Type Classes for Mathematics

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Goal

Build theory and programs on top of abstract interfaces instead of concrete implementations.

- Cleaner.
- Mathematically sound.
- Can swap implementations.

For example:

- Real number arithmetic based on an abstract interface for underlying dense ring.

Interfaces for mathematical structures

We need solid interfaces for:

- Algebraic hierarchy (groups, rings, fields, ...)
- Relations, orders, ...
- Categories, functors, universal algebra, ...
- Numbers: $\mathbb{N}$, $\mathbb{Z}$, $\mathbb{Q}$, ...
- Operations, ...

Interfaces for mathematical structures

Engineering challenges:

- Structure inference.
- Multiple inheritance/sharing.
- Convenient algebraic manipulation (e.g. rewriting).
- Idiomatic use of names and notations.

Solutions in Coq

Existing solutions:

- Dependent records
- Packed classes (Ssreflect)
- Modules

New solution: use type classes!

Fully unbundled

```
Definition reflexive {A: Type} (R : A → A → Prop) : Prop := ∀ a, R a a.
```

Flexible in theory, inconvenient in practice:

- Nothing to bind notations to
- Declaring/passing inconvenient
- No structure inference

Fully bundled

```
Record SemiGroup : Type := {
 sg_car :> Setoid ;
 sg_op : sg_car → sg_car → sg_car ;
 sg_proper : Proper ((=) ==> (=) ==> (=)) sg_op ;
 sg_ass : ∀ x y z, sg_op x (sg_op y z) = sg_op (sg_op x y) z) }
```

Problems:

- Prevents sharing, e.g. group together two CommutativeMonoids to create a SemiRing.
- Multiple inheritance (diamond problem).
- Long projection paths.

Unbundled using type classes

```
Class Equiv A := equiv: relation A.
Infix "=" := equiv: type_scope.
Class RingPlus A := ring_plus: A → A → A.
Infix "+" := ring_plus.

Class SemiRing A {e : Equiv A} {plus: RingPlus A}
  {mult: RingMult A} {zero: RingZero A} {one: RingOne A} : Prop := {
 semiring_mult_monoid :> @CommutativeMonoid A e mult one ;
 semiring_plus_monoid :> @CommutativeMonoid A e plus zero ;
 semiring_distr :> Distribute (.*.) (+) ;
 semiring_left_absorb :> LeftAbsorb (.*.) 0 }.
```

Changes:

1. Make SemiRing a type class ("predicate class").
2. Use *operational type classes* for relations and operations.

Examples

Instance syntax

```
Instance nat_equiv: Equiv nat := eq.
Instance nat_plus: RingPlus nat := plus.
Instance nat_0: RingZero nat := 0%nat.
Instance nat_1: RingOne nat := 1%nat.
Instance nat_mult: RingMult nat := mult.

Instance: SemiRing nat.
Proof.
  ...
Qed.
```

Examples

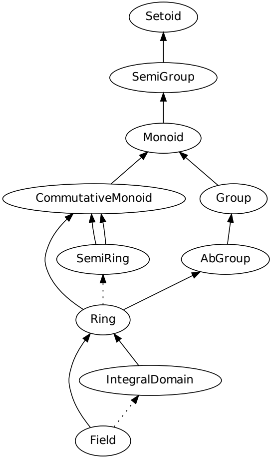
Usage syntax

```
(* z & x = z & y → x = y *)
Instance group_cancel `{Group G} : ∀ z, LeftCancellation (&) z.
Proof. ... Qed.

Lemma preserves_inv `{Group A} `{Group B}
 `{!Monoid_Morphism (f : A → B)} x : f (−x) = −f x.
Proof.
 apply (left_cancellation (&) (f x)). (* f x & f (-x) = f x - f x *)
 rewrite ← preserves_sg_op. (* f (x - x) = f x - f x *)
 rewrite 2!right_inverse. (* f unit = unit *)
 apply preserves_mon_unit.
Qed.

Lemma cancel_ring_test `{Ring R} x y z : x + y = z + x → y = z.
Proof.
 intros. (* y = z *)
 apply (left_cancellation (+) x). (* x + y = x + z *)
 now rewrite (commutativity x z).
Qed.
```

Algebraic hierarchy



Features:

- No distinction between axiomatic and derived inheritance.
- No sharing/multiple inheritance problems.
- No rebundling.
- No projection paths.
- Instances opaque.
- Terms never refer to proofs.
- Overlapping instances harmless.
- Seamless setoid/rewriting support.
- Seamless support for morphisms between structures.

Number structures

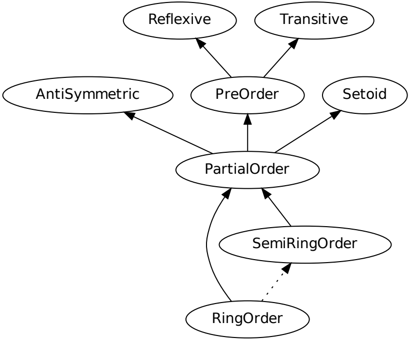
Our specifications:

- Naturals: initial semiring.
- Integers: initial ring.
- Rationals: field of fractions of $\mathbb{Z}$.

