

THE FROBENIUS MAP: THE POWER OF PRIME CHARACTERISTIC

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These are lecture notes and exercises for a short graduate lecture series on positive characteristic methods for the SLMath/SMS Summer School An Introduction to Recent Trends in Commutative Algebra in June 2025. My goal in this series is to give an appreciation for the power of techniques involving the Frobenius map to prove statements that have nothing to do with Frobenius. It is not my goal to thoroughly develop the tools needed for research in this area. The audience has a varied background, so I am not assuming any background beyond a first year graduate sequence on algebra. There is not enough time in this course to cover background material from commutative algebra and homological algebra in addition to the specific content of these lectures, so instead I will often give statements that are specialized to more concrete situations rather than giving the most general statements, and sometimes also offer a “more generally version” for those have have additional background. For time reasons, I will often sketch proofs, occasionally leaving some details to the exercises.

In the first lecture, I will discuss the basic perspectives and terminology of the Frobenius map. The first problem set is intended to solidify these notions, though there are also a few problems that build towards the later lectures. The second lecture will briefly introduce tight closure and an application. The third lecture will introduce a couple of notions of F-singularities and outline a couple more applications. The second problem set will explore the notions from the last two lectures, and fill in some details of the proofs.

Throughout these notes, all rings are commutative with $1 \neq 0$, and p will denote a positive prime integer.

1. Basics with the Frobenius map

Recall that a ring R has characteristic p if

$$p = \underbrace{1 + \cdots + 1}_{p \text{ times}}$$

is zero in R . This is equivalent to R containing a field of characteristic p as a subring: if R has characteristic p , the image of the homomorphism $\mathbb{Z} \rightarrow R$ is isomorphic to \mathbb{F}_p .

The Frobenius map. Let us start with an observation about binomial coefficients. For any integer i with $0 < i < p$, the binomial coefficient

$$\binom{p}{i} = \frac{p!}{(p-i)! \cdot i!}$$

has a factor of p in the numerator, but not the denominator. Since we also know this coefficient is an integer, e.g., for combinatorial reasons, the Fundamental Theorem of Arithmetic says that

it is a multiple of p . Thus, when R has characteristic p , for any $r, s \in R$, one has

$$\begin{aligned} (r+s)^p &= r^p + \binom{p}{1}r^{p-1}s + \binom{p}{2}r^{p-2}s^2 + \cdots + \binom{p}{p-1}rs^{p-1} + s^p \\ &= r^p + s^p, \quad \text{and} \\ (rs)^p &= r^p s^p, \end{aligned}$$

and $1^p = 1$, so the map

$$F: R \longrightarrow R, \quad F(r) = r^p$$

is a ring homomorphism from R to itself, called the **Frobenius map** on R . We may denote this as F_R to indicate the ring when useful.

One can apply the Frobenius map multiple times:

$$F^e: R \longrightarrow R, \quad F^e(r) = r^{p^e}$$

which we may call the **e-th Frobenius** or **e-th Frobenius iterate**. Note that no power map is a ring homomorphism in characteristic zero.

Example 1.1. For $R = \mathbb{F}_p$ the Frobenius map is the identity: this is Fermat's Little Theorem.

Example 1.2. For $R = \mathbb{F}_p[x]$, the Frobenius map is given by

$$F(a_n x^n + \cdots + a_1 x + a_0) = a_n x^{pn} + \cdots + a_1 x^p + a_0$$

and the iterates by

$$F^e(a_n x^n + \cdots + a_1 x + a_0) = a_n x^{p^e n} + \cdots + a_1 x^{p^e} + a_0.$$

Every ring of characteristic p has a Frobenius map, and the Frobenius map is compatible with every ring homomorphism between rings of characteristic p :

$$\begin{array}{ccc} R & \xrightarrow{\varphi} & S \\ F_R \downarrow & & \downarrow F_S \\ R & \xrightarrow{\varphi} & S \end{array} \quad \begin{array}{ccc} r & \longmapsto & \varphi(r) \\ \downarrow & & \downarrow \\ r^p & \longmapsto & \varphi(r^p) = \varphi(r)^p. \end{array}$$

This universality and naturality is a clear sign of the importance of the Frobenius map.

