

Quasi-coherent sheaves on the Moduli Stack of Formal Groups

Paul G. Goerss*

Abstract

The central aim of this monograph is to provide decomposition results for quasi-coherent sheaves on the moduli stack of formal groups. These results will be based on the geometry of the stack itself, particularly the height filtration and an analysis of the formal neighborhoods of the geometric points. The main theorems are algebraic chromatic convergence results and fracture square decompositions. There is a major technical hurdle in this story, as the moduli stack of formal groups does not have the finiteness properties required of an algebraic stack as usually defined. This is not a conceptual problem, but in order to be clear on this point and to write down a self-contained narrative, I have included a great deal of discussion of the geometry of the stack itself, giving various equivalent descriptions.

For years I have been echoing my betters, especially Mike Hopkins, and telling anyone who would listen that the chromatic picture of stable homotopy theory is dictated and controlled by the geometry of the moduli stack $\mathcal{M}_{\mathbf{fg}}$ of smooth, one-dimensional formal groups. Specifically, I would say that the height filtration of $\mathcal{M}_{\mathbf{fg}}$ dictates a canonical and natural decomposition of a quasi-coherent sheaf on $\mathcal{M}_{\mathbf{fg}}$, and this decomposition predicts and controls the chromatic decomposition of a finite spectrum. This sounds well, and is even true, but there is no single place in the literature where I could send anyone in order for him or her to get a clear, detailed, unified, and linear rendition of this story. This document is an attempt to set that right.

Before going on to state in detail what I actually hope to accomplish here, I should quickly acknowledge that the opening sentences of this introduction and, indeed, this whole point of view is not original with me. I have already mentioned Mike Hopkins, and just about everything I'm going to say here is encapsulated in the table in section 2 of [19] and can be gleaned from the notes of various courses Mike gave at MIT. See, for example, [18]. Further back, the intellectual journey begins, for myself as a homotopy theorist, with Quillen's fundamental insight linking formal groups, complex orientable cohomology theories, and complex cobordism – the basic papers are [44] and [45]. But the

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theory of formal groups predates Quillen’s work connecting algebraic topology and the algebraic geometry of formal groups: there was a rich literature already in place at the time he wrote his papers. Lazard did fundamental work in ’50s (see [34]), and there was work of Cartier [2] on what happens when you work localized at a prime, and even a thorough treatment of the deformation theory given by Lubin and Tate [35]. In short, Quillen’s work opened the door for the importation of a mature theory in geometry into homotopy theory.

It was Jack Morava, I think, who really had the vision of how this should go, but the 1970s saw a broad eruption of applications of formal groups to homotopy theory. The twin towers here are the paper of Miller, Ravenel, and Wilson [38] giving deep computations in the Adams-Novikov Spectral Sequence and Ravenel’s nilpotence conjectures [46], later largely proved by Devinatz, Hopkins, and Smith in [7] and [20]. This period fundamentally changed stable homotopy theory. Morava himself wrote a number of papers, most notably [40] (see also Doug Ravenel’s Math Review of this paper in [47]), but there are rumors of a highly-realized and lengthy manuscript on formal groups and their applications to homotopy theory. If so, it is a loss that Jack never thought this manuscript ready for prime-time viewing.

Let me begin the account of what you can find here with some indication of how stacks come into the narrative. One simple observation, due originally (I think) to Neil Strickland is that stacks can calculate homology groups. Specifically, if E_* and F_* are two 2-periodic Landweber exact homology theories and if G and H are the formal groups over E_0 and F_0 respectively, then there is a 2-category pull-back square

$$\begin{array}{ccc} \mathrm{Spec}(E_0F) & \longrightarrow & \mathrm{Spec}(F_0) \\ \downarrow & & \downarrow H \\ \mathrm{Spec}(E_0) & \xrightarrow{G} & \mathcal{M}_{\mathbf{fg}} \end{array}$$

This can be seen in Lemma 2.11 below. I heard Mike, in his lectures at Münster, noting this fact as piquing his interest in stacks. Beyond this simple calculation, Strickland should certainly get a lot of credit for all of this: while the reference [52] never actually uses the word “stack”, the point of view is clear and, in fact, much of what I say here can be found there in different – and sometimes not so different – language.

For computations, especially with the Adams-Novikov Spectral Sequence, homotopy theorists worked with the cohomology of comodules over Hopf algebroids. A succinct way to define such objects is to say that a Hopf algebroid represents an affine groupoid scheme; in particular, Quillen’s theorem mentioned above amounts to the statement that the affine groupoid scheme arising from the Hopf algebroid of complex cobordism is none other than the groupoid scheme which assigns to each commutative ring A the groupoid of formal group laws and their strict isomorphisms over A . Hopf algebroids were and are a powerful computational tool – as far as I know, the calculations of [38] remain, for the combination of beauty and technical prowess, in a class with Secretariat’s

run at the Belmont Stakes – but an early and fundamental result was “Morava’s Change of Rings Theorem”, which, in summary, says that if two Hopf algebroids represent equivalent (not isomorphic) groupoid schemes, then they have isomorphic cohomology. A more subtle observation is that the change of rings results holds under weaker hypotheses: the groupoid schemes need only be equivalent “locally in the flat topology”; that is, the presheaves π_0 of components and π_1 of automorphisms induces isomorphic sheaves in the *fpqc* topology. (See [21] and [14] for discussions of this result.) In modern language, we prove this result by combining the following three observations:

- the category of comodules over a Hopf algebroid is equivalent to the category of quasi-coherent sheaves on the associated stack;
- two groupoid schemes locally equivalent in the flat topology have equivalent associated stacks; and
- equivalent stacks have equivalent categories of quasi-coherent sheaves.

Note that in the end, we have a much stronger result than simply an isomorphism of cohomology groups – we have an entire equivalence of categories.

Once we’ve established an equivalence between the category of comodules and the category of quasi-coherent sheaves (see Equation 3.5) we can rewrite the cohomology of comodules as coherent cohomology of quasi-coherent sheaves; for example,

$$\mathrm{Ext}_{MU_*MU}^s(\Sigma^{2t}MU_*, MU_*) \cong H^s(\mathcal{M}_{\mathbf{fg}}, \omega^{\otimes t})$$

where ω is the invertible sheaf on $\mathcal{M}_{\mathbf{fg}}$ which assigns to each flat morphism $g : \mathrm{Spec}(R) \rightarrow \mathcal{M}_{\mathbf{fg}}$ the invariant differentials ω_G of the formal group classified by G . Thus, one of our most sensitive algebraic approximations to the stable homotopy groups of spheres can be computed as the cohomology of the moduli stack $\mathcal{M}_{\mathbf{fg}}$.

There are other reasons for wanting to pass from comodules over Hopf algebroids to quasi-coherent sheaves. For example, there are naturally occurring stacks which are not canonically equivalent, even in the local sense mentioned above, to an affine groupoid scheme. The most immediate example is the moduli stack $\mathcal{U}(n)$ of formal groups of height less than or equal to some fixed integer $n \geq 0$. These stacks have affine presentations, but not canonically; the canonical presentation is a non-affine open subscheme of $\mathrm{Spec}(L)$, where L is the Lazard ring. Thus the quasi-coherent sheaves on $\mathcal{U}(n)$ are equivalent to many categories of comodules, but no particular such category is preferred (except by tradition – this is one role for the Johnson-Wilson homology theories $E(n)_*$) and the quasi-coherent sheaves themselves remain the basic object of study. The point is taken up in [25] and [41].

Here is what I hope to accomplish in these notes.

- Give a definition of formal group which evidently satisfies the effective descent condition necessary to produce a moduli stack. See Proposition 2.6. This can be done in a number of ways, but the I have chosen to use

the notion of formal Lie varieties, a concept developed by Grothendieck to give a conceptual formulation of smoothness in the formal setting.

- A formal group law is equivalent to a formal group with a chosen coordinate. The scheme of all coordinates for a formal group G over a base scheme S is a torsor Coord_G over S for the group scheme Λ which assigns to each ring R the group of power series invertible under composition. Using coordinates we can identify $\mathcal{M}_{\mathbf{fg}}$ as the quotient stack of the scheme of formal groups by the algebraic group Λ . See Proposition 3.13. This makes transparent the fact that $\mathcal{M}_{\mathbf{fg}}$ is an algebraic stack (of a suitable sort) and it makes transparent the equivalence between comodules and quasi-coherent sheaves.
- The stack $\mathcal{M}_{\mathbf{fg}}$ is not an algebraic stack in the sense of the standard literature (for example, [33]) because it does not have a presentation by a scheme locally of finite type – the Lazard ring is a polynomial ring on infinitely many generators. It is, however, pro-algebraic: it can be written as 2-category (i.e., homotopy) inverse limit of the algebraic stacks $\mathcal{M}_{\mathbf{fg}}\langle n \rangle$ of n -buds of formal groups. This result is inherent in Lazard’s original work – it is the essence of the 2-cocycle lemma – but I learned it from Mike Hopkins and it has been worked out in detail by Brian Smithling [51]. An important point is that any *finitely presented* quasi-coherent sheaf on $\mathcal{M}_{\mathbf{fg}}$ is actually the pull-back of a quasi-coherent sheaf on $\mathcal{M}_{\mathbf{fg}}\langle n \rangle$ for some n . See Theorem 3.28.
- Give a coordinate-free definition of height and the height filtration. Working over $\mathbb{Z}_{(p)}$, the height filtration is a filtration by closed, reduced substacks

$$\cdots \subseteq \mathcal{M}(n) \subseteq \mathcal{M}(n-1) \subseteq \cdots \subseteq \mathcal{M}(1) \subseteq \mathcal{M}_{\mathbf{fg}}$$

so that inclusion $\mathcal{M}(n) \subseteq \mathcal{M}(n-1)$ is the effective Cartier divisor defined by a global section v_n of the invertible sheaf $\omega^{\otimes(p^n-1)}$ over $\mathcal{M}(n-1)$. This implies, among other things, that $\mathcal{M}(n) \subseteq \mathcal{M}_{\mathbf{fg}}$ is regularly embedded, a key ingredient in Landweber Exact Functor Theorem and chromatic convergence. The height filtration is essentially unique: working over $\mathbb{Z}_{(p)}$, any closed, reduced substack of $\mathcal{M}_{\mathbf{fg}}$ is either $\mathcal{M}_{\mathbf{fg}}$ itself, $\mathcal{M}(n)$ for some n , or $\mathcal{M}(\infty) = \bigcap \mathcal{M}(n)$. See Theorem 5.14. This is the geometric content of the Landweber’s invariant prime ideal theorem. The stack $\mathcal{M}(\infty)$ is not empty as the morphism classifying the additive formal group over \mathbb{F}_p factors through $\mathcal{M}(\infty)$. This point and the next can also be found in Smithling’s thesis [51]. Some of this material is also in the work of Hollander [15].

- Identify $\mathcal{H}(n) = \mathcal{M}(n) - \mathcal{M}(n+1)$, the moduli stack of formal groups of exact height n , as the neutral gerbe determined by the automorphism scheme of any height n formal group Γ_n over \mathbb{F}_p . See Theorem 5.38. This automorphism scheme is affine and, if we choose Γ_n to be the Honda formal group of height n , well known to homotopy theorists – its ring

of functions is the Morava stabilizer algebra (see [48], Chapter 6) and its group of \mathbb{F}_{p^n} points is the Morava stabilizer group. This is all a restatement of Lazard’s uniqueness theorem for height n formal groups in modern language; indeed, the key step in the argument is the proof, essentially due to Lazard, that given any two formal groups G_1 and G_2 over an \mathbb{F}_p -scheme S , then the scheme $\text{Iso}_S(G_1, G_2)$ of isomorphisms from G_1 to G_2 is either empty (if they have different heights) or pro-étale and surjective over S (if they have the same height). See Theorem 5.25; we give essentially Lazard’s proof, but similar results with nearly identical statements appear in [29].

- Describe the formal neighborhood $\widehat{\mathcal{H}}(n)$ of $\mathcal{H}(n)$ inside the open substack $\mathcal{U}(n)$ of $\mathcal{M}_{\mathbf{fg}}$ of formal groups of height at most n . Given a choice of Γ_n of formal group of height n over the algebraic closure $\overline{\mathbb{F}}_p$ of \mathbb{F}_p the morphism

$$\mathbf{Def}(\overline{\mathbb{F}}_p, \Gamma_n) \longrightarrow \widehat{\mathcal{H}}(n)$$

from the Lubin-Tate deformation space to the formal neighborhood is pro-Galois with Galois group $\mathbb{G}(\overline{\mathbb{F}}_p, \Gamma_n)$, the automorphism group of the pair $(\overline{\mathbb{F}}_p, \Gamma_n)$. Lubin-Tate theory identifies $\mathbf{Def}(\overline{\mathbb{F}}_p, \Gamma_n)$ as the formal spectrum of a power series ring; since a power series ring can have no finite étale extensions, we may say $\mathbf{Def}(\overline{\mathbb{F}}_p, \Gamma_n)$ is the universal cover of $\widehat{\mathcal{H}}(n)$. If Γ_n is actually defined over \mathbb{F}_p , then $\mathbb{G}(\overline{\mathbb{F}}_p, \Gamma_n)$ is known to homotopy theorists as the big Morava stabilizer group:

$$\mathbb{G}(\overline{\mathbb{F}}_p, \Gamma_n) \cong \text{Gal}(\overline{\mathbb{F}}_p/\mathbb{F}_p) \rtimes \text{Aut}_{\overline{\mathbb{F}}_p}(\Gamma_n).$$

From this theory, it is possible to describe what it means to be a module on the formal neighborhood of a height n point; that is, to give a definition of the category of “Morava modules”. See Remark 7.27.

- If $\mathcal{N} \rightarrow \mathcal{M}_{\mathbf{fg}}$ is a representable, separated, and flat morphism of algebraic stacks, then the induced height filtration

$$\cdots \subseteq \mathcal{N}(n) \subseteq \mathcal{N}(n-1) \subseteq \cdots \subseteq \mathcal{N}(1) \subseteq \mathcal{N}$$

with $\mathcal{N}(n) = \mathcal{M}(n) \times_{\mathcal{M}_{\mathbf{fg}}} \mathcal{N}$ automatically has that the inclusions $\mathcal{N}(n) \subseteq \mathcal{N}(n-1)$ are effective Cartier divisors. The Landweber Exact Functor Theorem (LEFT) is a partial converse to this statement. Here I wrote down a proof due to Mike Hopkins ([18]) of this fact. Other proofs abound – besides the original [32], there’s one due to Haynes Miller [37], and Sharon Hollander has an argument as well [15]. The morphism from the moduli stack of elliptic curves to $\mathcal{M}_{\mathbf{fg}}$ which assigns to each elliptic curve its associated formal group is an example. It is worth emphasizing that this is a special fact about the moduli stack of formal groups – the proof uses that $\mathcal{H}(n)$ has a unique geometric point.

- Give proofs of the algebraic analogs of the topological chromatic convergence and fracture square results for spectra. Work over $\mathbb{Z}_{(p)}$ and let

$i_n : \mathcal{U}(n) \rightarrow \mathcal{M}_{\mathbf{fg}}$ be the open inclusion of the moduli stack of formal groups of height at most n . If \mathcal{F} is a quasi-coherent sheaf on $\mathcal{M}_{\mathbf{fg}}$, we can form the derived push-forward of the pull-back $R(i_n)_* i_n^* \mathcal{F}$. As n varies, these assemble into a tower of cochain complexes of quasi-coherent sheaves on $\mathcal{M}_{\mathbf{fg}}$ and there is a natural map

$$\mathcal{F} \longrightarrow \operatorname{holim} R(i_n)_* i_n^* \mathcal{F}.$$

Chromatic convergence then says that if \mathcal{F} is finitely presented, this morphism is an equivalence. The result has teeth as the $\mathcal{U}(n)$ do not exhaust $\mathcal{M}_{\mathbf{fg}}$. To examine the transitions in this tower, we note that the inclusion $\mathcal{M}(n) = \mathcal{M}_{\mathbf{fg}} - \mathcal{U}(n-1) \subseteq \mathcal{M}_{\mathbf{fg}}$ is defined by the vanishing of a sheaf of ideals \mathcal{I}_n which is locally generated by regular sequence. Then for any quasi-coherent sheaf on $\mathcal{M}_{\mathbf{fg}}$ there is a homotopy Cartesian square (the fracture square)

$$\begin{array}{ccc} \mathcal{F} & \longrightarrow & L(\mathcal{F})_{\mathcal{I}(n)}^\wedge \\ \downarrow & & \downarrow \\ R(i_{n-1})_* i_{n-1}^* \mathcal{F} & \longrightarrow & R(i_{n-1})_* i_{n-1}^* (L(\mathcal{F})_{\mathcal{I}(n)}^\wedge) \end{array}$$

where $L(\mathcal{F})_{\mathcal{I}(n)}^\wedge$ is the total left derived functor of the completion of \mathcal{F} . Both proofs use the homotopy fiber of

$$\mathcal{F} \longrightarrow R(i_n)_* i_n^* \mathcal{F}$$

which is the total local cohomology sheaf $R\Gamma_{\mathcal{M}(n)} \mathcal{F}$. This can be analyzed using the fact that $\mathcal{M}(n) \subseteq \mathcal{M}_{\mathbf{fg}}$ is a regular embedding and Greenlees-May duality [12]; the requisite arguments can be lifted nearly verbatim from [1], but see also [8] – the fracture square appears in exactly this form in this last citation. Chromatic convergence is less general – the proof I give here uses that any finitely presented sheaf can be obtained as a pull-back from the stack of n -buds $\mathcal{M}_{\mathbf{fg}}\langle m \rangle$ for some m . This allows one to show that the transition map

$$R\Gamma_{\mathcal{M}(n+1)} \mathcal{F} \rightarrow R\Gamma_{\mathcal{M}(n)} \mathcal{F}$$

between the various total local cohomology sheaves is zero in cohomology for large n .

I have said very little about the direct applications all this geometry to stable homotopy theory. This is because of the Mahowald Uncertainty Principle, a term coined by Doug Ravenel to encapsulate the observation, due to Mark Mahowald, that any approximation to the stable homotopy groups of spheres obtained from purely algebraic input will be infinitely far away from the real answer. Under suitable hypotheses, the algebraic geometry and the homotopy theory become relatively close; see for example, the illuminating paper of Jens

Franke [9] for a thorough discussion of this point and many further references. The hypotheses in question usually require that we work at a prime p and consider only formal groups of height bounded by that prime.

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1 Schemes and formal schemes

This section is devoted entirely to a review of the algebraic geometry we need for the rest of the paper. It can – and perhaps should – be skipped by anyone knowledgeable in these matters.

1.1 Schemes and sheaves

We first recall some basic definitions about schemes and morphisms of schemes, then enlarge the category slightly to sheaves in the *fpqc*-topology. This is necessary as formal schemes and formal groups are not really schemes.

Fix a commutative ring R . Schemes over R can be thought of as functors from \mathbf{Alg}_R to the category of sets. We briefly review this material – mostly to establish language.

The basic schemes over R are the affine schemes $\mathrm{Spec}(B)$, where B is an R -algebra. As a functor

$$\mathrm{Spec}(B) : \mathbf{Alg}_R \longrightarrow \mathbf{Sets}$$

is the representable functor determined by R ; that is,

$$\mathrm{Spec}(B)(A) = \mathbf{Alg}_R(B, A).$$

If $I \subseteq B$ is an ideal we have the open subfunctor $U_I \subseteq \mathrm{Spec}(B)$ with

$$U_I(A) = \{ f : B \rightarrow A \mid f(I)A = A \} \subseteq \mathrm{Spec}(B).$$

This defines the Zariski topology on $\mathrm{Spec}(B)$. The complement of U_I is defined to be the closed subfunctor $Z_I = \mathrm{Spec}(B/I)$; thus,

$$Z_I(A) = \{ f : B \rightarrow A \mid f(I)A = 0 \} \subseteq \mathrm{Spec}(B).$$

Note that we can guarantee that

$$U_I(A) \cup Z_I(A) = \mathrm{Spec}(B)(A)$$

only if A is a field.

If $X : \mathbf{Alg}_R \rightarrow \mathbf{Sets}$ is any functor, we define a subfunctor $U \subseteq X$ to be *open* if the subfunctor

$$U \times_X \mathrm{Spec}(B) \subseteq \mathrm{Spec}(B)$$

is open for for all morphisms of functors $\mathrm{Spec}(B) \rightarrow X$. Such morphisms are in one-to-one correspondence with $X(B)$, by the Yoneda Lemma. A collection of subfunctors $U_i \subseteq X$ is called a cover if the morphism $\sqcup U_i(\mathbb{F}) \rightarrow X(\mathbb{F})$ is onto for all *fields* \mathbb{F} .

As a matter of language, a functor $X : \mathbf{Alg}_R \rightarrow \mathbf{Sets}$ will be called an *R-functor*.

1.1 Definition. An R -functor X is a scheme over R if it satisfies the following two conditions:

1. X is a sheaf in the Zariski topology; that is, if A is an R -algebra and $a_1, \dots, a_n \in A$ are elements so that $a_1 + \dots + a_n = 1$, then

$$X(A) \longrightarrow \prod X(A[a_i^{-1}]) \rightrightarrows \prod X(A[a_i^{-1}a_j^{-1}])$$

is an equalizer diagram; and

2. X has an open cover by affine schemes $\text{Spec}(B)$ where each B is an R -algebra

A morphism $X \rightarrow Y$ of schemes over R is a natural transformation of R -functors.

An open subfunctor U of scheme X is itself a scheme; the collection of all open subfunctors defines the *Zariski topology* on X .

1.2 Remark (Module sheaves and quasi-coherent sheaves). There is an obvious sheaf of rings \mathcal{O}_X in this topology on X called the *structure sheaf* of X . If $U = \text{Spec}(B) \subseteq X$ is an affine open, then $\mathcal{O}_X(U) = B$; this definition extends to other open subsets by the sheaf condition. A sheaf \mathcal{F} of \mathcal{O}_X -modules on X is a sheaf so that

1. for all open $U \subseteq X$, $\mathcal{F}(U)$ is an $\mathcal{O}_X(U)$ -module;
2. for all inclusions $V \rightarrow U$, the restriction map $\mathcal{F}(U) \rightarrow \mathcal{F}(V)$ is a morphism of $\mathcal{O}_X(U)$ -modules.

We now list some special classes of \mathcal{O}_X -module sheaves. The following definitions are all in [10], §0.5. Let X be a scheme. For any set I write $\mathcal{O}_X^{(I)}$ for the coproduct of \mathcal{O}_X with itself I times. This coproduct is the sheaf associated to the direct sum presheaf.

QC. A module sheaf \mathcal{F} is *quasi-coherent* if there is a cover of X by open subschemes U_i so that for each i there is an exact sequence of \mathcal{O}_{U_i} -sheaves

$$\mathcal{O}_{U_i}^{(J)} \rightarrow \mathcal{O}_{U_i}^{(I)} \rightarrow \mathcal{F}|_{U_i} \rightarrow 0.$$

LF. A quasi-coherent sheaf is *locally free* if the set J can be taken to be empty.

FP. A quasi-coherent sheaf \mathcal{F} is *finitely presented* if the sets I and J can be taken to be finite.

FT. A module sheaf \mathcal{F} is of *finite type* if there is an open cover by subschemes U_i and, for each i , a surjection

$$\mathcal{O}_{U_i}^{(I)} \rightarrow \mathcal{F}|_{U_i} \rightarrow 0.$$

with I finite.

C. A module sheaf \mathcal{F} is *coherent* if is of finite type and for all open subschemes U of X and all morphisms

$$f : \mathcal{O}_U^n \longrightarrow \mathcal{F}|_U$$

of sheaves, the kernel of f is of finite type.

There are examples of sheaves of finite type which are not quasi-coherent. Every coherent sheaf is finitely presented and, hence, quasi-coherent; however, a finitely presented module sheaf is coherent only if \mathcal{O}_X itself is coherent. For affine schemes $\text{Spec}(A)$, this is equivalent to A being a coherent ring – every finitely generated ideal is finitely presented. This will happen if A is a filtered colimit of a diagram of Noetherian rings with flat transition maps; for example, the Lazard ring L .

