Model Theory

no. 1 vol. 1 2022

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Model Theory
Vol. 1, No. 1, 2022
https://doi.org/10.2140/mt.2022.1.115

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We prove an assortment of results on (commutative and unital) NIP rings, especially $\mathbb{F}_p$-algebras. Let R be a NIP ring. Then every prime ideal or radical ideal of R is externally definable, and every localization $S^{-1}R$ is NIP. Suppose R is additionally an $\mathbb{F}_p$-algebra. Then R is a finite product of henselian local rings. Suppose in addition that R is integral. Then R is a henselian local domain, whose prime ideals are linearly ordered by inclusion. Suppose in addition that the residue field $R/\mathfrak{m}$ is infinite. Then the Artin–Schreier map $R \to R$ is surjective (generalizing the theorem of Kaplan, Scanlon, and Wagner for fields).

1. Introduction

The class of NIP theories has played a major role in contemporary model theory. See [Simon 2015] for an introduction to NIP. In recent years, much work has been done on the problem of classifying NIP fields and NIP rings. A conjectural classification of NIP fields has emerged through work of Anscombe, Halevi, Hasson, and Jahnke [Halevi et al. 2019; Anscombe and Jahnke 2019], and partial results towards this conjectural classification have been obtained by the author in the setting of finite dp-rank [Johnson 2015; 2020; 2021b].

NIP fields are closely connected to NIP valuation rings. Conjecturally:

- Every NIP valuation ring is henselian.
- Every infinite NIP field is elementarily equivalent to $\mathrm{Frac}(R)$ for some NIP nontrivial valuation ring R.

These conjectures form the basis for the proposed classification of NIP fields [Anscombe and Jahnke 2019], and are known to hold assuming finite dp-rank [Johnson 2020]. Additionally, the henselianity conjecture is known in positive characteristic: if R is a NIP valuation ring and $\mathrm{Frac}(R)$ has positive characteristic, then R is henselian [Johnson 2021a, Theorem 2.8].

More generally, one would like to understand (commutative) NIP rings, especially NIP integral domains. A first step in this direction is the recent work of d'Elbée and Halevi [2021] on dp-minimal integral domains. Among other things, they show

MSC2020: 03C60.
Keywords: NIP, henselian rings.

that if R is a dp-minimal integral domain, then R is a local ring, the prime ideals of R are a chain, the localization of R at any nonmaximal prime is a valuation ring, and R is a valuation ring whenever its residue field is infinite.

In the present paper, we consider a NIP integral domain R such that $\mathrm{Frac}(R)$ has positive characteristic. By analogy with [d'Elbée and Halevi 2021], we show that R is a local ring whose primes ideals are linearly ordered by inclusion. Generalizing the earlier henselianity theorem for valuation rings, we show that R is a henselian local ring. These results may help to extend the work of d'Elbée and Halevi to "positive characteristic" NIP integral domains.

Main results. All rings are assumed to be commutative and unital. In Section 2 we consider a general NIP ring R. Our main results are the following:

- Any localization $S^{-1}R$ is interpretable in the Shelah expansion R^{Sh}, and is therefore NIP (Theorem 2.11).
- Any radical ideal in R is externally definable (Theorem 2.14).

In Section 3, we restrict to the case where R is an $\mathbb{F}_p$-algebra, and obtain significantly stronger results:

- R is a finite product of henselian local rings (Theorem 3.21).
- If R is an integral domain, then R is a henselian local domain (Theorem 3.22), and the prime ideals of R are linearly ordered by inclusion (Theorem 3.15).
- If R is a local integral domain with maximal ideal $\mathfrak{m}$ and $R/\mathfrak{m}$ is infinite, then the Artin–Schreier map $R \to R$ is surjective (Theorem 3.4).

The henselianity results generalize [Johnson 2021a, Theorem 2.8], which handled the case where R is a valuation ring. The surjectivity of the Artin–Schreier map generalizes a theorem of Kaplan, Scanlon, and Wagner [Kaplan et al. 2011, Theorem 4.4], which handled the case where R is a field.

2. General NIP rings

2A. ***Finite width.*** The *width* of a poset $(P, \leq)$ is the maximum size of an antichain in P. We write $\operatorname{Spec} R$ for the poset of prime ideals in R, ordered by inclusion. This is an abuse of notation, since we are forgetting the usual scheme and topology structure on $\operatorname{Spec} R$, and then adding the poset structure.

Fact 2.1. *Let R be a NIP ring. Then* $\operatorname{Spec} R$ *has finite width. Moreover, there is a uniform finite bound on the width of* $\operatorname{Spec} R'$ *for $R' \succeq R$.*

Fact 2.1 is proved by d'Elbée and Halevi [2021, Proposition 2.1, Remark 2.2], who attribute it to Pierre Simon.

Fact 2.1 has a number of useful corollaries, which we shall use in later sections. First of all, Dilworth's theorem gives the following corollary:

Corollary 2.2. *If R is a NIP ring, then* Spec R *is a finite union of chains.*

Another trivial corollary of Fact 2.1 is the following:

Corollary 2.3. *If R is a NIP ring, then R has finitely many maximal ideals and finitely many minimal prime ideals.*

Also, using Beth's implicit definability, we see the following:

Corollary 2.4. *If R is a NIP ring, then the maximal ideals of R are definable.*

For completeness, we give the proof. The proof uses the following form of Beth's theorem:

Fact 2.5. *Let M be an L_0-structure. Let L be a language extending L_0 and let T be an L-theory. Suppose there is a cardinal κ such that for any $M' \succeq M$ there are at most κ-many expansions of M' to a model of T. Then every such expansion is an expansion by definitions.*

Proof of Corollary 2.4. Let L_0 be the language of rings and L be $L_0 \cup \{P\}$, where P is a unary predicate symbol. Let T be the statement saying that P is a maximal ideal, i.e.,

$$\forall x, y : P(x) \wedge P(y) \to P(x+y),$$
$$P(0),$$
$$\forall x, y : P(x) \to P(x \cdot y),$$
$$\neg P(1),$$
$$\forall x : \neg P(x) \to \exists y : P(xy-1).$$

If $R' \succeq R$, then an expansion of R' to a model of T is the same thing as a maximal ideal of R'. The number of such maximal ideals is uniformly bounded by Fact 2.1, and so Fact 2.5 shows that each such maximal ideal is definable. $\square$

(Of course, there are other, more direct, algebraic proofs of Corollary 2.4.)

