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Smart contracts in a proof assistant

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Aarhus University, Concordium Blockchain Research Center

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- Can we do better?

Proof assistants

Proof assistants — software for developing machine-checkable proofs.

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Some application in CS:

- Proving correctness of compilers, type checking/type inference, etc.
- **Program verification**.
- **"Extraction" of the bug-free implementation.**

The Coq proof assistant

- Coq means “rooster” in French.
- Mature system: more than 30 year!
- Used in many project in CS and mathematics:
  CompCert, Four color theorem, Feit-Thompson theorem, ...
- Based on dependent types: can express specs in types!
- Widely used in COBRA verification projects.

Notation

Java-like syntax

```
int my_func (int n, int m) {
  ...
}
```

Coq syntax

```
Definition my_func (n m : Z) : Z :=
  ...
```

- we write `Z` for the integer type;
- `n : Z` means that `n` is an integer.

Subset types in Coq

- Coq's version of refinement types.
- Types with a predicate.
- Notation: `{x : A | P x}`.
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- Examples:
  - {`n : nat | 0 < n`} — positive natural numbers;
  - {`i : Z | 0 <> i`} — non-zero integers;
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  - `{i : Z | 0 <> i}` — non-zero integers;
  - `{xs : list A | 0 < length xs}` — non-empty lists.
- `Program` environment for managing proof obligations.
- Convenient for the correct-by-construction approach.

We can do better now

We specify the invariant for division in the type

```
Program Definition safe_div (n : Z) (m : { i : Z | i <> 0}) : Z := ...
Definition safe_compute (n : Z) (m : { i : Z | i <> 0}) : Z :=
  n + safe_div n m.
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For each call of `safe_compute`, we must **provide a proof of the invariant**.

```
Program Definition compute_power_2 (n m : nat) : Z :=
  safe_compute (2^n) (2^m).
(* Here we prove that 2^m <> 0 *)
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A validation barrier at the entry point:
validate user input once and for all, the rest works on valid data

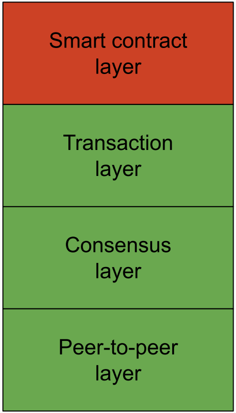
```
Program Definition public_compute (n m : Z) : option Z :=
  match is_zero m with
  | right p ⇒ Some (safe_compute n m)
  | left p ⇒ None (* signals that the validation has failed *)
  end.
```

NOTE: `option Z` means it is a partial function.

Smart contracts

Programs deployed on a blockchain

- Transaction protocols between parties.
- Use the underlying blockchain infrastructure.
- Often targeted by hackers.



Functional smart contract languages

- Contracts are (partial) state transition functions:

  $\texttt{contract} : \texttt{CallCtx} * \texttt{Msg} * \texttt{State} \to \texttt{option}\ (\texttt{State} * \texttt{list Action})$

  - takes a triple (`call_ctx`, `msg`, `st`);
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  - takes a triple (`call_ctx`, `msg`, `st`);
  - either returns a tuple (`st`, `actions`), or fails.
- A *scheduler*
  - updates the state;
  - handles transfers and calls to other contracts in `Action list`.

Fits well with modern blockchains: Concordium, Tezos, Dune.

ConCert: A Smart Contract Certification Framework

- Infrastructure for developing smart contracts in Coq.
- The execution layer (formalises the scheduler).
- Smart contract verification infrastructure.
- Generation of executable code for several target platforms: Concordium, Tezos, Dune.

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- Smart contract verification infrastructure.
- Generation of executable code for several target platforms: Concordium, Tezos, Dune.
- Verified: token standards implementations, escrow, crowdfunding ...
- Most recent (by Eske Hoy Nielsen): Dexter — a decentralised exchange for Tezos.
- WIP: formalisation of the Concordium's token standard (CTS).

