Lecture Notes on Commutative Algebra

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Contents

Preface

Here we will mainly follows [1]. We will assume all rings are commutative with unit. We assume the reader know the basic algebra an some homological algebra, including basic theory of groups, rings, modules, basic things of spectrum of rings and its basic properties, abelian categories, derived categories and derived functors.

Chapter 1

Rings, Ideals and Modules

1.1 Basic Properties

Lemma 1.1.1. *Let R be a ring and let M be an R-module. Then there exists a directed system of finitely presented R-modules M_i such that $M \cong \varinjlim M_i$.*

Proof. Consider any finite subset $S \subset M$ and any finite collection of relations E among the elements of S. So each $s \in S$ corresponds to $x_s \in M$ and each $e \in E$ consists of a vector of elements $f_{e,s} \in R$ such that $\sum f_{e,s} x_s = 0$. Let $M_{S,E}$ be the cokernel of the map

$$R^{\#E} \longrightarrow R^{\#S}, \quad (g_e)_{e \in E} \longmapsto \left(\sum g_e f_{e,s} \right)_{s \in S}.$$

There are canonical maps $M_{S,E} \to M$. If $S \subset S'$ and if the elements of E correspond, via this map, to relations in E', then there is an obvious map $M_{S,E} \to M_{S',E'}$ commuting with the maps to M. Let I be the set of pairs (S, E) with ordering by inclusion as above. It is clear that the colimit of this directed system is M. $\square$

Proposition 1.1.2. *Let R be a ring. Let N be an R-module. The following are equivalent*

(1) N is a finitely generated (finitely presented) R-module.

(2) for any filtered colimit $M = \varinjlim M_i$ of R-modules the map

$$\varinjlim \mathrm{Hom}_R(N, M_i) \to \mathrm{Hom}_R(N, M)$$

is injective (bijective).

Proof. Consider the case of finitely generated: Assume (1) and choose generators $x_1, \cdots, x_m$ for N. If $N \to M_i$ is a module map and the composition $N \to M_i \to M$ is zero, then because $M = \varinjlim_{i' \geq i} M_{i'}$ for each $j \in \{1, \ldots, m\}$ we can find a $i' \geq i$ such that x_j maps to zero in $M_{i'}$. Since there are finitely many x_j we can find a single i' which works for all of them. Then the composition $N \to M_i \to M_{i'}$ is zero and we conclude the map is injective, i.e., part (2) holds.

Assume (2). For a finite subset $E \subset N$ denote $N_E \subset N$ the R-submodule generated by the elements of E. Then $0 = \varinjlim N/N_E$ is a filtered colimit. Hence we see that $\mathrm{id} : N \to N$ maps into N_E for some E, i.e., N is finitely generated.

Consider the case of finitely presented: Assume (1) and choose an exact sequence $F_{-1} \to F_0 \to N \to 0$ with F_i finite free. Then we have an exact sequence

$$0 \to \mathrm{Hom}_R(N, M) \to \mathrm{Hom}_R(F_0, M) \to \mathrm{Hom}_R(F_{-1}, M)$$

functorial in the R-module M. The functors $\mathrm{Hom}_R(F_i, M)$ commute with filtered colimits as $\mathrm{Hom}_R(R^{\oplus n}, M) = M^{\oplus n}$. Since filtered colimits are exact, we see that (2) holds.

Assume (2). By Lemma 1.1.1 we can write $N = \varinjlim N_i$ as a filtered colimit such that N_i is of finite presentation for all i. Thus id_N factors through N_i for some i. This means that N is a direct summand of a finitely presented R-module (namely N_i) and hence finitely presented. □

Proposition 1.1.3. *Let R be a ring, and let M be a finitely generated R-module. There exists a filtration by R-submodules*

$$0 = M_0 \subset M_1 \subset \cdots \subset M_n = M$$

such that each quotient M_i/M_{i-1} is isomorphic to R/I_i for some ideal $I_i \subset R$.

Proof. By induction on the number of generators of M. Let $x_1, \cdots, x_r \in M$ be a minimal number of generators. Let $M' := Rx_1 \subset M$. Then M/M' has $r-1$ generators and the induction hypothesis applies. And clearly $M' \cong R/\operatorname{ann}(x_1)$, well done. □

1.2 Localizations

Definition 1.2.1. *Let R be a ring, S a subset of R. We say S is a* multiplicative subset of *R if $1 \in S$ and S is closed under multiplication, i.e., $s, s' \in S \Rightarrow ss' \in S$.*

Definition 1.2.2. *Given a ring A and a multiplicative subset S, we define a relation on $A \times S$ as follows:*

$$(x, s) \sim (y, t) \Leftrightarrow \exists u \in S \text{ such that } (xt - ys)u = 0.$$

It is easily checked that this is an equivalence relation. Let x/s be the equivalence class of (x, s) and $S^{-1}A$ be the set of all equivalence classes. Define addition and multiplication in $S^{-1}A$ as follows:

$$x/s + y/t = (xt + ys)/st, \quad x/s \cdot y/t = xy/st.$$

One can check that $S^{-1}A$ becomes a ring under these operations. Then this ring is called the localization of A with respect to S *.*

We have a natural ring map from A to its localization $S^{-1}A$,

$$A \longrightarrow S^{-1}A, \quad x \longmapsto x/1$$

which is sometimes called the localization map. In general the localization map is not injective, unless S contains no zerodivisors.

The localization of a ring has the following universal property.

