RIGIDITY AND UNLIKELY INTERSECTIONS
FOR FORMAL GROUPS

by
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Abstract. — Let $K$ be a $p$-adic field and let $F$ and $G$ be two formal groups over $\mathcal{O}_K$. We prove that if $F$ and $G$ have infinitely many torsion points in common, then $F = G$. This follows from a rigidity result: any bounded power series that sends infinitely many torsion points of $F$ to torsion points of $F$ is an endomorphism of $F$.

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Introduction

Let $K$ be a finite extension of $\mathbb{Q}_p$ (or, more generally, a finite extension of $W(k)[1/p]$ where $k$ is a perfect field of characteristic $p$). Let $\overline{K}$ be an algebraic closure of $K$ and let $\mathbb{C}_p$ be the $p$-adic completion of $\overline{K}$. Let $\mathcal{O}_K$ denote the ring of integers of $K$, and let $F(X, Y) = X \oplus Y \in \mathcal{O}_K[[X, Y]]$ be a formal group law over $\mathcal{O}_K$. Let $\text{Tors}(F)$ be the set of torsion points of $F$ in $\mathfrak{m}_{\mathbb{C}_p} = \{ z \in \mathbb{C}_p, |z|_p < 1 \}$. The question that motivates this paper is: to what extent is a formal group $F$ determined by $\text{Tors}(F)$? Our main result is an “unlikely intersections” result.

Theorem A. — If $F$ and $G$ are two formal groups over $\mathcal{O}_K$ and if $\text{Tors}(F) \cap \text{Tors}(G)$ is infinite, then $F = G$.

2010 Mathematics Subject Classification. — 11S31 (11F80; 11S82; 13J05; 37P35).

Key words and phrases. — Rigidity; unlikely intersections; formal groups; $p$-adic dynamical systems; preperiodic points.
If $n \geq 2$ and $[n](X)$ denotes the multiplication by $n$ map on $F$, then Tors($F$) is also the set of preperiodic points of $[n](X)$ in $\mathfrak{m}_{\mathbb{C}_p}$. We can therefore think of Tors($F$) as the set Preper($F$) of preperiodic points of a $p$-adic dynamical system attached to $F$. Theorem A then becomes a statement about preperiodic points of certain dynamical systems.

Some analogues of theorem A are known in other contexts. For example, if two elliptic curves over $\mathbb{Q}$ have infinitely many torsion points in common (in a suitable sense), then they are isomorphic (Bogomolov and Tschinkel, see §4 of [BT07]). In another context, if $f$ and $g$ are two rational fractions of degree at least 2 with coefficients in the complex numbers, and if Preper($f$) \cap Preper($g$) is infinite, then Preper($f$) = Preper($g$) (Baker and DeMarco, theorem 1.2 of [BD11]). In this case, $f$ and $g$ have the same Julia set (corollary 1.3 of ibid.). One can then show that, if $f$ and $g$ are polynomials of the same degree, then in most cases they are equal up to a linear symmetry that preserves their common Julia set (see for instance [BE87] and [SS95]).

Our proof of theorem A relies on a rigidity result for formal groups. We say that a subset $Z \subset \mathfrak{m}_d^{\mathbb{C}_p}$ is Zariski dense in $\mathfrak{m}_d^{\mathbb{C}_p}$ if every power series $h(X_1, \ldots, X_d) \in \mathcal{O}_K[[X_1, \ldots, X_d]]$ that vanishes on $Z$ is necessarily equal to zero. For example, if $d = 1$ then $Z \subset \mathfrak{m}_1^{\mathbb{C}_p}$ is Zariski dense in $\mathfrak{m}_1^{\mathbb{C}_p}$ if and only if it is infinite.

\textbf{Theorem B.} — If $F$ is a formal group over $\mathcal{O}_K$ and if $h(X) \in X \cdot \mathcal{O}_K[[X]]$ is such that $h(z) \in \text{Tors}(F)$ for infinitely many $z \in \text{Tors}(F)$, then $h \in \text{End}(F)$.

