

CATEGORICAL CHARACTERIZATION OF STRICT MORPHISMS OF FS LOG SCHEMES

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ABSTRACT. In the present paper, we study a categorical characterization of strict morphisms of fs log schemes. In particular, we prove that strictness of morphisms of fs log schemes is preserved by an arbitrary equivalence of categories between suitable categories of fs log schemes. The main result of the present paper leads us to a relatively simple alternative proof of a result on a categorical representation of fs log schemes proved by S. Mochizuki.

INTRODUCTION

Let S be an *fs log scheme* whose underlying scheme is *locally noetherian*. Then, by considering *noetherian fs log schemes of finite type* over S , we obtain a category $\mathrm{Sch}^{\mathrm{log}}(S)$ [cf. §0, Log Schemes]. In the present paper, we discuss a categorical characterization of *strict morphisms* in this category $\mathrm{Sch}^{\mathrm{log}}(S)$. Our main result is as follows [cf. Theorem 3.7]:

Theorem. *Let S and T be fs log schemes whose underlying schemes are locally noetherian,*

$$\phi: \mathrm{Sch}^{\mathrm{log}}(S) \xrightarrow{\sim} \mathrm{Sch}^{\mathrm{log}}(T)$$

*an equivalence of categories, and f a morphism in $\mathrm{Sch}^{\mathrm{log}}(S)$. Then it holds that f is **strict** if and only if $\phi(f)$ is **strict**.*

The content of Theorem is in fact a formal consequence of a result of *S. Mochizuki* [i.e., [Mzk2], Theorem A]. Moreover, Mochizuki also proved that a result concerning a *categorical representation* of fs log schemes follows from Theorem, together with some arguments [cf. Remark 3.7.1]. In particular, the proof of the main theorem of the present paper may be regarded as an *alternative proof* of the categorical representation of fs log schemes already proved by Mochizuki.

Here, let us discuss the *differences* between the arguments of [Mzk2] and the present paper. In the present paper, by establishing [cf. Proposition 2.5] a categorical characterization of *fs log points* [i.e., fs log schemes whose underlying schemes are isomorphic to the spectra of fields], we obtain a *simple proof* of Theorem. In particular,

Mathematics Subject Classification. Primary 14A20; Secondary 14A15.

Key words and phrases. fs log scheme, strict morphism, fs log point.

(i) the proof of the present paper may be regarded as a *relatively simple alternative proof* of Theorem, as well as the categorical representation of fs log schemes, i.e., [Mzk2], Theorem A.

Next, as explained in [Mzk2], Introduction, the theory of [Mzk2] arose as an attempt to correct errors contained in the theory of [Mzk1] that was supposed to lead us to Theorem. By comparing [Mzk2] with the present paper from this point of view, one may find that

(ii) the argument of [Mzk1] [that contains errors] is *closer to the argument of the present paper* than the argument of [Mzk2].

On the other hand, let us observe that, in the proof of the present paper, one cannot avoid the use of the following two *existence results*:

- the existence of certain *non-separated* schemes in the category $\text{Sch}^{\log}(S)$ [cf. the proof of Lemma 2.4],
- the existence of *closed points of noetherian* schemes [cf., e.g., the proof of Proposition 2.5].

By contrast, there is no need to use the above two *existence results* in the arguments of [Mzk2]. As a result,

(iii) the arguments of the present paper only work under relatively restricted conditions, whereas the arguments of [Mzk2] *can be applied in more general situations*, e.g., even if one replaces the category $\text{Sch}^{\log}(S)$ [of noetherian fs log schemes of finite type over S] by, for instance, the category of [not necessarily noetherian] separated fs log schemes locally of finite type over S .

In the proof of Theorem, we prove, by applying *Hilbert's Theorem 90*, a *sufficient condition* [cf. Proposition 1.3, Remark 1.3.1] for an fs log point to be *quasi-split* [cf. Definition 1.2, (ii)]. In Appendix of the present paper, we also discuss, by considering *twisted versions of Hilbert's Theorem 90*, further such *sufficient conditions* [cf. Theorem A.5]. Note that the proof of Theorem does *not depend* on these further sufficient conditions obtained in Appendix.

0. NOTATIONS AND CONVENTIONS

Monoids: We shall refer to a commutative semigroup with the unit element as a *monoid*. Let M be a monoid. Then we shall write $M^\times \subseteq M$ for the submonoid consisting of invertible elements of M , $\overline{M} \stackrel{\text{def}}{=} M/M^\times$, and M^{gp} for the groupification of M . Moreover,

- we shall say that M is *sharp* if M^\times has only the unit element;

- we shall say that M is *integral* if the natural homomorphism $M \rightarrow M^{\text{gp}}$ is injective [which thus implies that M may be regarded as a submonoid of M^{gp}];

- we shall say that M is *saturated* if M is integral, and, moreover, for each $x \in M^{\text{gp}}$, it holds that $x \in M$ if the submonoid of M^{gp} generated by x intersects nontrivially $M \subseteq M^{\text{gp}}$;

- we shall say that M is *fs* if M is finitely generated and saturated.

Let $h: M \rightarrow N$ be a homomorphism of fs monoids. Then we shall write $h^{\text{gp}}: M^{\text{gp}} \rightarrow N^{\text{gp}}$ for the homomorphism between the groupifications induced by h . Moreover,

- we shall say that h is *local* if $M^\times = h^{-1}(N^\times)$;

- we shall say that h is *exact* if $M = (h^{\text{gp}})^{-1}(N)$ [in M^{gp}].

Log Schemes: A basic reference for the notion of *log schemes* is [Kato].

Let X be an fs log scheme. Then we shall write $\overset{\circ}{X}$ for the underlying scheme of X , \mathcal{O}_X for the structure sheaf of $\overset{\circ}{X}$ [regarded as an étale sheaf], \mathcal{M}_X for the [étale] sheaf of monoids on $\overset{\circ}{X}$ which defines the log structure of X , and $\overline{\mathcal{M}}_X \stackrel{\text{def}}{=} \mathcal{M}_X / \mathcal{O}_X^\times$. Moreover,

- we shall say that X is *of log rank n* [where n is an integer] if the groupification [which is necessarily a *free module*] of the stalk of $\overline{\mathcal{M}}_X$ at any geometric point of $\overset{\circ}{X}$ is of rank n ;

- we shall say that X is an *fs log point* if $\overset{\circ}{X}$ is isomorphic to the spectrum of a field;

- we shall say that X is a *trivial log point* if X is an fs log point and of log rank 0;

- we shall say that X is a *standard log point* if X is an fs log point and of log rank 1.

Let $f: X \rightarrow Y$ be a morphism of log schemes. Then we shall write $\overset{\circ}{f}: \overset{\circ}{X} \rightarrow \overset{\circ}{Y}$ for the underlying morphism of schemes of f . Moreover,

- we shall say that f is *strict* if the natural homomorphism $\overset{\circ}{f}^{-1}\overline{\mathcal{M}}_Y \rightarrow \overline{\mathcal{M}}_X$ is an isomorphism;

• we shall say that f is *exact* if the homomorphism [of fs monoids] obtained by considering the stalk of the homomorphism $f^{-1}\overline{\mathcal{M}}_Y \rightarrow \overline{\mathcal{M}}_X$ at any geometric point of $\overset{\circ}{X}$ is exact.