Proposition 1.2.3. *Let $f : A \to B$ be a ring map that sends every element in S to a unit of B. Then there is a unique homomorphism $g : S^{-1}A \to B$ such that the following diagram commutes.*

$$\begin{tikzcd} A \arrow[rr, "f"] \arrow[dr] & & B \\ & S^{-1}A \arrow[ur, dashed, "\exists! g"'] & \end{tikzcd}$$

Proof. Existence. We define a map g as follows. For $x/s \in S^{-1}A$, let $g(x/s) = f(x)f(s)^{-1} \in B$. It is easily checked from the definition that this is a well-defined ring map. And it is also clear that this makes the diagram commutative.

Uniqueness. We now show that if $g' : S^{-1}A \to B$ satisfies $g'(x/1) = f(x)$, then $g = g'$. Hence $f(s) = g'(s/1)$ for $s \in S$ by the commutativity of the diagram. But then $g'(1/s)f(s) = 1$ in B, which implies that $g'(1/s) = f(s)^{-1}$ and hence $g'(x/s) = g'(x/1)g'(1/s) = f(x)f(s)^{-1} = g(x/s)$. $\square$

Lemma 1.2.4. *Let R be a ring. Let $S \subset R$ be a multiplicative subset. The category of $S^{-1}R$-modules is equivalent to the category of R-modules N with the property that every $s \in S$ acts as an automorphism on N.*

Proof. The functor which defines the equivalence associates to an $S^{-1}R$-module M the same module but now viewed as an R-module via the localization map $R \to S^{-1}R$. Conversely, if N is an R-module, such that every $s \in S$ acts via an automorphism s_N, then we can think of N as an $S^{-1}R$-module by letting x/s act via $x_N \circ s_N^{-1}$. We omit the verification that these two functors are quasi-inverse to each other. $\square$

The notion of localization of a ring can be generalized to the localization of a module.

Definition 1.2.5. *Let A be a ring, S a multiplicative subset of A and M an A-module. We define a relation on $M \times S$ as follows*

$$(m, s) \sim (n, t) \Leftrightarrow \exists u \in S \textit{ such that } (mt - ns)u = 0.$$

This is clearly an equivalence relation. Denote by m/s be the equivalence class of (m,s) and $S^{-1}M$ be the set of all equivalence classes. Define the addition and scalar multiplication as follows

$$m/s + n/t = (mt+ns)/st, \quad m/s \cdot n/t = mn/st.$$

It is clear that this makes $S^{-1}M$ an $S^{-1}A$-module. The $S^{-1}A$-module $S^{-1}M$ is called the localization *of M at S.*

Note that there is an A-module map $M \to S^{-1}M$, $m \mapsto m/1$ which is also called the localization map. It satisfies the following similar universal property.

Lemma 1.2.6. *Let R be a ring. Let $S \subset R$ a multiplicative subset. Let M, N be R-modules. Assume all the elements of S act as automorphisms on N. Then we have*

$$\begin{tikzcd} M \arrow[rr, "\beta"] \arrow[dr] & & N \\ & S^{-1}M \arrow[ur, dashed, "\exists!\alpha"'] & \end{tikzcd}$$

Moroever, the canonical map

$$\mathrm{Hom}_R(S^{-1}M, N) \longrightarrow \mathrm{Hom}_R(M, N)$$

induced by the localization map, is an isomorphism.

Proof. It is clear that the map is well-defined and R-linear. Injectivity: Let $\alpha \in \mathrm{Hom}_R(S^{-1}M, N)$ and take an arbitrary element $m/s \in S^{-1}M$. Then, since $s \cdot \alpha(m/s) = \alpha(m/1)$, we have $\alpha(m/s) = s^{-1}(\alpha(m/1))$, so α is completely determined by what it does on the image of M in $S^{-1}M$. Surjectivity: Let $\beta : M \to N$ be a given R-linear map. We need to show that it can be "extended" to $S^{-1}M$. Define a map of sets

$$M \times S \to N, \quad (m,s) \mapsto s^{-1}\beta(m).$$

Clearly, this map respects the equivalence relation from above, so it descends to a well-defined map $\alpha : S^{-1}M \to N$. It remains to show that this map is R-linear, so take $r, r' \in R$ as well as $s, s' \in S$ and $m, m' \in M$. Then

$$\begin{aligned} \alpha(r \cdot m/s + r' \cdot m'/s') &= \alpha((r \cdot s' \cdot m + r' \cdot s \cdot m')/(ss')) \\ &= (ss')^{-1}\beta(r \cdot s' \cdot m + r' \cdot s \cdot m') \\ &= (ss')^{-1}(r \cdot s'\beta(m) + r' \cdot s\beta(m')) \\ &= r\alpha(m/s) + r'\alpha(m'/s') \end{aligned}$$

and we win. $\square$

Example 1.2.1. *Let A be a ring and let M be an A-module. Here are some important examples of localizations.*

1. *Given $\mathfrak{p}$ a prime ideal of A consider $S = A \setminus \mathfrak{p}$. It is immediately checked that S is a multiplicative set. In this case we denote $A_{\mathfrak{p}}$ and $M_{\mathfrak{p}}$ the localization of A and M with respect to S respectively. These are called the* localization of A, resp. M at $\mathfrak{p}$ *.*

2. *Let $f \in A$. Consider $S = \{1, f, f^2, \ldots\}$. This is clearly a multiplicative subset of A. In this case we denote A_f (resp. M_f) the localization $S^{-1}A$ (resp. $S^{-1}M$). This is called the* localization of A, resp. M with respect to f*. Note that $A_f = 0$ if and only if f is nilpotent in A.*

3. *Let $S = \{f \in A : f$ is not a zerodivisor in $A\}$. This is a multiplicative subset of A. In this case the ring $Q(A) = S^{-1}A$ is called either the* total quotient ring *of A.*

4. *If A is a domain, then the total quotient ring $Q(A)$ is the field of fractions of A.*

Lemma 1.2.7. *Let R be a ring. Let $S \subset R$ be a multiplicative subset. Let M be an R-module. Then*

$$S^{-1}M = \varinjlim_{f \in S} M_f$$

where the preorder on S is given by $f \geq f' \Leftrightarrow f = f'f''$ for some $f'' \in R$ in which case the map $M_{f'} \to M_f$ is given by $m/(f')^e \mapsto m(f'')^e/f^e$.

