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Contents

Commutative algebras	5
1. Introduction	5
2. Graded commutative algebra	5
3. Graded algebraic geometry	15
4. Graded Riemann–Zariski spaces	15
5. Strictness in graded Riemann–Zariski spaces	18
6. The birational categories	21
7. The birational category à la Temkin	23
8. Miscellany	24
Bibliography	25

Commutative algebras

1. Introduction

2. Graded commutative algebra

Let G be an Abelian group. We write the group operation of G multiplicatively and denote the identity of G as 1.

Definition 2.1. Let A be an Abelian group. A G -grading on A is a coproduct decomposition

$$A = \bigoplus_{g \in G} A_g$$

of Abelian groups such that $A_g \subseteq A$. An Abelian group with a G -grading is called a G -graded Abelian group.

An element $a \in A$ is said to be *homogeneous* if there is $g \in G$ such that $a \in A_g$. If a is furthermore non-zero, we write $g = \rho(a)$. We set $\rho(0) = 0$. We will write $\rho(A)$ for the set of $\rho(a)$ when a runs over all homogeneous elements in A .

A G -graded homomorphism between G -graded Abelian groups A and B is a homogeneous of the underlying Abelian groups $f : A \rightarrow B$ such that $f(A_g) \subseteq B_g$ for any $g \in G$.

The category of G -graded Abelian groups is denoted by \mathcal{Ab}^G .

Remark 2.2. A usual Abelian group A can be given the *trivial G -grading*: $A_0 = A$ and $A_g = 0$ for $g \in G, g \neq 0$. In this way, we find a fully faithful embedding

$$\mathcal{Ab} \rightarrow \mathcal{Ab}^G.$$

When we regard an Abelian group as a G -graded Abelian group and there are no natural gradings, we always understand that we are taking the trivial G -grading.

More generally, let G' be a subgroup of G . Then any G' -graded Abelian group can be canonically identified with a G -graded Abelian group: for the extra pieces in the grading, we simply put 0.

Conversely, if G' be a subgroup of G and A is a G -graded Abelian group, we write

$$A^{G'} := \bigoplus_{g \in G'} A_g.$$

This is a G' -graded Abelian group.

The same remark applies to all the other constructions in this section, which we will not repeat.

Definition 2.3. A G -graded ring is a commutative ring A endowed with a G -grading:

$$A = \bigoplus_{g \in G} A_g$$

as Abelian groups and such that

- (1) $A_g A_h \subseteq A_{gh}$ for any $g, h \in G$;
- (2) $1 \in A_1$.

A *G-graded homomorphism* of G -graded rings A and B is a ring homomorphism $f : A \rightarrow B$ such that $f(A_g) \subseteq B_g$ for each $g \in G$. A *G-graded subring* of a G -graded ring B is a subring A of B such that the grading on B restricts to a grading on A .

The category of G -graded rings is denoted by $\mathcal{R}ing^G$.

Example 2.4. Let A be a G -graded ring, $n \in \mathbb{N}$ and $g = (g_1, \dots, g_n) \in G^n$. Then there is a unique G -grading on $A[T_1, \dots, T_n]$ extending the grading on A and such that $\rho(T_i) = g_i$ for $i = 1, \dots, n$. We will denote $A[T_1, \dots, T_n]$ with this grading as $A[g_1^{-1}T_1, \dots, g_n^{-1}T_n]$ or simply $A[g^{-1}T]$.

Example 2.5. Let A be a G -graded ring and S be a multiplicative subset of A consisting of homogeneous elements, then $S^{-1}A$ has a natural G -grading. To see this, recall the construction of $S^{-1}A$ in [Stacks, Tag 00CM]. One defines an equivalence relation on $A \times S$: $(x, s) \sim (y, t)$ if there is $u \in S$ such that $(xt - ys)u = 0$. For each $g \in G$, we define $(S^{-1}A)_g$ as the set of (x, s) for all $s \in S$ and $x \in A_{g\rho(s)}$. It is easy to verify that this is a well-defined G -grading on $S^{-1}A$. [Add details.](#)

In particular, if $f \in A$ is a non-zero homogeneous element, then we define A_f as $S^{-1}f$ with $S = \{f^n : n \in \mathbb{N}\}$.

Definition 2.6. Let A be a G -graded ring. A *G-homogeneous ideal* in A is an ideal I in G such that if $a \in A$ can be written as

$$a = \sum_{g \in G} a_g, \quad a_g \in A_g$$

with almost all $a_g = 0$, then $a_g \in I$.

Example 2.7. Let A be a G -graded ring and $n \in \mathbb{N}$ and a_1, \dots, a_n be homogeneous elements in A . Then a_1, \dots, a_n generate a G -homogeneous ideal (a_1, \dots, a_n) as follows:

$$(a_1, \dots, a_n)_g = \sum_{i=1}^n A_{g\rho(a_i)-1} a_i$$

for any $g \in G$.

Lemma 2.8. Let $f : A \rightarrow B$ be a G -homomorphism of G -graded rings. Then $\ker f$ is a G -homogeneous ideal in A .

PROOF. We need to show that

$$\ker f = \sum_{g \in G} (\ker f) \cap A_g.$$

Take $x \in \ker f$, we can write x as

$$\sum_{g \in G} a_g, \quad a_g \in A_g$$

and almost all a_g 's are 0. Then

$$f(x) = \sum_{g \in G} f(a_g), \quad f(a_g) \in B_g.$$

It follows that $f(a_g) = 0$ for each $g \in G$ and hence $a_g \in (\ker f) \cap A_g$. □

Definition 2.9. Let A be a G -graded ring and I be a G -homogeneous ideal in A . Then we define a G -grading on A/I as follows: for any $g \in G$

$$(A/I)_g := (A_g + I)/I.$$

Proposition 2.10. Let A be a G -graded ring and I be a G -homogeneous ideal in A . Then the construction in [Definition 2.9](#) defines a grading on A/I . The natural map $\pi : A \rightarrow A/I$ is a G -homomorphism.

For any G -graded ring B and any G -homomorphism $f : A \rightarrow B$ such that $I \subseteq \ker f$, there is a unique G -homomorphism $f' : A/I \rightarrow B$ such that $f' \circ \pi = f$.

PROOF. We first argue that for different $g, h \in G$, $(A/I)_g \cap (A/I)_h = 0$. Suppose $x \in (A/I)_g \cap (A/I)_h$, we can lift x to both $y_g + i_g \in A$ and $y_h + i_h \in A$ with $y_g, y_h \in A$ and $i_g, i_h \in I$. It follows that $y_g - y_h \in I$. But I is a G -homogeneous ideal, so it follows that $y_g, y_h \in I$ and hence $x = 0$.

Next we argue that

$$A/I = \sum_{g \in G} (A/I)_g.$$

Lift an element $x \in A/I$ by $a \in A$, we represent a as

$$a = \sum_{g \in G} a_g, \quad a_g \in A_g$$

with almost all a_g 's equal to 0. Then x can be represented as

$$x = \sum_{g \in G} \pi(a_g).$$

We have shown that the construction in [Definition 2.9](#) gives a G -grading on A . It is clear from the definition that π is a G -homomorphism.

Next assume that B and f are given as in the proposition. Then there is a ring homomorphism $f' : A/I \rightarrow B$ such that $f = f' \circ \pi$. We need to argue that f' is a G -homomorphism. For this purpose, take $g \in G$, $x \in (A/I)_g$, we need to show that $f'(x) \in B_g$. Lift x to $y + i$ with $y \in A_g$ and $i \in I$, then we know that $f'(x) = \pi(y + i) = \pi(y) \in B_g$. \square

Definition 2.11. Let A be a G -graded ring.

Let M an A -module which is also a G -graded Abelian group. We say M is a G -graded A -module if for each $g, h \in G$, we have

$$A_g M_h \subseteq M_{gh}.$$

A G -graded homomorphism of G -graded A -modules M and N is an A -module homomorphism $f : M \rightarrow N$ which is at the same time a homomorphism of the underlying G -graded Abelian groups.

The category of G -graded A -modules is denoted by Mod_A^G .

A G -graded A -algebra is a G -graded ring B together with a G -graded ring homomorphism $A \rightarrow B$ such that B is also a G -graded A -module.

A G -graded homomorphism between G -graded A -algebras B and C is a G -graded homomorphism between the underlying G -graded rings that is at the same time a G -graded homomorphism of G -graded A -modules.