If $X_1 \rightarrow Y \leftarrow X_2$ is a diagram of schemes, the evident fiber product $X_1 \times_Y X_2$ of functors is again a scheme; furthermore, if $U = X_1 \rightarrow Y$ is an open subscheme, then $U \times_Y X_2 \rightarrow X_2$ is also an open subscheme. Thus, if $f : X \rightarrow Y$ is a morphism of schemes, and \mathcal{F} is a sheaf in the Zariski topology on X , we get a *push-forward* sheaf $f_*\mathcal{F}$ on Y with

$$f_*\mathcal{F}(U) = \mathcal{F}(U \times_Y X).$$

In particular, $f_*\mathcal{O}_X$ is a sheaf of \mathcal{O}_Y -algebras and if \mathcal{F} is an \mathcal{O}_X -module sheaf, $f_*\mathcal{F}$ becomes a \mathcal{O}_Y -module sheaf. Extra hypotheses are needed for $f_*(-)$ to send quasi-coherent sheaves to quasi-coherent sheaves. See Proposition 1.6 below.

The functor f_* from \mathcal{O}_X -modules to \mathcal{O}_Y -modules has a left adjoint, of course. If $f : X \rightarrow Y$ is a morphism of schemes and \mathcal{F} is any sheaf on Y , define a sheaf $f^{-1}\mathcal{F}$ on X by

$$[f^{-1}\mathcal{F}](U) = \text{colim } \mathcal{F}(V)$$

where the colimit is taken over all diagrams of the form

$$\begin{array}{ccc} U & \longrightarrow & X \\ \downarrow & & \downarrow \\ V & \longrightarrow & Y \end{array}$$

with V open in Y . If \mathcal{F} is an \mathcal{O}_Y -module sheaf, then $f^{-1}\mathcal{F}$ is an $f^{-1}\mathcal{O}_Y$ -module sheaf and the *pull-back* sheaf is

$$f^*\mathcal{F} = \mathcal{O}_X \otimes_{f^{-1}\mathcal{O}_Y} f^{-1}\mathcal{F}.$$

Thus we have an adjoint pair

$$(1.1) \quad f^* : \mathbf{Mod}_Y \longleftarrow \mathbf{Mod}_X : f_*.$$

Here and always, the left adjoint is written on top and from left to right. If \mathcal{F} is quasi-coherent, so is $f^*\mathcal{F}$; if \mathcal{O}_X is coherent and \mathcal{F} is coherent, then $f^*\mathcal{F}$ is coherent.

1.3 Remark (The geometric space of a scheme). Usually, we define a scheme to be a locally ringed space with an open cover by prime ideal spectra. This is equivalent to the definition here, which is essentially that of Demazure and Gabriel. Since both notions are useful – even essential – we show how to pass from one to the other.

If X is a functor from commutative rings to sets, we define the associated *geometric space* $|X|$ as follows. A point in $|X|$ – also known as a *geometric point* of X – is an equivalence class of morphisms $f : \text{Spec}(\mathbb{F}) \rightarrow X$ with \mathbb{F} a field. The morphism f is equivalent to $f' : \text{Spec}(\mathbb{F}') \rightarrow X$ if they agree after some common extension. This becomes a topological space with open sets $|U|$ where $U \subseteq X$ is an open subfunctor.

If $X = \text{Spec}(B)$, then a geometric point of X is an equivalence class of homomorphisms of commutative rings $g : B \rightarrow \mathbb{F}$; this equivalence class is determined by the kernel of g , which must be a prime ideal. Furthermore, the open subsets of $|\text{Spec}(B)|$ are exactly the subsets $D(I)$ where $I \subseteq B$ is an ideal: $D(I)$ is complement of the closed set $V(I)$ of prime ideals containing I . Thus $|\text{Spec}(B)|$ is the usual prime ideal spectrum of B .

If $X = \text{Spec}(B)$, then $|X|$ becomes a locally ringed space, with structure sheaf \mathcal{O} the sheaf associated to the presheaf which assigns to each $D(I)$ the ring $S_I^{-1}B$ where

$$S_I = \{ a \in B \mid a + \mathfrak{p} \neq \mathfrak{p} \text{ for all } \mathfrak{p} \in D(I) \}.$$

The stalk \mathcal{O}_x of \mathcal{O} at the point x specified by the prime ideal \mathfrak{p} is exactly $B_{\mathfrak{p}}$. If X is a general functor, then there is a homeomorphism of topological spaces

$$\text{colim } |\text{Spec}(B)| \xrightarrow{\cong} |X|$$

where the colimit is over the category of all morphisms $\text{Spec}(B) \rightarrow X$. This equivalence specifies the structure sheaf on $|X|$ as well. Indeed, if $U \subseteq X$ is an open subfunctor, then, by definition $U \times_X \text{Spec}(B)$ is open in $\text{Spec}(B)$ for all $\text{Spec}(B) \rightarrow X$ and $\mathcal{O}(|U|)$ is determined by the sheaf condition.

If $|X|$ is a scheme, then $|X|$ has an open cover by open subsets of the form $V_i = |\text{Spec}(B_i)|$ and, in addition,

$$(\mathcal{O}_{|X|})|_{V_i} \cong \mathcal{O}_{|\text{Spec}(B_i)|}.$$

Whenever a locally ringed space (Y, \mathcal{O}) has such a cover, we will say that Y has a cover by prime ideal spectra.

The geometric space functor $|-|$ from \mathbb{Z} -functors to locally ringed spaces has a right adjoint $\mathbf{S}(-)$: if Y is a geometric space, then the R -points of $\mathbf{S}(Y)$ is the set of morphisms of locally ringed spaces

$$|\text{Spec}(B)| \rightarrow Y.$$

The following two statements are the content of the Comparison Theorem of §I.1.4.4 of [4].

1. Let (Y, \mathcal{O}) be a locally ringed space with an open cover V_i by prime ideal spectra. Then the adjunction morphism $|\mathbf{S}(Y)| \rightarrow Y$ is an isomorphism of locally ringed spaces,
2. If X be a functor from commutative rings to sets. Then $|X|$ has an open cover by prime ideal spectra if and only if X is a scheme and, in that case, $X \rightarrow \mathbf{S}|X|$ is an isomorphism.

Together these statements imply that adjoint pair $|-|$ and $\mathbf{S}(-)$ induce an equivalence of categories between schemes and locally ringed spaces with an open cover by prime ideal spectra. For this reason and from now on we use one or the other notion as is convenient.

1.4 Remark. If X is a scheme and x a geometric point of X represented by $f : \text{Spec}(\mathbb{F}) \rightarrow X$, then the stalk $\mathcal{O}_{X,x}$ of the structure sheaf at X can be calculated as

$$\mathcal{O}_{X,x} \cong \text{colim}_{U \subseteq X} \mathcal{O}_X(U).$$

where U runs over all open subschemes so that f factors through U . This is the global sections of $f^{-1}\mathcal{O}_X$. If f factors as $\text{Spec}(\mathbb{F}) \rightarrow \text{Spec}(B) \subseteq X$ with $\text{Spec}(B)$ open in X , then there is an isomorphism

$$\mathcal{O}_{X,x} \cong B_{\mathfrak{p}}$$

where \mathfrak{p} is kernel of $R \rightarrow \mathbb{F}$. It is easy to check this is independent of the choice of f .

If $X \rightarrow Y$ is a morphism of schemes, then we have a morphism of sheaves $f^{-1}\mathcal{O}_Y \rightarrow \mathcal{O}_X$. If $x \in X$ is a geometric point, we get an induced morphism of local rings $\mathcal{O}_{Y,f(x)} \rightarrow \mathcal{O}_{X,x}$.

1.5 Remark. We use this paragraph to give some standard definitions of properties of morphisms of schemes.

1.) A morphism $f : X \rightarrow Y$ of schemes is *flat* if for all geometric points of X geometric space, the induced morphism of local rings

$$\mathcal{O}_{Y,f(x)} \rightarrow \mathcal{O}_{X,x}$$

is flat. The morphism f is *faithfully flat* if it is flat and surjective. Here surjective means $X(\mathbb{F}) \rightarrow Y(\mathbb{F})$ is onto for all fields or, equivalently, the induced morphism of geometric spaces $|X| \rightarrow |Y|$ is surjective.

2.) A scheme X is called *quasi-compact* if every cover by open subschemes $U_i \subseteq X$ has a finite subcover. A morphism of schemes $X \rightarrow Y$ is quasi-compact if for every quasi-compact open $V \subseteq Y$, the scheme $V \times_Y X$ is quasi-compact.

3.) A morphism $f : X \rightarrow Y$ of schemes is called *quasi-separated* if the diagonal morphism $X \rightarrow X \times_Y X$ is quasi-compact.

4.) A morphism $f : X \rightarrow Y$ of schemes is *finitely presented* if for all open $U \subseteq Y$, $f_*\mathcal{O}_X(U)$ is a finitely presented $\mathcal{O}_Y(U)$ -algebra; that is, $f_*\mathcal{O}_X(U)$ is a quotient of $\mathcal{O}_Y(U)[x_1, \dots, x_n]$ by a finitely generated ideal.

Any affine scheme $\text{Spec}(B)$ is quasi-compact as the subschemes $\text{Spec}(B[1/f])$ form a basis for the Zariski topology. It follows that every morphism of affine schemes is quasi-compact and quasi-separated.

The following is in [4], Proposition I.2.2.4.

1.6 Proposition. *Let $f : X \rightarrow Y$ be a quasi-compact and quasi-separated morphism of schemes. If \mathcal{F} is a quasi-coherent \mathcal{O}_X -module sheaf, then $f_*\mathcal{F}$ is a quasi-coherent \mathcal{O}_Y module sheaf.*

Thus, if f is quasi-compact and quasi-separated, Equation 1.1 yields an adjoint pair

$$f^* : \mathbf{Qmod}_Y \rightleftarrows \mathbf{Qmod}_X : f_*$$

1.7 Remark (Faithfully flat descent). Let $f : X \rightarrow Y$ be an morphism of schemes and let

$$X^n = X \times_Y \cdots \times_Y X$$

where the product is taken n times. If $\phi : [m] \rightarrow [n]$ is any morphism in the ordinal number category, define $\phi^* : X^n \rightarrow X^m$ by the pointwise formula

$$\phi(x_0, \dots, x_n) = (x_{\phi(0)}, \dots, x_{\phi(n)}).$$

In this way we obtain a simplicial R -functor X_\bullet augmented to Y . This is the *coskeleton* of f .

A *descent problem* for f is a pair (\mathcal{F}, ψ) where \mathcal{F} is a sheaf on X and $\psi : d_1^*\mathcal{F} \rightarrow d_0^*\mathcal{F}$ is an isomorphism of sheaves on $X \times_Y X$ subject to the cocycle condition

$$d_1^*\psi = d_2^*\psi d_0^*\psi$$

over $X \times_Y X \times_Y X$. A solution to a descent problem is a sheaf \mathcal{E} over Y and an isomorphism $\phi_0 : f^*\mathcal{E} \rightarrow \mathcal{F}$ over X so that the following diagram commutes

$$\begin{array}{ccc} d_1^*f^*\mathcal{E} & \xrightarrow{c} & d_0^*f^*\mathcal{E} \\ d_1^*\psi_0 \downarrow & & \downarrow d_0^*\psi_0 \\ d_1^*\mathcal{F} & \xrightarrow{\psi} & d_0^*\mathcal{F} \end{array}$$

where c is the canonical isomorphism obtained from the equation $fd_1 = fd_0$. If f is faithfully flat, there is exactly one solution with \mathcal{E} quasi-coherent and we get an evident equivalence of categories. This has many refinements; for example, one could concentrate on algebra sheaves instead of module sheaves. See Proposition 1.17 below.

1.8 Notation. Let \mathcal{C} be a category, \mathcal{C}_0 a sub-category, and $X \in \mathcal{C}$. Let $\mathbf{Pre}(\mathcal{C}_0)$ the category of presheaves (i.e., contravariant functors) from \mathcal{C}_0 to sets.¹ Then

¹The category of presheaves as defined here is not a category as it might not have small Hom-sets. There are several ways to handle this difficulty, one being to bound the cardinality of all objects in question at a large enough cardinal that all objects of interest are included. The issues are routine, so will ignore this problem. The same remark applies to category of R -functors.

the assignment

$$X \mapsto \mathrm{Hom}_{\mathcal{C}}(-, X)$$

defines a functor $\mathcal{C} \rightarrow \mathbf{Pre}(\mathcal{C}_0)$ and we will write X equally for the object X and the associated representable presheaf. In our main examples, \mathcal{C} will be R -functors and \mathcal{C}_0 will be affine schemes or schemes over R . In this case, the $\mathcal{C} \rightarrow \mathbf{Pre}(\mathcal{C}_0)$ is an embedding; if \mathcal{C} is R -functors and $\mathcal{C}_0 = \mathbf{Aff}/R$, it is an equivalence.

1.9 Remark (Topologies). In [3] Exposé IV, topologies on schemes over a fixed base ring R are defined as follows.

First, if X is an R -functor, then a *sieve* on X is a subfunctor F of the functor on R -functors over X represented by X itself; thus for every $Y \rightarrow X$, $F(Y)$ is either empty or one point. The collection $E(F)$ of $Y \rightarrow X$ so that $F(Y) \neq \emptyset$ has the property that if $Y \in E(F)$ and $Z \rightarrow Y$, then $Z \in E(F)$. The collection $E(F)$ determines F ; conversely any such collection E determines a sieve F with $E(F) = E$.

Next, let $f_i : X_i \rightarrow X$ be a collection of morphisms R functors. This determines a sieve by taking E to be the set of $Y \rightarrow X$ which factor through some f_i . This collection of morphisms is the base of resulting sieve; any sieve has at least one base, for example $E(F)$. Thus, it may be convenient to specify sieves by families of morphisms.

In [3] IV.4.2., a topology on the category of R -functors is an assignment, to each R -functor, a set of *covering sieves* $J(X)$ subject to the following axioms:

1. $X \in J(X)$;
2. if F is a sieve for X and $\mathrm{Spec}(B) \times_X F \in J(\mathrm{Spec}(B))$ for all morphisms of R -functors $\mathrm{Spec}(B) \rightarrow X$ with affine source, then $F \in J(X)$;
3. (Base change) if $F \in J(X)$ and $Y \rightarrow X$ is a morphism of R -functors then $F \times_X Y \in J(Y)$;
4. (Composition) if $F \in J(X)$ and $G \in J(F)$, then $G \in J(X)$;
5. (Saturation) if F is a sieve for X , G a sieve for F and $G \in J(X)$, then $F \in J(X)$;

These axioms together imply

6. (Local) If F_1 and F_2 are in $J(X)$, so is $F_1 \cap F_2$.

As in [3] IV.4.2.3, these axioms can be reformulated in terms of families of morphisms: it is equivalent to assign to each R -functor X a collection $C(X)$ of sets of *covering families* of morphisms $\{X_i \rightarrow X\}$ of R -functors with the following properties:

1. If $Y \rightarrow X$ is an isomorphism, then $\{Y \rightarrow X\} \in C(X)$;

2. If $\{X_i \rightarrow X\}$ is a set of morphisms so that $\{\mathrm{Spec}(B) \times_X X_i \rightarrow \mathrm{Spec}(B)\} \in C(\mathrm{Spec}(B))$ whenever $\mathrm{Spec}(B) \rightarrow X$ is a morphism from an affine scheme, then $\{X_i \rightarrow X\} \in C(X)$;
3. (Base change) If $Y \rightarrow X$ is a morphism of schemes and $\{X_i \rightarrow X\} \in J(X)$, then $\{Y \times_X X_i \rightarrow Y\} \in C(Y)$;
4. (Composition) If $\{X_i \rightarrow X\} \in C(X)$ and $\{X_{ij} \rightarrow X_i\} \in C(X_i)$, then $\{X_{ij} \rightarrow X\} \in C(X)$;
5. (Saturation) If $\{X_i \rightarrow X\} \in J(X)$ and $\{Y_j \rightarrow X\}$ is a set of morphisms of R -functors so that for i there is a j and a factoring $X_i \rightarrow Y_j \rightarrow X$ of $X_i \rightarrow X$, then $\{Y_j \rightarrow X\} \in C(X)$.

These conditions imply

6. (Local) If $\{Y_j \rightarrow X\}$ is a set of morphisms so that there exists a set $\{X_i \rightarrow X\} \in C(X)$ with $\{Y_j \times_X X_i \rightarrow X_i\} \in C(Y_j)$ for all j , then $\{Y_j \rightarrow X\} \in C(X)$.

If we are simply given, for each X , a collection of morphisms $J_0(X)$ satisfying the axioms (1), (3), and (4), then we have a *pretopology*; the full topology can be obtained by completing in the evident manner using axioms (2) and (5).

Notice that while the preceding discussion defines a topology on R -functors we can restrict to a topology on schemes by simply considering only those R -functors which are schemes. Note, however, that the covering sieves $J(X)$ may contain R -functors which are not schemes.

A category of schemes \mathcal{C} with a collection $J(X)$ of covering sieves is called a *site*. For example, if X is a scheme, the *Zariski site* on X has base category \mathcal{C} the set of open immersions $U \rightarrow X$. A covering family for U is a finite set of open immersions $U_i \rightarrow U$ so that $\sqcup U_i \rightarrow U$ is surjective. This is a pretopology, and we get the topology by extending as above. The *small étale site* on X has base category the étale morphisms $U \rightarrow X$; a covering family is a finite family of étale maps $U_i \rightarrow U$ so that $\sqcup U_i \rightarrow U$ is surjective. The big étale topology has as its underlying category the category of all schemes over X . The covering families remain the same.

This examples can be produced in another way. Let P be a fixed property of schemes closed under base change and composition, and with the property that open immersions have property P . We then define a P -cover of an affine scheme U to be a finite collection of morphisms $U_i \rightarrow U$ with affine source and satisfying property P . For a general scheme X a P -cover is a finite collection of morphisms $V_i \rightarrow X$ so that for all affine open subschemes U of X , the morphisms $V_i \times_X U \rightarrow U$ become a P -cover. This is a pretopology and, from this, we get the P -topology. If P is the class of étale maps we recover the étale sites; if P is the class open immersions, the small P -site is the Zariski site.

We write $J_{\mathcal{P}}(X)$ for the resulting covering sieves. These topologies and the *fpqc* topology about to be defined are *sub-canonical*; that is, the presheaf of sets represented by a scheme X is a sheaf; see [3] IV. 6.3.1.iii.

1.10 Definition (The fpqc-topology). *The fpqc-topology on schemes is the topology obtained by taking the class P of morphisms of schemes to be flat maps. Thus a fpqc-cover of an affine scheme U is a finite collection $U_i \rightarrow U$ of flat morphisms so that $\sqcup U_i \rightarrow U$ is surjective and a fpqc-cover of an arbitrary scheme X is a finite collection of morphisms $V_i \rightarrow X$ so that $V_i \times_X U \rightarrow U$ is a cover for all affine open $U \subseteq X$. The fpqc-site on X is the category of all schemes over X with the fpqc-topology.*

A related topology, which we won't use is the *fppf*-topology, for which we take the class P to be the class of all flat, finitely presented, and quasi-finite maps. The acronym *fppf* stands for “fidèlement plat de présentation finie”; this is self-explanatory. The acronym *fpqc* stands for “fidèlement plat quasi-compact”. The name derives from the following result; see [3] IV. 6.3.1.v.

1.11 Proposition. *Let X be a scheme and let $X_i \rightarrow X$ be a finite collection of flat, quasi-compact morphisms with the property that*

$$\sqcup X_i \rightarrow X$$

is surjective. Then $\{X_i \rightarrow X\}$ is a cover for the fpqc-topology. In particular, any flat, surjective, quasi-compact morphism is a cover for the fpqc-topology.

1.12 Remark (Sheaves). Continuing of synopsis of [3] Exposé IV, we define and discuss sheaves. If X is an R -functor and F is a sieve on R , then F become a contravariant functor on the category \mathbf{Aff}/X of affines over X . Given a topology on schemes defined by covering sieves $J(-)$, a *sheaf* on X is a contravariant functor \mathcal{F} on \mathbf{Aff}/X so that for all affines $U \rightarrow X$ over X and all $G \in J(U)$, the evident morphism

$$\mathcal{F}(U) \cong \text{Hom}(U, \mathcal{F}) \rightarrow \text{Hom}(G, \mathcal{F})$$

is an isomorphism. Here Hom means natural transformations of contravariant functors. If G is defined by a covering family $U_i \rightarrow U$ of affines, then $\text{Hom}(G, \mathcal{F})$ is the equalizer of

$$\prod \mathcal{F}(U_i) \rightrightarrows \mathcal{F}(U_i \times_U U_j)$$

and we recover the more standard definition of a sheaf. By [3] IV.4.3.5, if the topology is generated by a class of covering families closed under base change, it is sufficient to check the sheaf condition on those families.

We will be considering only those topologies defined at the end of Remark 1.9; thus all our sieves will be obtained by saturation from a class of morphisms $V \rightarrow U$ on affine schemes which are closed under base change and composition and contains open immersions. For such topologies, we can restrict the domain of definition of presheaves to appropriate subcategories of \mathbf{Aff}/X .

Before proceeding, we need to isolate the following concept.

1.13 Definition. *Let I be an indexing category and let $X = X_\bullet$ be an I -diagram of schemes. A **cartesian** \mathcal{O}_X -module sheaf consists of*

1. for each $i \in I$ a quasi-coherent sheaf \mathcal{F}_i on X_i ;
2. for each morphism $f : X_i \rightarrow X_j$ in the diagram, an isomorphism

$$\theta_f : f^* \mathcal{F}_j \rightarrow \mathcal{F}_i$$

of quasi-coherent sheaves

subject to the following compatibility condition:

Given composable arrows $X_i \xrightarrow{f} X_j \xrightarrow{g} X_k$ in the diagram, then we have a commutative diagram

$$\begin{array}{ccc} f^* g^* \mathcal{F}_k & \xrightarrow{f^* \theta_g} & f^* \mathcal{F}_j \\ \cong \downarrow & & \downarrow \theta_f \\ (gf)^* \mathcal{F}_k & \xrightarrow{\theta_{gf}} & \mathcal{F}_i \end{array}$$

1.14 Remark (Quasi-coherent sheaves in other topologies). Let X be a scheme and consider the topology defined by some class of morphisms P closed under base change, composition, and containing open inclusions. We assume further that covering families are finite and faithfully flat. This includes the Zaraski, étale, and *fpqc* topologies. Then there is a structure sheaf \mathcal{O}_X^P on a site with this topology determined by

$$\mathcal{O}_X^P(\mathrm{Spec}(B) \rightarrow X) = B.$$

Notice that, by the sheaf condition, it is only necessary to specify \mathcal{O}_X^P on affines. This is a sheaf of rings and we write \mathbf{Mod}_X^P for the category of module sheaves over this sheaf. If \mathbf{Mod}_X is the category of module sheaves over \mathcal{O}_X in the Zariski topology (see 1.2), then there is an adjoint pair

$$(1.2) \quad \mathbf{Mod}_X \begin{array}{c} \xleftarrow{\epsilon^*} \\ \xrightarrow{\epsilon_*} \end{array} \mathbf{Mod}_X^P$$

with ϵ^* defined by pull-back. The right adjoint ϵ_* is defined by restricting the affine open inclusions $U \rightarrow X$ and then extending by the sheaf condition.

This theory extends well to quasi-coherent sheaves. Define a module sheaf $\mathcal{F} \in \mathbf{Mod}_X^P$ to be *cartesian* if it is cartesian (as in Definition 1.13) for the category of affines over X ; that is, given any morphism

$$\begin{array}{ccc} \mathrm{Spec}(B) & & \\ \downarrow & \searrow & \\ \mathrm{Spec}(A) & \xrightarrow{\quad} & X \end{array}$$

in \mathbf{Aff}/X , the induced map

$$B \otimes_A \mathcal{F}(\mathrm{Spec}(A) \rightarrow X) \rightarrow \mathcal{F}(\mathrm{Spec}(B) \rightarrow X)$$

is an isomorphism of R -modules. If $\mathcal{E} \in \mathbf{Mod}_X$ is quasi-coherent, then $\epsilon^*\mathcal{E}$ is cartesian; conversely if \mathcal{F} is cartesian, then $\epsilon_*\mathcal{F}$ is quasi-coherent. Thus the adjoint pair Equation 1.2 descends to an adjoint pair

$$(1.3) \quad \mathbf{Qmod}_X \begin{array}{c} \xrightarrow{\epsilon^*} \\ \xleftarrow{\epsilon_*} \end{array} \mathbf{Mod}_X^{\mathcal{P},\mathrm{cart}}.$$

This is an equivalence of categories; therefore, we drop the clumsy notation $\mathbf{Mod}_X^{\mathcal{P},\mathrm{cart}}$ and confuse the notion of a quasi-coherent sheaf with that of cartesian sheaf.