Let S be an *fs log scheme* whose underlying scheme $\overset{\circ}{S}$ is *locally noetherian*. Then we shall write

$$\text{Sch}^{\log}(S)$$

for the category defined as follows: An object of $\text{Sch}^{\log}(S)$ is a *morphism of log schemes* $X \rightarrow S$, where X is an *fs log scheme* whose underlying scheme is *noetherian*, whose underlying morphism of schemes is *of finite type*. A morphism in $\text{Sch}^{\log}(S)$ [from an object $X \rightarrow S$ to an object $Y \rightarrow S$] is a *morphism of log schemes* $X \rightarrow Y$ lying over S [whose underlying morphism of schemes is necessarily *of finite type*]. To simplify the exposition, we shall often refer to the domain X of an arrow $X \rightarrow S$ which is an object of $\text{Sch}^{\log}(S)$ as an “object of $\text{Sch}^{\log}(S)$ ”.

We shall say that a morphism in $\text{Sch}^{\log}(S)$ is an *fs* (respectively, a *trivial*; a *standard*) *log point* if the domain of the morphism is an fs (respectively, a *trivial*; a *standard*) *log point*.

1. CHARACTERIZATION OF TRIVIAL AND STANDARD LOG POINTS

In the present §1, we give a categorical characterization of *trivial and standard log points* [cf. Proposition 1.7 below]. In the present §1, let S be an fs log scheme whose underlying scheme is *locally noetherian*.

First, let us prove some facts on *sharp fs monoids*:

Lemma 1.1. *Let M be a sharp fs monoid. Write $V \stackrel{\text{def}}{=} M^{\text{gp}} \otimes_{\mathbb{Z}} \mathbb{Q}$ and $r \stackrel{\text{def}}{=} \dim_{\mathbb{Q}}(V)$. Then the following hold:*

(i) *For each $x \in M^{\text{gp}} \setminus \{0\}$, there exists a **local** homomorphism $h: M \rightarrow \mathbb{N}$ such that $h^{\text{gp}}(x) \neq 0$.*

(ii) *Let $L \subseteq V$ be a nonzero \mathbb{Q} -subspace. Then there exist r **local** homomorphisms $h_1, \dots, h_r: M \rightarrow \mathbb{N}$ which satisfy the following two conditions:*

(1) *The homomorphism $h^{\text{gp}}: M^{\text{gp}} \rightarrow \bigoplus_{i=1}^r \mathbb{Z}$ induced by the [necessarily **local**] homomorphism $h: M \rightarrow \bigoplus_{i=1}^r \mathbb{N}$ given by mapping $x \in M$ to $(h_i(x))_{i=1}^r \in \bigoplus_{i=1}^r \mathbb{N}$ is **injective**.*

(2) *For every $1 \leq i \leq r$, L is **not contained** in the kernel of the \mathbb{Q} -linear homomorphism $h_i^{\mathbb{Q}}: V \rightarrow \mathbb{Q}$ induced by h_i .*

(iii) Suppose that a finite group G acts on M . Then there exists a homomorphism $h: M \rightarrow \mathbb{N}$ which is **local** and **G -equivariant** [with respect to the trivial action of G on \mathbb{N}].

(iv) In the situation of (iii), suppose that $r \geq 2$. Then there exists a submonoid $P \subseteq M^{\text{gp}}$ such that $M \subsetneq P$, and, moreover, P is **G -stable**, **sharp**, and **fs**.

Proof. Assertion (i) follows from [Mzk1], Lemma 2.5, (iii). Next, we verify assertion (ii). It follows immediately from assertion (i) that there exist r local homomorphisms $h_1, \dots, h_r: M \rightarrow \mathbb{N}$ which satisfy condition (1). Thus, there exists $1 \leq i_0 \leq r$ such that $L \not\subseteq \text{Ker}(h_{i_0}^{\mathbb{Q}})$. Then one verifies easily that, by replacing h_i [where $1 \leq i \leq r$] by $h_i + h_{i_0}$ (respectively, h_i) if $L \subseteq \text{Ker}(h_i^{\mathbb{Q}})$ (respectively, $L \not\subseteq \text{Ker}(h_i^{\mathbb{Q}})$), we obtain r homomorphisms of the desired type. This completes the proof of assertion (ii). Assertion (iii) follows [by considering the sum $\sum_{g \in G} h \circ g: M \rightarrow \mathbb{N}$ for some local homomorphism $h: M \rightarrow \mathbb{N}$] from assertion (i).

Finally, we verify assertion (iv). Let $h: M \rightarrow \mathbb{N}$ be a G -equivariant local homomorphism [cf. assertion (iii)]. Let $x \in M^{\text{gp}} \setminus M$ be such that $h^{\text{gp}}(x) \in \mathbb{N} \setminus \{0\}$. [Note that one may verify *existence* of such an x as follows: Assume that $(h^{\text{gp}})^{-1}(\mathbb{N} \setminus \{0\}) \subseteq M$. Let $a \in M \setminus M^\times$. Then since $h(a) \in \mathbb{N} \setminus \{0\}$ by the fact that h is local, it holds that $\text{Ker}(h^{\text{gp}}) + a \subseteq (h^{\text{gp}})^{-1}(\mathbb{N} \setminus \{0\}) \subseteq M$, which thus implies that $\text{Ker}(h^{\text{gp}}) + a \subseteq h^{-1}(\{h(a)\})$. On the other hand, since M is finitely generated, and h is local, one verifies easily that $h^{-1}(\{h(a)\})$ is finite. In particular, $\text{Ker}(h^{\text{gp}}) + a$, hence also $\text{Ker}(h^{\text{gp}})$, is finite, in contradiction to our assumption that $r \geq 2$.] Write $P \subseteq M^{\text{gp}}$ for the saturation of the submonoid $N \subseteq M^{\text{gp}}$ generated by $M \subseteq M^{\text{gp}}$ and the G -orbit of $x \in M^{\text{gp}}$. Then it is immediate that $M \subsetneq P$, and that P is G -stable and fs. Moreover, since h is G -equivariant, it follows from our choice of x that the image of every nontrivial element of N via h^{gp} is contained in $\mathbb{N} \setminus \{0\}$, which thus implies that N , hence also P , is sharp. This completes the proof of assertion (iv), hence also of Lemma 1.1. \square

Definition 1.2. Let X be an fs log point. Thus, $\overset{\circ}{X}$ is isomorphic to the spectrum of a field k . Let k_{sep} be a separable closure of k . Write $G_k \stackrel{\text{def}}{=} \text{Gal}(k_{\text{sep}}/k)$, $\bar{x} \rightarrow \overset{\circ}{X}$ for the geometric point determined by the separable closure k_{sep} , and $M \stackrel{\text{def}}{=} \mathcal{M}_{X, \bar{x}}$. [Thus, the G_k -monoid \overline{M} is naturally isomorphic to the G_k -monoid obtained by forming the stalk $\overline{\mathcal{M}}_{X, \bar{x}}$; moreover, \overline{M} is sharp and fs.]

(i) We shall say that X is *split* if the action of G_k on \overline{M} is trivial.

