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SPECIALIZATIONS OF FINITELY GENERATED SUBGROUPS OF ABELIAN VARIETIES

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ABSTRACT. Given a generic Mordell-Weil group over a function field, we can specialize it down to a number field. It has been known for some time that the resulting homomorphism of groups is injective "infinitely often". We prove that this is in fact true "almost always", in a sense that is quantitatively nearly best possible.

1. INTRODUCTION

Let k be a global field, and let V be a variety defined over k. Suppose A is an abelian variety defined over the function field $k(V)$; we may think of this also as a family of abelian varieties parametrized by elements v of V. Let Γ be a finitely generated subgroup of $A(k(V))$. Replacing V by a nonempty open subset if necessary, we can suppose that for all v in $V(\bar{k})$ the corresponding specialization from $k(V)$ to $k(v)$ induces an abelian variety A_v defined over $k(v)$ and a group homomorphism σ_v from Γ to $A_v(k(v))$. We say that v is exceptional if σ_v is not injective. The object of this paper is to prove that when k is a number field the exceptional points are scarce in a rather strong sense.

We shall measure the scarcity as follows. For v in $V(\bar{k})$ we have a relative degree $d(v) = [k(v) : k]$. Assume henceforth that V is explicitly embedded in projective space. Then we also have a corresponding (logarithmic) Weil height $h(v)$ relative to k. For a finite subset S of $V(\bar{k})$ we write $\omega(S) = \omega_V(S)$ for the least degree of any homogeneous polynomial, defined over $\bar{k}$, that vanishes on S but not identically on V. Clearly ω is subadditive in the sense that

$$\omega(S \cup S') \leq \omega(S) + \omega(S') \tag{1}$$

for finite subsets S, S'.

Let $\mathscr{E}$ denote the set of exceptional points, and for $d \geq 1$, $h \geq 1$ let $\mathscr{E}(d, h)$ be the set of all v in $\mathscr{E}$ with $d(v) \leq d$, $h(v) \leq h$. From now on we assume that k is a number field; thus each $\mathscr{E}(d, h)$ is a finite subset of $V(\bar{k})$. Suppose A has dimension $n \geq 1$ and Γ has rank $r \geq 0$.

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Main Theorem. *For each $d \geq 1$ there exists C depending only on k, V, A, Γ and d, such that for any $h \geq 1$ we have*

$$\omega(\mathscr{E}(d, h)) \leq Ch^{\kappa},$$

where $\kappa = \max(0, (r+2)(nr+r-1))$.

For purposes of comparison we note that if $V(d, h)$ is the set of all points v in $V(\bar{k})$ with $d(v) \leq d$, $h(v) \leq h$ then $\omega(V(d, h))$ usually increases exponentially with h, at least if d is not too small. For example, in §4 we will prove the following result.

SCHOLIUM 1. Suppose V has positive dimension, and let δ be the degree of V. Then there are constants $c > 0$, h_0, depending only on k and V, such that for any $h \geq h_0$ we have

$$\omega(V(\delta, h)) \geq \exp(ch).$$

Thus, loosely speaking, we may say that the exceptional set $\mathscr{E}$ lies on a hypersurface of "logarithmically small degree". So certainly σ_v is injective for infinitely many v in $V(\bar{k})$; and we even recover Néron's result [Né] that if V is affine space $\mathbb{A}^m$ or projective space $\mathbb{P}_m$ then the same is true for infinitely many v in $V(k)$ itself. In particular, for these v the rank of $A_v(k(v))$ is at least r. Such observations were used by Néron in [Né] to construct abelian varieties over number fields with Mordell-Weil groups of large rank.

Of course our Theorem actually implies that σ_v is injective for "almost all" v in a suitable sense. It follows that Néron's constructions work for "almost all" choices of the parameters. We can illustrate this more clearly in terms of cardinalities, at least if $V = \mathbb{A}^m$, by using the following simple result (to be proved in §4).