Proof. Omitted. Just need to check the universal property. □

Proposition 1.2.8. *Let A denote a ring, and M, N denote modules over A. If S and S' are multiplicative sets of A, then it is clear that*

$$SS' = \{ss' : s \in S,\ s' \in S'\}$$

is also a multiplicative set of A. Then the following holds.

(1) *Let $\overline{S}$ be the image of S in $S'^{-1}A$, then $(SS')^{-1}A$ is isomorphic to $\overline{S}^{-1}(S'^{-1}A)$.*

(2) *View $S'^{-1}M$ as an A-module, then $S^{-1}(S'^{-1}M)$ is isomorphic to $(SS')^{-1}M$.*

(3) *Let $L \xrightarrow{u} M \xrightarrow{v} N$ be an exact sequence of R-modules. Then $S^{-1}L \to S^{-1}M \to S^{-1}N$ is also exact.*

(4) *If N is a submodule of M, then $S^{-1}(M/N) \simeq (S^{-1}M)/(S^{-1}N)$.*

(5) *Let I be an ideal of A, S a multiplicative set of A. Then $S^{-1}I$ is an ideal of $S^{-1}A$ and $\overline{S}^{-1}(A/I)$ is isomorphic to $S^{-1}A/S^{-1}I$, where $\overline{S}$ is the image of S in A/I.*

(6) *Any submodule N' of $S^{-1}M$ is of the form $S^{-1}N$ for some $N \subset M$. Indeed one can take N to be the inverse image of N' in M. In particular, each ideal I' of $S^{-1}A$ takes the form $S^{-1}I$, where one can take I to be the inverse image of I' in A.*

Proof. For (1), the map sending $x \in A$ to $x/1 \in (SS')^{-1}A$ induces a map sending $x/s \in S'^{-1}A$ to $x/s \in (SS')^{-1}A$, by universal property. The image of the elements in $\overline{S}$ are invertible in $(SS')^{-1}A$. By the universal property we get a map $f : \overline{S}^{-1}(S'^{-1}A) \to (SS')^{-1}A$ which maps $(x/t')/(s/s')$ to $(x/t')\cdot(s/s')^{-1}$. On the other hand, the map from A to $\overline{S}^{-1}(S'^{-1}A)$ sending $x \in A$ to $(x/1)/(1/1)$ also induces a map $g : (SS')^{-1}A \to \overline{S}^{-1}(S'^{-1}A)$ which sends x/ss' to $(x/s')/(s/1)$, by the universal property again. It is immediately checked that f and g are inverse to each other, hence they are both isomorphisms.

For (2), note that given a A-module M, we have not proved any universal property for $S^{-1}M$. Hence we cannot reason as in the preceding proof; we have to construct the isomorphism explicitly. We define the maps as follows

$$f : S^{-1}(S'^{-1}M) \longrightarrow (SS')^{-1}M, \quad \frac{x/s'}{s} \mapsto x/ss'$$
$$g : (SS')^{-1}M \longrightarrow S^{-1}(S'^{-1}M), \quad x/t \mapsto \frac{x/s'}{s} \text{ for some } s \in S, s' \in S', \text{ and } t = ss'$$

We have to check that these homomorphisms are well-defined, that is, independent the choice of the fraction. This is easily checked and it is also straightforward to show that they are inverse to each other.

For (3), first it is clear that $S^{-1}L \to S^{-1}M \to S^{-1}N$ is a complex since localization is a functor. Next suppose that x/s maps to zero in $S^{-1}N$ for some $x/s \in S^{-1}M$. Then by definition there is a $t \in S$ such that $v(xt) = v(x)t = 0$ in M, which means $xt \in \ker(v)$. By the exactness of $L \to M \to N$ we have $xt = u(y)$ for some y in L. Then x/s is the image of y/st. This proves the exactness.

For (4), from the exact sequence

$$0 \longrightarrow N \longrightarrow M \longrightarrow M/N \longrightarrow 0$$

we have

$$0 \longrightarrow S^{-1}N \longrightarrow S^{-1}M \longrightarrow S^{-1}(M/N) \longrightarrow 0$$

The corollary then follows.

For (5), The fact that $S^{-1}I$ is an ideal is clear since I itself is an ideal. Define

$$f : S^{-1}A \longrightarrow \overline{S}^{-1}(A/I), \quad x/s \mapsto \overline{x}/\overline{s}$$

where $\overline{x}$ and $\overline{s}$ are the images of x and s in A/I. We shall keep similar notations in this proof. This map is well-defined by the universal property of $S^{-1}A$, and $S^{-1}I$ is contained in the kernel of it, therefore it induces a map

$$\overline{f} : S^{-1}A/S^{-1}I \longrightarrow \overline{S}^{-1}(A/I), \quad \overline{x/s} \mapsto \overline{x}/\overline{s}$$

On the other hand, the map $A \to S^{-1}A/S^{-1}I$ sending x to $\overline{x/1}$ induces a map $A/I \to S^{-1}A/S^{-1}I$ sending $\overline{x}$ to $\overline{x/1}$. The image of $\overline{S}$ is invertible in $S^{-1}A/S^{-1}I$, thus induces a map

$$g : \overline{S}^{-1}(A/I) \longrightarrow S^{-1}A/S^{-1}I, \quad \frac{\overline{x}}{\overline{s}} \mapsto \overline{x/s}$$

by the universal property. It is then clear that $\overline{f}$ and g are inverse to each other, hence are both isomorphisms.

