

EQUATIONS 1.0 Reference Manual

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Introduction

EQUATIONS is a toolbox built as a plugin on top of the Coq proof assistant to program and reason on programs defined by full *dependent* pattern-matching and *well-founded* recursion. While the primitive core calculus of Coq allows definitions by *simple* pattern-matching on inductive families and *structural* recursion, EQUATIONS extends the set of easily definable constants by allowing a richer form of pattern-matching and arbitrarily complex recursion schemes. It can be thought of as a twin of the FUNCTION package for Isabelle that implements a *definitional* translation from partial, well-founded recursive functions to the HOL core logic. See [Ana Bove and Alexander Krauss and Matthieu Sozeau \(2015\)](#) for an overview of tools for defining recursive definitions in interactive proof assistants like (Coq, Agda or Isabelle).

The first version of the tool was described in [Sozeau \(2010\)](#), the most recent one is described in [Mangin and Sozeau \(2017\)](#). This manual provides an overview of the system by way of introductory examples (chapter 1), and a short documentation of the plugin commands (chapter 2).

This manual describes version 1.0 of the package.

Installation

Equations is available through the `opam`¹ package manager as package `coq-equations`. To install it on an already existing `opam` installation with the Coq repository, simply input the command:

```
# opam install coq-equations
```

The development version and detailed installation instructions are available at <http://mattam82.github.io/Coq-Equations>.

¹<http://opam.ocaml.org>

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Chapter 1

A gentle introduction to Equations

The source of this chapter that can be run in Coq with Equations installed is available at:

https://raw.githubusercontent.com/mattam82/Coq-Equations/master/doc/equations_intro.v

Equations is a plugin for **Coq** that comes with a few support modules defining classes and tactics for running it. We will introduce its main features through a handful of examples. We start our Coq primer session by importing the **Equations** module.

```
Require Import Arith Omega.  
From Equations Require Import Equations.
```

1.1 Inductive types

In its simplest form, **Equations** allows to define functions on inductive datatypes. Take for example the booleans defined as an inductive type with two constructors **true** and **false**:

```
Inductive bool : Set := true : bool | false : bool
```

We can define the boolean negation as follows:

```
Equations neg (b : bool) : bool :=  
neg true := false ;  
neg false := true.  
Print All.
```

Equations declarations are formed by a signature definition and a set of *clauses* that must form a *covering* of this signature. The compiler is then expected to automatically find a corresponding case-splitting tree that implements the function. In this case, it simply needs to split on the single variable *b* to

produce two new *programming problems* `neg true` and `neg false` that are directly handled by the user clauses. We will see in more complex examples that this search for a splitting tree may be non-trivial.

1.2 Reasoning principles

In the setting of a proof assistant like Coq, we need not only the ability to define complex functions but also get good reasoning support for them. Practically, this translates to the ability to simplify applications of functions appearing in the goal and to give strong enough proof principles for (recursive) definitions.

Equations provides this through an automatic generation of proofs related to the function. Namely, each defining equation gives rise to a lemma stating the equality between the left and right hand sides. These equations can be used as rewrite rules for simplification during proofs, without having to rely on the fragile simplifications implemented by raw reduction. We can also generate the inductive graph of any **Equations** definition, giving the strongest elimination principle on the function.

I.e., for `neg` the inductive graph is defined as:

```
Inductive neg_ind : bool → bool → Prop :=
| neg_ind_equation_1 : neg_ind true false
| neg_ind_equation_2 : neg_ind false true
```

Along with a proof of $\Pi b, \text{neg_ind } b (\text{neg } b)$, we can eliminate any call to `neg` specializing its argument and result in a single command. Suppose we want to show that `neg` is involutive for example, our goal will look like:

```
b : bool
=====
neg (neg b) = b
```

An application of the tactic `funelim (neg b)` will produce two goals corresponding to the splitting done in `neg`: `neg false = true` and `neg true = false`. These correspond exactly to the rewriting lemmas generated for `neg`.

In the following sections we will show how these ideas generalize to more complex types and definitions involving dependencies, overlapping clauses and recursion.

