An Efficient and Flexible Evidence-Providing Polynomial Solver in Agda

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Abstract

We provide an efficient implementation of a polynomial solver in the programming language Agda, and demonstrate its use in a variety of applications.

Contents

1 Introduction

Dependently typed languages such as Agda [9] and Coq [12] allow programmers to write machine-checked proofs as programs. They provide a degree of reassurance that handwritten proofs cannot, and allow for exploration of abstract concepts in a machine-assisted environment.

We will describe an efficient implementation of an automated prover for equalities in ring and ring-like structures, and show how it can be extended for use in settings more exotic than simple equality.

2 Monoids

Before describing the ring solver, first we will explain the simpler case of a monoid solver.

A monoid is a set equipped with a binary operation, $\bullet$, and a distinguished element ϵ, which obeys the laws:

$$x \bullet (y \bullet z) = (x \bullet y) \bullet z \quad \text{(Associativity)}$$
$$x \bullet \epsilon = x \quad \text{(Left Identity)}$$
$$\epsilon \bullet x = x \quad \text{(Right Identity)}$$

```
record Monoid c ℓ : Set (suc (c ⊔ ℓ)) where
  infixl 7 _•_
  infix 4 _≈_
  field
    Carrier   : Set c
    _≈_       : Rel Carrier ℓ
    _•_       : Op₂ Carrier
    ε         : Carrier
    isMonoid  : IsMonoid _≈_ _•_ ε
```

Figure 1: The definition of Monoid in the Agda Standard Library [2]

2.1 Equality Proofs

Monoids can be represented in Agda in a straightforward way, as a record (see figure 1).

These come equipped with their own equivalence relation, according to which proofs for each of the monoid laws are provided. Using this, we can prove identities like the one in figure 2.

```
ident : ∀ w x y z
      → w • (((x • ε) • y) • z)
      ≈ (w • x) • (y • z)
```

Figure 2: Example Identity

While it seems like an obvious identity, the proof is somewhat involved (figure 3).

The syntax mimics that of normal, handwritten proofs: the successive "states" of the expression are interspersed with equivalence proofs (in the brackets). Perhaps surprisingly, the syntax is not built-in: it's simply defined in the standard library.

Despite the powerful syntax, the proof is mechanical, and it's clear that similar proofs would become tedious with more variables or more complex algebras (like rings). Luckily, we can automate the procedure.

```
ident w x y z =
  begin
    w • (((x • ε) • y) • z)
  ≈⟨ refl ⟨ •-cong ⟩ assoc (x • ε) y z ⟩
    w • ((x • ε) • (y • z))
  ≈⟨ sym (assoc w (x • ε) (y • z)) ⟩
    (w • (x • ε)) • (y • z)
  ≈⟨ (refl ⟨ •-cong ⟩ identityʳ x) ⟨ •-cong ⟩ refl ⟩
    (w • x) • (y • z)
  ∎
```

Figure 3: Proof of identity in figure 2

2.2 Canonical Forms

Automation of equality proofs like the one above can be accomplished by first rewriting both sides of the equation into a canonical form. This form depends on the particular algebra used in the pair of expressions. For instance, a suitable canonical form for monoids is lists.

```
infixr 5 _::_
data List (i : ℕ) : Set where
  [] : List i
  _::_ : Fin i → List i → List i
```

This type can be thought of as an AST for the "language of lists". Crucially, it's equivalent to the "language of monoids": this is the language of expressions written using only variables and the monoid operations, like the expressions in figure 2. The neutral element and binary operator have their equivalents in lists: ϵ is simply the empty list, whereas $\bullet$ is list concatenation.

```
infixr 5 _++_
_++_ : ∀ {i} → List i → List i → List i
[] ++ ys = ys
(x :: xs) ++ ys = x :: xs ++ ys
```

We can translate between the language of lists and monoid expressions [1] with μ and η.