Observe that G -homogeneous ideals of A are G -graded submodules of A . Also observe that $\text{Mod}_{\mathbb{Z}}^G$ is isomorphic to Ab^G .

Proposition 2.12. Let A be a G -graded ring. Then \mathcal{Mod}_A^G is an Abelian category satisfying AB5.

PROOF. We first show that \mathcal{Mod}_A^G is preadditive. Given $M, N \in \mathcal{Mod}_A^G$, we can regard $\text{Hom}_{\mathcal{Mod}_A^G}(M, N)$ as a subgroup of $\text{Hom}_A(M, N)$. It is easy to see that this gives \mathcal{Mod}_A^G an enrichment over \mathcal{Ab} .

Next we show that \mathcal{Mod}_A^G is additive. The zero object is clearly given by 0 with the trivial grading. Given $M, N \in \mathcal{Mod}_A^G$, we define

$$(M \oplus N)_g := M_g \oplus N_g, \quad g \in G.$$

This construction makes $M \oplus N$ a G -graded A -module. It is easy to verify that $M \oplus N$ is the biproduct of M and N .

Next we show that \mathcal{Mod}_A^G is pre-Abelian. Given an arrow $f : M \rightarrow N$ in \mathcal{Mod}_A^G , we need to define its kernel and cokernel. We define

$$(\ker f)_g := (\ker f) \cap M_g$$

and $(\text{coker } f)_g$ as the image of N_g for any $g \in G$. It is straightforward to verify that these are kernels and cokernels.

Next, given a monomorphism $f : M \rightarrow N$, it is obvious that the map f is injective and f can be identified with the kernel of the natural map $N/\text{Im } f$. A dual argument shows that an epimorphism is the cokernel of some morphism as well.

The AB5 condition is easily verified. **Expand the details of this argument!** \square

Next we define the tensor product of G -graded modules.

Definition 2.13. Let A be a G -graded ring and M, N be G -graded A -modules. We define a G -grading on $M \otimes_A N$ as follows: for any $g \in G$, $(M \otimes_A N)_g$ is defined as the image of $\sum_{h \in G} M_h \times N_{gh^{-1}}$ in $M \otimes_A N$. We always endow $M \otimes_A N$ with this G -grading.

Verify the universal property; show that this is indeed a grading

Example 2.14. This is a continuation of **Example 2.5**. Let A be a G -graded ring and S be a multiplicative subset of A consisting of homogeneous elements. Consider a G -graded A -module M . We define a G -grading on $S^{-1}M$. Recall that $S^{-1}M$ can be realized as follows: one defines an equivalence relation on $M \times S$: $(x, s) \sim (y, t)$ if there is $u \in S$ such that $(xt - ys)u = 0$. For each $g \in G$, we define $(S^{-1}M)_g$ as the set of (x, s) for all $s \in S$ and $x \in M_{g\rho(s)}$. It is easy to verify that this is a well-defined G -grading on $S^{-1}M$ and $S^{-1}M$ is a G -graded $S^{-1}A$ -module. **Add details.**

Example 2.15. Let A be a G -graded ring and $g \in G$. We define $g^{-1}A$ as the G -graded A -module:

$$(g^{-1}A)_h = A_{g^{-1}h}$$

for any $h \in G$. Observe that $1 \in (g^{-1}A)_g$.

Definition 2.16. Let A be a G -graded ring and M be a G -graded A -module. We say M is *free* if there exists a family $\{g_i\}_{i \in I}$ in G such that

$$M = \coprod_{i \in I} g_i^{-1}A.$$

Definition 2.17. Let $f : A \rightarrow B$ be a G -graded homomorphism of G -graded rings. We say f is *finite* (resp. *finitely generated*, resp. *integral*) if it is finite (resp. finitely generated, resp. integral) as a usual ring map.

Proposition 2.18. Let $f : A \rightarrow B$ be a G -graded homomorphism of G -graded rings. Then

- (1) f is finite if and only if there are $n \in \mathbb{N}$, $g_1, \dots, g_n \in G$ and a surjective G -graded homomorphism

$$\bigoplus_{i=1}^n (g_i^{-1}A)^n \rightarrow B$$

of graded A -modules.

- (2) f is finitely generated if and only if there are $n \in \mathbb{N}$, $g_1, \dots, g_n \in G$ and a surjective G -graded A -algebra homomorphism

$$A[g_1^{-1}T_1, \dots, g_n^{-1}T_n] \rightarrow B.$$

- (3) f is integral if and only if for any non-zero homogeneous element $b \in B$, there is $n \in \mathbb{N}$ and homogeneous elements $a_1, \dots, a_n \in A$ such that

$$b^n + f(a_1)b^{n-1} + \dots + f(a_n) = 0.$$

- (4) A non-zero homogeneous element $b \in B$ is integral over A if there is $n \in \mathbb{N}$ and homogeneous elements $a_1, \dots, a_n \in A$ such that

$$b^n + f(a_1)b^{n-1} + \dots + f(a_n) = 0.$$

PROOF. (1) The non-trivial direction is the direct implication. Assume that f is finite. Take $b_1, \dots, b_n \in B$ so that $\sum_{i=1}^n f(A)b_i = B$. Up to replacing the collection $\{b_i\}_i$ by the finite collection of non-zero homogeneous components of the b_i 's, we may assume that each b_i is homogeneous. We define $g_i = \rho(b_i)$ and the map $\bigoplus_{i=1}^n (g_i^{-1}A)^n \rightarrow B$ sends 1 at the i -th place to b_i .

(2) The non-trivial direction is the direct implication. Suppose f is finitely generated, say by b_1, \dots, b_n . Up to replacing the collection $\{b_i\}_i$ by the finite collection of non-zero homogeneous components of the b_i 's, we may assume that each b_i is homogeneous. Then we define $g_i = \rho(b_i)$ for $i = 1, \dots, n$ and the A -algebra homomorphism $A[g_1^{-1}T_1, \dots, g_n^{-1}T_n] \rightarrow B$ sends T_i to b_i for $i = 1, \dots, n$.

(3) Assume that f is integral, then for any non-zero homogeneous element $b \in B$, we can find $a_1, \dots, a_n \in A$ such that

$$b^n + f(a_1)b^{n-1} + \dots + f(a_n) = 0.$$

Obviously, we can replace a_i by its component in $\rho(b)^i$ for $i = 1, \dots, n$ and the equation remains true.

The reverse direction follows from [Stacks, Tag 00GO].

- (4) This is argued in the same way as (3). □

Definition 2.19. A G -graded ring A is a G -graded field if

- (1) $A \neq 0$.
(2) A does not admit any non-zero proper G -homogeneous ideals.

Proposition 2.20. Let A be a non-zero G -graded ring. Then the following conditions are equivalent:

- (1) A is a G -graded field.

(2) Any non-zero homogeneous element in A is invertible.

PROOF. Assume that A is a G -graded field. Let $a \in A$ be a non-zero homogeneous element. Consider the G -homogeneous ideal (a) generated by a as in [Example 2.7](#). As $a \neq 0$, it follows that $(a) = 1$. Hence, a is invertible.

Conversely, suppose that any non-zero homogeneous element in A is invertible. If I is a non-zero G -homogeneous ideal in A . There is a non-zero homogeneous element $a \in I$. But we know that a is invertible and hence $I = A$. \square

Definition 2.21. A G -graded ring A is an *integral domain* if for any non-zero homogeneous elements $a, b \in A$, $ab \neq 0$.

Lemma 2.22. Let A be a G -graded integral domain. Let S denote the set of non-zero homogeneous elements in A . Then $S^{-1}A$ is a graded field. The natural map $A \rightarrow S^{-1}A$ is injective.

Recall that $S^{-1}A$ is defined in [Example 2.5](#).

PROOF. By [Proposition 2.20](#), it suffices to show that each non-zero homogeneous element in $S^{-1}A$ is invertible. Such an element has the form a/s for some homogeneous element $a \in A$ and $s \in S$. As A is a G -graded integral domain, a is invertible and hence $s/a \in S^{-1}A$.

In general, the kernel of the localization map is given by $\{a \in A : \text{there is } s \in S \text{ such that } sa = 0\}$. As $A \rightarrow S^{-1}A$ is a G -graded homomorphism, the kernel is in addition a G -homogeneous ideal in A by [Lemma 2.8](#). So it suffices to show that each homogeneous element in the kernel vanishes: if $a \in A$ is a homogeneous element and there is $s \in S$ such that $sa = 0$, then $a = 0$. Otherwise, a is invertible by [Proposition 2.20](#), which is a contradiction. \square

Definition 2.23. Let A be a G -graded integral domain. We call the graded field defined in [Lemma 2.22](#) the *fraction G -graded field* of A and denote it by $\text{Frac}^G A$.

