

# A formalization of Dedekind domains and class groups of global fields

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## Abstract

Dedekind domains and their class groups are notions in commutative algebra that are essential in algebraic number theory. We formalized these structures and several fundamental properties, including number theoretic finiteness results for class groups, in the Lean prover as part of the **mathlib** mathematical library. This paper describes the formalization process, noting the idioms we found useful in our development and ‘mathlib’s decentralized collaboration processes involved in this project.

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**Supplementary Material** Full source code of the formalization is part of **mathlib**. Copies of the source files relevant to this paper are available in a separate repository.

**Software:** <https://github.com/lean-forward/class-number>

archived at **Software Heritage Identifier**

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## 1 Introduction

In its basic form, number theory studies properties of the integers  $\mathbb{Z}$  and its fraction field, the rational numbers  $\mathbb{Q}$ .<sup>1</sup> Both for the sake of generalization, as well as for providing powerful techniques to answer questions about the original objects  $\mathbb{Z}$  and  $\mathbb{Q}$ , it is worthwhile to study finite extensions of  $\mathbb{Q}$ , called *number fields*, as well as their *rings of integers* (defined in Section 2 below), whose relations mirror the way  $\mathbb{Q}$  contains  $\mathbb{Z}$  as a subring. In this paper, we describe our project aiming to formalize these notions and some of their important properties. Our goal, however, is not to get to the definitions and properties as quickly as possible, but

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<sup>1</sup> From a classical point of view, one could even argue that the positive, or perhaps nonnegative, integers and rational numbers are the most basic objects of study of number theory. From an algebraic point of view, this would still quickly lead into studying  $\mathbb{Z}$  and  $\mathbb{Q}$ .



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rather to lay the foundations for future work, as part of a natural and more general theory as we shall explain below.

In particular, our project resulted in formalized definitions and elementary properties of number fields and their rings of integers (described in Section 3.3), Dedekind domains (Section 4), and the ideal class group and class number (Section 7). The main proofs that we formalized show that two definitions of Dedekind domains are equivalent (Section 4.3), that the ring of integers (or more generally: the integral closure of a Dedekind domain in a finite separable field extension) is a Dedekind domain (Section 6) and that the class group of a number field is finite (Section 7). In fact, most of our results for number fields are actually obtained in the more general setting of so-called *global fields*, i.e. number fields together with finite field extensions of  $\mathbb{F}(t)$  with  $\mathbb{F}$  a finite field (restricting to  $\mathbb{F} \simeq \mathbb{Z}/p\mathbb{Z}$  with  $p$  prime yields no loss of generality here).

Apart from the achievement of formalizing a non-trivial amount of mathematical theory, our formal definition of the class number is an essential requirement for the use of theorem provers in modern number theory research.

Our work is developed as part of the mathematical library `mathlib` [21] for the Lean 3 theorem prover [6]. The formal system of Lean is a dependent type theory based on the calculus of inductive constructions, with a proof-irrelevant impredicative universe `Prop` at the bottom of a noncumulative hierarchy of universes `Prop : Type : Type 1 : Type 2 : ...`.<sup>2</sup> Other important characteristics of Lean as used in `mathlib` are the use of quotient types, ubiquitous classical reasoning and the use of typeclasses to define the hierarchy of algebraic structures.

Organizationally, `mathlib` is characterized by a distributed and decentralized community of contributors, a willingness to refactor its basic definitions, and a preference for small yet complete contributions over larger projects added all at once. Our own project, being part of the development of `mathlib`, follows this philosophy by contributing pieces of our work as they are finished, in turn taking advantage of results contributed by others after the start of the project. At several points, we had just merged a formalization into `mathlib` that another contributor needed, immediately before they contributed a result that we needed. Due to the decentralized organization and fluid nature of contributions to `mathlib`, its contents are built up of many different contributions from many different authors. Attributing each formalization to a single set of main authors would not do justice to all others whose additions and tweaks are essential to its current use. Therefore, we will make clear whether a contribution is part of our project or not, but we will not stress whom we consider to be the main author(s).

The source files of the formalization are currently in the process of being merged into `mathlib`, an up-to-date branch being available <https://github.com/leanprover-community/mathlib/tree/dedekind-domain-dev>. We also maintain a repository containing the files relevant to this paper, available at <https://github.com/lean-forward/class-number>.

## 2 Mathematical background

Let us now introduce some of the main objects we study, described in a “standard” mathematical way.

A *number field*  $K$  is a finite extension of  $\mathbb{Q}$ , and as such has the structure of a finite dimensional vector space over  $\mathbb{Q}$ ; its dimension is called the *degree* of  $K$ . The smallest

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<sup>2</sup> In our code samples, we use `Type*` as abbreviation of “`Type u` for an arbitrary choice of `u`”.

example is  $\mathbb{Q}$  itself, and the two-dimensional cases are given by the quadratic number fields  $\mathbb{Q}(\sqrt{d}) = \{a + b\sqrt{d} : a, b \in \mathbb{Q}\}$  with  $d \in \mathbb{Z}$  not a square (which additionally may be taken squarefree). For an interesting cubic example, let  $\alpha$  be the unique real number satisfying  $\alpha^3 + \alpha^2 - 2\alpha + 8 = 0$ : it gives rise to the number field  $\mathbb{Q}(\alpha) = \{a + b\alpha + c\alpha^2 : a, b, c \in \mathbb{Q}\}$ . In general, taking any (say) complex root  $\alpha$  of an irreducible polynomial of degree  $n$  over  $\mathbb{Q}$  yields a number field of degree  $n$ :  $\mathbb{Q}(\alpha) = \{c_0 + c_1\alpha + \dots + c_{n-1}\alpha^{n-1} : c_0, c_1, \dots, c_{n-1} \in \mathbb{Q}\}$ , and, up to isomorphism, these are all the number fields of degree  $n$ .

The *ring of integers*  $\mathcal{O}_K$  of a number field  $K$  is defined as the integral closure of  $\mathbb{Z}$  in  $K$ , which boils down to

$$\mathcal{O}_K := \{x \in K : f(x) = 0 \text{ for some monic polynomial } f \text{ with integer coefficients}\},$$

where we recall that a polynomial is called *monic* if its leading coefficient equals 1. While it might not be immediately obvious that  $\mathcal{O}_K$  is a ring, this follows from general algebraic properties of integral closures. Some examples of  $\mathcal{O}_K$  are as follows. Taking  $K = \mathbb{Q}$ , we get  $\mathcal{O}_K = \mathbb{Z}$  back. For  $K = \mathbb{Q}(\sqrt{2})$  we get  $\mathcal{O}_K = \mathbb{Z}[\sqrt{2}] = \{a + b\sqrt{2} : a, b \in \mathbb{Z}\}$ . But for  $K = \mathbb{Q}(\sqrt{5})$  we do *not* simply get  $\mathbb{Z}[\sqrt{5}] = \{a + b\sqrt{5} : a, b \in \mathbb{Z}\}$  as  $\mathcal{O}_K$ , since the golden ratio  $\varphi := (1 + \sqrt{5})/2 \notin \mathbb{Z}[\sqrt{5}]$  satisfies the monic polynomial equation  $\varphi^2 - \varphi - 1 = 0$ , hence by definition  $\varphi \in \mathcal{O}_K$ ; it turns out that  $\mathcal{O}_K = \mathbb{Z}[\varphi] = \{a + b\varphi : a, b \in \mathbb{Z}\}$ . Finally, if  $K = \mathbb{Q}(\alpha)$  with  $\alpha$  as before, then  $\mathcal{O}_K = \{a + b\alpha + c(\alpha + \alpha^2)/2 : a, b, c \in \mathbb{Z}\}$ , illustrating that explicitly writing down  $\mathcal{O}_K$  can quickly become complicated.

Thinking of  $\mathcal{O}_K$  as a generalization of  $\mathbb{Z}$ , it is natural to ask which of its properties still hold in  $\mathcal{O}_K$  and, when this fails, if a reasonable weakening does.