[1]For simplicity's sake, instead of curried functions of n

```
_μ : ∀ {i} → List i → Vec Carrier i → Carrier
([] μ) ρ = ε
((x ∷ xs) μ) ρ = lookup x ρ • (xs μ) ρ

infix 9 η_
η_ : ∀ {i} → Fin i → List i
η x = x ∷ []
```

We have one half of the equality so far: that of the canonical forms. As such, we have an "obvious" proof of the identity in figure 2, expressed in the list language (figure 4).

```
obvious
  : (List 4 ∋
  η # 0 ++ (((η # 1 ++ []) ++ η # 2) ++ η # 3))
  ≡ (η # 0 ++ η # 1) ++ (η # 2 ++ η # 3)
obvious = ≡.refl
```

Figure 4: The identity in figure 2, expressed in the list language

2.3 Homomorphism

Figure 4 gives us a proof of the form:

$$\text{lhs}_{list} = \text{rhs}_{list} \tag{1}$$

What we want, though, is the following:

$$\text{lhs}_{mon} = \text{rhs}_{mon} \tag{2}$$

Equation 1 can be used to build equation 2, if we supply two extra proofs:

$$\text{lhs}_{mon} \overset{a}{=} \text{lhs}_{list} = \text{rhs}_{list} \overset{b}{=} \text{rhs}_{mon} \tag{3}$$

The proofs labeled a and b are the task of this section.

arguments, we'll deal with functions which take a vector of length n, that refer to each variable by position, using Fin, the type of finite sets. Of course these two representations are equivalent, but the translation is not directly relevant to what we're doing here: we refer the interested reader to the Relation.Binary.Reflection module of Agda's standard library [2].

```
data Expr (i : ℕ) : Set c where
  _⊕_ : Expr i → Expr i → Expr i
  e   : Expr i
  ν   : Fin i → Expr i
```

Figure 5: The AST for the Monoid Language

```
⟦_⟧ : ∀ {i} → Expr i → Vec Carrier i → Carrier
⟦ x ⊕ y ⟧ ρ = ⟦ x ⟧ ρ • ⟦ y ⟧ ρ
⟦ e ⟧ ρ     = ε
⟦ ν i ⟧ ρ   = lookup i ρ
```

Figure 6: Evaluating the Monoid Language AST

First, we'll define a concrete AST for the monoid language (figure 5). It has constructors for each of the monoid operations (⊕ and e are $\bullet$ and ϵ, respectively), and it's indexed by the number of variables it contains, which are constructed with ν. Converting back to an opaque function is accomplished in figure 6.

Finally, then, we must prove the equivalence of the monoid and list languages. This consists of the following proofs:

$$(\eta x)\mu\rho = [\![\nu x]\!]\,\rho \tag{4}$$
$$(x +\!\!+ y)\mu\rho = [\![x \oplus y]\!]\,\rho \tag{5}$$
$$[\,]\mu\rho = [\![e]\!]\,\rho \tag{6}$$

The latter two proofs comprise a monoid homomorphism.