Injectivity and surjectivity. Let us start with a simple relationship between the Frobenius map and something that has nothing to do with it.

Lemma 1.3. *Let R be a ring of characteristic p . The Frobenius map on R is injective if and only if R is reduced (meaning that R has no nonzero nilpotents).*

Proof. We will prove the contrapositive of each direction. (\Leftarrow): If F_R is not injective, then there is some $r \neq 0$ with $r^p = 0$; such an element is a nonzero nilpotent of R .

(\Rightarrow): If R is not reduced, then there is some $r \neq 0$ with $r^n = 0$ for some $n \geq 2$. Take n maximal such that $r^n \neq 0$; then $np > n$, so $F(r^n) = r^{pn} = 0$, and r^n is a nonzero element of the kernel of F_R . \square

It is rarer for the Frobenius map to be surjective. The image of the Frobenius map is evidently the p -th powers of elements in R . A ring of positive characteristic is **perfect** if its Frobenius map is bijective. You are likely familiar with this consideration for fields. Perfect fields include all finite fields, like \mathbb{F}_p and \mathbb{F}_{p^7} , and all algebraically closed fields, like $\overline{\mathbb{F}_p}$ and $\overline{\mathbb{F}_p}(t)$. However,

a field like $\mathbb{F}_p(t)$ is not perfect, as t is not a p -th power. However $\mathbb{F}_p[x]$ is evidently not perfect. One can show that when R is Noetherian then F_R is surjective if and only if R is a finite product of perfect fields.

Alternative perspectives. One of the most confusing aspects of the Frobenius map is the fact that the source and target are the same, though the map is typically not an isomorphism. It is often useful to separate the source and target of the Frobenius to clarify the situation. One can think of this as analogous to the case of linear algebra, where some aspects of an endomorphism of a vector space are easier to understand with separate bases on the source and target.

Our first alternative perspective on Frobenius is based on renaming the target copy of R . We will decorate every element in the target of the e -th Frobenius F^e with the decoration F_*^e . That is, $F_*^e R$ is just an collection of doppelgängers of elements R :

$$\begin{aligned} F_*^e R &= \{F_*^e r \mid r \in R\} \\ F_*^e r + F_*^e s &= F_*^e(r + s) \quad \text{and} \quad F_*^e r F_*^e s = F_*^e(rs), \end{aligned}$$

so the map

$$R \longrightarrow F_*^e R \quad r \longmapsto F_*^e r$$

is an isomorphism. After rewriting “target R ” as $F_*^e R$ via the isomorphism above, the e -th Frobenius map takes the form

$$R \longrightarrow F_*^e R \quad r \longmapsto F_*^e(r^{p^e}).$$

One should think of this as follows: the e -th Frobenius map sends $r \longrightarrow r^{p^e}$, and the F_*^e symbol simply says which copy of R the element r^{p^e} lives in. Put another way, we have the commutative diagram

$$\begin{array}{ccc} R & \xrightarrow{F^e} & R \\ \downarrow = & & \downarrow \cong \\ R & \longrightarrow & F_*^e R \end{array} \quad \begin{array}{ccc} r & \longmapsto & r^{p^e} \\ \downarrow & & \downarrow \\ r & \longmapsto & F_*^e(r^{p^e}) \end{array}$$

where the bottom row is the Frobenius from $R \longrightarrow F_*^e R$ and the right map is the isomorphism “adding the decoration F_*^e ”.

When R is a domain, there is another useful way to think of $F_*^e R$. In this case, R has a field of fractions K , which admits an algebraic closure \overline{K} . Every element of R has a unique p^e -th root r^{1/p^e} in \overline{K} , as \overline{K} is a perfect field. Define

$$R^{1/p^e} := \{r^{1/p^e} \in \overline{K} \mid r \in R\}.$$

One can verify that R^{1/p^e} is a subring of \overline{K} , and the map

$$R \longrightarrow R^{1/p^e} \quad r \longmapsto r^{1/p^e}$$

is a ring isomorphism. We can think of the exponent $1/p^e$ as a decoration that yields an isomorphic copy of R . After rewriting “target R ” as R^{1/p^e} via this isomorphism, the Frobenius map takes the form