(ii) We shall say that X is *quasi-split* if the G_k -equivariant surjection $M \rightarrow \overline{M}$ has a G_k -equivariant splitting [which thus determines a G_k -equivariant isomorphism $k_{\text{sep}}^\times \times \overline{M} \xrightarrow{\sim} M$ — i.e., an isomorphism of sheaves $\mathcal{O}_X^\times \times \overline{\mathcal{M}}_X \xrightarrow{\sim} \mathcal{M}_X$].

Note that one verifies easily that the issue of whether or not X is split (respectively, quasi-split) does not depend on the choice of k_{sep} .

Proposition 1.3. *Let X be an fs log point. Suppose that X is split. Then X is quasi-split. In particular, a standard log point is quasi-split.*

Proof. Since the monoid \mathbb{N} has no nontrivial automorphism, the final assertion follows from the first assertion. Let us verify the first assertion. Since we are in the situation of Definition 1.2, we shall apply the notation of Definition 1.2. Then we have an exact sequence $1 \rightarrow k_{\text{sep}}^\times \rightarrow M^{\text{gp}} \rightarrow \overline{M}^{\text{gp}} \rightarrow 1$ of G_k -modules. Thus, since \overline{M}^{gp} is a free module, to verify that the G_k -equivariant surjection $M^{\text{gp}} \rightarrow \overline{M}^{\text{gp}}$, hence also $M \rightarrow \overline{M}$, has a G_k -equivariant splitting, it suffices to verify that $H^1(G_k, \text{Hom}_{\mathbb{Z}}(\overline{M}^{\text{gp}}, k_{\text{sep}}^\times)) = \{0\}$. On the other hand, since the action of G_k on \overline{M} is trivial, this follows from Hilbert's Theorem 90. This completes the proof of Proposition 1.3. \square

Remark 1.3.1. Proposition 1.3 gives us a sufficient condition for an fs log point to be *quasi-split*. Now let us observe that Proposition 1.3 essentially follows from Hilbert's Theorem 90. In §A, we discuss, by considering twisted versions of Hilbert's Theorem 90, further such sufficient conditions.

Lemma 1.4. *Let X be an object of $\text{Sch}^{\text{log}}(S)$. Then the following hold:*

(i) *Suppose that X is an fs log point. Since we are in the situation of Definition 1.2, we shall apply the notation of Definition 1.2. Let $\phi: \overline{M} \rightarrow \mathbb{N}$ be a local homomorphism. Then there exists a finite separable extension K of k which satisfies the following condition: If we write X' for the object of $\text{Sch}^{\text{log}}(S)$ obtained by equipping the spectrum of K with the log structure induced by the log structure of X , then there exists a standard log point $Y \rightarrow X'$ such that the induced homomorphism between the stalks of “ $\overline{\mathcal{M}}$ ” coincides with ϕ .*

(ii) *Let $x \in \overset{\circ}{X}$ be a closed point. Then there exists a standard log point $f: Y \rightarrow X$ such that the image of f coincides with $\{x\}$.*

Proof. First, we verify assertion (i). We may assume without loss of generality, by replacing k by a suitable finite separable extension of k , that X is split, hence also quasi-split [cf. Proposition 1.3]. Thus, assertion (i) follows from the G_k -equivariant isomorphism $k_{\text{sep}}^\times \times \overline{M} \xrightarrow{\sim} M$ of Definition 1.2, (ii).

Next, we verify assertion (ii). We may assume without loss of generality, by replacing X by the log scheme obtained by equipping the spectrum of the residue field of $\overset{\circ}{X}$ at x with the log structure induced by the log structure of X , that X is an *fs log point*. Thus, by assertion (i), to verify assertion (ii), it suffices to verify *existence* of a *local* homomorphism $\overline{M} \rightarrow \mathbb{N}$. On the other hand, this follows from Lemma 1.1, (i). This completes the proof of assertion (ii), hence also of Lemma 1.4. \square

Definition 1.5. We shall say that an object X of $\text{Sch}^{\text{log}}(S)$ is *minimal* if X is non-initial, and, moreover, every monomorphism in $\text{Sch}^{\text{log}}(S)$ from a non-initial object to X is an isomorphism [cf. [Mzk1], Proposition 2.4]. We shall say that a morphism in $\text{Sch}^{\text{log}}(S)$ is a *minimal log point* if the domain of the morphism is minimal.

Lemma 1.6. *Let X be an object of $\text{Sch}^{\text{log}}(S)$. Then it holds that X is minimal if and only if X is either a **trivial log point** or a **standard log point**.*

Proof. This is the content of [Mzk2], Proposition 1.6, (ii). Note that *sufficiency* also follows immediately from the surjectivity portion of necessity of [Mzk1], Proposition 2.3 [cf. also [Mzk2], Appendix]. Here, we give a proof of *necessity* from the *point of view of the present paper* for the reader's convenience as follows:

Suppose that X is *minimal*. Since $\overset{\circ}{X}$ is *noetherian*, $\overset{\circ}{X}$ has a closed point. Thus, one verifies immediately, by considering the strict closed immersion into X determined by this closed point, that X is an *fs log point*. Now since we are in the situation of Definition 1.2, we shall apply the notation of Definition 1.2.

Assume that the free module \overline{M}^{gp} is of *rank* ≥ 2 . Then it follows from Lemma 1.1, (iv), that there exists a G_k -*stable* submonoid $P \subseteq \overline{M}^{\text{gp}}$ such that $\overline{M} \subsetneq P$, and, moreover, P is *sharp* and *fs*. Thus, we have a G_k -*stable* submonoid $N \stackrel{\text{def}}{=} (M^{\text{gp}} \rightarrow \overline{M}^{\text{gp}})^{-1}(P)$ of M^{gp} such that $M \subsetneq N$, and, moreover, the natural homomorphism $M^{\text{gp}} \rightarrow N^{\text{gp}}$ is an *isomorphism*.

Next, let us observe that since P is *sharp*, by mapping each element of $N \setminus M$ to $0 \in k_{\text{sep}}$, we obtain a G_k -*equivariant* extension $N \rightarrow k_{\text{sep}}$ of the homomorphism $M \rightarrow k_{\text{sep}}$ of monoids [where we regard k_{sep} as a monoid by multiplication] which defines the log structure of X . Moreover, one verifies easily that this homomorphism $N \rightarrow k_{\text{sep}}$ of monoids determines an *fs log structure* on $\overset{\circ}{X}$. Write Y for the resulting [*non-initial*] *fs log scheme*. Then since $M \subsetneq N$, and the natural homomorphism $M^{\text{gp}} \rightarrow N^{\text{gp}}$ is an *isomorphism*, the morphism $Y \rightarrow X$ [in $\text{Sch}^{\text{log}}(S)$] induced by the natural inclusion $M \hookrightarrow N$ is a *monomorphism* but *not an isomorphism*. In particular, we

conclude that X is *not minimal*, in *contradiction* to our assumption that X is *minimal*. This completes the proof of *necessity* of Lemma 1.6. \square

Proposition 1.7. *Let X be an object of $\text{Sch}^{\text{log}}(S)$. Then the following hold:*

(i) *The following two conditions are **equivalent**:*

(1) X is a **trivial log point**.

