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Well-founded recursion done right
(Coq programming pearl)

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Abstract
Several Coq libraries and extensions support the definition of non-structural recursive functions using well-founded orderings for termination. After pointing out some drawbacks of these existing approaches, we advocate going back to the basics and defining recursive functions by explicit structural induction on a proof of accessibility of the principal recursive argument.

1 Introduction
Coq and other proof assistants featuring inductive predicates provide excellent support for proofs by well-founded induction: to prove \( \forall x, P(x) \), just show \( P(x) \) assuming the induction hypothesis \( \forall y < x, P(y) \), where \(< \) is a well-founded ordering. The proof is constructive and proceeds by structural induction on a proof term for the “accessibility” of \( x \), namely the inductive fact that all descending chains originating from \( x \) are finite.

In this note, we focus on well-founded recursion: the definition of recursive functions that terminate not because recursive calls are made on structural subterms of the principal argument, but because they are made on principal arguments that are strictly smaller in a well-founded ordering. Examples of such functions include computing greatest common denominators by Euclid’s algorithm (shown below), computing least fixed points by Tarski iteration (appendix A), and DFS traversal of a DAG (appendix B).

2 Evaluating the existing approaches
When developing verified software in Coq, such as CompCert [4], function definitions are held to more stringent legibility requirements than proof terms. I found the following properties to be highly desirable:

1. The function definition should be easy to read for a functional programmer and make it obvious which algorithm is used. This rules out most definitions by tactics. Even the use of fixed-point combinators such as the Fix combinator from Coq’s standard library hurts legibility.

2. It should be easy to prove properties of the function after its definition. We should not be forced to prove all needed properties during the definition. This is a known problem with the Program mechanism.

3. The function definition and the proofs of its properties should not involve axioms. This is a known problem for curried multiple-argument functions defined with the Fix combinator: the Fix_eq proof rule has an extensionality hypothesis that cannot be proved without the function extensionality axiom.

4. Extraction should generate OCaml code that contains no extraneous computations and looks natural to an OCaml programmer. Tactics tend to generate awful code. Program Fixpoint and Equations leave unnecessary and noisy let bindings in extracted code.

Table 1 evaluates five known ways to implement well-founded recursion in Coq with respect to these properties: tactics in proof mode [2, §16.4] [3, §7.1], the Fix combinator from Coq’s standard library [1], the Function mechanism [6, §4.1.4], the Program Fixpoint mechanism [6, §2.2.9], and the Equations package [5]. Sadly, the only way that ticks all the box is Function, which is documented as “legacy functionality” [6, p. 585], and its claimed successor Equations is not quite as good extraction-wise yet.

3 Proposed approach
After 20 years of using and teaching a mixture of Fix, Function and Program Fixpoint, I realized that there is a simpler approach to well-founded recursion that meets requirements 1–4 above and requires no extension to Coq: just go back to the basics, namely structural recursion over accessibility proofs.

Here is an example for the GCD function. Start with the naive recursive definition that is rejected because it is not structurally recursive:

```
Fail Fixpoint gcd_rec (a b : nat): nat :=
  if Nat.eq_dec b 0 then a
  else gcd_rec b (a mod b).
```

```
Fail Definition gcd (a b : nat): nat :=
  if b <=? a then gcd_rec a b
  else gcd_rec b a.
```