Definition 2.24. Let A be a G -graded ring. A proper G -homogeneous ideal I in A is called *prime* if the G -graded ring A/I is a G -graded integral domain.

Proposition 2.25. Let A be a G -graded ring and I be a proper homogeneous ideal in A . Then the following are equivalent:

- (1) I is a G -graded prime ideal in A .
- (2) For any homogeneous elements $a, b \in A$ satisfying $ab \in I$, at least one of a and b lies in I .

PROOF. Assume that I is a G -graded prime ideal in A . Let $a, b \in A$ be homogeneous elements satisfying $ab \in I$. Let \bar{a}, \bar{b} be the images of a, b in A/I . Then \bar{a}, \bar{b} are homogeneous and $\bar{a}\bar{b} = 0$. So at least one of \bar{a} and \bar{b} is zero. That is, a or b lies in I .

Conversely, assume that the condition in (2) is satisfied. Take $x, y \in A/I$ with $xy = 0$. We need to show that at least one of x and y is 0. Lift x and y to $a + i$ and $b + i'$ in A with a, b being homogeneous and $i, i' \in I$. Then $ab \in I$ and hence $a \in I$ or $b \in I$. It follows that $x = 0$ or $y = 0$. \square

Definition 2.26. Let A be a G -graded ring and \mathfrak{p} be a prime G -homogeneous ideal in A . Then we define the *G -graded localization* $A_{\mathfrak{p}}^G$ of A at \mathfrak{p} as $S^{-1}A$, where S is the set of homogeneous elements in $A \setminus \mathfrak{p}$.

Similarly, let M be a G -graded A -module. We define the G -graded localization $M_{\mathfrak{p}}^G$ as $S^{-1}M$.

Recall that $S^{-1}A$ and $S^{-1}M$ are defined in [Example 2.5](#) and [Example 2.14](#).

Definition 2.27. Let A be a G -graded ring.

A G -homogeneous ideal I in A is said to be *maximal* if it is proper, and it is not contained in any other proper G -homogeneous ideals.

We call A a G -graded local ring if it has a unique maximal homogeneous ideal. This ideal is called the *maximal G -homogeneous ideal* of A .

Proposition 2.28. Let A be a G -graded ring and I be a G -homogeneous ideal in A . Then the following are equivalent:

- (1) I is a maximal G -homogeneous ideal in A ;
- (2) A/I is a G -graded field.

In particular, a maximal G -homogeneous ideal is a prime G -homogeneous ideal.

PROOF. Assume (1). Then I is a proper ideal, so A/I is non-zero. Suppose that A/I has a proper G -homogeneous ideal J , it lifts to an ideal J' of A . We claim that J' is G -homogeneous. In fact, we set $J'_g := \{x \in A_g : x + I \in J\}$ for $g \in G$, we need to show that

$$J' = \sum_{g \in G} J'_g.$$

For any $j \in J'$, we can expand $j + I$ as $\sum_{g \in G} a_g + I$ with $a_g \in A_g$ and almost all a_g 's are 0. We take $i \in I$ so that

$$j = i + \sum_{g \in G} a_g.$$

The desired equation follows. But then it follows that $J' = I$ and hence $J = 0$.

Assume (2). Then I is a proper ideal in A . If J is a G -homogeneous proper ideal of A containing I , then J/I is a G -homogeneous proper ideal of A/I . It follows that $J/I = 0$ and hence $J = I$. \square

Corollary 2.29. Let A be a non-zero G -graded ring, then A admits a prime G -homogeneous ideal.

PROOF. By our assumption, 0 is a proper ideal in A . By Zorn's lemma, A admits a maximal G -homogeneous ideal, which is prime by [Proposition 2.28](#). \square

Proposition 2.30. Let A be a G -graded ring and $a \in A$ be a homogeneous element. Then a is a unit in A if and only if a is not contained in any maximal G -homogeneous ideal of A .

PROOF. The direct implication is trivial. Assume that a is not a unit. Then the ideal (a) generated by a is G -homogeneous. By Zorn's lemma, there is a maximal G -homogeneous ideal containing (a) . \square

Lemma 2.31. Let $f : A \rightarrow B$ be a G -graded homomorphism of G -graded rings. Let $b_1, \dots, b_n \in B$ be a finite set of homogeneous elements integral over A , then there is a G -graded A -subalgebra $B' \subseteq B$ containing b_1, \dots, b_n such that $A \rightarrow B'$ is finite.

PROOF. We may assume that none of the b_i 's is zero. By [Proposition 2.18](#), we can find $m_1, \dots, m_n \in \mathbb{N}$ and homogeneous elements $a_{i,j} \in A$ for $i = 1, \dots, n$ and $j = 1, \dots, m_i$ such that

$$b_i^{m_i} + f(a_{i,1})b_i^{m_i-1} + \dots + f(a_{i,m_i}) = 0$$

for $i = 1, \dots, n$. It suffices to take B' as the A -submodule generated by $a_{i,j}$ for $i = 1, \dots, n$ and $j = 1, \dots, m_i$. \square

Proposition 2.32. Let $f : A \rightarrow B$ be an injective integral G -graded homomorphism of G -graded rings. Then for any prime G -homogeneous ideal \mathfrak{p} in A , there is a prime G -homogeneous ideal \mathfrak{p}' in B such that $\mathfrak{p} = f^{-1}\mathfrak{p}'$.

PROOF. We may assume that $A \neq 0$, as otherwise there is nothing to prove.

It suffices to show that $\mathfrak{p}B_{\mathfrak{p}} \neq B_{\mathfrak{p}}$. [Include a proof](#) We could localize that \mathfrak{p} and assume that \mathfrak{p} is a maximal G -homogeneous ideal. [Include details about localization](#) It suffices then to show that $\mathfrak{p}B \neq B$. Assume by contrary that we can write $1 = \sum_{i=1}^n f_i b_i$ for some homogeneous elements $f_i \in \mathfrak{p}$ and some homogeneous elements $b_i \in B$. Let B' be a G -graded subring of B containing A and b_1, \dots, b_n and such that $A \rightarrow B'$ is finite. The existence of B' is guaranteed by [Lemma 2.31](#). Then we find immediately $B' = \mathfrak{m}_A B'$. Then $B' = 0$ by the graded Nakayama's lemma. [Include details](#) So $A = 0$, which is a contradiction. \square

Lemma 2.33. Let A be a G -graded ring. Then the following are equivalent:

- (1) A is a G -graded local ring;
- (2) There is a proper homogeneous ideal I in A such that any non-invertible homogeneous element in A is contained in I .

In fact, I in (2) is just the maximal G -homogeneous ideal in A .

PROOF. Assume that (1) holds, let I be the maximal G -homogeneous ideal of A . Let a be a non-invertible homogeneous element in A . Then the image of a in A/I is invertible by [Proposition 2.28](#) and [Proposition 2.20](#).

Assume (2). We show that I is the maximal G -homogeneous ideal in A . By [Proposition 2.28](#), it suffices to show that A/I is a graded field. By [Proposition 2.20](#), we need to show that any non-zero homogeneous element $b \in A/I$ is invertible. Lift b to $a + i \in A$ with $a \in A$ homogeneous and $i \in I$. If a is not invertible, then $a \in I$ by the assumption hence $b = 0$. This is a contradiction. \square

Lemma 2.34. Let k be a G -graded field and A be a graded k -algebra. Suppose that $\rho(A) = \rho(k)$, then

- (1) For any $g \in G$, there is a natural isomorphism

$$A_g \cong A_1 \otimes_{k_1} k_g.$$

- (2) The map $I \mapsto I \cap A_1$ is a bijection between the set of G -homogeneous ideals (resp. prime G -homogeneous ideals) in A and ideals (resp. prime ideals) in A_1 .

PROOF. (1) Take $g \in \rho(A)$. As $\rho(A) = \rho(k)$, we can take a non-zero homogeneous element $b \in k_g$. Then b and b^{-1} induces inverse bijections between A_1 and A_g .

(2) The part about ideals can be proved in the same way as (1). The part about prime ideals follows easily. \square

Proposition 2.35. Let k be a G -graded field and M be a G -graded A -module. Then M is free as G -graded A -module.

