10 Extensions of complete DVRs

Recall that in our AKLB setup, A is a Dedekind domain with fraction field K, the field L is a finite separable extension of K, and B is the integral closure of A in L; as we proved in Theorem 5.25, this implies that B is also a Dedekind domain (with L as its fraction field).

We now want to consider the special case where A is a complete DVR; in this case B is also a complete DVR, but this will take a little bit of work to prove. We first show that B is a DVR.

**Theorem 10.1.** Assume AKLB and that A is a complete DVR with maximal ideal p. Then B is a DVR whose maximal ideal q is necessarily the unique prime above p.

**Proof.** We first show that \( \# \{q \mid pB \subseteq B \} = 1 \). At least one prime q of B lies above p, since the factorization of \( pB \subseteq B \) is non-trivial. Now suppose for the sake of contradiction that \( q_1, q_2 \in \{q \mid pB \} \) with \( q_1 \neq q_2 \). Choose \( b \in q_1 - q_2 \) and consider the ring \( A[b] \subseteq B \). The ideals \( q_1 \cap A[b] \) and \( q_2 \cap A[b] \) are distinct prime ideals of \( A[b] \) containing \( pA[b] \), and both are maximal, since they are nonzero and \( \dim A[b] = \dim A = 1 \) (note that \( A[b] \) is integral over A and therefore has the same dimension). The quotient ring \( A[b]/pA[b] \) thus has at least two maximal ideals. Let \( f \in A[x] \) be the minimal polynomial of \( b \) over \( K \), and let \( \bar{f} \in (A/p)[x] \) be its reduction to the residue field \( A/p \).

\[
(A/p)[x]/\langle f \rangle \sim (A[x]/\langle p, f \rangle) \sim (A[b]/pA[b]),
\]

thus the ring \( (A/p)[x]/\langle \bar{f} \rangle \) has at least two maximal ideals, which implies that \( \bar{f} \) is divisible by two distinct irreducible polynomials (because \( (A/p)[x] \) is a PID). We can thus factor \( f = gh \) with \( g \) and \( h \) coprime. By Hensel’s Lemma 9.19, we can lift this to a non-trivial factorization \( \bar{f} = \bar{g}\bar{h} \) of \( \bar{f} \) in \( \bar{A}[x] \), contradicting the irreducibility of \( f \).

Every maximal ideal of \( B \) lies above a maximal ideal of \( A \), but \( A \) has only the maximal ideal \( p \) and \( \# \{ q \mid p \} = 1 \), so \( B \) has a unique (nonzero) maximal ideal \( q \). Thus \( B \) is a local Dedekind domain, hence a local PID, and not a field, so \( B \) is a DVR, by Theorem 1.16. \( \Box \)

**Remark 10.2.** The assumption that \( A \) is complete is necessary. For example, if \( A \) is the DVR \( \mathbb{Z}(5) \) with fraction field \( K = \mathbb{Q} \) and we take \( L = \mathbb{Q}(i) \), then the integral closure of \( A \) in \( L \) is \( B = \mathbb{Z}(5)[i] \), which is a PID but not a DVR: the ideals \( (1 + 2i) \) and \( (1 - 2i) \) are both maximal (and not equal). But if we take completions we get \( A = \mathbb{Z}_5 \) and \( K = \mathbb{Q}_5 \), and now \( L = \mathbb{Q}_5(i) = \mathbb{Q}_5 = K \), since \( x^2 + 1 \) has a root in \( \mathbb{F}_5 \simeq \mathbb{Z}_5/5\mathbb{Z}_5 \) that we can lift to \( \mathbb{Z}_5 \) via Hensel’s lemma; thus if we complete \( A \) then \( B = A \) is a DVR as required.

**Definition 10.3.** Let \( K \) be a field with absolute value \(| \cdot |\) and let \( V \) be a \( K \)-vector space. A **norm** on \( V \) is a function \( \| \| : V \to \mathbb{R}_{\geq 0} \) such that

- \( \|v\| = 0 \) if and only if \( v = 0 \).
- \( \|\lambda v\| = |\lambda| \|v\| \) for all \( \lambda \in K \) and \( v \in V \).
- \( \|v + w\| \leq \|v\| + \|w\| \) for all \( v, w \in V \).

Each norm \( \| \| \) induces a topology on \( V \) via the distance metric \( d(v, w) := \|v - w\| \).

**Example 10.4.** Let \( V \) be a \( K \)-vector space with basis \( \{e_i\} \), and for \( v \in V \) let \( v_i \in K \) denote the coefficient of \( e_i \) in \( v = \sum_i v_i e_i \). The **sup-norm** \( \|v\|_\infty := \sup \{|v_i|\} \) is a norm on \( V \) (thus
every vector space has at least one norm). If \( V \) is also a \( K \)-algebra, an absolute value \( \| \| \) on \( V \) (as a ring) is a norm on \( V \) (as a \( K \)-vector space) if and only if it extends the absolute value on \( K \) (fix \( v \neq 0 \) and note that \( \| \lambda \| \| v \| = \| \lambda v \| = | \lambda | \| v \| \iff \| \lambda \| = | \lambda | \)).

