12 The different and the discriminant

12.1 The different

We continue in our usual $AKLB$ setup: A is a Dedekind domain, K is its fraction field, L/K is a finite separable extension, and B is the integral closure of A in L (a Dedekind domain with fraction field L). We would like to understand the primes that ramify in L/K. Recall that a prime $\mathfrak{q}|\mathfrak{p}$ of L is unramified if and only if $e_{\mathfrak{q}} = 1$ and $B/\mathfrak{q}$ is a separable extension of $A/\mathfrak{p}$, equivalently, if and only if $B/\mathfrak{q}^{e_{\mathfrak{q}}}$ is a finite étale $A/\mathfrak{p}$ algebra (by Theorem 4.40).[1] A prime $\mathfrak{p}$ of K is unramified if and only if all the primes $\mathfrak{q}|\mathfrak{p}$ lying above it are unramified, equivalently, if and only if the ring $B/\mathfrak{p}B$ is a finite étale $A/\mathfrak{p}$ algebra.[2]

Our main tools for studying ramification are the *different* $\mathcal{D}_{B/A}$ and *discriminant* $D_{B/A}$. The different is a B-ideal that is divisible by precisely the ramified primes $\mathfrak{q}$ of L, and the discriminant is an A-ideal divisible by precisely the ramified primes $\mathfrak{p}$ of K. Moreover, the valuation $v_{\mathfrak{q}}(\mathcal{D}_{B/A})$ will give us information about the ramification index $e_{\mathfrak{q}}$ (its exact value when $\mathfrak{q}$ is tamely ramified).

Recall from Lecture 5 the trace pairing $L \times L \to K$ defined by $(x, y) \mapsto \mathrm{T}_{L/K}(xy)$; under our assumption that L/K is separable, it is a perfect pairing. An A-lattice M in L is a finitely generated A-module that spans L as a K-vector space (see Definition 5.9). Every A-lattice M in L has a *dual lattice* (see Definition 5.11)

$$M^* := \{x \in L : \mathrm{T}_{L/K}(xm) \in A \ \forall m \in M\},$$

which is an A-lattice in L isomorphic to the dual A-module $M^\vee := \mathrm{Hom}_A(M, A)$ (see Theorem 5.12). In our $AKLB$ setting we have $M^{**} = M$, by Proposition 5.16.

Every fractional ideal I of B is finitely generated as a B-module, and therefore finitely generated as an A module (since B is finite over A). If I is nonzero, it necessarily spans L, since B does. It follows that every element of the group $\mathcal{I}_B$ of nonzero fractional ideals of B is an A-lattice in L. We now show that $\mathcal{I}_B$ is closed under the operation of taking duals.

Lemma 12.1. *Assume $AKLB$. If $I \in \mathcal{I}_B$ then $I^* \in \mathcal{I}_B$.*

Proof. The dual lattice I^* is a finitely generated A-module, thus to show that it is a finitely generated B-module it is enough to show it is closed under multiplication by elements of B. So consider any $b \in B$ and $x \in I^*$. For all $m \in I$ we have $\mathrm{T}_{L/K}((bx)m) = \mathrm{T}_{L/K}(x(bm)) \in A$, since $x \in I^*$ and $bm \in I$, so $bx \in I^*$ as desired. □

Definition 12.2. Assume $AKLB$. The *different* $\mathcal{D}_{L/K}$ of L/K (and the *different* $\mathcal{D}_{B/A}$ of B/A), is the inverse of B^* in $\mathcal{I}_B$. Explicitly, we have

$$B^* := \{x \in L : \mathrm{T}_{L/K}(xb) \in A \text{ for all } b \in B\},$$

and we define

$$\mathcal{D}_{L/K} := \mathcal{D}_{B/A} := (B^*)^{-1} = (B : B^*) = \{x \in L : xB^* \subseteq B\}.$$

Note that $B \subseteq B^*$, since $\mathrm{T}_{L/K}(ab) \in A$ for $a, b \in B$ (by Corollary 4.53), and this implies $\mathcal{D}_{B/A} = (B^*)^{-1} \subseteq B^{-1} = B$. Thus the different is an ideal, not just a fractional ideal.

[1] Note that $B/\mathfrak{q}^{e_{\mathfrak{q}}}$ is reduced if and only if $e_{\mathfrak{q}} = 1$; consider the image of a uniformizer in $B/\mathfrak{q}^{e_{\mathfrak{q}}}$.

[2] As usual, by a *prime* of A or K we mean a nonzero prime ideal of A, and similarly for B and L. The notation $\mathfrak{q}|\mathfrak{p}$ means that $\mathfrak{q}$ is a prime of B lying above $\mathfrak{p}$ (so $\mathfrak{p} = \mathfrak{q} \cap A$ and $\mathfrak{q}$ divides $\mathfrak{p}B$).

The different respects localization and completion.

