MATH 902 LECTURE NOTES, SPRING 2022

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In this class, all rings are assumed to be commutative, with associative multiplication and containing 1.

1. Finiteness conditions

1.1. **Finitely generated algebras.** We start by recalling a definition from last semester, specialized to the setting of commutative rings.

Definition 1.1 (Algebra). Given a ring A, an A-algebra is a ring R equipped with a ring homomorphism $\phi: A \to R$. This defines an A-module structure on R given by restriction of scalars, that is, for $a \in A$ and $r \in R$, $ar := \phi(a)r$ that is compatible with the internal multiplication of R i.e.,

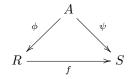
$$a(rs) = (ar)s = r(as)$$
 for all $a \in A, rs \in R$.

We will call ϕ the structure homomorphism of the A-algebra R.

Example 1.2. • If A is a ring and x_1, \ldots, x_n are indeterminates, the inclusion map $A \hookrightarrow A[x_1, \ldots, x_n]$ makes the polynomial ring into an A-algebra.

- When $A \subseteq R$ the inclusion map makes R an A-algebra. In this case the A-module multiplication ar coincides with the internal (ring) multiplication on R.
- Any ring comes with a unique structure as a Z-algebra.

The collection of A-algebras forms a category where the morphisms are ring homomorphisms $f: R \to S$ such that the following diagram commutes



for structural homomorphisms $\varphi:A\to R$ and $\psi:A\to S$.

Definition 1.3 (Algebra generation). Let R be an A-algebra and let $\Lambda \subseteq R$ be a set. The A-algebra generated by a subset Λ of R, denoted $A[\Lambda]$, is the smallest (w.r.t containment) subring of R containing Λ and $\varphi(A)$.

A set of elements $\Lambda \subseteq R$ generates R as an A-algebra if $R = A[\Lambda]$.

Note that there are two different meanings for the notation A[S] for a ring A and set S: one calls for a polynomial ring, and the other calls for a subring of something.

This can be unpackaged more concretely in a number of equivalent ways:

Lemma 1.4. The following are equivalent

- (1) Λ generates R as an Λ -algebra.
- (2) Every element in R admits a polynomial expression in Λ with coefficients in $\phi(A)$, i.e.

$$R = \left\{ \sum_{\text{finite}} \phi(a) \lambda_1^{i_1} \cdots \lambda_n^{i_n} \mid a \in A, \lambda_j \in \Lambda, i_j \in \mathbb{N} \right\}.$$

(3) The A-algebra homomorphism $\psi : A[X] \to R$, where A[X] is a polynomial ring on a set of indeterminates X in bijection with Λ and $\psi(x_i) = \lambda_i$, is surjective.

Proof. Let $S = \{\sum_{\text{finite}} \phi(a) \lambda_1^{i_1} \cdots \lambda_n^{i_n} \mid a \in A, \lambda_j \in \Lambda, i_j \in \mathbb{N} \}$. For the equivalence between (2) and (3) we note that S is the image of ψ . In particular, S is a subring of R. It then follows from the definition that (1) implies (2). Conversely, any subring of R containing $\phi(A)$ and Λ certainly must contain S, so (2) implies (1).

Example 1.5. We may have also seen these brackets used in $\mathbb{Z}[\sqrt{d}]$ for some $d \in \mathbb{Z}$ to describe the ring

$${a + b\sqrt{d} \mid a, b \in \mathbb{Z}}.$$

In fact, this is a special instance of generating: the \mathbb{Z} -algebra generated by \sqrt{d} in the most natural place, the algebraic closure of \mathbb{Q} , is exactly the set above. The point is that for any power $(\sqrt{2})^n$, write n = 2q + r with $r \in \{0, 1\}$, so $(\sqrt{2})^n = 2^d(\sqrt{2})^r$. Similarly, the ring $\mathbb{Z}[\sqrt[3]{d}]$ can be written as

$$\{a+b\sqrt[3]{d}+c\sqrt[3]{d^2}\mid a,b,c\in\mathbb{Z}\}.$$

Note that the homomorphism ψ in part (3) need not be injective.

- If the homomorphism ψ is injective (so an isomorphism) we say that A is a free algebra.
- the set $\ker(\psi)$ measures how far R is from being a free A-algebra and is called the set of relations on Λ .

Definition 1.6 (Algebra-finite). We say that $\varphi: A \to R$ is algebra-finite, or R is a finitely generated A-algebra, if there exists a finite set of elements f_1, \ldots, f_d that generates R as an A-algebra. We write $R = A[f_1, \ldots, f_d]$ to denote this.

The term *finite-type* is also used to mean this.

Remark 1.7. Note that, by the lemma on generating sets, an A-algebra is finitely generated if and only if it is isomorphic to a quotient of a polynomial ring over A in finitely many variables. The choice of an isomorphism with a quotient of a polynomial ring is equivalent to a choice of generating set.

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