(2) X is **minimal**, and, moreover, there exists a minimal log point $f: Y \rightarrow X$ such that Y has an endomorphism over X [relative to f] which is **not an isomorphism**.

(ii) *The following two conditions are **equivalent**:*

(3) X is a **standard log point**.

(4) X is **minimal but not a trivial log point**.

Proof. These assertions follow immediately from Lemma 1.6. \square

2. CHARACTERIZATION OF FS LOG POINTS

In the present §2, we give a categorical characterization of *fs log points* [cf. Proposition 2.5 below]. In the present §2, let S be an fs log scheme whose underlying scheme is *locally noetherian* and X an object of $\text{Sch}^{\text{log}}(S)$.

Definition 2.1.

(i) We shall say that a finite set $\{f_i: Y_i \rightarrow X\}_{i \in I}$ consisting of standard log points whose codomains are X is an *epimorphic family* of X if the morphism $\bigsqcup_{i \in I} Y_i \rightarrow X$ from the coproduct of the Y_i 's to X determined by the f_i 's is an epimorphism in $\text{Sch}^{\text{log}}(S)$.

(ii) We shall say that a collection consisting of standard log points whose codomains are X is an *indispensable collection* for X if every epimorphic family of X has an element which belongs to the collection.

Definition 2.2. Suppose that X is an fs log point. Since we are in the situation of Definition 1.2, we shall apply the notation of Definition 1.2. Write $V \stackrel{\text{def}}{=} \overline{M}^{\text{gp}} \otimes_{\mathbb{Z}} \mathbb{Q}$. Let $f: Y \rightarrow X$ be a standard log point. Then, by considering a geometric point $\overset{\circ}{Y}$ which lifts $\overline{x} \rightarrow \overset{\circ}{X}$, we obtain a [necessarily local] homomorphism $\overline{M} \rightarrow \mathbb{N}$. We shall write $L(f) \subseteq V$ for the kernel of the \mathbb{Q} -linear homomorphism $V \rightarrow \mathbb{Q}$ induced by this homomorphism $\overline{M} \rightarrow \mathbb{N}$. [Note that one verifies easily that $L(f)$ does not depend on the choice of the geometric point of $\overset{\circ}{Y}$.]

Lemma 2.3. *Suppose that X is an fs log point. Let $\{f_i: Y_i \rightarrow X\}_{i \in I}$ be a nonempty finite set consisting of standard log points whose codomains are X . Suppose that $\bigcap_i L(f_i) = \{0\}$. Then the finite set $\{f_i: Y_i \rightarrow X\}_{i \in I}$ is an epimorphic family of X .*

Proof. Let $\bar{x} \rightarrow \overset{\circ}{X}$ be a geometric point of $\overset{\circ}{X}$ and, for $i \in I$, $\bar{y}_i \rightarrow \overset{\circ}{Y}_i$ a geometric point of $\overset{\circ}{Y}_i$ which lifts $\bar{x} \rightarrow \overset{\circ}{X}$. Then since $\bigcap_i L(f_i) = \{0\}$, the homomorphism $\mathcal{M}_{X, \bar{x}} \rightarrow \prod_{i \in I} \mathcal{M}_{Y_i, \bar{y}_i}$ induced by the f_i 's is *injective*, which thus implies that the morphism $\bigsqcup_{i \in I} Y_i \rightarrow X$ is an *epimorphism*. This completes the proof of Lemma 2.3. \square

Lemma 2.4. *Let $f: Y \rightarrow X$ be an epimorphism in $\text{Sch}^{\text{log}}(S)$. Then every closed point of $\overset{\circ}{X}$ is contained in the image of $f: \overset{\circ}{Y} \rightarrow \overset{\circ}{X}$.*

Proof. Suppose that the image of f does *not* contain a closed point $x \in \overset{\circ}{X}$. Write Z for the object of $\text{Sch}^{\text{log}}(S)$ obtained by *glueing* two copies of X along the open log subscheme $X \setminus \{x\}$ [via the identity automorphism of $X \setminus \{x\}$]. Then we have two *distinct* natural open immersions $X \hookrightarrow Z$ whose restrictions to $X \setminus \{x\}$ *coincide*, which thus implies that f is *not* an epimorphism in $\text{Sch}^{\text{log}}(S)$. This completes the proof of Lemma 2.4. \square

Proposition 2.5. *The following two conditions are equivalent:*

- (1) X is an fs log point.
- (2) Every indispensable collection for X has a finite subset which forms an epimorphic family of X .

Proof. First, we verify the implication (1) \Rightarrow (2). Suppose that condition (1) is satisfied. Since we are in the situation of Definition 1.2, we shall apply the notation of Definition 1.2. Write $V \stackrel{\text{def}}{=} \overline{M}^{\text{gp}} \otimes_{\mathbb{Z}} \mathbb{Q}$.

Assume that there exists an *indispensable* collection A for X such that A does *not* have any finite subset which forms an *epimorphic family* of X . [Note that since there exists a *nonempty epimorphic family* of X by Lemma 1.1, (ii), Lemma 1.4, (i), and Lemma 2.3, it holds that $A \neq \emptyset$.] Then it follows immediately from Lemma 2.3 that $L \stackrel{\text{def}}{=} \bigcap_f L(f) \neq \{0\}$ — where f ranges over the members of A . Thus, one verifies immediately from Lemma 1.1, (ii), that there exists a finite set $\{g_j\}_{j \in J}$ consisting of standard log points whose codomains are X such that $L \not\subseteq L(g_j)$ [cf. condition (2) of Lemma 1.1, (ii)] — which thus implies that g_j does *not* belong to A for every $j \in J$ — and, moreover, $\bigcap_j L(g_j) = \{0\}$ [cf. condition (1) of Lemma 1.1, (ii)] — which thus implies [cf. Lemma 2.3] that this finite set $\{g_j\}_{j \in J}$ is an *epimorphic family*. In particular, since A is *indispensable*, we obtain a *contradiction*. This completes the proof of the implication (1) \Rightarrow (2).

Next, we verify the implication (2) \Rightarrow (1). Suppose that condition (2) is satisfied. Let $x \in \overset{\circ}{X}$ be a closed point of $\overset{\circ}{X}$. [Note that since $\overset{\circ}{X}$ is *noetherian*, a closed point of $\overset{\circ}{X}$ always *exists*.] Write A for the collection consisting of the standard log points whose codomains are X and images coincide with $\{x\} \subseteq \overset{\circ}{X}$. [Note that it follows from Lemma 1.4, (ii), that $A \neq \emptyset$.] Then it follows from Lemma 2.4 that A is *indispensable*. In particular, since some finite subset of A forms an *epimorphic family* of X [cf. condition (2)], again by Lemma 2.4, we conclude that x is the *unique* closed point of X , which thus implies that $\overset{\circ}{X}$ is isomorphic to the spectrum of a noetherian local ring R .