PROOF. We may assume that $M \neq 0$. Let $\{m_i\}_{i \in I}$ be a maximal set of non-zero homogeneous elements in M such that the corresponding homomorphism

$$F := \bigoplus_{i \in I} (\rho(f))^{-1} k \rightarrow M$$

is injective. The existence of $\{m_i\}_{i \in I}$ follows from Zorn's lemma.

If $f \in M/F$ is a non-zero homogeneous element, then we get a homomorphism $(\rho(f))^{-1} k \rightarrow M/F$. This map is necessarily injective as $(\rho(f))^{-1} k$ does not have non-zero proper graded submodules. This contradicts the definition of F . \square

Corollary 2.36. Let k be a G -graded field, C be a G -graded k -algebra. Consider a G -graded homomorphism of G -graded k -algebras $f : A \rightarrow B$. Then the following are equivalent:

- (1) f is finite (resp. finitely generated);
- (2) $f \otimes_k C$ is finite (resp. finitely generated).

PROOF. (1) \implies (2): This implication is trivial.

(2) \implies (1): By [Proposition 2.35](#), this implication follows from fpqc descent [\[Stacks, Tag 02YJ\]](#). \square

Definition 2.37. Let K be a G -graded field. A G -graded subring $A \subseteq K$ is a *G -graded valuation ring* in K if

- (1) A is a local G -graded ring;
- (2) the natural map $\text{Frac}^G A \rightarrow K$ is an isomorphism;
- (3) For any non-zero homogeneous element $f \in K$, either $f \in A$ or $f^{-1} \in A$.

Definition 2.38. Let K be a G -graded field and A, B be G -graded local subrings of K . We say B *dominates* A if $A \subseteq B$ and $\mathfrak{m}_B \cap A = \mathfrak{m}_A$, where \mathfrak{m}_A and \mathfrak{m}_B are the maximal G -homogeneous ideals in A and B .

Proposition 2.39. Let K be a G -graded field and $A \subseteq K$ be a G -graded local subring. Then the following are equivalent:

- (1) A is a G -graded valuation ring in K .
- (2) A is maximal among the G -graded local subrings of K with respect to the order of domination.

PROOF. Assume (1). We may assume that $A \neq K$. Then A is not a G -graded field as $\text{Frac}^G A = K$. Let \mathfrak{m} be a maximal G -homogeneous ideal in A . Then $\mathfrak{m} \neq 0$.

We argue first that A is a G -graded local ring. Assume the contrary. Let $\mathfrak{m}' \neq \mathfrak{m}$ be maximal G -homogeneous ideal in A . Choose non-zero homogeneous elements $x, y \in A$ with $x \in \mathfrak{m}' \setminus \mathfrak{m}$, $y \in \mathfrak{m} \setminus \mathfrak{m}'$. Then $x/y \notin A$ as otherwise $x = (x/y)y \in \mathfrak{m}$. Similarly, $y/x \notin A$. This is a contradiction.

Next suppose that A' is a G -graded local subring of K dominating A . Let $x \in A'$ be a non-zero homogeneous element, we need to show that $x \in A$. If not, we have $x^{-1} \in A$ and as x^{-1} is not a unit, $x^{-1} \in \mathfrak{m}_{A'}$. But then $x^{-1} \in \mathfrak{m}_{A'}$, the maximal G -homogeneous ideal in A' . This contradicts the fact that $x \in A'$.

Assume (2). Take a homogeneous element $x \in K \setminus A$, we need to argue that $x^{-1} \in A$. Let A' denote the minimal G -homogeneous subring of K containing A and x . It is easy to see that A' is the usual subring generated by A and x .

By our assumption, there is no G -graded prime ideal of A' lying over \mathfrak{m}_A , as otherwise, if \mathfrak{p} is such an ideal, the G -graded local subring $A'_{\mathfrak{p}}^G$ of K dominates A .

In other words, the G -graded ring $A'/\mathfrak{m}_A A'$ does not have any homogeneous prime ideals and hence $A' = \mathfrak{m}_A A'$ by [Corollary 2.29](#).

We can therefore write

$$1 = \sum_{i=0}^d t_i x^i$$

with some homogeneous elements $t_i \in \mathfrak{m}_A$. In particular,

$$(1 - t_0)(x^{-1})^d - \sum_{i=1}^d t_i (x^{-1})^{d-i} = 0.$$

So x^{-1} is integral over A . Let A'' be the subring of K generated by A and x^{-1} . Then $A \rightarrow A''$ is finite and there is a G -homogeneous prime ideal \mathfrak{m}'' of A'' lying over \mathfrak{m}_A by [Proposition 2.32](#). By our assumption, $A = A''_{\mathfrak{m}''}^G$ and hence $x^{-1} \in A$.

It remains to verify that $\text{Frac}^G A = K$. Suppose that it is not the case, let $B \subseteq K$ be a G -graded local subring dominating A . Take a homogeneous element $t \in K$ that is not in $\text{Frac}^G A$. Observe that t can not be transcendental over A , as otherwise $A[t] \subseteq K$ is a G -graded subring, and we can localize it at the prime G -homogeneous generated by t and \mathfrak{m}_A . We get a G -graded local ring dominating A that is different from A .

So t is algebraic over A . We can then take a non-zero homogeneous $a \in A$ such that at is integral over A . The ring $A' \subseteq K$ generated by A and ta is a G -graded subring and $A \rightarrow A'$ is finite. By [Proposition 2.32](#), there is a prime G -homogeneous ideal \mathfrak{m}' of A' lifting \mathfrak{m}_A . But then $A'_{\mathfrak{m}'}^G$ dominates A and so $A = A'_{\mathfrak{m}'}^G$. It follows that $t \in \text{Frac}^G A$, which is a contradiction. \square

Corollary 2.40. Let K be a G -graded field. Any G -graded local subring $B \subseteq K$ is dominated by a G -graded valuation subring of K .

PROOF. This follows from [Proposition 2.39](#) and Zorn's lemma. \square

In the next lemma, graded rings are written additively.

Lemma 2.41. Let $n \in \mathbb{N}$ and $R = \mathbb{Z}[1^{-1}A_1, \dots, n^{-1}A_n]$ be the \mathbb{Z} -graded polynomial ring in n -variables. Consider a ring homomorphism

$$\Phi : R[T_0, n^{-1}T_1, (n+1)^{-1}T_2, \dots, (2n-1)^{-1}T_n] \rightarrow R[T]$$

sending T_0 to T and T_i to $T^{i-1}(T^n + A_1T^{n-1} + \dots + A_n)$ for $i = 1, \dots, n$. Then for all $l \in \mathbb{N}$, there are homogeneous polynomials $G_l \in R[n^{-1}T_1, \dots, (2n-1)^{-1}T_n]$ and $H_l \in R[T_0]$ of degree l such that $\deg_{T_0} H_l \leq n-1$ and $T_0^l - G_l - H_l \in \ker \Phi$.

PROOF. Fix $l \geq 0$, consider a polynomial $G_l \in R[n^{-1}T_1, \dots, (2n-1)^{-1}T_n]$ homogeneous of degree l such that $\Phi(T_0^l - G_l)$ has the minimal possible degree. We have to show that this degree is less than n . If not, say the leading term is cT^a with $a \geq n$ and $c \in R$ is a homogeneous element. Observe the leading term of the image of T_i in $R[T]$ is T^{n+i-1} for $i = 1, \dots, n$. We can always find a monomial Q in T_1, \dots, T_n such that the leading term of its image in $R[T]$ is T^a . Then set $G'_l = G_l - cQ$, we find that $\deg \Phi(G'_l) < \deg \Phi(G_l)$. This is a contradiction.

Now we can write

$$\Phi(T_0^l - G_l) = c_{n-1}T^{n-1} + \dots + c_0.$$

It suffices to take $H_l = c_{n-1}T_0^{n-1} + \cdots + c_0$. \square

3. Graded algebraic geometry

Let G be an Abelian group. We write the group operation of G multiplicatively and denote the identity of G as 1.

Definition 3.1. Let A be a G -graded ring. We define the G -graded affine spectrum $\text{Spec}^G(A)$ as follows: as a set $\text{Spec}^G(A)$ consists of all prime G -homogeneous ideals of A ; we endow $\text{Spec}^G(A)$ with the *Zariski topology*, whose base consists of sets of the form

$$D(f) := \left\{ \mathfrak{p} \in \text{Spec}^G(A) : f \notin \mathfrak{p} \right\}$$

for all homogeneous elements $f \in A$.