The counter contract

```
Definition State := Z.
(* State inc_counter (State prev_st, int inc) { return (prev_st + inc) } *)
Program Definition inc_counter (prev_st : State) (inc : Z) : State
    := prev_st + inc.
```

```
Program Definition dec_counter (...) := ...
```

The counter contract

```
Definition State := Z.

Program Definition inc_counter
    (prev_st : State) (* take the previous state *)
    (inc : Z) :       (* increment by [inc] *)
    State             (* return a new (incremented!) state *)
    := prev_st + inc.


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Program Definition inc_counter
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pre-condition

post-condition

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validation barrier

```
Program Definition counter_receive (msg : Msg) (st : State)
    : option (State * list Action) :=
    match msg with
    | Inc i ⇒ match is_gt_zero i with
              | left H ⇒ Some (inc_counter st i, [])
              | right _ ⇒ None
              end
    | Dec i ⇒ ...
  end.
```

More properties!

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- **Crowdfunding:**
  individual contributions and the total balance agree.

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Record State := { contribs : Map Address Amount;
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- **Tokens:**
  balances are preserved.

```
Definition transfer (old_balances : FMap Address Amount)
                    (from : Address) (to : Address) :
                    { new_balances | sum old_balances = sum new_balances}.
```

More theorems!

- Sometimes subset types are not enough:
  - how different functions relate to each other

    `FMap.find k (FMap.add k v m) = Some v`
  - smart contract interactions
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  - ...
- Use a different verification style:
  state and proof theorems *after* writing all definitions.
- A property for `Counter` on execution traces:

```
Theorem counter_correct : forall init_val state contract_calls,
  reachable state → (* other conditions *)
  state = sum_inc_dec contract_calls init_val.
```

  the contract's state is exactly the sum of all increments and decrements sent to the contract, plus the initial counter value.

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We address these points in ConCert.

Extraction in ConCert

An **extensible** extraction pipeline with **small TCB**

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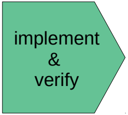
An **extensible** extraction pipeline with **small TCB**

- Implement the extraction pipeline in Coq.
- Use MetaCoq's verified erasure as a basis.
- Add verified pre- and post-processing steps.
- Let the users add transformations/target languages.

The extraction pipeline



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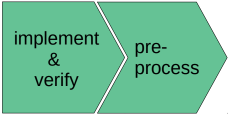

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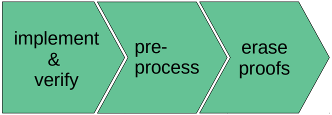

- preprocess: inlining, specialisation ... + generate proofs
- erase proofs: use the extended verified MetaCoq erasure

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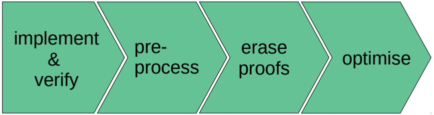

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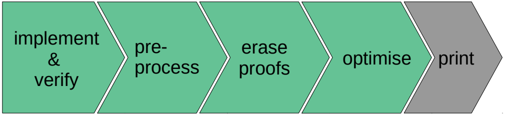

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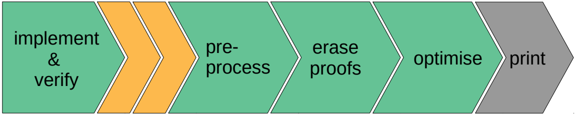

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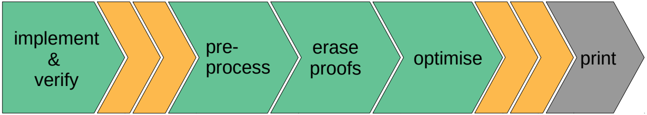

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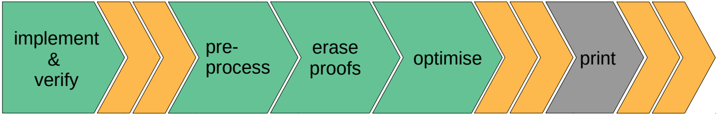

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- add new target languages

Extracted code

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           (P : A → Prop) : Type :=
 exist : forall (x : A), P x → {x : A | P x}

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```
pub enum Sig<A> {
  exist(A)
}

fn inc_counter(&'a self,
               prev_st: State<'a>,
               inc: &'a Sig<i64>)
   → &'a Sig<State<'a>> {
self.alloc(
 Sig::exist(
  self.add(prev_st, self.proj1_sig(inc))))
}
```

Conclusion and future work

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ConCert + extraction =

dependent types in your favorite SC language

Thank you for your attention!

Our development on GitHub:

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