There are important sheaves in $\mathbf{Mod}_X^{\mathcal{P}}$ which are not cartesian; for example, the sheaf $\Omega_{(-)/X}$ of differentials over X is quasi-coherent for the Zariski topology, cartesian for the étale topology, but not cartesian for the fpc topology.

We finish this section with a review of an important class of morphisms.

1.15 Definition. 1.) A morphism $f : X \rightarrow Y$ of schemes over R is called **affine** if for all morphisms $\mathrm{Spec}(B) \rightarrow Y$, the R -functor $\mathrm{Spec}(B) \times_Y X$ is isomorphic to an affine scheme.

2.) A morphism $f : X \rightarrow Y$ of schemes is a **closed embedding** if it is affine and for all flat morphisms $\mathrm{Spec}(B) \rightarrow Y$, the induced morphisms of rings

$$B = \mathcal{O}_Y(B) \longrightarrow f_*\mathcal{O}_X(B) = \mathcal{O}_X(\mathrm{Spec}(B) \times_Y X \rightarrow X)$$

is surjective.

3.) A morphism $f : X \rightarrow Y$ of schemes is **separated** if the diagonal morphism $X \rightarrow X \times_Y X$ is a closed embedding. A scheme over a commutative R is separated if the morphism $X \rightarrow \mathrm{Spec}(R)$ is separated.

If $f : X \rightarrow Y$ is an affine morphism of schemes, then the \mathcal{O}_Y algebra sheaf $f_*\mathcal{O}_X$ is quasi-coherent. Conversely, if \mathcal{B} is quasi-coherent \mathcal{O}_Y -algebra sheaf, define a R -functor $\mathrm{Spec}_Y(\mathcal{B})$ over Y by

$$\mathrm{Spec}_Y(\mathcal{B})(A) = \coprod_{\mathrm{Spec}(A) \rightarrow Y} \mathbf{Alg}_A(\mathcal{B}(\mathrm{Spec}(A) \rightarrow Y), A).$$

Then $q : \mathrm{Spec}_Y(\mathcal{B}) \rightarrow Y$ is an affine morphism of schemes and $q_*\mathcal{O}_{\mathrm{Spec}_Y(\mathcal{B})} \cong \mathcal{B}$. This gives an equivalence between the category of quasi-coherent \mathcal{O}_Y -algebras and the category of affine morphisms over Y . Restricting this equivalence gives a one-to-one correspondence between closed embeddings $X \rightarrow Y$ and ideal sheaves $\mathcal{I} \subseteq \mathcal{O}_Y$.

An analogous result with an analogous construction holds for quasi-coherent sheaves.

1.16 Proposition. *Let $f : X \rightarrow Y$ be an affine morphism of schemes. Then the push-forward functor f_* defines an equivalence of categories between quasi-coherent sheaves on X and quasi-coherent $f_*\mathcal{O}_X$ -module sheaves on Y . In particular, f_* is exact.*

If $f : T \rightarrow S$ is a morphism of schemes and $X \rightarrow S$ is an affine morphism, the $f^*X = T \times_S X$ is also affine. If f is faithfully flat, we have the following result.

1.17 Proposition. *Let $f : T \rightarrow S$ be a faithfully flat morphism of schemes. Then $f^*(-)$ defines an equivalence of categories from the category of schemes affine over S to the category of descent problems in schemes affine over T .*

1.2 The tangent scheme

If A is a commutative ring, let $A(\epsilon) = A[x]/(x^2)$ be the A -algebra of dual numbers. Here we have written $\epsilon = x + (x^2)$. There is an augmentation $q : A(\epsilon) \rightarrow A$ given by $\epsilon \mapsto 0$.

Let R be a commutative ring and let X be R -functor. Define the *tangent functor* $\mathcal{T}an_X \rightarrow X$ over X to be the functor

$$\mathcal{T}an_X(A) = X(A(\epsilon))$$

with the projection induced by the augmentation $q : A(\epsilon) \rightarrow A$. There is a *zero section* $s : X \rightarrow \mathcal{T}an_X$ induced by the unit map $A \rightarrow A(\epsilon)$. If $X \rightarrow S$ is a morphism of R -functors, then the relative tangent functor $\mathcal{T}an_{X/S}$ is defined by the pull-back diagram

$$\begin{array}{ccc} \mathcal{T}an_{X/S} & \longrightarrow & \mathcal{T}an_X \\ \downarrow & & \downarrow \\ S & \xrightarrow{s} & \mathcal{T}an_S \end{array}$$

If we let $A(\epsilon_1, \epsilon_2) = A[x, y]/(x^2, xy, y^2)$, then the natural A -algebra homomorphism $A(\epsilon) \rightarrow A(\epsilon_1, \epsilon_2)$ given by $\epsilon \mapsto \epsilon_1 + \epsilon_2$ defines a multiplication over X

$$\mathcal{T}an_{X/S} \times_X \mathcal{T}an_{X/S} \rightarrow \mathcal{T}an_{X/S}$$

so that $\mathcal{T}an_{X/S}$ is an abelian group R -functor over X .

If $X \rightarrow S$ is a morphism of schemes, then $\mathcal{T}an_{X/S}$ is an affine scheme over X . See Proposition 1.23. We will see this once we have discussed the connection between the $\mathcal{T}an_{X/S}$ and the sheaf of differentials $\Omega_{X/S}$.

Let X be an R -functor for some commutative ring R . Define the \mathcal{O}_X -module presheaf of differential $\Omega_{X/R}$ by the formula

$$\Omega_{X/R}(\text{Spec}(B) \rightarrow X) = \Omega_{B/R}.$$

This became a quasi-coherent sheaf in the Zariski topology. If $f : X \rightarrow Y$ is a morphism of R -functors, define $\Omega_{X/Y}$ by the exact sequence of \mathcal{O}_X -modules (in

the Zariski topology)

$$f^*\Omega_{Y/R} \rightarrow \mathcal{O}_{X/R} \rightarrow \Omega_{X/Y} \rightarrow 0.$$

Since $\Omega_{B/R} = J(B)/J(B)^2$ where $J(B)$ is the kernel of the multiplication map

$$B \otimes_R B \longrightarrow B$$

this definition can be reformulated as follows. A proof can be found in [4] §I.4.2.

1.18 Lemma. *Let $X \rightarrow S$ be a separated morphism of schemes, so that diagonal morphism $\Delta : X \rightarrow X \times_S X$ is a closed embedding. Then there is a natural isomorphism of quasi-coherent sheaves on X*

$$\Omega_{X/S} \cong \Delta^* \mathcal{J} / \mathcal{J}^2$$

where \mathcal{J} is the module of the closed embedding Δ .

If X is not separated, we can still identify the differentials by a variation on this method: if we factor the diagonal map as a closed embedding followed by an open inclusion

$$X \xrightarrow{j} V \longrightarrow X \times_S X$$

then $\Omega_{X/S} \cong j^* \mathcal{J} / \mathcal{J}^2$ where \mathcal{J} is the ideal defining j .

Needless to say, there is a close connection between differentials and derivations. If R is a commutative ring and M is an R -module, the *square-zero extension* of R by M is the R -algebra $R \rtimes M$ which is $R \times M$ as an R -module and multiplication

$$(a, x)(b, y) = (ab, ay + bx).$$

This has an extension to sheaves.

1.19 Definition. *Let \mathcal{F} be a quasi-coherent sheaf on a scheme X . Then we define the \mathcal{O}_X -algebra sheaf $\mathcal{O}_X \rtimes \mathcal{F}$ on X to be the square-zero extension of \mathcal{O}_X . Then a derivation of X with coefficients in \mathcal{F} is a diagram of sheaves of commutative rings*

$$\begin{array}{ccc} \mathcal{O}_X & \xrightarrow{f} & \mathcal{O}_X \rtimes \mathcal{F} \\ & \searrow = & \swarrow p_1 \\ & & \mathcal{O}_X. \end{array}$$

If $q : X \rightarrow S$ is a scheme over S , then an S -derivation of X with coefficients in \mathcal{F} is a derivation of X with coefficients in \mathcal{F} so that

$$q_* f : q_* \mathcal{O}_X \longrightarrow q_* \mathcal{O}_X \rtimes q_* \mathcal{F}$$

is a morphism of \mathcal{O}_S -algebra sheaves. We will write $\text{Der}_S(X, \mathcal{F})$ for the set of all S -derivations of X with coefficients in \mathcal{F} .

1.20 Example. Suppose $X \rightarrow S$ is a separated morphism of schemes. Then, by definition, $\Delta : X \rightarrow X \times_S X$ is a closed embedding; let \mathcal{J} be the ideal of this embedding. Write $(X \times_S X)_1 \subseteq X \times_S X$ for the subscheme defined by the vanishing of \mathcal{J}^2 . Then the splitting provided by the first projection $p_1 : X \times_S X \rightarrow X$ defines an isomorphism

$$\Delta^* \mathcal{O}_{(X \times_S X)_1} \cong \mathcal{O}_X \rtimes \Omega_{X/S}.$$

Then the second projection defines an S -derivation of X

$$f_u : \mathcal{O}_X \longrightarrow \mathcal{O}_X \rtimes \Omega_{X/S}$$

The morphisms f_u or the resulting morphism $d : \mathcal{O}_X \rightarrow \Omega_{X/S}$ is called the *universal derivation*.

The module of S -derivations is the global sections of the sheaf $\mathcal{D}er_S(X, \mathcal{F})$ which assigns to each Zariski open $U \subseteq X$ the module of derivations

$$\mathcal{D}er_S(U, \mathcal{F}|_U).$$

This is an \mathcal{O}_X -module sheaf, although not necessarily quasi-coherent.

1.21 Proposition. *There is a natural isomorphism of \mathcal{O}_X -module sheaves*

$$\mathrm{hom}_{\mathcal{O}_X}(\Omega_{X/S}, \mathcal{F}) \longrightarrow \mathcal{D}er_S(X, \mathcal{F})$$

given by composing with the universal derivation.

Proof. The inverse to this this morphism is given as follows. Let $f : \mathcal{O}_X \rightarrow \mathcal{O}_X \rtimes \mathcal{F}$ be any derivation and let f_0 be the zero derivation; that is, inclusion into the first factor. Also let $p : \mathcal{O}_X \rtimes \mathcal{F} \rightarrow \mathcal{O}_X$ be the projection. Consider the lifting problem

$$\begin{array}{ccc} X & \longrightarrow & (X \times_S X)_1 \\ p \downarrow & \nearrow & \downarrow \subseteq \\ \mathrm{Spec}_X(\mathcal{O}_X \rtimes \mathcal{F}) & \xrightarrow{f_0 \times f} & X \times_S X. \end{array}$$

Here we have written h for a morphism when we mean $\mathrm{Spec}_X(h)$. Since $\mathcal{O}_X \rtimes \mathcal{F}$ is a square-zero extension, this lifting problem has a unique solution g and that g yields a morphism

$$\Delta^* \mathcal{O}_{(X \times_S X)_1} \cong \mathcal{O}_X \rtimes \Omega_{X/S} \rightarrow \mathcal{O}_X \rtimes \mathcal{F}$$

of \mathcal{O}_X -algebra sheaves over \mathcal{O}_X as needed. \square

The following result follows immediately from the previous proposition upon taking global sections. Note that if $X = \mathrm{Spec}(B) \rightarrow \mathrm{Spec}(R)$, this amounts to the usual isomorphism

$$\mathbf{Mod}_B(\Omega_{B/R}, M) \cong \mathcal{D}er_R(B, M).$$

1.22 Corollary. *There is a natural isomorphism of modules over the global sections over X*

$$\mathbf{Mod}_X(\Omega_{X/S}, \mathcal{F}) \cong \mathrm{Der}_S(X, \mathcal{F})$$

given by composing with the universal derivation.

If \mathcal{F} is a quasi-coherent sheaf of \mathcal{O}_X -modules on a scheme X , we can form the symmetric algebra $\mathrm{Sym}_{\mathcal{O}_X}(\mathcal{F})$; this is a sheaf of quasi-coherent \mathcal{O}_X -algebras on X and we denote by

$$\mathbb{V}(\mathcal{F}) \longrightarrow X$$

the resulting affine morphism. If A is an R -algebra, then

$$\mathbb{V}(\mathcal{F})(A) = \coprod_{\mathrm{Spec}(A) \rightarrow X} \mathbf{Mod}_A(\mathcal{F}(A), A).$$

The diagonal map $\mathcal{F} \rightarrow \mathcal{F} \oplus \mathcal{F}$ gives $\mathbb{V}(\mathcal{F})$ the structure of an abelian group scheme over X .

Proposition 1.21 implies the following result – in the latter proposition set $\mathcal{F} = \mathcal{O}_X$ and note that

$$\mathcal{O}_X(\epsilon) = \mathcal{O}_X \rtimes \mathcal{O}_X.$$

1.23 Proposition. *If $X \rightarrow S$ is a separated morphism of schemes, there is a natural isomorphism of abelian group schemes over X*

$$\mathbb{V}(\Omega_{X/S}) \cong \mathcal{T}\mathrm{an}_{X/S}.$$

The following standard fact is useful for calculations.

1.24 Lemma. *Let $i : X \rightarrow Y$ be a closed embedding of separated schemes over S defined by an ideal $\mathcal{I} \subseteq \mathcal{O}_Y$. Then there is an exact sequence of sheaves on X*

$$i^*\mathcal{I}/\mathcal{I}^2 \xrightarrow{d} i^*\Omega_{Y/S} \longrightarrow \Omega_{X/S} \longrightarrow 0$$

where d is induced by the restriction of the universal derivation.

Proof. Let \mathcal{F} be a sheaf of \mathcal{O}_X -modules on X . The statement of the lemma is equivalent to the exactness of the sequence

$$0 \rightarrow \mathrm{Der}_S(X, \mathcal{F}) \rightarrow \mathrm{Der}_S(Y, i_*\mathcal{F}) \rightarrow \mathrm{hom}_{\mathcal{O}_Y}(\mathcal{I}/\mathcal{I}^2, i_*\mathcal{F})$$

which is easily checked. □

1.3 Formal Lie varieties

We next review the notion of a formal Lie variety, which can be interpreted as a notion of a smooth formal scheme affine over a base scheme S with a preferred section. The first concept (which appeared implicitly in Lemma 1.24) is important in its own right.

1.25 Definition. Let $i : X \rightarrow Y$ be a closed embedding of schemes defined by an ideal $\mathcal{I} \subseteq \mathcal{O}_Y$. Then the quasi-coherent \mathcal{O}_X -module

$$\omega_i \stackrel{\text{def}}{=} i^* \mathcal{I} / \mathcal{I}^2$$

is called the **conormal sheaf** or the module of the embedding i .

Note that the canonical map $\mathcal{I} / \mathcal{I}^2 \rightarrow i_* \omega_i$ of quasi-coherent sheaves on Y is an isomorphism.

1.26 Definition. If $i : X \rightarrow Y$ is a closed embedding of schemes defined by an ideal \mathcal{I} , define the **n th infinitesimal neighborhood**

$$Y_n = \text{Inf}_X^n(Y) \subseteq Y$$

of X in Y to be the closed subscheme of Y defined by the ideal \mathcal{I}^{n+1} .

More generally, suppose that $X \rightarrow Y$ is an injection of fpqc sheaves over some base scheme S . Define $\text{Inf}_X^n(Y) \subseteq Y$ to be the subsheaf with the following sections. If $U \rightarrow S$ is quasi-compact, then $[\text{Inf}_X^n(Y)](U)$ is the set of all $a \in Y(U)$ which satisfy the following condition: there is an fpqc cover $V \rightarrow U$ and a closed subscheme $V' \subseteq V$ defined by an ideal with vanishing $(n+1)$ st power so that

$$a|_V \in X(V').$$

1.27 Remark. The proof that the notion of infinitesimal neighborhoods for sheaves generalizes that for schemes is Lemma II.1.02 of [36]. This lemma is stated for the *fppf*-topology, but uses only properties of faithfully flat maps of affine schemes, so applies equally well to the *fpqc*-topology. In the same reference, Lemma II.1.03, Messing shows that infinitesimal neighborhoods behave well with respect to base change. Specifically, if $X \subseteq Y$ is an embedding of *fpqc*-sheaves over a scheme S and $f : T \rightarrow S$ is a morphism of schemes, then

$$(1.4) \quad \text{Inf}_{f^*X}^n(f^*Y) \cong f^* \text{Inf}_X^n(Y).$$

If $X \rightarrow Y$ is a closed embedding of schemes, we get an ascending chain of closed subschemes

$$X = Y_0 \subseteq Y_1 \subseteq Y_2 \subseteq \cdots \subseteq Y.$$

The conormal sheaves of $X \rightarrow Y_n$ are all canonically isomorphic; hence this module depends only on Y_1 . To get an invariant which depends on Y_n , filter \mathcal{O}_Y by the powers of the ideal \mathcal{I} to get a graded $\mathcal{O}_Y / \mathcal{I}$ -algebra sheaf on Y . By Proposition 1.16 this determines a unique graded \mathcal{O}_X -algebra sheaf $\text{gr}_*(Y)$ on X with

$$\text{gr}_k(Y) = i^*(\mathcal{I}^k / \mathcal{I}^{k+1})$$

In particular, $\text{gr}_1(Y) = \omega_i$. We immediately have that

$$\text{gr}_k(Y_n) = \begin{cases} \text{gr}_k(Y), & k \leq n; \\ 0, & k > n. \end{cases}$$

Now suppose Y is a scheme over S and $e : S \rightarrow Y$ is a closed inclusion and a section of the projection $Y \rightarrow S$. Let us define

$$(1.5) \quad \mathcal{O}_Y(e) \subseteq \mathcal{O}_Y$$

to be the ideal sheaf defining this inclusion. It can be thought of as the sheaf of functions vanishing at e . In this case the natural map of Lemma 1.24

$$d : \omega_e = e^* \mathcal{O}_Y(e) / \mathcal{O}_Y(e)^2 \longrightarrow e^* \Omega_{Y/S}$$

becomes an isomorphism; indeed, the exact sequence of the proof collapses to an isomorphism.

1.28 Remark. Let S be a scheme, X a sheaf in the *fpqc*-topology over S and $e : S \rightarrow X$ a section of the structure map $X \rightarrow S$. Then we can make the following definitions and constructions.

1. Let $X_n = \text{Inf}_S^n(X)$. We say X is *ind-infinitesimal* if the natural map

$$\text{colim } \text{Inf}_S^n(X) \rightarrow X$$

is an isomorphism of sheaves.

2. Suppose each of the X_n is representable. Then ω_e can be defined as the conormal sheaf of any of the embeddings $S \rightarrow X_n$; furthermore $\omega_e \cong e^* \Omega_{X_n/S}$ for all n .
3. More generally, if each of the X_n is representable define the graded ring $\text{gr}_*(X) = \lim \text{gr}_*(X_n)$; then if $k \leq n$

$$\text{gr}_k(X) \cong \text{gr}_k(X_n).$$

1.29 Definition (Formal Lie variety). Let S be a scheme, X a sheaf in the *fpqc*-topology over S and $e : S \rightarrow X$ a section of the structure map $X \rightarrow S$. Then (X, e) is a **formal Lie variety** if

1. X is *ind-infinitesimal* and $X_n = \text{Inf}_S^n(X)$ is representable and affine over S for all $n \geq 0$;
2. the quasi-coherent sheaf ω_e is locally free of finite rank on S ;
3. the natural map of graded rings $\text{Sym}_*(\omega_e) \rightarrow \text{gr}_*(X)$ is an isomorphism.

A morphism $f : (X, e) \rightarrow (X', e')$ of formal Lie varieties is morphism of sheaves which preserves the sections.

1.30 Remark. By Remark 1.27 and Equation 1.4 formal Lie varieties behave well under base change. If (X, e) is a formal Lie variety over a base scheme S and $T \rightarrow S$ is a morphism of schemes, then $f^*X \rightarrow T$ has an induced section f^*e and

$$f^*(X, e) \stackrel{\text{def}}{=} (f^*X, f^*e)$$

is a formal Lie variety. We will often drop the section e from the notation.

1.31 Remark. We show that, locally in the Zariski topology, every formal Lie variety is isomorphic to the formal spectrum of a power series ring.

1.) Let $S = \text{Spec}(A)$ and let X be the formal scheme $\text{Spf}(A[[x_1, \dots, x_t]])$. Thus for an A -algebra B ,

$$X(B) = \{ (b_1, \dots, b_t) \mid b_i \text{ is nilpotent} \} \subseteq B^n$$

Let $e : S \rightarrow X$ be the zero section, then

$$X_n = \text{Spec}(A[x_1, \dots, x_t]/(x_1, \dots, x_t)^{n+1})$$

and ω_e is the sheaf obtained from the free A -module of rank t generated by the residue classes of x_1, \dots, x_t . It follows that (X, e) is a formal Lie variety.

2.) Conversely, suppose that $S = \text{Spec}(A)$ and that the global sections of ω_e on S is a free A -module with a chosen basis x_1, \dots, x_t . There is an exact sequence of quasi-coherent \mathcal{O}_{X_n} -sheaves

$$0 \rightarrow \mathcal{O}_{X_n}(e) \rightarrow \mathcal{O}_{X_n} \rightarrow e_*\mathcal{O}_S \rightarrow 0$$

whence an exact sequences of quasi-coherent sheaves on \mathcal{O}_S

$$0 \rightarrow q_*\mathcal{O}_{X_n}(e) \rightarrow q_*\mathcal{O}_{X_n} \rightarrow \mathcal{O}_S \rightarrow 0.$$

Here we are writing $q : X_n \rightarrow S$ for the projection. Since $q_*\mathcal{O}_{X_n}(e) \rightarrow q_*\mathcal{O}_{X_{n-1}}(e)$ is onto for all n and $q_*\mathcal{O}_{X_1}(e) \cong \omega_e$ we may choose compatible (in n) splittings $\omega_e \rightarrow q_*\mathcal{O}_{X_n}(e)$ and get compatible maps

$$\text{Sym}_S(\omega_e) \rightarrow q_*\mathcal{O}_{X_n}$$

which, by Definition 1.29.3, induce isomorphisms

$$\text{Sym}_S(\omega_e)/\mathcal{J}^{n+1} \rightarrow q_*\mathcal{O}_{X_n}$$

where $\mathcal{J} = \bigoplus_{k>0} \text{Sym}_k(\omega_e)$ is the augmentation ideal. Since the global sections of $\text{Sym}_S(\omega_e)/\mathcal{J}^{n+1}$ are isomorphic to $A[x_1, \dots, x_t]/(x_1, \dots, x_t)^{n+1}$ we say that the choice of the basis for the global sections of ω_e and the choice of compatible splittings yield an isomorphism $X \cong \text{Spf}(A[[x_1, \dots, x_t]])$ of formal Lie varieties over $\text{Spec}(A)$. This isomorphism is very non-canonical, however.