**Proposition 10.5.** Let \( V \) be a vector space of finite dimension over a complete field \( K \). Every norm on \( V \) induces the same topology, in which \( V \) is a complete metric space.

**Proof.** See Problem Set 5.

**Theorem 10.6.** Let \( A \) be a complete DVR with fraction field \( K \), maximal ideal \( \mathfrak{p} \), discrete valuation \( v_\mathfrak{p} \), and absolute value \( |x|_\mathfrak{p} := c^{v_\mathfrak{p}(x)} \), with \( 0 < c < 1 \). Let \( L/K \) be a finite extension of degree \( n \). The following hold.

(i) There is a unique absolute value \( |x| := \left| N_{L/K}(x) \right|^{1/n}_\mathfrak{p} \) on \( L \) that extends \( | |_\mathfrak{p} \);

(ii) The field \( L \) is complete with respect to \( | | \), and its valuation ring \( \{ x \in L : |x| \leq 1 \} \) is equal to the integral closure \( B \) of \( A \) in \( L \);

(iii) If \( L/K \) is separable then \( B \) is a complete DVR whose maximal ideal \( \mathfrak{q} \) induces

\[
|x| = |x|_\mathfrak{q} := c^{e_\mathfrak{q}}v_\mathfrak{q}(x),
\]

where \( e_\mathfrak{q} \) is the ramification index of \( \mathfrak{q} \), that is, \( \mathfrak{p}B = \mathfrak{q}^{e_\mathfrak{q}} \).

**Proof.** Assuming for the moment that \( | \cdot | \) is actually an absolute value (which is not obvious!), for any \( x \in K \) we have

\[
|x| = |N_{L/K}(x)|^{1/n}_\mathfrak{p} = |x^n|^{1/n}_\mathfrak{p} = |x|_\mathfrak{p},
\]

so \( | \cdot | \) extends \( | \cdot |_\mathfrak{p} \) and is therefore a norm on \( L \). The fact that \( | \cdot |_\mathfrak{p} \) is nontrivial means that \( |x|_\mathfrak{p} \neq 1 \) for some \( x \in K^\times \), and \( |x|^a = |x|_\mathfrak{p} = |x| \) only for \( a = 1 \), which implies that \( | \cdot | \) is the unique absolute value in its equivalence class extending \( | \cdot |_\mathfrak{p} \). Every norm on \( L \) induces the same topology (by Proposition 10.5), so \( | \cdot | \) is the only absolute value on \( L \) that extends \( | \cdot |_\mathfrak{p} \).

We now show \( | \cdot | \) is an absolute value. Clearly \( |x| = 0 \iff x = 0 \) and \( | \cdot | \) is multiplicative; we only need to check the triangle inequality. It suffices to show \( |x| \leq 1 \Rightarrow |x + 1| \leq |x| + 1 \), since we always have \( |y + z| = |z||y/z + 1| \) and \( |y + z| = |z|(|y/z| + 1) \), and without loss of generality we assume \( |y| \leq |z| \). In fact the stronger implication \( |x| \leq 1 \Rightarrow |x + 1| \leq 1 \) holds:

\[
|x| \leq 1 \iff |N_{L/K}(x)|_\mathfrak{p} \leq 1 \iff N_{L/K}(x) \in A \iff x \in B \iff x + 1 \in B \iff |x + 1| \leq 1.
\]

The first biconditional follows from the definition of \( | \cdot | \), the second follows from the definition of \( | \cdot |_\mathfrak{p} \), the third is Corollary 9.21, the fourth is obvious, and the fifth follows from the first three after replacing \( x \) with \( x + 1 \). This completes the proof of (i), and also proves (ii).

We now assume \( L/K \) is separable. Then \( B \) is a DVR, by Theorem 10.1, and it is complete because it is the valuation ring of \( L \). Let \( \mathfrak{q} \) be the unique maximal ideal of \( B \). The valuation \( v_\mathfrak{q} \) extends \( v_\mathfrak{p} \) with index \( e_\mathfrak{q} \), by Theorem 8.20, so \( v_\mathfrak{q}(x) = e_\mathfrak{q}v_\mathfrak{p}(x) \) for \( x \in K^\times \). We have \( 0 < c^{1/e_\mathfrak{q}} < 1 \), so \( |x|_\mathfrak{q} := (c^{1/e_\mathfrak{q}})^{v_\mathfrak{q}(x)} \) is an absolute value on \( L \) induced by \( v_\mathfrak{q} \). To show it is equal to \( | \cdot | \), it suffices to show that it extends \( | \cdot |_\mathfrak{p} \), since we already know that \( | \cdot | \) is the unique absolute value on \( L \) with this property. For \( x \in K^\times \) we have