Recall that the Jacobson radical of a ring is the intersection of its maximal ideals.

Corollary 2.6. *Let R be a NIP integral domain. Then the Jacobson radical of R is nonzero.*

Proof. In a domain, the intersection of two nonzero ideals is nonzero. $\square$

Corollary 2.7. *Let R be a NIP integral domain that is not a field. Let $K = \mathrm{Frac}(R)$. There is a nontrivial, nondiscrete Hausdorff field topology on K characterized by either of the following:*

- *The family of sets $\{aR : a \in K^\times\}$ is a neighborhood basis of* 0.
- *The set of nonzero ideals of R is a neighborhood basis of* 0.

Proof. Everything follows formally by [Prestel and Ziegler 1978, Example 1.2], except that we only get a *ring* topology. It remains to see that the map $x \mapsto 1/x$ is continuous. It suffices to consider continuity around $x = 1$. Let I be a nonzero ideal in R. We claim there is a nonzero ideal I' such that if $x \in 1 + I'$, then $1/x \in 1 + I$. Indeed, take $I' = I \cap J$, where J is the Jacobson radical. Suppose $x \in 1 + (I \cap J)$. Then $x - 1$ is in every maximal ideal, implying that x is in no maximal ideals, so $x \in R^\times$. Also, $x \in 1+I$ implies that $1-x \in I$, and then $x^{-1}(1-x) \in I$, because x is a unit. But $x^{-1}(1-x) = x^{-1} - 1$, and so $x^{-1} \in 1 + I$ as desired. □

Lemma 2.8. *If R and S are NIP rings and $R \equiv S$, then R and S have the same number of maximal ideals.*

Proof. It suffices to show that S has as many maximal ideals as R. By Corollaries 2.3 and 2.4 we can write the maximal ideals of R as $\phi_1(R, a_1), \dots, \phi_n(R, a_n)$ for some formulas ϕ_i and parameters a_i from R. Let $\psi(y_1, \dots, y_n)$ be the formula asserting

> the sets $\phi_1(R, y_1), \dots, \phi_n(R, y_n)$ are pairwise distinct maximal ideals.

The formula ψ is satisfied by the tuple $(a_1, \dots, a_n)$ in R, so it is satisfied by some tuple in S, giving n distinct maximal ideals in S. □

2B. *Localizations.* If M is a structure, then M^{Sh} denotes the Shelah expansion of M. If M is NIP, then the definable sets in M^{Sh} are exactly the externally definable sets in M, and M^{Sh} is NIP [Simon 2015, Proposition 3.23, Corollary 3.24].

Say that a collection of sets $\mathcal{C}$ is "uniformly definable" in a structure M if $\mathcal{C} \subseteq \{X_a : a \in Y\}$ for some definable family of sets $\{X_a\}_{a \in Y}$.

Remark 2.9. Let M be a structure. Suppose $D = \bigcup_{i \in I} D_i$ is a directed union, and the D_i are uniformly definable in M. Then D is externally definable.

This is well known in certain circles, but here is the proof for completeness:

Proof. Take some $L(M)$-formula $\phi(x, y)$ such that $D_i = \phi(M, b_i)$ for some $b_i \in M^y$. Let $\Sigma(y)$ be the partial type

$$\{\phi(a, y) : a \in D\} \cup \{\neg\phi(a, y) : a \in M^x \setminus D\}.$$

Then $\Sigma(y)$ is finitely satisfiable, because for any $a_1, \dots, a_n \in D$ and $e_1, \dots, e_m \in M^x \setminus D$ we can find some i such that $D_i \supseteq \{a_1, \dots, a_n\}$, because the union is directed. Then $D_i \subseteq D$, so $D_i \cap \{e_1, \dots, e_m\} = \varnothing$. Thus b_i satisfies the relevant finite fragment of $\Sigma(y)$. By compactness there is a realization b of $\Sigma(y)$ in an elementary extension $N \succeq M$. Then $\phi(M, b) = D$, by definition of $\Sigma(y)$, so D is externally definable. □

Lemma 2.10. *Let R be a NIP ring. Let S be a multiplicative subset. Then there is an externally definable multiplicative subset $\overline{S}$ such that the localization $S^{-1}R$ is isomorphic (as an R-algebra) to $\overline{S}^{-1}R$.*

Proof. For any $x \in R$, let F_x denote the set of $y \in R$ such that $y \mid x$. Let $\bar{S} = \bigcup_{x \in S} F_x$. Note that if A is a ring and $f : R \to A$ is a homomorphism, then the following are equivalent:

- $f(s)$ is invertible for every $s \in S$.
- $f(x)$ is invertible for x, y, s with $xy = s$ and $s \in S$.
- $f(x)$ is invertible for x, s with $x \in F_s$ and $s \in S$.
- $f(x)$ is invertible for $x \in \bar{S}$.