3.) Finally, for a general base scheme S , choose an open cover by affines $U_i = \text{Spec}(A_i)$ so that the sections of ω_e over U_i is free. Then, after making suitable choices, we get an isomorphism

$$U_i \times_S X \cong \text{Spf}(A_i[[x_1, \dots, x_t]]).$$

1.32 Remark (The tangent scheme of a formal Lie variety). Let (X, e) be a formal Lie variety over a scheme S . Then $\mathcal{Tan}_{X/S}$ is not necessarily a

scheme, but only a sheaf in the *fpqc* topology. We'd like to give a description of $\mathcal{T}an_{X/S}$ as a formal Lie variety. Define $\text{Lie}_{X/S}$ as the pull-back

$$\begin{array}{ccc} \text{Lie}_{X/S} & \xrightarrow{\varepsilon} & \mathcal{T}an_{X/S} \\ \downarrow & & \downarrow \\ S & \xrightarrow{e} & X. \end{array}$$

More generally, define $(\mathcal{T}an_{X/S})_n$ by the pull-back diagram

$$\begin{array}{ccc} (\mathcal{T}an_{X/S})_n & \longrightarrow & \mathcal{T}an_{X/S} \\ \downarrow & & \downarrow \\ X_n & \longrightarrow & X, \end{array}$$

so that $(\mathcal{T}an_{X/S})_1 = \text{Lie}_{X/S}$. There are natural maps

$$\mathcal{T}an_{X_n/S} \rightarrow (\mathcal{T}an_{X/S})_n$$

but these are not in general isomorphisms; however, we do have that

$$\text{colim } \mathcal{T}an_{X_n/S} \rightarrow \text{colim}(\mathcal{T}an_{X/S})_n \rightarrow \mathcal{T}an_{X/S}$$

are all isomorphisms.

To analyze the sheaves $(\mathcal{T}an_{X/S})_n$ let us write $j_k : X_n \rightarrow X_{n+k}$ for the inclusion. Then Lemma 1.24 shows that for all $k > 0$, the natural map

$$j_{k+1}^* \Omega_{X_{n+k+1}/S} \rightarrow j_k^* \Omega_{X_{n+k}/S}$$

is an isomorphism of locally free sheaves on X_n . Write $(\Omega_{X/S})_n$ for this sheaf. Again Lemma 1.24 shows that there is a surjection

$$(\Omega_{X/S})_n \longrightarrow \Omega_{X_n/S}$$

but the source is a locally free sheaf and the target is not in general. For example, if $n = 1$, $(\Omega_{X/S})_1 = \omega_e$ but $\Omega_{X_1/S} = 0$. Now we check, using that $X = \text{colim } X_n$ and Lemma 1.23 that there is a natural isomorphism of abelian sheaves over X_n

$$\mathbb{V}_{X_n}((\Omega_{X/S})_n) \cong (\mathcal{T}an_{X/S})_n.$$

In particular

$$\mathbb{V}_S(\omega_e) \cong \text{Lie}_{X/S}.$$

The natural map $\omega_e = q_* e_* \omega_e \rightarrow q_*(\Omega_{X/S})_n$ of quasi-coherent sheaves on S defines a coherent sequence of projections

$$(\mathcal{T}an_{X/S})_n \longrightarrow \text{Lie}_{X/S}$$

and $\varepsilon : \text{Lie}_{X/S} \rightarrow (\mathcal{T}\text{an}_{X/S})_n$ is a section of this projection. Local calculations, using Remark 1.31, now imply that the map $(\mathcal{T}\text{an}_{X/S}, \varepsilon)$ is a formal Lie variety over $\text{Lie}_{X/S}$; the scheme $(\mathcal{T}\text{an}_{X/S})_n$ is the n th infinitesimal neighborhood of $\text{Lie}_{X/S}$ in $\mathcal{T}\text{an}_{X/S}$.

The local calculations are instructive. If $S = \text{Spec}(A)$ and suppose $X = \text{Spf}(A[[x_1, \dots, x_t]])$ with $e : S \rightarrow X$ defined by the ideal $I = (x_1, \dots, x_n)$, then

$$(\mathcal{T}\text{an}_{X/S})_n \cong \text{Spec}((A[[x_1, \dots, x_n]]/I^n)[dx_1, \dots, dx_t])$$

In particular

$$\text{Lie}_{X/S} \cong \text{Spec}(A[dx_1, \dots, dx_t]).$$

The projection $(\mathcal{T}\text{an}_{X/S})_n \rightarrow \text{Lie}_{X/S}$ is induced by the natural inclusion of A into $A[[x_1, \dots, x_t]]/I^n$.

It is worth noting that in the case where $t = 1$,

$$\mathcal{T}\text{an}_{X_n/S} = \text{Spec}(A[x, dx]/(x^n, nx^{n-1}dx)).$$

1.33 Remark. Let $f : (X, e_x) \rightarrow (Y, e_y)$ be a morphism of formal Lie varieties over a fixed base scheme S . Then f determines a sequence of morphisms of schemes affine over S

$$f_n : X_n = \text{Inf}_S^n(X) \rightarrow \text{Inf}_S^n(Y) = Y_n$$

with the property $\text{Inf}_S^n(f_k) = f_n$ when $k \geq n$. Conversely, given any such sequence of morphisms define $f : X \rightarrow Y$ by $f = \text{colim } f_n$; then f is a morphism of formal Lie varieties. Thus we have a one-to-one correspondence between morphisms of formal Lie varieties and compatible sequences of morphisms on infinitesimal neighborhoods. This is the key to following results.

1.34 Lemma. *Let X and Y be two formal Lie varieties over a scheme S and define the presheaf $\text{Iso}_S(X, Y)$ to be the functor which assigns to each morphism $i : U \rightarrow S$ of schemes the set of isomorphisms $i^*X \rightarrow i^*Y$ of formal Lie varieties. Then $\text{Iso}_S(X, Y)$ is a sheaf in the fpqc-topology.*

Proof. Suppose $f : T \rightarrow S$ is a quasi-compact and faithfully flat morphism of schemes and suppose $\phi : f^*X \rightarrow f^*Y$ is an isomorphism of formal Lie varieties so that $d_1^*\phi = d_0^*\phi$ over $T \times_S T$. Then

$$\phi_n : f^*X_n \longrightarrow f^*Y_n$$

also satisfies the sheaf condition. Thus, by faithfully flat descent for affine schemes (Proposition 1.17), there is a unique isomorphism of affine schemes $\psi_n : X_n \rightarrow Y_n$ so that $f^*\psi_n = \phi_n$. By uniqueness $\text{Inf}_S^n(\phi_k) = \phi_n$. Set $\psi = \text{colim } \psi_n$. Then $f^*\psi = \phi$ as needed. This argument extends to the entire site by replacing S by U and X and Y by i^*X and i^*Y respectively. \square

The notion of descent problem was defined in Remark 1.7. The following result can be upgraded to an equivalence of categories, as in Proposition 1.17.

1.35 Lemma. *Let $f : T \rightarrow S$ be a faithfully flat quasi-compact morphism of schemes. Let (X, ϕ) be a descent problem in formal Lie varieties over T . Then there is a unique (up to isomorphism) solution in formal Lie varieties over S .*

Proof. This again follows from faithfully flat descent. We begin by using Proposition 1.17 to get unique (up to isomorphism) schemes Y_n affine over S and isomorphisms $\phi_n : f^*Y_n \rightarrow X_n$ solving the descent problem for X_n . Uniqueness implies that there are unique isomorphisms $S \cong Y_0 \cong S$ and $\text{inf}_S^n(Y_k) \cong Y_n$. Thus $Y = \text{colim } Y_n$ is the candidate for the solution to the descent problem. We must verify points (2) and (3) of Definition 1.29.

For (2) we have that $f^*\omega_{e_Y} = \omega_{e_X}$. Since a quasi-coherent sheaf \mathcal{F} over Y is locally free and finitely generated if and only if $f^*\mathcal{F}$ is locally free and finitely generated. (See [11]§2.6.) For (3), the map (with $e = e_Y$)

$$\text{Sym}_*(\omega_e) \rightarrow \text{gr}_*(Y)$$

is an isomorphism because it becomes an isomorphism after applying $f^*(-)$. Thus point (3) is covered. \square

The notion of a category fibered in groupoids is defined in Définition 2.1 of [33]. The associated notion of stack is defined in Définition 3.1 of the same reference.

Define a category $\mathcal{M}_{\mathfrak{fv}}$ fibered in groupoids over schemes as follows. The objects of $\mathcal{M}_{\mathfrak{fv}}$ are pairs (S, X) where S a scheme and $X \rightarrow S$ is a formal Lie variety over S . A morphism $(T, Y) \rightarrow (S, X)$ in $\mathcal{M}_{\mathfrak{fv}}$ is a pair (f, ϕ) where $f : T \rightarrow S$ is a morphism of schemes and $\phi : Y \rightarrow f^*X$ is an isomorphism of formal Lie varieties over T .

1.36 Proposition. *The category $\mathcal{M}_{\mathfrak{fv}}$ fibered in groupoids is a stack in the fpqc-topology.*

Proof. For a category fibered in groupoids to be a stack, isomorphisms must form a sheaf (Lemma 1.34) and the groupoids must satisfy effective descent (Lemma 1.35). \square

1.37 Remark. With the notion of formal schemes developed by Neil Strickland in [52], it's possible to show that the fibered category of all formal schemes is a stack for the fpqc topology.

2 Formal groups and coordinates

In this section, we introduce formal groups and the moduli stack $\mathcal{M}_{\mathfrak{fg}}$ of formal groups – these are the basic objects of study of this monograph. Except on extremely rare occasions, “formal group” will mean a commutative group object in formal Lie varieties of relative dimensions 1 over S , as in Definition 2.2. Thus we may think of G as affine and smooth of dimension 1 over S .

We will begin with a definition of formal group which does not depend on a theory of coordinates for formal groups; however, that theory is important, and

we will spend part of the section working out the details. Specifically, we note that choices of coordinates amount to sections of scheme over S and we explore the geometry of that scheme. The main result is Theorem 2.25, which shows we are dealing with particularly simple scheme.

Part of this section also explores formal group laws, which are particularly familiar to homotopy theorists.

2.1 Formal groups

We first note that the category of formal Lie varieties has products. If X and Y are formal Lie varieties over a scheme S , let $X \times_S Y$ be the product sheaf in the $fpqc$ topology. We have that

$$X \times_S Y = \operatorname{colim}(X_n \times_S Y_n).$$

2.1 Lemma. *The sheaf $X \times_S Y$ is a formal Lie variety and the product of X and Y in the category for formal Lie varieties.*

Proof. We leave most of this as exercise. The key observations are that

$$\operatorname{Inf}_S^n(X \times_S Y) \subseteq \operatorname{Inf}_S^n(X) \times \operatorname{Inf}_S^n(Y) \subseteq \operatorname{Inf}_S^{2n}(X \times Y)$$

and that

$$\omega_{(e_X, e_Y)} = \omega_{e_X} \oplus \omega_{e_Y}.$$

□

This product has a simple description Zariski locally. (Compare 1.31.) If we choose an affine open $U = \operatorname{Spec}(A) \rightarrow S$ over which the global sections of ω_{e_X} and ω_{e_Y} are free with bases $\{x_1, \dots, x_m\}$ and $\{y_1, \dots, y_n\}$ respectively, then there is an isomorphism of formal Lie varieties

$$(X \times_S Y)|_U \cong \operatorname{Spf}(A[[x_1, \dots, x_m, y_1, \dots, y_n]]).$$

2.2 Definition. *Let S be a scheme. A **formal group** over S is an abelian group object (G, e) in the category of formal Lie varieties over S with the property that*

$$\omega_G \stackrel{\text{def}}{=} \omega_e$$

*is locally free of **rank 1**. A homomorphism of formal groups is a morphism of group objects.*

If $f : T \rightarrow S$ is a morphism of schemes and G is a formal group over S , then $f^*G = T \times_S G$ is a formal group over T . If $i : U \rightarrow S$ is a Zariski open, we write $G|_U$ for i^*G .

2.3 Example (Formal group laws). A formal group (G, e) defines and is defined by a formal group law Zariski locally. This is an expansion of Remark 1.31.

In more detail, if A is a commutative ring, a commutative *formal group law* of dimension 1 is a power series

$$F(x_1, x_2) = x_1 +_F x_2 \in A[[x_1, x_2]]$$

so that

1. $0 +_F x = x +_F 0 = x$;
2. $x_1 +_F x_2 = x_2 +_F x_1$;
3. $(x_1 +_F x_2) +_F x_3 = x_1 +_F (x_2 +_F x_3)$.

If we think of a formal group law F as the homomorphism $F : A[[x]] \rightarrow A[[x_1, x_2]]$ sending x to $F(x_1, x_2)$, then F defines a formal group G over $S = \text{Spec}(A)$ by setting $G = \text{Spf}(A[[x]])$ with multiplication

$$G \times_S G \cong \text{Spf}(A[[x_1, x_2]]) \xrightarrow{\text{Spf}(F)} \text{Spf}(A[[x]]) = G.$$

Conversely, if G is a formal group choose a cover $U_i = \text{Spec}(A_i) \rightarrow S$ by affines so that for each i , the sections of ω_G is free of rank 1. A choice of generator x for these sections defines an isomorphism

$$G|_{U_i} \cong \text{Spf}(A_i[[x]])$$

and the multiplication on G defines a continuous morphism of power series

$$\Delta : A_i[[x]] \longrightarrow A_i[[x_1, x_2]].$$

Then

$$F_i(x_1, x_2) \stackrel{\text{def}}{=} \Delta(x)$$

is a formal group law.

2.4 Example (Homomorphisms). Homomorphisms of formal groups are determined by power series, at least Zariski locally. A **homomorphism** $\phi : F \rightarrow F'$ of formal group laws over R is a power series $\phi(x) \in xA[[x]]$ so that

$$(2.1) \quad \phi(x_1 +_F x_2) = \phi(x_1) +_{F'} \phi(x_2).$$

A homomorphism is an **isomorphism** if it is invertible under composition; that is, if $\phi'(0)$ is a unit in A . Any homomorphism of formal group laws induces a homomorphism of the formal groups defined by the formal group laws.

Conversely, let $\psi : G \rightarrow G'$ be a homomorphism of formal groups over S and choose a cover $U_i = \text{Spec}(A_i)$ so that the global sections of both ω_G and $\omega_{G'}$ are free over A_i . Choose a generator x and y for these global sections and let F and F' be the associated formal group laws over A_i . Then we get a commutative diagram induced by ψ

$$\begin{array}{ccc} \text{Spf}(A_i[[x]]) & \xrightarrow{\psi} & \text{Spf}(A_i[[y]]) \\ \Delta_G \downarrow & & \Delta'_G \downarrow \\ \text{Spf}(A_i[[x_1, x_2]]) & \xrightarrow[\psi \times \psi]{} & \text{Spf}(A_i[[y_1, y_2]]) \end{array}$$

If we let $\phi_i(x) = \psi^*(y) \in A_i[[x]]$, this diagram implies $\phi_i : F \rightarrow F'$ is a homomorphism of formal group laws

We now introduce the moduli stack $\mathcal{M}_{\mathbf{fg}}$ of formal groups – meaning formal Lie groups of dimension 1. This stack will be algebraic, although not in the sense of [33]. See Theorem 2.30 below.

2.5 Definition. *The moduli stack of formal groups $\mathcal{M}_{\mathbf{fg}}$ is the following category fibered in groupoids over schemes. The objects in $\mathcal{M}_{\mathbf{fg}}$ are pairs (S, G) where S is a scheme and $G \rightarrow S$ is a (commutative, 1-dimensional) formal group over S . A morphism $(S, G) \rightarrow (T, H)$ is a pair (f, ϕ) where $f : S \rightarrow T$ is a morphism of schemes and $\phi : G \rightarrow f^*H$ is an isomorphism of formal groups.*

Of course, we still must prove the following result.

2.6 Proposition. *The category $\mathcal{M}_{\mathbf{fg}}$ fibered in groupoids over schemes is a stack in the fpqc topology.*

Proof. The argument exactly as in Proposition 1.36, once we note that the proofs of Lemmas 1.34 and 1.35 immediately apply to this case. \square

2.2 Formal group laws

Here we review some of the classical literature on formal group laws.

2.7 Theorem (Lazard). *1.) Let \mathbf{fgl} denote the functor from commutative rings to sets which assigns to each ring A the set of formal group laws over A . Then \mathbf{fgl} is an affine scheme; indeed, if $L \cong \mathbb{Z}[x_1, x_2, \dots]$ is the Lazard ring, then*

$$\mathbf{fgl} \cong \mathrm{Spec}(L).$$

2.) Let \mathbf{Isofgl} be the functor which assigns to each commutative ring A the set of isomorphisms $f : F \rightarrow F'$ of formal group laws over A . Then \mathbf{Isofgl} is an affine scheme; indeed, if $W \cong L[a_0^{\pm 1}, a_1, a_2, \dots]$, then

$$\mathbf{Isofgl} \cong \mathrm{Spec}(W).$$

Put another way, the functor which assigns to any commutative ring A the groupoid of formal group laws over A and their isomorphisms is an affine groupoid scheme; that is, the pair (L, W) is a *Hopf algebroid*.

2.8 Remark. It is worth noting that the isomorphism $L \cong \mathbb{Z}[x_1, x_2, \dots]$ is not canonical. The difficult part of Lazard’s argument is the symmetric 2-cocycle lemma ([48] A.2.12), which we now revisit. Let

$$C_n(x, y) = \frac{1}{d}[(x + y)^n - x^n - y^n]$$

where $d = p$ if n is a power of p and $d = 1$ otherwise. This is the n th homogeneous symmetric 2-cocycle. Then Lazard proves that if $F(x_1, x_2)$ is a formal group law over a ring A , then there are elements b_1, b_2, \dots in A so that

$$F(x_1, x_2) \equiv x_1 + x_2 + b_1 C_2(x_1, x_2) + b_2 C_3(x_1, x_2) + \dots$$

modulo $(b_1, b_2, \dots)^2$.

The isomorphism $W = L[a_0^{\pm 1}, a_1, \dots]$ depends only on the usual coordinates on power series.

We now introduce the prestack $\mathcal{M}_{\mathbf{fgl}}$ of formal group laws. It will not be a stack as it does not satisfy effective descent.

Let $\mathbf{Aff}_{\mathbb{Z}}$ be the category of affine schemes over $\mathrm{Spec}(\mathbb{Z})$. Recall from [33], Definition 3.1, that a *prestack* \mathcal{M} over $\mathbf{Aff}_{\mathbb{Z}}$ is a category fibered in groupoids over $\mathbf{Aff}_{\mathbb{Z}}$ so that isomorphisms between objects form a sheaf in the *fpqc* topology.

If $F(x_1, x_2)$ is a formal group law over a ring A and $f : A \rightarrow B$ is a ring homomorphism, let $f^*F(x_1, x_2)$ be the formal group law over B obtained by pushing forward the coefficients. The resulting formal group over $\mathrm{Spec}(B)$ is the pull-back of the formal group over $\mathrm{Spec}(A)$ defined by F ; hence, we will refer to f^*F as the pull-back of F along f .

2.9 Definition. *Define a category $\mathcal{M}_{\mathbf{fgl}}$ fibered in groupoids over $\mathbf{Aff}_{\mathbb{Z}}$ as follows. The objects are the pairs $(\mathrm{Spec}(A), F)$ where A is a commutative ring and F is a formal group law over A . A morphism $(\mathrm{Spec}(A), F) \rightarrow (\mathrm{Spec}(B), F')$ is a pair (f, ϕ) where $f : B \rightarrow A$ is a homomorphism of commutative rings and $\phi : F \rightarrow f^*F'$ is an isomorphism of formal group laws.*

2.10 Lemma. *The category $\mathcal{M}_{\mathbf{fgl}}$ fibered in groupoids over $\mathbf{Aff}_{\mathbb{Z}}$ is a prestack.*

Proof. Let $S = \mathrm{Spec}(A)$ and let F and F' be two formal group laws over S . We are asking that the functor which assigns to each morphism $\mathrm{Spec}(f) : U = \mathrm{Spec}(R) \rightarrow S$ the set of isomorphisms

$$\phi : (f^*F) \rightarrow (f^*F')$$

be a sheaf in the *fpqc*-topology. Theorem 2.7.2 gives that this functor is the affine scheme $\mathrm{Spec}(A \otimes_L W \otimes_L A)$. The assertion follows from the fact that the *fpqc* topology is sub-canonical. See the end of Remark 1.9. \square

The functor which assigns to each formal group law F over a ring A the associated formal group G_F over the affine scheme $\mathrm{Spec}(A)$ defines a morphism

$$\mathcal{M}_{\mathbf{fgl}} \longrightarrow \mathcal{M}_{\mathbf{fg}}$$

of prestacks over $\mathbf{Aff}_{\mathbb{Z}}$. This is not an equivalence, but we will see that this morphism identifies $\mathcal{M}_{\mathbf{fg}}$ as the stack associated to the prestack $\mathcal{M}_{\mathbf{fgl}}$. See Theorem 2.34.

The next result, which I learned from Neil Strickland, is an indication that stacks have a place in stable homotopy theory.

2.11 Lemma. *Suppose F_i , $i = 1, 2$ are formal group laws over commutative rings A_i respectively. Let*

$$G_i \rightarrow S_i = \mathrm{Spec}(A_i), \quad i = 1, 2$$

be the corresponding formal groups. Then the two category pull-back $S_1 \times_{\mathcal{M}_{\mathbf{fg}}} S_2$ is an affine scheme. Specifically, if $L \rightarrow A_i$ classifies F_i , then there is an isomorphism

$$S_1 \times_{\mathcal{M}_{\mathbf{fg}}} S_2 \cong \mathrm{Spec}(A_1 \otimes_L W \otimes_L A_2).$$

Proof. By construction we have a factoring

$$S_i \xrightarrow{F_i} \mathcal{M}_{\mathbf{fg}1} \longrightarrow \mathcal{M}_{\mathbf{fg}}.$$

of the morphism classifying G_i . By Remark 2.4, the reduction map $\mathcal{M}_{\mathbf{fg}1} \rightarrow \mathcal{M}_{\mathbf{fg}}$ is full and faithful; hence, the natural map

$$S_1 \times_{\mathcal{M}_{\mathbf{fg}1}} S_2 \rightarrow S_1 \times_{\mathcal{M}_{\mathbf{fg}}} S_2$$

is an isomorphism. If R is any commutative ring $(S_1 \times_{\mathcal{M}_{\mathbf{fg}1}} S_2)(R)$ is the trivial groupoid with object set the triples

$$(f_1, f_2, \phi : f_1^* F_1 \xrightarrow{\cong} f_2^* F_1)$$

where $f_i : A_i \rightarrow R$ are ring homomorphisms. Applying Theorem 2.7.2 now implies the result. \square

If G_1 and G_2 are two formal groups over a scheme S , let $\mathrm{Iso}_S(G_1, G_2)$ be the presheaf of sets which assigns to any morphism $f : U \rightarrow S$ with affine source the set of isomorphisms $f^* G_1 \rightarrow f^* G_2$. There is a pull-back diagram

$$\begin{array}{ccc} \mathrm{Iso}_S(G_1, G_2) & \longrightarrow & S \times_{\mathcal{M}_{\mathbf{fg}}} S \\ \downarrow & & \downarrow \\ S & \xrightarrow{\Delta} & S \times S. \end{array}$$

Proposition 2.6 implies that $\mathrm{Iso}_S(G_1, G_2)$ is actually a sheaf. Lemma 2.11 immediately implies the following.

2.12 Lemma. *Suppose F_i , $i = 1, 2$ are formal group laws over a single commutative ring A and let*

$$G_i \rightarrow S = \mathrm{Spec}(A), \quad i = 1, 2$$

be the corresponding formal groups. Then the sheaf $\mathrm{Iso}_S(G_1, G_2)$ is an affine scheme over S . Specifically, if $L \rightarrow A$ classifies F_i , then there is an isomorphism

$$\mathrm{Iso}_S(G_1, G_2) \cong \mathrm{Spec}(A \otimes_{A \otimes A} (A \otimes_L W \otimes_L A)).$$

2.3 Coordinates

We now begin to discuss when a formal group can arise from a formal group law. In the following definition, the base scheme need not be affine. The sheaves $\mathcal{O}_{G_n}(e)$ were defined in Equation 1.5 as the kernel of the map $\mathcal{O}_{G_n} \rightarrow e_*\mathcal{O}_S$. If G is a formal group with n th infinitesimal neighborhood G_n , then there is an exact sequence

$$0 \rightarrow q_*\mathcal{O}_{G_n}(e) \rightarrow q_*\mathcal{O}_{G_n} \rightarrow \mathcal{O}_S \rightarrow 0$$

of sheaves on S . If $S = \text{Spec}(A)$ and ω_e has a generating local section then

$$H^0(S, q_*\mathcal{O}_{G_n}(e)) \cong xA[x]/(x^{n+1}).$$

2.13 Definition. Let S be a scheme and $q : G \rightarrow S$ a formal group over S with conormal sheaf ω_e . Then a **coordinate** for G is a global section

$$x \in \lim H^0(S, q_*\mathcal{O}_{G_n}(e))$$

so that for all affine morphisms $f : U = \text{Spec}(A) \rightarrow S$, $x|_U$ generates the global sections of $(\omega_e)|_U$.