For (6), Let N be the inverse image of N' in M. Then one can see that $S^{-1}N \supset N'$. To show they are equal, take x/s in $S^{-1}N$, where $s \in S$ and $x \in N$. This yields that $x/1 \in N'$. Since N' is an $S^{-1}R$-submodule we have $x/s = x/1 \cdot 1/s \in N'$. This finishes the proof. □

1.3 Tensor Products and Flatness

1.3.1 Tensor Products

Proposition 1.3.1. *Let M, N be R-modules. Then there exists a pair $(M \otimes_R N, g)$ where $M \otimes_R N$ is an R-module, and $g : M \times N \to T$ an R-bilinear mapping, with the following universal property: For any R-module P and any R-bilinear mapping $f : M \times N \to P$, there exists a unique R-linear mapping $\tilde{f} : M \otimes_R N \to P$ such that $f = \tilde{f} \circ g$. In other words, the following diagram commutes:*

$$\begin{tikzcd} M \times N \arrow[rr, "f"] \arrow[dr, "g"'] & & P \\ & M \otimes_R N \arrow[ur, dashed, "\exists! \tilde{f}"'] & \end{tikzcd}$$

Then $M \otimes_R N$ is called the tensor product *of R-modules M and N*

Proof. We first prove the existence of such R-module T. Let M, N be R-modules. Let T be the quotient module P/Q, where P is the free R-module $R^{(M\times N)}$ and Q is the R-module generated by all elements of the following types: $(x \in M, y \in N)$

$$\begin{aligned} (x + x', y) - (x, y) - (x', y), \\ (x, y + y') - (x, y) - (x, y'), \\ (ax, y) - a(x, y), \\ (x, ay) - a(x, y) \end{aligned}$$

Let $\pi : M \times N \to T$ denote the natural map. This map is R-bilinear, as implied by the above relations when we check the bilinearity conditions. Denote the image $\pi(x, y) = x \otimes y$, then these elements generate T. Now let $f : M \times N \to P$ be an R-bilinear map, then we can define $f' : T \to P$ by extending the mapping $f'(x \otimes y) = f(x, y)$. Clearly $f = f' \circ \pi$. Moreover, f' is uniquely determined by the value on the generating sets $\{x \otimes y : x \in M, y \in N\}$. Suppose there is another pair (T', g') satisfying the same properties. Then there is a unique $j : T \to T'$ and also $j' : T' \to T$ such that $g' = j \circ g$, $g = j' \circ g'$. But then both the maps $(j \circ j') \circ g$ and g satisfies the universal properties, so by uniqueness they are equal, and hence $j' \circ j$ is identity on T. Similarly $(j' \circ j) \circ g' = g'$ and $j \circ j'$ is identity on T'. So j is an isomorphism. $\square$

Proposition 1.3.2. *Let R be a ring. Let M and N be R-modules.*

(1) If N and M are finite, then so is $M \otimes_R N$.

(2) If N and M are finitely presented, then so is $M \otimes_R N$.

Proof. Suppose M is finite. Then choose a presentation $0 \to K \to R^{\oplus n} \to M \to 0$. This gives an exact sequence $K \otimes_R N \to N^{\oplus n} \to M \otimes_R N \to 0$. We conclude that if N is finite too then $M \otimes_R N$ is a quotient of a finite module, hence finite. Similarly, if both N and M are finitely presented, then we see that K is finite and that $M \otimes_R N$ is a quotient of the finitely presented module $N^{\oplus n}$ by a finite module, namely $K \otimes_R N$, and hence finitely presented. $\square$

Proposition 1.3.3. *Let M be an R-module. Then the $S^{-1}R$-modules $S^{-1}M$ and $S^{-1}R \otimes_R M$ are canonically isomorphic, and the canonical isomorphism $f : S^{-1}R \otimes_R M \to S^{-1}M$ is given by*

$$f((a/s) \otimes m) = am/s, \forall a \in R, m \in M, s \in S.$$

Proof. Obviously, the map $f' : S^{-1}R \times M \to S^{-1}M$ given by $f'(a/s, m) = am/s$ is bilinear, and thus by the universal property, this map induces a unique $S^{-1}R$-module homomorphism $f : S^{-1}R \otimes_R M \to S^{-1}M$ as in the statement of the lemma. Actually every element in $S^{-1}M$ is of the form m/s, $m \in M, s \in S$ and every element in $S^{-1}R \otimes_R M$ is of the form $1/s \otimes m$. To see the latter fact, write an element in $S^{-1}R \otimes_R M$ as

$$\sum_k \frac{a_k}{s_k} \otimes m_k = \sum_k \frac{a_k t_k}{s} \otimes m_k = \frac{1}{s} \otimes \sum_k a_k t_k m_k = \frac{1}{s} \otimes m.$$

Where $m = \sum_k a_k t_k m_k$. Then it is obvious that f is surjective, and if $f(\frac{1}{s} \otimes m) = m/s = 0$ then there exists $t' \in S$ with $tm = 0$ in M. Then we have

$$\frac{1}{s} \otimes m = \frac{1}{st} \otimes tm = \frac{1}{st} \otimes 0 = 0.$$

Therefore f is injective. $\square$

Proposition 1.3.4. *Let M, N be R-modules, then there is a canonical $S^{-1}R$-module isomorphism $f : S^{-1}M \otimes_{S^{-1}R} S^{-1}N \to S^{-1}(M \otimes_R N)$, given by*

$$f((m/s) \otimes (n/t)) = (m \otimes n)/st.$$

Proof. We may use Proposition 1.3.3 repeatedly to see that these two $S^{-1}R$-modules are isomorphic, noting that $S^{-1}R$ is an $(R, S^{-1}R)$-bimodule:

$$\begin{aligned} S^{-1}(M \otimes_R N) &\cong S^{-1}R \otimes_R (M \otimes_R N) \\ &\cong S^{-1}M \otimes_R N \\ &\cong (S^{-1}M \otimes_{S^{-1}R} S^{-1}R) \otimes_R N \\ &\cong S^{-1}M \otimes_{S^{-1}R} (S^{-1}R \otimes_R N) \\ &\cong S^{-1}M \otimes_{S^{-1}R} S^{-1}N \end{aligned}$$

This isomorphism is easily seen to be the one stated in the lemma. □

1.3.2 Base-Change Properties

We formally introduce base change in algebra as follows.