SCHOLIUM 2. Let Z be a finite subset of $\mathbb{A}$ with cardinality $|Z|$. Then for any finite subset S of $\mathbb{A}^m$ the cardinality of $S \cap Z^m$ satisfies

$$|S \cap Z^m| \leq \omega(S)|Z|^{m-1}.$$

We take $k = \mathbb{Q}$, and we let $g_2 = g_2(\mathbf{t})$, $g_3 = g_3(\mathbf{t})$ be elements of $k(V) = \mathbb{Q}(\mathbf{t}) = \mathbb{Q}(t_1, \ldots, t_m)$ with $g_2^3 \neq 27g_3^2$. Denote by E the Weierstrass elliptic curve with invariants g_2, g_3, and suppose the rank of $E(\mathbb{Q}(\mathbf{t}))$ is r. For any rational integers $\tau_1, \ldots, \tau_m$ such that $g_2(\boldsymbol{\tau})$, $g_3(\boldsymbol{\tau})$ are defined at $\boldsymbol{\tau} = (\tau_1, \ldots, \tau_m)$ and satisfy $g_2^3(\boldsymbol{\tau}) \neq 27g_3^2(\boldsymbol{\tau})$, we have a specialized elliptic curve $E_{\boldsymbol{\tau}}$ defined over $\mathbb{Q}$. Let $r_{\boldsymbol{\tau}}$ be its rank. We find that for any $H \geq 2$ the set $S(H)$ of such $\boldsymbol{\tau}$ with $r_{\boldsymbol{\tau}} < r$ and

$$0 \leq \tau_1, \ldots, \tau_m \leq H \tag{2}$$

satisfies

$$\omega(S(H)) \leq C(\log H)^{\kappa}$$

where $\kappa = \max(0, (r+2)(2r-1))$ and C depends only on E. Thus by Scholium 2 we see that the cardinality of $S(H)$ is $O(H^{m-1}(\log H)^{\kappa})$ as $H \to \infty$. Since the number of $\boldsymbol{\tau}$ satisfying (2) alone is at least H^m, we conclude that specialization almost never, in a rather strong sense, reduces the Mordell-Weil rank.

Probably the best known concrete example is the following, also taken from [Né] (but watered down to give rank only 8). Select 8 generic points in $\mathbb{A}^2$ together with $(0,0)$, and let E be the (unique) plane cubic through these 9 points. If we specify the group identity as $(0,0)$, it is well known that E becomes an elliptic curve over $k(V)$ with $k = \mathbb{Q}$ and $V = \mathbb{A}^{16} = (\mathbb{A}^2)^8$ (in fact we can even choose g_2, g_3 in $k(V)$ as above). And it is not hard to see (for example by moving one of the generic points along the curve) that the generic rank r is 8. Thus, with at most $O(H^{15+\varepsilon})$ exceptions as $H \to \infty$, the elliptic curve through the integer points $(x_1, y_1), \dots, (x_8, y_8), (0,0)$ with $0 \le x_1, y_1, \dots, x_8, y_8 \le H$ has rank at least 8 over $\mathbb{Q}$.

Similar remarks apply to the explicit elliptic curves $\Gamma(S, T, V)$ constructed by Nakata [Na]. These are defined over $k(\mathbb{A}^3) = \mathbb{Q}(S, T, V)$, with points $P_i(S, T, V)$ $(1 \le i \le 9)$ also defined over $\mathbb{Q}(S, T, V)$. It is proved that there exists a modulus m $(= 20957209)$, together with residues s_0, t_0, v_0, such that for any integers s, t, v satisfying

$$s \equiv s_0, \quad t \equiv t_0, \quad v \equiv v_0 \pmod{m} \tag{3}$$

the specialized points $P_i(s, t, v)$ $(1 \le i \le 9)$ are independent on the specialized curve $\Gamma(s, t, v)$. Since the triples satisfying (3) do not lie on any fixed hypersurface, it follows easily that the generic curve $\Gamma(S, T, V)$ has rank at least 9 over $\mathbb{Q}(S, T, V)$. Our Main Theorem therefore implies that, with at most $O(H^{2+\varepsilon})$ exceptions as $H \to \infty$, the elliptic curve $\Gamma(s, t, v)$ has rank at least 9 over $\mathbb{Q}$ for any integers s, t, v (not necessarily subject to (3)) with $0 \le s, t, v \le H$.

It is possible that the more elaborate examples of Néron [Né] for rank 10 and 11 can be treated in this way (see also the article [F] of Fried, especially Proposition 3.9 of p. 628 and the sentence at the top of p. 629; and a preprint [T] of Top).