Remarks:

- Use some category theory and universal algebra for initiality.
- Models of these structures are unique up to isomorphism.
- Stdlib structures, `nat`, `N`, `Z`, `bigZ`, `Q`, `bigQ` are models.

Order theory



Features:

- Interacts well with algebraic hierarchy.
- Support for order morphisms.
- Default orders on $\mathbb{N}$, $\mathbb{Z}$ and $\mathbb{Q}$.
- Total semiring order uniquely specifies the order on $\mathbb{N}$.
- Total ring order uniquely specifies the order on $\mathbb{Z}$ and $\mathbb{Q}$.

Basic operations

- Common definitions:
  - nat_pow: repeated multiplication,
  - shiftl: repeated multiplication by 2.
- Implementing these operations this way is too slow.
- We want different implementations for different number representations.
- And avoid definitions and proofs becoming implementation dependent.

Hence we introduce abstract specifications for operations.

Abstract specifications of operations

Using Σ-types

- Well suited for simple functions.
- An example:

```
Class Abs A ‘{Equiv A} ‘{Order A} ‘{RingZero A} ‘{GroupInv A}
 := abs_sig: ∀ x, { y | (0 ≤ x → y = x) ∧ (x ≤ 0 → y = −x)}.
Definition abs ‘{Abs A} := λ x : A, ‘ (abs_sig x).
```

- Program allows to create instances easily.

```
Program Instance: Abs Z := Zabs.
```

- But unable to quantify over all possible input values.

Abstract specifications of operations

Bundled

- For example:

```
Class ShiftL A B `{Equiv A} `{Equiv B} `{RingOne A} `{RingPlus A}
  `{RingMult A} `{RingZero B} `{RingOne B} `{RingPlus B} := {
 shiftl : A → B → A ;
 shiftl_proper : Proper ((=) ==> (=) ==> (=)) shiftl ;
 shiftl_0 :> RightIdentity shiftl 0 ;
 shiftl_S : ∀ x n, shiftl x (1 + n) = 2 * shiftl x n }.
Infix "≪" := shiftl (at level 33, left associativity).
```

- Here shiftl is a δ-redex, hence simpl unfolds it.
- For BigN, x ≪ n becomes BigN.shiftl x n.
- As a result, rewrite often fails.

Abstract specifications of operations

Unbundled

- For example:

```
Class ShiftL A B := shiftl: A → B → A.
Infix "≪ " := shiftl (at level 33, left associativity).

Class ShiftLSpec A B (sl : ShiftL A B) `{Equiv A} `{Equiv B}
  `{RingOne A} `{RingPlus A} `{RingMult A}
  `{RingZero B} `{RingOne B} `{RingPlus B} := {
 shiftl_proper : Proper ((=) ==> (=) ==> (=)) (≪) ;
 shiftl_0 :> RightIdentity (≪) 0 ;
 shiftl_S : ∀ x n, x ≪ (1 + n) = 2 * x ≪ n }.
```

- The δ-redex is gone due to the operational class.
- Remark: not `shiftl x n := x * 2 ^ n` since we cannot take a negative power on the dyadics.

Theory on basic operations

- Theory on shifting with exponents in $\mathbb{N}$ and $\mathbb{Z}$ is similar.
- Want to avoid duplication of theorems and proofs.

```
Class Biinduction R `{Equiv R}
  `{RingZero R} `{RingOne R} `{RingPlus R} : Prop
 := biinduction (P: R → Prop) `{!Proper ((=) ==> iff) P} :
      P 0 → (∀ n, P n ↔ P (1 + n)) → ∀ n, P n.
```

- Some syntax:

```
Section shiftl.
 Context `{SemiRing A} `{!LeftCancellation (.*.) (2:A)}
   `{SemiRing B} `{!Biinduction B} `{!ShiftLSpec A B sl}.

 Lemma shiftl_base_plus x y n : (x + y) ≪ n = x ≪ n + y ≪ n.

 Global Instance shiftl_inj: ∀ n, Injective (≪n).
End shiftl.
```

Decision procedures

The Decision class collects types with a decidable equality.

Class Decision P := decide: sumbool P (¬ P).

- Declare a parameter ‘{∀ x y, Decision (x ≤ y)},
- Use decide (x ≤ y) to decide whether x ≤ y or ¬ x ≤ y.
- Canonical names for deciders.
- Easily define/compose deciders.

Decision procedures

Eager evaluation

Consider:

```
Record Dyadic := dyadic { mant : Int ; expo : Int }. (* m ∗ 2^e *)
Global Instance dy_precedes: Order Dyadic := λ x y,
  ZtoQ (mant x) ∗ 2 ^ (expo x) ≤ ZtoQ (mant y) ∗ 2 ^ (expo y)
```

Problem:

- decide (x ≤ y) is actually @decide Dyadic (x ≤ y) dyadic_dec.
- x ≤ y is evaluated due to eager evaluation (in Prop).