\[
|x|_\mathfrak{q} = c^{e_\mathfrak{q}}v_\mathfrak{q}(x) = c^{e_\mathfrak{q}e_\mathfrak{q}v_\mathfrak{p}(x)} = c^{v_\mathfrak{p}(x)} = |x|_\mathfrak{p},
\]

and the theorem follows. \( \square \)
**Remark 10.7.** The transitivity of $N_{L/K}$ in towers (Corollary 4.52) implies that we can uniquely extend the absolute value on the fraction field $K$ of a complete DVR to an algebraic closure $\overline{K}$. In fact, this is another form of Hensel’s lemma in the following sense: one can show that a (not necessarily discrete) valuation ring $A$ is Henselian if and only if the absolute value of its fraction field $K$ can be uniquely extended to $\overline{K}$; see [4, Theorem 6.6].

**Corollary 10.8.** Assume AKLB and that $A$ is a complete DVR with maximal ideal $p$ and let $q|p$. Then $v_q(x) = \frac{1}{e_q} v_p(N_{L/K}(x))$ for all $x \in L$.

**Proof.** $v_p(N_{L/K}(x)) = v_p(N_{L/K}((x))) = v_p(N_{L/K}(q^{1}(x))) = v_p(p^{e_q/(q^{1})(x)}) = f q^{v_p}(x)$.

**Remark 10.9.** One can generalize the notion of a discrete valuation to a valuation, a surjective homomorphism $v: K^\times \to \Gamma$, in which $\Gamma$ is a (totally) ordered abelian group and $v(x + y) \geq \min(v(x), v(y))$; we extend $v$ to $\overline{K}$ by defining $v(0) = \infty$ to be strictly greater than any element of $\Gamma$. In the AKLB setup with $A$ a complete DVR, one can then define a valuation $v(x) = \frac{1}{e_q} v_q(x)$ with image $\frac{1}{e_q} \mathbb{Z}$ that restricts to the discrete valuation $v_p$ on $K$.

The valuation $v$ then extends to a valuation on $\overline{K}$ with $\Gamma = \mathbb{Q}$. Some texts take this approach, but we will generally stick with discrete valuations (so our absolute value on $L$ restricts to $K$, but our discrete valuations on $L$ do not restrict to discrete valuations on $K$, they extend them with index $e_q$).

**Remark 10.10.** Recall that a valuation ring is an integral domain $A$ with fraction field $K$ such that for every $x \in K^\times$ either $x \in A$ or $x^{-1} \in A$ (possibly both). As you will show on Problem Set 6, if $A$ is a valuation ring, then there exists a valuation $v: K \to \Gamma \cup \{\infty\}$ for some totally ordered abelian group $\Gamma$ such that $A = \{x \in K : v(x) \geq 0\}$ is the valuation ring of $K$ with respect to this valuation.

### 10.1 The Dedekind-Kummer theorem in a local setting

Recall that the Dedekind-Kummer theorem (Theorem 6.14) allows us to factor primes in our AKLB setting by factoring polynomials over the residue field, provided that $B$ is monogenic (of the form $A[\alpha]$ for some $\alpha \in B$), or the prime of interest does not contain the conductor. We now show that in the special case where $A$ and $B$ are DVRs and the residue field extension is separable, $B$ is always monogenic; this holds, for example, whenever $K$ is a local field. To prove this, we first recall a form of Nakayama’s lemma.

**Lemma 10.11 (NAKAYAMA’S LEMMA).** Let $A$ be a local ring with maximal ideal $p$, and let $M$ be a finitely generated $A$-module. If the images of $x_1,\ldots,x_n \in M$ generate $M/pM$ as an $(A/p)$-vector space then $x_1,\ldots, x_n$ generate $M$ as an $A$-module.

**Proof.** See [1, Corollary 4.8b].

Before proving our theorem on local monogenicity, we record a few corollaries of Nakayama’s Lemma that will be useful later.

**Corollary 10.12.** Let $A$ be a local noetherian ring with maximal ideal $p$, let $g \in A[x]$, and let $B := A[x]/(g(x))$. Every maximal ideal $m$ of $B$ contains the ideal $pB$.

**Proof.** Suppose not. Then $m + pB = B$ for some maximal ideal $m$ of $B$. The ring $B$ is finitely generated over the noetherian ring $A$, hence a noetherian $A$-module, so its $A$-submodules are all finitely generated. Let $z_1,\ldots,z_n$ be $A$-module generators for $m$. Every coset of $pB$
in $B$ can be written as $z + pB$ for some $A$-linear combination $z$ of $z_1, \ldots, z_n$, so the images of $z_1, \ldots, z_n$ generate $B/pB$ as an $(A/p)$-vector space. By Nakayama’s lemma, $z_1, \ldots, z_n$ generate $B$, in which case $m = B$, a contradiction.

As a corollary, we immediately obtain a local version of the Dedekind-Kummer theorem that does not even require $A$ and $B$ to be Dedekind domains.