Proposition 12.3. *Assume AKLB and let S be a multiplicative subset of A. Then*

$$S^{-1}\mathcal{D}_{B/A} = \mathcal{D}_{S^{-1}B/S^{-1}A}.$$

Proof. This follows from the fact that inverses and duals are both compatible with localization, by Lemmas 3.5 and 5.15. □

Proposition 12.4. *Assume AKLB and let $\mathfrak{q}|\mathfrak{p}$ be a prime of B. Then*

$$\mathcal{D}_{\hat{B}_{\mathfrak{q}}/\hat{A}_{\mathfrak{p}}} = \mathcal{D}_{B/A}\hat{B}_{\mathfrak{q}},$$

where $\hat{A}_{\mathfrak{p}}$ and $\hat{B}_{\mathfrak{q}}$ are the completions of A and B at $\mathfrak{p}$ and $\mathfrak{q}$, respectively.

Proof. Let $\hat{L} := L \otimes K_{\mathfrak{p}}$ be the base change of the finite étale K-algebra L to $K_{\mathfrak{p}}$. By (5) of Theorem 11.23, we have $\hat{L} \simeq \prod_{\mathfrak{q}|\mathfrak{p}} L_{\mathfrak{q}}$. Note that even though $\hat{L}$ need not be a field, in general, is is a free $K_{\mathfrak{p}}$-module of finite rank, and is thus equipped with a trace map that necessarily satisfies $\mathrm{T}_{\hat{L}/K_{\mathfrak{p}}}(x) = \sum_{\mathfrak{q}|\mathfrak{p}} \mathrm{T}_{\hat{L}/K_{\mathfrak{p}}}(x)$ that defines a trace pairing on $\hat{L}$.

Now let $\hat{B} := B \otimes \hat{A}_{\mathfrak{p}}$; it is an $A_{\mathfrak{p}}$-lattice in the $K_{\mathfrak{p}}$-vector space $\hat{L}$. By Corollary 11.26, $\hat{B} \simeq \prod_{\mathfrak{q}|\mathfrak{p}} \hat{B}_{\mathfrak{q}} \simeq \bigoplus_{\mathfrak{q}|\mathfrak{p}} \hat{B}_{\mathfrak{q}}$, and therefore $\hat{B}^* \simeq \bigoplus_{\mathfrak{q}|\mathfrak{p}} \hat{B}_{\mathfrak{q}}^*$, by Corollary 5.13. It follows that $\hat{B}^* \simeq B^* \otimes_A \hat{A}_{\mathfrak{p}}$. In particular, B^* generates each fractional ideal $\hat{B}_{\mathfrak{q}}^* \in \mathcal{I}_{\hat{B}_{\mathfrak{q}}}$. Taking inverses, $\mathcal{D}_{B/A} = (B^*)^{-1}$ generates the $\hat{B}_{\mathfrak{q}}$-ideal $(\hat{B}_{\mathfrak{q}}^*)^{-1} = \mathcal{D}_{\hat{B}_{\mathfrak{q}}/\hat{A}_{\mathfrak{p}}}$. □

12.2 The discriminant

Definition 12.5. Let S/R be a ring extension in which S is a free R-module of rank n. For any $x_1, \ldots, x_n \in S$ we define the *discriminant*

$$\operatorname{disc}(x_1, \ldots, x_n) \coloneqq \operatorname{disc}_{S/R}(x_1, \ldots, x_n) \coloneqq \det[\mathrm{T}_{S/R}(x_i x_j)]_{i,j} \in R.$$

Note that we do not require $x_1, \ldots, x_n$ to be an R-basis for S, but if they satisfy a non-trivial R-linear relation then the discriminant will be zero (by linearity of the trace).

In our $AKLB$ setup, we have in mind the case where $e_1, \ldots, e_n \in B$ is a basis for L as a K-vector space, in which case $\operatorname{disc}(e_1, \ldots, e_n) = \det[\mathrm{T}_{L/K}(e_i e_j)]_{ij} \in A$. Note that we do not need to assume that B is a free A-module; L is certainly a free K-module. The fact that the discriminant lies in A when $e_1, \ldots, e_n \in B$ follows immediately from Corollary 4.53.

Proposition 12.6. *Let L/K be a finite separable extension of degree n, and let Ω/K be a field extension for which there are distinct $\sigma_1, \ldots, \sigma_n \in \operatorname{Hom}_K(L, \Omega)$. For any $e_1, \ldots, e_n \in L$ we have*

$$\operatorname{disc}(e_1, \ldots, e_n) = \det[\sigma_i(e_j)]_{ij}^2,$$

and for any $x \in L$ we have

$$\operatorname{disc}(1, x, x^2, \ldots, x^{n-1}) = \prod_{i<j} (\sigma_i(x) - \sigma_j(x))^2.$$

Such a field extension Ω/K always exists, since L/K is separable ($\Omega = K^{\mathrm{sep}}$ works).

Proof. For $1 \leq i, j \leq n$ we have $\mathrm{T}_{L/K}(e_i e_j) = \sum_{k=1}^n \sigma_k(e_i e_j)$, by Theorem 4.50. Therefore

$$\begin{aligned}\operatorname{disc}(e_1, \ldots, e_n) &= \det[\mathrm{T}_{L/K}(e_i e_j)]_{ij} \\ &= \det\left([\sigma_k(e_i)]_{ik}[\sigma_k(e_j)]_{kj}\right) \\ &= \det\left([\sigma_k(e_i)]_{ik}[\sigma_k(e_j)]^{\mathrm{t}}_{jk}\right) \\ &= \det[\sigma_i(e_j)]^2_{ij}\end{aligned}$$

since the determinant is multiplicative and $\det M = \det M^{\mathrm{t}}$ for any matrix M.