The proofs are constrained: we are only permitted to use the laws provided in the Monoid record, and the equivalence relation is kept abstract. The fact that we're not simply using propositional equality allows for some interesting applications (see section 7), but it also removes some familiar tools we may reach for in proofs. Congruence in particular must be specified explicitly: the combinator •-cong is provided for this purpose. With this understood, the proofs can be written:

```
conv : ∀ {i} → Expr i → List i
conv (x ⊕ y) = conv x ++ conv y
conv e = []
conv (ν x) = η x

++-hom : ∀ {i} (x y : List i)
         → (ρ : Vec Carrier i)
         → ((x ++ y) μ) ρ ≈ (x μ) ρ • (y μ) ρ
++-hom [] y ρ = sym (identityˡ _)
++-hom (x :: xs) y ρ =
  begin
    lookup x ρ • ((xs ++ y) μ) ρ
  ≈⟨ refl ⟨ •-cong ⟩ ++-hom xs y ρ ⟩
    lookup x ρ • ((xs μ) ρ • (y μ) ρ)
  ≈⟨ sym (assoc _ _ _) ⟩
    lookup x ρ • (xs μ) ρ • (y μ) ρ
  ■

correct : ∀ {i}
        → (x : Expr i)
        → (ρ : Vec Carrier i)
        → (conv x μ) ρ ≈ ⟦ x ⟧ ρ
correct (x ⊕ y) ρ =
  begin
    ((conv x ++ conv y) μ) ρ
  ≈⟨ ++-hom (conv x) (conv y) ρ ⟩
    (conv x μ) ρ • (conv y μ) ρ
  ≈⟨ •-cong (correct x ρ) (correct y ρ) ⟩
    ⟦ x ⟧ ρ • ⟦ y ⟧ ρ
  ■
correct e ρ = refl
correct (ν x) ρ = identityʳ _
```

2.4 Usage

Combining all of the components above, with some plumbing provided by the Relation.Binary.Reflection module, we can finally automate the solving of the original identity in figure 2:

```
ident′ : ∀ w x y z
       → w • (((x • ε) • y) • z)
       ≈ (w • x) • (y • z)
ident′ = solve 4
  ( λ w x y z
    → w ⊕ (((x ⊕ e) ⊕ y) ⊕ z)
    ⊜ (w ⊕ x) ⊕ (y ⊕ z))
  refl
```

2.5 Reflection

One annoyance of the automated solver is that we have to write the expression we want to solve twice: once in the type signature, and again in the argument supplied to solve. Agda can infer the type signature:

```
ident-infer : ∀ w x y z → _
ident-infer = solve 4
  ( λ w x y z
    → w ⊕ (((x ⊕ e) ⊕ y) ⊕ z)
    ⊜ (w ⊕ x) ⊕ (y ⊕ z))
  refl
```

But we would prefer to write the expression in the type signature, and have it infer the argument to solve, as the expression in the type signature is the desired equality, and the argument to solve is something of an implementation detail.

This inference can be accomplished using Agda's reflection mechanisms.

Fill in reflection section

3 A Polynomial Solver

We now know the components required for an automatic solver for some algebra: a canonical form, a concrete representation of expressions, and a proof of correctness. We now turn our focus to polynomials.

Prior work in this area includes [11], [8], [13], [1], and [10], but perhaps the state-of-the-art (at least in terms of efficiency) is Coq's `ring` tactic [12], which is based on an implementation described in [4].

That implementation has a number of optimizations which dramatically improve the complexity of evaluation, but it also includes a careful choice of algebra which allows for maximum reuse. The choice of algebra has been glossed over thus far, but it is an important design decision: choose one with too many laws, and the solver becomes unusable for several types; too few, and we may miss out on normalization opportunities.

The algebra defined in [4] is that of an *almost-ring*. This is a ring-like algebra, which discards the requirement that negation is an inverse $(x + (-x) = 0)$. Instead, it merely requires that negation distribute over addiction and multiplication appropriately. This allows the solver to be used with non-negative types, like $\mathbb{N}$, where negation is simply the identity function. Also, because the implementation uses coefficients in the underlying ring, we lose no opportunities for normalization, as identities like $x + (-x) = 0$ will indeed compute.