Therefore $S^{-1}R$ and $\bar{S}^{-1}R$ represent the same functor, and are isomorphic.

It remains to see that $\bar{S}$ is externally definable. This follows by Remark 2.9 because the sets F_x are uniformly definable, and the union $\bigcup_{x \in S} F_x$ is a directed union. Indeed, if $x, y \in S$, then $xy \in S$ and $F_{xy} \supseteq F_x \cup F_y$. □

Theorem 2.11. *Let R be a NIP ring. Let S be a multiplicative subset. Then the localization $S^{-1}R$ and the homomorphism $R \to S^{-1}R$ are interpretable in R^{Sh}.*

Proof. By Lemma 2.10, we may replace S with an externally definable set $\bar{S}$, and then the result is clear. □

Corollary 2.12. *Let R be a NIP ring. Let S be a multiplicative subset. Then the localization $S^{-1}R$ is also NIP.*

Proof. The localization $S^{-1}R$ is interpretable in the NIP structure R^{Sh}. □

Corollary 2.12 generalizes part of [d'Elbée and Halevi 2021, Proposition 2.8(2)], dropping the assumptions that S is externally definable and R is integral.

Proposition 2.13. *Let R be a NIP ring. Let $\mathfrak{p}$ be a prime ideal in R. Then $\mathfrak{p}$ is externally definable.*

Proof. By Theorem 2.11, we can interpret $R \to R_{\mathfrak{p}}$ in R^{Sh}. The maximal ideal of $R_{\mathfrak{p}}$ is definable in $R_{\mathfrak{p}}$, as the set of nonunits. It pulls back to $\mathfrak{p}$ in R. Therefore $\mathfrak{p}$ is definable in R^{Sh}, hence externally definable in R. □

Proposition 2.13 generalizes a theorem of d'Elbée and Halevi, who proved that (certain) prime ideals in dp-minimal domains are externally definable [d'Elbée and Halevi 2021, Lemma 3.3].

Theorem 2.14. *Let R be a NIP ring. Let I be a radical ideal in R. Then I is externally definable.*

Proof. By Corollary 2.2, we can cover the set $\operatorname{Spec} R$ of prime ideals in R with finitely many chains $\mathcal{C}_1, \dots, \mathcal{C}_n$. The ideal I is an intersection of prime ideals. Let $\mathfrak{p}_i$ be the intersection of the prime ideals $\mathfrak{p} \in \mathcal{C}_i$ with $\mathfrak{p} \supseteq I$. An intersection of a chain of prime ideals is prime, so $\mathfrak{p}_i$ is prime. Then I is a finite intersection $\bigcap_{i=1}^n \mathfrak{p}_i$. Each $\mathfrak{p}_i$ is externally definable by Proposition 2.13. □

Corollary 2.15. *Let R be a NIP ring. Let I be a radical ideal. The quotient R/I is NIP.*

Proof. The quotient R/I is interpretable in the NIP structure R^{Sh}. □

2C. ***Automatic connectedness.*** If G is a definable or type-definable group, then G^{00} is the smallest type-definable group of bounded index in G. In a NIP context, G^{00} always exists, and is type-definable over whatever parameters define G [Hrushovski et al. 2008, Proposition 6.1]

Proposition 2.16. *Let R be a NIP ring. Suppose that $R/\mathfrak{m}$ is infinite for every maximal ideal $\mathfrak{m}$ of R.*

(1) *If I is a definable ideal of R, then $I = I^{00}$.*

(2) *If R is a domain and $K = \text{Frac}(R)$ and if I is a definable R-submodule of K, then $I = I^{00}$.*

In particular, in either case, I has no definable proper subgroups of finite index.

Proof. We may assume R is a monster model, i.e., κ-saturated for some big cardinal κ. "Small" will mean "cardinality less than κ", and "large" will mean "not small."

Let $\mathfrak{m}_1, \dots, \mathfrak{m}_n$ be the maximal ideals of R. By Corollary 2.3 there are only finitely many, and by Corollary 2.4 they are all definable. The quotients $R/\mathfrak{m}_i$ are infinite, hence large. Therefore every simple R-module is large. Every nontrivial R-module has a simple subquotient, so every nontrivial R-module is large.

Now suppose I is a definable ideal. If $a \in R$, then the map $I \to I$ sending x to ax must map I^{00} into I^{00}. Indeed, if we let $J = \{x \in I : ax \in I^{00}\}$, then J is a type-definable subgroup of I of bounded index, so $J \supseteq I^{00}$. Thus we see that for any $a \in R$, we have $aI^{00} \subseteq I^{00}$. In other words, I^{00} is an ideal. The quotient I/I^{00} is an R-module. By definition of G^{00}, the quotient I/I^{00} is small. We saw that nontrivial R-modules are large, so I/I^{00} must be trivial, implying $I = I^{00}$. This proves (1), and (2) is similar. □

3. NIP $\mathbb{F}_p$-algebras

3A. ***A variant of the Kaplan–Scanlon–Wagner theorem.*** In [Kaplan et al. 2011, Theorem 4.4], Kaplan, Scanlon, and Wagner show that if K is an infinite NIP field of characteristic $p > 0$, then the Artin–Schreier map $x \mapsto x^p - x$ is a surjection from K onto K. The same idea can be applied to certain local rings, as we will see in Theorem 3.4 below.

Before proving the theorem, we need some (well-known) lemmas on additive polynomials. Fix a field K of characteristic p. If $c \in K$, define

$$g_c(x) = x^p - c^{p-1}x.$$

The polynomial $g_c(x)$ defines an additive homomorphism from K to K. If V is a finite-dimensional $\mathbb{F}_p$-linear subspace of K (i.e., a finite subgroup of $(K,+)$), define

$$f_V(x) = \prod_{a \in V} (x - a). \tag{1}$$

We will see shortly that f_V is an additive homomorphism.