Then, add an argument that is a proof of accessibility of \( b \), the argument that decreases at recursive calls. The function becomes structurally recursive on this proof.

```
Fixpoint gcd_rec (a b : nat) (ACC : Acc lt b)
{struct ACC : nat :=
  if Nat.eq_dec b 0 then a
  else gcd_rec b (a mod b) .
```

```
Now it remains to fill the hole _ with a proof of accessibility of \( \text{a mod } \text{b} \). The proof must be transparent and return a structural subterm of ACC, otherwise Coq rejects the recursion as not structural. A reliable way to ensure this is to explicitly use the ACC_inv lemma from the Coq standard library:

\[
\text{Fixpoint gcd_rec (a b: nat) (ACC: Acc lt b)} =
\begin{cases} 
\text{if } \text{Nat.eq_dec } \text{b } 0 \text{ then } \text{a } \text{else } \text{gcd_rec } \text{b } (\text{a mod b}) \ (\text{Acc_inv ACC } _). 
\end{cases}
\]

For reference, ACC_inv is just the inversion principle for the Acc inductive predicate:

\[
\text{Acc_inv: forall } (A: \text{Type}) \ (R: A \to A \to \text{Prop}) \ (x: A), \left( \begin{array}{l}
\text{Acc } R \ x \ \to \ \forall y, A, \ \text{R } y \ x \ \to \ \text{Acc } R \ y \\
\end{array} \right)
\]

Now, the hole in gcd_rec is any proof of \( \text{a mod } \text{b} < \text{b} \), and it can be opaque. I often use Program to fill these holes, but an explicit proof works well too, especially for teaching purposes.

\[
\text{Remark gcd_oblig:}
\left( \begin{array}{l}
\forall a b \ (\text{nat}) \ (\text{NE: b } \leq 0), \ \text{a mod b } < \text{b} \\
\end{array} \right)
\]

\[
\text{Proof.}
\begin{array}{l}
\text{intros. apply } \text{Nat.mod_bound_pos; lia. Qed.}
\end{array}
\]

Properties of the recursive function gcd_rec are easily proved by well-founded induction. It is tempting to do an induction on the ACC accessibility proof argument, to mimick the structure of the function definition, but this quickly runs into the usual problems with dependent induction. Instead, we just do well-founded induction over the decreasing argument b, followed by a destruction of the ACC argument and simplification, which unrolls the recursive definition — just like the Fix_eq lemma from the Coq standard library but without the unprovable-without-axioms extensionality hypothesis.

\[
\text{Lemma gcd_rec_correct: forall } b a \ (\text{ACC, b } \leq a \to \text{is_gcd } (\text{gcd_rec } a b \ \text{ACC }) a b).
\]

\[
\text{Proof.}
\begin{array}{l}
\text{induction } b \ \text{using } (\text{well_founded_induction lt_wf}); \\
\text{intros; destruct } \text{ACC; simpl.}
\end{array}
\]

\[
\begin{array}{l}
\text{destruct } (\text{Nat.eq_dec } b \ 0). \\
\text{(* base case *)}
\end{array}
\]

\[
\begin{array}{l}
\text{destruct } (\text{Nat.eq_dec } b \ a).
\end{array}
\]

\[
\text{Qed.}
\]

Finally, extraction produces optimal OCaml code, just by erasing the ACC argument because it has sort Prop.

\[
\text{let rec gcd_rec } a b =
\begin{array}{l}
\text{if } \text{Nat.eq_dec } b \ 0 \text{ then } \text{a } \text{else } \text{gcd_rec } b (\text{Nat.modulo } a b)
\end{array}
\]

\[
\begin{array}{l}
\text{let gcd } a b =
\begin{array}{l}
\text{if } \text{Nat.leb } b \ a \text{ then } \text{gcd_rec } a b \text{ else } \text{gcd_rec } b a
\end{array}
\end{array}
\]


terms (1) Legibility of definitions
(2) Ease of proving properties
(3) No axioms used
(4) Legibility of extracted code

<table>
<thead>
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\textbf{Table 1.} Comparing various approaches to well-founded recursive definitions. ✔: good, ≈: passable, ✘: bad.

\textbf{4 Conclusions}

That’s all there is to it! I believe this simple, back-to-the-basics approach makes non-structural recursive functions in Coq less mysterious and more accessible, both in the classroom and for developing verified software in Coq.

\textbf{References}


A  Additional example: Computing least fixed points by Tarski iteration

(* A semi-lattice *)
Variable A: Type.
Variable bot: A.
Hypothesis le_trans: forall x y z, le x y -> le y z -> le x z.
Hypothesis le_bot: forall x, le bot x.
Hypothesis eq_dec: forall (x y: A), {x=y} + {x<>y}.

(* There are no infinite ascending chains *)
Let gt (x y: A): Prop := x <> y /\ le y x.
Hypothesis wf: well_founded gt.

(* A monotonic operator *)
Variable F: A -> A.
Hypothesis F_mono: forall x y, le x y -> le (F x) (F y).

(* Tarski iteration from a pre-fixed point [x] *)
Program Fixpoint iter (x: A) (PRE: le x (F x)) (ACC: Acc gt x) {struct ACC}: A :=
  let x' := F x in
  match eq_dec x x' return _ with
  | left EQ => x
  | right NE => iter x' _ (Acc_inv ACC _)
  end.
Next Obligation. split; auto. Qed.

Program Definition lfp: A := iter bot _ (wf bot).

(* The result is a fixed point. *)
Theorem lfp_eq: F lfp = lfp.
Proof.
  unfold lfp. generalize bot lfp_obligation_1 (wf bot).
  induction bot0 using (well_founded_induction wf).
  rename bot0 into x. intros PRE ACC. destruct ACC; simpl.
  destruct (eq_dec x (F x)).
  - auto.
  - apply H. split; auto.
Qed.

(* The result is the smallest fixed point. *)
Theorem lfp_least: forall z, F z = z -> le lfp z.
Proof.
  (* exercise *)
Qed.

B  Additional example: DFS traversal of an acyclic graph

(* A directed graph *)
Variable node: Type.
Variable successors: node -> list node.
Variable eq_node: forall (x y: node), {x=y} + {x<>y}.

(* The 'x is a successor of y' relation *)
Definition succ (x y : node): Prop := In x (successors y).

(* The graph is acyclic iff there are no infinite chains of successors *)
Hypothesis acyclic : well_founded succ.

(* Preorder enumeration of the nodes, using DFS traversal *)
(* Note that the recursive call to [dfs] must have its accessibility argument
  of the form [Acc_inv A _] so that it is recognized as a structural subterm of [A].
  This leads to using [incl l (successors x)] as the precondition for
  the iteration over the list of successors of [x]. *)

Program Fixpoint dfs (x: node) (accu: list node) (A: Acc succ x) {struct A}: list node :=
  if In_dec eq_node x accu then accu else
  let fix dfs_list (l: list node) (accu: list node) {struct l} : incl l (successors x) -> list node :=
    match l return _ with
    | nil => fun INCL => accu
    | y :: l => fun INCL => dfs_list l (dfs y accu (Acc_inv A _)) _
  end in
  x :: dfs_list (successors x) accu _ .

Next Obligation. eapply incl_cons_inv; eauto. Qed.
Next Obligation. eapply incl_refl; eauto. Qed.

(* A key property of [dfs]. *)

Definition succ_closed (l: list node): Prop :=
  forall x y, In x l -> succ y x -> In y l.

Lemma dfs_correct: forall x l A,
  succ_closed l ->
  forall y, In y (dfs x l A) <-> In y l \ clos_refl_trans _ succ y x.
Proof.
  (* exercise *)
Qed.