Definition 1.3.5. *Let $\varphi : R \to S$ be a ring map. Let M be an S-module. Let $R \to R'$ be any ring map. The* base change *of φ by $R \to R'$ is the ring map $R' \to S \otimes_R R'$. In this situation we often write $S' = S \otimes_R R'$. The* base change *of the S-module M is the S'-module $M \otimes_R R'$.*

If $S = R[x_i]/(f_j)$ for some collection of variables x_i, $i \in I$ and some collection of polynomials $f_j \in R[x_i]$, $j \in J$, then $S \otimes_R R' = R'[x_i]/(f'_j)$, where $f'_j \in R'[x_i]$ is the image of f_j under the map $R[x_i] \to R'[x_i]$ induced by $R \to R'$. This simple remark is the key to understanding base change.

Proposition 1.3.6. *The finite generatedness/finite presentation of modules and rings are stable under base change.*

Proof. Trivial since the tensor product is right exact. □

Definition 1.3.7. *Let $\varphi : R \to S$ be a ring map. Given an S-module N we obtain an R-module N_R by the rule $r \cdot n = \varphi(r)n$. This is sometimes called the* restriction *of N to R.*

Proposition 1.3.8. *Let $R \to S$ be a ring map. The functors $Mod_S \to Mod_R$, $N \mapsto N_R$ (restriction) and $Mod_R \to Mod_S$, $M \mapsto M \otimes_R S$ (base change) are adjoint functors. In a formula*

$$\mathrm{Hom}_R(M, N_R) = \mathrm{Hom}_S(M \otimes_R S, N)$$

Proof. If $\alpha : M \to N_R$ is an R-module map, then we define $\alpha' : M \otimes_R S \to N$ by the rule $\alpha'(m \otimes s) = s\alpha(m)$. If $\beta : M \otimes_R S \to N$ is an S-module map, we define $\beta' : M \to N_R$ by the rule $\beta'(m) = \beta(m \otimes 1)$. We omit the verification that these constructions are mutually inverse. □

The lemma above tells us that restriction has a left adjoint, namely base change. It also has a right adjoint.

Proposition 1.3.9. *Let $R \to S$ be a ring map. The functors $Mod_S \to Mod_R$, $N \mapsto N_R$ (restriction) and $Mod_R \to Mod_S$, $M \mapsto \mathrm{Hom}_R(S, M)$ are adjoint functors. In a formula*

$$\mathrm{Hom}_R(N_R, M) = \mathrm{Hom}_S(N, \mathrm{Hom}_R(S, M))$$

Proof. If $\alpha : N_R \to M$ is an R-module map, then we define $\alpha' : N \to \mathrm{Hom}_R(S, M)$ by the rule $\alpha'(n) = (s \mapsto \alpha(sn))$. If $\beta : N \to \mathrm{Hom}_R(S, M)$ is an S-module map, we define $\beta' : N_R \to M$ by the rule $\beta'(n) = \beta(n)(1)$. We omit the verification that these constructions are mutually inverse. □

Proposition 1.3.10. *Let $R \to S$ be a ring map. Given S-modules M, N and an R-module P we have*

$$\mathrm{Hom}_R(M \otimes_S N, P) = \mathrm{Hom}_S(M, \mathrm{Hom}_R(N, P))$$

Proof. This can be proved directly, but it is also a consequence of Propositions 1.3.8 and 1.3.9. Namely, we have

$$\begin{aligned} \mathrm{Hom}_R(M \otimes_S N, P) &= \mathrm{Hom}_S(M \otimes_S N, \mathrm{Hom}_R(S, P)) \\ &= \mathrm{Hom}_S(M, \mathrm{Hom}_S(N, \mathrm{Hom}_R(S, P))) \\ &= \mathrm{Hom}_S(M, \mathrm{Hom}_R(N, P)) \end{aligned}$$

as desired. □

1.3.3 Flat Modules and Flat Ring Maps

1.3.4 Faithfully Flatness

1.4 Some Radicals

1.4.1 Radical of Rings

Definition 1.4.1. *For any ideal $I \subset R$, define $\sqrt{I} := \{x \in R : x^n \in I \text{ for some } n\}$.*

Proposition 1.4.2. *For any ideal $I \subset R$, we have*

$$\sqrt{I} = \bigcap_{I \subset \mathfrak{p}, \mathfrak{p} \text{ prime}} \mathfrak{p}.$$

Proof. The inclusion $\sqrt{I} \subset \bigcap_{I \subset \mathfrak{p}, \mathfrak{p} \text{ primes}} \mathfrak{p}$ is trivial by definitions.