Lemma 3.2. Let k be a G -graded field and A be a finitely generated G -graded k -algebra. Then $\text{Spec}^G(A)$ has only finitely many maximal points.

PROOF. Take a G -graded field K/k such that $\rho(A) \subseteq \rho(K)$. By [Lemma 2.34](#), the statement of the lemma holds for $A \otimes_k k'$. But each generic point of an irreducible component of $\text{Spec}^G(A)$ can be lifted to a generic point of an irreducible component in $\text{Spec}^G(A \otimes_k k')$. \square

4. Graded Riemann–Zariski spaces

Let G be an Abelian group. Let k be a G -graded field and K/k be a G -graded field extension.

Definition 4.1. We let $\mathbf{P}_{K/k}$ denote the set of G -graded valuation rings \mathcal{O} of K with G -graded fraction field K such that $k \subseteq \mathcal{O}$. If there is a risk of confusion, we write $\mathbf{P}_{K/k}^G$ instead.

We endow $\mathbf{P}_{K/k}$ with the weakest topology with respect to which $\{\mathcal{O} \in \mathbf{P}_{K/k} : f \in \mathcal{O}\}$ is open for any homogeneous element $f \in K$.

The space $\mathbf{P}_{K/k}$ is called the *Riemann–Zariski space* of K/k .

Given an inclusion of G -graded fields $i : L \rightarrow K$ over k , we have a natural continuous map $i^\# : \mathbf{P}_{K/k} \rightarrow \mathbf{P}_{L/k}$ sending \mathcal{O} to $i^{-1}(\mathcal{O}) \cap K$.

Given $X \subseteq \mathbf{P}_{K/k}$ and $A \subseteq K$ consisting of homogeneous elements, we write

$$\begin{aligned} X\{A\} &:= \{\mathcal{O} \in X : f \in \mathcal{O} \text{ for all non-zero } f \in A\}, \\ X\{\{A\}\} &:= \{\mathcal{O} \in X : f \in \mathfrak{m}_{\mathcal{O}} \text{ for all non-zero } f \in A\}, \end{aligned}$$

where $\mathfrak{m}_{\mathcal{O}}$ is the maximal G -homogeneous ideal of \mathcal{O} . When A consists of finitely many elements f_1, \dots, f_n , we will write $X\{f_1, \dots, f_n\}$ and $X\{\{f_1, \dots, f_n\}\}$ instead. When $A \subseteq K$ consists of non-homogeneous elements as well, $X\{A\}$ means $X\{B\}$, where B is the set of homogeneous elements in A .

Definition 4.2. An *affine subset* of $\mathbf{P}_{K/k}$ is a subset of $\mathbf{P}_{K/k}$ of the form: $\mathbf{P}_{K/k}\{F\}$ for some finite set F of homogeneous elements in K .

Lemma 4.3. Let $X \subseteq \mathbf{P}_{K/k}$ and $f \in K$ be a non-zero homogeneous element. Then

$$X \setminus X\{f\} = X\{\{f^{-1}\}\}.$$

PROOF. We first observe that $X\{f\} \cap X\{f^{-1}\} = \emptyset$. Otherwise, let \mathcal{O} be a G -graded valuation ring in this intersection, then $f \in \mathcal{O}$ and $f^{-1} \in \mathfrak{m}_{\mathcal{O}}$. So $1 \in \mathfrak{m}_{\mathcal{O}}$, which is a contradiction.

To show that $X\{f\} \cup X\{f^{-1}\} = X$, we may assume that $X = \mathbf{P}_{K/k}$. Let $\mathcal{O} \in \mathbf{P}_{K/k}$. We need to show that $f \in \mathcal{O}$ or $f^{-1} \in \mathfrak{m}_{\mathcal{O}}$.

By definition, either $f \in \mathcal{O}$ or $f^{-1} \in \mathcal{O}$. We may assume that $f \notin \mathcal{O}$ and $f^{-1} \in \mathcal{O}$. If $f^{-1} \notin \mathfrak{m}_{\mathcal{O}}$, then f^{-1} is invertible in \mathcal{O} by [Lemma 2.33](#). In particular, $f \in \mathcal{O}$, which is a contradiction. \square

Lemma 4.4. Let $A \subseteq K$ be a subset of K , then $\mathbf{P}_{K/k}\{A\}$ is quasi-compact.

PROOF. By our convention, we may assume that A consists of homogeneous elements.

We may replace A by the G -graded subring generated of K generated by A . So we may assume that A is a G -graded subring of K .

Write $X = \mathbf{P}_{K/k}\{A\}$. By definition, a sub-base for the topology on X is given by $X\{f\}$ for all non-zero homogeneous elements $f \in K$.

By Alexander sub-base theorem and [Lemma 4.3](#), in order to show that X is quasi-compact, it suffices to show that if $F \subseteq K$ consists of homogeneous elements and if for any finite subset $F_0 \subseteq F$, $X\{F_0\} \neq \emptyset$, then $X\{F\}$ is non-empty. We assume by contrary that $X\{F\}$ is empty.

Let B be the G -graded subring of K generated by A and F . Let \mathfrak{m} be the G -homogeneous ideal of B generated by elements in F . We claim that $\mathfrak{m} = B$. Otherwise, let \mathfrak{p} be a maximal G -homogeneous ideal of B containing \mathfrak{m} , then we can find a G -graded valuation subring \mathcal{O} of K dominating $B_{\mathfrak{p}}^G$. The existence of \mathcal{O} is guaranteed by [Proposition 2.39](#). It follows that $\mathcal{O} \in \{F\}$.

We write $1 = b_1 f_1 + \dots + b_n f_n$ for some $n \in \mathbb{Z}_{>0}$, $b_1, \dots, b_n \in B$ and $f_1, \dots, f_n \in F$. Then $X\{f_1, \dots, f_n\}$ is empty. \square

Lemma 4.5. Let $A \subseteq B \subseteq K$ be G -graded k -subalgebras of K . Assume that both A and B are finitely generated over k . Then the following are equivalent:

- (1) $\mathbf{P}_{K/k}\{A\} = \mathbf{P}_{K/k}\{B\}$;
- (2) B is finite over A ;
- (3) B is integral over A .

PROOF. (3) \implies (1): Let $\mathcal{O} \in \mathbf{P}_{K/k}\{A\}$ and $x \in B$ a non-zero homogeneous element, we need to show that $x \in \mathcal{O}$. If not, $x^{-1} \in \mathfrak{m}_{\mathcal{O}}$ by [Lemma 4.3](#). As x is integral over A , we can find $n \in \mathbb{Z}_{>0}$, homogeneous elements $a_1, \dots, a_n \in A$ such that

$$b^n + a_1 b^{n-1} + \dots + a_n = 0$$

by [Proposition 2.18](#). So

$$1 = -b^{-n} (a_1 b^{n-1} + \dots + a_n) \in \mathfrak{m}_{\mathcal{O}},$$

which is a contradiction.

(1) \implies (3): Suppose $x \in B$ is a homogeneous element which is not integral over A . The existence of x is guaranteed by [Proposition 2.18](#). Then x^{-1} is not invertible in $C = A[1/x]$: otherwise, we can find $n \in \mathbb{N}$, $a_1, \dots, a_n \in A$ such that

$$(a_n x^{-n} + a_{n-1} x^{1-n} + \dots + a_0) x^{-1} = 1$$

or equivalently,

$$x^{n+1} = a_0 x^n + \dots + a_n.$$

This contradicts the fact that x is not integral. In particular, there is a maximal G -homogeneous ideal \mathfrak{p} containing x^{-1} by [Proposition 2.30](#). Let \mathcal{O} be a G -graded valuation ring of K dominating $C_{\mathfrak{p}}^G$, whose existence is guaranteed by [Corollary 2.40](#). But then x^{-1} lies in the maximal ideal of \mathcal{O} and hence $x \notin \mathcal{O}$ by [Lemma 4.3](#). It follows that $B \not\subseteq \mathcal{O}$.

(2) \equiv (3): This followss from [\[Stacks, Tag 02JJ\]](#).

□

Definition 4.6. Let X be an open subset of $\mathbf{P}_{K/k}$. A *Laurent covering* of X is a covering of X of the form

$$\{X\{f_1^{\epsilon_1}, \dots, f_n^{\epsilon_n}\} : \epsilon_i = \pm 1 \text{ for } i = 1, \dots, n\},$$

where $n \in \mathbb{Z}_{>0}$, $f_1, \dots, f_n \in K$ are homogeneous. We say the Laurent covering is *generated by* f_1, \dots, f_n .