1.3 Building up

1.3.1 Polymorphism

Coq's inductive types can be parameterized by types, giving polymorphic datatypes. For example the list datatype is defined as:

```
Inductive list {A} : Type := nil : list | cons : A → list → list.
Arguments list : clear implicits.
Notation "x :: l" := (cons x l).
```

No special support for polymorphism is needed, as type arguments are treated like regular arguments in dependent type theories. Note however that one cannot match on type arguments, there is no intensional type analysis. We can write the polymorphic `tail` function as follows:

```
Equations tail {A} (l : list A) : list A :=
tail nil := nil ;
tail (cons a v) := v.
```

Note that the argument `{A}` is declared implicit and must hence be omitted in the defining clauses. In each of the branches it is named `A`. To specify it explicitly one can use the syntax `{A:=B}`, renaming that implicit argument to `B` in this particular case

1.3.2 Recursive inductive types

Of course with inductive types comes recursion. Coq accepts a subset of the structurally recursive definitions by default (it is incomplete due to its syntactic nature). We will use this as a first step towards a more robust treatment of recursion via well-founded relations. A classical example is list concatenation:

```
Equations app {A} (l l' : list A) : list A :=
app nil l' := l' ;
app (cons a l) l' := cons a (app l l').
```

Recursive definitions like `app` can be unfolded easily so proving the equations as rewrite rules is direct. The induction principle associated to this definition is more interesting however. We can derive from it the following *elimination* principle for calls to `app`:

```
app_elim :
∀ P : ∀ (A : Type) (l l' : list A), list A → Prop,
(∀ (A : Type) (l' : list A), P A nil l' l') →
(∀ (A : Type) (a : A) (l l' : list A),
P A l l' (app l l') → P A (a :: l) l' (a :: app l l')) →
∀ (A : Type) (l l' : list A), P A l l' (app l l')
```

Using this eliminator, we can write proofs exactly following the structure of the function definition, instead of redoing the splitting by hand. This idea is already present in the `Function` package [Barthe et al. \(2006\)](#) that derives induction principles from function definitions.

1.3.3 Moving to the left

The structure of real programs is richer than a simple case tree on the original arguments in general. In the course of a computation, we might want to scrutinize intermediate results (e.g. coming from function calls) to produce an answer. This literally means adding a new pattern to the left of our equations made available for further refinement. This concept is known as with clauses in

the Agda [Norell \(2007\)](#) community and was first presented and implemented in the Epigram language [McBride and McKinna \(2004\)](#).

The compilation of `with` clauses and its treatment for generating equations and the induction principle are quite involved in the presence of dependencies, but the basic idea is to add a new case analysis to the program. To compute the type of the new subprogram, we actually abstract the discriminatee term from the expected type of the clause, so that the type can get refined in the subprogram. In the non-dependent case this does not change anything though.

Each `with` node generates an auxiliary definition from the clauses in the curly brackets, taking the additional object as argument. The equation for the `with` node will simply be an indirection to the auxiliary definition and simplification will continue as usual with the auxiliary definition's rewrite rules.

```
Equations filter {A} (l : list A) (p : A → bool) : list A :=
  filter nil p := nil ;
  filter (cons a l) p <= p a => {
    filter (cons a l) p true := a :: filter l p ;
    filter (cons a l) p false := filter l p }.
```

By default, equations makes definitions opaque after definition, to avoid spurious unfoldings, but this can be reverted on a case by case basis, or using the global `Set Equations Transparent` option. `Global Transparent filter.`

A common use of `with` clauses is to scrutinize recursive results like the following:

```
Equations unzip {A B} (l : list (A × B)) : list A × list B :=
  unzip nil := (nil, nil) ;
  unzip (cons p l) <= unzip l => {
    unzip (cons (pair a b) l) (pair la lb) := (a :: la, b :: lb) }.
```

The real power of `with` however comes when it is used with dependent types.

1.4 Dependent types

Coq supports writing dependent functions, in other words, it gives the ability to make the results *type* depend on actual *values*, like the arguments of the function. A simple example is given below of a function which decides the equality of two natural numbers, returning a sum type carrying proofs of the equality or disequality of the arguments. The sum type $\{ A \} + \{ B \}$ is a constructive variant of disjunction that can be used in programs to give at the same time a boolean algorithmic information (are we in branch *A* or *B*) and a *logical* information (a proof witness of *A* or *B*). Hence its constructors `left` and `right` take proofs as arguments. The `eq_refl` proof term is the single proof of $x = x$ (the *x* is generally inferred automatically).

```
Equations equal (n m : nat) : { n = m } + { n ≠ m } :=
  equal 0 0 := left eq_refl ;
  equal (S n) (S m) with equal n m := {
```

```

equal (S n) (S ?(n)) (left eq_refl) := left eq_refl ;
equal (S n) (S m) (right p) := right _ } ;
equal x y := right _ .

