

PROGRAM-ing in COQ

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Foundations of Programming seminar
February 15th 2008
University of Nottingham



ML term t

```
let rec euclid x y =  
  if x < y then (0, x)  
  else  
    let (q, r) = euclid (x - y) y in  
    (S q, r)
```

The Big Picture

ML term t

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Simple type

```
nat -> nat -> nat * nat
```

```
graph TD; A[ML term t] --> C[Typecheck]; B[Simple type] --> C;
```

Typecheck

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Typecheck

The diagram illustrates a conceptual flow from an ML term and a simple type to a typechecking process. Two pink boxes at the top contain an ML term and a simple type. Arrows from both boxes point towards a blue box at the bottom labeled 'Typecheck'. This 'Typecheck' box is crossed out with a large black 'X', indicating that the typechecking process is either not applicable or has failed in this context.

The Big Picture

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Dependent type T

```
nat -> { y : nat | y > 0 } ->  
nat * nat
```

```
graph TD; A[ML term t] --> C[Typecheck]; B[Dependent type T] --> C;
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Typecheck

The Big Picture

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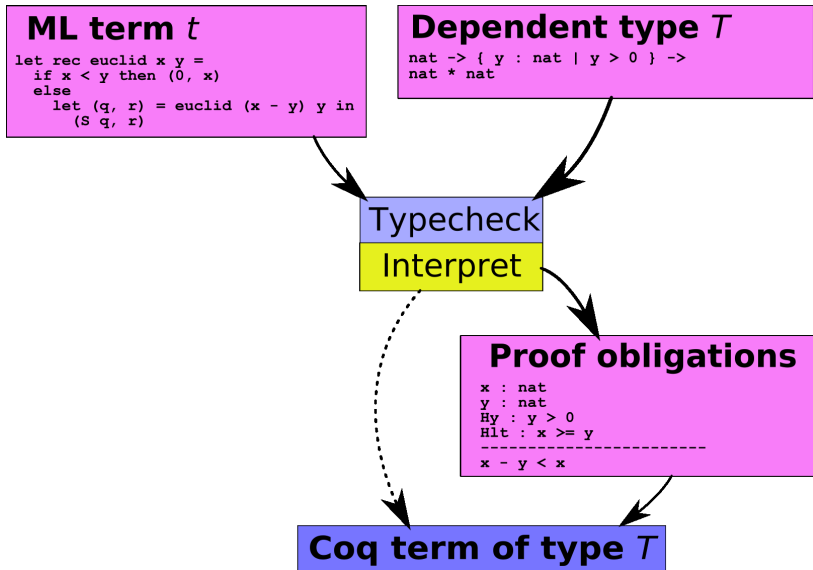
Typecheck

Interpret

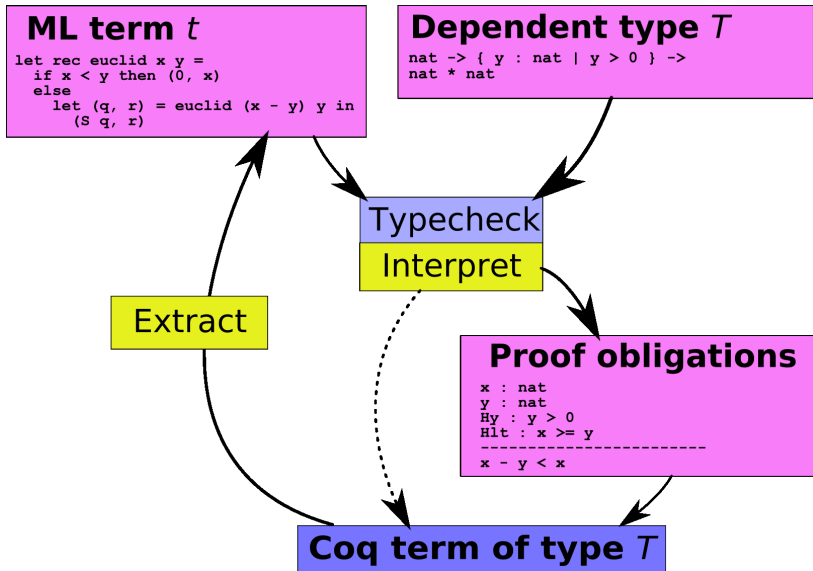
Proof obligations