$$R \longrightarrow R^{1/p^e} \quad r \longmapsto (r^{p^e})^{1/p^e} = r.$$

That is, after the identification above, the Frobenius map identifies with the inclusion of $R \subseteq R^{1/p^e}$. Put another way, we have the commutative diagram

$$\begin{array}{ccc} R & \xrightarrow{F^e} & R \\ \downarrow = & & \downarrow \cong \\ R & \longrightarrow & R^{1/p^e} \end{array} \quad \begin{array}{ccc} r & \longmapsto & r^{p^e} \\ \downarrow & & \downarrow \\ r & \longmapsto & r = (r^{p^e})^{1/p^e}, \end{array}$$

where the bottom row is the inclusion map and the right map is the isomorphism $R \cong R^{1/p^e}$ of taking p^e -th roots. This notion of roots equally well makes sense when R is reduced: in this case, R embeds into product of fields, which embeds into a product of algebraically closed fields, where every element again has a unique p^e -th root.

A third perspective on the Frobenius on a reduced ring is by identifying the source of Frobenius with R^{p^e} , the subring consisting of p^e -th powers of elements of R . In this case, the Frobenius map corresponds to the inclusion map $R^{p^e} \subseteq R$.

Typical constructions. We now discuss some typical constructions for ring maps applied to special case of the Frobenius. For a general ring homomorphism $\varphi : A \rightarrow B$, one has the notion of extension of an ideal $I \subseteq A$ given as the ideal of B given by $(\varphi(a) \mid a \in I)$. This leads to the notion of Frobenius powers. Given an ideal $I \subseteq R$, we define the **Frobenius powers** of I as

$$I^{[p^e]} = (a^{p^e} \mid a \in R) = (F^e(a) \mid a \in I).$$

If $I = (a_1, \dots, a_t)$, then $I^{[p^e]} = (a_1^{p^e}, \dots, a_t^{p^e})$, as is the case in general for extension of ideals. Observe that $I^{[p^e]} \subseteq I^{p^e}$, but these are typically different when I is not principal.

Another important construction comes from restriction of scalars. For a general ring homomorphism $\varphi : A \rightarrow B$, one can view B as an A -module by restriction of scalars: B becomes an A -module by the rule $a \cdot b = \varphi(a)b$. One can view R as an R -module by restriction of scalars through F^e , so R acts on R by the rule

$$r \cdot s = r^{p^e} s.$$

It is especially helpful to use the alternative notations for the Frobenius map in this setting. Consider the Frobenius map in the form

$$R \longrightarrow F_*^e R \quad r \longmapsto F_*^e(r^{p^e}).$$

The R -module action on $F_*^e R$ is then

$$r \cdot F_*^e s = F_*^e(r^{p^e} s).$$

For R reduced, we may also consider the Frobenius map in the form

$$R \subseteq R^{1/p^e}.$$

The R -module action on R^{1/p^e} is then the straightforward action

$$r \cdot s^{1/p^e} = r s^{1/p^e} = (r^{p^e} s)^{1/p^e}.$$

We will return to discuss this structure in great detail for a polynomial ring soon.

One can also apply the restriction of scalars to an arbitrary R -module. For a general ring homomorphism $\varphi : A \rightarrow B$, and B -module N , one can view N as an A -module by restriction

of scalars: N becomes an A -module by the rule $a \cdot n = \varphi(a)n$. To apply this with the Frobenius map, we let M be an R -module. Let us think of the Frobenius map in the form

