

The Book

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Chapter -1

Conventions

Words:

used

unused

implicit argument, place holder

existential/meta variable

language of canonical structures

hints

declarative program

logic program

type inference

pretyping, elaboration

Chapter 0

Mathematical Components

the library was originally developed to support the formalization of the oothm, a result that requires a wide panel of math theories.

0.1 challenges

This introduction explains the motivation of the book, which is to present the methodologies we propose to build libraries of formalized mathematics *that scale and can be reused*. Ideally, the content of the section is organized as a drawn-out comparison with the way mathematics on paper/blackboards are developed and written. Then the message is that in order to fulfill the technical needs, computer science techniques can be used and have worked well.

For instance, trying to formalize mathematical results from scratch in an empty context, without libraries and only with the tools proposed by the logic and the proof assistant is like trying to learn/invent mathematics without the help of the way mathematical concepts and notations have been shaped, structured, and denoted during the course of their (centuries long) study. In particular, this might lead the user to let the proof assistant impose a certain, usually more pedestrian proof, which we want to prevent as much as possible. (Another way to explain this could be to imagine how to explain some math to a kid that did receive no education, or trying to imagine that kid inventing new math... the cultural background is important to be up to speed. Maybe the aim of mathcomp is to implement that background at the quality of today's math).

There are several important issues that have to be solved in order to come up with a library that has a chance to be reusable. The most pervasive one is the line drawn between what is trivial and what is logged in the proofs (for humans). Some are obvious (reflexivity of relations, ...) but in general this should be analyzed by ... learning the maths and reading the literature in the domain of interest. This appreciation might also be depending on the knowledge the reader has: in 1st year texts you make dozen of proofs that certain sets are equipped with a structure of group, vector space or whatever, but very soon

you're supposed to *see* that it is obviously the case. Emphasizing this point and providing a methodology to implement this in a systematic way might be one of the original points of this document.

One of the great achievements attributed to Bourbaki is the generalization of the so-called axiomatic method, that promotes the design and use of abstract mathematical structures that factor theory and notations. This not only make maths more readable, but also more understandable and you need to play with the concepts for some times to come up with the right abstractions. Incidentally, notations are not only overloading of symbols, but also carry inference of properties. We should be able to do this and find a way to capture this inference, which is fact a (Prolog like) program run by the trained reader. And in general we would like the user to provide as much, but no more information in his statement/proof as he would in a proof, avoiding redundant information (where redundant covers inferable).

Another kind of implicit is behind reasoning patterns that should also be modeled in a convenient way for the user. For instance, *mutatis mutandis*, wlog, etc. These rely on the fact that the reader is able both to infer the mathematical statement involved in a cut formula and to run rather easily the simple piece of proof that justify it. This is modeled by techniques based on formula generation by subterm selection. This also overcome an unwanted behaviors that accessing to a subterm depends on the depth at which it occurs in the formula (usual bureaucracy in naive formalization).

The techniques that make this possible are adapted from standard methods in computer science/programming languages. We stand on the shoulders of a foundational system based on a type theory, which promotes functions as the initial concept of the formalism (as opposed to sets). In particular computations plays a privileged role there, allowing to model a notion of "similar" up to (implicit) computations. Things that are equal up to computations can be substituted one by the other in a transparent way. This is central to the way things are modeled and at the heart of (small) scale reflection. Computer science engineering techniques are also useful to organize the infrastructure content that make possible to work with some comfort in upper layers of the library, in order to configured the content so that the machine can use it (order of arguments, implicit status, naming policy...).

0.2 challenges faced and tools adopted

(tools in a broad sense, the logic is a tool, coq is a tool, the plugin is a tool, the ssr style is a tool,...)

Challenges:

- large body (scale up), make proofs small and robust. We need to say that we do use "deterministic automation". Use Laurent's data on de bruijn factor.
- model the use of math notations, their role in proofs, model proofs (also

it is about reasoning, not just computations). Another way to say that is: model Bourbaki (rationalization of Math via structure/interfaces) but not the first book (set theory) that is replaced by CIC (link with section computational thinking).

We build on Coq and an extension. The main tools follow (in random order):

0.3 Computational Thinking

This section should motivate the activity of formalizing mathematics with the **Coq** proof assistant, emphasizing its computing skills, and as opposed to other foundations like HOL. However the challenge is to keep mathematicians as the privileged target, while motivating the ssr approach to a CS oriented reader.

See `../coq/ch0.v`.

Aim of the chapter:

- should sound natural and easy to a CS person (but with the ssr twist)
- should sound different but well motivated to a Coq user (do show, maybe in the exercises, that `leqn` is 100 times better than "Inductive le"). Try to reproduce the shock we had the first time we used Boolean predicates. It may help to compare, in the `*advanced*` section, the approach with the standard one, so that one sees two proof scripts in the same page.

0.4 logic programming ... type inference

to model proof search, give a meaning to notations, teach coq the work an informed reader does (contextualizing otherwise ambiguous notations, knowledge of interface/instance of algebraic structures).

relation with proof search: no "blind" proof search (easy, ad-hoc, pervasive v.s. advanced, generalistic, potentially expensive and unstable).