```
x : nat  
y : nat  
Hy : y > 0  
Hlt : x >= y  
-----  
x - y < x
```

The Big Picture



The Big Picture



The Big Picture

Inductive *diveucl* $a b : \text{Set} :=$

divex : $\forall q r, b > r \rightarrow a = q \times b + r \rightarrow \text{diveucl } a b.$

Lemma *eucl_dev* : $\forall n, n > 0 \rightarrow \forall m:\text{nat}, \text{diveucl } m n.$

Proof.

intros b H a; pattern a in $\vdash \times$; apply gt_wf_rec; intros n H0.

elim (le_gt_dec b n).

intro lebn.

elim (H0 (n - b)); auto with arith.

intros q r g e.

apply divex with (S q) r; simpl in $\vdash \times$; auto with arith.

elim plus_assoc.

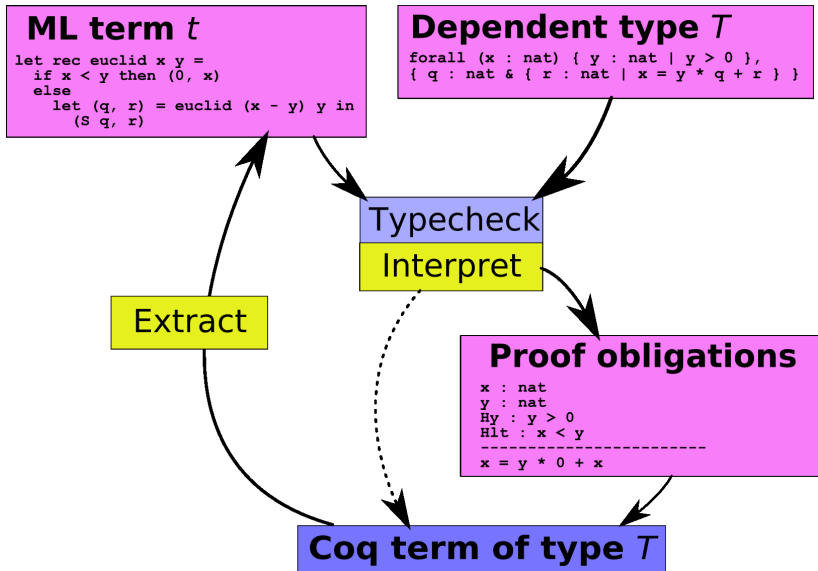
elim e; auto with arith.

intros gtbn.

apply divex with 0 n; simpl in $\vdash \times$; auto with arith.

Qed.

The Big Picture



The CURRY-HOWARD isomorphism

Programming language = Proof system

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PROGRAM **extends** the COQ proof-assistant into a dependently-typed programming environment.

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Epigram

PVS

DML

Ω mega

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PROGRAM **extends** the COQ proof-assistant into a dependently-typed programming environment.

- ▶ **Logical Framework** Type Theory.

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PROGRAM **extends** the COQ proof-assistant into a dependently-typed programming environment.

- ▶ **Logical Framework** Type Theory.
Separates proofs and programs using sorts \Rightarrow Extraction

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PROGRAM **extends** the COQ proof-assistant into a dependently-typed programming environment.

- ▶ **Logical Framework** Type Theory.
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- ▶ **Paradigm** Purely functional.

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- ▶ **Development style and proof automation** Interactive,
semi-automatic proof using tactics.

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- ▶ **Phase distinction** none

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- ▶ **Phase distinction** \Rightarrow in PROGRAM

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- 1 The idea
 - A simple idea
 - From PVS to Coq
- 2 Theoretical development
 - RUSSELL
 - Interpretation in Coq
 - Inductive types
- 3 PROGRAM
 - Architecture
 - Hello world
 - Extensions
- 4 Conclusion

Definition

$\{x : T \mid P\}$ is the set of objects of set T verifying property P .

- ▶ Useful for specifying, widely used in mathematics ;
- ▶ Links object and property.

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Adapting the idea

$$\frac{t : T \quad P[t/x]}{t : \{x : T \mid P\}} \quad \frac{t : \{x : T \mid P\}}{t : T}$$

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Adapting the idea

$$\frac{t : T \quad p : P[t/x]}{(t, p) : \{ x : T \mid P \}} \qquad \frac{t : \{ x : T \mid P \}}{\text{proj } t : T}$$

PVS

- ▶ Specialized typing algorithm for subset types, generating *Type-checking conditions*.

$t : \{ x : T \mid P \}$	used as	$t : T$	ok
$t : T$	used as	$t : \{ x : T \mid P \}$	if $P[t/x]$