Now let $x \in L$ and put $e_i := x^{i-1}$ for $1 \leq i \leq n$. Then

$$\operatorname{disc}(1, x, x^2, \ldots, x^{n-1}) = \det[\sigma_i(x^{j-1})]^2_{ij} = \det[\sigma_i(x)^{j-1}]^2_{ij} = \prod_{i<j}\left(\sigma_i(x) - \sigma_j(x)\right)^2,$$

since $[\sigma_i(x)^{j-1}]_{ij}$ is a Vandermonde matrix (rows of the form $z^0, \ldots, z^{n-1}$ for some z); see [2, p. 258] for a proof of this standard fact. □

Definition 12.7. For a polynomial $f(x) = \prod_i (x - \alpha_i)$, the *discriminant* of f is

$$\operatorname{disc}(f) := \prod_{i<j}(\alpha_i - \alpha_j)^2.$$

Equivalently, if A is a Dedekind domain, $f \in A[x]$ is a monic separable polynomial, and α is the image of x in $A[x]/(f(x))$, then

$$\operatorname{disc}(f) = \operatorname{disc}(1, \alpha, \alpha^2, \ldots, \alpha^{n-1}) \in A.$$

Example 12.8. $\operatorname{disc}(x^2 + bx + c) = b^2 - 4c$ and $\operatorname{disc}(x^3 + ax + b) = -4a^3 - 27b^2$.

Now assume $AKLB$ and let M be an A-lattice in L. Then M is a finitely generated A-module that contains a K-basis for L. We want to define the discriminant of M in a way that does not require us to choose a basis.

Let us first consider the case where M is a free A-lattice. If $e_1, \ldots, e_n \in M \subseteq L$ and $e_1', \ldots, e_n' \in M \subseteq L$ are two A-bases for M, then

$$\operatorname{disc}(e_1', \ldots, e_n') = u^2 \operatorname{disc}(e_1, \ldots, e_n)$$

for some unit $u \in A^\times$; this follows from the fact that the change of basis matrix $P \in A^{n \times n}$ is invertible and its determinant is therefore a unit u. This unit gets squared because we need to apply the change of basis matrix twice in order to change $\mathrm{T}(e_i e_j)$ to $\mathrm{T}(e_i' e_j')$. Explicitly, writing bases as row-vectors, let $e = (e_1, \ldots, e_n)$ and $e' = (e_1', \ldots, e_n')$ satisfy $e' = eP$. Then

$$\begin{aligned}\operatorname{disc}(e') &= \det[\mathrm{T}_{L/K}(e_i' e_j')]_{ij} \\ &= \det[\mathrm{T}_{L/K}((eP)_i (eP)_j)]_{ij} \\ &= \det[P^{\mathrm{t}}[\mathrm{T}_{L/K}(e_i e_j)]_{ij} P] \\ &= (\det P^{\mathrm{t}}) \operatorname{disc}(e) (\det P) \\ &= (\det P)^2 \operatorname{disc}(e),\end{aligned}$$

where we have used the linearity of $\mathrm{T}_{L/K}$ to go from the second equality to the third.

This actually gives us a basis independent definition when $A = \mathbb{Z}$. In this case B is always a free $\mathbb{Z}$-lattice, and the only units in $\mathbb{Z}$ are $u = \pm 1$, so $u^2 = 1$.

Definition 12.9. Assume $AKLB$, let M be an A-lattice in L, and let $n \coloneqq [L:K]$. The *discriminant* $D(M)$ of M is the A-module generated by $\{\operatorname{disc}(x_1,\ldots,x_n) : x_1,\ldots,x_n \in M\}$.

Lemma 12.10. *Assume $AKLB$ and let $M' \subseteq M$ be free A-lattices in L. The discriminants $D(M') \subseteq D(M)$ are nonzero principal fractional ideals. If $D(M') = D(M)$ then $M' = M$.*

Proof. Let $e \coloneqq (e_1,\ldots,e_n)$ be an A-basis for M. Then $\operatorname{disc}(e) \in D(M)$, and for any row vector $x \coloneqq (x_1,\ldots,x_n)$ with entries in M there is a matrix $P \in A^{n\times n}$ for which $x = eP$, and we then have $\operatorname{disc}(x) = (\det P)^2 \operatorname{disc}(e)$ as above. It follows that

$$D(M) = (\operatorname{disc}(e))$$

is principal, and it is nonzero because e is a basis for L and the trace pairing is nondegenerate. If we now let $e' \coloneqq (e'_1,\ldots,e'_n)$ be an A-basis for M' then $D(M') = (\operatorname{disc}(e'))$ is also a nonzero and principal. Our assumption that $M' \subseteq M$ implies that $e' = eP$ for some matrix $P \in A^{n\times n}$, and we have $\operatorname{disc}(e') = (\det P)^2 \operatorname{disc}(e)$. If $D(M') = D(M)$ then $\det P$ must be a unit, in which case P is invertible and $e = e'P^{-1}$. This implies $M \subseteq M'$, so $M' = M$. □