Every formal group has coordinates locally, as in Example 2.3; this definition asks for a global coordinate.

2.14 Remark. If $E^*(-)$ is a complex oriented 2-periodic homology theory, the associated formal group is $\text{Spf}(E^0(\mathbb{C}P^\infty))$ over $\text{Spec}(E^0)$. A coordinate is then a class $x \in \tilde{E}^0\mathbb{C}P^\infty$ which reduces to generator of $\tilde{E}^0\mathbb{C}P^1$. This is the usual topological definition. See [48], Definition 4.1.1.

2.15 Remark. 1.) Let (G, x) be a formal group law over S with a coordinate x . Since x provides a global trivialization of the locally free sheaf ω_e , Definition 1.29.3 allows us to conclude that

$$(2.2) \quad G_n \cong \text{Spec}_S(\mathcal{O}_S[x]/(x^{n+1})).$$

Equivalently, we have $q_*\mathcal{O}_{G_n} = \mathcal{O}_S[x]/(x^{n+1})$. In particular,

$$\lim H^0(S, q_*\mathcal{O}_{G_n}) \cong H^0(S, \mathcal{O}_S)[[x]].$$

2.) Suppose F is a formal group law over a commutative ring A and G_F is the associated formal group over $\text{Spec}(A)$, as in Example 2.3. Then, as in Remark 1.31.1, G_F has a preferred coordinate x defined by the definition

$$G_F = \text{Spf}(A[[x]]).$$

Then there is an equality of formal group laws

$$x_1 +_{(G_F, x)} x_2 = x_1 +_F x_2.$$

Conversely, if G is a formal group over $\text{Spec}(A)$ with a coordinate x , then Equation 2.2 provides a natural isomorphism (*not* an equality) of formal groups over $\text{Spec}(A)$

$$G_F \xrightarrow{\cong} G.$$

3.) If $f : (G, x) \rightarrow (H, y)$ is a homomorphism of formal groups over S with chosen coordinates, then f is defined by a morphism of \mathcal{O}_S -algebra sheaves

$$\phi : q_* \mathcal{O}_{H_n} \cong \mathcal{O}_S[[y]]/(y^{n+1}) \rightarrow \mathcal{O}_S[[x]]/(x^{n+1}) \cong p_* \mathcal{O}_{G_n}$$

and, thus, is defined by the power series

$$\phi(y) = f(x) \in H^0(S, (\mathcal{O}_S)[[x]])$$

which is a homomorphism of formal group laws:

$$f(x_1) +_{F_H} f(x_2) = f(x_1 +_{F_G} x_2).$$

Conversely, any such power series defines a homomorphism of formal group laws.

4.) Suppose we are given a 2-commuting diagram

$$\begin{array}{ccc} T & \xrightarrow{H} & \mathcal{M}_{\text{fg}} \\ g \downarrow & & \nearrow G \\ S & & \end{array}$$

and a coordinate for x for G over S . Then there is an induced coordinate for H over T . Let $\phi : H \rightarrow g^*G$ be the given isomorphism. Then the coordinate for H is the image of x under the homomorphisms

$$H^0(S, q_* \mathcal{O}_{G_n}(e)) \longrightarrow H^0(T, g^* q_* \mathcal{O}_{G_n}(e)) \xleftarrow[\cong]{\phi^*} H^0(T, q_* \mathcal{O}_{H_n}(e)).$$

The next step is to examine the geometry of the scheme of possible coordinates for G . We begin with the following result.

2.16 Lemma. *Let $q : G \rightarrow S$ be a formal group over a quasi-compact and quasi-separated scheme S . Then there is a quasi-compact and quasi-separated scheme T and a faithfully flat and quasi-compact morphism $f : T \rightarrow S$ so that f^*G has a coordinate.*

Proof. Choose a finite cover $U_i \rightarrow S$ by affine open subschemes so that the global sections of $(\omega_e)|_{U_i}$ are free. Set $f : T = \sqcup U_i \rightarrow S$ to be the evident map. Then f is faithfully flat, quasi-compact and $f^*\omega_e$ is isomorphic to \mathcal{O}_T . Since T is a coproduct of affines, the map

$$\lim H^0(T, \mathcal{O}_{f^*G_n}(e)) \rightarrow H^0(T, f^*\omega_e)$$

is onto, and we choose as our coordinate any preimage of a generator. \square

2.17 Definition. *Define a category $\mathcal{M}_{\text{coord}}$ fibered in groupoids over schemes as follows. The objects of $\mathcal{M}_{\text{coord}}$ are pairs $(q : G \rightarrow S, x)$ where G is a formal group over a scheme S and x is a coordinate for G . A morphism in $\mathcal{M}_{\text{coord}}$*

$$(q : G \rightarrow S, x) \longrightarrow (q' : G' \rightarrow S', x')$$

*is a morphism of schemes $f : S \rightarrow S'$ and an isomorphism of formal groups $\phi : G \rightarrow f^*G'$.*

By forgetting the coordinate we get a projection map $\mathcal{M}_{\text{coord}} \rightarrow \mathcal{M}_{\text{fg}}$; if we consider this as morphism of categories fibered in groupoids over affine schemes, Remark 2.15.3 factors this projection as the composite

$$\mathcal{M}_{\text{coord}} \xrightarrow{i} \mathcal{M}_{\text{fgl}} \longrightarrow \mathcal{M}_{\text{fg}}.$$

2.18 Proposition. *The morphism $i : \mathcal{M}_{\text{coord}} \rightarrow \mathcal{M}_{\text{fgl}}$ of categories fibered in groupoids is an equivalence over affine schemes; that is, for all commutative rings A , the morphism of groupoids*

$$\mathcal{M}_{\text{coord}}(A) \longrightarrow \mathcal{M}_{\text{fgl}}(A)$$

is an equivalence of groupoids.

Proof. This is a restatement of Remark 2.15.3 and Remark 2.15.4. \square

2.19 Corollary. *The category $\mathcal{M}_{\text{coord}}$ fibered in groupoids over schemes is a prestack.*

Proof. This requires only that if (G, x) and (H, y) are two objects over a scheme S , the the isomorphisms $\text{Iso}_S((G, x), (H, y))$ form a sheaf. But

$$\text{Iso}_S((G, x), (H, y)) = \text{Iso}_S(G, H)$$

where $\text{Iso}_S(G, H)$ is the the sheaf (by Proposition 2.6) of isomorphisms of formal groups. \square

We now give extensions of Lemmas 2.12 and 2.11, in that order.

2.20 Proposition. *Let G_1 and G_2 be two formal groups over a quasi-compact and quasi-separated scheme S . Then*

$$\text{Iso}_S(G_1, G_2) \rightarrow S$$

is an affine morphism of schemes.

Proof. We prove this by appealing to Lemma 2.12 and faithfully flat descent.

First, suppose G_1 and G_2 can be each given a coordinate. Then, for a fixed choice of coordinate for G_1 and G_2 and for any morphism of schemes $f : U = \text{Spec}(A) \rightarrow S$, the formal groups f^*G_i over U has an induced coordinate, and Lemma 2.12 shows

$$f^*\text{Iso}_S(G_1, G_2) = \text{Iso}_U(f^*G_1, f^*G_2) \rightarrow U$$

is affine over U ; indeed,

$$(2.3) \quad \text{Iso}_U(f^*G_1, f^*G_2) \cong \text{Spec}(A \otimes_{A \otimes A} (A \otimes_L W \otimes_L A)).$$

Expanding this thought, define a presheaf $\mathcal{A}(G_1, G_2)$ of \mathcal{O}_S algebras by

$$\mathcal{A}(G_1, G_2)(f : U \rightarrow S) = H^0(U, \text{Iso}_U(f^*G_1, f^*G_2))$$

where $f : U \rightarrow S$ runs over all flat morphisms with affine source. Then Equation 2.3 implies that $\mathcal{A}(G_1, G_2)$ is a quasi-coherent sheaf of \mathcal{O}_S -algebras. We then have

$$\mathrm{Spec}_S(\mathcal{A}(G_1, G_2)) \cong \mathrm{Iso}_S(G_1, G_2)$$

over S . If $f : T \rightarrow S$ is any morphism of schemes, then f^*G_i also can be given a coordinate, by Remark 2.15.4, and then Lemma 2.12 implies that

$$(2.4) \quad f^*\mathcal{A}(G_1, G_2) \cong \mathcal{A}(f^*G_1, f^*G_2)$$

as quasi-coherent \mathcal{O}_T -algebra sheaves. This is equivalent to the statement that

$$(2.5) \quad T \times_S \mathrm{Iso}_S(G_1, G_2) \cong \mathrm{Iso}_T(f^*G_1, f^*G_2).$$

For the general case, we appeal to Lemma 2.16 to choose an *fpqc*-cover $f : T \rightarrow S$ so that f^*G_i can each be given a coordinate. Then $\mathrm{Iso}_T(f^*G_1, f^*G_2) \cong \mathrm{Spec}_T(\mathcal{A}(f^*G_1, f^*G_2))$ and Equation 2.4 (or Equation 2.5) yields an isomorphism of quasi-coherent $\mathcal{O}_{T \times_S T}$ -algebra sheaves

$$\phi : p_1^*\mathcal{A}(f^*G_1, f^*G_2) \longrightarrow p_2^*\mathcal{A}(f^*G_1, f^*G_2).$$

We check that this isomorphism satisfies the cocycle condition and we get, by faithfully flat descent, a quasi-coherent \mathcal{O}_S -algebra sheaf $\mathcal{A}(G_1, G_2)$. Uniqueness of descent and Equation 2.5 imply that $\mathrm{Spec}_S(\mathcal{A}(G_1, G_2)) \cong \mathrm{Iso}_S(G_1, G_2)$ over S . \square

2.21 Corollary. *Let $G \rightarrow S$ and $H \rightarrow T$ be formal groups over quasi-compact and quasi-separated schemes. Then the projection morphism*

$$S \times_{\mathcal{M}_{\mathrm{fg}}} T \longrightarrow S \times T$$

is an affine morphism of schemes. In particular $S \times_{\mathcal{M}_{\mathrm{fg}}} T$ is a scheme over S and it is an affine scheme over S if T is an affine scheme.

Proof. One easily checks that there is an isomorphism

$$S \times_{\mathcal{M}_{\mathrm{fg}}} T \cong \mathrm{Iso}_{S \times T}(p_1^*G, p_2^*H).$$

Now we use Proposition 2.20. \square

In the following definition we are going to have a functor F on affine schemes over a scheme S . We'll write $F|_U$ for $F(U)$ to in order to avoid too many parentheses.

2.22 Definition. *1.) Let G be a formal group over a scheme S . Define a functor $\mathrm{Coord}(G/S)$ from affine schemes over S to groupoids as follows. If $i : U \rightarrow S$ is any affine morphism, then the objects of $\mathrm{Coord}(G/S)|_U$ are pairs (i^*G, x) where x is a coordinate for i^*G . The morphisms $f : (i^*G, x) \rightarrow (i^*G, y)$ of $\mathrm{Coord}(G/S)|_U$ are those morphisms of formal group laws so that the underlying morphism of formal groups $f_0 = 1 : i^*G \rightarrow i^*G$ is the identity.*

2.) Let us write $\text{Coord}_G \rightarrow S$ for the functor of objects of the groupoid functor $\text{Coord}(G/S)$

3.) By 2.15.4, a morphism $f : (G, x) \rightarrow (G, y)$ so that the underlying morphism of formal groups is the identity amounts to writing the coordinate y as a power series in x . We will call this a change of coordinates.

In the following result, note that we have an isomorphism, not simply an equivalence.

2.23 Lemma. *Let $G \rightarrow S$ be a formal group over a scheme S and let $S \rightarrow \mathcal{M}_{\text{fg}}$ classify G . Then there is an isomorphism of groupoids over S*

$$\lambda : \text{Coord}(G/S) \longrightarrow S \times_{\mathcal{M}_{\text{fg}}} \mathcal{M}_{\text{fgl}}.$$

Proof. First we define the morphism. Let $f : U = \text{Spec}(A) \rightarrow S$ be a morphism out of an affine scheme and let $(f^*G, x) \in \text{Coord}(G/S)|_U$. Define $\lambda(f^*G, x)$ to be the triple

$$(f : U \rightarrow S, F, \phi : G_F \rightarrow f^*G)$$

where F is the formal group law determined by x (Remark 2.15.2) and ϕ is the natural isomorphism from the formal group determined by F (Example 2.4) to f^*G . The inverse of λ sends (f, F, ϕ) to the pair (f^*G, x) where x is the coordinate defined by ϕ (Remark 2.15.4). \square

The next result follows immediately from Proposition 2.18. Notice we only have an equivalence in this case.

2.24 Corollary. *Let $G \rightarrow S$ be a formal group over a scheme S and let $S \rightarrow \mathcal{M}_{\text{fg}}$ classify G . Then there is an equivalence of groupoids over S*

$$\lambda : \text{Coord}(G/S) \longrightarrow S \times_{\mathcal{M}_{\text{fg}}} \mathcal{M}_{\text{coord}}.$$

In the following result, we will call a groupoid scheme \mathcal{G} over S affine over S if both the projection maps $\text{ob}\mathcal{G} \rightarrow S$ and $\text{mor}\mathcal{G} \rightarrow S$ are affine morphisms.

2.25 Theorem. 1.) *Let $G \rightarrow S$ be a formal group over a quasi-compact and quasi-separated scheme S . Then $\text{Coord}(G/S) \rightarrow S$ is a groupoid scheme affine over S .*

2.) *For all morphisms $f : T \rightarrow S$ of schemes, the groupoid $\text{Coord}(G/S)|_T$ is either empty or contractible.*

3.) *The objects $\text{Coord}_G \rightarrow S$ of $\text{Coord}(G/S)$ form an affine scheme over S .*

Proof. Lemma 2.23 and Theorem 2.7 imply together that the objects and morphisms of $\text{Coord}(G/S)$ are, respectively,

$$S \times_{\mathcal{M}_{\text{fg}}} \text{Spec}(L)$$

and

$$S \times_{\mathcal{M}_{\text{fg}}} \text{Spec}(W).$$

Part (1) of the theorem follows from Corollary 2.21. Since Coord_G is the scheme of objects in $\text{Coord}(G/S)$, part (3) follows from part (1).

For part (2), if f^*G has no coordinate, then $\text{Coord}(G/S)|_T$ is empty. If, however, f^*G has a coordinate, then any two coordinates are connected by a unique isomorphism, by Remark 2.15.3, and the groupoid is contractible. \square

We remark that we have shown that the scheme Coord_G of objects is actually a torsor for an appropriate group scheme. See Lemma 3.11.

2.26 Remark. Since the proof of Theorem 2.25 is at the end of a logical thread which winds in way through most of this section, it might be worthwhile to consider the example where $S = \text{Spec}(B)$ is affine and G is a formal group which can be given a coordinate y . Then if $f : \text{Spec}(A) = U \rightarrow S$ is any morphism from an affine scheme, and $(f^*G, x) \in \text{Coord}(G/S)|_U$ is any coordinate for G over U , then x can be written in terms of y ; that is,

$$x = a_0y + a_1y^2 + a_2y^3 + \cdots \stackrel{\text{def}}{=} a(y)$$

where $a_i \in A$ and a_0 is invertible. From this we see that the choice of the coordinate y defines an isomorphism of schemes

$$\text{Coord}_G \cong \text{Spec}(B[a_0^{\pm 1}, a_1, a_2, \dots]) \cong \text{Spec}(B \otimes_L W) \cong S \times_{\mathcal{M}_{\text{fg}}} \text{Spec}(L).$$

An isomorphism $\phi : (f^*G, x_0) \rightarrow (f^*G, x_1)$ in $\text{Coord}(G/S)|_U$ is determined by a power series

$$x_1 = \lambda_0x_0 + \lambda_1x_0^2 + \lambda_2x_0^3 + \cdots = \lambda(x_0)$$

and $x_1 = \lambda(a(y))$. This shows the choice of the coordinate y defines an isomorphism of schemes from the morphisms of $\text{Coord}(G/S)$ to

$$\text{Spec}(B[a_0^{\pm 1}, a_1, \dots, \lambda_0^{\pm 1}, \lambda_1, \dots]) \cong \text{Spec}(B \otimes_L W \otimes_L W).$$

2.4 \mathcal{M}_{fg} is an *fpqc*-algebraic stack

We recall the notion of a representable morphism of stacks and what it means for such a morphism to have geometric properties. All our stacks are categories fibered in groupoids over affine schemes.

2.27 Definition. 1.) A morphism $\mathcal{N} \rightarrow \mathcal{M}$ of stacks is **representable** if for all morphisms $U \rightarrow \mathcal{M}$ with affine source, the 2-category pull-back $U \times_{\mathcal{M}} \mathcal{N}$ is a scheme.

2.) Let P be some property of morphisms of schemes closed under base change and let $f : \mathcal{N} \rightarrow \mathcal{M}$ be a representable morphism of stacks, then f has property P if the induced morphism

$$U \times_{\mathcal{M}} \mathcal{N} \longrightarrow U$$

has property P for all morphisms $U \rightarrow \mathcal{M}$ with affine source.

In the situations which arise here, there are times when we only have to check the property P once. This will happen, for example, with flat maps. The results is the following.

2.28 Lemma. *Let P be some property of morphisms of schemes closed under base change, and suppose P has the following further property:*

- *Let $f : X \rightarrow Y$ be a morphism of schemes and let $g : Z \rightarrow Y$ be a faithfully flat morphism of schemes. Then f has property P if and only if $Z \times_Y X \rightarrow Z$ has property P .*

Then if $X \rightarrow \mathcal{M}$ is a presentation of \mathcal{M} by an affine scheme, a representable morphism of stacks $\mathcal{N} \rightarrow \mathcal{M}$ has property P if and only if $X \times_{\mathcal{M}} \mathcal{N} \rightarrow X$ has property P .

Now we define the notion of algebraic stack used in this monograph.

2.29 Definition. *Let Y be a scheme and \mathcal{M} any stack over Y . Then \mathcal{M} is an **algebraic stack** in the fpqc-topology or more succinctly an **fpqc-stack** if*

1. *the diagonal morphism $\mathcal{M} \rightarrow \mathcal{M} \times_Y \mathcal{M}$ is representable, separated, and quasi-compact; and*
2. *there a scheme X and a surjective, flat, and quasi-compact morphism $X \rightarrow \mathcal{M}$. The morphism $X \rightarrow \mathcal{M}$ is called a **presentation** of \mathcal{M} .*

Note that if the diagonal morphism is representable, as in point (1), then all morphism $X \rightarrow \mathcal{M}$ are representable (cf. [33], Corollaire 3.13); hence point (2) makes sense.

Definition 2.29 is a relaxation of the usual definition of algebraic stack (as in [33], Définition 4.1) where the presentation $X \rightarrow \mathcal{M}$ is required to be smooth, so in particular flat and locally of finite type. It turns out that $\mathcal{M}_{\mathbf{fg}}$ can be approximated by such stacks, as we see in the next chapter.

The following result is obtained by combining Propositions 2.31 and 2.32 below.

2.30 Theorem. *The moduli stack $\mathcal{M}_{\mathbf{fg}}$ is an algebraic stack over $\mathrm{Spec}(\mathbb{Z})$ in the fpqc-topology. Let $\mathbf{fgl} = \mathrm{Spec}(L)$ be the affine scheme of formal group laws and let $G_F \rightarrow \mathbf{fgl}$ be the formal group arising from the universal formal group law. Then*

$$G_F : \mathbf{fgl} \longrightarrow \mathcal{M}_{\mathbf{fg}}$$

is a presentation for $\mathcal{M}_{\mathbf{fg}}$.

Let \mathcal{M} be a stack and $x_1, x_2 : S \rightarrow \mathcal{M}$ be two 1-morphisms. Then the 2-category pull-back of

$$\begin{array}{ccc} & & \mathcal{M} \\ & & \downarrow \Delta \\ S & \xrightarrow{(x_1, x_2)} & \mathcal{M} \times_Y \mathcal{M} \end{array}$$

is equivalent to the *fpqc*-sheaf $\text{Iso}_S(x_1, x_2)$ which assigns to each affine scheme $U \rightarrow S$ over S the isomorphisms $\text{Iso}_U(f^*x_1, f^*x_2)$.

2.31 Proposition. *The diagonal morphism*

$$\mathcal{M}_{\mathbf{fg}} \longrightarrow \mathcal{M}_{\mathbf{fg}} \times \mathcal{M}_{\mathbf{fg}}$$

is representable, quasi-compact, and separated.

Proof. We use Proposition 2.20: for any affine scheme S and any two formal groups G_1 and G_2 , the morphism

$$\text{Iso}_S(G_1, G_2) \rightarrow S$$

is an affine morphism of schemes. Hence the diagonal is representable ([33], 3.13), quasi-compact, and separated ([33], 3.10). \square

2.32 Proposition. *Let $\mathbf{fgl} = \text{Spec}(L)$ be the affine scheme of formal group laws and let $G_F \rightarrow \mathbf{fgl}$ be the formal group arising from the universal formal group law. Then*

$$G_F : \mathbf{fgl} \longrightarrow \mathcal{M}_{\mathbf{fg}}$$

is surjective, flat, and quasi-compact.

Proof. The morphism G_F is surjective because every formal group over a field can be given a coordinate, and hence arises from a formal group law. To check that it is quasi-compact and flat, we need to check that for all morphisms

$$G : \text{Spec}(A) \longrightarrow \mathcal{M}_{\mathbf{fg}}$$

with affine source, the resulting map

$$\text{Spec}(A) \times_{\mathcal{M}_{\mathbf{fg}}} \mathbf{fgl} \rightarrow \text{Spec}(A)$$

is quasi-compact and flat. It is quasi-compact because it is affine (by Proposition 2.21). To check that it is flat, we choose a faithfully flat extension $A \rightarrow B$ and check that

$$\text{Spec}(B) \times_{\mathcal{M}_{\mathbf{fg}}} \mathbf{fgl} \cong \text{Spec}(B) \times_{\text{Spec}(A)} \text{Spec}(A) \times_{\mathcal{M}_{\mathbf{fg}}} \mathbf{fgl} \rightarrow \text{Spec}(B)$$

is flat. Put another way, we may assume G has a coordinate and arises from a formal group law. Then, by Lemma 2.11

$$\text{Spec}(A) \times_{\mathcal{M}_{\mathbf{fg}}} \mathbf{fgl} \cong \text{Spec}(A \otimes_L W)$$

and $A \rightarrow A \otimes_L W \cong A[a_0^{\pm 1}, a_1, \dots]$ is certainly faithfully flat. \square

2.33 Theorem. *The 1-morphism of prestacks*

$$\mathcal{M}_{\mathbf{coord}} \longrightarrow \mathcal{M}_{\mathbf{fg}}$$

identifies $\mathcal{M}_{\mathbf{fg}}$ as the stack associated to the prestack $\mathcal{M}_{\mathbf{coord}}$.

Proof. We begin by giving a formal description of the stack $\tilde{\mathcal{M}}_{\mathbf{coord}}$ associated to $\mathcal{M}_{\mathbf{coord}}$. Then we prove that there is an appropriate equivalence $\tilde{\mathcal{M}}_{\mathbf{coord}} \rightarrow \mathcal{M}_{\mathbf{fg}}$.

First, we define an equivalence class of coordinates for a formal group G over S as follows. A representative of this equivalence class will be a coordinate x for $f^*G = T \times_S G \rightarrow T$ where $f : T \rightarrow S$ is a faithfully flat and quasi-compact morphism. If x_1 and x_2 are coordinates for $T_1 \times_S G$ and $T_2 \times_S G$ respectively, then we say they are equivalent if $p_1^*x_1 = p_2^*x_2$ as coordinates for $(T_1 \times_S T_2) \times_S G$. That this is an equivalence relation follows from the fact that Coord_G is a sheaf in the *fpqc* topology.

