When Bécassine brings automation to Coq

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- **Coq**: **proof assistant** based on **type theory** and the **Curry-Howard isomorphism**

  Formulas = types, proofs = programs

  - Four Colors Theorem
  - Feit-Thomson Theorem
  - `CompCert` (certified compiler)

- These successes are possible because of its design
  - Strong **type-checking** within `Coq`
  - **Rich specification** language
  - **Highly trusted** (small logical kernel)

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Goal forall (A : Type) (l : list A) (n : nat), length l = S n → l ≠ [].
Proof. intros A l n H H'. rewrite H' in H. discriminate. Qed.
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Proof. intros A H x l1 l2 l3. rewrite !search_app.
rewrite orb_comm with (b1 := search x l3).
rewrite orb_comm with (b1 := search x l2) (b2 := search x l1).
rewrite orb_assoc. reflexivity . Qed.
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- The user must be very specific
- Difficult for the beginner/non-formal method specialist
- May discourage new users (*e.g.*, maths, industry)

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Motivation: improving the automation of Coq

Coq (Proof assistant)	First-order provers
Very expressive logic	**Limited expressivity**
Checks proofs	**Finds proofs**
Highly trustable	**Less so**

- `Coq` **difficult to automatize**
- Even the first-order part of the proofs
- **FOL highly automated** outside `Coq`
- Line of software development:
  call external solvers to handle the first-order parts of the proofs
  (avoid **redundant code**!)
- Partial transformations from `Coq` logic to FOL

Plan

1. `Coq` *vs.* automated provers

2. `Sniper`

Why trust Coq?

Trusting Coq:

- Typing system

  strong normalization/consistency

- Implementation of the typing rules

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Type checker

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- Tactics (automation), *e.g.*, Ltac
- Plugins (incl. `SMTCoq` and `MetaCoq`)
- Machine learning

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Trusting Coq:

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  strong normalization/consistency

- Implementation of the typing rules

≠ First-order provers

whole code has to be trusted

(autom., search, optim.)

Coq

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Coq
based on the *Calculus of Inductive Constructions (CIC)*

First-order logic (FOL)
- functions and relations
- basic datatypes (**bool**, **int**, **float**)
- boolean equality
- quantification over objects

incl. linear integer arithmetics, etc

In CIC but not in FOL:

- Higher-order computation (functions are first-class objects):

```
map f [x1 ; ... ; xn] := [f x1 ; ... ; f xn ]
```
⇝ `map f` is a function on lists

- Higher-order quantification

```
forall (A B C : Type) (f : A -> B) (g : B -> C), (map g) o (map f) = map (g o f)
```

- Dependent types, *e.g.*, `Vec A n` is definable

the type of lists of length `n` whose elements have type `A`

Coq Logic *vs.* First-Order Logic

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Zoom on Coq inductives

- Inductive types

```
Inductive list (A : Type) : Type :=
[ ] : list A | _ :: _ : → list A → list A
```

- Fixpoints and pattern-matching:

```
Fixpoint length { A : Type } (l: list A) := match l with
  [ ] ⇒ 0 | a :: l0 ⇒ 1 + length l0
```

- Generic (non-boolean) Leibniz equality on any type

Leibniz equality is a dependent type

- When we make two programs interact, we need an interface

```
Theorem destruct_list : forall l : list A, {x:A & {tl:list A | l = x::tl}}+{l = nil}.
Proof.
  induction l as [|a tl].
  right; reflexivity.
  left; exists a; exists tl; reflexivity.
Qed.
```

A Coq Theorem and its proof

```
1:(input (#1:(= op_3 #2:(op_1 op_4 op_5))))
2:(input (#3:(forall ( (RelName10 Tindex_1) (RelName11 Tindex_2) ) #4:(=> #5:(= op_3 #6:(op_1 RelName11 R
3:(tmp_betared (#7:(forall ( (@vr10 Tindex_1) (@vr11 Tindex_2) ) #8:(=> #9:(= op_3 #10:(op_1 @vr11 @vr10)
4:(tmp_qnt_tidy (#11:(forall ( (@vr14 Tindex_1) (@vr16 Tindex_2) ) #12:(=> #13:(= op_3 #14:(op_1 @vr16 @v
5:(forall_inst (#15:(or (not #11) #16:(=> #1 false))))
6:(false ((not false)))
7:(implies_pos ((not #16) (not #1) false))
```

Excerpt of an smt2 certificate

The problem of reification

- When we make two programs interact, we need an interface

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⇝ translating programs of a language $\mathcal{L}$ into another language $\mathcal{L}'$.