Conversely, take $g \in R \backslash \sqrt{I}$, then $g^n \notin I$ for any n. Let $\bar{\mathfrak{p}} \subset R_g$ be a prime such that $IR_g \subset \bar{\mathfrak{p}} \subset R_g$. Take $\mathfrak{p} \subset R$ be the inverse image of $\bar{\mathfrak{p}}$, then $I \subset \mathfrak{p}$ but $P \cap \{1, g, g^2, ...\} = \emptyset$. Well done. □

1.4.2 Jacobson Radical and Nilradical of Rings

Definition 1.4.3. *Let R be a ring.*

(1) *The Jacobson radical of a ring R is*

$$\mathrm{rad}(R) = \bigcap_{\mathfrak{m}, \mathfrak{m} \text{ maximal}} \mathfrak{m}.$$

(2) *The nilradical of a ring R is*

$$\mathrm{nil}(R) = \sqrt{0} = \bigcap_{\mathfrak{p}, \mathfrak{p} \text{ prime}} \mathfrak{p}.$$

Proposition 1.4.4. *Let R be a ring with Jacobson radical $\mathrm{rad}(R)$. Let $I \subset R$ be an ideal. The following are equivalent*

1. *$I \subset \mathrm{rad}(R)$, and*
2. *every element of $1 + I$ is a unit in R.*

In this case every element of R which maps to a unit of R/I is a unit.

Proof. If $f \in \mathrm{rad}(R)$, then $f \in \mathfrak{m}$ for all maximal ideals $\mathfrak{m}$ of R. Hence $1 + f \notin \mathfrak{m}$ for all maximal ideals $\mathfrak{m}$ of R. Thus the closed subset $V(1 + f)$ of $\mathrm{Spec}(R)$ is empty. This implies that $1 + f$ is a unit.

Conversely, assume that $1 + f$ is a unit for all $f \in I$. If $\mathfrak{m}$ is a maximal ideal and $I \not\subset \mathfrak{m}$, then $I + \mathfrak{m} = R$. Hence $1 = f + g$ for some $g \in \mathfrak{m}$ and $f \in I$. Then $g = 1 + (-f)$ is not a unit, contradiction.

For the final statement let $f \in R$ map to a unit in R/I. Then we can find $g \in R$ mapping to the multiplicative inverse of $f \bmod I$. Then $fg = 1 \bmod I$. Hence fg is a unit of R by (2) which implies that f is a unit. □

Lemma 1.4.5. *Let $\varphi : R \to S$ be a ring map such that the induced map $\mathrm{Spec}(S) \to \mathrm{Spec}(R)$ is surjective. Then an element $x \in R$ is a unit if and only if $\varphi(x) \in S$ is a unit.*

Proof. If x is a unit, then so is $\varphi(x)$. Conversely, if $\varphi(x)$ is a unit, then $\varphi(x) \notin \mathfrak{q}$ for all $\mathfrak{q} \in \mathrm{Spec}(S)$. Hence $x \notin \varphi^{-1}(\mathfrak{q}) = \mathrm{Spec}(\varphi)(\mathfrak{q})$ for all $\mathfrak{q} \in \mathrm{Spec}(S)$. Since $\mathrm{Spec}(\varphi)$ is surjective we conclude that x is a unit. □

1.5 Prime Ideals, some Interesting Things

1.5.1 Prime Avoidance

This is an easy but important result.

Lemma 1.5.1. *Let R be a ring, I and J two ideals and $\mathfrak{p}$ a prime ideal containing the product IJ. Then $\mathfrak{p}$ contains I or J.*

Proof. Assume the contrary and take $x \in I \setminus \mathfrak{p}$ and $y \in J \setminus \mathfrak{p}$. Their product is an element of $IJ \subset \mathfrak{p}$, which contradicts the assumption that $\mathfrak{p}$ was prime. □

Proposition 1.5.2 (Prime Avoidance)**.** *Let R be a ring. Let $I_i \subset R$, $i = 1, \dots, r$, and $J \subset R$ be ideals. Assume*

1. *$J \not\subset I_i$ for $i = 1, \dots, r$, and*
2. *all but two of I_i are prime ideals.*

Then there exists an $x \in J$, $x \notin I_i$ for all i.

Proof. The result is true for $r = 1$. If $r = 2$, then let $x, y \in J$ with $x \notin I_1$ and $y \notin I_2$. We are done unless $x \in I_2$ and $y \in I_1$. Then the element $x + y$ cannot be in I_1 (since that would mean $x + y - y \in I_1$) and it also cannot be in I_2.

For $r \geq 3$, assume the result holds for $r - 1$. After renumbering we may assume that I_r is prime. We may also assume there are no inclusions among the I_i. Pick $x \in J$, $x \notin I_i$ for all $i = 1, \dots, r-1$. If $x \notin I_r$ we are done. So assume $x \in I_r$. If $JI_1 \dots I_{r-1} \subset I_r$ then $J \subset I_r$ (by Lemma 1.5.1) a contradiction. Pick $y \in JI_1 \dots I_{r-1}$, $y \notin I_r$. Then $x + y$ works. □

1.5.2 Oka Families and Its Applications

Here we introduce a very interesting thing.

Definition 1.5.3. *Let R be a ring. If I is an ideal of R and $a \in R$, we define*

$$(I : a) = \{x \in R : xa \in I\}.$$

More generally, if $J \subset R$ is an ideal, we define

$$(I : J) = \{x \in R : xJ \subset I\}.$$

Definition 1.5.4 (Oka Family)**.** *Let R be a ring. Let $\mathcal{F}$ be a set of ideals of R. We say $\mathcal{F}$ is an Oka family if $R \in \mathcal{F}$ and whenever $I \subset R$ is an ideal and $(I : a), (I, a) \in \mathcal{F}$ for some $a \in R$, then $I \in \mathcal{F}$.*

Here is the fundamental property of Oka family:

Proposition 1.5.5. *If $\mathcal{F}$ is an Oka family of ideals, then any maximal element of the complement of $\mathcal{F}$ is prime.*

