =
      case xs of
        Nil → initVal
        Cons x xs' → f x (go xs')
     in go
```

A fragment of λ_{smart} AST (deep embedding)

```
Definition Functions := [( "foldr", eTyLam "A" (eTyLam "A" (eLambda "x" (
     tyArr (tyRel 1) (tyArr (tyRel 0) (tyRel 0))) (eLambda "x" (tyRel 0)
      (eLetIn "f" (eFix "rec" "x" ))))));
```

Code in Coq

```
(** Run the translation in the Template Monad (translate and unquote) *)
Run TemplateProgram (translateDefs gEnv Functions).

Print foldr.
(* fun (A A0 : Set)(x : A → A0 → A0) (x0 : A0) ⇒
   fix rec (x1 : List A) : A0 :=
      match x1 with
      | @Nil_coq _ ⇒ x0
      | @Cons_coq _ x2 x3 ⇒ x x2 (rec x3)
      end *)
```

Computational soundness

Translation: $[\![-]\!]^t_\Sigma : \lambda_{\text{smart}} \to \texttt{PCUIC}$

Theorem

For any closed λ_{smart} expression e if $\texttt{eval}^n_{\Sigma,[]}(e) = \texttt{Ok}\ v$, then there is a derivation in MetaCoq's CBV big-step evaluation relation:

$$[\![e]\!]^t_\Sigma \Downarrow [\![\texttt{of\_val}(v)]\!]^t_\Sigma$$

- We support only structurally recursive λ_{smart} programs.
- We rely on correctness of MetaCoq's `unquote`.

Execution model

- Remember the signature
  `contract : CallCtx * Msg * State → State * Action list`?
- `Actions` can be transfers, calls to other contracts (including self calls), contract deployments.
- The execution model formalises the *scheduler*:
  - blockchain state updates (account balances, contract deployments);
  - executing the calls in the `Action list` in *some* order;
  - adding new blocks.
- Provides a reasoning framework on traces — chains of one-step executions.
- Outgoing actions might be arbitrary reordered.
- Implementation and partial correctness of the Congress contract (simplified DAO).

Jakob Botsch Nielsen, Bas Spitters. Smart Contract Interactions in Coq. FMBC'19

Crowdfunding

Crowdfunding: a smart contract allowing arbitrary users to donate money within a deadline.

- Will the users get their money back if the campaign is not funded (goal is not reached)?
- Are all contributions recorded correctly in the contract?
- Does the contract have enough money at the account to cover all contributions?
- ...

```
(* The contract balance "on a blockchain" is consistent the sum of
    individual contributions *)
Corollary cf_donations_backed_after_block {_ : ChainBuilderType}
  prev hd acts new cf_addr lstate :

  builder_add_block prev hd acts = Some new →
(* [cf_contract] - produced from the deep embedding *)
  env_contracts new cf_addr = Some cf_contract  →
  cf_state new cf_addr = Some lstate →
  ∼ lstate.(done_coq) →

  account_balance (env_chain new) cf_addr >=
                  sum_map (lstate.( donations_coq)).
```

Conclusions

- Deep and shallow embeddings in one framework.
- Soundness through the PCUIC formalisation.
- Acorn code verification: parts of the standard library and simple contracts.
- Example: properties of a crowdfunding contract.
- Integration with the execution model.
- Extraction to a functional smart contract language.

ConCert on GitHub:

`https://github.com/AU-COBRA/ConCert`

Future work

- Static semantics of λ_{smart}.
- Gas analysis.
- Connect the development to CertiCoq.