```

Of particular interest here is the inner program refining the recursive result. As `equal n m` is of type $\{ n = m \} + \{ n \neq m \}$ we have two cases to consider:

- Either we are in the `left p` case, and we know that `p` is a proof of $n = m$, in which case we can do a nested match on `p`. The result of matching this equality proof is to unify n and m , hence the left hand side patterns become `S n` and `S ?(n)` and the return type of this branch is refined to $\{ n = n \} + \{ n \neq n \}$. We can easily provide a proof for the left case.
- In the right case, we mark the proof unfilled with an underscore. This will generate an obligation for the hole, that can be filled automatically by a predefined tactic or interactively by the user in proof mode (this uses the same obligation mechanism as the Program extension [Sozeau \(2007\)](#)). In this case the automatic tactic is able to derive by itself that $n \neq m \rightarrow S n \neq S m$.

Dependent types are also useful to turn partial functions into total functions by restricting their domain. Typically, we can force the list passed to `head` to be non-empty using the specification: *Derive NoConfusion for list.*

```

Equations head {A} (l : list A) (pf : l ≠ nil) : A :=
head nil pf := False_rect _ (pf eq_refl);
head (cons a v) _ := a.

```

We decompose the list and are faced with two cases:

- In the first case, the list is empty, hence the proof `pf` of type $nil \neq nil$ allows us to derive a contradiction. We make use of another category of right-hand sides, which we call *empty* nodes to inform the compiler that a contradiction is derivable in this case. In general we cannot expect the compiler to find by himself that the context contains a contradiction, as it is undecidable ([Oury \(2007\)](#); [Goguen et al. \(2006\)](#)).
- In the second case, we simply return the head of the list, disregarding the proof.

1.4.1 Inductive families

The next step is to make constraints such as non-emptiness part of the datatype itself. This capability is provided through inductive families in Coq [Paulin-Mohring \(1993\)](#), which are a similar concept to the generalization of algebraic datatypes to GADTs in functional languages like Haskell [Schrijvers et al. \(2009\)](#). Families provide a way to associate to each constructor a different type, making it possible to give specific information about a value in its type.

Equality

The alma mater of inductive families is the propositional equality `eq` defined as:

```
Inductive eq (A : Type) (x : A) : A → Prop :=
  eq_refl : eq A x x.
```

Equality is a polymorphic relation on A . (The `Prop` sort (or kind) categorizes propositions, while the `Set` sort, equivalent to \star in Haskell categorizes computational types.) Equality is *parameterized* by a value x of type A and *indexed* by another value of type A . Its single constructor states that equality is reflexive, so the only way to build an object of `eq x y` is if $x \sim y$, that is if x is definitionally equal to y .

Now what is the elimination principle associated to this inductive family? It is the good old Leibniz substitution principle:

```
∀ (A : Type) (x : A) (P : A → Type), P x → ∀ y : A, x = y → P y
```

Provided a proof that $x = y$, we can create an object of type $P y$ from an existing object of type $P x$. This substitution principle is enough to show that equality is symmetric and transitive. For example we can use pattern-matching on equality proofs to show:

```
Equations eqt {A} (x y z : A) (p : x = y) (q : y = z) : x = z :=
  eqt x ?(x) ?(x) eq_refl eq_refl := eq_refl.
```

Let us explain the meaning of the non-linear patterns here that we slipped through in the `equal` example. By pattern-matching on the equalities, we have unified x , y and z , hence we determined the *values* of the patterns for the variables to be x . The `?(x)` notation is essentially denoting that the pattern is not a candidate for refinement, as it is determined by another pattern. This particular patterns are called “inaccessible”.

Indexed datatypes

Functions on `vectors` provide more striking examples of this situation. The `vector` family is indexed by a natural number representing the size of the vector:

```
[ Inductive vector (A : Type) : nat → Type := | Vnil : vector A 0 | Vcons : A → ∀ n : nat, vector A n → vector A (S n) ]
```

The empty vector `Vnil` has size `0` while the `cons` operation increments the size by one. Now let us define the usual map on vectors: **Notation** `Vnil` := `Vector.nil`.

```
Notation Vcons := Vector.cons.
```

```
Equations vmap {A B} (f : A → B) {n} (v : vector A n) :
  vector B n :=
  vmap f {n:=?(0)} Vnil := Vnil ;
  vmap f {n:=?(S n)} (Vcons a n v) := Vcons (f a) (vmap f v).
```

Here the value of the index representing the size of the vector is directly determined by the constructor, hence in the case tree we have no need to eliminate

n . This means in particular that the function `vmap` does not do any computation with n , and the argument could be eliminated in the extracted code. In other words, it provides only *logical* information about the shape of v but no computational information.