$$R \longrightarrow F_*^e R \quad r \longmapsto F_*^e(r^{p^e}),$$

and think of M as a module over the target; we will rewrite M as

$$F_*^e M = \{F_*^e m \mid m \in M\}$$

with $F_*^e R$ -action

$$F_*^e r \cdot F_*^e m = F_*^e(rm).$$

The action of R on $F_*^e M$ is then

$$r \cdot F_*^e m = F_*^e(r^{p^e})F_*^e m = F_*^e(r^{p^e} m).$$

Finally, we discuss extension of scalars. For a general ring homomorphism $\varphi : A \longrightarrow B$, and A -module M , one can create a new B -module by extension of scalars. The construction is most naturally stated in terms of tensor products, but we give a slightly more concrete construction. One can write M in terms of generators and relations: M has generating set $\{m_i\}_i$ with relations $\{\sum_i a_{ij}m_i\}_j$, meaning $\sum_i a_{ij}m_i = 0$ in M for all j , and that these generate the tuples of relations on these generators. The module φ^*M is then the B -module with generating set $\{m_i\}_i$ with relations $\{\sum_i \varphi(a_{ij})m_i\}_j$. To apply this with the Frobenius map, we let M be an R -module. If M is as above, the Frobenius restriction of scalars module is the R -module $F_*^e(M)$ with generating set $\{m_i\}_i$ with relations $\{\sum_i a_{ij}^{p^e} m_i\}_j$.

Polynomial rings and Kunz' Theorem. We will now analyze the R -module structure of $F_*^e R$ in detail in an important case.

Theorem 1.4. *Let K be a perfect field of characteristic p , and $S = K[x_1, \dots, x_n]$ be a polynomial ring in n variables over K . Then $F_*^e S$ is a free S -module with basis*

$$B = \{F_*^e(x_1^{a_1} \cdots x_n^{a_n}) \mid 0 \leq a_i < p^e\}.$$

Proof. We need to show that every element of $F_*^e S$ can be written as an S -linear combination of the elements above.

Every element of $F_*^e S$ is a sum of elements of the form $F_*^e(\gamma x_1^{b_1} \cdots x_n^{b_n})$ with $\gamma \in K$ and $b_1, \dots, b_n \geq 0$. Write $b_i = p^e c_i + a_i$ with $0 \leq a_i < p^e$. Then

$$\begin{aligned} F_*^e(\gamma x_1^{b_1} \cdots x_n^{b_n}) &= F_*^e(\gamma x_1^{p^e c_1 + a_1} \cdots x_n^{p^e c_n + a_n}) \\ &= F_*^e(\gamma x_1^{p^e c_1} \cdots x_n^{p^e c_n}) F_*^e(x_1^{a_1} \cdots x_n^{a_n}) \\ &= \gamma^{1/p^e} x_1^{c_1} \cdots x_n^{c_n} \cdot F_*^e(x_1^{a_1} \cdots x_n^{a_n}) \end{aligned}$$

Note that we have used that K is perfect in the last step. This shows that the purported basis spans.

To see this set is linearly independent, suppose that we have some $\beta_1, \dots, \beta_t \in B$ and $s_1, \dots, s_t \in S$ such that $\sum_i s_i \beta_i = 0$. Note that in a product

$$s_i \beta_i = s_i \cdot F_*^e(x_1^{a_1} \cdots x_n^{a_n}) = F_*^e(s_i^{p^e} x_1^{a_1} \cdots x_n^{a_n}),$$

every monomial occurring in the polynomial $s_i^{p^e} x_1^{a_1} \cdots x_n^{a_n}$ has exponents b_1, \dots, b_n such that $b_i \equiv a_i \pmod{p^e}$. In particular, writing each $s_i \beta_i$ as F_*^e of some polynomial as above, the polynomials that occur have mutually distinct monomials, and thus cannot cancel each other.

It follows that $s_i \beta_i = 0$ for each i , which implies $s_i = 0$ for each i . This shows that B is a free basis. \square

Intuitively, this proof shows that viewing S as the S -module $F_*^e S$ breaks apart into pieces of the form $S \cdot F_*^e(x_1^{a_1} \cdots x_n^{a_n})$ consisting of all polynomials whose exponent vectors are coordinatewise congruent to (a_1, \dots, a_n) . Various applications of the Frobenius are based on taking an element of S , viewing it as an element $F_*^e S$, and breaking it into its components in this free S -basis, or equivalently, applying S -linear maps from $F_*^e S$ back to S . We will return to this idea soon.

This decomposition is a special case of the “Fundamental Theorem of Frobenius”.

Theorem 1.5 (Kunz). *Let R be a Noetherian ring of characteristic p , and let $e \geq 1$. The module $F_*^e R$ is a flat R -module if and only if R is a regular ring.*

A flat module is a weakening of free module (free implies flat), and a polynomial ring over a field is a key example of a regular ring.

We end with a technical definition that is useful for many purposes.