0.5 automation in tactics

the main points:

- 1/3 is rewrite, term selection/search (one does not need to reach a sub formula as a goal in order to make progress for example, no monkey puzzle as in GG terminology).
- Create a formula without writing it: some advanced forms of forward reasoning tactics to deal with symmetries, generalizations (boils down to synthesize the cut formula out of the minimum possible user input, as in a text where one says "similarly to that, we can also prove that". (this is not very pervasive, dunno if it is worth putting it here in this chapter). Also `elim` does that. (technically also rewrite, but we may want to separate things)

This section is where one talks about the plugin, and some of the main design points of tactics: compositional (a language, not a list of commands), predictable (documented!!!), finally compact (symbols for uninteresting steps).

0.6 discipline

MAKE an howto out of that. Maybe one should also add a few notes on the style in scripts? like:

- you must be able to model (at least) 1 proof step in a sentence (line), e.g. "rewrite preparegoal dostep ?cleanup."
- uninteresting/recurrent lemmas/steps should be small (short names, easy to gray out)
- lemma statements are designed, not just written, having in mind their use (forward, backward, implicit arguments, arguments order) and the class of trivial hypotheses since an extra hyp that is provable triviality (via //, hint resolve, canonical) is for free. E.g. "x is a toto", " $0 \leq n$ ", ...
- also not every possible lemma, but a few that combine well
- proofs/definitions are reworked many times, why (understand recurrent proof schemas, compact, factor, make more stable/robust) and what is needed (like meaningful names, clear structure)

0.7 trivial=implicit (for a trained mathematician)

The idea is to try to identify what is trivial (mathematically speaking) and be sure you can model it as such:

- (level basic) make explicit the trivialities of each theory (what one expects to be proved by //).
- (level advanced) when you do new stuff, you must decide what is trivial/implicitly proved.
- (hard) which technique to make Coq prove it automatically (hint resolve, canon, comput... in the type)

This may also be another way to present the whole chapter

Mantra

(basic) if you see `toto=false` you should perform the case analysys via `fooP`



Part I

The art of formalizing

Chapter 1

Logics

From calculability to proofs, hence the CC, and the fact that reasoning principles without a computational content become axioms.

This is a non technical chapter and message should be:

- instantiation of a universal statement is application (also the pair)
- Excluded middle is not available by default (choice?)
- Conversion as a pervasive indistinguishably, what inside (beta, definition unfolding,...)
- Dependent types: eq, sigma (which example?)

One options is: avoid relating type theory and other logics. We say: we have a formal game where the basic elements are programs/functions that come with types to avoid confusion. full stop. (no relation with proof theory, set theory). maybe mention that roots are in calculability (hence the choice to pick functions as primitive and not sets). This is lucky because (computable) functions are today executable by a computer. Still not all concepts are "computable" hence some principles are problematic: EM,... we mainly stay in the lucky fragment (again no propaganda on intuitionistic logic, constructive math; just a mention).

Chapter 2

Programming

Presentation of inductive data structures, recursive programs on these data. Bool, Boolean connectives, Boolean reflection (cf ch. [0.3](#)), views. Examples of equality tests (`==`, with a forward reference to explain the magic if needed), operations on sequences, nats, exercises on prime, div.

Chapter 3

Proofs

Where one learns to do proofs. Boolean reflection in practice, views, discussion on the definition of `leq`, proofs on things defined in the previous chapter, associated tactics, exercises on prime, div, binomial, etc.

`spec?` A new vernacular to declare specs without typing coinductive and by writing explicitly the equations.

Chapter 4

Type Inference

Teaching Coq how to read Math (step 1)

The rules of the Calculus of Inductive Constructions are expressed on the syntax on terms and are implemented by the kernel of Coq. Such software component performs *type checking*: given a term and type it checks if such term has the given type. To keep type checking simple and decidable the syntax of terms makes all information explicit. As a consequence the terms written in such verbose syntax are pretty large.

Luckily the user very rarely interacts directly with the kernel. Instead she almost always interacts with the refiner, a software component that is able to accept open terms. Open terms are in general way smaller than regular terms because some information can be left implicit. In particular one can omit any subterm by writing “_” in place of it. Each missing piece of information is either reconstructed automatically by the *type inference* algorithm, or provided interactively by means of proof commands. In this chapter we focus on type inference.

Type inference is *ubiquitous*: whenever the user inputs a term (or a type) the system tries to infer a type (or a sort) for it. One can think of the work of the type inference algorithm as trying to give a meaning to the input of the user possibly completing and constraining it by inferring some information. If the algorithm succeeds the term is accepted, otherwise an error is given.

What is crucial to the Mathematical Components library is that the type inference algorithm is *programmable*: one can extend the basic algorithm with small declarative programs that have access to the library of already formalized facts. In this way one can make the type inference algorithm aware of the contents of the library and make Coq behave as a trained reader that is able to guess the intended meaning of a mathematical expressions from the context thanks to his background knowledge.

Introducing the reader to the type inference algorithm and helping her to

I'm a bit uneasy about citations, here I think I want to add one[?]. They are good readings but a bit arbitrary and not easy to find. We should define a policy for citations.

make good use of it is the ultimate goal of this chapter.