The `vmap` function works on every member of the `vector` family, but some functions may work only for some subfamilies, for example `vtail`:

Equations `vtail` $\{A\ n\}$ $(v : \text{vector } A\ (S\ n)) : \text{vector } A\ n :=$
`vtail (Vcons a n v') := v'.`

The type of v ensures that `vtail` can only be applied to non-empty vectors, moreover the patterns only need to consider constructors that can produce objects in the subfamily `vector A (S n)`, excluding `Vnil`. The pattern-matching compiler uses unification with the theory of constructors to discover which cases need to be considered and which are impossible. In this case the failed unification of 0 and $S\ n$ shows that the `Vnil` case is impossible. This powerful unification engine running under the hood permits to write concise code where all uninteresting cases are handled automatically.

1.4.2 Derived notions, No-Confusion

For this to work smoothly, the package requires some derived definitions on each (indexed) family, which can be generated automatically using the generic `Derive` command. Here we ask to generate the signature, heterogeneous no-confusion and homogeneous no-confusion principles for vectors:

`Derive NoConfusion for nat.`
`Derive Signature NoConfusion NoConfusionHom for vector.`

The precise specification of these derived definitions can be found in the manual section (§2.1). Signature is used to “pack” a value in an inductive family with its index, e.g. the “total space” of every index and value of the family. This can be used to derive the heterogeneous no-confusion principle for the family, which allows to discriminate between objects in potentially different instances/fibers of the family, or deduce injectivity of each constructor. The `NoConfusionHom` variant derives the homogeneous no-confusion principle between two objects in the *same* instance of the family, e.g. to simplify equations of the form `Vnil = Vnil` $:>$ `vector A 0`. This last principle can only be defined when pattern-matching on the inductive family does not require the `K` axiom and will otherwise fail.

1.4.3 Unification and indexed datatypes

Back to our example, of course the equations and the induction principle are simplified in a similar way. If we encounter a call to `vtail` in a proof, we can use the following elimination principle to simplify both the call and the argument which will be automatically substituted by an object of the form `Vcons - - -`:

$\forall P : \forall (A : \text{Type}) (n : \text{nat}), \text{vector } A\ (S\ n) \rightarrow \text{vector } A\ n \rightarrow \text{Prop},$

```

(∀ (A : Type) (n : nat) (a : A) (v : vector A n),
  P A n (Vcons a v) v) →
∀ (A : Type) (n : nat) (v : vector A (S n)), P A n v (vtail v)

```

As a witness of the power of the unification, consider the following function which computes the diagonal of a square matrix of size $n \times n$.

```

Equations diag {A n} (v : vector (vector A n) n) : vector A n :=
diag {n:=O} Vnil := Vnil ;
diag {n:=(S ?(n))} (Vcons (Vcons a n v) ?(n) v') :=
  Vcons a (diag (vmap vtail v')).

```

Here in the second equation, we know that the elements of the vector are necessarily of size $S\ n$ too, hence we can do a nested refinement on the first one to find the first element of the diagonal.

An issue appears here: the elimination principle can not be proved automatically for `diag`, as the automatic proof generates an ill-formed fixpoint definition. This is because the guard checking of *Coq* is too weak to see through the manipulations of equality necessary for this definition to typecheck. One can however resolve this by using the induction principle of natural numbers:

Next Obligation.

```

induction n. depelim v. simp diag. depelim v. depelim h. constructor.
apply IHn.

```

Defined.

1.4.4 Recursion

Notice how in the `diag` example above we explicitly pattern-matched on the index n , even though the `Vnil` and `Vcons` pattern matching would have been enough to determine these indices. This is because the following definition also fails:

```

Fail Equations diag' {A n} (v : vector (vector A n) n) : vector A n :=
diag' Vnil := Vnil ;
diag' (Vcons (Vcons a n v) ?(n) v') :=
  Vcons a (diag' (vmap vtail v')).