**Corollary 10.13.** Let $A$ be a local noetherian ring with maximal ideal $p$, let $g \in A[x]$ be a polynomial with reduction $\bar{g} \in (A/p)[x]$, and let $\alpha$ be the image of $x$ in the ring $B := A[x]/(g(x)) = A[\alpha]$. The maximal ideals of $B$ are $(p, \bar{g}(\alpha))$, where $g_1, \ldots, g_m \in A[x]$ are lifts of the distinct irreducible polynomials $\bar{g}_i \in (A/p)[x]$ that divide $\bar{g}$.

**Proof.** By Corollary 10.12, the quotient map $B \to B/pB$ gives a one-to-one correspondence between maximal ideals of $B$ and maximal ideals of $B/pB$, and we have

$$
\frac{B}{pB} \cong \frac{A[x]}{(p, g(x))} \cong \frac{(A/p)[x]}{\bar{g}(x)}.
$$

Each maximal ideal of $(A/p)[x]/(\bar{g}(x))$ is the reduction of an irreducible divisor of $\bar{g}$, hence one of the $\bar{g}_i$ (because $(A/p)[x]$ is a PID). The corollary follows.

**Theorem 10.14.** Assume $AKLB$, with $A$ and $B$ DVRs with residue fields $k := A/p$ and $l := B/q$. If $l/k$ is separable then $B = A[\alpha]$ for some $\alpha \in B$; if $L/K$ is unramified this holds for every lift $\alpha$ of any generator $\bar{\alpha}$ for $l = k(\bar{\alpha})$.

**Proof.** Let $pB = q^e$ be the factorization of $pB$ and let $f = [l : k]$ be the residue field degree, so that $ef = n := [L : K]$. The extension $l/k$ is separable, so we may apply the primitive element theorem to write $l = k(\alpha_0)$ for some $\alpha_0 \in l$ whose minimal polynomial $\bar{g}$ is separable of degree equal to $f$. Let $g \in A[x]$ be a monic lift of $\bar{g}$, and let $\alpha_0$ be any lift of $\bar{\alpha}_0$ to $B$. If $v_q(g(\alpha_0)) = 1$ then let $\alpha := \alpha_0$. Otherwise, let $\pi_0$ be any uniformizer for $B$ and let $\alpha := \alpha_0 + \pi_0 \in B$ (so $\alpha \equiv \bar{\alpha}_0 \mod q$) Writing $g(x + \pi_0) = g(x) + \pi_0g'(x) + \pi_0^2h(x)$ for some $h \in A[x]$ via Lemma 9.11, we have

$$
v_q(g(\alpha)) = v_q(g(\alpha_0 + \pi_0)) = v_q(g(\alpha_0) + \pi_0g'(\alpha_0) + \pi_0^2h(\alpha_0)) = 1,
$$

so $\pi := g(\alpha)$ is also a uniformizer for $B$.

We now claim $B = A[\alpha]$, equivalently, that $1, \alpha, \ldots, \alpha^{n-1}$ generate $B$ as an $A$-module. By Nakayama’s lemma, it suffices to show that the reductions of $1, \alpha, \ldots, \alpha^{n-1}$ span $B/pB$ as an $k$-vector space. We have $p = q^e$, so $pB = (\pi^e)$. We can represent each element of $B/pB$ as a coset

$$
b + pB = b_0 + b_1\pi + b_2\pi^2 \cdots + b_{e-1}\pi^{e-1} + pB,
$$

where $b_0, \ldots, b_{e-1}$ are determined up to equivalence modulo $\pi B$. Now $1, \bar{\alpha}, \ldots, \bar{\alpha}^{f-1}$ are a basis for $B/\pi B = B/q$ as a $k$-vector space, and $\pi = g(\alpha)$, so we can rewrite this as

$$
b + pB = \left( (a_0 + a_1\alpha + \cdots a_{f-1}\alpha^{f-1}) + (a_0 + a_1\alpha + \cdots a_{f-1}\alpha^{f-1})g(\alpha) + \cdots + (a_{ef-f+1} + a_{ef-f+2} + \cdots a_{ef-1}\alpha^{f-1})g(\alpha)^{e-1} + pB \right)
$$

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Since \( \text{deg } g = f \), and \( n = ef \), this expresses \( b + pB \) in the form \( b' + pB \) with \( b' \) in the \( A \)-span of \( 1, \ldots, \alpha^{-1} \). Thus \( B = A[\alpha] \).

We now note that if \( L/K \) is unramified then \( l/k \) is separable (this is part of the definition of unramified), and \( e = 1, f = n \), in which case there is no need to require \( g(\alpha) \) to be a uniformizer and we can just take \( \alpha = \alpha_0 \) to be any lift of any \( \bar{\alpha}_0 \) that generates \( l \) over \( k \). 