More generally, if $h(X_1, \ldots, X_d) \in \mathcal{O}_K[[X_1, \ldots, X_d]]$ is such that $h(0) = 0$ and $h(z) \in \text{Tors}(F)$ for all $z$ in a subset of $\text{Tors}(F)^d$ that is Zariski dense in $\mathfrak{m}_d^{\mathbb{C}_p}$, then there exists $h_1, \ldots, h_d \in \text{End}(F)$ such that $h = h_1(X_1) \oplus \cdots \oplus h_d(X_d)$.

This theorem generalizes corollary 4.2 of Hida’s [Hid14], which concerns the case $F = \mathbb{G}_m$. Our proof uses ideas coming from the theory of $p$-adic dynamical systems (developed in large part by Lubin, see [Lub94]) rather than the “special subvarieties” argument of Hida (which is in the spirit of Chai’s [Cha08]). Other kinds of “unlikely intersections” results for certain formal groups can be found in [Ser18].

\textbf{Acknowledgements.} This paper is motivated by Holly Krieger’s talk “A dynamical approach to common torsion points” at the CNTA XV meeting. I am grateful to Holly Krieger for useful discussions and to the organizers of CNTA XV for inviting me.
1. Formal groups

For the basic definitions and results about formal groups that we need, we refer for instance to Lubin’s [Lub64, Lub67]. Let \( F(X, Y) = X \oplus Y \in \mathcal{O}_K[X, Y] \) be a formal group law over \( \mathcal{O}_K \). If \( n \in \mathbb{Z} \), let \( [n](X) \) denote the multiplication by \( n \) map on \( F \). More generally, if \( a \in \mathcal{O}_K \), let \( [a](X) \) be the unique endomorphism of \( F \) such that \( [a]'(0) = a \) if it exists. Let \( \text{Tors}(F) \) be the set of torsion points of \( F \). If \( F \) is of finite height, then \( \text{Tors}(F) \) is infinite, while if \( F \) is of infinite height, then \( \text{Tors}(F) \) is finite and our results are vacuous. We therefore assume from now on that \( F \) is of finite height \( h \).

Let \( \mathcal{T}_p F = \lim \leftarrow n \mathcal{O}_K[p^n] \) be the Tate module of \( F \). If \( F \) is of height \( h \), then \( \mathcal{T}_p F \) is a free \( \mathbb{Z}_p \)-module of rank \( h \), equipped with an action of \( \text{Gal}(\mathcal{K}/K) \). If we choose a basis of \( \mathcal{T}_p F \), this gives a Galois representation \( \rho_F : \text{Gal}(\mathcal{K}/K) \to \text{GL}_h(\mathbb{Q}_p) \). Let \( E \) be the fraction field of \( \text{End}(F) \). It is a finite extension of \( \mathbb{Q}_p \) whose degree \( e \) divides \( h \) (theorem 2.3.2 of [Lub64]), so that we can view \( \text{GL}_{h/e}(E) \) as a subgroup of \( \text{GL}_h(\mathbb{Q}_p) \).

**Theorem 1.1.** — The image of \( \rho_F \) is an open subgroup of a conjugate of \( \text{GL}_{h/e}(E) \).

**Proof.** — This is an unpublished theorem of Serre (see however the remark after theorem 5 on page 130 of [Ser67]), which is proved in [Sen73] (see theorem 3 on page 168 and the remark that follows).

**Corollary 1.2.** — The image of \( \rho_F \) contains an open subgroup of \( \mathbb{Z}_p^\times \cdot \text{Id} \).

If \( \sigma \in \text{Gal}(\mathcal{K}/K) \) is such that \( \rho_F(\sigma) = a \cdot \text{Id} \), then \( \sigma(z) = [a](z) \) for all \( z \in \text{Tors}(F) \).

2. \( p \)-adic dynamical systems

In this §, we prove a number of results about power series that commute under composition (sometimes also called permutable power series). These results are all inspired by Lubin’s theory of \( p \)-adic dynamical systems (see [Lub94]).