Proposition 12.11. *Assume $AKLB$ and let M be an A-lattice in L. Then $D(M) \in \mathcal{I}_A$.*

Proof. The A-module $D(M) \subseteq K$ is nonzero because M contains a K-basis $e = (e_1,\ldots,e_n)$ for L and $\operatorname{disc}(e) \neq 0$ because the trace pairing is nondegenerate. To show that $D(M)$ is a finitely generated A-module (and thus a fractional ideal), we use the usual trick: make it a submodule of a noetherian module. So let N be the free A-lattice in L generated by e and then pick a nonzero $a \in A$ such that $M \subseteq a^{-1}N$ (write each generator for M in terms of the K-basis e and let a be the product of all the denominators that appear; note that M is finitely generated). We then have $D(M) \subseteq D(a^{-1}N)$, and $D(a^{-1}N)$ is a principal fractional ideal of A, hence a noetherian A-module (since A is noetherian), so its submodule $D(M)$ must be finitely generated. □

Definition 12.12. Assume $AKLB$. The *discriminant* $D_{L/K}$ of L/K (and the *discriminant* $D_{B/A}$ of B/A) is the discriminant of B as an A-module:

$$D_{L/K} \coloneqq D_{B/A} \coloneqq D(B) \in \mathcal{I}_A,$$

which is an A-ideal, since $\operatorname{disc}(x_1,\ldots,x_n) = \det[T_{B/A}(x_i x_j)]_{i,j} \in A$ for all $x_1,\ldots,x_n \in B$.

Example 12.13. Consider the case $A = \mathbb{Z}$, $K = \mathbb{Q}$, $L = \mathbb{Q}(i)$, $B = \mathbb{Z}[i]$. Then B is a free A-lattice with basis $(1,i)$ and we can compute $D_{L/K}$ in three ways:

- $\operatorname{disc}(1,i) = \det \begin{bmatrix} \mathrm{T}_{L/K}(1\cdot 1) & \mathrm{T}_{L/K}(1\cdot i) \\ \mathrm{T}_{L/K}(i\cdot 1) & \mathrm{T}_{L/K}(i\cdot i) \end{bmatrix} = \det \begin{bmatrix} 2 & 0 \\ 0 & -2 \end{bmatrix} = -4.$
- The non-trivial automorphism of L/K fixes 1 and sends i to $-i$, so we could instead compute $\operatorname{disc}(1,i) = \left(\det \begin{bmatrix} 1 & 1 \\ i & -i \end{bmatrix}\right)^2 = (-2i)^2 = -4.$
- We have $B = \mathbb{Z}[i] = \mathbb{Z}[x]/(x^2+1)$ and can compute $\operatorname{disc}(x^2+1) = -4$.

In every case the discriminant $D_{L/K}$ is the ideal $(-4) = (4)$.

Remark 12.14. If $A = \mathbb{Z}$ then B is the ring of integers of the number field L, and B is a free A-lattice, because it is a torsion-free module over a PID and therefore a free module. In this situation it is customary to define the *absolute discriminant* D_L of the number field L to be the *integer* $\operatorname{disc}(e_1, \ldots, e_n) \in \mathbb{Z}$, for any basis $(e_1, \ldots, e_n)$ of B, rather than the ideal it generates. As noted above, this integer is independent of the choice of basis because $u^2 = 1$ for all $u \in \mathbb{Z}^\times$; in particular, the sign of D_L is well defined (as we shall see, the sign of D_L carries information about L). In the example above, the absolute discriminant is $D_L = -4$.

Like the different, the discriminant respects localization.

Proposition 12.15. *Assume AKLB and let S be a multiplicative subset of A. Then*

$$S^{-1}D_{B/A} = D_{S^{-1}B/S^{-1}A}.$$

Proof. Let $x = s^{-1}\operatorname{disc}(e_1, \ldots, e_n) \in S^{-1}D_{B/A}$ for some $s \in S$ and $e_1, \ldots, e_n \in B$. Then $x = s^{2n-1}\operatorname{disc}(s^{-1}e_1, \ldots, s^{-1}e_n)$ lies in $D_{S^{-1}B/S^{-1}A}$. This proves the forward inclusion.

Conversely, for any $e_1, \ldots, e_n \in S^{-1}B$ we can choose a single $s \in S \subseteq A$ so that each se_i lies in B. We then have $\operatorname{disc}(e_1, \ldots, e_n) = s^{-2n}\operatorname{disc}(se_1, \ldots, se_n) \in S^{-1}D_{B/A}$, which proves the reverse inclusion. □

Proposition 12.16. *Assume AKLB and let $\mathfrak{p}$ be a prime of A. Then*

$$D_{B/A}\hat{A}_\mathfrak{p} = \prod_{\mathfrak{q}|\mathfrak{p}} D_{\hat{B}_\mathfrak{q}/\hat{A}_\mathfrak{p}}$$

where $\hat{A}_\mathfrak{p}$ and $\hat{B}_\mathfrak{q}$ are the completions of A and B at $\mathfrak{p}$ and $\mathfrak{q}$, respectively.