4.1 Type inference and Higher Order unification

Learns HO unif is hard
Requires
Provides terminology
Level 1

The type inference algorithm is quite similar to the type checking one: it recursively traverses a term checking that each subterm has a type compatible with the type expected by its context. During type checking types are compared taking computation into account. Terms that compare as equal are said to be *convertible*. Termination of reduction and uniqueness of normal forms provide guidance for implementing the convertibility test, for which a complete and sound algorithm indeed exists. Unfortunately type inference works on open terms, and this fact turns convertibility into a much harder problem called *higher order unification*. The special placeholder “_”, usually called *implicit argument*, may occur inside types and stands for one, and only one, term that is not explicitly given. Type inference does not check if two types are convertible, it checks if they unify. Unification is allowed to assigning values to implicit arguments in order to make the resulting terms convertible. For example unification is expected find an assignment that makes the type `(list _)` convertible to `(list nat)`. By picking the value `nat` for the placeholder the two types become syntactically equal and hence convertible.

Unfortunately it is not hard to come up with classes of examples where guessing appropriate values for implicit arguments is, in general, not possible. In fact such guessing has been shown to be as hard as proof search in presence of higher order constructs. For example to unify `(prime _)` with `true` one has to guess a prime number. Remember that `prime` is a boolean function that fed with a natural number returns either `true` or `false`. While assigning 2 to the implicit argument would be a perfectly valid solution, it is clear that it is not the only one. Enumerating all possible values until one finds a valid one is not a good strategy either, since the good value may not exist. Just think at the problem `(prime (4 * _))` versus `true`. An even harder class of problems is the one of synthesizing programs. Take for example the unification problem `(_ 17)` versus `[:: 17]`. Is the function we are looking for the list constructor? Or maybe, is it a factorization algorithm?

Given that there is no silver bullet for higher order unification COQ makes a sensible design choice: provide an (almost) heuristic-free algorithm and let the user extend it via an extension language. We refer to such language as the language of *Canonical Structures*. Despite being a very restrictive language, it is sufficient to program a wide panel of useful functionalities. The one described in this chapter is notation overloading.

The concrete syntax for implicit arguments, an underscore character, does not let one name the missing piece of information.¹ If an expression contains multiple occurrence of the placeholder “_” they are all considered as potentially different by the system, and hence hold (internally) unique names. For the

¹This may change in Coq 8.5

sake of clarity we take the freedom to use the alternative syntax $?_x$ for implicit arguments (where x is a unique name).

4.2 Type inference by examples

Lets start with the simplest example one could imagine: defining the polymorphic identity function and checking its application to 3.

Polymorphic identity	Response
<pre> 1 Definition id (A : Type) (a : A) : A := a. 2 Check (id nat 3). 3 Check (id _ 3).</pre>	<pre> id nat 3 : nat id nat 3 : nat</pre>

Learns type and term inference

Requires have, move, exact

Provides Arguments (setting implicit)

Level 1

In the expression `(id nat 3)` no subterm was omitted, and indeed COQ accepted the term and printed its type. In the third line even if the sub term `nat` was omitted, COQ accepted the term. Type inference found a value for the place holder for us by proceeding in the following way: it traversed the term recursively from left to right, ensuring that the type of each argument of the application had the type expected by the function. In particular `id` takes two arguments. The former argument is expected to have type `Type` and the user left such argument implicit (we name it $?_A$). Type inference imposes that $?_A$ has type `Type`, and this constraint is satisfiable. The algorithm continues checking the remaining argument. According to the definition of `id` the type of the second argument must be the value of the first argument. Hence type inference runs recursively on the argument `3` discovering it has type `nat` and imposes that it unifies with the value of the first argument (that is $?_A$). For this to be true $?_A$ has to be assigned the value `nat`. As a result the system prints the input term, where the place holder has been replaced by the value type inference assigned to it.

At the light of that we observe that every time we apply the identity function to a term we can omit to specify its first argument, since COQ is able to infer it and complete the input term for us. This phenomenon is so frequent that one can ask the system to insert the right number of `_` for him. For more details see Section 4.6 or refer to the user manual. Here we only provide a simple example.

Setting implicit arguments	Response
<pre> 1 Arguments id {A} a. 2 Check (id 3). 3 Check (@id nat 3).</pre>	<pre> id 3 : nat id 3 : nat</pre>

The **Arguments** directive “documents” the constant `id`. In this case it just marks then argument that has to be considered as implicit by surrounding it with curly braces. The declaration of implicit arguments can be locally disabled by prefixing the name of the constant with the `@` symbol.

Another piece of information that is often left implicit is the type of abstracted or quantified variables.

Omitting type annotations	Response
<pre> 1 Check (fun x => @id nat x). 2 3 Lemma prime_gt1 p : prime p → 1 < p.</pre>	<pre> fun x : nat => id x : nat → nat</pre>

In the first line the syntax `(fun x => ...)` is sugar for `(fun x : _ => ...)` where we leave the type of `x` open. Type inference fixes it to `nat` when it reaches the last argument of the identity function. It unifies the type of `x` with the value of the first argument given to `id` that in this case is `nat`. This last example is emblematic: most of the times the type of abstracted variables can be inferred by looking at how they are used. This is very common in lemma statements. For example the third line states a theorem on `p` without explicitly giving its type. Since the statement uses `p` as the argument of the `prime` predicate, it is automatically constrained to be of type `nat`.