4 Horner Normal Form

The canonical representation of polynomials is a list of coefficients, least significant first ("Horner Normal Form"). Our initial attempt at encoding this representation will begin like so:

```
open import Algebra

module Dense {ℓ} (coeff : RawRing ℓ) where
  open RawRing coeff
```

The entire module is parameterized by the choice of coefficient. This coefficient should support the ring operations, but it is "raw", i.e. it doesn't prove the ring laws. The operations on the polynomial itself are defined like so[2]:

```
Poly : Set ℓ
Poly = List Carrier

_⊞_ : Poly → Poly → Poly
[] ⊞ ys = ys
(x :: xs) ⊞ [] = x :: xs
(x :: xs) ⊞ (y :: ys) = x + y :: xs ⊞ ys

_⊠_ : Poly → Poly → Poly
[] ⊠ ys = []
(x :: xs) ⊠ [] = []
(x :: xs) ⊠ (y :: ys) =
  x * y :: (map (x *_) ys ⊞ (xs ⊠ (y :: ys)))
```

[2]Symbols chosen for operators use the following mnemonic:

1. Operators preceded with "ℕ." are defined over $\mathbb{N}$; e.g. ℕ.+, ℕ.∗.
2. Plain operators, like + and ∗, are defined over the coefficients.
3. Boxed operators, like ⊞ and ⊠, are defined over polynomials.
4. Operators which are boxed on one side are defined over polynomials on the corresponding side, and the coefficient on the other; e.g. ⋉, ⋊.

4.1 Sparse Horner Normal Form

As it stands, the above representation has two problems:

Redundancy The representation suffers from the problem of trailing zeroes. In other words, the polynomial $2x$ could be represented by any of the following:

$$0, 2$$
$$0, 2, 0$$
$$0, 2, 0, 0$$
$$0, 2, 0, 0, 0, 0, 0$$

This is a problem for a solver: the whole *point* is that equivalent expressions are represented the same way.

Inefficiency Expressions will tend to have large gaps, full only of zeroes. Something like x^5 will be represented as a list with 6 elements, only the last one being of interest. Since addition is linear in the length of the list, and multiplication quadratic, this is a major concern.

In [4], the problem is addressed primarily from the efficiency perspective: they add a field for the "power index". For our case, we'll just store a list of pairs, where the second element of the pair is the power index[3].

[3]In [4], the expression $(c, i) :: P$ represents $P \times X^i + c$. We found that $X^i \times (c + X \times P)$ is a more natural translation, and it's what we use here. A power index of i in this representation is equivalent to a power index of $i + 1$ in [4].

As an example, the polynomial:

$$3 + 2x^2 + 4x^5 + 2x^7$$

Will be represented as:

$$(3, 0), (2, 1), (4, 2), (2, 1)$$

Or, mathematically:

$$x^0(3 + xx^1(2 + xx^2 * (4 + xx^1(2 + x0))))$$

4.1.1 Uniqueness

While this form solves our efficiency problem, we still have redundant representations of the same polynomials. In [4], care is taken to ensure all operations include a normalizing step, but this is not verified: in other words, it is not proven that the polynomials are always in normal form.

Expressing that a polynomial is in normal form turns out to be as simple as disallowing zeroes: without them, there can be no trailing zeroes, and all gaps must be represented by power indices. To check for zero, we require the user supply a decidable predicate on the coefficients. This changes the module declaration like so:

```
module Sparse
  {a ℓ}
  (coeffs : RawRing a)
  (Zero : Pred (RawRing.Carrier coeffs) ℓ)
  (zero? : Decidable Zero)
  where
  open RawRing coeffs
```

Finally, we can define a sparse encoding of Horner Normal Form:

```
infixl 6 _≠0
record Coeff : Set (a ⊔ ℓ) where
  inductive
  constructor _≠0
  field
    coeff : Carrier
    .{coeff≠0} : ¬ Zero coeff
open Coeff

Poly : Set (a ⊔ ℓ)
Poly = List (Coeff × ℕ)
```

The proof of nonzero is marked irrelevant (preceded with a dot) to avoid computing it at runtime.