Proof. Suppose $I \notin \mathcal{F}$ is maximal with respect to not being in $\mathcal{F}$ but I is not prime. Note that $I \neq R$ because $R \in \mathcal{F}$. Since I is not prime we can find $a, b \in R - I$ with $ab \in I$. It follows that $(I, a) \neq I$ and $(I : a)$ contains $b \notin I$ so also $(I : a) \neq I$. Thus $(I : a), (I, a)$ both strictly contain I, so they must belong to $\mathcal{F}$. By the Oka condition, we have $I \in \mathcal{F}$, a contradiction. □

Now we discover some special Oka families which will induce many interesting results! Before that, we introduce a lemma:

Lemma 1.5.6. *Let R be a ring. For a principal ideal $J \subset R$, and for any ideal $I \subset J$ we have $I = J(I : J)$.*

Proof. Say $J = (a)$. Then $(I : J) = (I : a)$. Since $I \subset J$ we see that any $y \in I$ is of the form $y = xa$ for some $x \in (I : a)$. Hence $I \subset J(I : J)$. Conversely, if $x \in (I : a)$, then $xJ = (xa) \subset I$, which proves the other inclusion. □

Corollary 1.5.7. *Let R be a ring and let S be a multiplicative subset of R.*

(1) The family $\mathcal{F} = \{I \subset R \mid I \cap S \neq \emptyset\}$ is an Oka family.

(2) An ideal $I \subset R$ which is maximal with respect to the property that $I \cap S = \emptyset$ is prime.

In particular, we have the following things.

(3) An ideal maximal among the ideals which do not contain a nonzerodivisor is prime.

(4) If R is nonzero and every nonzero prime ideal in R contains a nonzerodivisor, then R is a domain.

Proof. For (1), suppose that $(I : a), (I, a) \in \mathcal{F}$ for some $a \in R$. Then pick $s \in (I, a) \cap S$ and $s' \in (I : a) \cap S$. Then $ss' \in I \cap S$ and hence $I \in \mathcal{F}$. Thus $\mathcal{F}$ is an Oka family.

For (2), this follows directly from (1) and Proposition 1.5.5.

For (3), consider the set S of nonzerodivisors. It is a multiplicative subset of R. Hence any ideal maximal with respect to not intersecting S is prime by (1).

Thus for (4), if every nonzero prime ideal contains a nonzerodivisor, then (0) is prime, i.e., R is a domain. □

Corollary 1.5.8. *Let R be a ring.*

(1) The family of finitely generated ideals is an Oka family.

(2) *An ideal $I \subset R$ maximal with respect to not being finitely generated is prime.*

(3) *If every prime ideal of R is finitely generated, then every ideal of R is finitely generated, that is, R is Noetherian.*

Proof. For (1), Let $I \subset R$ an ideal, and $a \in R$. If $(I : a)$ is generated by $a_1, \ldots, a_n$ and (I, a) is generated by $a, b_1, \ldots, b_m$ with $b_1, \ldots, b_m \in I$, we claim that I is generated by $aa_1, \ldots, aa_n, b_1, \ldots, b_m$.

Indeed, note that if $x \in I$, then $x \in (I, a)$ is a linear combination of $a, b_1, \ldots, b_m$, but the coefficient of a must lie in $(I : a)$. As a result, we deduce that the family of finitely generated ideals is an Oka family.

For (2), this is an immediate consequence of (1) and Proposition 1.5.5.

For (3), suppose that there exists an ideal $I \subset R$ which is not finitely generated. The union of a totally ordered chain $\{I_\alpha\}$ of ideals that are not finitely generated is not finitely generated; indeed, if $I = \bigcup I_\alpha$ were generated by $a_1, \ldots, a_n$, then all the generators would belong to some I_α and would consequently generate it. By Zorn's lemma, there is an ideal maximal with respect to being not finitely generated. By (2) this ideal is prime. $\square$

Corollary 1.5.9. *Let R be a ring.*

(1) *The family of principal ideals of R is an Oka family.*

(2) *An ideal $I \subset R$ maximal with respect to not being principal is prime.*

(3) *If every prime ideal of R is principal, then every ideal of R is principal.*

Proof. For (1), suppose $I \subset R$ is an ideal, $a \in R$, and (I, a) and $(I : a)$ are principal. Note that $(I : a) = (I : (I, a))$. Setting $J = (I, a)$, we find that J is principal and $(I : J)$ is too. By Lemma 1.5.6 we have $I = J(I : J)$. Thus we find in our situation that since $J = (I, a)$ and $(I : J)$ are principal, I is principal.

For (2), this follows from (1) and Proposition 1.5.5.

For (3), suppose that there exists an ideal $I \subset R$ which is not principal. The union of a totally ordered chain $\{I_\alpha\}$ of ideals that not principal is not principal; indeed, if $I = \bigcup I_\alpha$ were generated by a, then a would belong to some I_α and a would generate it. By Zorn's lemma, there is an ideal maximal with respect to not being principal. This ideal is necessarily prime by (2). $\square$

Corollary 1.5.10. *Let A be a ring, $I \subset A$ an ideal, and $a \in A$ an element. Let P is a property of A-modules that is stable under extensions and holds for* 0.

(1) *The family of ideals I such that A/I has P is an Oka family.*

(2) *The ideal maximal such that P does not holds is prime.*

Proof. For (1), there is a short exact sequence $0 \to A/(I : a) \to A/I \to A/(I, a) \to 0$ where the first arrow is given by multiplication by a. Thus if P is a property of A-modules that is stable under extensions and holds for 0, then the family of ideals I such that A/I has P is an Oka family.

For (2), this follows from (1) and Proposition 1.5.5. □

1.6 Cayley-Hamilton

Here we introduce Cayley-Hamilton theorem of general rings and its applications.