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$t : T$ used as $t : \{ x : T \mid P \}$ if $P[t/x]$

+ Practical success ;

PVS

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$t : \{ x : T \mid P \}$ used as $t : T$ ok
 $t : T$ used as $t : \{ x : T \mid P \}$ if $P[t/x]$

- + Practical success ;
- No strong safety guarantee in PVS.

- 1 A property-irrelevant language (RUSSELL) with **decidable** typing ;

$$\frac{\Gamma \vdash t : \{ x : T \mid P \}}{\Gamma \vdash t : T}$$

$$\frac{\Gamma \vdash t : T \quad \Gamma, x : T \vdash P : \mathbf{Prop}}{\Gamma \vdash t : \{ x : T \mid P \}}$$

... to Subset coercions

- 1 A property-irrelevant language (RUSSELL) with **decidable** typing ;
- 2 A total interpretation to COQ terms with holes ;

$$\frac{\Gamma \vdash t : \{ x : T \mid P \}}{\Gamma \vdash \text{proj } t : T}$$

$$\frac{\Gamma \vdash t : T \quad \Gamma, x : T \vdash P : \text{Prop}}{\Gamma \vdash (t, ?) : \{ x : T \mid P \}} \quad \Gamma \vdash ? : P[t/x]$$

... to Subset coercions

- 1 A property-irrelevant language (RUSSELL) with **decidable** typing ;
- 2 A total interpretation to COQ terms with holes ;
- 3 A mechanism to turn the holes into proof obligations and manage them.

$$\frac{\Gamma \vdash t : \{ x : T \mid P \}}{\Gamma \vdash \text{proj } t : T}$$

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$x \in \mathcal{V}$

$s, t, u, v ::= x$
| Set
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| $\lambda x : s.t$
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| $(u, v)_{\Sigma x : s.t}$
| $\pi_1 s \mid \pi_2 s$
| $\Sigma x : s.t$

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| $\{ x : s \mid t \}$

Calculus of Constructions with

$$\frac{\Gamma \vdash t : U \quad \Gamma \vdash U \equiv_{\beta\pi} T : s}{\Gamma \vdash t : T}$$

Calculus of Constructions with

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$$\frac{\Gamma \vdash U \triangleright V : \mathbf{Set} \quad \Gamma, x : U \vdash P : \mathbf{Prop}}{\Gamma \vdash \{ x : U \mid P \} \triangleright V : \mathbf{Set}}$$

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Example
$$\frac{\Gamma \vdash 0 : \mathbb{N} \quad \Gamma \vdash \mathbb{N} \triangleright \{ x : \mathbb{N} \mid x \neq 0 \} : \mathbf{Set}}{\Gamma \vdash 0 : \{ x : \mathbb{N} \mid x \neq 0 \}}$$

Calculus of Constructions with

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$\Gamma \vdash ? : 0 \neq 0$

Calculus of Constructions with

$$\begin{array}{c}
 \frac{\Gamma \vdash t : U \quad \Gamma \vdash U \triangleright T : s}{\Gamma \vdash t : T} \qquad \frac{\Gamma \vdash T \equiv_{\beta\pi} U : s}{\Gamma \vdash T \triangleright U : s} \\
 \\
 \frac{\Gamma \vdash U \triangleright V : \mathbf{Set} \quad \Gamma, x : U \vdash P : \mathbf{Prop}}{\Gamma \vdash \{ x : U \mid P \} \triangleright V : \mathbf{Set}} \\
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 \\
 \frac{\Gamma \vdash U \triangleright T : s_1 \quad \Gamma, x : U \vdash V \triangleright W : s_2}{\Gamma \vdash \Pi x : T.V \triangleright \Pi x : U.W : s_2} \\
 \\