The kind of information filled in by type inference can also be of another, more interesting, nature. So far all place holders were standing for types, but the user is also allowed to put `_` in place of a term.

Inferring a term	Goal after line 3
<pre> 1 Lemma example q : prime q → 0 < q. 2 Proof. 3 move=> pr_q. 4 have q_gt1 := prime_gt1 _ pr_q. 5 exact: lt_nW q_gt1. 6 Qed.</pre>	<pre> q : nat pr_q : prime q ===== 0 < q</pre>

The proof begins by giving the name `pr_q` to the assumption `prime q`. Then it builds a proof term by hand using the lemma stated in the previous example and names it `q_gt1`. In the expression `(prime_gt1 _ pr_q)` the place holder, that we name `?p`, stands for a natural number. When type inference reaches `?p` it fixes its type to `nat`. What is more interesting is what happens when type inference reaches the `pr_q` term. Such term has its type fixed by the context: `(prime q)`. The type of the second argument expected by `prime_gt1` is `(prime ?p)` (i.e. the type of `prime_gt1` were we substitute `?p` for `p`). Unifying `(prime ?p)` with `(prime q)` is possible by assigning `q` to `?p`. Hence the proof term just constructed is well typed, its type is `(1 < q)` and the place holder has been set to be `q`. As we did for the identity function we can declare the `p` argument of `prime_gt1` as implicit. Choosing a good declaration of implicit arguments for lemmas is tricky and requires one to think ahead how the lemma is used. Section 4.6 is dedicated to that.

maybe also tell why one
does not need two
underscores in the last line

So far type inference and in particular unification has been used in its simplest form, and indeed a first order unification algorithm incapable of computing or synthesizing functions would have sufficed. In the next section we introduce the encoding of the relations that is at the base of the declarative programs we

write to extend unification in the higher order case. As of today there is no precise, published, documentation of the type inference and unification algorithms implemented in COQ. For a technical presentation of a type inference algorithm close enough to the one of COQ we suggest the interested reader to consult [?]. The reader interested in a technical presentation of a simplified version of the unification algorithm implemented in COQ can read [?, ?].

4.3 Records as first class relations

In computer science a record is a very common data structure. It is a compound data type, a container with named fields. Records are represented faithfully in the Calculus of Inductive Constructions as inductive data types with just one constructor holding all the data. The peculiarity of the records we are going to use is that they are dependently typed: the type of each field is allowed to depend on the values of the fields that precedes it.

COQ provides syntactic sugar for declaring record types.

```
1 Record eqType : Type := Pack {
2   sort : Type;
3   eq_op : sort → sort → bool
4 }.
```

The sentence above declares a new inductive type called `eqType` with one constructor named `Pack` with two arguments. The first one is named `sort` and holds a type; the second and last one is called `eq_op` and holds a comparison function on terms of type `sort`. What this special syntax does is declaring at once the following inductive type plus a named projection for each record field:

```
1 Inductive eqType : Type :=
2   Pack sort of sort → sort → bool.
3 Definition sort (c : eqType) : Type :=
4   let: Pack t _ := c in t.
5 Definition eq_op (c : eqType) : sort c → sort c → bool :=
6   let: Pack _ f := c in f.
```

Note that the type dependency between the two fields requires the first projection to be used in order to define the type of the second projection.

We think of the `eqType` record type as a relation linking a data type with a comparison function on that data type. Before putting the `eqType` relation to good use we declare an inhabitant of such type, that we call an *instance*, and we examine a crucial property of the two projections just defined.

We relate the following comparison function with the `nat` data type:

Learns records as relations, canonical base instances
Requires
Provides Canonical
Level 1

Maybe this function has been shown already

```

1  Fixpoint eqn m n {struct m} :=
2    match m, n with
3    | 0, 0   true
4    | m'.+1, n'.+1  eqn m' n'
5    | _, _   false
6    end.
7  Definition nat_eqType : eqType := Pack nat eqn.

```

Projections, when applied to a record instance like `nat_eqType` compute and extract the desired component.

Computation of projections	Response
<pre> 1 Eval simpl in sort nat_eqType. 2 Eval simpl in eq_op nat_eqType. </pre>	<pre> = nat = eqn </pre>

Maybe `simpl` is already explained?

Given that `(sort nat_eqType)` and `nat` are convertible, equal up to computation, we can use the two terms interchangeably. The same holds for `(eq_op nat_eqType)` and `eqn`. Thanks to this fact COQ can type check the following term:

<pre> 1 Check (eq_op nat_eqType 3 4). </pre>	<pre> eq_op nat_eqType 3 4 : bool </pre>
---	--

This term is well typed, but checking it is not as simple as one may expect. The `eq_op` function is applied to three arguments. The first one is `nat_eqType` and its type, `eqType`, is trivially equal to the one expected by `eq_op`. The following two arguments are hence expected of to be of type `(sort nat_eqType)` but 3 and 4 are of type `nat`. Recall that unification takes computation into account exactly as the convertibility relation. In this case the unification algorithm unfolds the definition of `nat_eqType` obtaining `(sort (Pack nat eqn))` and reduces the projection extracting `nat`. The obtained term literally matches the type of the last two arguments given to `eq_op`.