Now define the category $\tilde{\mathcal{M}}_{\mathbf{coord}}$ fibered in groupoids over $\mathbf{Aff}_{\mathbb{Z}}$ as follows. The objects are pairs $(G \rightarrow S, [x])$ where G is a formal group over S and $[x]$ is an equivalence class of coordinates, as in the previous paragraph. A morphism $f : (G, [x]) \rightarrow (H, [y])$ is given by a morphism $f_0 : G \rightarrow H$ in $\mathcal{M}_{\mathbf{fg}}$. That $\tilde{\mathcal{M}}_{\mathbf{coord}}$ is a stack is proved exactly as in Lemma 2.6. The projection map $\mathcal{M}_{\mathbf{coord}} \rightarrow \mathcal{M}_{\mathbf{fg}}$ has an evident factorization

$$\mathcal{M}_{\mathbf{coord}} \longrightarrow \tilde{\mathcal{M}}_{\mathbf{coord}} \longrightarrow \mathcal{M}_{\mathbf{fg}}.$$

We will prove that the first map has the universal property necessary for the associated stack, and we will show the second map is an equivalence of stacks.

First, we must show that any factorization problem

$$\begin{array}{ccc} \mathcal{M}_{\mathbf{coord}} & \xrightarrow{\lambda} & \mathcal{N} \\ \downarrow & \nearrow & \\ \tilde{\mathcal{M}}_{\mathbf{coord}} & & \end{array}$$

has a solution $\bar{\lambda} : \tilde{\mathcal{M}}_{\mathbf{coord}} \rightarrow \mathcal{N}$ so that the triangle 2-commutes. To do this, let $(G \rightarrow S, [x])$ be an object in $\tilde{\mathcal{M}}_{\mathbf{coord}}$ and choose an *fpqc* cover $d : T \rightarrow S$ so that d^*G has a coordinate x representing $[x]$. If we apply λ to the effective descent data

$$\phi : (d_1^*d^*G, d_1^*x) \rightarrow (d_0^*d^*G, d_0^*x)$$

we obtain a object $w \in \mathcal{N}(S)$ and a unique isomorphism

$$(2.6) \quad d^*w \cong \lambda(d^*G, x).$$

Set $\bar{\lambda}(G, [x]) = w$. In like manner, $\bar{\lambda}$ can be defined on morphisms. The unique isomorphisms of Equation 2.6 shows that the resulting diagram 2-commutes.

Second, to show that $\tilde{\mathcal{M}}_{\mathbf{coord}} \rightarrow \mathcal{M}_{\mathbf{fg}}$ is an equivalence, note that for all schemes S , the morphism of groupoids

$$\tilde{\mathcal{M}}_{\mathbf{coord}}(S) \longrightarrow \mathcal{M}_{\mathbf{fg}}(S)$$

is a fibration. That is, given any object $(H, [y])$ in $\tilde{\mathcal{M}}_{\mathbf{coord}}(S)$ and any morphism $\phi : G \rightarrow H$ in $\mathcal{M}_{\mathbf{fg}}(S)$, there is a morphism $\phi : (G : [x]) \rightarrow (H, [y])$ in $\tilde{\mathcal{M}}_{\mathbf{coord}}(S)$

whose underlying morphism is ψ . This follows from Remark 2.15.5. If $G \in \mathcal{M}_{\mathbf{fg}}(S)$ is a fixed formal group, then the fiber at G is

$$\operatorname{colim}_{T \rightarrow S} \operatorname{Coord}(G/T)$$

where T runs over all *fpqc* covers of S . Combining Theorem 2.25.2 and Lemma 2.16 we see that this fiber is contractible. \square

The following is an immediate consequence of the previous result and Proposition 2.18.

2.34 Theorem. *The 1-morphism of prestacks*

$$\mathcal{M}_{\mathbf{fg}1} \longrightarrow \mathcal{M}_{\mathbf{fg}}$$

identifies $\mathcal{M}_{\mathbf{fg}}$ as the stack associated to the prestack $\mathcal{M}_{\mathbf{fg}1}$.

2.5 Quasi-coherent sheaves

Here we define the notion of a quasi-coherent sheaf on an *fpqc*-algebraic stack and give some preliminary examples for the moduli stack of formal groups. We then recall the connection between quasi-coherent sheaves and comodules over a Hopf algebroid and relate the cohomology of a quasi-coherent sheaf to Ext in the category of comodules.

In 1.14 we noted that if X is scheme, then the category of quasi-coherent sheaves over X is equivalent to the category of cartesian \mathcal{O}_X -module sheaves in the *fpqc*-topology. We will take the latter notion as the *definition* of a quasi-coherent sheaf on an *fpqc*-stack.

The *fpqc*-topology and *fpqc*-site were defined in Definition 1.10 and Remark 1.12 respectively.

2.35 Definition. *Let \mathcal{M} be an *fpqc*-algebraic stack. We define the *fpqc site* on \mathcal{M} to have*

1. *an underlying category with objects all schemes $U \rightarrow \mathcal{M}$ over \mathcal{M} and, as morphisms, all 2-commuting diagram over \mathcal{M} ; and*
2. *for all morphisms $U \rightarrow \mathcal{M}$ in this category we assign the *fpqc*-topology on U .*

We often specify sheaves only on affine morphisms $\operatorname{Spec}(A) \rightarrow \mathcal{M}$, extending as necessary to other morphisms by the sheaf condition.

2.36 Remark. Let me expand on the notion of a 2-commuting diagram. This is pair (f, ϕ) expressed as a diagram

$$\begin{array}{ccc} V & & \\ \downarrow f & \searrow y & \\ U & \xrightarrow{x} & \mathcal{M} \end{array} \quad \begin{array}{c} \phi \\ \Downarrow \\ \end{array}$$

where $f : V \rightarrow U$ is a morphism of schemes and $\phi : y \rightarrow f^*x$ is an isomorphism of objects (usually formal groups in this monograph) over V . The composition of two such pairs can be written

$$(f, \phi)(g, \psi) = (fg, (g^*\phi)\psi).$$

Note the twisting. If ϕ is understood, or the notation gets cumbersome, then ϕ may be dropped from the diagram.

The structure sheaf on $\mathcal{O} = \mathcal{O}_{\mathcal{M}}$ is defined by

$$\mathcal{O}(\mathrm{Spec}(A) \rightarrow \mathcal{M}) = B.$$

This is a sheaf of rings and has a corresponding category of module sheaves, which we will write as $\mathbf{Mod}_{\mathcal{M}}$ or, perhaps, $\mathbf{Mod}_{\mathbf{fg}}$ if we have some stack such as the moduli stack of formal groups.

The notion of a cartesian sheaf can be found in Definition 1.13.

2.37 Definition. *Let \mathcal{M} be an fpqc-algebraic stack. A **quasi-coherent sheaf** \mathcal{F} on \mathcal{M} is a cartesian $\mathcal{O}_{\mathcal{M}}$ -module sheaf for the category of affines over \mathcal{M} . In detail we have*

1. for each morphism $u : \mathrm{Spec}(A) \rightarrow \mathcal{M}$ an A -module $\mathcal{F}(u)$;
2. for each 2-commuting diagram

$$\begin{array}{ccc} \mathrm{Spec}(B) & & \\ \downarrow f & \searrow v & \\ & \phi \Downarrow & \mathcal{M} \\ \mathrm{Spec}(A) & \nearrow u & \end{array}$$

a morphism of A -modules $\mathcal{F}(u) \rightarrow \mathcal{F}(v)$ so that the induced map

$$\theta_{\phi} B \otimes_A \mathcal{F}(u) \rightarrow \mathcal{F}(v)$$

is an isomorphism.

These isomorphisms must satisfy the following cocycle condition

if (g, ψ) and (f, ϕ) are composable 2-commuting diagrams, then

$$\theta_{(g^*\phi)\psi} = \theta_{\psi}(g^*\theta_{\phi}).$$

2.38 Example. Here I give an ad hoc construction of the sheaf of invariant differentials on $\mathcal{M}_{\mathbf{fg}}$. A more intrinsic definition will be given later. See Section 4.2.

Because of faithfully flat descent, we can define an $\mathcal{O}_{\mathbf{fg}}$ -module sheaf \mathcal{F} on $\mathcal{M}_{\mathbf{fg}}$ by specifying

$$\mathcal{F}(G) = \mathcal{F}(G : \mathrm{Spec}(A) \rightarrow \mathcal{M}_{\mathbf{fg}})$$

for those formal groups for which we can choose a coordinate. Given such a coordinate x for G , we define the invariant differentials

$$f(x)dx \in A[[x]]dx$$

to be those continuous differentials which satisfy the identity

$$f(x +_F y)d(x +_F y) = f(x)dx + f(y)dy$$

where $x +_F y$ is the formal group law of G with coordinate x . The A -module ω_G of invariant differentials is free of rank 1 and independent of the choice of coordinate. See Example 4.9. Given a 2-commuting diagram

$$\begin{array}{ccc} \mathrm{Spec}(B) & & \\ \downarrow f & \searrow H & \\ \mathrm{Spec}(A) & \xrightarrow{G} & \mathcal{M}_{\mathbf{fg}} \end{array}$$

with isomorphism $\phi : H \rightarrow f^*G$, then we have an induced isomorphism

$$d\phi : f^*\omega_G = B \otimes_A \omega_G \rightarrow \omega_H.$$

See Example 4.10 for an explicit formula. Thus we have a quasi-coherent sheaf ω on $\mathcal{M}_{\mathbf{fg}}$. This sheaf is locally free of rank 1 and we have also have all its tensor powers

$$\omega^{\otimes n} \stackrel{\mathrm{def}}{=} \omega^n, \quad n \in \mathbb{Z}.$$

2.39 Remark (Quasi-coherent sheaves and comodules). Suppose \mathcal{M} is an *fpgc*-algebraic stack with an affine presentation $\mathrm{Spec}(A) \rightarrow \mathcal{M}$ with the property that

$$\mathrm{Spec}(A) \times_{\mathcal{M}} \mathrm{Spec}(A) \cong \mathrm{Spec}(\Gamma)$$

is also affine. Then we get induced isomorphisms

$$\mathrm{Spec}(A) \times_{\mathcal{M}} \cdots \times_{\mathcal{M}} \mathrm{Spec}(A) \cong \mathrm{Spec}(\Gamma \otimes_A \cdots \otimes_A \Gamma)$$

where the product has $n \geq 2$ factors and the tensor product has $(n-1)$ -factors. The Čech nerve of the cover $\mathrm{Spec}(A) \rightarrow \mathcal{M}$ then becomes the diagram of affine schemes associated to the cobar complex

$$(2.7) \quad \cdots \mathrm{Spec}(\Gamma \otimes_A \Gamma) \begin{array}{c} \rightrightarrows \\ \rightleftarrows \\ \rightleftarrows \\ \rightrightarrows \end{array} \mathrm{Spec}(\Gamma) \begin{array}{c} \rightrightarrows \\ \rightleftarrows \\ \rightleftarrows \\ \rightrightarrows \end{array} \mathrm{Spec}(A) \longrightarrow \mathcal{M}.$$

The pair (A, Γ) , with all these induced arrows, becomes a *Hopf algebroid*. If we set $M = \mathcal{F}(\mathrm{Spec}(A) \rightarrow \mathcal{M})$, then one of the arrows $\mathrm{Spec}(\Gamma) \rightarrow \mathrm{Spec}(A)$ defines an isomorphism

$$\Gamma \otimes_A M \cong \mathcal{F}(\mathrm{Spec}(\Gamma) \rightarrow \mathcal{M})$$

and the other defines a morphism $M \rightarrow \Gamma \otimes_A M$ which gives the module M the structure of an (A, Γ) -comodule. This defines a functor from quasi-coherent sheaves on \mathcal{M} to (A, Γ) -comodules. This is an equivalence of categories. See [21] and [33] Proposition 12.8.2. The proof in the latter case is carried out in a different topology, but goes through unchanged for the *fpqc* topology, as it is an application of faithfully flat descent.

A pair $f : \text{Spec}(A) \rightarrow \mathcal{M}$ where \mathcal{M} is an *fpqc*-stack and f is a presentation so that $\text{Spec}(A) \times_{\mathcal{M}} \text{Spec}(A)$ is itself affine is called a *rigidified* stack. Such a choice leads to the equivalence of categories in the previous paragraph, but any stack \mathcal{M} may have many (or no) rigidifications and the Hopf algebroid (A, Λ) may not be in any sense canonical. An example is the moduli stack $\mathcal{U}(n)$ of formal groups of height at most n . Rigidified stacks are discussed in [42] and [16].

For the moduli stack $\mathcal{M}_{\mathbf{fg}}$, the universal formal group law gives a cover $\text{Spec}(L) \rightarrow \mathcal{M}_{fg}$ and we conclude that the category of quasi-coherent sheaves on $\mathcal{M}_{\mathbf{fg}}$ is equivalent to the category of (L, W) comodules, where

$$W = L[a_0^{\pm 1}, a_1, a_2, \dots]$$

as in Remark 2.8. The structure sheaf $\mathcal{O}_{\mathbf{fg}}$ corresponds to the L with its standard comodule structure given by the right unit $\eta_R : L \rightarrow W$; the powers of the sheaf of invariant differentials ω^n correspond to the comodule $L[n]$ where $\psi : L[n] \rightarrow W \otimes_L L[n]$ is given by

$$\psi(x) = a_0^n \eta_R(x).$$

2.40 Remark (Cohomology). If \mathcal{M} is an *fpqc*-algebraic stack and \mathcal{F} is a quasi-coherent sheaf, then the cohomology $H^*(\mathcal{M}, \mathcal{F})$ is obtained by taking derived functors of global sections. If $\text{Spec}(A) \rightarrow \mathcal{M}$ is a rigidified stack with corresponding Hopf algebroid (A, Γ) , then the equivalence of categories between quasi-coherent sheaves and comodules yields an isomorphism

$$(2.8) \quad H^s(\mathcal{M}, \mathcal{F}) \cong \text{Ext}_{\Lambda}^s(A, M)$$

where $M = \mathcal{F}(\text{Spec}(A) \rightarrow \mathcal{M})$ is the comodule corresponding to \mathcal{F} . The Čech nerve of Equation 2.7 yields the usual cobar complex for computing Hopf algebroid Ext .

2.6 At a prime: p -typical coordinates

When making calculations, especially with the Adams-Novikov spectral sequence, it is often very convenient to use p -typical formal group laws instead of arbitrary formal group laws. We delve a little into that theory here. A point to be made is that it is not a formal group which is p -typical, but a formal group law or, equivalently, a coordinate for a formal group.

If F is a formal group over a ring A in which an integer n is invertible, the power series

$$[n](x) \stackrel{\text{def}}{=} x +_F \dots +_F x$$

with the sum taken n -times has a unit as its leading coefficient; hence, it has composition inverse $[1/n](x)$.

Let A be a commutative ring over $\mathbb{Z}_{(p)}$ and let F be a formal group law over A . Then, given any integer n prime to p and a primitive n th root of unity ζ , we can form the power series

$$(2.9) \quad f_n(x) = \left[\frac{1}{n}\right]_F(x +_F \zeta x +_F \cdots +_F \zeta^{n-1} x).$$

Note that this is a power series over A .

More generally, if S is a scheme over $\mathbb{Z}_{(p)}$, G a formal group over S , and x a coordinate for G , then we have a formal group law $x_1 +_{(F,x)} x_2$ over $H^0(S, \mathcal{O}_S)$ and we can form the power series $f_n(x)$ over $H^0(S, \mathcal{O}_S)$.

2.41 Definition. 1.) A p -typical formal group law F over a commutative ring A is a formal group law F over A so that

$$f_\ell(x) = 0$$

for all primes $\ell \neq p$. A homomorphism of p -typical formal group laws is simply a homomorphism of formal groups.

2.) Let G be a formal group over a scheme S over $\mathbb{Z}_{(p)}$. Then a coordinate x for G is p -typical if the associated formal group law over $H^0(S, \mathcal{O}_S)$ is p -typical. A morphism $\phi : (G, x) \rightarrow (H, y)$ of formal groups with p -typical coordinates is simply a homomorphism of the underlying formal groups.

The symmetry condition $f_\ell(x) = 0$ arises naturally when considering the theory of Dieudonné modules associated to formal groups. See [2].

2.42 Remark (Properties of p -typical formal group laws). Let us record some of the standard properties of p -typical coordinates. A reference, with references to references, can be found in [48], Appendix 2.

1. Let G be a formal group over a $\mathbb{Z}_{(p)}$ -algebra A with a p -typical coordinate x . Then there are elements $u_i \in A$ so that

$$[p]_G(x) = px +_G u_1 x^p +_G u_2 x^{p^2} +_G \cdots .$$

Furthermore, the elements u_i determine the p -typical formal group law. However, the elements u_i depend on the pair (G, x) , hence are not invariant under changes of coordinate. Nonetheless, if $f : A \rightarrow B$ is a homomorphism of $\mathbb{Z}_{(p)}$ -algebras, then

$$[p]_{f^*G}(x) = px +_G f(u_1)x^p +_G f(u_2)x^{p^2} +_G \cdots .$$

Thus, this presentation of $[p]_G(x)$ extends to schemes: given a p -typical formal group law (G, x) over a $\mathbb{Z}_{(p)}$ scheme, there are elements $u_i \in H^0(S, \mathcal{O}_S)$ so that $[p]_G(x)$ can be written as above.

2. Let us write **pfgl** for the functor which assigns to each $\mathbb{Z}_{(p)}$ -algebra A the set of p -typical formal group laws over A . Then **pfgl** is an affine scheme. Indeed, if we write $V = \mathbb{Z}_{(p)}[u_1, u_2, \dots]$ there is a p -typical formal group law F over V so that

$$[p]_F(y) = py +_F u_1 y^p +_F u_2 y^{p^2} +_F \dots$$

The evident morphism of schemes $\mathrm{Spec}(V) \rightarrow \mathbf{pfgl}$ is an isomorphism.

3. Let $\phi : (G, x) \rightarrow (H, y)$ be an isomorphism of formal groups with p -typical coordinates and let $f(x) \in R[[x]]$ be the power series determined by ϕ . Then there are elements $t_i \in R$ so that

$$f^{-1}(x) = t_0 x +_G t_1 x^p +_G t_2^{p^2} +_G \dots$$

More is true. If x is a p -typical coordinate, then y is p -typical if and only if $f^{-1}(x)$ has this form.

As in Definitions 2.9 and 2.17 and Lemmas 2.10 and 2.19, we have prestacks $\mathcal{M}_{\mathbf{pfgl}}$ of p -typical formal group laws and $\mathcal{M}_{\mathbf{pcoord}}$ of formal groups with p -typical coordinates. We also have the analog of Proposition 2.18:

2.43 Proposition. *The canonical morphism of prestacks*

$$\mathcal{M}_{\mathbf{pcoord}} \longrightarrow \mathcal{M}_{\mathbf{pfgl}}$$

is an equivalence.

A much deeper result is the following. If X is a sheaf over $\mathrm{Spec}(R)$ in the $fpqc$ -topology and $R \rightarrow S$ is a ring homomorphism, we will write

$$X \otimes_R S \stackrel{\mathrm{def}}{=} X \times_{\mathrm{Spec}(R)} \mathrm{Spec}(S).$$

2.44 Theorem (Cartier's idempotent). *The canonical 1-morphism of categories fibered in groupoids over $\mathbf{Aff}_{\mathbb{Z}_{(p)}}$*

$$\mathcal{M}_{\mathbf{pfgl}} \longrightarrow \mathcal{M}_{\mathbf{fgl}} \otimes \mathbb{Z}_{(p)}$$

is an equivalence.

Proof. Let A be a commutative $\mathbb{Z}_{(p)}$ -algebra. Cartier's theorem (see, for example, [48]A.2.1.18) is usually phrased as follows: Given any formal group law F over A there is a p -typical formal group law eF over A and an isomorphism $\phi_F : F \rightarrow eF$ of formal group laws; furthermore, if F is p -typical, then $eF = F$ and ϕ is the identity. This implies that if $\psi : F \rightarrow F'$ is any isomorphism of formal groups laws, then there is a unique isomorphism $e\psi$ so that the following diagram commutes:

$$\begin{array}{ccc} F & \xrightarrow{\phi_F} & eF \\ \psi \downarrow & & \downarrow e\psi \\ F' & \xrightarrow{\phi_{F'}} & eF' \end{array}$$

Rephrased, we see that we have a retraction $e : \mathcal{M}_{\mathbf{fgl}}(A) \rightarrow \mathcal{M}_{\mathbf{pfgl}}(A)$ of the inclusion of groupoids $\iota : \mathcal{M}_{\mathbf{pfgl}}(A) \rightarrow \mathcal{M}_{\mathbf{fgl}}(A)$ and a natural transformation $\phi : 1 \rightarrow \iota e$. \square

The following is now an immediate consequence of Theorem 2.34 and Theorem 2.44.

2.45 Corollary. *The canonical 1-morphism of prestacks*

$$\mathcal{M}_{\mathbf{pcoord}} \longrightarrow \mathcal{M}_{\mathbf{fg}} \otimes \mathbb{Z}_{(p)}$$

identifies $\mathcal{M}_{\mathbf{fg}} \otimes \mathbb{Z}_{(p)}$ as the stack associated to the prestack $\mathcal{M}_{\mathbf{pcoord}}$.

Similarly $\mathcal{M}_{\mathbf{pcoord}} \rightarrow \mathcal{M}_{\mathbf{fg}} \otimes \mathbb{Z}_{(p)}$ identifies the target as the stack associated to the prestack source. Compare Theorem 2.33.

The following now follows from Corollary 2.45 and Remark 2.42, parts 2 and 3.

2.46 Corollary. *Let $V = \mathbb{Z}_{(p)}[u_1, u_2, \dots]$ and let $G_F \rightarrow \mathrm{Spec}(V)$ be the formal group formed from the universal p -typical formal group law F . Then the map*

$$\mathrm{Spec}(V) \longrightarrow \mathcal{M}_{\mathbf{fg}} \otimes \mathbb{Z}_{(p)}$$

classifying G is an fpqc-presentation of $\mathcal{M}_{\mathbf{fg}} \otimes \mathbb{Z}_{(p)}$. There is an isomorphism of affine schemes

$$\mathrm{Spec}(V) \times_{\mathcal{M}_{\mathbf{fg}}} \mathrm{Spec}(V) \cong \mathrm{Spec}(V[t_0^{\pm 1}, t_1, t_2, \dots]).$$

2.47 Remark (Gradings and formal group laws). There is a natural grading on the Lazard ring L and the ring $V = \mathbb{Z}_{(p)}[u_1, u_2, \dots]$ which supports the universal p -typical formal group law. This can be useful for computations.

To get the grading, we put an action of the multiplication group $\mathbb{G}_m = \mathrm{Spec}(\mathbb{Z}[t^{\pm 1}])$ on the scheme $\mathbf{fgl} = \mathrm{Spec}(L)$ of formal group laws as follows. If

$$x +_F y = \sum c_{ij} x^i y^j$$

is a formal group law over a ring R and $\lambda \in R^\times$ is a unit in R , define a new formal group law λF over R by

$$x +_{\lambda F} y = \lambda^{-1}((\lambda x) +_F (\lambda y)).$$

This action translates into a coaction

$$\psi : L \longrightarrow \mathbb{Z}[t^{\pm 1}] \otimes L$$

and hence a grading on L : $x \in L$ is of degree n if $\psi(x) = t^n \otimes x$. Then coefficients a_{ij} of the universal formal group law have degree $i + j - 1$; since

$$x +_F y = x + y + b_1 C_2(x, y) + b_2 C_3(x, y) + \dots$$

modulo decomposables, we have that b_i has degree i . In particular, c_{ij} is a homogeneous polynomial in b_k with $k < i + j$.