A power series \( h(X) \in X \cdot K[X] \) is said to be stable if \( h'(0) \) is neither 0 nor a root of unity. If \( h'(0) \neq 0 \), then there exists a unique power series \( h^{-1}(X) \in X \cdot K[X] \) such that \( h \circ h^{-1} = h^{-1} \circ h = X \). If in addition \( h(X) \in X \cdot \mathcal{O}_K[X] \) and \( h'(0) \in \mathcal{O}_K^\times \), then \( h^{-1}(X) \in X \cdot \mathcal{O}_K[X] \).

**Theorem 2.1.** — Let \( u(X) \in X \cdot K[X] \) be a stable power series.

A power series \( h(X_1, \ldots, X_d) \in K[X_1, \ldots, X_d] \) such that \( h(0) = 0 \) and such that \( h \circ u = u \circ h \) is determined by \( \{dh/dX_i(0)\}_{1 \leq i \leq d} \).
Proof. — Suppose that \( h^{(1)} \) and \( h^{(2)} \) are two such power series, and that they coincide in degrees \( \leq m \). Let \( h_m \) be the sum of the terms of \( h^{(i)} \) of total degree \( \leq m \). We have \( h^{(i)} = h_m + r^{(i)} \) with \( r^{(i)} \) of degree \( \geq m + 1 \), and
\[
\begin{aligned}
(h_m + r^{(i)}) \circ u &= h_m \circ u + r^{(i)} \circ u \equiv h_m \circ u + u'(0)^{m+1}r^{(i)} \mod \deg (m + 2), \\
u \circ (h_m + r^{(i)}) &\equiv u \circ h_m + r^{(i)}u'(h_m) \mod \deg (m + 2).
\end{aligned}
\]
Since \( u'(0)^m \neq 1 \), the fact that \( h^{(i)} \circ u = u \circ h^{(i)} \) implies that
\[
\frac{h_m \circ u - u \circ h_m}{u'(0) - u'(0)^{m+1}} \mod \deg (m + 2).
\]
If \( h^{(1)} \) and \( h^{(2)} \) coincide in degrees \( \leq m \), they therefore have to coincide in degrees \( \leq m + 1 \). This implies the theorem by induction on \( m \).

Let us say that an endomorphism of a formal group is stable if the corresponding power series is stable.

**Corollary 2.2.** — Let \( F \) be a formal group and let \( u \) be a stable endomorphism of \( F \). If \( h(X) \in X \cdot \mathcal{O}_K[X] \) is such that \( h \circ u = u \circ h \), then \( h \) is an endomorphism of \( F \).

Proof. — The power series \( F \circ h \) and \( h \circ F \) both commute with \( u \), and have the same derivatives at 0, so that \( F \circ h = h \circ F \) by theorem 2.1.

**Corollary 2.3.** — If \( u \) is a stable endomorphism of a formal group and if \( h(X_1, \ldots, X_d) \in \mathcal{O}_K[\{X_1, \ldots, X_d\}] \) is such that \( h(0) = 0 \) and \( h \circ u = u \circ h \), then there exists \( a_1, \ldots, a_d \in \mathcal{O}_K \) such that \( h(X_1, \ldots, X_d) = [a_1](X_1) \oplus \cdots \oplus [a_d](X_d) \).

Proof. — Let \( h_i(X) \) be the power series \( h \) evaluated at \( X_i = X \) and \( X_k = 0 \) for \( k \neq i \). We have \( h_i \circ u = u \circ h_i \) and hence by corollary 2.2, \( h_i(X) = [a_i](X) \) where \( a_i = h'_i(0) \in \mathcal{O}_K \).

The two power series \( h(X_1, \ldots, X_d) \) and \( [a_1](X_1) \oplus \cdots \oplus [a_d](X_d) \) commute with \( u \) and have the same derivatives at 0, so that they are equal by theorem 2.1.

### 3. Rigidity and unlikely intersections

We first recall and prove theorem B.