In our \( AKLB \) setup, if \( A \) is a complete DVR with maximal ideal \( p \) then \( B \) is a complete DVR with maximal ideal \( q | p \) and the formula \( [L : K] = \sum_{q|p} e_q f_q \) given by Theorem 5.35 has only one term \( e_q f_q \). We now simplify matters even further by reducing to the two extreme cases \( f_q = 1 \) (a totally ramified extension) and \( e_q = 1 \) (an unramified extension, provided that the residue field extension is separable).\(^1\)

10.2 Unramified extensions of a complete DVR

Let \( A \) be a complete DVR with fraction field \( K \) and residue field \( k \). Associated to any finite unramified extension of \( L/K \) of degree \( n \) is a corresponding finite separable extension of residue fields \( l/k \) of the same degree \( n \). Given that the extensions \( L/K \) and \( l/k \) are finite separable extensions of the same degree, we might wonder how they are related. More precisely, if we fix \( K \) with residue field \( k \), what is the relationship between finite unramified extensions \( L/K \) of degree \( n \) and finite separable extensions \( l/k \) of degree \( n \)? Each \( L/K \) uniquely determines a corresponding \( l/k \), but what about the converse?

This question has a surprisingly nice answer. The finite unramified extensions \( L \) of \( K \) form a category \( C^\text{unr}_K \) whose morphisms are \( K \)-algebra homomorphisms, and the finite separable extensions \( l \) of \( k \) form a category \( C^\text{sep}_k \) whose morphisms are \( k \)-algebra homomorphisms. These two categories are equivalent.

**Theorem 10.15.** Let \( A \) be a complete DVR with fraction field \( K \) and residue field \( k := A/p \). The categories \( C^\text{unr}_K \) and \( C^\text{sep}_k \) are equivalent via the functor \( \mathcal{F} : C^\text{unr}_K \to C^\text{sep}_k \) that sends each unramified extension \( L \) of \( K \) to its residue field \( l \), and each \( K \)-algebra homomorphism \( \varphi : L_1 \to L_2 \) to the \( k \)-algebra homomorphism \( \bar{\varphi} : l_1 \to l_2 \) defined by \( \bar{\varphi}(\bar{\alpha}) := \bar{\varphi}(\alpha) \), where \( \alpha \) is any lift of \( \bar{\alpha} \in l_1 := B_1/q_1 \) to \( B_1 \) and \( \bar{\varphi}(\alpha) \) is the reduction of \( \varphi(\alpha) \in B_2 \) to \( l_2 := B_2/q_2 \); here \( q_1, q_2 \) are the maximal ideals of the valuation rings \( B_1, B_2 \) of \( L_1, L_2 \), respectively.

In particular, \( \mathcal{F} \) gives a bijection between the isomorphism classes in \( C^\text{unr}_K \) and \( C^\text{sep}_k \), and if \( L_1, L_2 \) and have residue fields \( l_1, l_2 \) then \( \mathcal{F} \) induces a bijection of finite sets

\[
\text{Hom}_K(L_1, L_2) \sim \text{Hom}_k(l_1, l_2).
\]

**Proof.** Let us first verify that \( \mathcal{F} \) is well-defined. It is clear that it maps finite unramified extensions \( L/K \) to finite separable extensions \( l/k \), but we should check that the map on morphisms does not depend on the lift \( \alpha \) of \( \bar{\alpha} \) we pick. So let \( \varphi : L_1 \to L_2 \) be a \( K \)-algebra homomorphism, and for \( \bar{\alpha} \in l_1 \), let \( \alpha \) and \( \alpha' \) be two lifts of \( \bar{\alpha} \) to \( B_1 \). Then \( \alpha - \alpha' \in q_1 \), and this implies that \( \varphi(\alpha - \alpha') \in \varphi(q_1) = \varphi(B_1) \cap q_2 \subseteq q_2 \), and therefore \( \varphi(\alpha) = \varphi(\alpha') \). The identity \( \varphi(q_1) = \varphi(B_1) \cap q_2 \subseteq q_2 \) follows from the fact that \( \varphi \) restricts to an injective ring homomorphism \( B_1 \to B_2 \) and \( B_2/\varphi(B_1) \) is a finite extension of DVRs in which \( q_2 \) lies over the prime \( \varphi(q_1) \) of \( \varphi(B_1) \). It’s easy to see that \( \mathcal{F} \) sends identity morphisms to identity morphisms and that it is compatible with composition, so we have a well-defined functor.

To show that \( \mathcal{F} \) is an equivalence of categories we need to prove two things:

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\(^1\)Recall from Definition 5.37 that separability of the residue field extension is part of the definition of an unramified extension. If the residue field is perfect (as when \( K \) is a local field, for example), the residue field extension is automatically separable, but in general it need not be, even when \( L/K \) is unramified.
\( \mathcal{F} \) is essentially surjective: each separable \( l/k \) is isomorphic to the residue field of some unramified \( L/K \).

\( \mathcal{F} \) is full and faithful: the induced map \( \text{Hom}_K(L_1, L_2) \to \text{Hom}_k(l_1, l_2) \) is a bijection.