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A `Coq` Theorem and its proof

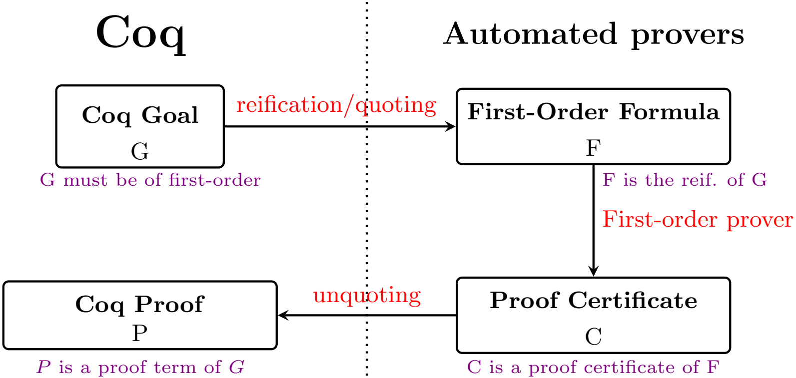
> Need for **reification** (or quoting)
> $\rightsquigarrow$ translating programs of a language $\mathcal{L}$ into another language $\mathcal{L}'$.

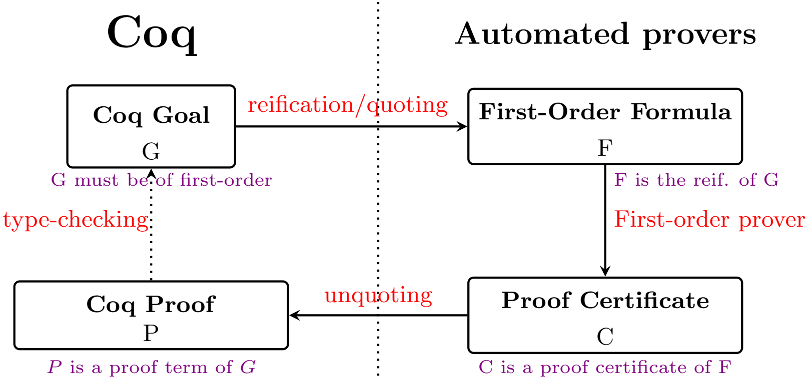
e.g., `forall (A : Set), A → A` (type)

$\rightsquigarrow$ `Prod (name "A") Set_reif (Prod unnamed A (dB 0) (dB 1))`

=reif. with de Bruijn indexes

Plugging in provers: autarkic approach




Coq
Automated provers
Coq Goal
G
reification/quoting
First-Order Formula
F
G must be of first-order
F is the reif. of G
type-checking
First-order prover
Coq Proof
P
unquoting
Proof Certificate
C
P is a proof term of G
C is a proof certificate of F