Next we discuss to what extent the estimate of our Main Theorem can be improved. It is easy to find examples where the exceptional set $\mathscr{E}$ is large but contained in a fixed hypersurface (so the exponent $m - 1$ is best possible in the cardinality estimate corresponding to (2)). But we can do much more by generalizing an example of Silverman as follows. Let A be any simple abelian variety of dimension n defined over a number field k, and let l be the rank of $A(k)$. If A is explicitly embedded in projective space, we can take $V = A$ in the above, and so we can regard A as defined over its own function field $k(A)$. Suppose also that the endomorphism rank of A is trivial. Then it is not hard to see that the rank r of $\Gamma = A(k(A))$ is $l + 1$.

For the exceptional set in this situation we will prove in §4 the following result.

SCHOLIUM 3. There are constants $c > 0$, h_0, depending only on k and A, such that for any $h \geq h_0$ we have

$$\omega(\mathscr{E}(1, h)) \geq ch^{\lambda},$$

where $\lambda = \frac{1}{2}(r-1)/n$.

Thus in general it appears that a positive power of h cannot be avoided. However, when A has no constant part (that is, when there is no nonzero abelian subvariety of A defined over $\bar{k}$) some results of Silverman suggest that $\omega(\mathscr{E}(d, h))$ might be bounded independently of h. In fact if V is a curve and A has no constant part, Silverman [S1, Theorem C, p. 208] proved that the set $\mathscr{E}$ of all exceptional points over $\bar{k}$ is a set of bounded height in V (even for an arbitrary global field k). So in this case $\omega(\mathscr{E}(d, h))$ is indeed bounded independently of h.

Finally let us remark that one may replace the abelian variety A in the Main Theorem by the multiplicative group $\mathbb{G}_m$ and obtain analogous estimates. These are useful in recent work [PS] of van der Poorten and Schlickewei. The proofs are similar but easier; see §5 for a further discussion.

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2. PRELIMINARIES

We shall need a Néron-Tate height on each of the specialized abelian varieties A_v. To obtain these in a uniform manner, we first choose a very ample symmetric divisor D, defined over $k(V)$, on the generic abelian variety A. Replacing V by a nonempty open subset if necessary, we can assume that for all v in $V(\bar{k})$ this divisor specializes down to a very ample symmetric divisor D_v, defined over $k(v)$, on A_v. Let q_v be the associated Néron-Tate height on $A_v(\bar{k})$. This is positive definite on $A_v(\bar{k})$ modulo torsion.

Define the quantity

$$\mu_v = \inf q_v(Q),$$

where Q runs over all nontorsion points of $A_v(k(v))$. Also define τ_v as the cardinality of the torsion group of $A_v(k(v))$. For $r \geq 1$ and $\mathbf{m} = (m_1, \ldots, m_r)$ in $\mathbb{Z}^r$ write

$$|\mathbf{m}| = \max(|m_1|, \ldots, |m_r|).$$

Proposition 1. *For $q \geq \mu_v$ let $Q_1, \ldots, Q_r$ be linearly dependent points of $A_v(k(v))$ with Néron-Tate heights at most q. Then there exists $\mathbf{m}$ in $\mathbb{Z}^r$ with $0 < |\mathbf{m}| \leq r^{r-1}\tau_v(q/\mu_v)^{(r-1)/2}$ such that*

$$m_1 Q_1 + \cdots + m_r Q_r = 0. \tag{4}$$

Proof. This follows immediately from Theorem A of [M2], with $K = k(v)$.

To estimate μ_v and τ_v we appeal to the work of [M1]; again it may be necessary to replace V by a nonempty open subset.

Proposition 2. *For each $d \geq 1$ there exists $c > 0$, depending only on k, V, A, D and d, such that for any $h \geq 1$ and any v in $V(d, h)$ we have*

$$\mu_v \geq (ch^{2n+1})^{-1}, \quad \tau_v \leq ch^n.$$

Proof. This follows immediately from Corollaries 1 and 2 of [M1]; note that the constants C_1, C_2 therein depend only on the degree of $K = k(v)$.

To estimate q we need to choose Weil heights uniformly on each A_v. For this we fix basis elements $\varphi_0, \dots, \varphi_N$, defined over $k(V)$, of the linear system corresponding to the very ample divisor D on A. Again replacing V by a nonempty open subset, we may suppose that for all v in $V(\bar{k})$ the specializations of $\varphi_0, \dots, \varphi_N$ define a projective embedding of A_v into $\mathbb{P}_N$. Let h_v denote the associated Weil height on $A_v(\bar{k})$.