```

Indeed, *Coq* cannot guess the decreasing argument of this fixpoint using its limited syntactic guard criterion: `vmap vtail v'` cannot be seen to be a (large) subterm of v' using this criterion, even if it is clearly “smaller”. In general, it can also be the case that the compilation algorithm introduces decorations to the proof term that prevent the syntactic guard check from seeing that the definition is structurally recursive.

To alleviate this problem, *Equations* provides support for *well-founded* recursive definitions which do not rely on syntactic checks.

The simplest example of this is using the `lt` order on natural numbers to define a recursive definition of identity:

```

Require Import Equations.Subterm.
Equations id (n : nat) : nat :=

```

```

id n by rec n lt :=
id 0 := 0;
id (S n') := S (id n').

```

Here `id` is defined by well-founded recursion on `lt` on the (only) argument `n` using the `by rec` node. At recursive calls of `id`, obligations are generated to show that the arguments effectively decrease according to this relation. Here the proof that $n' < S\ n'$ is discharged automatically.

Wellfounded recursion on arbitrary dependent families is not as easy to use, as in general the relations on families are *heterogeneous*, as the must related inhabitants of potentially different instances of the family. `Equations` provides a `Derive` command to generate the subterm relation on any such inductive family and derive the well-foundedness of its transitive closure, which is often what's required. This provides course-of-values or so-called “mathematical” induction on these objects, mimicking the structural recursion criterion in the logic.

Derive Subterm for vector.

For vectors for example, the relation is defined as:

```

Inductive t_direct_subterm (A : Type) :
  ∀ n n0 : nat, vector A n → vector A n0 → Prop :=
  t_direct_subterm_1_1 : ∀ (h : A) (n : nat) (H : vector A n),
    t_direct_subterm A n (S n) H (Vcons h H)

```

That is, there is only one recursive subterm, for the subvector in the `Vcons` constructor. We also get a proof of:

```

Check well_founded_t_subterm : ∀ A, WellFounded (t_subterm A).

```

The relation is actually called `t_subterm` as `vector` is just a notation for `Vector.t`. `t_subterm` itself is the transitive closure of the relation seen as an homogeneous one by packing the indices of the family with the object itself. Once this is derived, we can use it to define recursive definitions on vectors that the guard condition couldn't handle. The signature provides a `signature_pack` function to pack a vector with its index. The well-founded relation is defined on the packed vector type.

```

Module UNZIPVECT.
Context {A B : Type}.

```

We can use the packed relation to do well-founded recursion on the vector. Note that we do a recursive call on a subterm of type `vector A n` which must be shown smaller than a `vector A (S n)`. They are actually compared at the packed type `{ n : nat & vector A n }`.

```

Equations unzip {n} (v : vector (A × B) n) : vector A n × vector B n
:=
  unzip v by rec (signature_pack v) (@t_subterm (A × B)) :=
  unzip Vnil := (Vnil, Vnil) ;
  unzip (Vector.cons (pair x y) n v) with unzip v := {
    | pair xs ys := (Vector.cons x xs, Vector.cons y ys) }.
End UNZIPVECT.

```

For the diagonal, it is easier to give n as the decreasing argument of the function, even if the pattern-matching itself is on vectors:

```

Equations diag' {A n} (v : vector (vector A n) n) : vector A n :=
  diag' {n:=n} v by rec n lt :=
  diag' Vnil := Vnil ;
  diag' (Vcons (Vcons a n v) ?(n) v') :=
    Vcons a (diag' (vmap vtail v')).

```

One can check using **Extraction** `diag'` that the computational behavior of `diag'` is indeed not dependent on the index n .

While this was just mimicking simple structural recursion, we can of course use this for more elaborate termination arguments. We put ourselves in a section to parameterize a *skip* function by a predicate:

Section Skip.

```

Context {A : Type} (p : A → bool).
Equations skip_first {n} (v : vector A n) : &{ n : nat & vector A n } :=
  skip_first Vnil := &(0 & Vnil);
  skip_first (Vcons a n v') <= p a => {
    | true => skip_first v';
    | false => &(_ & Vcons a v') }.

```

It is relatively straitforward to show that *skip* returns a (large) subvector of its argument

```

Lemma skip_first_subterm {n} (v : vector A n) : clos_refl _ (t_subterm _)
(skip_first v) &(_ & v).

```

Proof.

```

  funelim (skip_first v).
  constructor 2.
  depelim H.
  constructor 1.
  eapply clos_trans_stepr. simpl.
  apply (t_direct_subterm_1_1 _ _ (&(_ & t).2)). apply H.
  rewrite <- H. constructor. eauto with subterm_relation.
  constructor 2.