An important property of  $\mathbb{Z}$  is that every ideal is generated by one element, which implies that every nonzero nonunit element can be written as a finite product of prime elements, which is unique up to reordering and multiplying by  $\pm 1$ : a ring where this holds is called a unique factorization domain, or UFD. For example, 6 can be factorized in exactly 4 ways, namely  $6 = 2 \cdot 3 = 3 \cdot 2 = (-2) \cdot (-3) = (-3) \cdot (-2)$ . Some well-known rings of integers are the Gaussian integers  $\mathbb{Z}[i] = \{a + bi : a, b \in \mathbb{Z}\}$  (where  $i^2 = -1$ ), the Eisenstein integers  $\mathbb{Z}[(1 + \sqrt{-3})/2]$ , and the ring  $\mathbb{Z}[\sqrt{2}]$ . In fact, these examples are UFDs, but this is certainly not true for all rings of integers. For example, unique factorization *does not* hold in  $\mathbb{Z}[\sqrt{-5}]$ : it is easy to prove that  $6 = 2 \cdot 3$  and  $6 = (1 + \sqrt{-5})(1 - \sqrt{-5})$  provide two essentially different ways to factor 6 into prime elements of  $\mathbb{Z}[\sqrt{-5}]$ .

As it turns out, there is a way to remedy this. Namely, by considering factorization of *ideals* instead of elements: given a number field  $K$ , with ring of integers  $\mathcal{O}_K$ , a beautiful and classical result by Dedekind shows that every nonzero ideal of  $\mathcal{O}_K$  can be factored as a product of prime ideals in a unique way, up to the reordering.

Although unique factorization in terms of ideals is of great importance and beauty, it is still very interesting, and for many arithmetic applications necessary, to also consider factorization properties in terms of elements. We mentioned that unique factorization in  $\mathbb{Z}$  follows from the fact that every ideal is generated by a single element. A convenient way to rephrase this algebraically is to first consider the notion of *fractional ideal* of  $\mathbb{Z}$ , i.e. a subgroup of  $\mathbb{Q}$  of the form  $\frac{1}{d}I$  with  $I$  an ideal of  $\mathbb{Z}$  and  $d$  a nonzero integer. An advantage of this generalization of the notion of *ideal* of  $\mathbb{Z}$  is that nonzero fractional ideals naturally form a multiplicative group (whereas there is no ideal  $I \subseteq \mathbb{Z}$  such that  $I * (2\mathbb{Z}) = (1)$ ). With this notion at one's disposal, the statement that every ideal is generated by a single element translates to the fact that the quotient group of nonzero fractional ideals modulo  $\mathbb{Q}^\times$  (where  $a/b \in \mathbb{Q}^\times$  corresponds to the fractional ideal  $a\mathbb{Z} * (b\mathbb{Z})^{-1}$ ) is trivial.

It turns out that this procedure can be performed for every ring of integers  $\mathcal{O}_K$ . The fundamental theoretical notion beneath this construction is that of Dedekind domain: these

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are integral domains  $R$  which are Noetherian (every ideal of  $R$  is finitely generated), integrally closed (if an element  $x$  in the fraction field of  $R$  is a root of a monic polynomial with coefficients in  $R$ , then actually  $x \in R$ ), and of Krull dimension at most 1 (every nonzero prime ideal of  $R$  is maximal). It can be proved that the nonzero fractional ideals of  $D$  again form a group, and the quotient of this group by the image of the natural embedding of  $\text{Frac } R^\times$  is called the (ideal) class group  $\mathcal{Cl}_R$ .

What is arithmetically crucial is the theorem ensuring that the ring of integers  $\mathcal{O}_K$  of every number field  $K$  is a Dedekind domain, and that in this case the class group  $\mathcal{Cl}_{\mathcal{O}_K}$  is actually *finite*. In particular,  $\mathcal{Cl}_{\mathcal{O}_K}$  can be seen as “measuring” by what extent ideals of  $\mathcal{O}_K$  are far from being generated by a single element and hence, in turn, as a measure of the failure of unique factorization: somewhat intuitively, the smaller the class group, the fewer factorizations are possible. In particular, as long as we are concerned with “uniqueness” of factorization, and with measuring the lack thereof, already the *order* of  $\mathcal{Cl}_{\mathcal{O}_K}$ , called the *class number* of  $K$ , is a tremendously interesting arithmetic feature. Actually, the same statement holds for a larger class of fields, the so-called “global fields”. They encompass all number fields and all fields which are finite extensions of  $\text{Frac } \mathbb{F}_q(t)$ , where  $\mathbb{F}_q$  is a *finite field* with  $q$  elements. A prototypical example is  $K = \mathbb{Z}/p\mathbb{Z}(t) = \mathbb{F}_p(t)$ , or an extension of the form, for instance,  $K = \mathbb{F}_{p^2}(t)[s]/s^2 - t$ , obtained by adjoining to  $\mathbb{F}_p(t)$  a square root of  $t$  as well as the  $(p^2 - 1)$ -st roots of unity. The fields of this second class are called *function fields*.

In this project, we formalized Dedekind domains, their class group, number fields together with their ring of integers, and the definition of the class number, via the proof that the class group of a ring of integers is finite. In the next sessions we will describe this formalization.

### 3 Number fields, global fields and rings of integers

We refer the reader to Section 2 for the mathematical background needed in this section.

We formalized number fields as the following typeclass:

```
class is_number_field (K : Type*) [field K] :=
  [cz : char_zero K] [fd : finite_dimensional ℚ K]
```

The condition `[cz : char_zero K]` states that  $K$  has characteristic zero, so the canonical ring homomorphism  $\mathbb{Z} \rightarrow K$  is an embedding. This implies that there is a  $\mathbb{Q}$ -algebra structure on  $K$  (found by typeclass search), and from this follows the vector space structure used in the `[fd : finite_dimensional ℚ K]` hypothesis.

We define the function fields  $K$  over a finite field  $\mathbb{F}_q$  using the following typeclass:

```
class is_function_field_over {F_q F : Type*} [field F_q] [fintype F_q] [field F]
  (f : fraction_map (polynomial F_q) F) (L : Type*) [field L]
  [algebra f.codomain L] : Prop :=
  [fd : finite_dimensional f.codomain L]
```

«««< HEAD The map `f` witnesses that  $F$  is a fraction field of the polynomial ring  $\mathbb{F}_q[t]$ , the notation `f.codomain` endows  $K$  with the algebra structure of  $F = \mathbb{F}_q(t)$ . We present a more detailed examination of `fraction_map` in Section 3.5. ===== The map `f` witnesses that  $L$  is the field of fractions of the polynomial ring  $K[X]$ , the notation `f.codomain` endows  $L$  with the algebra structure of  $K(X)$ . We present a more detailed examination of `fraction_map` in Section 3.5. »»»> d9fa398bca1dda9f9cda1ba2881dd2430c76c305

### 3.1 Field extensions

The definition of `is_number_field` illustrates our treatment of field extensions. In informal mathematics, a field  $L$  containing a subfield  $K$  is said to be a field extension  $L/K$ . Often we encounter towers of field extensions: we might have that  $\mathbb{Q}$  is contained in  $K$ ,  $K$  is contained in  $L$ ,  $L$  is contained in an algebraic closure  $\bar{K}$  of  $K$ , and  $\bar{K}$  is contained in  $\mathbb{C}$ . We might formalize this situation by viewing  $\mathbb{Q}$ ,  $K$ ,  $L$  and  $\bar{K}$  to be sets of complex numbers  $\mathbb{C}$  and defining field extensions as subset relations between these subfields. This way, no coercions need to be inserted to map elements of one field into a larger field. In type theory we cannot define  $\mathbb{Q}$  as a subset of  $\mathbb{C}$  since we need  $\mathbb{Q}$  to define  $\mathbb{C}$ . Thus, some coercion is always needed to go from the original definition of  $\mathbb{Q}$  to its image in  $\mathbb{C}$ ; and similar issues arise for other subfields that were not originally defined as such. Moreover, such an approach loses flexibility since we need to fix the top field, of which all others are subfields, at the start of our development and cannot adjoin more elements when needed.