Proposition 3. *For each $d \geq 1$ there exists c, depending only on k, V, A, $\varphi_0, \dots, \varphi_N$ and d, such that for any $h \geq 1$, any v in $V(d, h)$, and any Q in $A_v(\bar{k})$ we have*

$$|q_v(Q) - h_v(Q)| \leq ch.$$

Proof. This is essentially Theorem A (p. 201) of [S1], due to Silverman and Tate.

3. Proof of the Main Theorem

We start by noting that our repeated removal of proper closed sets from V has the effect of reducing the function ω by a bounded quantity. Thus no generality is lost in this procedure.

We may clearly assume that Γ is nonzero. Our basic observation is that for each fixed nonzero P in Γ the set of v in $V(\bar{k})$ for which $\sigma_v(P) = 0$ is contained in a proper closed subset of V. Thus if the rank r of Γ is zero this proves the Theorem at once, for we see that $\omega(\mathscr{E}(d, h)) \leq C$ independently of d and h. So henceforth we will suppose $r \geq 1$.

Let $P_1, \dots, P_r$ be generators for the free part of Γ. For $\mathbf{m} = (m_1, \dots, m_r)$ in $\mathbb{Z}^r$ write $P_{\mathbf{m}} = m_1 P_1 + \cdots + m_r P_r$, and define $V_{\mathbf{m}}$ as the set of all v in $V(\bar{k})$ for which there exists a torsion point P in Γ such that

$$P_{\mathbf{m}} + P \neq 0, \quad \sigma_v(P_{\mathbf{m}} + P) = 0. \tag{5}$$

Thus our exceptional set $\mathscr{E}$ satisfies

$$\mathscr{E} \subseteq \bigcup_{\mathbf{m}} V_{\mathbf{m}}. \tag{6}$$

Each $V_{\mathbf{m}}$ lies in a proper closed subset of V, and we start by estimating ω on $V_{\mathbf{m}}$. Throughout this section, $c_1, c_2, \dots$ will denote positive constants depending only on k, V, A, the basis elements $\varphi_0, \dots, \varphi_N$ of §2, the generators $P_1, \dots, P_r$, and (from Lemma 2 onwards) the positive integer d.

Lemma 1. *For any* $\mathbf{m}$ *in* $\mathbb{Z}^r$ *and any finite subset* S *of* $V_{\mathbf{m}}$ *we have*

$$\omega(S) \le c_1(|\mathbf{m}|^2 + 1).$$

Proof. This is an easy deduction from the work of Altman [A]. We can find algebraically independent elements $t_1, \dots, t_m$ of $k(V)$ and we can then write $k(V) = \mathbb{Q}(t_1, \dots, t_m, u)$ for u integral of degree $q \ge 1$ over $\mathbb{Z}[t_1, \dots, t_m]$. Now Theorem 3.5 (p. 159) of [A] shows that for any $\mathbf{m}$ in $\mathbb{Z}^r$ and any torsion point P in $A(k(V))$ the point $P_{\mathbf{m}} + P$ has projective coordinates of the form

$$\xi_j = \sum_{i=0}^{q-1} X_{ij}(t_1, \dots, t_m)u^i \qquad (0 \le j \le N),$$

where the X_{ij} are polynomials in $\mathbb{Z}[t_1, \dots, t_m]$ of total degrees at most $c_2(|\mathbf{m}|^2 + 1)$ (we will not need bounds for their coefficients). Similarly the origin of $A(k(V))$ has projective coordinates of the form

$$\alpha_j = \sum_{i=0}^{q-1} A_{ij}(t_1, \dots, t_m)u^i \qquad (0 \le j \le N)$$

for polynomials A_{ij} in $\mathbb{Z}[t_1, \dots, t_m]$ of degrees at most c_3.

Replacing V by a nonempty open subset, we may suppose that the functions $t_1, \dots, t_m, u$ are regular on V. Let v be any point of $V_{\mathbf{m}}$, so that (5) holds for some torsion P. Since $P_{\mathbf{m}} + P \ne 0$, we can find a, b with $0 \le a, b \le N$ such that $\delta = \xi_a\alpha_b - \xi_b\alpha_a$ is not zero in $k(V)$. In particular $\xi = \xi_e$ is nonzero for some e $(= a$ or $b)$, and $\alpha = \alpha_f$ is nonzero for some f $(= a$ or $b)$. Now we see that $\delta\xi\alpha$ must vanish at v. For if $\xi\alpha$ does not vanish at v, then the $\xi_j(v)$, $\alpha_j(v)$ $(0 \le j \le N)$ must be projective coordinates of $\sigma_v(P_{\mathbf{m}} + P) = 0$ and $\sigma_v(0) = 0$ respectively; thus δ vanishes at v. Hence all points of $V_{\mathbf{m}}$ lie in the subsets, defined by $\delta\xi\alpha = 0$, which arise in such a way from the choices of P and a, b, e, f. This leads easily to the required estimate for $\omega(S)$ when S is any finite subset of $V_{\mathbf{m}}$, and so completes the proof.