Now, why this complication? Why should one prefer `(eq_op nat_eqType 3 4)` to `(eqn 3 4)`? The answer is *overloading*. It is recurrent in mathematics and computer science to reuse a symbol, a notation, in two different contexts. A typical example coming from the mathematical practice is to use the same infix symbol `*` to denote any ring multiplication. A typical computer science example is the use of the same infix `==` symbol to denote the comparison over any data type. Of course the underlying operation one intends to use depends on the values it is applied to, or better their type.² Using records lets us model these practices. Note that, thanks to its higher order nature, the term `eq_op` can always be the head symbol denoting a comparison. This makes it possible to recognize, hence print, comparisons in a uniform way as well as to input them. On the contrary, in the simpler expression `(eqn 3 4)` the name of the head symbol

² Actually the meaning of a symbol in math is even deeper: by writing $a * b$ one expects the reader to figure out from the context which ring we are talking about, recall its theory, and use this knowledge to eventually justify the steps that follow in a proof. This very same approach let us also model this practice, but we discuss it only in the next chapter

is very specific to the type of the objects we are comparing. Also note that polymorphism, in the sense of the ML programming language, is not what we are looking for, since it would impose the comparison function to behave uniformly on every type. What we are looking for is closer to the ad-hoc polymorphism of the Haskell programming language or the notion of subtyping provided by object oriented languages.

In the rest of this chapter we focus on the overloading of the `==` symbol and we start by defining another comparison function, this time for the `bool` data type.

```
1 Definition eqb (a b : bool) := if a then b else (not b).
2 Definition bool_eqType : eqType := Pack bool eqb.
```

Now the idea is to define a notation that applies to any occurrence of the `eq_op` head constant and use such notation for both printing and parsing.

I need the reader to know something about Notation

Overloaded notation	Response
<pre>1 Notation "x == y" := (eq_op _ x y). 2 Check (eq_op bool_eqType true false). 3 Check (eq_op nat_eqType 3 4).</pre>	<pre>true == false : bool 3 == 4 : bool</pre>

As a printing rule, the place holder stands for a wild card: the notation be used no matter the value of the first argument of `eq_op`. As a result both occurrences of `eq_op`, line 2 and 3, are printed using the infix `==` syntax. Of course the two operations are different, they are specific to the type of the arguments and the typing discipline ensures the arguments match the type of the comparison function packaged in the record.

When the notation is used as a parsing rule, the place holder is interpreted as a itself: type inference is expected to find a value for it. Unfortunately such notation does not work as a parsing rule yet.

Error	Response
<pre>1 Check (3 == 4). 2</pre>	<pre>Error: complete this with the real error</pre>

If we unravel the notation the input term is really `(eq_op _ 3 4)`. We name the placeholder $?_e$. If we replay the type inference steps seen before, the unification step is now failing. Instead of `(sort nat_eqType)` versus `nat`, now unification has to solve the problem `(sort $?_e$)` versus `nat`. This problem falls in one of the problematic classes we presented in Section 4.1: the system has to synthesize a comparison function.

COQ gives up, leaving to the user the task of extending the unification algorithm with a program that is able to solve unification problems of the form `(sort $?_e$)` versus `T` for any `T`. Given the current context it seems reasonable to write an extension that picks `nat_eqType` when `T` is `nat` and `bool_eqType` when `T` is `bool`. In the language of Canonical Structures such program is expressed as follows.

Declaring Canonical Structures

```
1 Canonical nat_eqType.
2 Canonical bool_eqType.
```

The keyword `Canonical` was chosen to stress that the program is deterministic: each type τ is related to (at most) one *canonical* comparison function.

Testing CS Inference

```
1 Check (3 == 4).
2 Check (true == false).
3 Eval compute in (3 == 4).
```

Response

```
3 == 4 : bool
true == false : bool
= false
```

The mechanics of the small program we wrote using the `Canonical` keyword can be explained using the global table of canonical solutions. Whenever a record instance is declared as canonical COQ adds to such table an entry for each field of the record type.

Canonical Structures Index		
projection	value	solution
sort	nat	nat_eqType
sort	bool	bool_eqType

Whenever a unification problem with the following shape is encountered, the table of canonical solution is consulted.

(projection ?_S) versus value

The table is looked up using as keys the projection name and the value. The corresponding solution is assigned to the implicit argument ?_S.

In the table we reported only the relevant entries. Entries corresponding to the `eq_op` projection play no role and in the Mathematical Components library the name of such projections is usually omitted to signal that fact.

What makes this approach interesting for a large library is that record types can play the role of interfaces. Once a record type has been defined and some functionality associated to it, like a notation, one can easily hook a new concept up by defining a corresponding record instance and declaring it canonical. One gets immediately all the functionalities tied to such interface work on the new concept. For example a user defining new data type with a comparison function can immediately take advantage of the overloaded `==` notation by packing the type and the comparison function in an `eqType` instance.