**Theorem 3.1.** — If \( F \) is a formal group over \( \mathcal{O}_K \) and if \( h(X_1, \ldots, X_d) \in \mathcal{O}_K[\{X_1, \ldots, X_d\}] \) is such that \( h(0) = 0 \) and \( h(z) \in \text{Tors}(F) \) for all \( z \) in a subset \( Z \) of \( \text{Tors}(F)^d \) that is Zariski dense in \( \mathfrak{m}_{\mathcal{O}_p}^d \), then there exists \( h_1, \ldots, h_d \in \text{End}(F) \) such that \( h = h_1(X_1) \oplus \cdots \oplus h_d(X_d) \).
**Proof.** — Since $\text{Tors}(F)$ is infinite, $F$ is of finite height. By corollary 1.2, there exists $\sigma \in \text{Gal}(\overline{K} / K)$ and a stable endomorphism $u$ of $F$ such that $\sigma(z) = u(z)$ for all $z \in \text{Tors}(F)$. If $z \in Z$, then we have $\sigma(h(z)) = u(h(z))$ as well as $\sigma(h(z)) = h(\sigma(z)) = h(u(z))$. The power series $u \circ h - h \circ u$ therefore vanishes on $Z$. Since $Z$ is Zariski dense in $mC_p$, we have $u \circ h = h \circ u$. The theorem now follows from corollary 2.3.

**Remark 3.2.** — If $Y_1, \ldots, Y_d$ are infinite subsets of $\text{Tors}(F)$, then $Y_1 \times \cdots \times Y_d$ is Zariski dense in $mC_p$.

We now recall and prove theorem A.

**Theorem 3.3.** — If $F$ and $G$ are two formal groups over $\mathcal{O}_K$ and if $\text{Tors}(F) \cap \text{Tors}(G)$ is infinite, then $F = G$.

**Proof.** — By corollary 1.2, there exists an element $\sigma \in \text{Gal}(\overline{K} / K)$ and a stable endomorphism $u$ of $F$ such that $\sigma(z) = u(z)$ for all $z \in \text{Tors}(F)$. The set $\Lambda = \text{Tors}(F) \cap \text{Tors}(G)$ is stable under the action of $\text{Gal}(\overline{K} / K)$. If $z \in \Lambda$, we therefore have $\sigma(z) \in \Lambda$ and hence $u(z) \in \text{Tors}(G)$ for all $z \in \Lambda$, since $u(z) = \sigma(z)$. By theorem B applied to $G$, we get that $u \in \text{End}(G)$. The power series $F$ and $G$ commute with $u$ and have the same linear terms, hence $F = G$ by theorem 2.1.

### 4. Generalizations and perspectives

**4.1. Universal bounds.** — In §4 of [BT07], Bogomolov and Tschinkel prove that two nonisomorphic elliptic curves over $\overline{\mathbb{Q}}$ have only finitely many torsion points in common. In [BFT18], the authors raise the question of the existence of a universal bound for the maximum number of torsion points that two nonisomorphic elliptic curves over $\overline{\mathbb{Q}}$ (or even over the complex numbers) can share. The same kind of question is raised, for preperiodic points of rational fractions, in the forthcoming paper [DKY].

The following proposition shows that in our situation, there is no straightforward refinement of theorem A.

**Proposition 4.1.** — For all $m \geq 1$, there exists a formal group $F$ over $\mathbb{Z}_p$, of height 1, such that $F$ is not isomorphic to $\mathbb{G}_m$ but such that $\text{Tors}(F) \cap \text{Tors}(\mathbb{G}_m)$ contains at least $m$ points.

**Proof.** — Take $n \geq 1$ and let $q(X) = (1 + X)^p - 1$ and $u(X) = 1 + ((1 + X)^p - 1)/X$ and $f(X) = u(X)q(X)$. We have $f(X) = p(1 + p^n)X + O(X^2)$ and $f(X) \equiv X^p \mod p$. 