Definition 4.7. Let X be an open subset of $\mathbf{P}_{K/k}$. A *rational covering* of X is a covering of the form:

$$\left\{X \left\{ \frac{f_1}{f_i}, \dots, \frac{f_n}{f_i} \right\} : i = 1, \dots, n \right\},$$

where $n \in \mathbb{Z}_{>0}$, $f_1, \dots, f_n \in K$ are non-zero homogeneous elements. We say the rational covering is *generated by* f_1, \dots, f_n .

Lemma 4.8. Let X be an open subset of $\mathbf{P}_{K/k}$. Any finite covering \mathcal{U} of X by open subsets of the form $X\{A\}$ for some finite set of homogeneous elements $A \subseteq K$ has a refinement which is a Laurent covering of X .

PROOF. Step 1. We show that \mathcal{U} admits a refinement by a rational covering. We may assume that there is $n \in \mathbb{Z}_{>0}$ such that \mathcal{U} consists of U_1, \dots, U_m below:

$$U_i = X\{f_{i1}, \dots, f_{in}\}$$

with $f_{ij} \in K$ being non-zero and homogeneous for $i = 1, \dots, m$ and $j = 1, \dots, n$. In addition, we may assume that $f_{in} = 1$ for $i = 1, \dots, m$.

Let

$$J := \left\{ \alpha = (\alpha_1, \dots, \alpha_m) \in \mathbb{N}^m : 1 \leq \alpha_i \leq n \text{ for } i = 1, \dots, m; \max_{i=1, \dots, m} \alpha_i = n \right\}.$$

We claim that the rational covering generated by $g_\alpha = f_{1\alpha_1} \cdots f_{m\alpha_m}$ with $\alpha = (\alpha_1, \dots, \alpha_m) \in J$ refines \mathcal{U} .

Given $\alpha = (\alpha_1, \dots, \alpha_m) \in J$, we consider the set

$$V_\alpha = X\{g_\beta/g_\alpha : \beta \in J\}.$$

Let $i \in \{1, \dots, m\}$ such that $j_i = n$. We claim that

$$V_\alpha \subseteq U_i.$$

Suppose it is not the case, let $\mathcal{O} \in V_\alpha$ not lying in U_i , we need to verify that $f_{ik} \in \mathcal{O}$ for $k = 1, \dots, n$. Take $l \neq i$ so that $\mathcal{O} \in U_l$. So $f_{lj_l} \in \mathcal{O}$. On the other hand, if $\beta \in J$ with $\beta_l = n$ and $\beta_k = \alpha_k$ for $k \neq l$, we have $f_{lj_l}^{-1} = g_\beta/g_\alpha \in \mathcal{O}$, so f_{lj_l} is invertible in \mathcal{O} .

Fix $k = 1, \dots, n$, consider $\gamma \in J$ given by $\gamma_i = k$, $\gamma_l = n$ and $\gamma_p = \alpha_p$ otherwise. Then $g_\gamma/g_\alpha = f_{ik}/f_{lj_l} \in \mathcal{O}$ and $f_{ik} \in \mathcal{O}$.

Step 2. It remains to show that each rational covering generated by non-zero homogeneous elements $f_1, \dots, f_n \in K$ admits a refinement by Laurent coverings.

We claim that the Laurent covering of X generated by $g_{ij} = f_i/f_j$ with $1 \leq i < j \leq n$ refines the given covering. Let V be a subset of the form

$$V = X\{g_{ij}^{\epsilon_{ij}} : 1 \leq i < j \leq n\}$$

for some $\epsilon_{ij} = \pm 1$ for $1 \leq i < j \leq n$. We need to show that V is contained in a set in \mathcal{U} .

For $1 \leq i, j \leq n$ and $i \neq j$, we write $i \preceq j$ if $i < j$ and $\epsilon_{ij} = 1$ or $i > j$ and $\epsilon_{ji} = -1$. This is an ordering on $\{1, \dots, n\}$. Choose a maximal element i . Then $f_j/f_i \in \mathcal{O}$ for all $\mathcal{O} \in V$, so

$$V \subseteq X\{f_1/f_i, \dots, f_n/f_i\}.$$

□

5. Strictness in graded Riemann–Zariski spaces

In this section, graded will mean $\mathbb{R}_{>0}$ -graded unless we explicitly state the grading. Similarly, a graded Riemann–Zariski space without specifying the grading means the $\mathbb{R}_{>0}$ -graded one.

Let H be a subgroup of $\mathbb{R}_{>0}$. Fix graded field extension K/k .

Definition 5.1. Consider the natural continuous map

$$\psi_{K/k}^H : \mathbf{P}_{K/k} \rightarrow \mathbf{P}_{K^H/k^H}$$

defined by sending a graded valuation ring \mathcal{O} to \mathcal{O}^H .

A quasi-compact open subset U of $\mathbf{P}_{K/k}$ is *H-strict* if U is the preimage of some quasi-compact open subset U' of \mathbf{P}_{K^H/k^H} .

Lemma 5.2. Let $U \subseteq \mathbf{P}_{K/k}$ be a quasi-compact open subset. The following are equivalent:

- (1) U is *H-strict*;
- (2) U is $\sqrt{\rho(k^\times) \cdot H}$ -strict.

PROOF. (1) \implies (2): This is trivial.

(2) \implies (1): Let $S \subseteq L^{\sqrt{\rho(k^\times) \cdot H}}$ be a finite set. For any $f \in S$, we can find a non-zero homogeneous element $a_f \in k$ and $n_f \in \mathbb{Z}_{>0}$ such that $a_f f^{n_f} \in L^H$. We let $S' = \{a_f f^{n_f}\}_{f \in S}$, then

$$\mathbf{P}_{L/K}\{S\} = \mathbf{P}_{L/K}\{S'\}.$$

□

Lemma 5.3. Let A be a graded k -subalgebra of K . Then

$$\psi_{K/k}^H(\mathbf{P}_{K/k}\{A\}) = \mathbf{P}_{K^H/k^H}\{A^H\}.$$

In particular, $\psi_{K/k}^H$ is a surjective open map.

PROOF. The inclusion

$$\psi_{K/k}^H(\mathbf{P}_{K/k}\{A\}) \subseteq \mathbf{P}_{K^H/k^H}\{A^H\}$$

is obvious. Conversely, let $\mathcal{O} \in \mathbf{P}_{K^H/k^H}\{A^H\}$. We set

$$B = A \cdot \mathcal{O}.$$

Observe that for $h \in H$, $B_h = A_h$, so

$$B \cap K^H = \mathcal{O}, \quad \mathfrak{m}_{\mathcal{O}} B \cap \mathcal{O} = \mathfrak{m}_{\mathcal{O}}.$$

In particular, there is a prime homogeneous ideal \mathfrak{p} of B with $\mathfrak{p} \cap \mathcal{O} = \mathfrak{m}_{\mathcal{O}}$. Take a graded valuation ring $\mathcal{O}' \in \mathbf{P}_{K/k}$ dominating $B_{\mathfrak{p}}^{\mathbb{R}_{>0}}$. The existence of \mathcal{O}' follows from [Corollary 2.40](#). Moreover, $\mathcal{O}' \cap K_H = \mathcal{O}$ the left-hand side dominates \mathcal{O} . But then

$$\mathcal{O}' \in \mathbf{P}_{K/k}\{A\}$$

and $\psi_{K/k}^H(\mathcal{O}') = \mathcal{O}$. \square

Corollary 5.4. Suppose that $n \in \mathbb{N}$ and f_1, \dots, f_n is a finite set of non-zero homogeneous elements in K . Then the following are equivalent:

- (1) $\mathbf{P}_K\{f_1, \dots, f_n\}$ is H -strict;
- (2) $\rho(f) \in \sqrt{\rho(k^\times) \cdot H}$.

PROOF. (2) \implies (1): This follows from [Lemma 5.2](#).

(2) \implies (1): Let A be the graded k -algebra generated by f_1, \dots, f_n . By [Lemma 5.3](#), $\mathbf{P}_{K/k}\{f_1, \dots, f_n\} = \mathbf{P}_{K/k}\{A\}$ is H -strict if and only if it coincides with $\mathbf{P}_{K/k}\{A^H\}$. By [Lemma 4.5](#), the latter is equivalent to that A is integral over A_H . But then it is clear that

$$\rho(A) \subseteq \sqrt{\rho(A_H)}$$

and (1) follows. \square

Corollary 5.5. The natural map

$$\mathbf{P}_{K\sqrt{\rho(k^\times) \cdot H}/k} \rightarrow \mathbf{P}_{K^H/k^H}$$

is a homeomorphism.