Next, it follows from (6) that each finite set $\mathscr{E}(d, h)$ is contained in a union of finitely many sets $V_{\mathbf{m}}$.

Lemma 2. *For any* $d \ge 1$, $h \ge 1$ *we have*

$$\mathscr{E}(d, h) \subseteq \bigcup_{|\mathbf{m}| \le M} V_{\mathbf{m}},$$

where $M \le c_4 h^{nr+r-1}$.

Proof. Let v be an arbitrary element of $\mathscr{E}(d, h)$. If v is in $V_{\mathbf{0}}$ there is nothing to prove. Otherwise (6) shows that some linear combination, not identically zero, of $Q_1 = \sigma_v(P_1), \dots, Q_r = \sigma_v(P_r)$ is a torsion point. Thus $Q_1, \dots, Q_r$ are dependent. Therefore by Proposition 1 there is a relation (4) with $0 < |\mathbf{m}| \le r^{r-1}\tau_v(q/\mu_v)^{(r-1)/2}$, where $q \ge \mu_v$ is an upper bound for the Néron-Tate heights of $Q_1, \dots, Q_r$. Hence by Proposition 2 we have $0 < |\mathbf{m}| \le c_5 h^n (qh^{2n+1})^{(r-1)/2}$.

Also it is clear that the Weil heights $h_v(Q_1), \ldots, h_v(Q_r)$ do not exceed $c_6 h$; and thus by Proposition 3 we can take $q \le c_7 h$. We conclude that $0 < |\mathbf{m}| \le c_8 h^{nr+r-1}$. Since $\mathbf{m} \ne \mathbf{0}$, we have $P_{\mathbf{m}} \ne 0$; but $\sigma_v(P_{\mathbf{m}}) = 0$ by (4), and therefore v lies in $V_{\mathbf{m}}$; which proves the lemma.

The Main Theorem follows immediately. From (1) and Lemma 2 we see that

$$\omega(\mathscr{E}(d, h)) \le \sum_{|\mathbf{m}| \le M} \omega(S_{\mathbf{m}}),$$

where $S_{\mathbf{m}} = \mathscr{E}(d, h) \cap V_{\mathbf{m}}$. And Lemma 1 gives $\omega(S_{\mathbf{m}}) \le c_9 M^2$, whence

$$\omega(\mathscr{E}(d, h)) \le c_{10} M^r \cdot M^2 \le c_{11} h^{(r+2)(nr+r-1)}.$$

This completes the proof.

4. Proof of the scholia

We shall need an auxiliary result on heights (also used in [M1]). Let V, W be (quasiprojective) varieties, embedded in projective space and defined over our number field k. We write h for the (logarithmic) height on both $V(\bar{k})$ and $W(\bar{k})$, and d for the degree functions, all taken relative to k.

Heights Lemma. *Let f be a morphism from V to W, defined over k. Then there is a constant c, depending only on k, V, W, and f, with the following property. Suppose w in $W(\bar{k})$ is such that $f^{-1}(w)$ is a finite set of cardinality $p \ge 1$. Then $p \le c$, and for any v in $f^{-1}(w)$ we have*

$$d(v) \le pd(w), \quad h(v) \le c(h(w) + 1).$$

Proof. I am grateful to Silverman for pointing out that this can be deduced from his work [S2], and also to Philippon for showing me another proof based on [P]. We give here a third proof relying on the methods of [MW2]. Here $c_1, c_2, \ldots$ depend only on k, V, W and f.

To start with, it is clear by conjugation that $d(v) \le pd(w)$. Next, writing $K = k(w)$ and introducing projective coordinates $X_0, \ldots, X_M$ for the space $\mathbf{P}_M$ containing V, we see that the equations $f(v) = w$, together with the equations defining the Zariski closure $\bar{V}$, give rise to generators $P_1, \ldots, P_r$ of a homogeneous ideal in $K[X_0, \ldots, X_M]$ which has an isolated prime (maximal) component for each v in $f^{-1}(w)$. It is classical that the number of such components can be bounded only in terms of the degrees of the generators (see for example [MW2, Theorem II, p. 419]). This shows that $p \le c_1$.