Proof. After localizing at $\mathfrak{p}$ we can assume A is a DVR and B is a free A-module of rank n. As in the proof of Proposition 12.4, we have a trace pairing on the finite étale $K_\mathfrak{p}$-algebra $\hat{L} := L \otimes K_\mathfrak{p}$ and $\hat{B} := B \otimes \hat{A}_\mathfrak{p} \simeq \bigoplus_{\mathfrak{q}|\mathfrak{p}} \hat{B}_\mathfrak{q}$ is an $\hat{A}_\mathfrak{p}$-lattice in the $K_\mathfrak{p}$-vector space $\hat{L}$ that is a direct sum of free $\hat{A}_\mathfrak{p}$-modules, and thus a free $\hat{A}_\mathfrak{p}$-module of rank $n = \sum e_\mathfrak{q} f_\mathfrak{q}$; see Corollary 11.26.

We can choose $\hat{A}_\mathfrak{p}$ bases for each $\hat{B}_\mathfrak{q}$ using elements in B; this follows from weak approximation (Theorem 8.5) and the fact that B is dense in $\hat{B}_\mathfrak{q}$ (or see [1, Thm. 2.3]). From these bases we can construct an $\hat{A}_\mathfrak{p}$-basis $\hat{e}$ for the direct sum $\bigoplus_{\mathfrak{q}|\mathfrak{p}} \hat{B}_\mathfrak{q} \simeq \hat{B}$ whose elements each have nonzero projections to exactly one of the $\hat{B}_\mathfrak{q}$, along with a corresponding A-basis e for B obtained from $\hat{e}$ as the union of these projections.

The matrix $[T_{\hat{L}/K_\mathfrak{p}}(\hat{e}_i\hat{e}_j)]$ is block diagonal; each block corresponds to a matrix whose determinant is the discriminant of the $\hat{A}_\mathfrak{p}$-basis we chose for one of the $\hat{B}_\mathfrak{q}$. It follows that $D_{\hat{B}/\hat{A}_\mathfrak{p}} = \prod_{\mathfrak{q}|\mathfrak{p}} D_{\hat{B}_\mathfrak{q}/\hat{A}_\mathfrak{p}}$ (here we are using the fact that $\hat{B} \simeq \bigoplus_{\mathfrak{q}|\mathfrak{p}} \hat{B}_\mathfrak{q}$ is both an isomorphism of rings and an isomorphism of $A_\mathfrak{p}$-modules, hence it preserves traces to $\hat{A}_\mathfrak{p}$). We now observe that

$$\operatorname{disc}_{B/A}(e_1, \ldots, e_n) = \operatorname{disc}_{(B\otimes A_\mathfrak{p})/\hat{A}_\mathfrak{p}}(e_1 \otimes 1, \ldots, e_n \otimes 1)$$

generates $D_{B/A}$ as an A-ideal, and also generates $D_{\hat{B}/\hat{A}_\mathfrak{p}}$ as an $\hat{A}_\mathfrak{p}$-ideal (note that $\hat{B}$ is a free $\hat{A}_\mathfrak{p}$-module, so $D_{B/\hat{A}_\mathfrak{p}}$ is the principal ideal generated by the discriminant of any $A_\mathfrak{p}$-basis for $\hat{B}$). It follows that $D_{B/A}\hat{A}_\mathfrak{p} = D_{\hat{B}/\hat{A}_\mathfrak{p}} = \prod_{\mathfrak{q}|\mathfrak{p}} D_{\hat{B}_\mathfrak{q}/\hat{A}_\mathfrak{p}}$. □

We have defined two different ideals associated to a finite separable extension of Dedekind domains B/A in the $AKLB$ setup. We have the different $\mathcal{D}_{B/A}$, which is a fractional ideal of B, and the discriminant $D_{B/A}$, which is a fractional ideal of A. We now relate these two ideals in terms of the ideal norm $N_{B/A}\colon \mathcal{I}_B \to \mathcal{I}_A$, which for $I \in \mathcal{I}_B$ is defined as $\mathrm{N}_{B/A}(I) := [B : I]_A$, where $[B : I]_A$ is the module index (see Definitions 6.1 and 6.5).

Theorem 12.17. *Assume $AKLB$. Then $D_{B/A} = N_{B/A}(\mathcal{D}_{B/A})$.*

Proof. The different and discriminant are both compatible with localization, by Propositions 12.3 and 12.15, and the A-modules $D_{B/A}$ and $N_{B/A}(\mathcal{D}_{B/A})$ of A are both determined by the intersections of their localizations at maximal ideals (Proposition 2.6), so it suffices to prove that the theorem holds when we replace A by its localization A at a prime of A. Then A is a DVR and B is a free A-lattice in L; let us fix an A-basis $(e_1, \ldots, e_n)$ for B.