We first show that \( \mathcal{F} \) is essentially surjective. Given a finite separable extension \( l/k \), we may apply the primitive element theorem to write
\[
l \simeq k(\bar{\alpha}) = \frac{k[x]}{(\bar{g}(x))},\]
for some \( \bar{\alpha} \in l \) whose minimal polynomial \( \bar{g} \in k[x] \) is necessarily monic, irreducible, separable, and of degree \( n := [l : k] \). Let \( g \in A[x] \) be any monic lift of \( \bar{g} \); then \( g \) is also irreducible, separable, and of degree \( n \). Now let
\[
L := \frac{K[x]}{(g(x))} = K(\alpha),
\]
where \( \alpha \) is the image of \( x \) in \( K[x]/g(x) \). Then \( L/K \) is a finite separable extension, and by Corollary 10.13, \( (p, g(\alpha)) \) is the unique maximal ideal of \( A[\alpha] \) (since \( \bar{g} \) is irreducible) and
\[
\frac{B}{q} \simeq \frac{A[\alpha]}{(p, g(\alpha))} \simeq \frac{A[x]}{(p, g(x))} \simeq \frac{(A/p)[x]}{(\bar{g}(x))} \simeq l.
\]
We thus have \( [L : K] = \deg g = [l : k] = n \), and it follows that \( L/K \) is an unramified extension of degree \( n = f := [l : k] \); the ramification index of \( q \) is necessarily \( e = n/f = 1 \), and the extension \( l/k \) is separable by assumption (so in fact \( B = A[\alpha] \), by Theorem 10.14).

We now show that the functor \( \mathcal{F} \) is full and faithful. Given finite unramified extensions \( L_1, L_2 \) with valuation rings \( B_1, B_2 \) and residue fields \( l_1, l_2 \), we have induced maps
\[
\text{Hom}_K(L_1, L_2) \longrightarrow \text{Hom}_A(B_1, B_2) \longrightarrow \text{Hom}_k(l_1, l_2).
\]
The first map is given by restriction from \( L_1 \) to \( B_1 \), and since tensoring with \( K \) gives an inverse map in the other direction, it is a bijection. We need to show that the same is true of the second map, which sends \( \varphi : B_1 \to B_2 \) to the \( k \)-homomorphism \( \overline{\varphi} \) that sends \( \overline{\alpha} \in l_1 = B_1/q_1 \) to the reduction of \( \varphi(\alpha) \) modulo \( q_2 \), where \( \alpha \) is any lift of \( \bar{\alpha} \).

As above, use the primitive element theorem to write \( l_1 = k(\overline{\alpha}) = k[\bar{x}]/(\bar{g}(x)) \) for some \( \overline{\alpha} \in l_1 \). If we now lift \( \bar{\alpha} \) to \( \alpha \in B_1 \), we must have \( L_1 = K(\alpha) \), since \( [L_1 : K] = [l_1 : k] \) is equal to the degree of the minimal polynomial \( \bar{g} \) of \( \bar{\alpha} \) which cannot be less than the degree of the minimal polynomial \( g \) of \( \alpha \) (both are monic). Moreover, we also have \( B_1 = A[\alpha] \), since this is true of the valuation ring of every finite unramified extension in our category.

Each \( A \)-module homomorphism in
\[
\text{Hom}_A(B_1, B_2) = \text{Hom}_A \left( \frac{A[x]}{(g(x))}, B_2 \right)
\]
is uniquely determined by the image of \( x \) in \( B_2 \). Thus gives us a bijection between \( \text{Hom}_A(B_1, B_2) \) and the roots of \( g \) in \( B_2 \). Similarly, each \( k \)-algebra homomorphism in
\[
\text{Hom}_k(l_1, l_2) = \text{Hom}_k \left( \frac{k[x]}{(g(x))}, l_2 \right)
\]
is uniquely determined by the image of \( x \) in \( l_2 \), and there is a bijection between \( \text{Hom}_k(l_1, l_2) \) and the roots of \( \bar{g} \) in \( l_2 \). Now \( \bar{g} \) is separable, so every root of \( \bar{g} \) in \( l_2 = B_2/q_2 \) lifts to a unique root of \( g \) in \( B_2 \), by Hensel’s Lemma 9.15. Thus the map \( \text{Hom}_A(B_1, B_2) \longrightarrow \text{Hom}_k(l_1, l_2) \) induced by \( \mathcal{F} \) is a bijection.

\[\square\]
Remark 10.16. In the proof above we actually only used the fact that \( L_1/K \) is unramified. The map \( \text{Hom}_K(L_1, L_2) \to \text{Hom}_k(l_1, l_2) \) is a bijection even if \( L_2/K \) is not unramified.