Instead, we formalize results about field extensions by parametrization. The fields  $K$  and  $L$  are represented by arbitrary types and the hypothesis “ $L$  is a field extension of  $K$ ” is represented by an instance parameter `[algebra K L]`. This provides us with a canonical ring homomorphism `algebra_map K L : K → L`; this map is injective because  $K$  and  $L$  are fields. In other words, field extensions are given by their canonical embeddings.

### 3.2 Scalar towers

The main drawback of using arbitrary embeddings to represent field extensions is that we need to prove that these maps commute. For example, we might start with a field extension  $L/\mathbb{Q}$ , then define a subfield  $K$  of  $L$ , resulting in a tower of extensions  $L/K/\mathbb{Q}$ . In such a tower, the map  $\mathbb{Q} \rightarrow L$  should be equal to the composition  $\mathbb{Q} \rightarrow K \rightarrow L$ . The example has other maps depend on the map  $\mathbb{Q} \rightarrow L$ , so we cannot arrange the coherence condition by defining  $\mathbb{Q} \rightarrow L$  after the fact.

The solution in `mathlib` is to parametrize over all three maps, as long as there is also a proof of coherency: a hypothesis of the form “ $L/K/F$  is a tower of field extensions” is translated to three instance parameters `[algebra F K]`, `[algebra K L]` and `[algebra F L]`, along with an additional parameter `[is_scalar_tower F K L]` expressing that the maps commute.

The `is_scalar_tower` typeclass derives its name from its applicability to any three types between which exist scalar multiplication operations:

```
class is_scalar_tower (M N α : Type*) [has_scalar M N] [has_scalar N α]
  [has_scalar M α] : Prop :=
  (smul_assoc : ∀ (x : M) (y : N) (z : α), (x · y) · z = x · (y · z))
```

For example, if  $R$  is a ring,  $A$  is an  $R$ -algebra and  $M$  an  $A$ -module, we can express the fact that  $M$  is also an  $R$ -module by adding a `[is_scalar_tower R A M]` parameter. Since  $x \cdot y$  for an  $R$ -algebra  $A$  is defined as `algebra_map R A x * y`, applying `smul_assoc` for each  $x$  with  $y = z = 1$  shows that the `algebra_map`s indeed commute.

The typeclass system is set up to automatically provide common `is_scalar_tower` instances, such as for the maps  $R \rightarrow S \rightarrow A$  when  $S$  is a  $R$ -subalgebra of  $S$ . The effect is that almost all coherence proof obligations are automatically solved from known results or filled in from parameters. In our formalization, we found that the `is_scalar_tower` typeclass translates towers of field extension well.

### 223 3.3 Ring of integers

224 When  $K$  is a number field, the ring  $\mathcal{O}_K$  of integers in  $K$  is defined as the integral closure of  
 225  $\mathbb{Z}$  in  $K$ . This is the subring containing those  $x : K$  that are the root of a monic polynomial  
 226 with coefficients in  $\mathbb{Z}$ :

```
227
228 def number_field_ring_of_integers (K : Type*) [field K]
229   [is_number_field K] : subalgebra  $\mathbb{Z}$  K :=
230   integral_closure  $\mathbb{Z}$  K
231
```

232 where `integral_closure` was previously defined in `mathlib` as follows:

```
233
234 def integral_closure (R A : Type*) [comm_ring R] [comm_ring A]
235   [algebra R A] : subalgebra R A :=
236   { carrier := { r | is_integral R r }, .. /- proofs omitted -/ }
237
```

238 Some examples of rings of integers include  $\mathbb{Z}$  and  $\mathbb{Z}[i]$ .

239 When  $K$  is a function field over the finite field  $\mathbb{F}_q$ , we define  $\mathcal{O}_K$  analogously as  
 240 `integral_closure (polynomial K) F`. In order to reason uniformly for both concepts  
 241 of the ring of integers, we will work with the integral closure of any principal ideal domain  
 242 when possible.

### 243 3.4 Subobjects

244 The ring of integers are one example of a subobject, such as a subfield, subring or subalgebra,  
 245 defined through a characteristic predicate. In `mathlib`, a subobject is defined as a bundled  
 246 structure comprising the carrier set, along with proofs showing the carrier set is closed under  
 247 the relevant operations.

248 Two new subobjects we needed in our development were `subfield` and `intermediate-`  
 249 `_field`. We define a subfield of a field  $K$  as a subset of  $K$  that contains 0 and 1 and is  
 250 closed under addition, negation, multiplication, and taking inverses. If  $L$  is a field extension  
 251 of  $K$ , we define an intermediate field as a subfield that is also a subalgebra: a subfield that  
 252 contains the image of `algebra_map K L`. Other examples of subobjects available in `mathlib`  
 253 are submonoids, subgroups and submodules (with ideals as a special case of submodules).

254 The new definitions found immediate use: soon after we contributed our definition of  
 255 `intermediate_field` to `mathlib`, the Berkeley Galois theory group used it in a proof of  
 256 the primitive element theorem. Soon after the primitive element theorem was merged into  
 257 `mathlib`, we used it in our development of the trace form. This anecdote illustrates the  
 258 decentralized development style of `mathlib`, with different groups and people building on each  
 259 other's results in a collaborative process.

260 By providing a coercion from subobjects to types, sending a subobject  $S$  to the subtype  
 261 of all elements of  $S$ , and putting typeclass instances on this subtype, we can reason about  
 262 inductively defined rings such as  $\mathbb{Z}$  and subrings such as `integral_closure  $\mathbb{Z}$  K` uniformly. If  
 263  $S : \text{subfield } K$ , the map that sends  $x : S$  to  $K$  by “forgetting” that  $x \in S$  is a ring embedding,  
 264 and we register this map as a `algebra S K` instance, also allowing us to treat field extensions  
 265 of the form  $\mathbb{Q} \rightarrow \mathbb{C}$  and subfields uniformly. Similarly, for  $F : \text{intermediate\_field } K L$ ,  
 266 we defined the corresponding `algebra K F`, `algebra F L` and `is_scalar_tower K F L`  
 267 instances.



### 3.5 Fields of fractions

The fraction field  $\text{Frac } R$  of an integral domain  $R$  can be defined explicitly as a quotient type as follows: starting from the set of pairs  $(a, b)$  with  $a, b \in R$  such that  $b \neq 0$ , one quotients by the equivalence relation stating that  $(\alpha a, \alpha b) \sim (a, b)$  for all  $\alpha \neq 0 : R$ , writing the equivalence class of  $(a, b)$  as  $\frac{a}{b}$ . It can easily be proved that the ring structure on  $R$  extends uniquely to a ring structure turning  $\text{Frac } R$  into a field. When  $R = \mathbb{Z}$ , this yields the traditional description of  $\mathbb{Q}$  as the set of equivalence classes of fractions, where  $\frac{2}{3} = \frac{-4}{-6}$ , etc. The drawback of this construction is that there are many other fields that can serve as the field of fractions for the same ring. For instance, although there is an isomorphism of  $\text{Frac } \mathbb{C}[[t]]$  with the field

$$\mathbb{C}((t)) = \left\{ \sum_{i=a}^{+\infty} a_i t^i \quad \text{with } a \in \mathbb{Z} \right\}$$

of Laurent series, there is no (definitional) equality between the types. Another example comes from the field

$$\mathbb{Q}(i) = \{z \in \mathbb{C} : \Re z \in \mathbb{Q}, \Im z \in \mathbb{Q}\}$$

which is isomorphic to  $\text{Frac}(\mathbb{Z}[i])$ , but not definitionally equal to it. In fact, even the rational numbers in Lean are a counterexample: for computational efficiency,  $\mathbb{Q}$  is defined as a subtype where the numerator and denominator are coprime, instead of a quotient by “scalar multiplication”. A definition like

```
def fraction_field (R : Type*) : Type* :=
{ab : R × R // ab.2 ≠ 0}
```

would require transferring results across isomorphisms as soon as one needs to handle a different construction of a field isomorphic to  $\text{Frac } R$ .