```

Qed.

End Skip.

Opaque skip_first.

This function takes an unsorted vector and returns a sorted vector corresponding to it starting from its head a , removing all elements smaller than a and recursing.

```

Equations sort {n} (v : vector nat n) : &{n' : _ & vector nat n'} :=
  sort v by rec (signature_pack v) (t_subterm nat) :=
  sort Vnil := &(_ & Vnil );
  sort (Vcons a n v) := let sk := skip_first (fun x => Nat.leb x a) v in &(_ &
  Vcons a (sort sk.2).2).

```

Here we prove that the recursive call is correct as skip preserves the size of its argument

Next Obligation.

```
red. simpl.
eapply clos_trans_stepr_refl.
simpl. apply (t_direct_subterm_1_1 _ _ (&(_ & v).2)).
refine (skip_first_subterm _ _).
```

Qed.

To prove it we need a few supporting lemmas, we first write a predicate on vectors equivalent to *List.forall*.

```
Equations forall_vect {A} (p : A → bool) {n} (v : vector A n) : bool :=
forall_vect _ Vnil := true;
forall_vect p (Vcons x n v) := p x && forall_vect p v.
```

Require Import Bool.

By functional elimination it is easy to prove that this respects the implication order on predicates

```
Lemma forall_vect_impl {A} p p' {n} (v : vector A n)
(fp : ∀ x, p x = true → p' x = true) :
forall_vect p v = true → forall_vect p' v = true.
```

Proof.

```
funelim (forall_vect p v). auto.
simp forall_vect. rewrite !andb_true_iff; intuition auto.
```

Qed.

We now define a simple-minded sorting predicate

```
Inductive sorted : ∀ {n}, vector nat n → Prop :=
| sorted_nil : sorted Vnil
| sorted_cons x n (v : vector nat n) :
  forall_vect (fun y ⇒ Nat.leb x y) v = true →
  sorted v → sorted (Vcons x v).
```

Again, we show this by repeated functional eliminations.

```
Ltac simple_funelim c :=
let elimc := get_elim c in
let elimfn := match elimc with fun_elim (f:=?f) ⇒ constr:(f) end in
let elimn := match elimc with fun_elim (n:=?n) ⇒ constr:(n) end in
let elimt := make_refine elimn elimc in
(unshelve refine_ho elimt || epose elimt); simpl; intros.
```

```
Lemma fn_sorted n (v : vector nat n) : sorted (sort v).2.
```

Proof.

```
revert n v.
```

```
simple_funelim @sort. The first elimination just gives the two sort cases.
```

- constructor.

```
- constructor; auto.
```

Here we have a nested call to `skip_first`, for which the induction hypothesis holds:

```

H : sorted (sort (skip_first (fun x : nat => x <=? h) t).2).2
=====
forall_vect (fun y : nat => h <=? y) (sort (skip_first (fun x : nat => x <=?
h) t).2).2 = true

```

We can apply functional elimination likewise, even if the predicate argument is instantiated here.

```

revert H.
simple_funelim (@skip_first _ (fun x : nat => Nat.leb x h)).
revert H. unshelve refine_ho (y _ t); simpl. Unshelve. simpl. simp
sort. intros.
simpl. intros. simpl in *. auto. simpl. intros.
simp sort forall_vect. rewrite andb_true_iff.
split; auto. admit. simp sort in H. simpl in H. depelim H.
eapply forall_vect_impl in H. eauto.
intros. simpl.
(* FIXME *)
Admitted.

(*      t);   simp   sort   forall_vect   in   *;   simpl   in   *.   *)

(*      apply   H.   rewrite   Heqcall.   auto.   *)
(*      (* *   After   further   simplifications,   we   get:   [
*)
(*      Heq   :   (h0   <=?   h)   =   false   *)
(*      H   :   sorted   (Vcons   h0   (sort   (skip_first   (fun   x   :   nat   =>   x
(*
(*      =====   *)
(*      (h   <=?   h0)   &&   forall_vect   (fun   y   :   nat   =>   h   <=?   y)   (sort
(*      ]]   *)

(*      This   requires   inversion   on   the   sorted   predicate   to   find   out
(*      h0   is   smaller   than   all   of   fn (skip_first ...),   and   hence   h
(*      This   is   just   regular   reasoning.   Just   note   how   we   got   to   th
(*      two   invocations   of   funelim.   *)   *)
(*      depelim   H.   *)
(*      revert   H.   refine   (DepElim.eq_simplification_signal_dep   -   -   -   -
(*      simpl.   Transparent   skip_first.   simpl.   *)
(*      rewrite   andb_true_iff.   *)