Let us note the following corollary, which follows from our proof of Theorem 10.15.

\begin{corollary}
Assume \( ALB \) with \( A \) a complete DVR with residue field \( k \). Then \( L/K \) is unramified if and only if \( B = \alpha[A] \) for some \( \alpha \in L \) whose minimal polynomial \( g \in A[x] \) has separable image \( \bar{g} \) in \( k[x] \).
\end{corollary}

\begin{proof}
The forward direction was proved in the proof of the theorem, and for the reverse direction note that \( \bar{g} \) must be irreducible, since otherwise we could use Hensel's lemma to lift a non-trivial factorization of \( \bar{g} \) to a non-trivial factorization of \( g \), so the residue field extension is separable and has the same degree as \( L/K \), so \( L/K \) is unramified. \( \square \)
\end{proof}

\begin{corollary}
Let \( A \) be a complete DVR with fraction field \( K \) and residue field \( k \), and let \( \zeta_n \) be a primitive \( n \)th root of unity in some algebraic closure of \( K \), with \( n \) prime to the characteristic of \( k \). The extension \( K(\zeta_n)/K \) is unramified.
\end{corollary}

\begin{proof}
The field \( K(\zeta_n) \) is the splitting field of \( f(x) = x^n - 1 \) over \( K \). The image \( \bar{f} \) of \( f \) in \( k[x] \) is separable when \( p \nmid n \), since \( \gcd(f, \bar{f}') \neq 1 \) only when \( \bar{f}' = nx^{n-1} \) is zero, equivalently, only when \( p | n \). When \( f \) is separable, so are all of its divisors, including the reduction of the minimal polynomial of \( \zeta_n \), which must be irreducible since otherwise we could obtain a contradiction by lifting a non-trivial factorization via Hensel's lemma. It follows that the residue field of \( K(\zeta_n) \) is a separable extension of \( k \), thus \( K(\zeta_n)/K \) is unramified. \( \square \)
\end{proof}

When the residue field \( k \) is finite (always the case if \( K \) is a local field), we can give a precise description of the finite unramified extensions \( L/K \).

\begin{corollary}
Let \( A \) be a complete DVR with fraction field \( K \) and finite residue field \( \mathbb{F}_q \), and let \( L \) be a degree \( n \) extension of \( K \). Then \( L/K \) is unramified if and only if \( L \cong K(\zeta_{q^n-1}) \).
\end{corollary}

\begin{proof}
The reverse implication is implied by Corollary 10.18; note that \( K(\zeta_{q^n-1}) \) has degree \( n \) over \( K \) because its residue field is the splitting field of \( x^{q^n-1} - 1 \) over \( \mathbb{F}_q \), which is an extension of degree \( n \) (indeed, one can take this as the definition of \( \mathbb{F}_{q^n} \)).

Now suppose \( L/K \) is unramified. The residue field has degree \( n \) and is thus isomorphic to \( \mathbb{F}_{q^n} \), so its multiplicative group is a cyclic of order \( q^n - 1 \) generated by some \( \bar{\alpha} \). The minimal polynomial \( \bar{g} \in \mathbb{F}_q[x] \) of \( \bar{\alpha} \) divides \( x^{q^n-1} - 1 \), and since \( \bar{g} \) is irreducible, it is coprime to the quotient \((x^{q^n-1} - 1)/\bar{g})\). By Hensel's Lemma 9.19, we can lift \( \bar{g} \) to a polynomial \( g \in A[x] \) that divides \( x^{q^n-1} - 1 \in A[x] \), and by Hensel's Lemma 9.15 we can lift \( \bar{\alpha} \) to a root \( \alpha \) of \( g \), in which case \( \alpha \) is also a root of \( x^{q^n-1} - 1 \); it must be a primitive \( (q^n - 1) \)-root of unity because its reduction \( \bar{\alpha} \) is.

Let \( B \) be the integral closure of \( A \) in \( L \). We have \( B \cong A[\zeta_{q^n-1}] \) by Theorem 10.14, and \( L \) is the splitting field of \( x^{q^n-1} - 1 \), since its residue field \( \mathbb{F}_{q^n} \) is (we can lift the factorization of \( x^{q^n-1} - 1 \) from \( \mathbb{F}_{q^n} \) to \( L \) via Hensel's lemma). It follows that \( L/K \) is Galois, and the bijection between \( (q^n - 1) \)-roots of unity in \( L \) and \( \mathbb{F}_{q^n} \) induces an isomorphism \( \text{Gal}(L/K) \cong \text{Gal}(l/k) = \text{Gal}(\mathbb{F}_{q^n}/\mathbb{F}_q) \cong \mathbb{Z}/n\mathbb{Z} \). \( \square \)
\end{proof}

\begin{corollary}
Let \( A \) be a complete DVR with fraction field \( K \) and finite residue field of characteristic \( p \), and suppose that \( K \) does not contain a primitive \( p \)th root of unity. The extension \( K(\zeta_m)/K \) is ramified if and only if \( p \) divides \( m \).
\end{corollary}
Proof. If \( p \) does not divide \( m \) then Corollary 10.18 implies that \( K(\zeta_m)/K \) is unramified. If \( p \) divides \( m \) then \( K(\zeta_m) \) contains \( K(\zeta_p) \), which by Corollary 10.19 is unramified if and only if \( K(\zeta_p) \simeq K(\zeta_{p^n - 1}) \) with \( n := [K(\zeta_p) : K] \), which occurs if and only if \( p \) divides \( p^n - 1 \) (since \( \zeta_p \not\in K \)), which it does not; thus \( K(\zeta_p) \) and therefore \( K(\zeta_m) \) is ramified when \( p|m \). \( \square \)