The strategy used in `mathlib` is to rather allow for many different *fraction fields* of our given integral domain  $R$ , as fields  $F$  along with an injective *fraction map*  $f : R \rightarrow F$  which witnesses that all elements of  $F$  are “fractions” of elements of  $R$ <sup>3</sup>, and to parametrize every result over the choice of  $f$ . The conditions on  $f$  imply that  $F$  is the smallest field containing  $R$ , by showing each injective map  $g : R \rightarrow A$  to a ring  $A$  such that  $g(x)$  has a multiplicative inverse for all  $x \neq 0 : R$ , can be extended uniquely to a map  $F \rightarrow A$  compatible with  $f$  and  $g$ . In particular, if  $f_1 : R \rightarrow F_1$  and  $f_2 : R \rightarrow F_2$  are fraction maps, they induce an isomorphism  $F_1 \simeq F_2$ . The construction of  $\text{Frac } R$  then results in a field of fractions rather than *the* field of fractions.

This came at a price: informally, at any given stage of one’s reasoning, the field  $F$  is fixed and the map  $f : R \rightarrow F$  is applied implicitly, just viewing every  $x : R$  as  $x : F$ . It is now impossible to view  $\text{range } f \leq F$  as an inclusion of subalgebras, because the map  $f$  is needed explicitly to give the  $R$ -algebra structure on  $F$ . We use a type synonym `f.codomain`  $:= F$  and instantiate the  $R$ -algebra structure given by  $f$  on this synonym.

In the following sections, let  $f : R \rightarrow F$  be a fraction map.

<sup>3</sup> In the definition used by `mathlib`, a fraction map is a special case of a *localization map*. Different localizations restrict the denominators to different subsets of  $R \setminus \{0\}$ .

### 3.6 Representing simple field extensions

We have seen in Section 2 that every number field  $K$  can be written as  $K = \mathbb{Q}(\alpha)$  by adjoining to  $\mathbb{Q}$  the root of a polynomial: there is an irreducible polynomial  $p \in \mathbb{Q}[X]$  such that  $\mathbb{Q}[X]/p \simeq K$ ; we set  $\alpha$  to be the image of  $X$  in  $\mathbb{Q}[X]/p$ . We can also take  $\alpha : K$  and let  $\mathbb{Q}(\alpha)$  to be the smallest subfield of  $K$  containing  $\alpha$ ; then  $K = \mathbb{Q}(\alpha)$  means that  $\mathbb{Q}(\alpha)$ , as a subfield of  $K$ , is equal to the subfield  $\top$  containing all elements of  $K$ . We could also view  $K$  and  $\mathbb{Q}(\alpha)$  as subfields of an arbitrary larger field  $F$ . Because  $\alpha$  is algebraic, the smallest subring containing  $\alpha$  and  $\mathbb{Q}$  will be a field, thus we can add two more representations, replacing “smallest subfield” with “smallest subring”. Moreover, all subfields/subrings containing  $\mathbb{Q}$  are also  $\mathbb{Q}$ -algebras, so we can additionally replace “subfield” with “intermediate field” and “subring” with “ $\mathbb{Q}$ -subalgebra”. The same continues to hold if we replace the base field  $\mathbb{Q}$  with  $F$ , thus considering extensions of the form  $F(\alpha)$ , now requiring that  $\alpha$  be a root of some  $p \in F[X]$ .

The ability to switch between these representations is important: sometimes  $K$  and  $F$  are fixed and we want an arbitrary  $\alpha$ ; sometimes  $\alpha$  is fixed and we want an arbitrary type representing  $F(\alpha)$ . The different constructions of  $F(\alpha)$  have already been formalized in `mathlib`,

To find a uniform way to reason about all these equivalent definitions, we chose to formalize the notion of *power basis* to represent simple field extensions, a basis of the form  $1, x, x^2, \dots, x^{n-1} : K$  (viewing  $K$  as a  $F$ -vector space)<sup>4</sup>. We call  $x$  the *generator* and  $n$  the *dimension* of this power basis. We defined the following type of power basis, bundling the information of a power basis:

```
structure power_basis (F K : Type*) [field F] [field K] [algebra F K] :=
  (gen : S) (dim : ℕ)
  (is_basis : is_basis F (λ (i : fin dim), gen ^ (i : ℕ)))
```

We proved that the various notions of simple field extensions are equivalent to the existence of a power basis.

With the `power_basis` structure, we have the ability to parametrize our results, being able to choose the  $F$  and  $K$  in a simple field extension  $K/F$ , or being able to choose the  $\alpha$  generating  $F(\alpha)$  (by setting `power_basis.gen pb` equal to  $\alpha$ ). Specializing a result from an arbitrary  $K$  with a power basis over  $F$ , to a specific value of  $K$  such as  $F(\alpha) = \text{algebra.adjoin } F \ \{\alpha\}$ , is a matter of applying the result to the power basis generated by  $\alpha$ , and rewriting `power_basis.gen (adjoin.power_basis F  $\alpha$ ) =  $\alpha$` .

## 4 Dedekind domains

The aim of this section is to introduce the notion of *Dedekind domain* which, as discussed in Section 2 is the right setting to study algebraic properties of number fields.

### 4.1 Definitions

There are various equivalent conditions, used at various times, for an integral domain  $R$  to be a Dedekind domain, of which the following three have been formalized in `mathlib`:

- `is_dedekind_domain R`:  $R$  is a Noetherian integral domain, integrally closed in its fraction field and has Krull dimension at most 1;

<sup>4</sup> In the formalization we generalize this notion to any algebra  $A$  over a commutative ring  $R$



350 ■ `is_dedekind_domain_inv`  $R$ :  $R$  is an integral domain and nonzero fractional ideals of  $R$   
 351 have a multiplicative inverse (we discuss the notion and formalization of fractional ideals  
 352 in Section 4.2);

353 ■ `is_dedekind_domain_dvr`  $R$ :  $R$  is a Noetherian integral domain and the localization of  
 354  $R$  at each prime ideal is a discrete valuation ring.

355 We did not use `is_dedekind_domain_dvr` in our project, so we will not discuss this definition  
 356 further.

357 Some authors exclude fields from being Dedekind domains, a convention we initially  
 358 followed. Since we did not encounter any cases where excluding fields was necessary to prove  
 359 a theorem, we decided to simplify the definition of a Dedekind domain. It is still possible to  
 360 exclude fields in a theorem by adding an extra hypothesis  $\neg \text{is\_field } R$ .

361 The “main” definition was chosen to be `is_dedekind_domain`, since this condition  
 362 is usually the one checked in practice [19]. The other two equivalent definitions were  
 363 added `mathlib`, before the proof they are indeed equivalent. Having multiple definitions  
 364 allowed us to do our work in parallel without depending on unformalized results. For  
 365 example, the proof of unique ideal factorization in a Dedekind domain initially assumed  
 366 `is_dedekind_domain_inv`  $R$ , and the proof that the ring of integers  $\mathcal{O}_K$  is a Dedekind  
 367 domain concluded `is_dedekind_domain` (`ring_of_integers`  $K$ ). After the equivalence be-  
 368 tween `is_dedekind_domain`  $R$  and `is_dedekind_domain_inv`  $R$  was formalized, we could  
 369 painlessly replace usages of `is_dedekind_domain_inv`  $R$  with `is_dedekind_domain`  $R$ . Sep-  
 370 arating the different definitions meshed well with the contribution philosophy followed  
 371 by `mathlib`, preferring small, standalone additions over in-progress work or entire finished  
 372 projects.

373 The conditions `is_dedekind_domain` and `is_dedekind_domain_inv` require a fraction  
 374 field  $K$ , although the truth value of the predicates does not depend on the choice of  $K$ .  
 375 For ease of use, we let the type of `is_dedekind_domain` only depend on the domain  $R$  by  
 376 instantiating  $K$  in the definition as `fraction_ring`  $R$ .

```
377 class is_dedekind_domain (R : Type*) [integral_domain R] : Prop :=  

  378 (to_is_noetherian_ring : is_noetherian_ring R)  

  379 (dimension_le_one : dimension_le_one R)  

  380 (is_integrally_closed : integral_closure R (fraction_ring R) = ⊥)  

  381  

  382
```

383 Applications of `is_dedekind_domain` can choose a specific fraction field through the following  
 384 lemma exposing the alternate definition:

```
385 lemma is_dedekind_domain_iff (f : fraction_map R K) :  

  386 is_dedekind_domain R ↔  

  387 is_noetherian_ring R ∧ dimension_le_one R ∧  

  388 integral_closure R f.codomain = ⊥  

  389  

  390
```

391 We mark `is_dedekind_domain` as a typeclass by using the keyword `class` rather than  
 392 `structure`, allowing the typeclass system to automatically infer the Dedekind domain  
 393 structure when an appropriate instance is declared, such as for principal ideal domains or  
 394 rings of integers.