It follows easily that we can find a linear form in $k[X_0, \ldots, X_M]$, with coefficients of heights at most c_2, which is nonzero at all points of $f^{-1}(w)$; and without loss of generality we can suppose that this linear form is X_0. Similarly, by considering the ideal of polynomials vanishing on $\bar{V} - V$, we can find a homogeneous polynomial Q_0 in $k[X_0, \ldots, X_M]$, of degree at most c_3 and with coefficients of heights at most c_3, that vanishes on $\bar{V} - V$ but not at any point of $f^{-1}(w)$.

Write also $Q_0, P_1, \ldots, P_r$ for the above polynomials evaluated at the affine coordinates 1, $x_1 = X_1/X_0, \ldots, x_M = X_M/X_0$. Fix x as one of these coordinates, and let $\xi_1, \ldots, \xi_p$ be the values of x at the points of $f^{-1}(w)$. Then the Nullstellensatz applies to

$$Q = (x - \xi_1) \cdots (x - \xi_p) Q_0$$

and $P_1, \ldots, P_r$; and so by Theorem IV (p. 437) of [MW2] there exists a positive integer $e \leq c_4$ such that

$$Q^e = A'_1 P_1 + \cdots + A'_r P_r$$

for polynomials $A'_1, \ldots, A'_r$ in $K[x_1, \ldots, x_M]$ of degrees at most c_5. In particular, there are polynomials $A'_0, A'_1, \ldots, A'_r$ in $K[x_1, \ldots, x_M]$, of degrees at most c_6, such that

$$(7') \qquad A'_0 Q_0^e = A'_1 P_1 + \cdots + A'_r P_r$$

with A'_0 in $K[x]$ of exact degree $ep \leq c_7$.

Now let $\mathscr{A}_1, \ldots, \mathscr{A}_r$ be polynomials in $x_1, \ldots, x_M$ of degrees at most c_6, and let $\mathscr{A}_0$ be a polynomial in x of degree ep, all of whose coefficients are independent variables. The equation

$$\mathscr{A}_0 Q_0^e = \mathscr{A}_1 P_1 + \cdots + \mathscr{A}_r P_r$$

is then equivalent to a system of homogeneous linear equations over K in these coefficients. By $(7')$ this system has a solution over K with one particular coefficient nonzero (that corresponding to the highest power in $\mathscr{A}_0$). An explicit such solution over K can now be written down using determinants, as in Lemma 4 (p. 442) of [MW2]. We find without difficulty that there are polynomials $A_0, A_1, \ldots, A_r$ in $K[x_1, \ldots, x_M]$, of degrees at most c_6, and with coefficients of height at most $c_8(h(w) + 1)$, such that

$$(7) \qquad A_0 Q_0^e = A_1 P_1 + \cdots + A_r P_r$$

with A_0 in $K[x]$ of exact degree ep; in particular $A_0 \neq 0$.

Now substituting the affine coordinates of each point of $f^{-1}(w)$ into (7) shows that $\xi_1, \ldots, \xi_p$ must be zeroes of $A_0(x)$. It follows that $\xi_1, \ldots, \xi_p$ have heights at most $c_9(h(w)+1)$. Finally on varying the particular affine coordinate chosen, we see that each v in $f^{-1}(w)$ has height at most $c_{10}(h(w) + 1)$; and this completes the proof.

We proceed to prove Scholium 1. The constants now depend only on k and V. Suppose V has dimension $m \geq 1$ and is embedded in $\mathbb{P}_M$ with projective coordinates $X_0, \ldots, X_M$. After making a linear transformation over $\bar{k}$, we can assume that the quotients $X_1/X_0, \ldots, X_m/X_0$ give a map π from V to $\mathbb{A}^m$, defined over $\bar{k}$, that is generically surjective and of degree δ. Replacing V by a nonempty open subset, and choosing a suitable nonempty open subset W of $\mathbb{A}^m$, we may even suppose that π is a morphism from V to W and that

$\pi^{-1}(w)$ has cardinality at most δ for each w in W. We may further suppose that $W = \mathbb{A}^m - X$ for some hypersurface X of $\mathbb{A}^m$ defined over $\bar{k}$. Also, by taking norms over the corresponding function fields, and clearing denominators, we can easily verify that

$$\omega(\pi(S)) \leq c_{11}(\omega(S) + 1) \tag{8}$$

for any finite set S in V, where the ω on the left is taken in $\mathbb{A}^m$.