PROOF. We may assume that $\rho(K^\times) \subseteq \sqrt{\rho(k^\times) \cdot H}$ and identify the given map with $\psi_{K/k}^H$. We know that $\psi_{K/k}^H$ is open by [Lemma 5.3](#). It is continuous by construction. So it remains to argue that $\psi_{K/k}^H$ is bijective.

By [Lemma 5.3](#) again, we know that $\psi_{K/k}^H$ is surjective. On the other hand, if $|\bullet|$ is the valuation corresponding to $\mathcal{O} \in \mathbf{P}_{K^H/k^H}$, it is clear that the extension to $K = K\sqrt{\rho(k^\times) \cdot H}$ is unique: if f is a non-zero homogeneous element in K , then we can find a non-zero homogeneous element $a \in K$, a non-zero homogeneous element $g \in K^H$ and an integer $n \in \mathbb{Z}_{>0}$ such that

$$f^n = ag.$$

The valuation is uniquely determined at a and g , hence so is its value at f . \square

Proposition 5.6. The fibers of

$$\psi_{K/k}^H : \mathbf{P}_{K/k} \rightarrow \mathbf{P}_{K^H/k^H}$$

are connected.

PROOF. Let $\mathcal{O} \in \mathbf{P}_{K^H/k^H}$ and $X = \psi_{K/k}^{H,-1}(\{\mathcal{O}\})$. We need to show that X is connected.

Assume to the contrary that X is the disjoint union of two non-empty open subsets U and V .

Step 1. We show that X is quasi-compact.

We set

$$\begin{aligned} Y &= \{\mathcal{O}' \in \mathbf{P}_{K^H/k^H} : \mathcal{O}' \supseteq \mathcal{O}\}, \\ X_Y &= \{\mathcal{O}' \in \mathbf{P}_{K/k} : \mathcal{O}' \supseteq \mathcal{O}\}. \end{aligned}$$

In other words, $X_Y = \psi_{K/k}^{H,-1}(Y)$. Observe that Y and X_Y are both quasi-compact by [Lemma 4.4](#).

Observe that \mathcal{O} is a closed point in Y :

$$Y \setminus \{\mathcal{O}\} = \bigcup_f Y\{f\},$$

where f runs over all non-zero homogeneous elements of K not lying in \mathcal{O} . It follows that X is closed in X_Y . In particular, X is quasi-compact.

In particular, U and V are both quasi-compact.

Step 2. We reduce to the case where $H \supseteq \rho(k^\times)$, $\sqrt{H} = H$ and $\rho(K^\times)/H$ is finitely generated.

By Step 1, U and V can be both covered by finitely many sets of the form $X\{f_1, \dots, f_n\}$ with $f_1, \dots, f_n \in K$ being some homogeneous elements. Let H' be the subgroup of $\mathbb{R}_{>0}$ generated by H and $\rho(f_i)$ for the f_i 's to guarantee that the inverse image of $\{\mathcal{O}\}$ in $\mathbf{P}_{K^{H'}/k}$ is not connected. It suffices to prove the theorem with $K^{H'}$ in place of K . Moreover, by [Corollary 5.5](#), we may assume that $H \supseteq \rho(k^\times)$ and $\sqrt{H} = H$.

In particular, $\rho(K^\times)/H$ is locally free of finite rank. Let n be its rank.

Step 3. We provide a contradiction when $n = 1$.

We claim that in this case, $K = K^H[g^{-1}T, gT^{-1}]$ for some $g \in \rho(K^\times) \setminus H$.

In fact, let $g \in \rho(K^\times) \setminus H$ and take $f \in K_g$. Then we have an obvious $\rho(K^\times)$ -graded ring homomorphism

$$K^H[g^{-1}T, gT^{-1}] \rightarrow K$$

sending T to f . But $K^H[g^{-1}T, gT^{-1}]$ is clearly a $\rho(K^\times)$ -graded field. So this map is injective. It is an isomorphism by [Lemma 2.34](#).

Observe that a basis of the topology on X is given by sets of the form $X\{aT^i, bT^{-j}\}$ with $a, b \in K^H$ and $i, j \in \mathbb{Z}_{>0}$. Up to replacing aT^i by a^jT^{ij} and bT^{-j} by b^iT^{-ij} , we may assume that $i = j$.

We cover U and V by W_1, \dots, W_l and W_{l+1}, \dots, W_m respectively such that

$$W_i = X\{a_iT^{k_i}, b_iT^{-k_i}\},$$

where $a_i, b_i \in K^H$ and $k_i \in \mathbb{Z}_{>0}$ for $i = 1, \dots, m$. By the same argument as above, we may guarantee that $k_1 = \dots = k_m$, and we call this common value k .

Let $|\bullet|$ be the valuation determined by \mathcal{O} , we may assume that $|a_1| \leq |a_i|$ for all $i = 1, \dots, m$. Then U, V are both contained in $X\{a_1T^k\}$ so $X\{a_1T^k\} = X$ and $a_1 = 0$.

If $W_i \cap W_1 \neq \emptyset$ for some $i = 2, \dots, m$, then $a_ib_1 \in \mathcal{O}$ and $W'_1 := W_1 \cup W_i$ is the same as $X\{\max\{b_1, b_i\}T^{-k}\}$, where $\max\{b_1, b_i\}$ is one of b_1 and b_i such that the valuation under $|\bullet|$ is smaller. We could remove W_i from the list and replace W_1 with W'_1 . Repeating this process, we may guarantee that W_1 is disjoint with all other W_i 's.

But then W_1 is an open and closed subset of X contained in U . So $b_1 \neq 0$. We claim that the set $W_1 = X\{b_1T^{-k}\}$ is not closed: consider

$$\mathcal{O}'_1 := \{\mathcal{O}[xT^k, yT^{-k}] : x, y \text{ are homogeneous elements in } K \text{ such that } |y| < |b_1|, |x| \leq |b_1|^{-1}\}$$

and

$$\mathcal{O}'_2 := \{\mathcal{O}[xT^k, yT^{-k}] : x, y \text{ are homogeneous elements in } K \text{ such that } |y| \leq |b_1|, |x| \leq |b_1|^{-1}\}.$$

Extend them to graded valuation rings \mathcal{O}_1 and \mathcal{O}_2 of K . These extensions exist and are unique by [Corollary 5.5](#). Then $\mathcal{O}_1 \notin W_1$ while $\mathcal{O}_2 \in W_1$. But \mathcal{O}_2 contains \mathcal{O}_1 so \mathcal{O}_1 is a specialization of \mathcal{O}_2 . This is a contradiction.

Step 4. We argue the general case by induction on $n > 1$. Assume that we have shown the result for smaller n .

Choose a subgroup L of $\rho(K^\times)$ such that $L \supseteq H$ and $\rho(K^\times)/L \cong \mathbb{Z}$. We can factorize $\psi_{K/k}^H$ as

$$\mathbf{P}_{K/k} \xrightarrow{\psi_{K/k}^L} \mathbf{P}_{K^L/k} \xrightarrow{\psi_{K^L/k}^H} \mathbf{P}_{K^H/k}.$$

Both maps have connected fibers, hence so is their composition. \square

6. The birational categories

In this section, graded will mean $\mathbb{R}_{>0}$ -graded unless we explicitly state the grading.

Fix graded field extension K/k . Let H be a subgroup of $\mathbb{R}_{>0}$.

Definition 6.1. The category $\mathcal{T}_{K/k}$ is the full subcategory of the category $\mathcal{Top}/\mathbf{P}_{K/k}$ consisting of objects $X \rightarrow \mathbf{P}_{K/k}$ satisfying

- (1) X is quasi-compact and quasi-separated;
- (2) $X \rightarrow \mathbf{P}_{K/k}$ is a local homeomorphism.

We will also say X is an object of $\mathcal{T}_{K/k}$.

Let X be an object of $\mathcal{T}_{K/k}$. A *chart* of X is a quasi-compact open subset U of X such that $U \rightarrow \mathbf{P}_{K/k}$ is a homeomorphism onto an open subset of $\mathbf{P}_{K/k}$. An *atlas* is a finite covering of X by charts.

Recall that a topological space is quasi-compact if each quasi-compact open subset is retrocompact.