Example 10.21. Consider \( A = \mathbb{Z}_p, K = \mathbb{Q}_p, k = \mathbb{F}_p \), and fix \( \overline{\mathbb{F}}_p \) and \( \overline{\mathbb{Q}}_p \). For each positive integer \( n \), the finite field \( \mathbb{F}_p \) has a unique extension of degree \( n \) in \( \overline{\mathbb{F}}_p \), namely, \( \mathbb{F}_{p^n} \). Thus for each positive integer \( n \), the local field \( \mathbb{Q}_p \) has a unique unramified extension of degree \( n \); it can be explicitly constructed by adjoining a primitive root of unity \( \zeta_{p^n - 1} \) to \( \mathbb{Q}_p \). The element \( \zeta_{p^n - 1} \) will necessarily have minimal polynomial of degree \( n \) dividing \( x^{p^n - 1} - 1 \).

Another useful consequence of Theorem 10.15 that applies when the residue field is finite is that the norm map \( N_{L/K} \) restricts to a surjective map \( B^\times \to A^\times \) on unit groups; in fact, this property characterizes unramified extensions.

Theorem 10.22. Assume \( AKLB \) with \( A \) a complete DVR with finite residue field. Then \( L/K \) is unramified if and only if \( N_{L/K}(B^\times) = A^\times \).

Proof. See Problem Set 6. \( \square \)

Definition 10.23. Let \( L/K \) be a separable extension. The maximal unramified extension of \( K \) in \( L \) is the subfield

\[ \bigcup_{E/K \text{ fin. unram.}} E \subseteq L \]

where the union is over finite unramified subextensions \( E/K \). When \( L = K^{\text{sep}} \) is the separable closure of \( K \), this is the maximal unramified extension of \( K \), denoted \( K^{\text{unr}} \).

Example 10.24. The field \( \mathbb{Q}_p^{\text{unr}} \) is an infinite extension of \( \mathbb{Q}_p \) with Galois group

\[ \text{Gal}(\mathbb{Q}_p^{\text{unr}}/\mathbb{Q}_p) \simeq \text{Gal}(\mathbb{F}_p/\mathbb{F}_p) = \varprojlim_n \text{Gal}(\mathbb{F}_{p^n}/\mathbb{F}_p) \simeq \varprojlim_n \mathbb{Z}/n\mathbb{Z} =: \hat{\mathbb{Z}}, \]

where the inverse limit is taken over positive integers \( n \) ordered by divisibility. The ring \( \hat{\mathbb{Z}} \) is the profinite completion of \( \mathbb{Z} \). The field \( \mathbb{Q}_p^{\text{unr}} \) has value group \( \mathbb{Z} \) and residue field \( \mathbb{F}_p \).

Theorem 10.25. Assume \( AKLB \) with \( A \) a complete DVR and separable residue field extension \( l/k \). Let \( e_{L/K} \) and \( f_{L/K} \) be the ramification index and residue field degrees, respectively. The following hold:

(i) There is a unique intermediate field extension \( E/K \) that contains every unramified extension of \( K \) in \( L \) and it has degree \( [E : K] = f_{L/K} \).

(ii) The extension \( L/E \) is totally ramified and has degree \( [L : E] = e_{L/K} \).

(iii) If \( L/K \) is Galois then \( \text{Gal}(L/E) = I_{L/K} \), where \( I_{L/K} = I_q \) is the inertia subgroup of \( \text{Gal}(L/K) \) for the unique prime \( q \) of \( B \).

Proof. (i) Let \( E/K \) be the finite unramified extension of \( K \) in \( L \) corresponding to the finite separable extension \( l/k \) given by Theorem 10.15; then \( [E : K] = [l : k] = f_{L/K} \) as desired. The maximal unramified extension \( E' \) of \( K \) in \( L \) has the same residue field \( l \) as \( L \), which is also the residue field of \( E \), and equivalence of categories given by Theorem 10.15 implies that the trivial isomorphism \( \ell \simeq \ell \) corresponds to an isomorphism \( E \simeq E' \) that allows us to
view $E$ as a subfield of $L$; the same applies to any unramified extension of $K$ with residue field $l$, so $E$ is unique up to isomorphism.

(ii) We have $f_{L/E} = [l : l] = 1$, so $e_{L/E} = [L : E] = [L : K]/[E : K] = e_{L/K}$.

(iii) By Proposition 7.13, we have $I_{L/E} = \text{Gal}(L/E) \cap I_{L/K}$, and these three groups all have the same order $e_{L/K}$ so they must coincide.

\[ \square \]

References