## 395 4.2 Fractional ideals

396 The notion which is pivotal to the definition of the ideal class group of a Dedekind domain is  
 397 that of *fractional ideals*: given any integral domain  $R$ , these are  $R$ -ideals divided by some

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$x : R$ , or equivalently  $R$ -submodules  $J$  of  $K$  such that there is an  $x : R$  with  $xJ \subseteq R$ . The reason for introducing them is that, unlike their subset of proper ideals, they form a group under multiplication. As it should be clear from Section 3.5, this notion depends on the field  $K$  as well as on the localization map  $f : R \rightarrow K$  allowing to speak about  $R$ -submodules of  $K$  and, more importantly, to see an element  $x : R$  as the element  $fx : K$ , so as to be able to write the inclusion  $f(x)J \subseteq f(R)$ . We formalized the definition of fractional ideals relative to a map  $f : R \rightarrow K$  as a type `fractional_ideal f`. We encoded that the structure of fractional ideals does not depend on the choice of fraction map  $f$ , which we formalized as an isomorphism `fractional_ideal.canonical_equiv` between the fractional ideals relative to embeddings  $f_1 : R \rightarrow K_1$  and  $f_2 : R \rightarrow K_2$ .

We defined the addition, multiplication and intersection operations on fractional ideals, by showing the corresponding operations on submodules map fractional ideals to fractional ideals. We also proved that these operations give a commutative semiring structure on the type of fractional ideals. For example, multiplication of fractional ideals is defined as:

```

412 lemma fractional_mul (I J : fractional_ideal f) :
413   is_fractional f (I.1 * J.1) := _ -- proof omitted
414
415
416 instance : has_mul (fractional_ideal f) :=
417   ⟨λ I J, ⟨I.1 * J.1, fractional_mul I J⟩⟩
418
  
```

Defining the quotient of two fractional ideals requires slightly more work. Consider any  $R$ -algebra  $A$  and an injection  $R \hookrightarrow A$ , allowing to look at  $x : R$  as  $x : A$ : given ideals  $I, J \leq R$ , the submodule quotient  $I/J \leq A$  is characterized by the property

```

422 lemma submodule.mem_div_iff_forall_mul_mem {x : A} {I J : submodule R A} :
423   x ∈ I / J ↔ ∀ y ∈ J, x * y ∈ I
424
425
  
```

In our setting, we consider a field of fractions  $K$ , together with a localization map  $f : R \rightarrow K$ : we can look at every ideal as the fractional ideal  $I/1 \leq K$ . The first main theoretical result that we need to define the ideal class group is to show that every non-zero ideal  $0 < I \leq R$  becomes invertible when seen as a fractional ideal: this means, by definition, that the equality

$$f(I) * \frac{1}{f(I)} = 1 = f(R) \leq K \quad (1)$$

as  $R$ -submodules of  $K$ , holds. Beware that the notation  $1/I$  might be misleading here: indeed, for general integral domains, equation (1) might not hold. An example comes from the product

$$\frac{1}{(X, Y)} * (X, Y) = (X, Y) < \mathbb{C}[X, Y]$$

of the fractional ideals  $1/(X, Y)$  and  $(X, Y)$  in the fraction field  $\mathbb{C}(X, Y)$  of  $\mathbb{C}[X, Y]$ . On the other hand, it can be proved that Dedekind domain are precisely the right class of integral domains for which (1) always holds. This was formalised as the following

```

439 lemma fractional_ideal.is_unit {hR : is_dedekind_domain R}
440   (I : fractional_ideal f) (hne : I ≠ ⊥) : is_unit I :=
441
442
  
```

together with

```

444
445 noncomputable instance [is_dedekind_domain R] (g : fraction_map R K) :
446   has_inv (fractional_ideal g) :=
447   ⟨λ I, 1 / I⟩
448

```

asserting that the inverse of any fractional ideal  $I$  (defined as another fractional ideal  $J$  such that  $I * J = 1$ )—which always exists thanks to the lemma `fractional_ideal.is_unit`—is unique and coincides with  $1/I$ .

Two remarks are in order. The first is that in lemma `fractional_ideal.is_unit` the hypothesis (`hne : I ≠ ⊥`) that  $I$  be non-zero is added, and apparently dropped in the `has_inv` instance: this reflects the existence of the typeclass `group_with_zero` in `mathlib`, consisting of groups endowed with an extra element 0 whose inverse is again 0. In particular, the zero fractional ideal is invertible (in the `mathlib` sense) but is not a unit, leading to the strange phenomenon above. Even more fundamentally, the fact that (1) might fail to hold in certain circumstances shows that, for general domains,  $1/I \neq I^{-1}$ . Since `a / b` used to have the built-in definition  $a/b = a * b^{-1}$ , the notation  $1/I$ , defined for every non-zero  $I$ , was conflicting with the fact that  $I$  might not be invertible. Since, for Dedekind domains, we wanted to *define*  $I^{-1}$  as  $1/I$ , a major refactor of a core definition was needed. In particular, to break the circularity, we had to weaken the definitional equality to a proposition; this involved many small changes throughout `mathlib`.

### 4.3 Equivalence of the definitions

We now describe how we proved and formalized that the two definitions `is_dedekind_domain` and `is_dedekind_domain_inv` of being a Dedekind domain are equivalent.

To show that `is_dedekind_domain_inv` implies `is_dedekind_domain`, we follow the proof given by Fröhlich in [13, Chapter 1, § 2, Proposition 1]. A constant challenge that was faced while coding this proof was already mentioned in Section 3.5, namely the fact that elements of the ring must be traced along the fixed morphism to the fields of fractions. The proofs for being integrally closed and of dimension being less than or equal to 1 are fairly straightforward.

Proving the Noetherian condition was the most challenging. In the original proof by Fröhlich, he considers elements  $a_1, \dots, a_n \in I$  and  $b_1, \dots, b_n \in I^{-1}$  for any nonempty fractional ideal  $I$ , satisfying  $\sum_i a_i b_i = 1$ . However, it is quite challenging to prove that an element of the product of two  $R$ -submodules  $M$  and  $N$  must be of the form  $\sum_{i=1}^m a_i * b_i$ , for  $a_i \in A$  and  $b_i \in B$  for all  $1 \leq i \leq m$ . Instead, we show that, for every element of an ideal, there exists a `s : finset R` whose span is contained in the ideal, and which contains the element. This is accomplished by the lemma `submodule.mem_span_mul_finite_of_mem_span_mul`. Now considering an ideal  $I$  of the ring  $R$ , due to its invertibility (as a fractional ideal), by `submodule.mem_span_mul_finite_of_mem_span_mul`, we obtain finite sets  $T \subset I$  and  $T' \subset 1/I$  of type `finset R`, such that 1 is contained in the  $R$ -span of  $T * T'$ . With coercions, the actual statement of the latter expression in Lean is  $\uparrow T' \subseteq \uparrow \uparrow (1 / \uparrow s)$ , which reads :

```

484
485 (T' : set (localization_map.codomain (fraction_ring.of A))) ⊆ (((1 / (s :
486   fractional_ideal (fraction_ring.of A))) : submodule A (
487     localization_map.codomain (fraction_ring.of A))) set (localization_map.
488     codomain (fraction_ring.of A)))
489

```

This is then sufficient to show that  $I$  is finitely generated, as shown in the lemma `fg_of_one_mem_span_mul`.