Lemma 3.1. *If $c \in K$ is nonzero, then $g_c(x) = f_{\mathbb{F}_p \cdot c}(x)$. In particular, $f_{\mathbb{F}_p \cdot c}(x)$ is an additive homomorphism.*

Proof. Note that $g_c(c) = 0$. Therefore, $\ker g_c$ contains the subgroup generated by c, which is $\mathbb{F}_p \cdot c$. Since g_c is monic of degree p, and $|\mathbb{F}_p \cdot c| = p$, we must have

$$g_c(x) = \prod_{a \in \mathbb{F}_p \cdot c} (x - a) = f_{\mathbb{F}_p \cdot c}(x). \qquad \square$$

Lemma 3.2. *Suppose $V_1 \subseteq V_2$ are finite-dimensional subspaces of K such that $\dim V_2 = \dim V_1 + 1$. Suppose f_{V_1} is an additive homomorphism on K. Then there is $c \in f_{V_1}(V_2)$ such that $f_{V_2} = g_c \circ f_{V_1}$, and in particular f_{V_2} is an additive homomorphism on K.*

Proof. Take $a \in V_2 \setminus V_1$ and let $c = f_{V_1}(a)$. Let $h = g_c \circ f_{V_1}$. Then h is an additive homomorphism on K, and it suffices to show that $h = f_{V_2}$. Note that if $x \in V_1$, then $h(x) = g_c(f_{V_1}(x)) = g_c(0) = 0$, since f_{V_1} vanishes on V_1. Additionally, $h(a) = g_c(f_{V_1}(a)) = g_c(c) = 0$. Thus the kernel of h contains V_1 as well as a. It therefore contains the group they generate, which is $V_1 + \mathbb{F}_p \cdot a = V_2$. If $d = \dim V_1$, then $|V_1| = p^d$ and $|V_2| = p^{d+1}$. The polynomial f_{V_1} is a monic polynomial of degree p^d, and g_c is a monic polynomial of degree p. Therefore the composition h is a monic polynomial of degree p^{d+1}. We have just seen that h vanishes on the set V_2 of size p^{d+1}, so $h(x)$ must be $\prod_{u \in V_2}(x - u) = f_{V_2}(x)$. $\square$

Lemma 3.3. *If V is a finite-dimensional subspace of K, then f_V is an additive homomorphism with kernel V.*

Proof. The fact that f_V is an additive homomorphism follows by induction on $\dim V$ using Lemma 3.2. The fact that $\ker f_V = V$ is immediate from the definition of f_V. $\square$

We now can prove our desired theorem on NIP local domains in positive characteristic:

Theorem 3.4. *Let $p > 0$ be a prime. Let R be a NIP $\mathbb{F}_p$-algebra with the following properties: R is a local ring, R is an integral domain with maximal ideal $\mathfrak{m}$, and the quotient field $k = R/\mathfrak{m}$ is infinite. Then $x \mapsto x^p - x$ is a surjection from R onto R.*

Proof. Let $K = \operatorname{Frac}(R)$. Note that if V is a finite-dimensional $\mathbb{F}_p$-subspace of R, then $f_V(x) \in R[x]$, and if $c \in R$, then $g_c(x) \in R[x]$.

Claim 3.5. *It suffices to find $c \in R^\times$ such that $g_c(x)$ is a surjection from R to R.*

Proof of claim. Note that $c^{-p} g_c(cx) = c^{-p}(c^p x^p - c^{p-1}cx) = x^p - x$. The maps $x \mapsto cx$ and $x \mapsto c^{-p}x$ are bijections on R, so if g_c is surjective then so is $g_1(x) = x^p - x$. □

For any $c \in R$, the polynomial $g_c(x)$ defines an additive map $R \to R$, whose image $g_c(R)$ is an additive subgroup of R. Let $\mathcal{G} = \{g_c(R) : c \in R\}$. By the Baldwin–Saxl theorem for NIP groups, there is some integer n such that if $G_1, \ldots, G_n \in \mathcal{G}$, then there is some i such that

$$G_i \supseteq G_1 \cap \cdots \cap G_{i-1} \cap G_{i+1} \cap \cdots \cap G_n.$$

Fix such an $n \geq 2$.

The residue field k is infinite, and therefore we can find $\mathbb{F}_p$-linearly independent $\alpha_1, \ldots, \alpha_n \in k$. Take $a_i \in R$ lifting $\alpha_i \in k$. Note $\alpha_i \neq 0$, so $a_i \notin \mathfrak{m}$, and thus $a_i \in R^\times$. Also note that the elements $\{a_1, \ldots, a_{n-1}\}$ are $\mathbb{F}_p$-linearly independent in K.

Let $[n] = \{1, \ldots, n\}$. If $S \subseteq [n]$ and $i \in [n]$, we write $S \cup i$ and $S \setminus i$ as abbreviations for $S \cup \{i\}$ and $S \setminus \{i\}$. Even worse, we sometimes abbreviate $\{i\}$ as i.

For $S \subseteq [n]$, let V_S be the $\mathbb{F}_p$-linear span of $\{a_i : i \in S\}$. Then V_S has dimension $|S|$. Let

$$f_S(x) := f_{V_S}(x) = \prod_{a \in V_S} (x - a).$$

This is a monic polynomial in $R[x]$. By Lemma 3.3 $f_S(x)$ induces an additive homomorphism $K \to K$, and therefore an additive homomorphism $R \to R$.