The dual A-lattice

$$B^* = \{x \in L : \mathrm{T}_{L/K}(xb) \in A \ \forall b \in B\} \in \mathcal{I}_B$$

is also a free A-lattice in L, with basis $(e_1^*, \ldots, e_n^*)$ uniquely determined by $\mathrm{T}_{L/K}(e_i^* e_j) = \delta_{ij}$, where δ_{ij} is the Kronecker delta function; see Corollary 5.14. If we write $e_i = \sum a_{ij} e_j^*$ in terms of the K-basis $(e_1^*, \ldots, e_n^*)$ for L then

$$T_{L/K}(e_i e_j) = T_{L/K}\left(\sum_k a_{ik} e_k^* e_j\right) = \sum_k a_{ik} T_{L/K}(e_k^* e_j) = \sum_k a_{ik}\delta_{kj} = a_{ij}.$$

It follows that $P \coloneqq [\mathrm{T}_{L/K}(e_i e_j)]_{ij}$ is the change-of-basis matrix from $e^* \coloneqq (e_1^*, \ldots, e_n^*)$ to $e \coloneqq (e_1, \ldots, e_n)$ (as row vectors we have $e = e^* P$). If we let ϕ denote the K-linear transformation with matrix P (or its transpose, if you prefer to work with column vectors), then ϕ is an isomorphism of free A-modules and

$$D_{B/A} = \big(\det[\mathrm{T}_{L/K}(e_i e_j)]_{ij}\big) = (\det \phi) = [B^* : B]_A,$$

where $[B^* : B]_A$ is the module index (see Definition 6.1). Applying Corollary 6.8 yields

$$D_{B/A} = [B^* : B]_A = N_{B/A}((B : B^*)) = N_{B/A}((B^*)^{-1}) = N_{B/A}(\mathcal{D}_{B/A}).$$

(the last three equalities each hold by definition). ☐

12.3 Ramification

Having defined the different and discriminant ideals we now want to understand how they relate to ramification. Recall that in our $AKLB$ setup, if $\mathfrak{p}$ is a prime of A then we can factor the B-ideal $\mathfrak{p}B$ as

$$\mathfrak{p}B = \mathfrak{q}_1^{e_1} \cdots \mathfrak{q}_r^{e_r}.$$

The Chinese remainder theorem implies

$$B/\mathfrak{p}B \simeq B/\mathfrak{q}_1^{e_1} \times \cdots \times B/\mathfrak{q}_r^{e_r}.$$

This is a commutative $A/\mathfrak{p}$-algebra of dimension $\sum e_i f_i$, where $f_i = [B/\mathfrak{q}_i : A/\mathfrak{p}]$ is the residue degree (see Theorem 5.35). It is a product of fields if and only if we have $e_i = 1$ for all i, and it is a finite étale-algebra if and only if it is a product of fields that are separable extensions of $A/\mathfrak{p}$. The following lemma relates the discriminant to the property of being a finite étale algebra.

Lemma 12.18. *Let k be a field and let R be a commutative k-algebra with k-basis $r_1, \ldots, r_n$. Then R is a finite étale k-algebra if and only if* $\operatorname{disc}(r_1, \ldots, r_n) \neq 0$.

Proof. By Theorem 5.20, R is a finite étale k-algebra if and only if the trace pairing on R is a perfect pairing, which is equivalent to being nondegenerate, since k is a field.

If the trace pairing is degenerate then for some nonzero $x \in R$ we have $\mathrm{T}_{R/k}(xy) = 0$ for all $y \in R$. If we write $x = \sum_i x_i r_i$ with $x_i \in k$ then $\mathrm{T}_{R/k}(xr_j) = \sum_i x_i \mathrm{T}_{R/k}(r_i r_j) = 0$ for all r_j (take $y = r_j$), and this implies that the columns of the matrix $[\mathrm{T}_{R/k}(r_i r_j)]_{ij}$ are linearly dependent and $\operatorname{disc}(r_1, \ldots, r_n) = \det[\mathrm{T}_{R/k}(r_i r_j)]_{ij} = 0$.

Conversely, if $\operatorname{disc}(r_1, \ldots, r_n) = 0$ then the columns of $\det[\mathrm{T}_{R/k}(r_i r_j)]_{ij}$ are linearly dependent and for some $x_i \in k$ not identically zero we must have $\sum_i x_i \mathrm{T}_{R/k}(r_i r_j) = 0$ for all j. For $x \coloneqq \sum_i x_i r_i$ and any $y = \sum_j y_j r_j \in R$ we have $\mathrm{T}_{R/k}(xy) = \sum_j y_j \sum_i x_i \mathrm{T}_{R/k}(r_i r_j) = 0$, which shows that the trace pairing is degenerate. □

Theorem 12.19. *Assume AKLB, let $\mathfrak{q}$ be a prime of B lying above a prime $\mathfrak{p}$ of A such that $B/\mathfrak{q}$ is a separable extension of $A/\mathfrak{p}$. The extension L/K is unramified at $\mathfrak{q}$ if and only if $\mathfrak{q}$ does not divide $\mathcal{D}_{B/A}$, and it is unramified at $\mathfrak{p}$ if and only if $\mathfrak{p}$ does not divide $D_{B/A}$.*

Proof. We first consider the different $\mathcal{D}_{B/A}$. By Proposition 12.4, the different is compatible with completion, so it suffices to consider the case that A and B are complete DVRs (complete K at $\mathfrak{p}$ and L at $\mathfrak{q}$ and apply Theorem 11.23). We then have $[L : K] = e_{\mathfrak{q}} f_{\mathfrak{q}}$, where $e_{\mathfrak{q}}$ is the ramification index and $f_{\mathfrak{q}}$ is the residue field degree, and $\mathfrak{p}B = \mathfrak{q}^{e_{\mathfrak{q}}}$.