Definition 1.6. A ring R of characteristic p is **F-finite** if $F_* R$ is a finitely generated R -module; equivalently, $F_*^e R$ is a finitely generated R -module for all e .

This is a finiteness property, somewhat akin to Noetherianity. In the exercises, you will show that every finitely generated algebra over a perfect field is F-finite. We can get a more concrete version of Kunz’ theorem when R is F-finite and local. Recall that a **local ring** is a ring with a unique maximal ideal. We often write (R, \mathfrak{m}) for a local ring to denote R and its maximal ideal, or (R, \mathfrak{m}, k) to denote the residue field $k = R/\mathfrak{m}$ as well. Given any ring R and prime ideal \mathfrak{p} , we can obtain a local ring $R_{\mathfrak{p}}$ for adjoining inverses to every element outside of \mathfrak{p} , a process called localization.

A typical example of a local ring is, for a field K and some variables x_1, \dots, x_n , the collection of rational functions for the form

$$\left\{ \frac{f(x)}{g(x)} \mid g(x) \text{ has nonzero constant term} \right\}.$$

This is the local ring $K[x_1, \dots, x_n]_{(x_1, \dots, x_n)}$ obtained from the polynomial ring by localization at the prime (maximal) ideal consisting of polynomials with constant term zero. Another key example of a local ring is the power series ring $K[[x_1, \dots, x_n]]$. These are the two typical examples to keep in mind of regular local rings.

Corollary 1.7 (Kunz). *Let (R, \mathfrak{m}) be an F-finite Noetherian local ring of characteristic p . The module $F_*^e R$ is a free R -module if and only if R is a regular ring.*

Example 1.8. If K is a perfect field and S is either

$$K[x_1, \dots, x_n]_{(x_1, \dots, x_n)} \quad \text{or} \quad K[[x_1, \dots, x_n]],$$

then $F_*^e S$ is free with basis

$$B = \{F_*^e(x_1^{a_1} \cdots x_n^{a_n}) \mid 0 \leq a_i < p^e\}$$

as in the polynomial case.

Exercise set #1

Throughout this problem set all rings have characteristic p .

- (1) * Convince yourself, as succinctly as possible, that $r \in I$ if and only if $F_*^e r \in F_*^e I$.
- (2) Let $S = \mathbb{F}_3[x, y]$. Find an element in $(x, y)^3$ that is not in $(x, y)^{[3]}$.
- (3) Let $S = \mathbb{F}_3[x, y]$. Write out the free basis B for $F_* S$ from the proof of Theorem 1.4 and write the element $F_*(2x^6y^7 + x^5y^3 + x^3y^4 + 2xy^2)$ as an S -linear combination of B .
- (4) Let \mathfrak{p} be a prime ideal in R . Show that $F^{-1}(\mathfrak{p}) = \mathfrak{p}$.
- (5) * Let R be a ring and I be an ideal. Show that $F_*^e(I^{[p^e]}) = IF_*^e(R)$.
- (6) Show that $R^{p^e} = \{r^{p^e} \mid r \in R\}$ is a subring of R .
- (7) Suppose that R is reduced. Show that $R \cong R^{p^e}$, and that after identifying the source of the e -th Frobenius map with R^{p^e} via the isomorphism you found, the Frobenius map identifies with the inclusion map $R^{p^e} \subseteq R$.
- (8) * Let $R = \mathbb{F}_p[x, y]/(xy)$.
 - (a) Explain why R has \mathbb{F}_p -vector space basis $\{1, x, x^2, x^3, \dots, y, y^2, y^3, \dots\}$ (where, by abuse of notation, we write x for the equivalence class of x in the quotient).
 - (b) Find an \mathbb{F}_p -vector space basis for $F_*^e R$, and describe the action of R on $F_*^e R$ explicitly in terms of the action of each basis element of R with each basis element of $F_*^e R$.
 - (c) Show that the ideal (x) of multiples of x in R is isomorphic to $R/(y)$ as an R -module.
 - (d) Show that, as R -modules,

$$F_*^e R \cong R \cdot F_*^e 1 \oplus \bigoplus_{0 < i < p^e} R/(y) \cdot F_*^e(x^i) \oplus \bigoplus_{0 < j < p^e} R/(x) \cdot F_*^e(y^j).$$