Note that $f_i(x) = f_{V_i}(x) = f_{\mathbb{F}_p \cdot a_i}(x) = g_{a_i}(x)$ by Lemma 3.1. By Claim 3.5, it suffices to show that f_i is a surjection from R to R, for at least one i.

If $S \subseteq [n]$ and $i \in [n] \setminus S$, then $V_{S \cup i}$ has dimension one more than V_S. By Lemma 3.2, there is some $c_{S,i} \in f_S(V_{S \cup i})$ such that $g_{c_{S,i}} \circ f_S = f_{S \cup i}$. Let $g_{S,i} := g_{c_{S,i}}$. Then

$$g_{S,i} \circ f_S = f_{S \cup i}.$$

Now $c_{S,i} \in f_S(V_{S \cup i})$, but $f_S(x) \in R[x]$ and $V_{S \cup i} \subseteq R$. Therefore $c_{S,i} \in R$, and $g_{S,i}(x) \in R[x]$.

Claim 3.6. *If $S \subseteq [n]$ and i, j are distinct elements of $[n] \setminus S$, then $c_{S,i}^{p-1} - c_{S,j}^{p-1} \notin \mathfrak{m}$.*

Proof of claim. Otherwise, the two polynomials $g_{S,i}(x)$ and $g_{S,j}(x)$ have the same reduction modulo $\mathfrak{m}$. From the identities $f_{S \cup i} = g_{S,i} \circ f_S$ and $f_{S \cup j} = g_{S,j} \circ f_S$, it follows that $f_{S \cup i} \equiv f_{S \cup j} \pmod{\mathfrak{m}}$. Let V'_S be the $\mathbb{F}_p$-linear span of $\{\alpha_i : i \in S\}$, or equivalently, the image of V_S under $R \to R/\mathfrak{m}$. By inspection, the reduction of f_S modulo $\mathfrak{m}$ is $\prod_{u \in V'_S}(x - u)$. Since $V'_{S \cup i} \neq V'_{S \cup j}$, it follows immediately that $f_{S \cup i}$ and $f_{S \cup j}$ cannot have the same reduction modulo $\mathfrak{m}$, a contradiction. □

Each of the groups $g_{[n]\setminus i,i}(R)$ is in the family $\mathcal{G}$. By choice of n, one of the factors in the intersection $\bigcap_{i=1}^n g_{[n]\setminus i,i}(R)$ is irrelevant. Without loss of generality, it is the first factor:

$$g_{[n]\setminus 1,1}(R) \supseteq \bigcap_{i=2}^{n} g_{[n]\setminus i,i}(R). \tag{2}$$

We claim that $f_1(x)$ defines a surjection from R to R. As $f_1(x) = g_{a_1}(x)$, this suffices, by Claim 3.5.

Take some $b_1 \in R$. It suffices to show that $b_1 \in f_1(R)$. Take some $b_\varnothing \in K^{\mathrm{alg}}$ such that $f_1(b_\varnothing) = b_1$. It suffices to show that $b_\varnothing \in R$. For $S \subseteq [n]$, define $b_S = f_S(b_\varnothing) \in K^{\mathrm{alg}}$. (When $S = \{1\}$ this recovers b_1, and when $S = \varnothing$ this recovers $b_\varnothing$, so the notation is consistent.) Note that

$$g_{S,i}(b_S) = g_{S,i}(f_S(b_\varnothing)) = f_{S\cup i}(b_\varnothing) = b_{S\cup i}. \tag{3}$$

Claim 3.7. *If* $1 \in S \subseteq [n]$, *then* $b_S \in R$.

Proof of claim. Take a minimal counterexample S. If $S = \{1\}$, then $b_S = b_1 \in R$. Otherwise, take $i \in S \setminus 1$ and let $S_0 = S \setminus i$. By choice of S, we have $b_{S_0} \in R$. Then $b_S = g_{S_0,i}(b_{S_0})$. But $g_{S_0,i}(x) \in R[x]$, so $b_S \in R$. □

In particular, $b_S \in R$ for $S = [n]$, as well as $S = [n] \setminus i$ for $i > 1$. Then

$$b_{[n]} = g_{[n]\setminus i,i}(b_{[n]\setminus i}) \in g_{[n]\setminus i,i}(R)$$

for $1 < i \le n$. By (2), $b_{[n]} \in g_{[n]\setminus 1,1}(R)$. Take $v \in R$ such that $g_{[n]\setminus 1,1}(v) = b_{[n]}$. Then $g_{[n]\setminus 1,1}(v) = b_{[n]} = g_{[n]\setminus 1,1}(b_{[n]\setminus 1})$, and so

$$v - b_{[n]\setminus 1} \in \ker g_{[n]\setminus 1,1} = \mathbb{F}_p \cdot c_{[n]\setminus 1,1} \subseteq R.$$

Therefore $b_{[n]\setminus 1} \in R$. So we see that

$$b_{[n]\setminus i} \in R \quad \text{for all } 1 \le i \le n. \tag{4}$$

Claim 3.8. $b_\varnothing \in R$.