This pattern is so widespread and important that the Mathematical Components consistently uses the synonym keyword `Structure` in place of `Record` in order to make record types playing the role of interfaces easily recognizable.

Records are first class values in the Calculus of Inductive Constructions. As we have seen projections are no special, they are simple functions that pattern match on an inductive data type to access the record fields. Being first class citizens means that one can write a term that combines the fields of two records

and builds a new record. Thanks to this fact the language of Canonical Structures is able to forge new record instances by combining the existing ones via a set of user definable combinators. This is the subject of the next section.

4.4 Synthesizing a new comparison function

So far we have used the `==` symbol terms whose type is atomic, like `nat` or `bool`. If we try for example to use it on terms whose type was built using a type constructor like the Cartesian product we encounter an error.

Error	Response
<pre>1 Check ((3,true) == (false,4)). 2</pre>	<p>Error: complete this with the real error</p>

The term `(3,true)` has type `(nat * bool)` and, so far, we only taught COQ how to compare booleans and natural numbers, not how to compare pairs. Intuitively the way to compare pairs is to compare their components *using the appropriate comparison function*. Let's write a comparison function for pairs.

Comparing pairs
<pre>1 Definition prod_cmp eqA eqB x y := 2 eq_op eqA x.1 y.1 && eq_op eqB x.2 y.2.</pre>

What is interesting about this comparison function is that the pairs `x` and `y` are not allowed to have an arbitrary, product, type here. The typing constraints imposed by the two `eq_op` occurrences forces the type of `x` and `y` to be `(sort eqA * sort eqB)`. This means that the records `eqA` and `eqB` hold a sensible comparison function for, respectively, terms of type `(sort eqA)` and `(sort eqB)`.

It is not sufficient to pack together the Cartesian product type constructor and this comparison function in an `eqType` instance to extend the canonical structures inference machinery with a new combinator.

Recursive canonical structure
<pre>1 Definition prod_eqType (eqA eqB : eqType) : eqType := 2 Pack (sort eqA * sort eqB) (cmp_pair eqA eqB) 3 Canonical prod_eqType.</pre>

The global table of canonical solutions is extended as follows.

Canonical Structures Index			
projection	value	solution	combines solutions for
sort	nat	nat_eqType	$pA \leftarrow (\text{sort}, T1), pB \leftarrow (\text{sort}, T2)$
sort	bool	bool_eqType	
sort	$T1 * T2$	prod_eqType pA pB	

Learns derived instances
Requires Canonical
Provides RecCanonical
 Level 1

Do we have the Sections
mechanism here?

The third column is empty for base instances while it contains the recursive calls for instance combinators. With the updated table when the unification problem

(sort ?_e) versus (T1 * T2)

is encountered a solution for ?_e is found by proceeding in the following way. Two new unification problems are generated: (sort ?_{eqA}) versus T1 and (sort ?_{eqB}) versus T2. If both are successful and v1 is the solution for ?_{eqA} and v2 for ?_{eqB}, the solution for ?_e is (prod_eqType v1 v2).

After the table of canonical solutions has been extended our example is accepted.

no idea if that output can
be produce by COQ

Example	Response
<pre>1 Check (3,true) == (false,4). 2 3</pre>	<pre>eq_op (prod_eqType nat_eqType bool_eqType) (3,true) (false,4) : bool</pre>

Make other examples?
Other overloaded stuff:
maybe and example of how
to hook up to infix in ? or
locked? or whatever? In any
case a table with “all” the
interfaces should probably
be part of the book

In the running example of this chapter we use the canonical structures language to express structurally recursive programs on the syntax of types. The Calculus of Inductive Constructions allows arbitrary terms to occur inside types. As a consequence the language of canonical structure can express also structurally recursive programs on the syntax of terms. This capability is used, for example, in the next chapter to related Monoid laws to function symbols to model the syntax and theory of iterated, “big”, operators.

4.5 Other aspects of type inference

Learns Coercions
Requires
Provides
Level 1

Even if the main way to extend the type inference algorithm is via Canonical Structures, another mechanism is available and used all over the library, even if it plays a minor role. The language of Canonical Structures lets one program how the value of an implicit argument can be synthesized, but can hardly be used to explain COQ how to “fix” an ill-typed term written by the user.

When a typing error arises, it always involves three objects: a term t , its type ity and the type expected by its context ety . Of course, for this situation to be an error, the two types ity and ety do not compare as equal. The simplest way one has to explain COQ how to fix t , is to provide a functional term c of type $(ity \rightarrow ety)$ that is inserted around t . In other words, whenever the user writes t in a context that expects a term of type ety , the system instead of raising an errors replaces t by $(c\ t)$.

A function automatically inserted by COQ to prevent a type error is called *coercion*. The most pervasive coercion in the Mathematical Components library is `is_true` that lets one write statements using boolean predicates..