Choose now any $h \geq 1$. For a positive number R shortly to be determined in terms of h let $Z \subseteq \mathbb{A}$ be the set of rational integers r with $0 \leq r \leq R$. Thus for any w in $Z^m \subseteq \mathbb{A}^m$ we have $d(w) = 1$ and $h(w) \leq [k : \mathbb{Q}] \log R$. If further w is in W then $w = \pi(v)$ for some v in $V(\bar{k})$; and from the Heights Lemma we see that

$$d(v) \leq \delta, \quad h(v) \leq c_{12}(\log R + 1).$$

So if $R = \exp(c_{13}h)$ for sufficiently small c_{13}, and $h \geq 2c_{12}$, we conclude that $h(v) \leq h$ and hence v lies in $V(\delta, h)$. The set S of v arising in this way therefore satisfies

$$S \subseteq V(\delta, h), \quad \pi(S) = Z^m \cap W.$$

Thus by (8)

$$\omega(V(\delta, h)) \geq \omega(S) \geq c_{14}\omega(\pi(S)) - 1 = c_{14}\omega(Z^m \cap W) - 1. \tag{9}$$

But by subadditivity (1)

$$\omega(Z^m \cap W) \geq \omega(Z^m) - \omega(Z^m \cap X).$$

The second factor on the right is bounded independently of h by the the degree of X, and it is well known that the first factor on the right is just the cardinality $|Z|$ of Z. Since $|Z| \geq R = \exp(c_{13}h)$, we obtain the estimate of Scholium 1 by putting all these together with (9).

Next we prove Scholium 2, using a minor variant of the proof of Lemma 3A (p. 147) of [Sch]. It suffices to show that, given any nonzero polynomial $P(x_1, \dots, x_m)$ of degree at most d, the cardinality of the set T of $(z_1, \dots, z_m)$ in Z^m with $P(z_1, \dots, z_m) = 0$ is at most $d|Z|^{m-1}$. We do this by induction on m, the case $m = 1$ being trivial.

So assume the above statement holds with m replaced by $m - 1 \geq 1$, and write

$$P(x_1, \dots, x_m) = \sum_{i=0}^{e} P_i(x_1, \dots, x_{m-1})x_m^{e-i}$$

for some $e \leq d$ and polynomials $P_0, \dots, P_e$, with nonzero P_0 of degree at most $d - e$. Split T into disjoint sets T_0, T_1 according as to whether $P_0(z_1, \dots, z_{m-1})$ is zero or not. On T_0 each $(z_1, \dots, z_{m-1})$ determines at most $|Z|$ values of z_m, so the induction hypothesis gives

$$|T_0| \leq (d - e)|Z|^{m-2} \cdot |Z|.$$

On T_1 each $(z_1, \dots, z_{m-1})$ determines at most e values of z_m, so

$$|T_1| \leq e|Z|^{m-1}.$$

Therefore

$$|T| = |T_0| + |T_1| \leq d|Z|^{m-1}$$

as required. This completes the proof.

Finally we prove Scholium 3. Here constants depend only on k and A. Now the rank r of $A(k(A))$ is $l+1$ because of the extra generic point. So if this point is specialized to any v in $A(k)$ the map σ_v will fail to be injective. Hence $A(k) \subseteq \mathscr{E}$. Fix generators $Q_1, \dots, Q_t$ of $A(k)$.

Choose any $h \geq 1$. For a positive number R shortly to be determined in terms of h let S be the set of elements of the form $v = r_1 Q_1 + \cdots + r_t Q_t$ for rational integers $r_1, \dots, r_t$ with $0 \leq r_1, \dots, r_t \leq R$. For any such v we have $h(v) \leq c_{15}(R^2 + 1)$. Thus if $R = c_{16} h^{1/2}$ for sufficiently small c_{16}, and $h \geq 2c_{15}$, we conclude that $h(v) \leq h$, and therefore v lies in $\mathscr{E}(1, h)$. So $S \subseteq \mathscr{E}(1, h)$ and

$$\omega(\mathscr{E}(1, h)) \geq \omega(S).$$

Now the Main Theorem of [MW1, p. 490] gives the lower bound $\omega(S) \geq c_{17} R^{\mu}$ where μ is the usual generalized Dirichlet exponent. But since A is simple we find easily that $\mu = l/n$ (see for example [MW1, p. 510]). Hence

$$\omega(\mathscr{E}(1, h)) \geq c_{18} h^{(r-1)/2n}$$

as desired.