Proof of claim. Suppose otherwise. Take S maximal such that $b_S \notin R$. By Claim 3.7 and (4), S is neither $[n]$ nor $[n] \setminus i$ for $1 \le i \le n$. Therefore $[n] \setminus S$ contains at least two elements i, j. By choice of S, we have $b_{S\cup i} \in R$ and $b_{S\cup j} \in R$. By (3),

$$b_{S\cup i} = g_{S,i}(b_S) = b_S^p - c_{S,i}^{p-1} b_S \quad \text{and} \quad b_{S\cup j} = g_{S,j}(b_S) = b_S^p - c_{S,j}^{p-1} b_S.$$

Therefore

$$(c_{S,i}^{p-1} - c_{S,j}^{p-1}) b_S = b_{S\cup j} - b_{S\cup i} \in R.$$

By Claim 3.6, $c_{S,i}^{p-1} - c_{S,j}^{p-1} \in R \setminus \mathfrak{m} = R^\times$, and so $b_S \in R$, a contradiction. □

This completes the proof. We see that $b_\varnothing \in R$, and so $b_1 = f_1(b_\varnothing) \in f_1(R)$. As b_1 was an arbitrary element of R, it follows that f_1 gives a surjection from R to R. But $f_1(x) = g_{a_1}(x)$, and $a_1 \in R^\times$ (since its residue mod $\mathfrak{m}$ is the nonzero element α_1), and so we are done by Claim 3.5. $\square$

3B. *Linearly ordering the primes.*

Lemma 3.9. *Let R be an $\mathbb{F}_p$-algebra that is integral and has exactly two maximal ideals $\mathfrak{m}_1$ and $\mathfrak{m}_2$. Suppose that $R/\mathfrak{m}_1$ and $R/\mathfrak{m}_2$ are infinite. Then R isn't NIP.*

The proof uses an identical strategy to [Johnson 2021a, Lemma 2.6].

Proof. Suppose R is NIP. By Corollary 2.4, $\mathfrak{m}_1$ and $\mathfrak{m}_2$ are definable. Let $K = \mathrm{Frac}(R)$. Regard the localizations $R_{\mathfrak{m}_1}$ and $R_{\mathfrak{m}_2}$ as definable subrings of K. Note that $R_{\mathfrak{m}_1} \cap R_{\mathfrak{m}_2} = R$, by commutative algebra. (If $x \in K \setminus R$, then let $I = \{a \in R : ax \in R\}$; this is a proper ideal in R, so it is contained in some $\mathfrak{m}_i$, and then $I \subseteq \mathfrak{m}_i$ means precisely that $x \notin R_{\mathfrak{m}_i}$.)

Claim 3.10. *If $x \in R$, then the Artin–Schreier roots of x are in R.*

Proof of claim. The rings $R_{\mathfrak{m}_1}$ and $R_{\mathfrak{m}_2}$ satisfy the conditions of Theorem 3.4. (The residue field of $R_{\mathfrak{m}_i}$ is isomorphic to $R/\mathfrak{m}_i$, hence infinite.) Therefore, there are $y \in R_{\mathfrak{m}_1}$ and $z \in R_{\mathfrak{m}_2}$ such that $y^p - y = x = z^p - z$. Then $y - z$ is in the kernel of the Artin–Schreier map, which is $\mathbb{F}_p$, so $y \in z + \mathbb{F}_p \subseteq R_{\mathfrak{m}_2}$. As $y \in R_{\mathfrak{m}_1}$, this implies $y \in R_{\mathfrak{m}_1} \cap R_{\mathfrak{m}_2} = R$. Thus, at least one Artin–Schreier root (y) is in R. The other Artin–Schreier roots of x are the elements of $y + \mathbb{F}_p$, which are all in R. $\square$

Let $J = \mathfrak{m}_1 \cap \mathfrak{m}_2$. This is the Jacobson radical of R. By Proposition 2.16, $J = J^{00}$, and there are no definable subgroups of finite index. Consider the sets

$$\Delta = \{(x, i, j) \in R \times \mathbb{F}_p \times \mathbb{F}_p : x - i \in \mathfrak{m}_1,\ x - j \in \mathfrak{m}_2\},$$
$$\Gamma = \{(x^p - x, i - j) : (x, i, j) \in \Delta\}.$$

Then $(\Delta, +)$ and $(\Gamma, +)$ are definable groups.

Claim 3.11. *Γ is the graph of a group homomorphism ψ from $(J, +)$ onto $(\mathbb{F}_p, +)$.*

Proof of claim. First, we show that $\Gamma \subseteq J \times \mathbb{F}_p$. Suppose that $(x, i, j) \in \Delta$. Then $x \equiv i \pmod{\mathfrak{m}_1}$, so $x^p - x \equiv i^p - i \equiv 0 \pmod{\mathfrak{m}_1}$, and $x^p - x \in \mathfrak{m}_1$. Similarly, $x^p - x \in \mathfrak{m}_2$, and therefore $x^p - x \in J$. Thus $(x^p - x, i - j) \in J \times \mathbb{F}_p$.

Next we show that Γ projects onto J. Take $y \in J$. By Claim 3.10 there is $x \in R$ with $x^p - x = y$. Then $x^p - x \equiv y \equiv 0 \pmod{\mathfrak{m}_1}$, so $x^p - x \equiv i \pmod{\mathfrak{m}_1}$ for some $i \in \mathbb{F}_p$. Similarly, $x^p - x \equiv j \pmod{\mathfrak{m}_2}$ for some $j \in \mathbb{F}_p$. Then $(x, i, j) \in \Delta$ and $(x^p - x, i - j) = (y, i - j) \in \Gamma$.

Next we show that the projection $\Gamma \to J$ is one-to-one. Otherwise, $\Gamma \to J$ has nontrivial kernel, so there is $(x, i, j) \in \Delta$ with $x^p - x = 0$ but $i - j \neq 0$. The fact that $x^p - x = 0$ implies $x \in \mathbb{F}_p$, and so $x \equiv i \pmod{\mathfrak{m}_1}$ implies $x = i$. Similarly, $x = j$. But then $i - j = 0$, a contradiction.