I guess in a way or another
is true has already been
introduced

Coercion <code>is_true</code>	Goal after line 3
<pre> 1 Lemma example : prime 27. 2 Proof. 3 Set Printing Coercions. 4 by []. 5 Qed.</pre>	<pre> ===== is_true (prime 27)</pre>

The statement of the example is processed by type inference, it is enforced to be a type, but `(prime 27)` is actually a term of type `bool`. Early in the library the function `is_true` is declared as a coercion from `bool` to `Prop` and hence is it inserted by COQ automatically.

```

1 Definition is_true b := b = true.
2 Coercion is_true : bool >→ Sortclass. (* Prop *)
```

Another coercion that is widely used injects booleans into naturals. Two examples follow.

```

1 Fixpoint count (a : pred T) (s : seq T) :=
2   if s is x :: s' then a x + count s' else 0.
3 Lemma count_uniq_mem s x : uniq s → count_mem x s = (x \in s).
```

In line number 2 the term `(a x)` is a boolean. The `nat_of_bool` function is automatically inserted to turn `true` into 1 and `false` into 0. Similarly, in the last line the membership test is turned into a number, that is shown to be equivalent to the count of any element in a list that is duplicate free.

Another example of a coercion that is related to the running example of the current chapter is `sort`. Typically the projection of a record type extracting the data type is declared as a coercion letting one state generic theorems like in the following example.

```

1 Lemma (e : eqType) : ∀ x y : e, x == y → ...
```

Here the type of `x` and `y` is `(sort e)` and not `e` as the user initially wrote. Indeed `e` is a term (of type `eqType`) while the `forall` quantification expects a type after the colon. The `sort` function mapping an `eqType` into a `Type` is inserted automatically.

Coercions are composed transitively.

```

1 Check ∀ b : bool, (b + 3)%Z.
```

For the convenience of the reader we list here the most widely used coercions. there are also a bunch on `Funclass` not listed and `elimT` surely deserves some explanation.

Coercions		
coercion	source	target
Posz	nat	int
nat_of_bool	bool	nat
elimT	reflect	Funcclass
isSome	option	bool
is_true	bool	Sortclass

Another device that is used to help type inference is the `Implicit Types` directive. This directive lets one attach a default type to variable names.

Example of `Implicit Types`

```
1 Implicit Types m n : nat.
2 Check ∀ m n, n == m.
```

In the example above the statement we `Check` does not contain enough information alone to be well types. The overloaded `==` notation needs the terms to which it is applied to have a type for which a `Canonical Structure` is declared. Even if we did not annotate `n` and `m` with a type, the directive on the first line does it for us.

The reader already familiar with the concept of coercion may find the presentation of this chapter nonstandard. Indeed coercions are usually presented as a device to model subtyping in a theory that, like Calculus of Inductive Constructions, does not feature subtyping. As we will see in Chapter ?? the role played by coercions is in the modelling of the hierarchy of algebraic structure is minor. Indeed what is hard is not to forget some fields of a structure to obtain a simpler one. What is hard is to reconstruct the missing fields of a structure or compare two structures finding the minimum super structure. These tasks are mainly implemented using canonical structures.

4.6 Declaring implicit arguments

Learns Declaring implicit arguments
Requires Canonical
Provides stating lemmas
Level 2

here we describe how to choose which arguments are implicit, that one has to think ahead how a lemma is used and hence which data type inference has at hand. Also that the order of quantifiers is relevant.

- lemmas: fwd/backward reasoning
- equations, look at the concl too, free vars are abstracted
- compare with eapply style

4.7 Declaring overloaded notations

Notations must be stable.

- Arguments nosimpl
- + that becomes * with a CS inference
- scopes the effect %R when using a bigop lemma.

Learns Declaring over-
loaded notations
Requires Canonical
Provides Notation
Level 2

4.8 Triggering type inference



One does a minimal presentation of phantoms here, so pave the way to the 2 stars section in next chapter where one defines the smart constructor of an algebraic structure.

- lifting a term into a type
- notations are untyped

Learns Implement [foo of
nat]
Requires Canonical
Provides Phantom
Level 3

4.9 Discussion about type inference



The points I want to make are:

- during type inference, HO infers (morally) the minimum info necessary to make things well typed (if we were 1st order that would really be true). hence we KNOW when CS inference is triggered EXACTLY. this is a big difference w.r.t. type classes. It is like a Prolog program where goals are reordered randomly
- I also want to talk about the overlapping instances problem, that is “easy” with TC, hard with CS and envisage an extension.
- limitation of coercions, from both the usability perspective and the expressive power they offer

Learns difference with
type classes, limitations
Requires RecCanonical, Coercions
Provides
Level 2

Chapter 5

Mixing data and proofs

What is a sub-type?

one of the peculiarity of Calculus of Inductive Constructions is that proofs are a first class entity. one can use this fact to model the operation of building the set of terms of that type that satisfy a given property. the idea is to build the type of paris x px. it is well known that in TT building sets is problematic, proofs are not irrelevant in general. hott seems to provide answers to this problem in general turning the problem upside down, defining the class of more propositions, and then... in CIC we don't have a notion of mere proposition as powerful as in hott, but thanks to a famous result of heideberg we know that the class of decidable eq, hence decidable predicates ... has uip. This fits well our framework where all predicates that are decidable are expressed as booleans, and $p \times = \text{true}$ is the usual way to state things. this also makes the overloading mechanism we have seen in the prev chapter perform proof search. eqtype for pairs. but also more interesting

5.1 Types with a decidable equality

Please use \mcbLEVEL

refine eqtype adding the proposition of compatibility with leibnitz show that == finds proofs

Learns	Please	use
\mcbLEARN		
Requires	Please	use
\mcbREQUIRE		
Provides	Please	use
\mcbPROVIDE		
Level 4		

5.2 Types with an enumeration

Please use \mcbLEVEL

here we cheat, saying that the precise hierarchy is in the next chapter. also the nesting of records will be fake.