We can wrap up the implementation with a cleaner interface by providing a normalizing version of :::

```
infixr 8 _△_
_△_ : Poly → ℕ → Poly
[] △ i = []
((x , j) :: xs) △ i = (x , j ℕ.+ i) :: xs

infixr 5 _::↓_
_::↓_ : Carrier × ℕ → Poly → Poly
(x , i) ::↓ xs with zero? x
... | yes p = xs △ suc i
... | no ¬p = (_≠0 x {¬p} , i) :: xs
```

4.1.2 Comparison

Our addition and multiplication functions will need to properly deal with the new gapless formulation. First things first, we'll need a way to match the power indices. We can use a function from [6] to do so.

```
data Ordering : ℕ → ℕ → Set where
  less    : ∀ m k
          → Ordering m (suc (m ℕ.+ k))
  equal   : ∀ m
          → Ordering m m
  greater : ∀ m k
          → Ordering (suc (m ℕ.+ k)) m

compare : ∀ m n → Ordering m n
compare zero    zero    = equal zero
compare (suc m) zero    = greater zero m
compare zero    (suc n) = less zero n
compare (suc m) (suc n) with compare m n
compare (suc .m) (suc .(suc m ℕ.+ k))
  | less m k = less (suc m) k
compare (suc .m) (suc .m)
  | equal m = equal (suc m)
compare (suc .(suc m ℕ.+ k)) (suc .m)
  | greater m k = greater (suc m) k
```

This is a classic example of a "leftist" function: after pattern matching on one of the constructors of

Ordering, it gives you information on type variables to the *left* of the pattern. In other words, when you run the function on some variables, the result of the function will give you information on its arguments.

4.1.3 Efficiency

The implementation of compare may raise suspicion with regards to efficiency: if this encoding of polynomials improves time complexity by skipping the gaps, don't we lose all of that when we encode the gaps as Peano numbers?

The answer is a tentative no. Firstly, since we are comparing gaps, the complexity can be no larger than that of the dense implementation. Secondly, the operations we're most concerned about are those on the underlying coefficient; and, indeed, this sparse encoding does reduce the number of those significantly. Thirdly, if a fast implementation of compare is really and truly demanded, there are tricks we can employ.

Agda has a number of built-in functions on the natural numbers: when applied to closed terms, these call to an implementation on Haskell's `Integer` type, rather than the unary implementation. For our uses, the functions of interest are -, +, <, and ==. The comparison functions provide booleans rather than evidence, but we can prove they correspond to the evidence-providing versions. Combined with judicious use of erase, we get the following:

```
less-hom : ∀ n m
         → ((n < m) ≡ true)
         → m ≡ suc (n + (m - n - 1))
less-hom zero zero ()
less-hom zero (suc m) _ = refl
less-hom (suc n) zero ()
less-hom (suc n) (suc m) n<m =
  cong suc (less-hom n m n<m)

eq-hom : ∀ n m
       → ((n == m) ≡ true)
       → n ≡ m
eq-hom zero zero _ = refl
eq-hom zero (suc m) ()
eq-hom (suc n) zero ()
eq-hom (suc n) (suc m) n≡m =
  cong suc (eq-hom n m n≡m)

gt-hom : ∀ n m
       → ((n < m) ≡ false)
       → ((n == m) ≡ false)
       → n ≡ suc (m + (n - m - 1))
gt-hom zero zero n<m ()
gt-hom zero (suc m) () n≡m
gt-hom (suc n) zero n<m n≡m = refl
gt-hom (suc n) (suc m) n<m n≡m =
  cong suc (gt-hom n m n<m n≡m)

compare : (n m : ℕ) → Ordering n m
compare n m with n < m | inspect (_<_ n) m
... | true | [ n<m ]
  rewrite erase (less-hom n m n<m) =
    less n (m - n - 1)
... | false | [ n≮m ]
  with n == m | inspect (_==_ n) m
... | true | [ n≡m ]
  rewrite erase (eq-hom n m n≡m) =
    equal m
... | false | [ n≢m ]
  rewrite erase (gt-hom n m n≮m n≢m) =
    greater m (n - m - 1)
```