Let $\pi \in R \setminus R^\times$. Write \mathbb{A}_X^1 for the fs log scheme over X obtained by equipping $\text{Spec}(R[t])$ — where t is an indeterminate — with the log structure induced by the log structure of X . Then we have two strict closed immersions $f_0, f_\pi: X \hookrightarrow \mathbb{A}_X^1$ over X determined by the R -linear homomorphisms $R[t] \rightarrow R$ given by mapping $t \in R[t]$ to 0, $\pi \in R$, respectively. Now let us observe that one verifies immediately that, for an fs log point $f: Y \rightarrow X$, if the image of f is $\{x\}$, then it holds that $f_0 \circ f = f_\pi \circ f$. Thus, since some finite subset of A forms an *epimorphic family* of X as verified above, we conclude that $f_0 = f_\pi$, hence also $\pi = 0$, which thus implies that R is a *field*. This completes the proof of the implication (2) \Rightarrow (1), hence also of Proposition 2.5. \square

3. CHARACTERIZATION OF STRICT MORPHISMS

In the present §3, we prove the main theorem of the present paper [cf. Theorem 3.7 below]. In the present §3, let S be an fs log scheme whose underlying scheme is *locally noetherian*, X and Y objects of $\text{Sch}^{\text{log}}(S)$, and $f: X \rightarrow Y$ a morphism in $\text{Sch}^{\text{log}}(S)$.

Lemma 3.1. *Suppose that X is an fs log point, and that f is a **monomorphism**. Then it holds that f is **strict** if and only if f is a **terminal object** among the fs log points $Z \rightarrow Y$ which satisfy that $X \times_Y Z$ is **non-initial**.*

Proof. This is [Mzk1], Corollary 2.13. However, since the proof contains an *error* [cf. [Mzk2], Appendix], we give a proof as follows: Let us first observe that, to verify Lemma 3.1, we may assume without loss of generality, by replacing Y by the log scheme obtained by equipping the spectrum of the residue field of $\overset{\circ}{Y}$ at the image of f with the log structure induced by the log structure of Y , that Y is an *fs log point*. Now, to verify *necessity*, suppose that f is *strict*. Then since f is a *strict monomorphism*, one verifies easily that f is an *isomorphism*. Thus, *necessity* is immediate. Next, we

verify *sufficiency*. Since the identity automorphism of Y is an *fs log point* which satisfies that $X \times_Y Y = X$ is *non-initial*, by our condition, f has a *splitting* over Y [i.e., a morphism $s: Y \rightarrow X$ over Y such that the composite $Y \xrightarrow{s} X \xrightarrow{f} Y$ is the identity automorphism of Y]. Thus, f is an *isomorphism*. This completes the proof of *sufficiency*, hence also of Lemma 3.1. \square

Lemma 3.2. *It holds that f is **strict** if and only if, for every commutative diagram in $\text{Sch}^{\text{log}}(S)$*

$$\begin{array}{ccc} Z & \longrightarrow & X \\ \downarrow & & \downarrow f \\ W & \longrightarrow & Y \end{array}$$

— where the horizontal arrows are **fs log points**, **monomorphisms**, and **strict** — it holds that the left-hand vertical arrow is **strict**.

Proof. This is [Mzk1], Corollary 2.14. However, since the proof contains an error [cf. [Mzk2], Appendix], we give a proof as follows: *Necessity* may be easily verified. Next, we verify *sufficiency*. Let x be a closed point of $\overset{\circ}{X}$. [Note that since $\overset{\circ}{X}$ is *noetherian*, a closed point of $\overset{\circ}{X}$ always *exists*.] Write $Z \rightarrow X$ for the *strict* morphism whose underlying morphism of schemes is given by the natural morphism from the spectrum of the residue field of $\overset{\circ}{X}$ at x and $W \rightarrow Y$ for the *strict* morphism whose underlying morphism of schemes is given by the natural morphism from the spectrum of the residue field of $\overset{\circ}{Y}$ at $f(x)$. Then one verifies easily that $Z \rightarrow X$, hence also $W \rightarrow Y$, is a morphism in $\text{Sch}^{\text{log}}(S)$. Moreover, it holds that $Z \rightarrow X$ and $W \rightarrow Y$ are *monomorphisms*. Thus, by our condition, the natural morphism $Z \rightarrow W$ is *strict*, which thus implies that $f^{-1}\overline{\mathcal{M}}_Y \rightarrow \overline{\mathcal{M}}_X$ is an *isomorphism* at $x \in \overset{\circ}{X}$. This implies *sufficiency*. \square

Lemma 3.3. *Suppose that both X and Y are **fs log points**. Then the following hold:*

(i) *It holds that f is **exact** if and only if, for every fs log point $Z \rightarrow Y$, the fiber product $X \times_Y Z$ is **non-initial**.*

(ii) *It holds that f is **strict** if and only if the following condition is satisfied: f is **exact**, and, moreover, for every minimal log point $Z \rightarrow Y$, the second projection $X \times_Y Z \rightarrow Z$ is **strict**.*

Proof. Assertion (i) is essentially [Naka], (A.1), Proposition [cf. also the proof of [Naka], (A.1), Proposition]. Next, we verify assertion (ii). *Necessity* may be easily verified. We verify *sufficiency*. Write M for the stalk of $\overline{\mathcal{M}}_X$

at a geometric point of $\overset{\circ}{X}$, N for the stalk of $\overline{\mathcal{M}}_Y$ at the geometric point of $\overset{\circ}{Y}$ determined by the geometric point of $\overset{\circ}{X}$, and $\phi: N \rightarrow M$ for the [necessarily *exact* — cf. our condition] local homomorphism induced by f .

Let $\psi: N \rightarrow \mathbb{N}$ be a local homomorphism [cf. Lemma 1.1, (i)]. Write P for the quotient by the torsion elements of the saturation of the pushout [in the category of monoids] of $M \xleftarrow{\phi} N \xrightarrow{\psi} \mathbb{N}$. Then, by our condition in the end of the statement of assertion (ii) [cf. also Lemma 1.6], together with [Naka], Proposition (2.1.1), the natural homomorphism $\mathbb{N} \rightarrow P$ is an *isomorphism*. Thus, it follows that $\text{rank}_{\mathbb{Z}}(\text{Coker}(\phi^{\text{gp}}: N^{\text{gp}} \rightarrow M^{\text{gp}})) = \text{rank}_{\mathbb{Z}}(\text{Coker}(\mathbb{Z} = \mathbb{N}^{\text{gp}} \rightarrow P^{\text{gp}})) = 0$.

Assume that f is *not strict*, i.e., that ϕ is *not an isomorphism*. Then, since ϕ is *exact*, and $\text{Coker}(\phi^{\text{gp}})$ is of *rank 0*, it holds that $\text{Coker}(\phi^{\text{gp}})$ has a *nontrivial torsion*. In particular, there exists a homomorphism $\pi: N^{\text{gp}} \rightarrow \mathbb{Z}$ which does *not factor* through ϕ^{gp} . Next, observe that since N is *finitely generated*, there exists a positive integer n such that the homomorphism $N^{\text{gp}} \rightarrow \mathbb{Z}$ given by mapping $x \in N^{\text{gp}}$ to $\pi(x) + n \cdot \psi^{\text{gp}}(x) \in \mathbb{Z}$ maps $N \subseteq N^{\text{gp}}$ to $\mathbb{N} \subseteq \mathbb{Z}$, and the resulting homomorphism $\psi_0: N \rightarrow \mathbb{N}$ is *local*. Then it follows from our choice of π [together with the fact that ψ *factors* through ϕ — cf. the above discussion concerning P] that ψ_0 does *not factor* through ϕ . Thus, by means of ψ_0 , together with Lemma 1.4, (i), one may construct a minimal log point $Z \rightarrow Y$ such that the second projection $X \times_Y Z \rightarrow Z$ is *not strict*, in *contradiction* to our condition. This completes the proof of assertion (ii), hence also of Lemma 3.3. \square