Proposition 1.6.1 (Cayley-Hamilton)**.** *Let R be a ring. Let $A = (a_{ij})$ be an $n \times n$ matrix with coefficients in R. Let $P(x) \in R[x]$ be the characteristic polynomial of A (defined as $\det(x\mathrm{id}_{n\times n} - A)$). Then $P(A) = 0$ in $Mat(n \times n, R)$.*

Proof. We reduce the question to the well-known Cayley-Hamilton theorem from linear algebra in several steps:

1. If $\phi : S \to R$ is a ring morphism and b_{ij} are inverse images of the a_{ij} under this map, then it suffices to show the statement for S and (b_{ij}) since ϕ is a ring morphism.

2. If $\psi : R \hookrightarrow S$ is an injective ring morphism, it clearly suffices to show the result for S and the a_{ij} considered as elements of S.

3. Thus we may first reduce to the case $R = \mathbb{Z}[X_{ij}]$, $a_{ij} = X_{ij}$ of a polynomial ring and then further to the case $R = \mathbb{Q}(X_{ij})$ where we may finally apply Cayley-Hamilton.

Then well done. □

Corollary 1.6.2. *Let R be a ring. Let M be a finite R-module. Let $\varphi : M \to M$ be an endomorphism. Then there exists a monic polynomial $P \in R[T]$ such that $P(\varphi) = 0$ as an endomorphism of M.*

Proof. Consider

$$\begin{tikzcd} R^{\oplus n} \arrow[r] \arrow[d, "A"'] & M \arrow[d, "\varphi"] \\ R^{\oplus n} \arrow[r] & M \end{tikzcd}$$

By Proposition 1.6.1 there exists a monic polynomial P such that $P(A) = 0$. Then it follows that $P(\varphi) = 0$. □

Corollary 1.6.3. *Let R be a ring. Let $I \subset R$ be an ideal. Let M be a finite R-module. Let $\varphi : M \to M$ be an endomorphism such that $\varphi(M) \subset IM$. Then there exists a monic polynomial $P = t^n + a_1 t^{n-1} + \ldots + a_n \in R[T]$ such that $a_j \in I^j$ and $P(\varphi) = 0$ as an endomorphism of M.*

Proof. Consider again

$$\begin{tikzcd} R^{\oplus n} \arrow[r] \arrow[d, "A"'] & M \arrow[d, "\varphi"] \\ I^{\oplus n} \arrow[r] & M \end{tikzcd}$$

By Proposition 1.6.1 the polynomial $P(t) = \det(t\mathrm{id}_{n \times n} - A)$ has all the desired properties. □

As a fun example application we prove the following surprising property.

Corollary 1.6.4. *Let R be a ring. Let M be a finite R-module. Let $\varphi : M \to M$ be a surjective R-module map. Then φ is an isomorphism.*

Proof. Write $R' = R[x]$ and think of M as a finite R'-module with x acting via φ. Set $I = (x) \subset R'$. By our assumption that φ is surjective we have $IM = M$. Hence we may apply Corollary 1.6.3 to M as an R'-module, the ideal I and the endomorphism id_M. We conclude that $(1 + a_1 + \ldots + a_n)\mathrm{id}_M = 0$ with $a_j \in I$. Write $a_j = b_j(x)x$ for some $b_j(x) \in R[x]$. Translating back into φ we see that $\mathrm{id}_M = -(\sum_{j=1,\ldots,n} b_j(\varphi))\varphi$, and hence φ is invertible. □

1.7 Nakayama's Lemma

1.8 The Spectrums of a Ring

1.8.1 Fundamental Diagram of Ring Maps

Proposition 1.8.1. *A fundamental commutative diagram associated to a ring map $\varphi : R \to S$, a prime $\mathfrak{q} \subset S$ and the corresponding prime $\mathfrak{p} = \varphi^{-1}(\mathfrak{q})$ of R is the following:*

$$\begin{tikzcd} \kappa(\mathfrak{q}) = S_{\mathfrak{q}}/\mathfrak{q}S_{\mathfrak{q}} & S_{\mathfrak{q}} \arrow[l] & S \arrow[l] \arrow[r] & S/\mathfrak{q} \arrow[r] & \kappa(\mathfrak{q}) \\ \kappa(\mathfrak{p}) \otimes_R S = S_{\mathfrak{p}}/\mathfrak{p}S_{\mathfrak{p}} \arrow[u] & S_{\mathfrak{p}} \arrow[l] \arrow[u] & S \arrow[l] \arrow[r] \arrow[u] & S/\mathfrak{p}S \arrow[r] \arrow[u] & (R\backslash\mathfrak{p})^{-1}S/\mathfrak{p}S \arrow[u] \\ \kappa(\mathfrak{p}) = R_{\mathfrak{p}}/\mathfrak{p}R_{\mathfrak{p}} \arrow[u] & R_{\mathfrak{p}} \arrow[l] \arrow[u] & R \arrow[l] \arrow[r] \arrow[u, "\varphi"'] & R/\mathfrak{p} \arrow[r] \arrow[u] & \kappa(\mathfrak{p}) \arrow[u] \end{tikzcd}$$

In this diagram the arrows in the outer left and outer right columns are identical. The horizontal maps induce on the associated spectra always a homeomorphism onto the image. The lower two rows of the diagram make sense without assuming $\mathfrak{q}$ exists. The lower squares induce fibre squares of topological spaces. This diagram shows that $\mathfrak{p}$ is in the image of the map on Spec if and only if $S \otimes_R \kappa(\mathfrak{p})$ is not the zero ring.

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[1] Stacks project collaborators. *The Stacks Project*. `https://stacks.math.columbia.edu/`, 2023.