```

```

(*      enough    (h    <=?    h0    =    true).    split;    auto.    *)

(*      eapply    forall_vect_impl    in    H.    *)
(*      apply    H.    *)
(*      intros    x    h0x.    simpl.    rewrite    Nat.leb_le    in    *.    omega.    *)

(*      rewrite    Nat.leb_le,    Nat.leb_nle    in    *.    omega.    *)

(*      Qed.    *)

```

Pattern-matching and axiom K

To use the K axiom with `Equations`, one must first require the `DepElimK` module. `Require Import Equations.DepElimK.`

`Module KAXIOM.`

By default we disallow the K axiom, but it can be set.

`Set Equations WithK.`

In this case the following definition uses the K axiom just imported.

```

Equations K {A} (x : A) (P : x = x → Type) (p : P eq_refl) (H : x = x)
: P H :=
  K x P p eq_refl := p.

```

However, types enjoying a provable instance of the K axiom are fine. This relies on an instance of the `EqDec` typeclass for natural numbers. Note that the computational behavior of this definition on open terms is not to reduce to `p` but pattern-matches on the decidable equality proof. However the defining equation still holds as a *propositional* equality.

```

Unset Equations WithK.
Set Equations WithKDec.

Equations K' (x : nat) (P : x = x → Type) (p : P eq_refl) (H : x = x) : P
H :=
  K' x P p eq_refl := p.

Print Assumptions K'. (*      Closed    under    the    global    context    *)

End KAXIOM.

```

Going further More examples are available at <http://mattam82.github.io/Coq-Equations/examples>

Chapter 2

Manual

2.1 The Equations Vernacular

The `Equations` command takes a few options using the syntax

`Equations(opts) f ...`

- **noind**: Do not generate the inductive graph of the function and the derived eliminator.
- **noeqns**: Do not generate the equations corresponding to the (expanded) clauses of the program. This implies **noind**.
- **struct *x***: Declare the function structurally recursive on variable *x*.

The syntax of `EQUATIONS` itself is described in [Mangin and Sozeau \(2017\)](#).

2.2 Global Options

The `Equations` command obeys a few global options:

- **Equations Transparent**: governs the opacity of definitions generated by `Equations`. By default this is off and means that definitions are declared *opaque* for reduction, avoiding spurious unfoldings when using the `simpl` tactic for example. The `simpl c` tactic is favored in this case to do simplifications using the equations generated for `c`.
- **Equations WithKDec**: governs the use of instances of `K` derived by the user using the decidable equality class `Equations.EqDec.EqDec`. By default *off*. When switched on, equations will look for an instance of **EqDec** when solving equalities of the form

$$\forall(e : x = x :> A), Pe$$

, i.e. to apply the deletion rule to such equations, or report an error if it cannot find any. Note that when this option is on, the computational behavior of EQUATIONS definitions on open terms does not follow the clauses: it might block on the decidable equality test. The rewriting equations and functional elimination principle can still be derived though and are the preferred way to reason on the definition.

- **Equations WithK**: governs the use of the K axiom. By default *off*. Users *must* require the `Equations.DepElimK` module before using this option, to load the K axiom in the current module. When switched on, equations will use the axiom if it needs to simplify reflexivity proofs

$$\forall(e : x = x \Rightarrow A), P \ e$$

and no instance of **EqDec** is available. The computational behavior of definitions using the axiom changes entirely: their reduction will get stuck even on closed terms. It is advised to keep such definitions opaque and use the derived rewriting equations and functional elimination principle to reason on such definitions.

2.3 Derive

EQUATIONS comes with a suite of deriving commands that take inductive families and generate definitions based on them. The common syntax for these is:

Derive **C**₁ ... **C**_n for **ind**₁ ... **ind**_n.