By Lubin-Tate theory (see §1 of [LT65]) there exists a formal group $F$ such that $[p(1 + p^n)](X) = f(X)$. This group is attached to the uniformizer $p(1 + p^n)$ of $Q_p$. Likewise, $G_m$ is attached to $p$. The formal group $F$ is not isomorphic to $G_m$ over $Q_p$ as $p \neq p(1 + p^n)$ and any Lubin-Tate group attached to a uniformizer $\pi$ determines $\pi$.

However, we have $f(\zeta_p - 1) = 0$ and $f(\zeta_p^k - 1) = \zeta_p^{k-1}$ for all $k \leq n$, so that $\zeta_p - 1 \in \text{Tors}(F)$ for all $k \leq n$. This proves the proposition.

If $\text{Tors}(F) \cap \text{Tors}(G)$ is large, then are $F$ and $G$ close to each other in some sense?

4.2. The logarithm of a formal group. — Using the logarithms of formal groups, we can give a very short proof of a weaker form of theorem A, namely: if $\text{Tors}(F) = \text{Tors}(G)$ (and this common set is infinite), then $F = G$. Indeed, $\log_F$ is holomorphic on $mC_p$ and its zeroes are precisely the elements of $\text{Tors}(F)$, with multiplicity 1. In addition, $\log'_F$ is a bounded power series since $d\log_F$ is the normalized invariant differential on $F$. If $\text{Tors}(F) = \text{Tors}(G)$, then $\log_F$ and $\log_G$ have the same zeroes, so that they differ by a unit $u$. A unit is necessarily bounded. We have $\log_G = u \cdot \log_F$ and hence $\log'_G = u \cdot \log'_F + u' \cdot \log_F$. Since $\log'_G$ and $\log'_F$ and $u$ are bounded, but not $\log_F$, we must have $u' = 0$ (the sup norms $\|\cdot\|_r$ on circles are multiplicative). This implies that $u \in \mathcal{O}_K^\times$ and then that $u = 1$ since $\log'_F(0) = \log'_G(0) = 1$, so that $\log_F = \log_G$ and $F = G$. The same argument gives the following characterization of the logarithm of a formal group of finite height.

**Proposition 4.2.** — If $F$ is a formal group of finite height, then the power series $\log_F$ is the unique element of $X + X^2 \cdot K[X]$ that is holomorphic on $mC_p$, whose zero set is precisely $\text{Tors}(F)$, with multiplicity 1, and whose derivative is bounded.

4.3. More rigidity. — A common generalization of theorems A and B would be the assertion that if a power series $h$ maps infinitely many torsion points of $F$ to torsion points of $G$, then $h \in \text{Hom}(F, G)$. In order to prove this using the same method as in the proof of theorem B, we would need to show that there exists $\sigma \in \text{Gal}(\overline{K}/K)$ that acts on $\text{Tors}(F)$ and $\text{Tors}(G)$ by two power series $u_F$ and $u_G$, satisfying some stability condition. If $G$ is a Lubin-Tate formal group (for some finite extension of $Q_p$ contained in $\overline{K}$), there is a character $\chi_G : \text{Gal}(\overline{K}/K) \to \mathcal{O}_K^\times$ such that $\sigma(z) = [\chi_G(\sigma)](z)$ for all $z \in \text{Tors}(G)$ (theorem 2 of [LT65]).

**Theorem 4.3.** — If $F$ is a formal group and $G$ is a Lubin-Tate formal group, both defined over $\mathcal{O}_K$, and if $h(X) \in X \cdot \mathcal{O}_K[X]$ is such that $h'(0) \neq 0$ and $h(z) \in \text{Tors}(G)$ for infinitely many $z \in \text{Tors}(F)$, then $h \in \text{Hom}(F, G)$. 


Proof. — Since $\text{Tors}(F)$ is infinite, $F$ is of finite height. By corollary 1.2, there exists an element $\sigma \in \text{Gal}(\overline{K}/K)$ and a stable endomorphism $u_F$ of $F$ such that $\sigma(z_F) = u_F(z_F)$ if $z_F \in \text{Tors}(F)$. Let $u_G(X) = [\chi_G(\sigma)](X)$, so that $\sigma(z_G) = u_G(z_G)$ if $z_G \in \text{Tors}(G)$.