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The theorem `fractional_ideal.mul_inv_cancel` proves the converse, namely that `is_dedekind_domain` implies `is_dedekind_domain_inv`. The classical proof first shows that every maximal ideal  $M : \text{ideal } R$ , seen as a fractional ideal, is invertible; from this, some work allows to show that every non-zero ideal is invertible, using that it is contained in a maximal ideal; and, finally, the fact that every fractional ideal  $J : \text{fractional\_ideal } f$  satisfies  $xJ \leq I$  for a suitable  $x : R$  and  $I : \text{ideal } R$  allows to show that every fractional ideal is invertible, concluding the proof that non-zero fractional ideals form a group. We have found that formalizing the second step, so passing from the case where  $M$  is maximal to the general case, required more code than directly showing invertibility of arbitrary non-zero ideals. We have coded this in the following

```
lemma coe_ideal_mul_one_div [hR : is_dedekind_domain R] (hNF : ¬ is_field R)
  (I : ideal R) (hne : I ≠ ⊥) :
  ↑I * ((1 : fractional_ideal f) / ↑I) = (1 : fractional_ideal f) :=
```

from where it becomes apparent that, over and over again, we had to carefully distinguish between the ideal  $I$ , which is a term of type `ideal R`, and its coercion  $\uparrow I$ , which is of type `fractional_ideal f`, although these objects, from a mathematical point of view, are identical.

The proof of the above result relies mainly on the lemma `exists_not_mem_one_of_ne_bot`, which says that for every non-trivial ideal  $0 \subsetneq I \subsetneq R$ , there exists an element in the field  $K$  which is not integral (so, not in `f.range`) but lies in  $1/I$ . This depends crucially on  $R$  being Noetherian, since the proof begins by invoking that every non-zero ideal in a Noetherian ring contains a product of non-zero prime ideals. This result was not previously available in `mathlib`, and we formalized it as `exists_prime_spectrum_prod_le_and_ne_bot_of_domain`. It is when applying this that the dimension condition shows its full force: the constructed prime ideal, being non-zero, will be maximal because the Krull dimension of  $R$  is at most 1; from this, the conclusion follows straightforwardly. Having the above lemma at our disposal, we can prove that every ideal  $I \neq 0$  is invertible by arguing by contradiction: if  $I * 1/I \subsetneq R$ , we can find an element  $x \in K \setminus f(R)$  which is in  $1/(1 * 1/I)$  thanks to `exists_not_mem_one_of_ne_bot` and some easy algebraic manipulation will imply that  $x$  is actually integral over  $R$ . Since  $R$  is integrally closed, it must lie in  $f(R)$ , contradicting its construction.

The final step, when we prove that invertibility of ideals implies that of fractional ones as well, was easy: the material developed for the general theory of `fractional_ideals f` allowed to smoothly deduce that a fractional ideal  $J$  must be invertible as soon as a certain multiple  $xJ$  of it is, and since there always exists a  $x : R$  satisfying the latter condition (because  $xJ$  can be made into a “usual” ideal), this leads to the final lemma `fractional_ideal.is_unit` quoted above.

## 5 Principal ideal domains are Dedekind

As an example of our definitions, we will discuss in some detail our formalization of the fact that a principal ideal domain is a Dedekind domain. A principal ideal domain (PID) is an integral domain  $R$  such that each ideal is generated by one element. There is no explicit definition of PIDs in `mathlib`, rather it is split up into two hypotheses. One uses `[integral_domain R] [is_principal_ideal_ring R]` to denote a PID  $R$ , where `is_principal_ideal_ring` is a typeclass defined for all commutative rings:

```

539
540 class is_principal_ideal_ring (R : Type*) [comm_ring R] : Prop :=
541 (principal : ∀ (S : ideal R), S.is_principal)
542

```

Our proof that the hypotheses `[integral_domain A] [is_principal_ideal_ring A]` imply `is_dedekind_domain A` is relatively short:

```

545
546 instance principal_ideal_ring.to_dedekind_domain (A : Type*)
547 [integral_domain A] [is_principal_ideal_ring A] :
548 is_dedekind_domain A :=
549 ⟨principal_ideal_ring.is_noetherian_ring,
550 dimension_le_one.principal_ideal_ring _,
551 unique_factorization_monoid.integrally_closed (fraction_ring.of A)⟩
552

```

Making this an `instance` instead of a `lemma` ensures that the typeclass system can now automatically infer a Dedekind domain structure whenever a principal ideal structure is already available.

The Noetherian property of a Dedekind domain follows easily by the previously defined lemma `principal_ideal_ring.is_noetherian_ring`, since, by definition, each ideal in a principal ideal ring is finitely generated (by a single element).

The lemma `dimension_le_one.principal_ideal_ring` is an instantiation of the existing result `is_prime.to_maximal_ideal` showing a nonzero prime ideal in a PID is maximal. The latter lemma uses the characterization that  $I$  is a maximal ideal if and only if any strictly larger ideal  $J > I$  is the full ring  $\top$ . If  $I$  is a nonzero prime ideal and  $J > I$  in the PID  $R$ , we have that the generator  $j$  of  $J$  is a divisor of the generator  $i$  of  $I$ . Since  $I$  is prime, this implies that either  $j \in I$ , contradicting the assumption that  $J > I$ ,  $i = 0$ , contradicting that  $I$  is nonzero, or that  $j$  is a unit, implying  $J = \top$  as desired.

The final condition of a PID being integrally closed is the most challenging. We use the previously defined instance `principal_ideal_ring.to_unique_factorization_monoid` that a PID is a unique factorisation monoid (UFM), to instantiate our proof that every UFM is integrally closed. In the same way that principal ideal domains are generalized to principal ideal rings, `mathlib` generalizes unique factorization domains to unique factorization monoids. A commutative monoid  $R$  with an absorbing element 0 and injectivity of multiplication is defined to be a UFM, if the relation “ $x$  properly divides  $y$ ” is well-founded (implying each element can be factored as a product of irreducibles) and an element of  $R$  is prime if and only if it is irreducible (implying the factorization is unique). The first condition is satisfied for a PID since the Noetherian property implies that the division relation is well-founded. The second condition follows from `principal_ideal_ring.irreducible_iff_prime`. To prove that an irreducible element  $p$  is prime, the proof uses that prime elements generate prime ideals and irreducible elements of a PID generate maximal ideals. Since all maximal ideals are prime ideals, the ideal generated by  $p$  is maximal, hence prime, thus  $p$  is prime. The lemma `irreducible_of_prime` proves the converse holds in any commutative monoid with zero.

In order to show that a UFM is integrally closed, we first proved the Rational Root Theorem, named `denom_dvd_of_is_root`, which states that for polynomial  $p : R[X]$  and  $x$  an element of the fraction field  $K$  such that  $p(x) = 0$ , the denominator of  $x$  divides the leading coefficient of  $p$ . If  $x$  is integral with minimal polynomial  $p$ , the leading coefficient is 1, therefore the denominator is a unit and  $x$  is an element of  $R$ . This gives us the required lemma `unique_factorization_monoid.integrally_closed`, which states that the integral closure of  $A$  in its fraction field is  $A$  itself.

## 6 Rings of integers are Dedekind domains

An important class of Dedekind domains consists of the rings of integers of number fields. Recall that we defined the ring of integers of a number field  $K$  as the integral closure of  $\mathbb{Z}$  in  $K$ . We proved a stronger result: give a Dedekind domain  $R$  with fraction field  $K$ , if  $L$  is a finite separable extension of  $K$ , then the integral closure of  $R$  in  $L$  is a Dedekind domain with fraction field  $L$ . Our approach adapts [19], Theorem 3.1. Throughout this section,  $R$  will be an integral domain with a field of fractions  $K$  (given by the map  $f: R \rightarrow K$ ),  $L$  a field extension of  $K$  and  $S$  will denote the integral closure of  $R$  in  $L$ .