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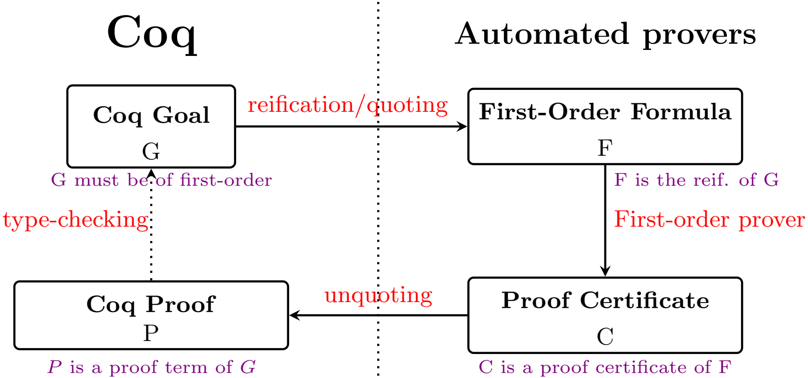
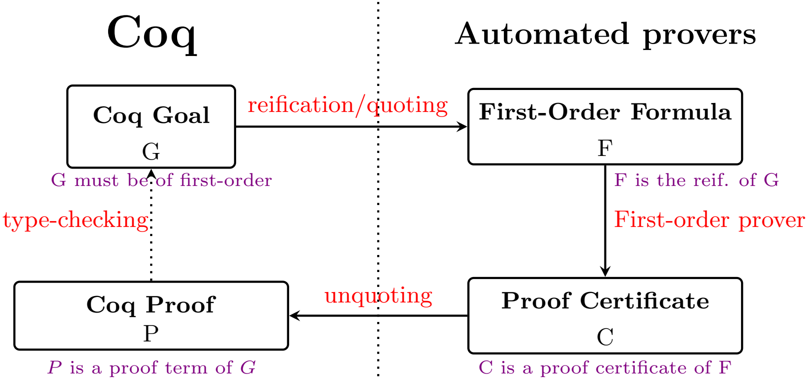


- Horizontal arrows: some `OCaml`



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- Any arrow may fail (reification, solving. . .)

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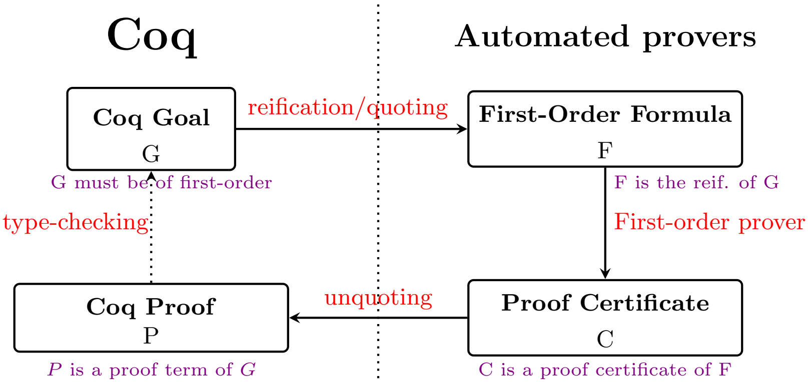
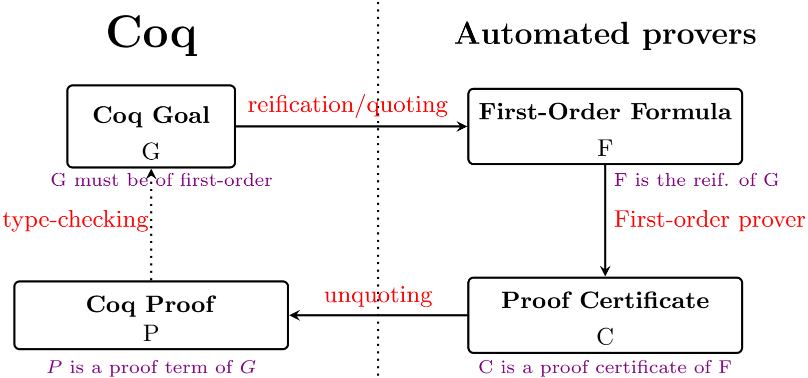
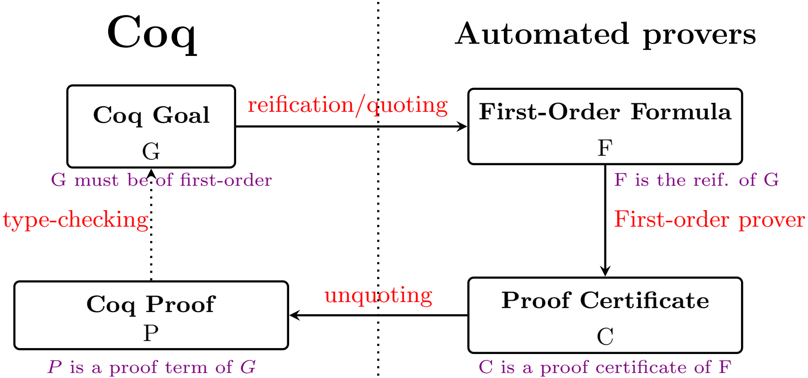