So now we see that $\Gamma \to J$ is one-to-one and onto, implying that Γ is the graph of some group homomorphism ψ from J to $\mathbb{F}_p$. It remains to show that ψ is onto. Equivalently, we must show that Γ projects onto $\mathbb{F}_p$. Let $i \in \mathbb{F}_p$ be given. By the Chinese remainder theorem, there is $x \in R$ such that $x \equiv i \pmod{\mathfrak{m}_1}$ and $x \equiv 0 \pmod{\mathfrak{m}_2}$. Then $(x, i, 0) \in \Delta$, so $(x^p - x, i - 0) \in \Gamma$. The element $(x^p - x, i)$ projects onto i. Equivalently, $\psi(x^p - x) = i$. □

Therefore there is a definable surjective group homomorphism $\psi : J \to \mathbb{F}_p$. The kernel $\ker \psi$ is a definable subgroup of J of index p. This contradicts Proposition 2.16. □

Lemma 3.12. *Let R be a NIP integral $\mathbb{F}_p$-algebra. Let $\mathfrak{p}_1$ and $\mathfrak{p}_2$ be prime ideals such that $R/\mathfrak{p}_1$ and $R/\mathfrak{p}_2$ are infinite. Then $\mathfrak{p}_1$ and $\mathfrak{p}_2$ are comparable.*

Proof. Suppose otherwise. Let $S = R \setminus (\mathfrak{p}_1 \cup \mathfrak{p}_2)$. Then S is a multiplicative subset of R. Let $R' = S^{-1}R$. Then R' is NIP by Corollary 2.12. The ring R' has exactly two maximal ideals $\mathfrak{m}_1$ and $\mathfrak{m}_2$, where $\mathfrak{m}_i = \mathfrak{p}_i R'$. The map $R/\mathfrak{p}_i \to R'/\mathfrak{m}_i$ is injective, so $R'/\mathfrak{m}_i$ is infinite, for $i = 1, 2$. This contradicts Lemma 3.9. □

Lemma 3.13. *Let R be an $\mathbb{F}_p$-algebra that is integral and has exactly two maximal ideals $\mathfrak{m}_1$ and $\mathfrak{m}_2$. Then R isn't NIP.*

Proof. Assume otherwise. Going to an elementary extension, we may assume that R is very saturated (Lemma 2.8). By the Chinese remainder theorem, there is some $a \in R$ such that $a \equiv 0 \pmod{\mathfrak{m}_1}$ but $a \equiv 1 \pmod{\mathfrak{m}_2}$.

Let $\Sigma(x)$ be the partial type saying that $x \in \mathfrak{m}_1$, $x \notin \mathfrak{m}_2$, and x does not divide a^n for any n.

Claim 3.14. *$\Sigma(x)$ is finitely satisfiable.*

Proof of claim. Let n be given. We claim there is an x such that $x \in \mathfrak{m}_1$, $x \notin \mathfrak{m}_2$, and x does not divide a^i for $i \leq n$. Take $x = a^{n+1}$. Then $x \equiv 0^{n+1} \equiv 0 \pmod{\mathfrak{m}_1}$, so $x \in \mathfrak{m}_1$. But $x \equiv 1^{n+1} \equiv 1 \pmod{\mathfrak{m}_2}$, so $x \notin \mathfrak{m}_2$. Finally, suppose $x = a^{n+1}$ divides a^i for some $i \leq n$. Then there is $u \in R$ with $ua^{n+1} = a^i$. Since R is a domain, we can cancel a factor of a^i from both sides, and see $ua^{n+1-i} = 1$. This implies that a is a unit, contradicting the fact that $a \in \mathfrak{m}_1$. □

By saturation, there is $a' \in R$ satisfying $\Sigma(x)$. The principal ideal (a') does not intersect the multiplicative set $S := a^{\mathbb{N}}$, by definition of $\Sigma(x)$. Let $\mathfrak{p}_1$ be maximal among ideals containing (a') and avoiding S. Then $\mathfrak{p}_1$ is a prime ideal. (In general, any ideal that is maximal among ideals avoiding a multiplicative set is prime.)

Now $\mathfrak{p}_1 \not\subseteq \mathfrak{m}_2$, because $a' \in \mathfrak{p}_1$ but $a' \notin \mathfrak{m}_2$. But $\mathfrak{p}_1$ must be contained in *some* maximal ideal, and so $\mathfrak{p}_1 \subseteq \mathfrak{m}_1$. The inclusion is strict, because $a \in \mathfrak{m}_1$ but $a \notin \mathfrak{p}_1$. Thus $\mathfrak{p}_1 \subsetneq \mathfrak{m}_1$ and $\mathfrak{p}_1 \not\subseteq \mathfrak{m}_2$. In particular, $\mathfrak{p}_1$ is not a maximal ideal.

Similarly, there is a nonmaximal prime ideal $\mathfrak{p}_2$ with $\mathfrak{p}_2 \subsetneq \mathfrak{m}_2$ and $\mathfrak{p}_2 \not\subseteq \mathfrak{m}_1$. Then $\mathfrak{p}_1$ and $\mathfrak{p}_2$ are incomparable. Otherwise, say, $\mathfrak{p}_1 \subseteq \mathfrak{p}_2 \subsetneq \mathfrak{m}_2$, and so $\mathfrak{p}_1 \subseteq \mathfrak{m}_2$, a contradiction. For $i = 1, 2$, the fact that $\mathfrak{p}_i$ is a nonmaximal prime ideal implies that $R/\mathfrak{p}_i$ is a nonfield integral domain, and therefore infinite. This contradicts Lemma 3.12. □

Theorem 3.15. *Let R be a NIP integral $\mathbb{F}_p$-algebra. Then the prime ideals of R are linearly ordered by inclusion.*

Proof. The same proof as Lemma 3.12, using Lemma 3.13 instead of Lemma 3.9. □

Corollary 3.16. *Let R be a NIP $\mathbb{F}_p$-algebra. Let $\mathfrak{p}_1$, $\mathfrak{p}_2$, and $\mathfrak{q}$ be prime ideals. If $\mathfrak{p}_i \supseteq \mathfrak{q}$ for $i = 1, 2$, then $\mathfrak{p}_1$ is comparable to $\mathfrak{p}_2$.*

Proof. Otherwise, $\mathfrak{p}_1$ and $\mathfrak{p}_2$ induce incomparable primes in the NIP domain $R/\mathfrak{q}$. □

3C. *Henselianity.*

Definition 3.17. A *forest* is a poset $(P, \leq)$ with the property that if $x \in P$, then the set $\{y \in P : y \geq x\}$ is linearly ordered.