The first step is to show that  $L$  is a field of fractions for the integral closure, i.e. that there is a map `fraction_map_of_finite_extension`  $f: L \rightarrow \text{fraction\_map } S \text{ } L$ . We formalized the following definition, which implies the desired result:

```
def fraction_map_of_algebraic (alg : is_algebraic R L)
  (inj : function.injective (algebra_map R L)) :
  fraction_map S L
```

The main content of `fraction_map_of_algebraic` consists of showing that all elements  $x: L$  can be written as  $y/z$  for elements  $y \in S$ ,  $z \in R \subseteq S$ ; the standard proof of this fact (e.g. [7, Theorem 15.29]) formalizes readily.

Now we are ready to show that the integral closure of  $R$  in  $L$  is a Dedekind domain, by proving it is integrally closed in  $L$ , has Krull dimension at most 1 and is Noetherian. The fact that the integral closure is integrally closed is immediate.

To show the Krull dimension is at most 1, we needed to develop basic going-up theory for ideals. In particular, we show that an ideal  $I$  in an integral extension is maximal if it lies over a maximal ideal, and use a result already available in `mathlib` that a prime ideal  $I$  in an integral extension lies over a prime ideal.

```
lemma is_maximal_of_is_integral_of_is_maximal_comap
  {S : Type*} [integral_domain S] [algebra R S]
  (hRS : algebra.is_integral R S) (I : ideal S) [I.is_prime]
  (hI : is_maximal (I.comap (algebra_map R S))) : is_maximal I

theorem is_prime.comap [hK : K.is_prime] : (comap f K).is_prime
```

The final condition, that the integral closure  $S$  of  $R$  in  $L$  is a Noetherian ring, requires the most work. We start by following the first half of [7, Theorem 15.29], so that it suffices to find a nondegenerate bilinear form  $B$  such that all integral  $x, y: L$  satisfy  $B(x, y) \in \text{integral\_closure } R \text{ } L$ . We formalized the results in [19], 2.5–2.8, to show the *trace form* is a bilinear form satisfying these requirements.

### 6.1 The trace form

If  $L/K$  is a field extension, we have a bilinear form  $\text{lmul} = \lambda xy: S, xy$ . The trace of the linear map `lmul x` is called the *algebra trace*  $\text{Tr}_{L/K}(x)$  of  $x$ . We define the algebra trace as a linear map from  $L$  to  $K$ :

```
noncomputable def trace : L →L[K] K :=
  (linear_map.trace K L).comp (lmul K L).to_linear_map
```



This definition is marked noncomputable since `linear_map.trace` makes a case distinction on the existence of a basis, choosing an arbitrary basis if one exists and returning 0 otherwise. This latter case does not occur in our development.

The *trace form* is a  $K$ -bilinear form on  $L$ , mapping  $x, y : L$  to  $\text{Tr}(xy)$ .

```

640 noncomputable def trace_form : bilin_form K L :=
641 { bilin := λ x y, trace K L (x * y), .. /- proofs omitted -/ }
642
643

```

In fact, we define the trace and trace form for any algebra over a commutative ring. For simplicity of exposition in this paper we will only consider finite extensions of fields. In the following, let  $K/L/F$  be a tower of finite extensions of fields, namely we assume `[algebra K L] [algebra L F] [algebra K F] [is_scalar_tower K L F]`, as described in Section 3.2.

The value of the trace depends on the choice of  $K$  and  $L$ ; we formalized this as lemmas `trace_algebra_map x : trace K L (algebra_map K L x) = findim K L • x` and `trace_comp L x : trace K F x = trace K L (trace L F x)`. These results follow by direct computation.

To compute  $\text{Tr}_{K:L}(x)$  it therefore suffices to consider the trace of  $x$  in the smallest field containing  $x$  and  $K$ , which is the simple extension  $K(x)$  discussed in Section 3.6. There is a nice formula for the trace in  $K(x)$ , although the terms in this formula are elements in a larger field  $F$  (such as the *splitting field* of the minimal polynomial of  $x$ ). In formalizing this formula, we must first map the trace to  $F$  using the canonical embedding `algebra_map K F`, giving the following lemma statement:

```

659 lemma power_basis.trace_gen_eq_sum_roots (pb : power_basis K L)
660 (h : polynomial.splits (algebra_map K F) pb.minpoly_gen) :
661 algebra_map K F (trace K L pb.gen) =
662 (pb.minpoly_gen.map (algebra_map K F)).roots.sum
663
664

```

We formulate the lemma in terms of the power basis, since we will need to use it for  $K(x)$  here and for an arbitrary finite separable extension  $L/K$  later in the proof.

The elements of `(pb.minpoly_gen.map (algebra_map K F)).roots` are called *conjugates* of  $x$  in  $F$ . Each conjugate of  $x$  is integral since it is a root of (the same) monic polynomial, and integer multiples and sums of integral elements are integral. Combining `trace_gen_eq_sum_roots` and `trace_algebra_map` together shows that the trace of  $x$  is an integer multiple (namely `findim K(x) L`) of a sum of conjugate roots, hence we conclude that the trace (and trace form) of an integral element is also integral.

Finally, we show the trace form is nondegenerate, following [19], Proposition 2.8. Since  $L/K$  is a finite, separable field extension, it has a power basis `pb` generated by  $x$ . Letting  $x_k$  denote the  $k$ -th conjugate of  $x$  in an algebraically closed field  $F/L/K$ , the main difficulty lies in checking the equality  $\sum_k x_k^{i+j} = \text{Tr}_{L/K}(x^{i+j})$ . Directly applying `trace_gen_eq_sum_roots` is tempting, since we have a sum over conjugates of powers on both sides. However, the two expressions will not precisely match: the left hand side is a sum of conjugates of  $x$ , where each conjugate is raised to the power  $i+j$ , while the conclusion of `trace_gen_eq_sum_roots` results in a sum over conjugates of  $x^{i+j}$ .

Instead, the informal proof switches here to an equivalent definition of conjugate: the conjugates of  $x$  in  $F$  are the images (counted with multiplicity) of  $x$  under each embedding  $\sigma : K(x) \rightarrow F$  that fixes  $K$ . This equivalence between the two notions of conjugate was contributed to `mathlib` by the Berkeley group in the week before we realized we needed it. Mapping `trace_gen_eq_sum_roots` through the equivalence gives  $\text{Tr}_{L/K}(x) = \sum_{\sigma : L \rightarrow_a [K]F} \sigma x$ .

## XX:16 Dedekind domains and class groups

686 Since  $\sigma$  is a ring homomorphism,  $\sigma x^{i+j} = (\sigma x)^{i+j}$ , so the conjugates of  $x^{i+j}$  are the  
687  $(i+j)$ -th powers of conjugates of  $x$ , concluding the proof.

### 688 7 Class group and class number

689 Recall that the ideal class group of an integral domain  $R$  is defined as the quotient  
690 of the invertible fractional ideals modulo the principal fractional ideals. We formalize  
691 this notion in Lean by defining a map `to_principal_ideal f : units f.codomain →`  
692 `units (fractional_ideal f)`, and define the class group to be the quotient group modulo  
693 `to_principal_ideal.range`. In general, Dedekind domains can have infinite class groups.  
694 However, the ring of integers in a global field is a Dedekind domain with finite class group.

695 Let  $R$  denote the ring of integers inside some number field, and let  $S$  denote the ring of  
696 integers inside some function field. Most proofs of the finiteness of  $\mathcal{C}l_R$  one finds in a modern  
697 textbook (see e.g. [19, Theorems 4.4, 5.3, 6.3]) depend on Minkowski's lattice point theorem,  
698 a result from the geometry of numbers (which has e.g. been formalized in Isabelle/HOL [8]).  
699 Extending this proof to show the finiteness of  $\mathcal{C}l_S$  is quite involved and does not result in  
700 a uniform proof for  $\mathcal{C}l_R$  and  $\mathcal{C}l_S$ . Instead we were inspired by a more classical approach to  
701 the finiteness of  $\mathcal{C}l_R$ , where the use of Minkowski's theorem is replaced by the pigeonhole  
702 principle. This approach seems to go back to Kronecker and can e.g. be found in [16]. Our  
703 formalization adapts and generalizes this approach. We note that some other “uniform”  
704 approaches can be found in [1] and [20].