Lemma 3.4. *Suppose that Y is **minimal**. Then it holds that f is **strict** if and only if every fs log point $Z \rightarrow X$ **factors** through a minimal log point $W \rightarrow X$ such that the composite $W \rightarrow X \xrightarrow{f} Y$ is **strict**.*

Proof. First, we verify *necessity*. Suppose that f is *strict*. Let $Z \rightarrow X$ be an fs log point. Write W for the log scheme obtained by equipping $\overset{\circ}{Z}$ with the log structure induced by the log structure of X . Thus, we have a factorization $Z \rightarrow W \rightarrow X$, where $W \rightarrow X$ is *strict*. Since f is *strict* and Y is *minimal*, the composite $W \rightarrow X \xrightarrow{f} Y$ is *strict* and W is *minimal* [cf. Lemma 1.6]. This completes the proof of *necessity*.

Next, we verify *sufficiency*. Suppose that f is *not strict*. Then since $\overset{\circ}{X}$ is *noetherian*, one verifies easily that there exists a closed point x of $\overset{\circ}{X}$ such that the homomorphism $f^{-1}\overline{\mathcal{M}}_Y \rightarrow \overline{\mathcal{M}}_X$ is *not an isomorphism* at $x \in \overset{\circ}{X}$. Thus, to verify *sufficiency*, we may assume without loss of generality, by replacing X by the log scheme obtained by equipping [the reduced closed

subscheme determined by] $\{x\}$ with the log structure induced by the log structure of X , that X is an *fs log point*.

Assume that the identity automorphism $X \rightarrow X$ [which is in fact an *fs log point*] *factors* through a minimal log point $W \rightarrow X$ which satisfies that the composite $W \rightarrow X \xrightarrow{f} Y$ is *strict*.

If Y is a *trivial log point*, then since the composite $W \rightarrow X \xrightarrow{f} Y$ is *strict*, it follows that W is a *trivial log point*, which thus implies that X is a *trivial log point*. In particular, f is *strict*, in *contradiction* to our assumption that f is *not strict*.

Thus, it follows from Lemma 1.6 that we may assume without loss of generality that Y is a *standard log point*. Then since the composite $W \rightarrow X \xrightarrow{f} Y$ is *strict*, it follows that W is a *standard log point*. Thus, it follows immediately, by considering our factorization $X \rightarrow W \rightarrow X$ of the identity automorphism of X , that X is a *standard log point*, and, moreover, $X \rightarrow W$, hence also the composite $X \rightarrow W \rightarrow X \rightarrow Y$ [i.e., f], is *strict*, in *contradiction* to our assumption that f is *not strict*. This completes the proof of *sufficiency*, hence also of Lemma 3.4. \square

Lemma 3.5. *Suppose that both X and Y are **minimal**. Then it holds that f is **strict** if and only if the following condition is satisfied: There exists a factorization $X \rightarrow Z \rightarrow Y$ of f such that Z is **connected** and either of **log rank 0** or of **log rank 1**, $X \rightarrow Z$ is a **monomorphism**, and $Z \rightarrow Y$ has a **splitting** [i.e., a morphism $s: Y \rightarrow Z$ such that $Y \xrightarrow{s} Z \rightarrow Y$ is the identity automorphism].*

Proof. This follows from [Mzk2], Proposition 2.4. \square

Lemma 3.6. *It holds that X is of **log rank 0** (respectively, **1**) if and only if every *fs log point* $Z \rightarrow X$ **factors** through a **trivial** (respectively, **standard**) *log point* $W \rightarrow X$.*

Proof. *Necessity* follows by considering a suitable *strict monomorphism* $W \rightarrow X$. Next, we verify *sufficiency*. One verifies easily that X is of *log rank 0* if every *fs log point* $Z \rightarrow X$ *factors* through a *trivial log point* $W \rightarrow X$. Thus, suppose that every *fs log point* $Z \rightarrow X$ *factors* through a *standard log point* $W \rightarrow X$. Then it follows immediately from our condition that the module $\overline{\mathcal{M}}_{X, \bar{x}}^{\text{gp}}$ is of *rank 1* for every geometric point $\bar{x} \rightarrow \overset{\circ}{X}$ whose image is *closed* in $\overset{\circ}{X}$. Write $U \subseteq \overset{\circ}{X}$ for the maximal [necessarily *open* — cf. the well-known *constructibility* of $\overline{\mathcal{M}}_X$] subset on which $\overline{\mathcal{M}}_X$ is *trivial*. If $U \neq \emptyset$, then since U has a *closed point* [by the fact that U is *noetherian*], we obtain a *contradiction* by our condition. This completes the proof of *sufficiency*, hence also of Lemma 3.6. \square

Theorem 3.7. *Let S and T be fs log schemes whose underlying schemes are locally noetherian,*

$$\phi: \text{Sch}^{\log}(S) \xrightarrow{\sim} \text{Sch}^{\log}(T)$$

*an equivalence of categories, and f a morphism in $\text{Sch}^{\log}(S)$. Then it holds that f is **strict** if and only if $\phi(f)$ is **strict**.*

Proof. Let X be an object of $\text{Sch}^{\log}(S)$ and g a morphism in $\text{Sch}^{\log}(S)$. Let us first observe that it follows from Proposition 1.7, Proposition 2.5 that

(1) it holds that X is a *trivial* (respectively, a *standard*; an *fs log point*) if and only if $\phi(X)$ is a *trivial* (respectively, a *standard*; an *fs log point*).

Moreover, it follows from Lemma 3.1, together with assertion (1), that

(2) if g [hence also $\phi(g)$ — cf. (1)] is an *fs log point* and a *monomorphism*, then it holds that g is *strict* if and only if $\phi(g)$ is *strict*.

Thus, it follows from Lemma 3.2 that, to verify Theorem 3.7, it is enough to verify the following assertion (3):

(3) If the domain and codomain of g [hence also of $\phi(g)$ — cf. (1)] are *fs log points*, then it holds that g is *strict* if and only if $\phi(g)$ is *strict*.

Next, let us observe that, to verify assertion (3), it follows from Lemma 3.3, together with assertion (1), that it suffices to verify the following assertion (4):

(4) If the codomain of g [hence also of $\phi(g)$] is *minimal*, then it holds that g is *strict* if and only if $\phi(g)$ is *strict*.

Next, to verify assertion (4), it follows from Lemma 3.4, together with assertion (1), that it is sufficient to verify the following assertion (5):

(5) If the domain and codomain of g [hence also of $\phi(g)$] are *minimal*, then it holds that g is *strict* if and only if $\phi(g)$ is *strict*.

Thus, to verify Theorem 3.7, it follows from Lemma 3.5 that it suffices to verify the following assertion (6):

(6) It holds that X is either *of log rank 0* or *of log rank 1* if and only if $\phi(X)$ is either *of log rank 0* or *of log rank 1*.