If $z \in \text{Tors}(F)$ is such that $h(z) \in \text{Tors}(G)$, then $\sigma(h(z)) = u_G(h(z))$ and $\sigma(h(z)) = h(\sigma(z)) = h(u_F(z))$. The power series $u_G \circ h - h \circ u_F$ therefore vanishes at infinitely many points of $\mathfrak{m}_{C_F}$, so that $u_G \circ h = h \circ u_F$. Since $h'(0) \neq 0$, we have $u'_F(0) = u'_G(0)$ and $u_G$ is stable. The theorem now follows from lemma 4.4 below.

Lemma 4.4. — Let $F$ and $G$ be two formal groups and let $f$ and $g$ be endomorphisms of $F$ and $G$, with $g$ stable. If $h(X) \in X \cdot \mathcal{O}_K[X]$ is such that $h'(0) \neq 0$ and $h \circ f = g \circ h$, then $h \in \text{Hom}(F,G)$.

Proof. — Consider the power series $K(X,Y) = h \circ F(h^{-1}(X), h^{-1}(Y))$. We have

$$K \circ g = h \circ F \circ h^{-1} \circ g = h \circ F \circ f \circ h^{-1} = h \circ f \circ F \circ h^{-1} = g \circ h \circ F \circ h^{-1} = g \circ K$$

Since $K$ and $G$ commute with $g$ and have the same derivatives at 0, we have $K = G$ by theorem 2.1 and hence $h \circ F = G \circ h$, so that $h \in \text{Hom}(F,G)$.

Note that the hypothesis of the lemma imply that $f'(0) = g'(0)$ so that if one series is stable, then both are.

4.4. Homotheties and stable $p$-adic dynamical systems. — If $F$ is a formal group of finite height, then $\text{End}(F)$ is a set of power series that commute with each other under composition. One can forget about the formal group and study certain sets $\mathcal{D}$ of elements of $X \cdot \mathcal{O}_K[[X]]$ that commute with each other under composition. This is the object of Lubin’s theory of $p$-adic dynamical systems (see [Lub94]).

Let us say that $\mathcal{D} \subset X \cdot \mathcal{O}_K[[X]]$ is a stable $p$-adic dynamical system of finite height if the elements of $\mathcal{D}$ commute with each other under composition, and if $\mathcal{D}$ contains a stable series $f$ such that $f'(0) \in \mathfrak{m}_K$ and $f(X) \equiv 0 \mod \mathfrak{m}_K$ (i.e. $f$ is of finite height) as well as a stable series $u$ such that $u'(0) \in \mathcal{O}_K^\times$. We can then assume that $\mathcal{D}$ is as large as possible, namely that any power series $g \in X \cdot \mathcal{O}_K[[X]]$ that commutes with the elements of $\mathcal{D}$ belongs to $\mathcal{D}$. For example, if $F$ is a formal group of finite height, then $\text{End}(F)$ is a stable $p$-adic dynamical system.

Given a stable $p$-adic dynamical system of finite height $\mathcal{D}$, the set $\text{Preper}(g)$ is independent of the choice of a stable $g \in \mathcal{D}$ (see §3 of [Lub94]). One can then define $\text{Preper}(\mathcal{D})$ as the preperiodic set of any stable element of $\mathcal{D}$. To what extent does $\text{Preper}(\mathcal{D})$ determine a stable $p$-adic dynamical system of finite height $\mathcal{D}$?
In order to extend our results from formal groups to stable $p$-adic dynamical systems of finite height, we can ask whether the consequence of corollary 1.2 holds in more generality: for which stable $p$-adic dynamical systems of finite height $D$ is there a stable power series $w \in D$ and an element $\sigma \in \text{Gal}(K/K)$ such that $\sigma(z) = w(z)$ for all $z \in \text{Preper}(D)$?

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