 \frac{\Gamma \vdash T \triangleright U : s \quad \Gamma, x : T \vdash V \triangleright W : s}{\Gamma \vdash \Sigma x : T.V \triangleright \Sigma y : U.W : s} \quad s \in \{\mathbf{Set}, \mathbf{Prop}\}
 \end{array}$$

Calculus of Constructions with

$$\frac{\Gamma \vdash t : U \quad \Gamma \vdash U \triangleright T : s}{\Gamma \vdash t : T} \qquad \frac{\Gamma \vdash T \equiv_{\beta\pi} U : s}{\Gamma \vdash T \triangleright U : s}$$

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$$\frac{\Gamma \vdash U \triangleright T : s_1 \quad \Gamma, x : U \vdash V \triangleright W : s_2}{\Gamma \vdash \Pi x : T.V \triangleright \Pi x : U.W : s_2}$$

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\triangleright is symmetric!

Theorem (Decidability of type checking and type inference)

$\Gamma \vdash t : T$ is decidable.

$$\frac{\Gamma \vdash f : T \quad \Gamma \vdash T \triangleright \Pi x : A. B : s \quad \Gamma \vdash e : E \quad \Gamma \vdash E \triangleright A : s'}{\Gamma \vdash (f e) : B[e/x]}$$

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Coq corner

Mechanised proofs of Subject Reduction and equivalence between declarative and algorithmic presentations of the system.

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- A simple idea
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3 PROGRAM

- Architecture
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4 Conclusion

The target system : CIC with metavariables

$$\frac{\Gamma \vdash_{?} t : T \quad \Gamma \vdash_{?} p : P[t/x]}{\Gamma \vdash_{?} \mathbf{elt} \ T \ P \ t \ p : \{ x : T \mid P \}}$$

$$\frac{\Gamma \vdash_{?} t : \{ x : T \mid P \}}{\Gamma \vdash_{?} \sigma_1 \ t : T} \quad \frac{\Gamma \vdash_{?} t : \{ x : T \mid P \}}{\Gamma \vdash_{?} \sigma_2 \ t : P[\sigma_1 \ t/x]}$$

$$\frac{\Gamma \vdash_{?} P : \mathbf{Prop}}{\Gamma \vdash_{?} ?_P : P}$$

We build an interpretation $\llbracket - \rrbracket_{\Gamma}$ from RUSSELL to CIC_? terms.

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We build an interpretation $\llbracket - \rrbracket_{\Gamma}$ from RUSSELL to $\text{CIC}_{?}$ terms.

Our goal

If $\Gamma \vdash t : T$ then $\llbracket \Gamma \rrbracket \vdash_{?} \llbracket t \rrbracket_{\Gamma} : \llbracket T \rrbracket_{\Gamma}$.

Interpretation of coercions

If $\Gamma \vdash T \triangleright U : s$ then $\Gamma \vdash_{?} c[\bullet] : T \triangleright U$ which implies
$$\llbracket \Gamma \rrbracket, x : \llbracket T \rrbracket_{\Gamma} \vdash_{?} c[x] : \llbracket U \rrbracket_{\Gamma}.$$

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Definition

$$\frac{T \equiv_{\beta\pi} U}{\Gamma \vdash_{?} \quad : T \triangleright U}$$

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$$\Gamma \vdash_{?} \mathbf{elt} _ _ \bullet \ ?_{\llbracket P \rrbracket_{\Gamma, x:T}[\bullet/x]} : T \triangleright \{ x : T \mid P \}$$

Example

$$\frac{\Gamma \vdash_{?} 0 : \mathbb{N} \quad \Gamma \vdash_{?} \mathbf{elt} _ _ \bullet \ ?_{(x \neq 0)[\bullet/x]} : \mathbb{N} \triangleright \{ x : \mathbb{N} \mid x \neq 0 \}}{\Gamma \vdash_{?} \mathbf{elt} _ _ 0 \ ?_{0 \neq 0} : \{ x : \mathbb{N} \mid x \neq 0 \}}$$

Example (Application)