Which will try to generate an instance of type class **C** on inductive type **Ind**. We assume **ind**_i : $\Pi \Delta.s$. The derivations provided by EQUATIONS are:

- **DependentEliminationPackage**: generates the dependent elimination principle for the given inductive type, which can differ from the standard one generated by COQ. It derives an instance of the class `Equations.DepElim.DependentEliminationPackage`.
- **Signature**: generate the signature of the inductive, as a sigma type packing the indices Δ (again as a sigma type) and an object of the inductive type. This is used to produce homogeneous constructions on inductive families, by working on their packed version (total space in HoTT lingo). It derives an instances of the class `Equations.Signature.Signature`.
- **NoConfusion**: generate the no-confusion principle for the given family, as an heterogeneous relation. It embodies the discrimination and injectivity principles for the total space of the given inductive family: i.e. $\Sigma \Delta, \mathbf{I} \bar{\Gamma} \Delta$ for a family $\mathbf{I} : \forall \Gamma, \Delta \rightarrow \mathbf{Type}$ where Γ are (uniform) parameters of the inductive and Δ its indices.

It derives an instance of the class `Equations.DepElim.NoConfusionPackage`.

- **NoConfusionHom**: generate the *homogeneous* no-confusion principle for the given family, which embodies the discrimination and injectivity principles for (non-propositional) inductive types. This principle can be derived if and only if pattern-matching on the inductive family does not involve the K axiom. In case of success it generates an instance of the class `Equations.DepElim.NoConfusionPackage` for the type $\mathbf{I} \Delta \Gamma$ applicable to equalities of two objects in the *same* instance of the family \mathbf{I} .
- **EqDec** This derives a decidable equality on C , assuming decidable equality instances for the parameters and supposing any primitive inductive type used in the definition also has decidable equality. If successful it generates an instance of the class (in `Equations.EqDec`):

```
Class EqDec (A : Type) :=
  eq_dec : forall x y : A, { x = y } + { x <> y }.
```

- **Subterm**: this generates the direct subterm relation for the inductive (assuming it is in `Set` or `Type`) as an inductive family. It then derives the well-foundedness of this relation and wraps it as an homogeneous relation on the signature of the datatype (in case it is indexed). These relations can be used with the `by rec` clause of equations. It derives an instance of the class `Equations.Classes.WellFounded`.

Bibliography

- Ana Bove and Alexander Krauss and Matthieu Sozeau. *Partiality and recursion in interactive theorem provers – an overview*. *Mathematical Structures in Computer Science*, FirstView:1–51, 2 2015. ISSN 1469-8072.
- Gilles Barthe, Julien Forest, David Pichardie, and Vlad Rusu. *Defining and Reasoning About Recursive Functions: A Practical Tool for the Coq Proof Assistant*. *Functional and Logic Programming*, pages 114–129, 2006.
- Coq. The Coq proof assistant. coq.inria.fr.
- Healfdene Goguen, Conor McBride, and James McKinna. *Eliminating Dependent Pattern Matching*. In Kokichi Futatsugi, Jean-Pierre Jouannaud, and José Meseguer, editors, *Essays Dedicated to Joseph A. Goguen*, volume 4060 of *Lecture Notes in Computer Science*, pages 521–540. Springer, 2006.
- Cyprien Mangin and Matthieu Sozeau. *Equations Reloaded*. Submitted, 2017.
- Conor McBride and James McKinna. *The view from the left*. *J. Funct. Program.*, 14(1):69–111, 2004.
- Ulf Norell. *Towards a practical programming language based on dependent type theory*. PhD thesis, Department of Computer Science and Engineering, Chalmers University of Technology, SE-412 96 Göteborg, Sweden, September 2007.
- Nicolas Oury. *Pattern matching coverage checking with dependent types using set approximations*. In Aaron Stump and Hongwei Xi, editors, *PLPV*, pages 47–56. ACM, 2007.
- Christine Paulin-Mohring. *Inductive Definitions in the System Coq - Rules and Properties*. In *Typed Lambda Calculi and Applications*, volume 664 of *Lecture Notes in Computer Science*, pages 328–345. Springer-Verlag, 1993.
- Tom Schrijvers, Simon P. Jones, Martin Sulzmann, and Dimitrios Vytiniotis. *Complete and decidable type inference for GADTs*. In *ICFP '09: Proceedings of the 14th ACM SIGPLAN international conference on Functional programming*, pages 341–352, New York, NY, USA, 2009. ACM.

Matthieu Sozeau. **Program-ing Finger Trees in Coq**. In *ICFP'07*, pages 13–24, Freiburg, Germany, 2007. ACM Press.

Matthieu Sozeau. **Equations: A Dependent Pattern-Matching Compiler**. In *First International Conference on Interactive Theorem Proving*. Springer, July 2010.