- Horizontal arrows: some `OCaml`
- Any arrow may fail (reification, solving. . .)
- **Autarkic approach**: each certificate is checked on the run

Plugging in provers: autarkic approach

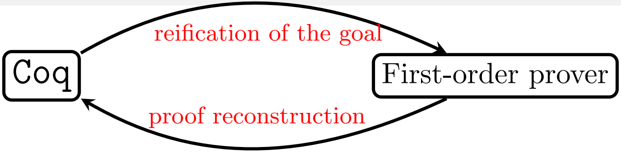




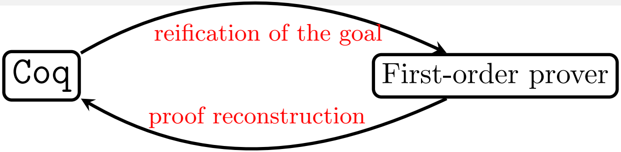
In our case:

- Plugin = `SMTCoq`
- Automated provers = SMT solvers, *e.g.*, veriT
- Under the carpet: casting Leibniz equality into boolean eq. (decidable types only)

Bécassine comes into play



- **Question.** Why aren't we happy with this?



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Problem 1
Avoid harmless polymorphism and higher-order

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- forall (A : Type) (l1 l2 : list A),
   length (l1 ++ l2) = length l1 + length l2
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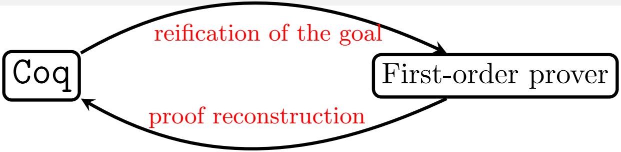
- `f = g` with `f,g: nat -> nat`
  instead of $\forall$`(x : nat), f x = g x`



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Some info. is lost during goal reification

type constructors uninterpreted *e.g.*,

- `S` $n =$ `S` $n' \rightarrow n = n'$ is forgotten
- nothing known about `List.length`

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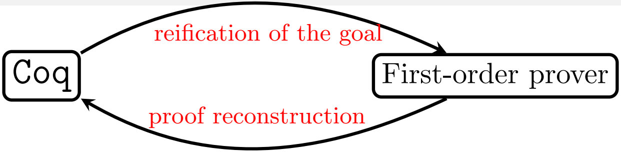

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- eliminates harmless polymorphism
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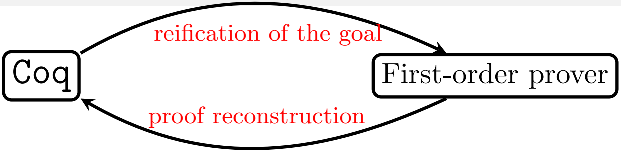

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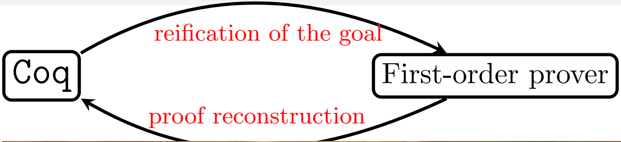

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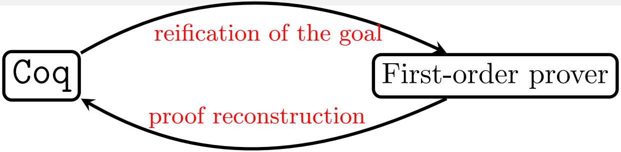

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Plan

1. Coq *vs.* automated provers

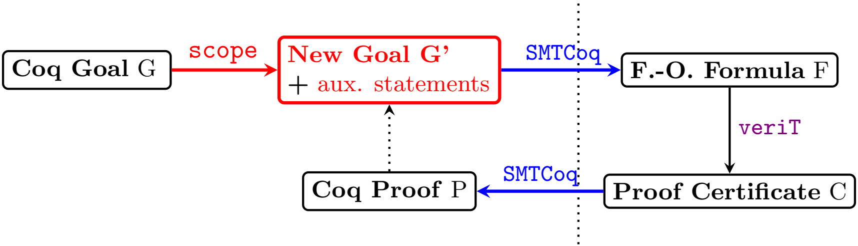
2. Sniper

Sniper is a two-fold tactic.