On the other hand, assertion (6) follows from Lemma 3.6, together with assertion (1). This completes the proof of Theorem 3.7. \square

Remark 3.7.1. The content of Theorem 3.7 is in fact a formal consequence of a result of *S. Mochizuki* [i.e., [Mzk2], Theorem A]. Moreover, Mochizuki also proved that a result concerning a *categorical representation* of fs log

schemes [i.e., [Mzk1], Theorem B; [Mzk2], Theorem A] follows from Theorem 3.7, together with some discussions [cf. the portion of [Mzk2] from the discussion preceding [Mzk2], Proposition 3.7, to the end of [Mzk2], §3 — also [Mzk2], Appendix].

APPENDIX A. TWISTED VERSIONS OF HILBERT'S THEOREM 90

In §1, we gave a *sufficient condition* for an fs log point to be *quasi-split* [cf. Proposition 1.3, Remark 1.3.1]. In the present §A, we discuss, by considering *twisted versions of Hilbert's Theorem 90*, further such *sufficient conditions*. In the present §A, let k be a field and k_{sep} a separable closure of k . Write $G_k \stackrel{\text{def}}{=} \text{Gal}(k_{\text{sep}}/k)$. Let M be a *sharp fs monoid* equipped with a continuous action of G_k [with respect to the *discrete topology* on M].

Proposition A.1. *Let X be an fs log point. Then the following three conditions are equivalent:*

- (1) X is **quasi-split**.
- (2) *There exist an fs log point Y and a morphism $f: Y \rightarrow X$ such that Y is **quasi-split**, and, moreover, $\overset{\circ}{f}$ is an **isomorphism**.*
- (3) *There exist a **standard log point** Y and a morphism $f: Y \rightarrow X$ such that $\overset{\circ}{f}$ is an **isomorphism**.*

Proof. The implication (3) \Rightarrow (2) follows from Proposition 1.3. The implication (1) \Rightarrow (3) follows from Lemma 1.1, (iii).

Finally, to verify the implication (2) \Rightarrow (1), suppose that condition (2) is satisfied. By means of the isomorphism $\overset{\circ}{f}$, let us identify $\overset{\circ}{X}$ with $\overset{\circ}{Y}$. Since Y is *quasi-split*, it follows from Definition 1.2, (ii), that the natural inclusion $\mathcal{O}_Y^\times \hookrightarrow \mathcal{M}_Y$ has a splitting $\mathcal{M}_Y \twoheadrightarrow \mathcal{O}_Y^\times (= \mathcal{O}_X^\times)$. Thus, by considering the composite of the homomorphism $\mathcal{M}_X \rightarrow \mathcal{M}_Y$ induced by f and the above splitting $\mathcal{M}_Y \twoheadrightarrow \mathcal{O}_X^\times$, we obtain a splitting $\mathcal{M}_X \twoheadrightarrow \mathcal{O}_X^\times$ of the natural inclusion $\mathcal{O}_X^\times \hookrightarrow \mathcal{M}_X$. In particular, X is *quasi-split*, i.e., condition (1) is satisfied. This completes the proof of the implication (2) \Rightarrow (1), hence also of Proposition A.1. \square

Definition A.2. We shall say that the pair (k, M) is *quasi-split* if the following condition is satisfied: For every fs log scheme X whose underlying scheme is the spectrum of k , if there exists a G_k -equivariant isomorphism of M with the stalk of $\overline{\mathcal{M}}_X$ at the geometric point $\bar{x} \rightarrow \overset{\circ}{X}$ determined by the separable closure k_{sep} , then X is quasi-split.

Proposition A.3. *It holds that the pair (k, M) is **quasi-split** if and only if $H^1(G_k, \text{Hom}_{\mathbb{Z}}(M^{\text{gp}}, k_{\text{sep}}^{\times})) = \{0\}$ [where the action of G_k on $\text{Hom}_{\mathbb{Z}}(M^{\text{gp}}, k_{\text{sep}}^{\times})$ is given by $g \cdot \phi \stackrel{\text{def}}{=} g \circ \phi \circ g^{-1}$].*

Proof. One can prove *sufficiency* in the same way as the proof of Proposition 1.3. Next, we verify *necessity*. Suppose that (k, M) is *quasi-split*. Let $1 \rightarrow k_{\text{sep}}^{\times} \rightarrow E \rightarrow M^{\text{gp}} \rightarrow 1$ be an exact sequence of G_k -modules corresponding to an element of $\text{Ext}_{G_k}^1(M^{\text{gp}}, k_{\text{sep}}^{\times}) = H^1(G_k, \text{Hom}_{\mathbb{Z}}(M^{\text{gp}}, k_{\text{sep}}^{\times}))$. Write $N \stackrel{\text{def}}{=} (E \twoheadrightarrow M^{\text{gp}})^{-1}(M) \subseteq E$. [Thus, N is isomorphic, as an abstract monoid, to $k_{\text{sep}}^{\times} \times M$.] Then since M is *sharp* [which thus implies that $N^{\times} = k_{\text{sep}}^{\times}$], by mapping each element of $N \setminus k_{\text{sep}}^{\times}$ to $0 \in k_{\text{sep}}^{\times}$, we obtain a G_k -equivariant homomorphism $N \rightarrow k_{\text{sep}}^{\times}$ of monoids [where we regard k_{sep}^{\times} as a monoid by multiplication] which is an extension of the natural inclusion $k_{\text{sep}}^{\times} \hookrightarrow k_{\text{sep}}^{\times}$. Moreover, one verifies easily that this homomorphism $N \rightarrow k_{\text{sep}}^{\times}$ of monoids determines an *fs log structure* on $\text{Spec}(k)$. On the other hand, since (k, M) is *quasi-split*, the resulting fs log scheme is *quasi-split*, which thus implies that the above exact sequence of G_k -modules has a G_k -equivariant splitting. This completes the proof of Proposition A.3. \square

Lemma A.4. *Let K be a finite Galois extension of k . Write $G \stackrel{\text{def}}{=} \text{Gal}(K/k)$. Let $H \subseteq N \subseteq G$ be subgroups such that N is **normal** in G . Let us define an action of G on the module $\text{Map}(G/N, (K^H)^{\times})$ [consisting of maps of sets $G/N \rightarrow (K^H)^{\times}$] by $g \cdot \phi \stackrel{\text{def}}{=} \phi \circ g^{-1}$; moreover, let us also define an action of G on the module $\text{Map}(G/H, K^{\times})$ [consisting of maps of sets $G/H \rightarrow K^{\times}$] by $g \cdot \phi \stackrel{\text{def}}{=} g \circ \phi \circ g^{-1}$. Then the homomorphism*

$$\begin{array}{ccc} \text{Map}(G/N, (K^H)^{\times}) & \longrightarrow & \text{Map}(G/H, K^{\times}) \\ \phi & \longmapsto & (gH \mapsto g\phi(gN)) \end{array}$$

*determines a **G**-equivariant isomorphism*

$$\text{Map}(G/N, (K^H)^{\times}) \xrightarrow{\sim} \text{Map}(G/H, K^{\times})^N$$

*of G -modules. In particular, the G/N -module $\text{Map}(G/H, K^{\times})^N$ is a **coinduced module**.*

Proof. This follows from a straightforward computation. \square

Theorem A.5. *If one of the following three conditions is satisfied, then the pair (k, M) is **quasi-split**.*

- (1) *The action of G_k on M is **trivial**.*
- (2) *The Brauer group of every finite separable extension of k is **zero**.*

(3) *There exists a [not necessarily G_k -equivariant] isomorphism $M \xrightarrow{\sim} \mathbb{N}^{\oplus n}$ of monoids for some positive integer n .*

Proof. Theorem A.5 in the case where condition (1) is satisfied follows formally from Proposition 1.3. Theorem A.5 in the case where condition (2) is satisfied follows from Proposition A.3 and [Serre], Chapter X, Proposition 11, as well as [Serre], Chapter X, Corollary to Proposition 11.