$$\frac{\Gamma \vdash f : T \quad \Gamma \vdash T \triangleright \Pi x : V.W : s \quad \Gamma \vdash u : U \quad \Gamma \vdash U \triangleright V : s'}{\Gamma \vdash (f \ u) : W[u/x]}$$

$$\llbracket f \ u \rrbracket_{\Gamma} \triangleq \mathbf{let} \ \pi = \mathbf{coerce}_{\Gamma} \ T \ (\Pi x : V.W) \ \mathbf{in} \\ \mathbf{let} \ c = \mathbf{coerce}_{\Gamma} \ U \ V \ \mathbf{in} \\ (\pi[\llbracket f \rrbracket_{\Gamma}]) (c[\llbracket u \rrbracket_{\Gamma}])$$

Theorem (Soundness)

If $\Gamma \vdash t : T$ then $\llbracket \Gamma \rrbracket \vdash? \llbracket t \rrbracket_{\Gamma} : \llbracket T \rrbracket_{\Gamma}$.

$\vdash_?$'s equational theory:

$$\begin{array}{llll}
 (\beta) & (\lambda x : X.e) v & \equiv & e[v/x] \\
 (\pi_i) & \pi_i (e_1, e_2)_T & \equiv & e_i \\
 (\sigma_i) & \sigma_i (\mathbf{elt} E P e_1 e_2) & \equiv & e_i \\
 (\eta) & (\lambda x : X.e x) & \equiv & e \quad \text{if } x \notin FV(e) \\
 (\text{SP}) & \mathbf{elt} E P (\sigma_1 e) (\sigma_2 e) & \equiv & e
 \end{array}$$

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$$\begin{array}{lll}
 (\beta) & (\lambda x : X.e) v & \equiv e[v/x] \\
 (\pi_i) & \pi_i (e_1, e_2)_T & \equiv e_i \\
 (\sigma_i) & \sigma_i (\mathbf{elt} E P e_1 e_2) & \equiv e_i \\
 (\eta) & (\lambda x : X.e x) & \equiv e \quad \text{if } x \notin FV(e) \\
 (\text{SP}) & \mathbf{elt} E P (\sigma_1 e) (\sigma_2 e) & \equiv e \\
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 \end{array}$$

\Rightarrow Proof Irrelevance

$\vdash_?$'s equational theory:

$$\begin{array}{lll}
 (\beta) & (\lambda x : X.e) v & \equiv e[v/x] \\
 (\pi_i) & \pi_i (e_1, e_2)_T & \equiv e_i \\
 (\sigma_i) & \sigma_i (\mathbf{elt} E P e_1 e_2) & \equiv e_i \\
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\Rightarrow **Proof Irrelevance**

... have practical effects

Difficulty to reason on code: $\mathbf{elt} T P x p_1 \neq \mathbf{elt} T P x p_2$ where $p_1, p_2 : P x$.

Different representations

$\text{vector } n \triangleq \{ x : \text{list } A \mid \text{length } x = n \}$ or

$\text{vector } n \triangleq \text{vnil} : \text{vector } 0 \mid \text{vcons} : A \rightarrow \forall n, \text{vector } n \rightarrow \text{vector } (S n) ?$

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$$\frac{\Gamma \vdash v : \text{vector } x \quad \frac{\Gamma \vdash x = y : \text{Prop}}{\Gamma \vdash \text{vector } x \triangleright \text{vector } y : \text{Set}}}{\Gamma \vdash v : \text{vector } y}$$

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 - From PVS to Coq

- 2 Theoretical development
 - RUSSELL
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 - Inductive types

- 3 PROGRAM
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- 4 Conclusion

Architecture

Wrap around COQ's vernacular commands (Definition, Fixpoint, Lemma, ...).

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Restriction We assume $\Gamma \vdash_{CCI} \llbracket T \rrbracket_{\Gamma} : s$.

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DEMO

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Pattern-matching revisited

Put **logic** into the terms.

Let $e : \mathbb{N}$:

```
match  $e$       return       $T$  with  
|  $S\ n \Rightarrow$        $t_1$   
|  $0 \Rightarrow$           $t_2$   
end
```

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Let $e : \mathbb{N}$:

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match  $e$  as  $t$  return  $t = e \rightarrow T$  with  
|  $S\ n \Rightarrow$  fun ( $H : S\ n = e$ )  $\Rightarrow t_1$   
|  $0 \Rightarrow$  fun ( $H : 0 = e$ )  $\Rightarrow t_2$   
end (refl_equal  $e$ )
```

Put **logic** into the terms.

Further refinements

- ▶ Each branch typed only once ;

Let $e : \mathbb{N}$:

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match  $e$  as  $t$  return  $t = e \rightarrow T$  with  
|  $S (S n) \Rightarrow$  fun ( $H : S (S n) = e$ )  $\Rightarrow t_1$   
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Further refinements

- ▶ Each branch typed only once ;
- ▶ Add inequalities for intersecting patterns ;
- ▶ Generalized to dependent inductive types.

Let $e : \text{vector } n$:

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|  $\text{vnil} \Rightarrow t_1$   
|  $\text{vcons } x \ n' \ v' \Rightarrow t_2$   
end
```

Put **logic** into the terms.

Further refinements

- ▶ Each branch typed only once ;
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Let $e : \text{vector } n$:

```
match  $e$  as  $t$  in  $\text{vector } n'$  return  $n' = n \rightarrow t \simeq e \rightarrow T$  with  
|  $\text{vnil} \Rightarrow$  fun ( $H : 0 = n$ )( $Hv : \text{vnil} \simeq e$ )  $\Rightarrow t_1$   
|  $\text{vcons } x \ n' \ v' \Rightarrow$  fun ( $H : S \ n' = n$ )( $Hv : \text{vcons } x \ n' \ v' \simeq e$ )  $\Rightarrow t_2$   
end( $\text{refl\_equal } n$ )( $\text{JMeq\_refl } e$ )
```

Obligations

Unresolved implicits (`_`) are turned into obligations, à la **refine**.

Bang

$! \triangleq (\text{False_rect } _ _)$ where $\text{False_rect} : \forall A : \text{Type}, \text{False} \rightarrow A$. It corresponds to ML's `assert(false)`.

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match 0 with 0 \Rightarrow 0 | n \Rightarrow ! end

Destruction

Let **let | p := t in e \triangleq match t with p \Rightarrow e end**. *p* can be an arbitrary pattern.

Support for well-founded recursion and measures.

Program Fixpoint $f (a : \mathbb{N}) \{ \mathbf{wf} < a \} : \mathbb{N} := b.$

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Program Fixpoint $f (a : \mathbb{N}) \{ \mathbf{wf} < a \} : \mathbb{N} := b.$

$$\frac{\begin{array}{l} a : \mathbb{N} \\ f : \{x : \mathbb{N} \mid x < a\} \rightarrow \mathbb{N} \end{array}}{b : \mathbb{N}}$$

DEMO

Our contributions

- ▶ A more **flexible** programming language, (almost) **conservative** over CIC, **integrated** with the existing environment and a formal **justification** of “*Predicate subtyping*”.
- ▶ A tool to make **programming** in Coq using the **full** language possible, which can **effectively** be used for non-trivial developments.

Ongoing and future work

- ▶ Reasoning support through tactics
- ▶ Implementation of proof-irrelevance in Coq’s kernel
- ▶ Overloading support through a typeclass mechanism.

`http://www.lri.fr/~sozeau/research/russell.en.html`