Learns	Please	use
\mcbLEARN		
Requires	Please	use
\mcbREQUIRE		
Provides	Please	use
\mcbPROVIDE		
Level 4		

5.3 Finite sets

Plase use `\mcbLEVEL`

Learns	Please	use
<code>\mcbLEARN</code>		
Requires	Please	use
<code>\mcbREQUIRE</code>		
Provides	Please	use
<code>\mcbPROVIDE</code>		
Level 4		
Learns	Please	use
<code>\mcbLEARN</code>		
Requires	Please	use
<code>\mcbREQUIRE</code>		
Provides	Please	use
<code>\mcbPROVIDE</code>		
Level 4		

once we have finite types we can carve sets into them and discuss their main property.

5.4 subtype (proof search)

Plase use `\mcbLEVEL`

Boolean sigma types, records, coercions, UIP. Examples: ordinals, tuples (not their use which requires CS). This chapter might come after some presentation of basic canonical structures, i.e. reorganize the content between this chapter and the next.

example of tuples here? better ordinals?

GG: makes many points here (not fully understood by Enrico):

- ordinals/tuples are easy to use but hard to build
- it is a tradeoff, but is not clear if we can give hints on when a specific datatype like ordinals is better than unpackaged stuff.

UIP is advanced, the basic user should just be told that putting bools inside a record is just fine.

- record (flat)

Chapter 6

Hierarchy

Packaging records, the bigop hierarchy. Scaling with packed classes and mixins, to the ssralg hierarchy. Presentation of the content of ssralg in terms of structures and of the theory? Should the latter be a separate chapter.

Maybe a plugin for a new vernacular to script the creation/declaration of structures/instances so that the level basic can touch the argument easily.

Explain what the abstraction barrier is (like unfolding a GRing projection)

gotcha: if you see GRing.toto then you broke an abstraction barrier

Mantra

if you have a proof in mind, don't let the system drive
you to another, less clean and abstract, proof.



Declaring an instance is hard... we need to document the multiple processes for each structure in each hierarchy and possibly make a program out of it.

Chapter 7

Larger scale reflection (out of place)

Four colours, decomposition in primes, example in peterfalvi. In particular example where a case analysis does not follow the constructors of an existing inductive type: then craft an ad hoc one to hint the proof. This topic is probably at a wrong place.

Part II

**Mathematics in
Mathematical Components**

7.1 STYLE of these chapters

These chapters hopefully in the following style:

- first math mode to review the (not so standard) definitions and
- then touch some real proof script to show why/how the definition make it possible to model the proofs (as they are in math)
- use the (few) examples to illustrate a cool proof strategy if any (not necessarily typical of the math subject, but that happens to be there, like in OOTHM paper: circular leq, symmetries, ad hoc decision procedure, ...)
- try hard to show how CIC helps (which feature: HO, computation, dependent types ...), so that at the end we can sum up and make a synthesis of all that.

Maybe it is simpler to do it in 2 steps: 1) in this second part one identifies where CIC or the SSR style plays a crucial role 2) then we advertise these use cases in the first part to motivate the techniques, the complexity of the logic...

Chapter 8

Numbers

What are the numbers available in the library? How to use them, casts between types... Non trivial point in the formalisation: axiomatization, order is defined from norm, partial orders (in particular for complex numbers).

Chapter 9

Polynomials, Linear algebra

2-stage presentation: interface plus explicit. Expansion of Georges'ITP paper.
Here is one of the main application of the choice operator (complement a base).

Chapter 10

Quotients

Chapter 11

Finite group theory

Data-structures, how to craft the set of variants of a same theorem to make the formalization handy. Permutations. Presentations?

Chapter 12

Representation theory, Character theory

As an example of application, in particular of the linear algebra theory.

Chapter 13

Galois Theory

Chapter 14

Real closed fields

Chapter 15

Algebraic closure

Part III

Conclusion and perspectives

Let's be brave: This part looks back to the techniques, methodologies and achieved formalized libraries described in the book and summarizes the role played by each on them, in the spirit of the introduction to the ssr manual. May be also discusses the possible extensions (like CoqEAL) or adaptation to the future evolutions of the system and formalism (Cubical Coq, HITs...).

Part IV

Annexes

Chapter 16

What is done where?

Chapter 17

How tos

suggestions:

- Get more information when you do not understand the error message
- Search in the library
- Canonical structures: define a new instance
- Canonical structures: add a new structure
- Give a relevant name to the lemma I just stated
- Forbid unwanted expansions
- Choose a notation (what not to do...)
- Compute “for real” (Natbin, Coqeval)
- MathComp script style

Chapter 18

Naming conventions

Chapter 19

Index of notations