5. The multiplicative group

Again let V be a variety defined over a number field k. Let Γ be a finitely generated subgroup of $\mathbb{G}_m(k(V))$ of rank r. As before we can suppose that for all v in $V(\bar{k})$ there is a specialization map σ_v from Γ to $\mathbb{G}_m(k(v))$, and we say that v is exceptional if σ_v is not injective. For $d \geq 1$, $h \geq 1$ denote by $\mathscr{E}(d, h)$ the corresponding finite subset of the exceptional set $\mathscr{E}$. Then we can prove the following analogue of the Main Theorem of §1.

Theorem. *For each $d \geq 1$ there exists C, depending only on k, V, Γ and d, such that for any $h \geq 1$ we have*

$$\omega(\mathscr{E}(d, h)) \leq C h^{\kappa},$$

where $\kappa = \max(0, r^2 - 1)$.

We do not give the proof in detail; the method of §3 carries over, provided we have the appropriate versions of Propositions 1 and 2 in §2. In order to state these we first embed $\mathbb{G}_m$ into $\mathbb{P}_1$ in the standard way. This gives us a logarithmic Weil height on $\mathbb{G}_m(\bar{k})$, which for uniformity we will also denote by q. For v in $V(\bar{k})$ define

$$\mu_v = \inf q(Q),$$

where Q runs over all nontorsion points of $\mathbb{G}_m(k(v))$. Also define τ_v as the cardinality of the torsion group of $\mathbb{G}_m(k(v))$. Then we can state the following multiplicative analogue of Proposition 1.

(I) For $q \geq \mu_v$ let $Q_1, \ldots, Q_r$ be linearly dependent points of $\mathbb{G}_m(k(v))$ with heights at most q. Then there exists $\mathbf{m}$ in $\mathbb{Z}^r$ with

$$0 < |\mathbf{m}| \leq r^{r-1}\tau_v(q/\mu_v)^{r-1}$$

such that $m_1Q_1 + \cdots + m_rQ_r = 0$.

This is an immediate deduction from Theorem $\mathbb{G}_m$ of [M2], with $K = k(v)$.

We can also state the following multiplicative analogue of Proposition 2.

(II) For each $d \geq 1$ there exists $c > 0$, depending only on k and d, such that for any $h \geq 1$ and any v in $V(d, h)$ we have $\mu_v \geq c^{-1}$, $\tau_v \leq c$.

This follows from the classical observations (see for example §4 of [M2]) that if K is a number field, there is a positive constant c, depending only on the degree of K over $\mathbb{Q}$, such that every element of K which is not a root of unity has logarithmic height at least c^{-1}; and such that the cardinality of the group of roots of unity of K is at most c.

We could also mention that the analogue of Lemma 1 of §3 now takes the form $\omega(S) \leq c(|\mathbf{m}| + 1)$; and the estimate for Lemma 2 becomes $M \leq ch^{r-1}$ (for $r \geq 1$). The proof of the Theorem may now be safely left to the reader.

Taking into account Scholium 1, we deduce that σ_v is injective for infinitely many v in $V(\bar{k})$; or, less precisely, that if given algebraic functions over $\bar{k}$ are multiplicatively independent, then so are their values at infinitely many points over $\bar{k}$. Strangely enough, this result does not seem to have been stated explicitly before. It was needed to complete an argument in [PS].

Again the positive power of h really is needed in the Theorem, although in this case there is a very simple example. We take $k = \mathbb{Q}$ and $V = \mathbb{A}$, with $k(V) = \mathbb{Q}(t)$. Identifying $\mathbb{G}_m(k(V))$ with the multiplicative group of $\mathbb{Q}(t)$, we see that the functions

$$t, p_1t, \ldots, p_{r-1}t \tag{10}$$

are independent provided $p_1, \ldots, p_{r-1}$ are multiplicatively independent in $\mathbb{Q}$. But for integers $e_1, \ldots, e_{r-1}$ and $t = p_1^{e_1} \cdots p_{r-1}^{e_{r-1}}$ the values (10) become dependent. It follows easily that for any $h \geq 1$ we have in this example $\omega(\mathcal{E}(1, h)) \geq ch^{r-1}$ with some $c > 0$ independent of h.

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