Since B is a DVR with maximal ideal $\mathfrak{q}$, we must have $\mathcal{D}_{B/A} = \mathfrak{q}^m$ for some $m \geq 0$. By Theorem 12.17 we have

$$D_{B/A} = N_{B/A}(\mathcal{D}_{B/A}) = N_{B/A}(\mathfrak{q}^m) = \mathfrak{p}^{f_{\mathfrak{q}} m}.$$

Thus $\mathfrak{q}|\mathcal{D}_{B/A}$ if and only if $\mathfrak{p}|D_{B/A}$. Since A is a PID, B is a free A-module and we may choose an A-module basis $e_1, \ldots, e_n$ for B that is also a K-basis for L. Let $k \coloneqq A/\mathfrak{p}$, and let $\bar{e}_i$ be the reduction of e_i to the k-algebra $R \coloneqq B/\mathfrak{p}B$. Then $(\bar{e}_1, \ldots, \bar{e}_n)$ is a k-basis for R: it clearly spans, and we have $[R : k] = [B/\mathfrak{q}^{e_{\mathfrak{q}}} : A/\mathfrak{p}] = e_{\mathfrak{q}} f_{\mathfrak{q}} = [L : K] = n$.

Since B has an A-module basis, we may compute its discriminant as

$$D_{B/A} = (\operatorname{disc}(e_1, \ldots, e_n)).$$

Thus $\mathfrak{p}|D_{B/A}$ if and only if $\operatorname{disc}(e_1, \ldots, e_n) \in \mathfrak{p}$, equivalently, $\operatorname{disc}(\bar{e}_1, \ldots, \bar{e}_n) = 0$ (note that $\operatorname{disc}(e_1, \ldots, e_n)$ is a polynomial in the $\mathrm{T}_{L/K}(e_i e_j)$ and $T_{R/k}(\bar{e}_i \bar{e}_j)$ is the trace of the multiplication-by-$\bar{e}_i \bar{e}_j$ map, which is the same as the reduction to $k = A/\mathfrak{p}$ of the trace of the multiplication-by-$e_i e_j$ map $T_{L/K}(e_i e_j) \in A$). By Lemma 12.18, $\operatorname{disc}(\bar{e}_1, \ldots, \bar{e}_n) = 0$ if and only if the k-algebra $B/\mathfrak{p}B$ is not finite étale, equivalently, if and only if $\mathfrak{p}$ is ramified. Thus $\mathfrak{p}|D_{B/A}$ if and only if $\mathfrak{p}$ is ramified. There is only one prime $\mathfrak{q}$ above $\mathfrak{p}$, so we also have $\mathfrak{q}|\mathcal{D}_{B/A}$ if and only if $\mathfrak{q}$ is ramified. □

We now note an important corollary of Theorem 12.19.

Corollary 12.20. *Assume AKLB. Only finitely many primes of A (or B) ramify.*

Proof. A and B are Dedekind domains, so the ideals $D_{B/A}$ and $\mathcal{D}_{B/A}$ both have unique factorizations into prime ideals in which only finitely many primes appear. □

12.4 The discriminant of an order

Recall from Lecture 6 that an order $\mathcal{O}$ is a noetherian domain of dimension one whose conductor is nonzero (see Definitions 6.16 and 6.19), and the integral closure of an order is always a Dedekind domain. In our $AKLB$ setup, the orders with integral closure B are precisely the A-lattices in L that are rings (see Proposition 6.22); if $L = K(\alpha)$ with $\alpha \in B$, then $A[\alpha]$ is an example. The discriminant $D_{\mathcal{O}/A}$ of such an order $\mathcal{O}$ is its discriminant $D(\mathcal{O})$ as an A-module. The fact that $\mathcal{O} \subseteq B$ implies that $D(\mathcal{O}) \subseteq D_{B/A}$ is an A-ideal.

If $\mathcal{O}$ is an order of the form $A[\alpha]$, where $\alpha \in B$ generates $L = K(\alpha)$ with minimal polynomial $f \in A[x]$, then $\mathcal{O}$ is a free A-lattice with basis $1, \alpha, \ldots, \alpha^{n-1}$, where $n = \deg f$, and we may compute its discriminant as

$$D_{\mathcal{O}/A} = (\operatorname{disc}(1, \alpha, \ldots, \alpha^{n-1})) = (\operatorname{disc}(f)),$$

which is a principal A-ideal contained in $D_{B/A}$. If B is also a free A-lattice, then as in the proof of Lemma 12.10 we have

$$D_{\mathcal{O}/A} = (\det P)^2 D_{B/A} = [B:\mathcal{O}]_A^2 D_{B/A},$$

where P is the matrix of the A-linear map $\phi\colon B \to \mathcal{O}$ that sends an A-basis for B to an A-basis for $\mathcal{O}$ and $[B:\mathcal{O}]_A$ is the module index (a principal A-ideal).