The same construction applies to p -typical formal group laws and the p -series

$$[p]_G(x) = px +_G u_1x^p +_G u_2x^{p^2} +_G \cdots$$

shows that, under the action of \mathbb{G}_m , u_k has degree $p^k - 1$. Since the universal p -typical formal group is defined over the ring $V = \mathbb{Z}_{(p)}[u_1, u_2, \dots]$ we have that the coefficients c_{ij} of the universal p -typical formal group are homogeneous polynomials in the u_k where $p^k \leq i + j$.

The action of \mathbb{G}_m extends to the entire groupoid scheme of formal group laws and their isomorphisms. If $\phi(x) = \sum_{i \geq 0} a_i x^i$ is an isomorphism from F to G , define

$$(\lambda\phi)(x) = \lambda^{-1}\phi(\lambda x).$$

Then $\lambda\phi$ is an isomorphism from λF to λG . If ϕ is universal isomorphism over $W = L[a_0^{\pm 1}, a_1, \dots]$, the a_i has degree i . More interesting is the case of p -typical formal group laws; if ϕ is the universal isomorphism of p -typical formal group laws over $V[t_0^{\pm 1}, t_1, t_2, \dots]$, then

$$\phi^{-1}(x) = t_0x +_G t_1x^p +_G t_2x^{p^2} +_G \cdots$$

and we see that the degree of t_k is $p^k - 1$. Thus if a_i is the i th coefficient of this power series, we have that a_i is a homogeneous polynomial in t_k and u_k with $p^k \leq i$.

Warning: The grading here is not the topological grading; in order to obtain the usual topological gradings we should double the degree – so that, for example, the degree of v_i is $2(p^i - 1)$. Also, I'll say nothing about the role of odd degree elements in comodules – and there are some subtleties here. See [37] for a systematic treatment.

3 The moduli stack of formal groups as a homotopy orbit

One of the main points of this chapter is to describe the moduli stack $\mathcal{M}_{\mathbf{fg}}$ as the homotopy inverse limit of the moduli stacks $\mathcal{M}_{\mathbf{fg}}\langle n \rangle$ of n -buds for formal groups. This is a restatement of classical results of Lazard. See Theorem 3.22. This has consequences for the quasi-coherent sheaves on $\mathcal{M}_{\mathbf{fg}}$; see Theorem 3.28.

3.1 Algebraic homotopy orbits

First some generalities, from [33] §§2.4.2, 3.4.1, and 4.6.1. Let Λ be an group scheme over a base scheme S . Let $X \rightarrow S$ be a right- Λ -scheme. Thus, there is an action morphism

$$X \times_S \Lambda \longrightarrow X$$

over S such that the evident diagrams commute. From this data, we construct a stack $X \times_{\Lambda} E\Lambda$, called the *homotopy orbits* of the action of Λ on X , as follows.²

Recall that an Λ -torsor is a scheme $P \rightarrow S$ with a right action of Λ so that there is an *fpqc* cover $T \rightarrow S$ and an isomorphism of Λ -schemes over T

$$T \times_S \Lambda \cong T \times_S P.$$

If you want a choice-free way of stating this last, we remark that this is equivalent to requiring that the natural map

$$(T \times_S P) \times_T (T \times_S \Lambda) \longrightarrow (T \times_S P) \times_T (T \times_S \Lambda)$$

over $(T \times_S \Lambda)$ sending (x, g) to (xg, g) is an isomorphism.

To define $X \times_{\Lambda} E\Lambda$ we need to specify a category fibered in groupoids. Suppose $U \rightarrow S$ is a scheme over S . Define the objects $[X \times_{\Lambda} E\Lambda](U)$ to be pairs (P, α) where $P \rightarrow U$ is a $\Lambda \times_S U$ -torsor and

$$\alpha : P \rightarrow U \times_S X$$

is a Λ -morphism over U . A morphism $(P, \alpha) \rightarrow (Q, \beta)$ is an equivariant isomorphism $P \rightarrow Q$ so that the evident diagram over $U \times_S X$ commutes. If $V \rightarrow U$ is a morphism of schemes over S , then the map $[X \times_{\Lambda} E\Lambda](U) \rightarrow [X \times_{\Lambda} E\Lambda](V)$ is defined by pull-back. This gives a stack (see [33], 3.4.2) ; we discuss to what extent it is an algebraic stack.

There is a natural map $X \rightarrow X \times_{\Lambda} E\Lambda$ defined as follows. If $f : U \rightarrow X$ is a morphism of schemes over S define $P = U \times_S \Lambda$ and let α be the evident composition over U

$$U \times_S \Lambda \xrightarrow{f \times \Lambda} U \times_S X \times_S \Lambda \longrightarrow U \times_S X$$

given pointwise by $(u, g) \mapsto (u, f(u)g)$.

Note that if $U \rightarrow X \times_{\Lambda} E\Lambda$ classifies $P \rightarrow U \times_S X$, then a factoring

$$\begin{array}{ccc} & & X \\ & \nearrow & \downarrow \\ U & \longrightarrow & X \times_{\Lambda} E\Lambda \end{array}$$

is equivalent to a choice of section of $P \rightarrow U$ and hence a chosen equivariant isomorphism $U \times_S \Lambda \rightarrow P$ over U . The notion of an algebraic stack in the *fpqc* topology was defined in Definition 2.29.

3.1 Proposition. *Let Λ be a group scheme over S and suppose the structure morphism $\Lambda \rightarrow S$ is flat and quasi-compact. Let X be a scheme over S with a right Λ -action. Then $X \times_{\Lambda} E\Lambda$ is an algebraic stack in the *fpqc* topology and*

$$q : X \longrightarrow X \times_{\Lambda} E\Lambda$$

²Under appropriate finiteness hypotheses which will not apply in our examples, the homotopy orbit stack can become an algebraic *orbifold*.

is an fpqc presentation. There is a natural commutative diagram

$$\begin{array}{ccc}
X \times_S \Lambda & \begin{array}{c} \xrightarrow{d_0} \\ \xrightarrow{d_1} \end{array} & X \\
\cong \downarrow & & \downarrow = \\
X \times_{X \times_{\Lambda} E\Lambda} X & \begin{array}{c} \xrightarrow{p_1} \\ \xrightarrow{p_2} \end{array} & X
\end{array}$$

where $d_0(x, g) = x$ and $d_1(x, g) = xg$ and the vertical isomorphism sends (x, g) to the triple $(x, xg, g : xg \rightarrow x)$.

3.2 Example. There are two evident examples. First we can take $X = S$ itself with the necessarily trivial right action, and we'll write

$$B\Lambda \stackrel{\text{def}}{=} S \times_{\Lambda} E\Lambda.$$

This is the moduli stack of Λ -torsors on S -schemes or the *classifying stack* of Λ . The other example sets $X = \Lambda$ with the canonical right action. Let's assume Λ is an affine group scheme over S . Then the projection map

$$\Lambda \times_{\Lambda} E\Lambda \rightarrow S$$

is an equivalence. For if $\alpha : P \rightarrow U \times_S \Lambda$ is any morphism of Λ -torsors over U , then α becomes an isomorphism on some faithfully flat cover. Since $\Lambda \rightarrow S$ is affine, α is then an isomorphism by faithfully flat descent. It follows that the groupoid $[\Lambda \times_{\Lambda} E\Lambda](U)$ is contractible.

3.3 Remark. Note that the Čech cover of $X \times_{\Lambda} E\Lambda$ that arises from the cover $X \rightarrow X \times_{\Lambda} E\Lambda$ is the standard bar complex given by the action of Λ on X . Thus, $X \times_{\Lambda} E\Lambda$ is that analog of the geometric realization of this bar complex, whence the name homotopy orbits.

3.4 Remark. Suppose that $S = \text{Spec}(R)$, $X = \text{Spec}(A)$ and $\Lambda = \text{Spec}(\Gamma)$. Then the group action $X \times_S \Lambda \rightarrow X$ yields a Hopf algebroid structure on the pair $(A, A \otimes_R \Gamma)$. This is a *split* Hopf algebroid. By Remark 2.39 the category of quasi-coherent sheaves over $X \times_{\Lambda} E\Lambda$ is equivalent to the category of $(A, A \otimes_R \Gamma)$ -comodules.

3.5 Remark. Let's compare this construction of $X \times_{\Lambda} E\Lambda$ with a construction in simplicial sets. Suppose Λ is a discrete group (in sets) and X is a discrete right Λ -set. Then the simplicial set $X \times_{\Lambda} E\Lambda$ is defined to be the nerve of the groupoid with object set X and morphism set $X \times G$. However, this groupoid is equivalent to the groupoid with objects $\alpha : P \rightarrow X$ where P is a free and transitive G -set; morphisms are the evident commutative triangles. This is a direct translation of the construction above. Equivalent groupoids have weakly equivalent nerves; hence, if we are only interested in homotopy type, we could define $X \times_{\Lambda} E\Lambda$ to be the nerve of the larger groupoid.

Next let us say some words about naturality. This is simpler if we make some assumptions on our group schemes. A group scheme Λ over S is *affine over S* if the structure map $q : \Lambda \rightarrow S$ is an affine morphism. Since affine morphisms are closed under composition and base change, the multiplication map $\Lambda \times_S \Lambda \rightarrow \Lambda$ is a morphism of schemes affine over S . Thus the quasi-coherent \mathcal{O}_S -algebra sheaf $q_* \mathcal{O}_\Lambda$ is a sheaf of Hopf algebras. In most of our examples, $S = \text{Spec}(A)$ is itself affine; in this case, $\Lambda = \text{Spec}(\Gamma)$ for some Hopf algebra Γ over A .

If Λ is a group scheme affine over S and $P \rightarrow S$ is a Λ -torsor, then $P \rightarrow S$ is an affine morphism by faithfully flat descent. If $\phi : \Lambda_1 \rightarrow \Lambda_2$ is a morphism of group schemes affine over S and $P \rightarrow S$ a Λ_1 torsor, let $P \times_{\Lambda_1} \Lambda_2$ be the sheaf associated to the presheaf

$$A \mapsto (P(A) \times_{S(A)} \Lambda_2(A)) / \sim$$

where \sim is the equivalence relation given pointwise by

$$(xb, a) \sim (x, ba)$$

with $x \in P(A)$, $a \in \Lambda_2(A)$, and $b \in \Lambda_1(A)$.

3.6 Lemma. *Let $\Lambda_1 \rightarrow \Lambda_2$ be a morphism of groups schemes affine over S and let $P \rightarrow S$ be a Λ_1 -torsor. Then $P \times_{\Lambda_1} \Lambda_2$ is actually a Λ_2 -torsor over S .*

Proof. If we can choose an isomorphism $P \cong \Lambda_1$ over S , then we get an induced isomorphism $P \times_{\Lambda_1} \Lambda_2 \cong \Lambda_2$. More generally, let $f : T \rightarrow S$ be an *fpqc*-cover so that

$$T \times_S P \cong T \times_S \Lambda_1.$$

Then

$$T \times_S (P \times_{\Lambda_1} \Lambda_2) \cong (T \times_S P) \times_{T \times_S \Lambda_1} (T \times_S \Lambda_2) \cong T \times_S \Lambda_2.$$

Since Λ_2 is affine over S , $T \times_S \Lambda_2$ is affine over T and faithfully flat descent implies $P \times_{\Lambda_1} \Lambda_2$ is an affine torsor over S . \square

Now suppose X_1 is a right Λ_1 -scheme, X_2 is a right Λ_2 -scheme and $q : X_1 \rightarrow X_2$ is a morphism of Λ_1 -schemes. Then we get a morphism of stacks

$$X_1 \times_{\Lambda_1} E\Lambda_1 \rightarrow X_2 \times_{\Lambda_2} E\Lambda_2$$

sending the pair (P, α) to the pair $(P \times_{\Lambda_1} \Lambda_2, q\alpha)$; that is, there is a commutative diagram of Λ_1 -schemes

$$\begin{array}{ccc} P & \xrightarrow{\alpha} & X_1 \\ \downarrow & & \downarrow q \\ P \times_{\Lambda_1} \Lambda_2 & \longrightarrow & X_2. \end{array}$$

Such morphisms have quite nice properties. Recall that a morphism of groupoids $f : G \rightarrow H$ is a fibration if for all $x \in H$, all $y \in G$ and all morphisms $\phi : x \rightarrow f(y)$ in H , there is a morphism $\psi : x' \rightarrow y$ in G with $f\psi = \phi$.

Equivalently the morphism of nerves $BG \rightarrow BH$ is a Kan fibration of simplicial sets. We will say that a morphism of stacks $\mathcal{M} \rightarrow \mathcal{N}$ is a fibration if for all commutative rings R , the map $\mathcal{M}(R) \rightarrow \mathcal{N}(R)$ is a fibration of groupoids.³

A topological version of the following result can be found in Remark 3.9 below.

3.7 Proposition. *Suppose $f : \Lambda_1 \rightarrow \Lambda_2$ is a morphism of group schemes affine over S , X_1 is a Λ_1 -scheme, X_2 is a Λ_2 -scheme, and $q : X_1 \rightarrow X_2$ is a morphism of Λ_1 -schemes. Then*

$$X_1 \times_{\Lambda_1} E\Lambda_1 \longrightarrow X_2 \times_{\Lambda_2} E\Lambda_2$$

is a fibration of algebraic stacks in the fpqc topology.

Proof. Suppose we are given a diagram (over a base-scheme U suppressed from the notation)

$$\begin{array}{ccc} P & \xrightarrow{\alpha} & X \\ \downarrow & & \downarrow q \\ Q' & \xrightarrow{\phi} & Q \xrightarrow{\beta} Y \end{array}$$

with (1) P a Λ_1 -torsor and α a Λ_1 -morphism; (2) Q' and Q both Λ_2 -torsors, β Λ_2 -map and ϕ is Λ_2 -isomorphism; and (3) $P \rightarrow Q$ a morphism of Λ_1 -schemes with $P \times_{\Lambda_1} \Lambda_2 \cong Q$. Then we take the pull-back

$$\begin{array}{ccc} Q' \times_Q P & \xrightarrow{\psi} & P \\ \downarrow & & \downarrow \\ Q' & \xrightarrow{\phi} & Q. \end{array}$$

Then $Q' \times_Q P$ is a Λ_1 -torsor and ψ is a Λ_1 -isomorphism. Finally, we must check that the natural map $(Q' \times_Q P) \times_{\Lambda_1} \Lambda_2 \rightarrow Q'$ is an isomorphism of Λ_2 -torsors. If we can choose isomorphisms $P \cong \Lambda_1$ and $Q \cong \Lambda_2$ this is clear. The general case follows from faithfully flat descent. \square

It is also relatively easy to identify fibers in this setting. We restrict ourselves to a special case.

3.8 Proposition. *Suppose $f : \Lambda_1 \rightarrow \Lambda_2$ is flat surjective morphism of group schemes affine over S with kernel K . Suppose that X_1 is a Λ_1 -scheme, X_2 is a Λ_2 -scheme, and $q : X_1 \rightarrow X_2$ is a morphism of Λ_1 -schemes. Then there is a homotopy pull-back diagram*

$$\begin{array}{ccc} X_1 \times_K EK & \longrightarrow & X_1 \times_{\Lambda_1} E\Lambda_1 \\ \downarrow & & \downarrow \\ X_2 & \longrightarrow & X_2 \times_{\Lambda_2} E\Lambda_2. \end{array}$$

³This begs for a much more extensive and sophisticated discussion. See [27] and [14].

Proof. Let $f : U \rightarrow X_2$ be a morphism of schemes. Then the composition $U \rightarrow X_2 \times_{\Lambda_2} E\Lambda_2$ classifies the pair $(U \times_S \Lambda_2, \alpha)$ where α is the composition

$$U \times_S \Lambda_2 \xrightarrow{f \times \Lambda_2} U \times_S X_2 \times_S \Lambda_2 \longrightarrow U \times_S X_2.$$

The homotopy fiber at U is the groupoid with objects the commutative diagrams

$$\begin{array}{ccc} P & \xrightarrow{\beta} & U \times_S X_1 \\ \downarrow g & & \downarrow \\ U \times_S \Lambda_2 & \xrightarrow{\alpha} & U \times_S X_2 \end{array}$$

where (P, β) is an object in $[X_1 \times_{\Lambda_1} E\Lambda_1](U)$ and g is a Λ_1 morphism so that the induced map $P \times_{\Lambda_1} \Lambda_2 \rightarrow U \times_S \Lambda_2$ is an isomorphism. Let P' be the pull-back of g at inclusions induced by the identity $U \rightarrow U \times_S \Lambda_2$. Then $P' \rightarrow U \times_S X_2$ is an equivariant morphism from a K -torsor to X_2 . This defines the functor from the pull-back to $X_1 \times_K EK$.

Conversely, given a K -torsor P over U and a K -morphism $P \rightarrow X_1$ we can produce a diagram

$$\begin{array}{ccc} P \times_{U \times_S K} (U \times_S \Lambda_1) & \longrightarrow & U \times_S X_1 \\ \downarrow g & & \downarrow \\ P \times_{U \times_S K} (U \times_S \Lambda_2) & \longrightarrow & U \times_S X_2. \end{array}$$

Since K is the kernel of $\Lambda_1 \rightarrow \Lambda_2$, projection gives a natural morphism of Λ_2 -torsors over U

$$P \times_{U \times_S K} (U \times_S \Lambda_2) \rightarrow U \times_S \Lambda_2$$

of Λ_2 torsors over U . This defines the functor back and gives the equivalence of categories. \square

3.9 Remark. In the topological setting of Remark 3.5 we gave two ways to construct $X \times_{\Lambda} E\Lambda$. With the smaller, and more usual construction, a morphism

$$X_1 \times_{\Lambda_1} E\Lambda_1 \longrightarrow X_2 \times_{\Lambda_2} E\Lambda_2$$

is a fibration only if $\Lambda_1 \rightarrow \Lambda_2$ is onto. However, in the larger construction using transitive and free Λ -sets, this morphism is always a fibration, by the same argument as that given for Proposition 3.7. Either model allows us to prove the analog of Proposition 3.8.

As a final generality we have:

3.10 Proposition. *Suppose $f : \Lambda_1 \rightarrow \Lambda_2$ is flat surjective morphism of group schemes affine over S and let K be the kernel. Suppose that X_1 is a Λ_1 -scheme,*

X_2 is a Λ_2 -scheme, and $q : X_1 \rightarrow X_2$ is a morphism of Λ_1 -schemes. If $X_1 \rightarrow X_2$ is a K -torsor over X_2 , then

$$X_1 \times_{\Lambda_1} E\Lambda_1 \longrightarrow X_2 \times_{\Lambda_2} E\Lambda_2$$

is an equivalence of algebraic stacks.

Proof. The hypothesis of $X_1 \rightarrow X_2$ means that when the action is restricted to K , then X_1 is (after pulling back to an *fqc*-cover of X_1) isomorphic to $X_2 \times_S K$. The result follows immediately from Propositions 3.7 and 3.8, but can also be proved directly. For if $\alpha : P \rightarrow U \times_S X_2$ is some Λ_2 -equivariant morphism from a Λ_2 -torsor over U , then we can form the pull back square

$$\begin{array}{ccc} Q & \xrightarrow{\beta} & U \times_S X_1 \\ \downarrow & & \downarrow \\ P & \xrightarrow{\alpha} & U \times_S X_2 \end{array}$$

and $\beta : Q \rightarrow U \times_S X_1$ is a Λ_1 -equivariant morphism from a Λ_1 -torsor over U . This defines the necessary equivalence of categories. \square

3.2 Formal groups

We now specialize to the case where $S = \text{Spec}(\mathbb{Z})$, $\Lambda = \text{Spec}(\mathbb{Z}[a_0^{\pm 1}, a_1, \dots])$ is the group scheme of power series invertible under composition. We set $X = \mathbf{fgl} = \text{Spec}(L)$ where L is the Lazard ring. Thus for a commutative ring R

$$\Lambda(R) = xR[[x]]^\times$$

and $X(R) = \mathbf{fgl}(R)$ is the set of formal group laws over R . The group scheme Λ acts on \mathbf{fgl} by the formula

$$(F\phi)(x_1, x_2) = \phi^{-1}(F(\phi(x_1), \phi(x_2))).$$

In Theorem 2.25 we produced, for any formal group G over an affine scheme U , an affine morphism of schemes

$$\text{Coord}_G \longrightarrow S.$$

The following is essentially a combination of Lemma 2.16 and Theorem 2.25.2.

3.11 Lemma. *For a formal group G over a quasi-compact and quasi-separated scheme U , the scheme of coordinates $\text{Coord}_G \rightarrow U$ is a Λ -torsor over U .*

Proof. The formal group G over U may not have a coordinate. However, Lemma 2.16 implies that there is an *fqc*-cover $f : V \rightarrow U$ so that f^*G has a coordinate. Reading the proof of Lemma 2.16 we see that V can be chosen to be affine. Then

$$V \times_U \text{Coord}_G = \text{Coord}_{f^*G}$$

is certainly a free right Λ -scheme over V . See Remark 2.26 for explicit formulas. \square

The following result implies that every Λ -torsor over \mathbf{fgl} arises in this way from a formal group.

3.12 Lemma. *Let S be a quasi-compact and quasi-separated scheme. Let $P \rightarrow S$ be a Λ -torsor and let $P \rightarrow S \times \mathbf{fgl}$ be a morphism Λ -schemes over S . Then there is a formal group $G \rightarrow S$ and an isomorphism $P \rightarrow \text{Coord}_G$ of Λ -torsors over S . This isomorphism is stable under pull-backs in S and natural in P . Furthermore, if $P = \text{Coord}_H$, then there is a natural isomorphism $G \cong H$.*

Proof. We begin with an observation. Let $f : U \rightarrow S$ be any morphism of schemes so that fiber $P(U, f)$ of $P(U) \rightarrow S(U)$ at f is a free $\Lambda(U)$ -set. Then we have a commutative diagram

$$\begin{array}{ccc} P(U, f) & \longrightarrow & \mathbf{fgl}(U) \\ \downarrow & & \downarrow \\ P(U, f)/\Lambda(U) = * & \longrightarrow & \mathbf{fg}(U) \end{array}$$

and the image of the bottom map is a formal group G_f over U . Since the fiber of $\mathbf{fgl}(U) \rightarrow \mathbf{fg}(U)$ at G_f is $\text{Coord}_{G_f}(U)$ we have that G_f has a coordinate and we have an isomorphism of free $\Lambda(U)$ -sets

$$(3.1) \quad P(U, f) \cong \text{Coord}_{G_f}(U).$$

To get a formal group over S we use descent. Choose a faithfully flat and quasi-compact map $q : T \rightarrow S$ so that fiber $P(T, q)$ is a free $\Lambda(T)$ -set. This yields a formal group G_q over T as above. Next examine the commutative diagram

$$\begin{array}{ccc} P(T) & \rightrightarrows & P(T \times_S T) \\ \downarrow & & \downarrow \\ S(T) & \rightrightarrows & S(T \times_S T) \end{array}$$

where the horizontal maps are given by the two projections. Since the two maps

$$T \times_S T \begin{array}{c} \xrightarrow{p_1} \\ \xrightarrow{p_2} \end{array} T \xrightarrow{q} S$$

are equal the projection maps yield morphisms between fibers

$$P(T, q) \begin{array}{c} \xrightarrow{p_1^*} \\ \xrightarrow{p_2^*} \end{array} P(T \times_S T, qp_1)$$

and hence a unique isomorphism $p_1^*G_q \cong p_2^*G_q$. This isomorphism will satisfy the cocycle condition, using uniqueness. Now descent gives the formal group $G \rightarrow S$. Note that if $P = \text{Coord}_H$, then $G_q = q^*H$; therefore, $G \cong H$.

We now define the isomorphism of torsors $P \rightarrow \text{Coord}_G$ over S . Since both P and Coord_G are sheaves in the $fpqc$ topology, it is sufficient to define a natural

isomorphism $P(U, f) \rightarrow \text{Coord}_G(U, f)$ for all $f : U \rightarrow S$ so that both $P(U, f)$ and $\text{Coord}_G(U, f)$ are free $\Lambda(U)$ -sets. This isomorphism is defined by Equation 3.1 using the observation that

$$\text{Coord}_{f^*G}(U) = \text{Coord}_G(U, f).$$

□

3.13 Proposition. *This morphism*

$$\mathcal{M}_{\mathbf{fg}} \longrightarrow \mathbf{fgl} \times_{\Lambda} E\Lambda$$

is an equivalence of algebraic stacks.