4.1.4 Termination

Unfortunately, we cannot yet define addition and multiplication. Using compare above in the most obvious way won't pass the termination checker.

```
{-# NON_TERMINATING #-}
_⊞_ : Poly → Poly → Poly
[] ⊞ ys = ys
(x ∷ xs) ⊞ [] = x ∷ xs
((x , i) ∷ xs) ⊞ ((y , j) ∷ ys) with compare i j
... | less .i k = (x , i) ∷ xs ⊞ ((y , k) ∷ ys)
... | greater .j k = (y , j) ∷ ((x , k) ∷ xs) ⊞ ys
... | equal .i =
  (coeff x + coeff y , i) ∷↓ (xs ⊞ ys)
```

Agda needs to be able to see that one of the numbers returned by compare always reduces in size: however, since the difference is immediately packed up in a list in the recursive call, it's buried too deeply in constructors for the termination checker to see it.

The solution is twofold: unpack any constructors into function arguments as soon as possible, and eliminate any redundant pattern matches in the offending functions. Taken together, these form an optimization known as "call pattern specialization" [5]: it's performed automatically in GHC, here we're doing it manually. Perhaps a similar transformation could be automatically applied before termination checking in Agda's compiler.

Until then, the structurally terminating function is defined like so:

```
mutual
  infixl 6 _⊞_
  _⊞_ : Poly → Poly → Poly
  [] ⊞ ys = ys
  ((x , i) :: xs) ⊞ ys = ⊞-zip-r x i xs ys

  ⊞-zip-r : Coeff → ℕ → Poly → Poly → Poly
  ⊞-zip-r x i xs [] = (x , i) :: xs
  ⊞-zip-r x i xs ((y , j) :: ys) =
    ⊞-zip (compare i j) x xs y ys

  ⊞-zip : ∀ {p q}
        → Ordering p q
        → Coeff
        → Poly
        → Coeff
        → Poly
        → Poly
  ⊞-zip (less i k) x xs y ys =
    (x , i) :: ⊞-zip-r y k ys xs
  ⊞-zip (greater j k) x xs y ys =
    (y , j) :: ⊞-zip-r x k xs ys
  ⊞-zip (equal i) x xs y ys =
    (coeff x + coeff y , i) ::↓ (xs ⊞ ys)
```

Ever helper function in the mutual block matches on exactly one argument, eliminating redundancy. Happily, this makes the function more efficient, as well as more obviously terminating.

5 Binary

Before continuing with polynomials, we'll take a short detour to look at binary numbers. These have a number of uses in dependently typed programming: as well as being a more efficient alternative to Peano numbers, their structure informs that of many data structures, such as binomial heaps, and as such they're used in proofs about those structures.

Similarly to polynomials, though, the naïve representation suffers from redundancy in the form of trailing zeroes. There are a number of ways to overcome this (see [7] and [3], for example); yet another is the repurposing of our sparse polynomial from above.

```
Bin : Set
Bin = List ℕ
```

We don't need to store any coefficients, because 1 is the only permitted coefficient. Effectively, all we store is the distance to another 1.

Addition (elided here for brevity) is linear in the number of bits, as expected, and multiplication takes full advantage of the sparse representation:

```
pow : ℕ → Bin → Bin
pow i [] = []
pow i (x :: xs) = (x ℕ.+ i) :: xs

infixl 7 _*_
_*_ : Bin → Bin → Bin
_*_ [] _ = []
_*_ (x :: xs) =
  pow x ∘ foldr (λ y ys → y :: xs + ys) []
```

6 Multivariate

Up until now our polynomial has been an expression in just one variable. For it to be truly useful, though, we'd like to be able to extend it to many: luckily there's a well-known isomorphism we can use to extend our earlier implementation. A multivariate polynomial is one where its coefficients are polynomials with one fewer variable [1].

6.1 Sparse

6.2 K

7 Setoid Applications

7.1 Traced

7.2 Isomorphisms

7.3 Counterexamples

8 The Correct-by-Construction Approach

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