In the important special case where $A = \mathbb{Z}$ and L is a number field, the integer $(\det P)^2$ is uniquely determined and it necessarily divides $\operatorname{disc}(f)$, the generator of the principal ideal $D(\mathcal{O}) = D(A[\alpha])$. It follows that if $\operatorname{disc}(f)$ is squarefree then we must have $B = \mathcal{O} = A[\alpha]$. More generally, any prime p for which $v_p(\operatorname{disc}(f))$ is odd must be ramified, and any prime that does not divide $\operatorname{disc}(f)$ must be unramified. Another useful observation that applies when $A = \mathbb{Z}$: the module index $[B:\mathcal{O}]_{\mathbb{Z}} = ([B:\mathcal{O}])$ is the principal ideal generated by the index of $\mathcal{O}$ in B (as $\mathbb{Z}$-lattices), and we have the relation

$$D_{\mathcal{O}} = [B:\mathcal{O}]^2 D_B$$

between the absolute discriminant of the order $\mathcal{O}$ and its integral closure B.

Example 12.21. Consider $A = \mathbb{Z}$, $K = \mathbb{Q}$ with $L = \mathbb{Q}(\alpha)$, where $\alpha^3 - \alpha - 1 = 0$. We can compute the absolute discriminant of $\mathbb{Z}[\alpha]$ as

$$\operatorname{disc}(1, \alpha, \alpha^2) = \operatorname{disc}(x^3 - x - 1) = -4(-1)^3 - 27(-1)^2 = -23.$$

The fact that -23 is squarefree immediately implies that 23 is the only prime of A that ramifies, and we have $D_{\mathbb{Z}[\alpha]} = -23 = [\mathcal{O}_L : \mathbb{Z}[\alpha]]^2 D_L$, which forces $[\mathcal{O}_L : \mathbb{Z}[\alpha]] = 1$, so $D_L = -23$ and $\mathcal{O}_L = \mathbb{Z}[\alpha]$.

More generally, we have the following theorem.

Theorem 12.22. *Assume $AKLB$ and let $\mathcal{O}$ be an order with integral closure B and conductor $\mathfrak{c}$. Then $D_{\mathcal{O}/A} = \mathrm{N}_{B/A}(\mathfrak{c}) D_{B/A}$.*

Proof. See Problem Set 6. □

12.5 Computing the discriminant and different

We conclude with a number of results that allow one to explicitly compute the discriminant and different in many cases.

Proposition 12.23. *Assume AKLB. If $B = A[\alpha]$ for some $\alpha \in L$ and $f \in A[x]$ is the minimal polynomial of α, then*

$$\mathcal{D}_{B/A} = (f'(\alpha))$$

is the B-ideal generated by $f'(\alpha)$.

Proof. See Problem Set 6. □

The assumption $B = A[\alpha]$ in Proposition 12.23 does not always hold, but if we want to compute the power of $\mathfrak{q}$ that divides $\mathcal{D}_{B/A}$ we can complete L at $\mathfrak{q}$ and K at $\mathfrak{p} = \mathfrak{q} \cap A$ so that A and B become complete DVRs, in which case $B = A[\alpha]$ does hold (by Lemma 10.14), so long as the residue field extension is separable (always true if K and L are global fields, since the residue fields are then finite, hence perfect). The following definition and proposition give an alternative approach.

Definition 12.24. Assume $AKLB$ and let $\alpha \in B$ have minimal polynomial $f \in A[x]$. The *different of α* is defined by

$$\delta_{B/A}(\alpha) \coloneqq \begin{cases} f'(\alpha) & \text{if } L = K(\alpha), \\ 0 & \text{otherwise.} \end{cases}$$

Proposition 12.25. *Assume AKLB. Then $\mathcal{D}_{B/A} = \big(\delta_{B/A}(\alpha) : \alpha \in B\big)$.*

Proof. See [3, Thm. III.2.5]. □

We can now more precisely characterize the ramification information given by the different ideal.

Theorem 12.26. *Assume AKLB and let $\mathfrak{q}$ be a prime of L lying above $\mathfrak{p} = \mathfrak{q} \cap A$ for which the residue field extension $(B/\mathfrak{q})/(A/\mathfrak{p})$ is separable. Then*

$$e_\mathfrak{q} - 1 \;\le\; v_\mathfrak{q}(\mathcal{D}_{B/A}) \;\le\; e_\mathfrak{q} - 1 + v_\mathfrak{q}(e_\mathfrak{q}),$$

and the lower bound is an equality if and only if $\mathfrak{q}$ is tamely ramified.

Proof. See Problem Set 6. □

We also note the following proposition, which shows how the discriminant and different behave in a tower of extensions.

Proposition 12.27. *Assume AKLB and let M/L be a finite separable extension and let C be the integral closure of A in M. Then*

$$\mathcal{D}_{C/A} = \mathcal{D}_{C/B} \cdot \mathcal{D}_{B/A}$$

(where the product on the right is taken in C), and

$$D_{C/A} = (D_{B/A})^{[M:L]} N_{B/A}(D_{C/B}).$$

Proof. See [4, Prop. III.8]. □

If $M/L/K$ is a tower of finite separable extensions, we note that the primes $\mathfrak{p}$ of K that ramify are precisely those that divide either $D_{L/K}$ or $N_{L/K}(D_{M/L})$.

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