Example 6.2. Each quasi-compact open subset U of $\mathbf{P}_{K/k}$ can be identified with an object in $\mathcal{T}_{K/k}$ using the natural inclusion.

The only non-trivial point is to show that U is quasi-separated. For this, it suffices to show that $\mathbf{P}_{K/k}$ is quasi-separated. This follows from the fact that the intersection of two affine open subsets is still affine.

Definition 6.3. Let X be an object of $\mathcal{T}_{K/k}$.

A chart U of X is *H-strict* if its image in $\mathbf{P}_{K/k}$ is *H-strict*.

An atlas $\{U_i\}_{i \in I}$ of X is *H-strict* if $U_i, U_i \cap U_j$ are *H-strict* for all $i, j \in I$.

We say X is *H-strict* if it admits an *H-strict* atlas.

A quasi-compact open subset of X is *H-strict* if it is *H-strict* as an object of $\mathcal{T}_{K/k}$.

The notion of *H-strictness* of a quasi-compact open subset of $\mathbf{P}_{K/k}$ in [Definition 6.3](#) is the same as in [Definition 5.1](#).

Observe that X is *H-strict* if and only if

$$X = Y \times_{\mathbf{P}_{K^H/k^H}} \mathbf{P}_{K/k}$$

for some object Y in \mathbf{P}_{K^H/k^H} . The fiber product is taken in \mathcal{Top} . We will say X is the *base change* of Y to K/k in this case. The base change is clearly functorial. The natural map $X \rightarrow Y$ is denoted by $\psi_{K/k}^H$.

Proposition 6.4. The base change $\mathcal{T}_{K^H/k^H} \rightarrow \mathcal{T}_{K/k}$ is fully faithful.

In particular, for each H -strict object $X \in \mathcal{T}_{K/k}$, there is a unique object (up to canonical isomorphisms) \mathcal{T}_{K^H/k^H} whose base change to K/k is X . We will denote this object by X^H .

PROOF. Let $Y, Y' \in \mathcal{T}_{K^H/k^H}$ and X, X' be their base changes to K/k . We let $f : X \rightarrow X'$ be a morphism in $\mathcal{T}_{K/k}$.

We are looking for a dotted morphism making the diagram below commutative:

$$\begin{array}{ccccc} X & \xrightarrow{\psi_{K/k}^H} & Y & \longrightarrow & \mathbf{P}_{K^H/k^H} \\ \downarrow f & & \vdots & \nearrow & \\ X' & \xrightarrow{\psi_{K/k}^H} & Y' & & \end{array}$$

As $\psi_{K/k}^H : X \rightarrow Y$ is open and surjective by [Lemma 5.3](#), it suffices to show that set-theoretically the dotted map exists and is unique.

Let Z be a fiber of $\psi_{K/k}^H : X \rightarrow Y$, then Z is connected by [Proposition 5.6](#). The image of Z in \mathbf{P}_{K^H/k^H} is a single point, so the image of Z in Y' is a discrete set. As Z is connected, its image in Y' is a single point. This shows the existence and uniqueness of the dotted map. \square

Proposition 6.5. Let F/K be a graded extension of fields. Consider an object Y (resp. X) in $\mathbf{P}_{F/k}$ (resp. $\mathbf{P}_{K/k}$) and a continuous map $Y \rightarrow X$ making the following diagram commutative:

$$\begin{array}{ccc} Y & \longrightarrow & \mathbf{P}_{F/k} \\ \downarrow & & \downarrow \\ X & \longrightarrow & \mathbf{P}_{K/k} \end{array},$$

where the horizontal maps are the maps in the definition of X and Y , the map on the right-hand side is the restriction map. We assume that Y and X are H -strict, then there is a unique continuous map $Y^H \rightarrow X^H$ making the following diagram commutative:

$$\begin{array}{ccccc} & Y & \longrightarrow & \mathbf{P}_{F/k} & \\ & \swarrow & \downarrow & \swarrow & \downarrow \\ Y^H & \longrightarrow & \mathbf{P}_{F^H/k^H} & & \\ & \downarrow & \downarrow & & \downarrow \\ & X & \longrightarrow & \mathbf{P}_{K/k} & \\ & \swarrow & \downarrow & \swarrow & \downarrow \\ & X^H & \longrightarrow & \mathbf{P}_{K^H/k^H} & \end{array}.$$

PROOF. The uniqueness follows from the surjectivity of $Y \rightarrow Y^H$. The latter follows from [Lemma 5.3](#).

The existence follows from the same arguments as [Proposition 6.4](#). \square

Proposition 6.6. Let X be an H -strict object of $\mathcal{T}_{K/k}$, then there is a bijection from the set of quasi-compact open subsets of X^H to the set of H -strict quasi-compact open subsets of X .

The forward direction sends V to $V \times_{X^H} X$.

PROOF. It suffices to establish a quasi-inverse functor.

Let U be an H -strict quasi-compact open subset of X . By [Proposition 6.4](#), we can find a continuous map $U^H \rightarrow X^H$ inducing the inclusion map $U \rightarrow X$ by base change. Consider the commutative diagram

$$\begin{array}{ccccc} U & \longrightarrow & X & \longrightarrow & \mathbf{P}_{K/k} \\ \downarrow & & \downarrow & & \downarrow \\ U^H & \longrightarrow & X^H & \longrightarrow & \mathbf{P}_{K/k}^H \end{array} .$$

Observe that $U^H \rightarrow X^H$ is injective as $U \rightarrow X$ is. So U^H is a quasi-compact open subset of X^H . This construction is functorial in U .

This functor is clearly quasi-inverse to the given functor. \square

7. The birational category à la Temkin

The gradings refer to $\mathbb{R}_{>0}$ -grading in this section. Let k be a graded field.

Definition 7.1. The category bir_k is defined as follows:

- (1) the objects are pairs (X, K) , where K is a graded field extension of k and X is an object in $\mathcal{T}_{K/k}$;
- (2) a morphism

$$(X, K)$$

to (Y, L) is a pair (h, i) , where $h : X \rightarrow Y$ is a continuous map and $i : L \rightarrow K$ is an embedding of G -graded fields such that the following diagram commutes:

$$\begin{array}{ccc} X & \longrightarrow & \mathbf{P}_{K/k} \\ \downarrow h & & \downarrow i^\# \\ Y & \longrightarrow & \mathbf{P}_{L/k} \end{array} ;$$

- (3) the composition of morphisms (h, i) and (h', i') is $(h \circ h', i \circ i')$.

We will always omit i from our notations.

We observe that there is a final object in bir_k : X is a single point, $K = k$.

Definition 7.2. Let $(X, K), (Y, L) \in \text{bir}_k$ and $h : (X, K) \rightarrow (Y, L)$ be a morphism. We say the morphism is *separated* (resp. *proper*) if $X \rightarrow Y \times_{\mathbb{P}_{L/k}} \mathbb{P}_{K/k}$ is injective (resp. bijective).

Here the fiber product is in the category of topological spaces.

We say $(X, K) \in \text{bir}_k$ is *separated* (resp. *proper*) if the morphism to the final object is separated (resp. proper).

Observe that $X \rightarrow Y \times_{\mathbb{P}_{L/k}} \mathbb{P}_{K/k}$ is automatically an open embedding (resp. a homeomorphism).

8. Miscellany

Proposition 8.1. Let R be a noetherian N-2 integral domain. Let $\psi : R \rightarrow S$ be a ring homomorphism such that S is reduced, torsion-free as R -module and has finite rank as R -module. Then ψ is finite.

[BGR84, Page 122]. Reproduce the argument later.

PROOF. As ψ is injective by assumption, we may assume that R is a subring of S and ψ is identity. The ring $S_{R \setminus \{0\}} = \text{Frac } S$ is a finite-dimensional reduced $\text{Frac } R$ -algebra, hence as a ring, $\text{Frac } S$ is the product of finitely many finite field extensions of $\text{Frac } R$, say K_1, \dots, K_t . As R is N-2, the integral closure R_i of R in K_i is finite as R -module for $i = 1, \dots, t$. As S is integral over R , we have

$$S \subseteq R_1 \times \cdots \times R_t.$$

Since R is noetherian, we conclude that S is finite as R -module. \square

Lemma 8.2. Let R be a commutative ring. A polynomial $a_0 + a_1X + \cdots + a_nX^n \in R[X]$ is a unit if and only if a_0 is a unit in R and a_1, \dots, a_n are nilpotents.

Bibliography

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