We avoid this problem introducing a λ-abstraction:

```
Definition decide_rel `(R : relation A) {dec : ∀ x y, Decision (R x y)}
  (x y : A) : Decision (R x y) := dec x y.
```

Decision procedures

Example

```
Context `{!PartialOrder (≤) } {!TotalOrder (≤) } `{∀ x y, Decision (x ≤ y)}.
Global Program Instance sprecedes_dec: ∀ x y, Decision (x < y) | 9 := λ x y,
  match decide_rel (≤) y x with
  | left E ⇒ right _
  | right E ⇒ left _
  end.
```

Quoting

- Find syntactic representation of semantic expression
- Required for proof by reflection (ring, omega)

Usually implemented at meta-level (Ltac, ML).
Alternative: object level quoting.

- Unification hints (MATITA)
- Canonical structures (SSREFLECT)

Quoting

Our implementation: type classes!

Instance resolution:

- Syntax-directed
- Prolog-style resolution
- Unification-based programming language

Quoting
Example

Trivial example:

```
Class Quote (x : A) := { quote : Exp ; eval_quote : x ≡ Denote quote }.

Instance q_unit: Quote mon_unit := { quote := Unit }.
Instance q_op ‘(q1 : Quote t1) ‘(q2 : Quote t2) : Quote (t1 & t2)
  := { quote := Op (quote t1) (quote t2) }.
```

More interestingly: use type classes to represent heaps.

Quoting

- Automatically rewrite to point-free.
- Automatically derive uniform continuity.
- Plan: integrate with universal algebra.

Implementation of the reals

- Define the reals over a dense set A as [O'Connor]:

$$\mathbb{R} := \mathfrak{C}A := \{f : \mathbb{Q}_+ \to A \mid f \textit{ is regular}\}$$

- $\mathfrak{C}$ is a monad.
- To define a function $\mathbb{R} \to \mathbb{R}$: define a *uniformly continuous function* $f : A \to \mathbb{R}$, and obtain $\check{f} : \mathbb{R} \to \mathbb{R}$.
- Efficient combination of proving and programming.

Need an abstract specification of the dense set.

Implementation of the reals

Approximate rationals

```
Class AppDiv AQ := app_div : AQ → AQ → Z → AQ.
Class AppApprox AQ := app_approx : AQ → Z → AQ.

Class AppRationals AQ {e plus mult zero one inv} `{!Order AQ}
  {AQtoQ : Coerce AQ Q_as_MetricSpace} `{!AppInverse AQtoQ}
  {ZtoAQ : Coerce Z AQ} `{!AppDiv AQ} `{!AppApprox AQ}
  `{!Abs AQ} `{!Pow AQ N} `{!ShiftL AQ Z}
  `{∀ x y : AQ, Decision (x = y)} `{∀ x y : AQ, Decision (x ≤ y)} : Prop := {
  aq_ring :> @Ring AQ e plus mult zero one inv ;
  aq_order_embed :> OrderEmbedding AQtoQ ;
  aq_ring_morphism :> SemiRing_Morphism AQtoQ ;
  aq_dense_embedding :> DenseEmbedding AQtoQ ;
  aq_div : ∀ x y k, B_{2^k}('app_div x y k) ('x / 'y) ;
  aq_approx : ∀ x k, B_{2^k}('app_approx x k) ('x) ;
  aq_shift :> ShiftLSpec AQ Z (≪) ;
  aq_nat_pow :> NatPowSpec AQ N (^) ;
  aq_ints_mor :> SemiRing_Morphism ZtoAQ }.
```

Implementation of the reals

Verified versions of:

- Basic field operations ($+$, $*$, -, $/$)
- Exponentiation by a natural.
- Computation of power series.
- exp, arctan, sin and cos.
- $\pi := 176 * \mathsf{arctan}\frac{1}{57} + 28 * \mathsf{arctan}\frac{1}{239} - 48 * \mathsf{arctan}\frac{1}{682} + 96 * \mathsf{arctan}\frac{1}{12943}$.
- Square root using Wolfram iteration.

Implementation of the reals

Benchmarks

- Our HASKELL prototype is $\sim$15 times faster.
- Our COQ implementation is $\sim$100 times faster.
- Now able to compute 2,000 decimals of π and 425 decimals of $\exp \pi - \pi$ within one minute in COQ!
- (Previously 300 and 25 decimals)
- Type classes only yield a 3% performance loss.
- COQ is still too slow compared to unoptimized HASKELL (factor 30 for Wolfram iteration).

Implementation of the reals

Improvements

- FLOCQ: more fine grained floating point algorithms.
- Type classified theory on metric spaces.
- native_compute: evaluation by compilation to OCAML.
- Newton iteration to compute the square root.

Conclusions

- Works well in practice.
- Match mathematical practice.
- Abstract interfaces allow to swap implementations and share theory and proofs.
- Type classes yield no apparent performance penalty.
- Nice notations with unicode symbols.
- Greatly improved the performance of the reals.

Issues

- Type classes are quite fragile.
- Instance resolution is too slow.
- Need to adapt definitions to avoid evaluation in Prop.
- Universe polymorphism (finite sequences as free monoid).
- Setoid rewriting with relations in Type.
- Dependent pattern match (quoting to UA-terms).

Sources

http://robbertkrebbers.nl/research/reals/