First Step. The tactic `scope`

- Eliminates harmless higher-order and polymorphism in the goal if needed
- Produces and proves first-order auxiliary statements in the local context (currently 6 transformations,)

Second step. The transformed goal and the auxiliary statement are sent to the SMT solver `veriT`, *via* `SMTCoq`.



Example (scope): facts about inductives datatypes

Question. What should a first-order prover know about an inductive datatype `T`?

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⇝ **Use MetaCoq**
reification of Coq in Coq

+ quoting/unquoting mechanisms

How does the transformations work?

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1. Generation of the reified statements in `MetaCoq` (*e.g.*, constructors are injective)
2. Unreify these statements
3. Proof of these statements with `Coq` regular tactics (`Ltac`)
4. The statements are now in the local context

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Currently implemented transformations

- Make explicit the semantics of symbols
- Eliminate higher-order equalities
- Eliminate prenex polymorphism

Example

Action of `scope` on a goal

`A : Type`

$\texttt{forall (l : list A) (n : nat), length A l} = \texttt{S n} \rightarrow \texttt{l} \neq [\,]$

Example

Action of `scope` on a goal

1. inductive datatypes

`A` : `Type`

1: `forall B (x y : B) (l l' : list B), x :: l = y :: l' → x = y ∧ l = l'`

1: `forall B (x : B) (l : list B), [ ] ≠ x :: l`

1: `forall (n n': nat), S n = S n' → n = n'`

1: `forall (n : nat), O ≠ S n`

`forall (l : list A) (n : nat), length A l = S n → l ≠ [ ]`

Example

Action of `scope` on a goal

1. inductive datatypes
2. definitions

A : Type
1: forall B (x y : B) (l l' : list B), x :: l = y :: l' → x = y ∧ l = l'
1: forall B (x : B) (l : list B), [ ] ≠ x :: l
1: forall (n n': nat), S n = S n' → n = n'
1: forall (n : nat), 0 ≠ S n
2: length = (fun B ⇒ fix length l := match l with … end)

---

forall (l : list A) (n : nat), length A l = S n → l ≠ [ ]

Example

Action of `scope` on a goal

1. inductive datatypes
2. definitions
3. expansion

```
A : Type
1: forall B (x y : B) (l l' : list B), x :: l = y :: l' → x = y ∧ l = l'
1: forall B (x : B) (l : list B), [ ] ≠ x :: l
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1: forall (n : nat), O ≠ S n
2: length = (fun B ⇒ fix length l := match l with … end)
3: forall B l, length B l = (fun B ⇒ fix length l := match l with … end) B l
```

```
forall (l : list A) (n : nat), length A l = S n → l ≠ [ ]
```

Example

Action of `scope` on a goal

1. inductive datatypes
2. definitions
3. expansion
4. fixpoints

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Example

Action of `scope` on a goal

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4: forall B l, length B l = match l with … end
5: forall B, length B [ ] = 0
5: forall B (l : list B) (x : B), length B x :: l = S (length B l)
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Example

Action of `scope` on a goal

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Example

Action of scope on a goal

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2. definitions
3. expansion
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----------------------------------------------------------------
  forall (l : list A) (n : nat), length A l = S n → l ≠ [ ]
```

Conclusion and Future Work

- General methodology: small transformations from a subset of `Coq` logic to FOL
- Proof of concept: six transformations combined in a tactic (`snipe` = `scope` + `verit`) which calls an external SMT solver.

These transformations are independent from `SMTCoq`!

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In the Future.

- More complex transformations: (simple) **dependent types**, dependent pattern matching...
- Add user-defined tactics
- **Benchmarks**

+ improving the performance of our tactic

Try Sniper!

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