Definition 3.18. A ring R is *good* if Spec R is a forest of finite width.

Lemma 3.19. (1) *If R is a NIP $\mathbb{F}_p$-algebra, then R is good.*

(2) *If R is good, then any quotient R/I is good.*

(3) *If R is good, then R is a finite product of local rings.*

Proof. (1) Fact 2.1 and Corollary 3.16.

(2) This is clear, since Spec R/I is a subposet of Spec R.

(3) We now break our usual convention, and regard Spec R as a scheme, or at least a topological space. By scheme theory, it suffices to write Spec R as a finite disjoint union of clopen sets U_i such that each U_i contains a unique closed point. Let $\mathfrak{m}_1, \ldots, \mathfrak{m}_n$ be the maximal ideals of R. There are finitely many because Spec R has finite width. Note that every prime ideal $\mathfrak{p} \in R$ satisfies $\mathfrak{p} \subseteq \mathfrak{m}_i$ for a unique i. (There is at least one i by Zorn's lemma, and at most one i because Spec R is a forest.) Let U_i be the set of primes below $\mathfrak{m}_i$. Then Spec R is a disjoint union of the U_i. It remains to show that each U_i is clopen. It suffices to show that each U_i is closed. Take $i = 1$. Let $\mathfrak{p}_1, \ldots, \mathfrak{p}_m$ be the minimal primes contained in $\mathfrak{m}_1$. (There are finitely many, because of finite width.) Let V_j be the set of primes containing $\mathfrak{p}_j$. Then V_j is a closed subset of Spec R — it is the closed subset cut out by the ideal $\mathfrak{p}_j$. Moreover, $V_j \subseteq U_1$, because Spec R is a forest. The sets $V_1, \ldots, V_m$ cover U_1, because every prime contains a minimal prime. Then U_1 is a finite union of closed sets $\bigcup_{i=1}^m V_i$, and so U_1 is closed. □

Proposition 3.20. *Let R be a NIP local $\mathbb{F}_p$-algebra. Then R is a henselian local ring.*

Proof. By [Stacks 2005–, Lemma 04GG, condition (9)], it is sufficient to prove the following: any finite R-algebra is a product of local rings. Let S be a finite R-algebra. Let $a_1, \ldots, a_n$ be elements of S which generate S as an R-module. Each a_i is integral over R [Dummit and Foote 2004, Proposition 15.23], so there is a monic polynomial $P_i(x) \in R[x]$ such that $P_i(a) = 0$ in S. Then there is a surjective homomorphism

$$R[x_1, \ldots, x_n]/(P_1(x_1), \ldots, P_i(x_i)) \to S.$$

The ring on the left is interpretable in R — it is a finite-rank free R-module with basis the monomials $\prod_{i=1}^n x_i^{n_i}$ for $\bar{n} \in \prod_{i=1}^n \{0, 1, \ldots, \deg P_i - 1\}$. Therefore, the left-hand side is a NIP ring. By Lemma 3.19, it is good, S is good, and S is a finite product of local rings. □

Theorem 3.21. *Let R be a NIP $\mathbb{F}_p$-algebra. Then R is a finite product of henselian local rings.*

Proof. By Lemma 3.19, R is good, and R is a finite product of local rings. These local rings are easily seen to be interpretable in R, so they are also NIP. By Proposition 3.20, they are henselian local rings. □

Theorem 3.22. *Let R be a NIP, integral $\mathbb{F}_p$-algebra. Then R is a henselian local domain.*

Proof. R is a local ring by Theorem 3.15. So it is henselian by Proposition 3.20. □

Recall that a field K is *large* (also called *ample*) if every smooth irreducible K-curve with at least one K-point contains infinitely many K-points [Pop 2014]. By [Pop 2010, Theorem 1.1], if R is a henselian local domain that is not a field, then $\mathrm{Frac}(R)$ is large. Therefore we get the following corollary:

Corollary 3.23. *Let R be a NIP integral domain, and $K = \mathrm{Frac}(R)$. Suppose $R \neq K$ and K has positive characteristic. Then K is large.*

Large stable fields are classified [Johnson et al. 2020]. If we could extend this classification to large NIP fields, then Corollary 3.23 would tell us something very strong about NIP integral domains of positive characteristic.

Acknowledgement

The author was supported by Fudan University, and by grant no. 12101131 of the National Natural Science Foundation of China.

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Received 4 Nov 2021. Revised 7 Dec 2021.

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Model Theory (ISSN 2832-904X electronic, 2832-9058 printed) at Mathematical Sciences Publishers, 798 Evans Hall #3840, c/o University of California, Berkeley, CA 94720-3840 is published continuously online.

MT peer review and production are managed by EditFlow® from MSP.

PUBLISHED BY

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nonprofit scientific publishing

https://msp.org/

Model Theory

no. 1 vol. 1 2022