705 Let  $R$  be a Dedekind domain and  $L$  be a finite separable field extension of the fraction field  
706  $K$  of  $R$  (with fraction map  $f : R \rightarrow K$ ). We prove in the theorem `class_group.finite_of_admissible`  
707 that the integral closure of  $R$  in  $L$  has a finite class group if it has an “admissible” absolute  
708 value `abs`. Informally, the admissibility conditions require that the remainder operator  
709 produces values that are not too far apart. Formally, we define the type of admissible  
710 absolute values on  $R$  as:

```
711 structure admissible_absolute_value (R : Type*) [euclidean_domain R]  
712 extends euclidean_absolute_value R ℤ :=  
713 (card : ℝ → ℕ) (exists_partition :  
714   ∀ (n : ℕ) (ε > (0 : ℝ)) (b ≠ (0 : R)) (A : fin n → R),  
715   ∃ (t : fin n → fin (card ε)), ∀ i₀ i₁, t i₀ = t i₁ →  
716   (to_fun (A i₁ % b - A i₀ % b) : ℝ) < to_fun b · ε)  
717  
718
```

719 Here, `to_fun` stands for an application of the absolute value operator.

720 The above condition formalizes an intermediate result in the typical finiteness proofs; the  
721 different proofs for number fields and function fields are the same after this point. We use  
722 division with remainder to replace the *fractional part* operator on  $K$  in the classical proof,  
723 allowing our proof to stay entirely within  $R$  to avoid casts.

724 The absolute value extends to a norm `abs_norm f abs : integral_closure R L →`  
725  $\mathbb{Z}$ . We use the admissibility of `abs` to find a finite set `finset_approx L f abs` of elements  
726 of  $R$ , such that the following generalization of [16, Theorem 12.2.1] holds.

```
727 theorem exists_mem_finset_approx' (a b : integral_closure R L) :=  
728   ∃ (q : integral_closure R L) (r ∈ finset_approx L f abs),  
729   abs_norm f abs (r · a - q * b) < abs_norm f abs b  
730  
731
```

732 After this, the classical approach mentioned above formalizes smoothly.

It remains to define an admissible absolute value for  $\mathbb{Z}$  and  $K[t]$  (where  $K$  is a finite field). On  $\mathbb{Z}$ , the usual Archimedean absolute value does the job (which is straightforward to formalize). For  $K[t]$ , let  $q$  be the cardinality of  $K$ , then we show  $|f|_{\deg} := q^{\deg f}$  for  $f \in \mathbb{F}_q[t]$  works in the function field setting (which is somewhat more involved). (Note that these absolute values coincide with cardinalities in corresponding residue rings, but we do not need this result.) We conclude that the class group is finite:

```

noncomputable instance : fintype
  (class_group (number_field.ring_of_integers.fraction_map K)) :=
class_group.finite_of_admissible K int.fraction_map int.admissible_abs

noncomputable instance : fintype
  (class_group (function_field.ring_of_integers.fraction_map f F)) :=
class_group.finite_of_admissible F f polynomial.admissible_char_pow_degree

```

Finally, we define `number_field.class_number` and `function_field.class_number` as the cardinality of the respective class groups.

## 8 Discussion

### 8.1 Related work

Broadly speaking, one could see the formalization work as part of number theory. There are several formalization result in this direction; see e.g. [5, Section 6], most notably the formalization in Isabelle/HOL of a substantial part of analytic number theory [9]. Narrowing somewhat in on our more algebraic setting, we are not aware of any other formal developments of fractional ideals, Dedekind domains or class groups of global fields. Since our project touches upon the theories of field extensions, ideals, number fields and number rings, we provide here a partial overview of formalizations in these areas.

There are many libraries formalizing basic notions of commutative algebra such as field extensions and ideals, including the Mathematical Components library in Coq [17], the algebraic library for Isabelle/HOL [11], the `set.mm` database for MetaMath [18] and the Mizar Mathematical Library [15]. The field of algebraic numbers, or more generally algebraic closures of arbitrary fields, are also available in many provers, for example Coq [4, 17], Isabelle/HOL [23], MetaMath [2], and Mizar [24]. To our knowledge, the Coq Mathematical Components library is the only formal development except ours specifically dealing with number fields [17, `field/alnum.v`].

Apart from the general theory of algebraic numbers, there are formalizations of specific number rings: the Gaussian integers  $\mathbb{Z}[i]$  are available in Isabelle/HOL [10], MetaMath [3] and Mizar [14]. The Isabelle/HOL formalization deserves special mention since it introduces techniques from algebraic number theory, defining the integer-valued norm on  $\mathbb{Z}[i]$  and classifying the prime elements of  $\mathbb{Z}[i]$ .

### 8.2 Future directions

Having formalized the basics of algebraic number theory, there are several natural directions for future formalization work. These include the following.

- Finiteness of the class group for the ring of integers in all global fields. This would entail dropping the separability condition in the result mentioned in the third line of Section 6, and consequently adapt some of the details in the final steps for the finiteness of the class

- group in the admissible case. Some basic prerequisites would be setting up some field theory dealing with (finite) inseparable field extensions, especially the purely inseparable ones. Al in all this seems a tedious though reasonable project.
- Finite generation of the group of units of the ring of integers in a number field, or slightly stronger, Dirichlet’s unit theorem [19, Theorem 7.4]. This seems a somewhat more involved, but still reasonable, project. The finite generation result also holds for function fields, so actually it would be nice (and doable) to consider all global fields (which would involve finite inseparable field extensions, as in the previous item).
  - Other finiteness results in algebraic number theory, most notably Hermitte’s theorem about the existence of only finitely many number fields (up to isomorphism, or embedded in a fixed algebraically closed field containing  $\mathbb{Q}$ , e.g.  $\mathbb{C}$ ) with discriminant below a given bound [19, Theorem 2.16]. This would be significantly more involved than the previous items and would require, amongst other things, setting up a lot of ramification theory (which is very important for algebraic number theory). As usual, there are analogue results in the function field setting, though they are less straightforward. One reason being that the nondegenerateness of the trace form from Section 6.1 does not hold any more when the separability condition is dropped.
  - Computational aspect. Our formalization lays some foundations to the verification of number theoretic software, such as KASH/KANT [12] and PARI/GP [22]. Verifying computations for class groups, or just class numbers, in the case of “small” (e.g. some quadratic) number fields, looks within reach. Of course, getting really efficient algorithms (or certificates), is a hard research topic.
  - Number theoretic applications. All of the above items consider theoretical of computational aspects within algebraic number theory itself. There are many applications of these, e.g. solving Diophantine equations. Solving Mordell equations, i.e. for a given nonzero integer  $D$  determining all pairs of integers  $(x, y)$  such that  $y^2 = x^3 + D$ , could be an interesting first case study (dealing with some values of  $D$  where elementary methods fail).

### 8.3 Conclusion

In this project, we found that the rule holds that the hardest part of formalization is to get the definitions just right. Once this is accomplished, the informal proof almost always translated to a formal proof without too much effort. In particular, we regularly had to invent abstractions to treat instances the “same” situation uniformly. Instead of fixing a canonical representation such  $K \subseteq L \subseteq F$  as subfields,  $\text{Frac } F$  as the field of fractions, or  $K(\alpha)$  as the simple field extension, we find that making the essence of the situation an explicit parameter, as in `is_scalar_tower`, `fraction_map` or `power_basis`, treats equivalent viewpoints uniformly without the need for transferring results.

The formalization efforts described in this paper cannot be cleanly separated from the development of `mathlib` as a whole. The decentralized organization and highly integrated design of `mathlib` meant we could contribute our formalizations as we completed them, resulting in a quick integration into the rest of the library. Other contributors building on these results often extended them to meet our requirements, before we could identify that we needed them, as the anecdote in Section 3.4 illustrates. In other words, the low barriers for contributions ensured mutually beneficial collaboration.

The formalization project described in this paper resulted in the contribution of thousands of lines of Lean code involving hundreds of declarations. We validated existing design choices used in `mathlib`, refactored those that did not scale well and contributed our own set of designs.

The real achievement was not to complete each proof, but to build a better foundation for formal mathematics.

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