Finally, we verify Theorem A.5 in the case where condition (3) is satisfied. Suppose that condition (3) is satisfied. Let us first observe that one verifies easily that each automorphism of the monoid $\mathbb{N}^{\oplus n}$ arises from some *permutation of the n factors*. Thus, it follows from Proposition A.3 that, to complete the verification of Theorem A.5, it suffices to verify that

(\dagger): for a finite set S and a finite Galois extension K of k whose Galois group $G \stackrel{\text{def}}{=} \text{Gal}(K/k)$ acts on S , it holds that $H^1(G, \text{Map}(S, K^\times)) = \{0\}$ [where the action of G on $\text{Map}(S, K^\times)$ is given by $g \cdot \phi \stackrel{\text{def}}{=} g \circ \phi \circ g^{-1}$].

Next, let us observe that we may assume without loss of generality, by replacing G by a p -Sylow subgroup of G [where p is a prime number], that G in (\dagger) is a [nontrivial] p -group. Next, let us observe that we may assume without loss of generality, by replacing S by the G -orbit of an element of S , that S in (\dagger) is the G -set G/H for a subgroup $H \subseteq G$. Observe that if $H = G$, then (\dagger) follows from *Hilbert's Theorem 90*; thus, we may assume without loss of generality that $H \neq G$.

Let $N \subseteq G$ be a *normal* subgroup such that $H \subseteq N$, and, moreover, $[G : N] = p$. [Note that one may verify *existence* of such a normal subgroup N as follows: Since G is a nontrivial p -group, there exists a subgroup $Z \subseteq G$ such that Z is of order p and contained in the center of G . If $H \cdot Z = G$, which thus implies that $H \times Z = G$, then one may take H itself as “ N ”. If $H \cdot Z \neq G$, then, by *induction* on the cardinality of “ G ”, one obtains a normal subgroup of G/Z of index p which contains the image of H . Thus, by considering the inverse image in G of this normal subgroup of G/Z , one obtains a subgroup of the desired type.] Thus, by *induction* on the cardinality of G , to verify (\dagger), it suffices to verify that

$$H^1(G/N, \text{Map}(G/H, K^\times)^N) = \{0\}.$$

On the other hand, this follows from Lemma A.4. This completes the proof of Theorem A.5. \square

Remark A.5.1. Examples of “ k ” which satisfies condition (2) in the statement of Theorem A.5 are given in the discussion entitled “Examples of

Fields with Zero Brauer Group” in [Serre], p.162. For instance, a *quasi-algebraically closed field* [i.e., a field which has property C_1] — e.g., a *finite field* — satisfies condition (2) in the statement of Theorem A.5.

Remark A.5.2. An example of an fs log point which is *not quasi-split* is given as follows: Write M for the monoid obtained by taking the quotient of $\mathbb{N}^{\oplus 3}$ by the relation $(a, a, 0) \sim (0, 0, 2a)$, where $a \in \mathbb{N}$. Let us define an action of the Galois group $\text{Gal}(\mathbb{C}/\mathbb{R})$ on $\mathbb{C}^\times \times M$ by $\sigma(z, [a, b, c]) \stackrel{\text{def}}{=} ((-1)^c \cdot \sigma(z), [b, a, c])$ — where we write $\sigma \in \text{Gal}(\mathbb{C}/\mathbb{R})$ for the unique nontrivial element and “[$-$]” ($\in M$) for the image of “[$-$]” ($\in \mathbb{N}^{\oplus 3}$) in M — as well as a $\text{Gal}(\mathbb{C}/\mathbb{R})$ -equivariant homomorphism $\mathbb{C}^\times \times M \rightarrow \mathbb{C}$ of monoids by $(z, [a, b, c]) \mapsto z$ if $(a, b, c) = (0, 0, 0)$ (respectively, $\mapsto 0$ if $(a, b, c) \neq (0, 0, 0)$).

Then one verifies immediately that this $\text{Gal}(\mathbb{C}/\mathbb{R})$ -equivariant homomorphism $\mathbb{C}^\times \times M \rightarrow \mathbb{C}$ determines an *fs log structure* on $\text{Spec}(\mathbb{R})$. Next, let us verify that the resulting fs log point is *not quasi-split*, i.e., that there is *no* $\text{Gal}(\mathbb{C}/\mathbb{R})$ -equivariant splitting $M^{\text{gp}} \rightarrow \mathbb{C}^\times \times M^{\text{gp}}$ of the natural surjection $\mathbb{C}^\times \times M^{\text{gp}} \twoheadrightarrow M^{\text{gp}}$. To this end, assume that there is a $\text{Gal}(\mathbb{C}/\mathbb{R})$ -equivariant splitting $\phi: M^{\text{gp}} \rightarrow \mathbb{C}^\times \times M^{\text{gp}}$. Write $s, t, u \in M^{\text{gp}}$ for the respective images of $[1, 0, 0]$, $[0, 1, 0]$, $[0, 0, 1]$ in M^{gp} , $(z_s, s) \stackrel{\text{def}}{=} \phi(s)$, $(z_t, t) \stackrel{\text{def}}{=} \phi(t)$, and $(z_u, u) \stackrel{\text{def}}{=} \phi(u)$. Then since ϕ is $\text{Gal}(\mathbb{C}/\mathbb{R})$ -equivariant, it holds that

- $(\sigma(z_s), t) = \sigma(\phi(s)) = \phi(\sigma(s)) = (z_t, t)$, i.e., $\sigma(z_s) = z_t$, and that
- $(-\sigma(z_u), u) = \sigma(\phi(u)) = \phi(\sigma(u)) = (z_u, u)$, i.e., $-\sigma(z_u) = z_u$.

Moreover, since ϕ is a homomorphism, it holds that

- $s + t = 2u$ implies $z_s \cdot z_t = z_u^2$.

Thus, we conclude that

$$|z_s|^2 = z_s \cdot \sigma(z_s) = z_s \cdot z_t = z_u^2 = z_u \cdot (-\sigma(z_u)) = -|z_u|^2,$$

which thus implies that $z_s = 0$, in *contradiction* to our assumption that $z_s \in \mathbb{C}^\times$. This completes the proof of the fact that our fs log point is *not quasi-split*.

ACKNOWLEDGEMENT

The first author was supported by JSPS KAKENHI Grant Number 15K04780. The second author was supported by JSPS KAKENHI Grant Numbers 22540011, 23340008, 16K05093. The authors would like to thank Shinichi Mochizuki and the referee for helpful comments. The second author thanks J. C. for suggesting this paper.

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(Received February 18, 2016)

(Accepted May 13, 2016)