- (9) Let $R = \mathbb{F}_2[x^2, xy, y^2]$; i.e., R is the subring of the polynomial ring $\mathbb{F}_2[x, y]$ with \mathbb{F}_2 vector space basis consisting of $\{x^i y^j \mid i + j \text{ is even}\}$. Find a generating set for $F_* R$ as an R -module. Is your generating set a free basis?
- (10) Let $K = \mathbb{F}_p(t_1, t_2, t_3, \dots)$, the field of rational functions over \mathbb{F}_p in countably many variables. Is K an F-finite field?
- (11) (a) Let R be an F-finite ring and I be an ideal. Show that R/I is also F-finite.
 (b) Let R be an F-finite ring and x be an indeterminate. Show that $R[x]$ is also F-finite.
 Deduce that every finitely generated algebra over a perfect field is F-finite.
- (12) Let R be as in (9). Verify directly that $F_* R$ has no free basis.
 It may be useful to use the fact that if M is a free R -module with basis B and I is an ideal, then M/IM is a free R/I -module with basis given by the images of B ; try different maximal ideals.

*To be used later in the lectures.

- (13) [§] Let K be a perfect field and $S = K[x_1, \dots, x_n]$. Consider $\text{Hom}_S(F_*^e S, S)$, the set of S -linear maps from $F_*^e S$ to S . Let $A = \{(a_1, \dots, a_n) \in \mathbb{Z}^n \mid 0 \leq a_i < p^e\}$.
- (a) Show that for each $\alpha \in A$, there is a map $\Phi_\alpha \in \text{Hom}_S(F_*^e S, S)$ such that
- $$\Phi_\alpha(F_*^e(x_1^{a_1} \cdots x_n^{a_n})) = \begin{cases} 1 & \text{if } (a_1, \dots, a_n) = \alpha \\ 0 & \text{if } (a_1, \dots, a_n) \in A \setminus \{\alpha\}. \end{cases}$$
- (b) Consider $\text{Hom}_S(F_*^e S, S)$ as an S -module by the rule $s \cdot \varphi(-) = s\varphi(-)$. Show that $\text{Hom}_S(F_*^e S, S)$ is a free S -module with this action, and find a basis.
- (c) Consider $\text{Hom}_S(F_*^e S, S)$ as an $F_*^e S$ -module by the rule $F_*^e s \cdot \varphi(-) = \varphi(F_*^e s \cdot -)$. Show that $\text{Hom}_S(F_*^e S, S)$ is a free $F_*^e S$ -module with basis the singleton $\{\Phi := \Phi_{(p^{e-1}, \dots, p^{e-1})}\}$.
- (14) Let R be a ring and I be an ideal. Show that $F_*^{e*}(R/I) \cong R/I^{[p^e]}$.
- (15) [†] Let W be a multiplicatively closed subset of R . Show that $F_*^e(W^{-1}R) \cong W^{-1}F_*^e R$.
- (16) Let $K = \mathbb{F}_p(t_1, t_2, t_3, \dots)$, and $R = K[[x]]$. Show that $F_* R$ is not a free module. Compare with Corollary 1.7.
- (17) Let R be a ring and I be an ideal. Is $F_*^{e*}(I) \cong I^{[p^e]}$ in general?
- (18) Let R be a ring containing \mathbb{Q} , let n be a positive integer, and I an ideal of R . Show that the ideal $(a^n \mid a \in I)$ is equal to I^n . Compare to problem (2).
- (19) [†] Let R be a Noetherian ring of positive characteristic. Show that F_R is surjective if and only if R is a finite product of perfect fields.
- (20) [†] Let R be an F-finite Noetherian ring. Show that the singular locus of R is a closed subset of $\text{Spec}(R)$.
- (21) [†] Let R be a regular Noetherian ring and M be a finitely generated module.
- (a) Show that $\text{Ass}_R(M) = \text{Ass}_R(F_*^e M)$ for all e .
- (b) Show that $\text{Ass}_R(M) = \text{Ass}_R(F_*^{e*} M)$ for all e .
- (c) Do the statements (21a) and (21b) hold if R is not assumed to be regular?

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[§]To be used in Problem set #2.

[†]Requires some background from Commutative Algebra.