Proof. Lemma 3.12 at once supplies the map $\mathbf{fgl} \times_{\Lambda} E\Lambda \rightarrow \mathcal{M}_{\mathbf{fg}}$ and the needed natural transformations from either of the two composites to the identity. □

3.14 Remark (More on gradings). In Remarks 2.39 and 3.4 we noted that the category of quasi-coherent sheaves on $\mathcal{M}_{\mathbf{fg}}$ is equivalent to the category of (L, W) -comodules. In Remark 2.47 we noted that (L, W) has a natural grading. We'd now like to put the gradings into the comodules and recover the E_2 -term of the Adams Novikov Spectral Sequence as the cohomology of the moduli stack $\mathcal{M}_{\mathbf{fg}}$.

Let Λ_0 be a group scheme with a right action by another group scheme H . Then we can form the semi-direct product $\Lambda_0 \rtimes H = \Lambda$. To specify a right action of Λ on a scheme X is to specify actions of Λ_0 and H on X so that for all rings A and all $x \in X(A)$, $g \in \Lambda_0(A)$, and $u \in H(A)$, we have

$$x(gu) = (xu)(gu).$$

We then get a morphism of algebraic stacks

$$(3.2) \quad X//\Lambda_0 \stackrel{\text{def}}{=} X \times_{\Lambda_0} E\Lambda_0 \longrightarrow X \times_{\Lambda} E\Lambda \stackrel{\text{def}}{=} X//\Lambda$$

If H and Λ_0 are both flat over the base ring R , then this is a representable and flat morphism. We now want to identify the fiber product $X//\Lambda_0 \times_{X//\Lambda} X//\Lambda_0$.

Let A be a commutative ring and P_0 a Λ_0 -torsor over A . If $u \in H(A)$ is an A -point of H , then we get a new A -torsor P^u with underlying scheme P but a new action defined pointwise by

$$x * g = x(gu).$$

Here we have used $*$ for the new action and juxtaposition for the old. If $\alpha : P \rightarrow A \otimes X$ is a morphism of Λ_0 -schemes then we get a new morphism $\alpha^u : P^u \rightarrow X$ given pointwise by

$$\alpha^u(x) = \alpha(x)u^{-1}.$$

Conjugation by u in Λ defines an isomorphism $\phi_u : P \times_{\Lambda_0} \Lambda \rightarrow P^u \times_{\Lambda_0} \Lambda$ of Λ -torsors over A so that the following diagram commutes

$$\begin{array}{ccc} P \times_{\Lambda_0} \Lambda & & \\ \downarrow \phi_u & \searrow \alpha & \\ P^u \times_{\Lambda_0} \Lambda & \nearrow \alpha^u & A \otimes X. \end{array}$$

Thus we have defined a morphism

$$X//\Lambda_0 \times H \rightarrow X//\Lambda_0 \times_{X//\Lambda} X//\Lambda_0$$

given pointwise by

$$((P, \alpha), u) \mapsto ((P, \alpha), (P^u, \alpha^u), \phi_u)$$

and we leave it to the reader to show that this is an equivalence.

From this equivalence we can conclude that the category of quasi-coherent sheaves on $X \times_{\Lambda} E\Lambda$ is equivalent to the category of cartesian quasi-coherent sheaves on the Čech nerve induced by the morphism of Equation 3.2:

$$(3.3) \quad \cdots X//\Lambda_0 \times H \times H \begin{array}{c} \xrightarrow{\quad} \\ \xleftarrow{\quad} \\ \xrightarrow{\quad} \\ \xleftarrow{\quad} \end{array} X//\Lambda_0 \times H \begin{array}{c} \xrightarrow{\quad} \\ \xleftarrow{\quad} \\ \xrightarrow{\quad} \\ \xleftarrow{\quad} \end{array} X//\Lambda_0 \longrightarrow X//\Lambda.$$

This translates into comodules as follows. Suppose that $\Lambda_0 = \text{Spec}(\Gamma_0)$ and $H = \text{Spec}(K)$ for Hopf algebras Γ_0 and K respectively. Then $\Lambda = \text{Spec}(\Gamma)$ where $\Gamma = \Gamma_0 \otimes K$ with the twisted Hopf algebra structure determined by the action of H on Λ_0 . Suppose $X = \text{Spec}(A)$. If M is an $(A, A \otimes K)$ -comodule, then $M \otimes_{\Lambda_0}$ has an induced structure as an $(A, A \otimes K)$ -comodule using the diagonal coaction. We define the category of $(A, A \otimes K)$ -comodules in $(A, A \otimes \Lambda_0)$ -comodules to be those comodules so that the comodule structure map

$$M \longrightarrow M \otimes_A (A \otimes \Lambda_0)$$

is a morphism of $(A, A \otimes K)$ -comodules. We have

1. the category of quasi-coherent sheaves on $X \times_{\Lambda} E\Lambda$ is equivalent to the category of $(A, A \otimes \Gamma)$ -comodules; and
2. the category of cartesian sheaves on the Čech nerve of $X//\Lambda_0 \rightarrow X//\Lambda$ is equivalent to the category of $(A, A \otimes K)$ comodules in the category $(A, A \otimes \Lambda_0)$ -comodules.

From this we conclude that the category of $(A, A \otimes \Gamma)$ -comodules is equivalent to the category of $(A, A \otimes K)$ -comodules in $(A, A \otimes \Lambda_0)$ -comodules.

As example, suppose $H = \mathbb{G}_m$. Then the action of \mathbb{G}_m on G_0 and X gives a grading to Λ_0 and A and the category of $(A, A \otimes K)$ comodules in the category of $(A, A \otimes K)$ -comodules in $(A, A \otimes \Lambda_0)$ -comodules is equivalent to the

category of *graded* $(A, A \otimes \Lambda_0)$ -comodules. Thus we conclude that the category $(A, A \otimes \Lambda_0[a_0^{\pm 1}])$ comodules is equivalent to the category of graded $(A, A \otimes \Lambda_0)$ -comodules. In this case it is possible to give completely explicit formulas for the equivalence. For example, if M is an $(A, A \otimes \Lambda_0[a_0^{\pm 1}])$ comodule, the comodule structure map induces a homomorphism

$$M \longrightarrow M \otimes_A (A \otimes \Lambda_0[a_0^{\pm 1}]) \xrightarrow{\cong} M \otimes \Lambda \otimes \mathbb{Z}[a_0^{\pm 1}] \xrightarrow{1 \otimes \epsilon \otimes 1} M \otimes \mathbb{Z}[a_0^{\pm 1}]$$

which defines the grading and the map

$$M \longrightarrow M \otimes_A (A \otimes \Lambda_0[a_0^{\pm 1}]) \xrightarrow{a_0=1} M \otimes_A (A \otimes \Lambda_0)$$

induces the comodule structure.

This equivalence of categories can be used to refine the isomorphism of Equation 2.8. If \mathcal{F} is a quasi-coherent sheaf of $X \times_{\Lambda} E\Lambda$, let M be the associated comodule. Then we have natural isomorphisms – where we have added asterisks (*) to indicate where we are working with graded comodules.

$$(3.4) \quad \begin{aligned} H^s(X \times_G EG, \mathcal{F}) &\cong \text{Ext}_{\Lambda}(A, M) \\ &\cong \text{Ext}_{\Lambda_0, *}^s(A_*, M_*). \end{aligned}$$

In the case of formal groups, we get the grading on the Lazard ring of this yields the isomorphism of Remark 2.47; write L_* for this graded ring. Then

$$W_{0,*} = L_*[a_1, a_2, a_3, \dots]$$

represents the functor of strict isomorphisms. The complex cobordism ring MU_* is L_* with the grading doubled; likewise, MU_*MU is $W_{0,*}$ with the grading doubled. With all of this done, we can identify sheaf cohomology with E_2 -term on the Adams-Novikov spectral sequence. For example,

$$(3.5) \quad \begin{aligned} H^s(\mathcal{M}_{\mathbf{fg}}, \omega^t) &\cong \text{Ext}_W(L, L[t]) \\ &\cong \text{Ext}_{MU_*MU}^s(MU_*, \Omega^{2t} MU_*) \\ &\cong \text{Ext}_{MU_*MU}^s(\Sigma^{2t} MU_*, MU_*) \end{aligned}$$

The extra factor of 2 arises as part of the topological grading.

3.3 Buds of formal groups

One of the difficulties with the moduli stack $\mathcal{M}_{\mathbf{fg}}$ of formal groups is that it does not have good finiteness properties. We have written $\mathcal{M}_{\mathbf{fg}}$ as $\mathbf{fgl} \times_{\Lambda} E\Lambda$ and neither the group Λ or the scheme \mathbf{fgl} is of finite type over \mathbb{Z} . However, we can write $\mathcal{M}_{\mathbf{fg}}$ as the homotopy inverse limit of stacks $\mathcal{M}_{\mathbf{fg}}\langle n \rangle$ which has an affine smooth cover of dimension n .

Let $n \geq 1$ and $\Lambda\langle n \rangle$ be the affine group scheme over $\text{Spec}(\mathbb{Z})$ which assigns to each commutative ring R , the partial power series of degree n

$$f(x) = a_0x + a_1x^2 + \dots + a_{n-1}x^n \in R[[x]]/(x^{n+1})$$

with a_0 a unit. This becomes a group under composition of power series. Of course,

$$\Lambda\langle n \rangle = \text{Spec}(\mathbb{Z}[a_0^{\pm 1}, a_1, \dots, a_{n-1}]).$$

Similarly, let $\mathbf{fgl}\langle n \rangle$ be the affine scheme of n -buds of formal group laws

$$F(x, y) \in R[[x, y]]/(x, y)^{n+1}.$$

Thus we are requiring that $F(x, 0) = x = F(0, x)$, $F(x, y) = F(y, x)$, and

$$F(x, F(y, z)) = F(F(x, y), z)$$

all modulo $(x, y)^{n+1}$. The symmetric 2-cocycle lemma [48] A.2.12 now implies that

$$\mathbf{fgl}\langle n \rangle = \text{Spec}(\mathbb{Z}[x_1, x_2, \dots, x_{n-1}]) \stackrel{\text{def}}{=} \text{Spec}(L\langle n \rangle)$$

and modulo $(x_1, \dots, x_n)^2$, the universal n -bud reads

$$F_u(x, y) = x + y + x_1 C_2(x, y) + \dots + x_{n-1} C_n(x, y)$$

where $C_k(x, y)$ is the k th symmetric 2-cocycle. The group $\Lambda\langle n \rangle$ acts on $\mathbf{fgl}\langle n \rangle$.

3.15 Definition. *The moduli stack of n -buds of formal groups is the homotopy orbit stack*

$$\mathcal{M}_{\mathbf{fg}}\langle n \rangle = \mathbf{fgl}\langle n \rangle \times_{\Lambda\langle n \rangle} E\Lambda\langle n \rangle.$$

3.16 Remark. 1.) **Warning:** The stacks $\mathcal{M}_{\mathbf{fg}}\langle n \rangle$ are not related to the spectra $BP\langle n \rangle$ which appear in chromatic stable homotopy – see [48] – but I was running out of notation. I apologize for the confusion. The objects $BP\langle n \rangle$ will not appear in these notes, although the cognoscenti should contemplate Lemma 3.24 below.

2.) Using Remarks 2.47 and 3.14 we see that the category of quasi-coherent sheaves is equivalent to the category of graded comodules over the graded Hopf algebroid $(L\langle n \rangle_*, W\langle n \rangle_{0,*})$ where $L\langle n \rangle_*$ is the ring $L\langle n \rangle$ with the degree of x_i equal to i and

$$W\langle n \rangle_{0,*} = L\langle n \rangle_*[a_1, a_2, \dots, a_{n-1}]$$

with the degree of a_i equal to i . This will be important later in the proof of Theorem 3.28. Note that $W\langle n \rangle_{0,*}$ represents the functor of strict isomorphisms of buds.

There are canonical maps

$$\mathcal{M}_{\mathbf{fg}} \longrightarrow \mathcal{M}_{\mathbf{fg}}\langle n \rangle \longrightarrow \mathcal{M}_{\mathbf{fg}}\langle n-1 \rangle.$$

3.17 Example. To make your confusion specific⁴, note that

$$\mathcal{M}_{\mathbf{fg}}\langle 1 \rangle = B\mathbb{G}_m = \text{Spec}(\mathbb{Z}) \times_{\mathbb{G}_m} E\mathbb{G}_m.$$

⁴This is a quote from Steve Wilson. See [56].

This is because $\Lambda_1(R) = R^\times = \mathbb{G}_m(R)$ is the group of units in R and, modulo $(x, y)^2$, the unique bud of a formal group law is $x + y$. We also have

$$\mathcal{M}_{\mathbf{fg}}\langle 2 \rangle = \mathbb{A}^1 \times_{\Lambda_2} E\Lambda_2$$

where Λ_2 acts on \mathbb{A}^1 by

$$(b, a_0x + a_1x^2) \mapsto a_0b - 2(a_1/a_0).$$

Note that, modulo $(x, y)^3$, any bud of a formal group law is of the form $x + y + bxy$.

The following implies that $\mathcal{M}_{\mathbf{fg}}\langle n \rangle$ is an algebraic stack in the sense of [33] Définition 4.1. See also [33], Exemple 4.6.

3.18 Proposition. *The morphism*

$$\mathrm{Spec}(L\langle n \rangle) \rightarrow \mathcal{M}_{\mathbf{fg}}\langle n \rangle$$

classifying the universal n -bud of a formal group law is a presentation and smooth of relative dimension n .

Proof. That the morphism is a presentation follows from Proposition 3.1. To see that it is smooth of relative dimension n , we must check that for all morphisms $\mathrm{Spec}(R) \rightarrow \mathcal{M}_{\mathbf{fg}}\langle n \rangle$ the resulting pull-back

$$\mathrm{Spec}(R) \times_{\mathcal{M}_{\mathbf{fg}}\langle n \rangle} \mathrm{Spec}(L\langle n \rangle) \rightarrow \mathrm{Spec}(R)$$

is smooth of relative dimension n . Since smoothness is local for the *fpqc* topology, we may assume that $\mathrm{Spec}(R) \rightarrow \mathcal{M}_{\mathbf{fg}}\langle n \rangle$ classifies a bud of formal group law. Then

$$\mathrm{Spec}(R) \times_{\mathcal{M}_{\mathbf{fg}}\langle n \rangle} \mathrm{Spec}(L\langle n \rangle) \cong \mathrm{Spec}(R[a_0^{\pm 1}, a_1, \dots, a_{n-1}]) = \mathrm{Spec}(R) \times \Lambda_n$$

and this suffices. \square

Recall that that n th symmetric 2-cocycle is

$$C_n(x, y) = \frac{1}{d_n}[(x + y)^n - x^n - y^n].$$

where

$$d_n = \begin{cases} p, & n = p^k \text{ for a prime } p; \\ 1, & \text{otherwise.} \end{cases}$$

Let \mathbb{G}_a be the additive group scheme and let $\mathbb{A}^1\langle n \rangle$ be the \mathbb{G}_a scheme with action $\mathbb{A}^1\langle n \rangle \times \mathbb{G}_a \rightarrow \mathbb{A}^1\langle n \rangle$ given by

$$(x, a) \mapsto x - d_n a.$$

3.19 Lemma. *The morphism $\Lambda\langle n \rangle \rightarrow \Lambda\langle n-1 \rangle$ of affine group schemes is flat and surjective with kernel \mathbb{G}_a . Furthermore there is an equivariant isomorphism of \mathbb{G}_a schemes over $\mathbf{fgl}\langle n-1 \rangle$*

$$\mathbf{fgl}\langle n \rangle \cong \mathbf{fgl}\langle n-1 \rangle \times \mathbb{A}^1\langle n \rangle.$$

Proof. The kernel of $\Lambda\langle n \rangle(R) \rightarrow \Lambda\langle n-1 \rangle(R)$ is all power series of the form $\phi_a(x) = x + ax^n$ modulo (x^{n+1}) . Since $\phi_a(\phi_{a'}(x)) = \phi_{(a+a')}(x)$ modulo (x^{n+1}) , the first statement follows. For the splitting of $\mathbf{fgl}\langle n \rangle$ note that if $\phi_a(x)$ is an isomorphism of buds of formal group laws $F \rightarrow F'$, then

$$\begin{aligned} F'(x, y) &= F(x, y) + a[x^n - y^n - (x+y)^n] \\ &= F(x, y) - d_n a C(x, y). \end{aligned}$$

Thus the coaction morphism on coordinate rings

$$\mathbb{Z}[x_1, \dots, x_n] \longrightarrow \mathbb{Z}[x_1, \dots, x_n] \otimes \mathbb{Z}[a]$$

sends x_i to x_i is $i \neq n$ and x_n to

$$x_n \otimes 1 - 1 \otimes d_n a.$$

This gives the splitting. □

3.20 Remark. In Theorem 3.22, I am going to take a 2-category limit of a tower of algebraic stacks. These limits can be defined inside the theory, but they can also be defined using homotopy theory; therefore, I'm going to call it a homotopy inverse limit. The category of categories fibered in groupoids over affine schemes is a model category, by [14] and I'll define the 2-category limit of a diagram of stacks to be the homotopy inverse limit in that category. If we have a 2-sink

$$\mathcal{N}_1 \longrightarrow \mathcal{M} \longleftarrow \mathcal{N}_2$$

of stacks, then the usual 2-category pull-back will be equivalent to the homotopy pull-back simply because it is exactly the usual homotopy pull-back. As another example, note that if we have a tower of stacks

$$\cdots \rightarrow \mathcal{M}_n \rightarrow \mathcal{M}_{n-1} \rightarrow \cdots \rightarrow \mathcal{M}_2 \rightarrow \mathcal{M}_1$$

then the homotopy inverse limit will be equal to the actual inverse limit if each of the maps is a locally a fibration of groupoids.

3.21 Proposition. *For all $n \geq 1$ the reduction map*

$$\mathcal{M}_{\mathbf{fg}}\langle n \rangle \longrightarrow \mathcal{M}_{\mathbf{fg}}\langle n-1 \rangle$$

is a fibration. If R is any commutative ring in which d_n is a unit, then

$$\mathcal{M}_{\mathbf{fg}}\langle n \rangle \otimes R \longrightarrow \mathcal{M}_{\mathbf{fg}}\langle n-1 \rangle \otimes R$$

is an equivalence of algebraic stacks.

Proof. This follows immediately from Example 3.2, Propositions 3.7 and 3.10, Lemma 3.19, and the following fact: if d_n is a unit in A , then $\mathbb{A}^1\langle n \rangle$ is isomorphic to \mathbb{G}_a as a right \mathbb{G}_a -scheme. \square

3.22 Theorem. *The natural map*

$$\mathcal{M}_{\mathbf{fg}} \longrightarrow \operatorname{holim} \mathcal{M}_{\mathbf{fg}}\langle n \rangle$$

is an equivalence of stacks.

Proof. We must prove that for all rings R the natural morphism of groupoids

$$\mathcal{M}_{\mathbf{fg}}(R) \longrightarrow \operatorname{holim} \mathcal{M}_{\mathbf{fg}}\langle n \rangle(R)$$

is an equivalence. By Proposition 3.21 we have that the projection map

$$\mathcal{M}_{\mathbf{fg}}\langle n \rangle(R) \longrightarrow \mathcal{M}_{\mathbf{fg}}\langle n-1 \rangle(R)$$

is a fibration of groupoids for all n . Thus we need only show $\mathcal{M}_{\mathbf{fg}}(R) \cong \lim \mathcal{M}_{\mathbf{fg}}\langle n \rangle(R)$, but this is obvious. \square

The next result is an incredibly complicated way to prove that every formal group over an algebra over the rationals is isomorphic to the additive formal group. It proves more, however, as it also identifies the automorphisms of the additive formal group. For the proof combine Theorem 3.22 and Proposition 3.21.

3.23 Corollary. *The projection map*

$$\mathcal{M}_{\mathbf{fg}} \otimes \mathbb{Q} \longrightarrow \mathcal{M}_{\mathbf{fg}}\langle 1 \rangle \otimes \mathbb{Q} \simeq B(\mathbb{G}_m \otimes \mathbb{Q})$$

is an equivalence.

When working at a prime p , the moduli stacks $\mathcal{M}_{\mathbf{fg}}\langle p^n \rangle \otimes \mathbb{Z}_{(p)}$ form the significant layers in the tower. These should have covers by “ p -typical buds”; the next result makes that thought precise. Recall that the universal p -typical formal group law F is defined over the the ring $V \cong \mathbb{Z}_{(p)}[u_1, u_2, \dots]$. See Corollary 2.46.

3.24 Lemma. *Let $V_n = \mathbb{Z}_{(p)}[u_1, \dots, u_n]$ be the subring of V generated by u_k , $k \leq n$. The p^n -bud F_{p^n} of the universal p -typical formal group law F is defined over V_n and the morphism*

$$F_{p^n} : \operatorname{Spec}(V_n) \rightarrow \mathcal{M}_{\mathbf{fg}}\langle p^n \rangle \otimes \mathbb{Z}_{(p)}$$

classifying this bud is a presentation. Furthermore there is an isomorphism

$$\operatorname{Spec}(V_n) \times_{\mathcal{M}_{\mathbf{fg}}\langle n \rangle} \operatorname{Spec}(V_n) \cong \operatorname{Spec}(V_n[t_0^{\pm 1}, t_1, \dots, t_n]).$$

Proof. We use the gradings of Remark 2.47. The n -bud of a formal group law G is given by the equation

$$G_n(x, y) = \sum_{i+j \leq n} c_{ij} x^i y^j.$$

If F is the universal p -typical formal group law, we see that F_n is defined over the subring of V generated by the u_k with $p^k \leq n$. Similarly if $\phi(x)$ is the universal isomorphism of p -typical formal group laws, then its bud

$$\phi_n(x) = \sum_{i=0}^{n-1} a_i x^{i+1}$$

is defined over the subring of $V[t_0^{\pm 1}, t_1, \dots]$ generated by t_k and u_k with $p^k \leq n$.

To show that we have a presentation, suppose G is a p^n -bud of a formal group over a field \mathbb{F} which is a $\mathbb{Z}_{(p)}$ -algebra. Since \mathbb{F} is a field, we may assume G arises from the bud of formal group law, which we also call G . Choose any formal group law G' whose p^n -bud is G and choose an isomorphism $G' \rightarrow G''$ where G'' is p -typical. Then the p^n -bud of G'' is isomorphic to G and, by the previous paragraph, arises from a morphism $g : V_n \rightarrow \mathbb{F}$. Thus we obtain the requisite 2-commuting diagram

$$\begin{array}{ccc} & & \text{Spec}(V_n) \\ & \nearrow \text{Spec}(g) & \downarrow F_{p^n} \\ \text{Spec}(\mathbb{F}) & \xrightarrow[G]{} & \mathcal{M}_{\mathbf{fg}}\langle p^n \rangle \otimes \mathbb{Z}_{(p)}. \end{array}$$

A similar argument computes the homotopy pull-back. \square

3.25 Remark. It is possible to give an intrinsic geometric definition of an n -bud of a formal group in the style of Definition 1.29 and Definition 2.2. First an n -germ of a formal Lie variety X over a scheme S is an affine morphism of schemes $X \rightarrow S$ with a closed section e so that

1. $X = \text{Inf}_S^n(X)$;
2. the quasi-coherent sheaf ω_e is locally free of finite rank on S ;
3. the natural map of graded rings $\text{Sym}_*(\omega_e) \rightarrow \text{gr}_*(X)$ induces an isomorphism

$$\text{Sym}_*(\omega_e)/\mathcal{J}^{n+1} \rightarrow \text{gr}_*(X)$$

where $\mathcal{J} = \bigoplus_{k>0} \text{Sym}_k(\omega_e)$ is the augmentation ideal.

An n -bud of a formal group is then an n -germ $G \rightarrow S$ so that $\omega_e = \omega_G$ is locally free of rank 1 and there is a ‘‘multiplication’’ map

$$\text{Inf}_S^n(G \times_S G) \rightarrow G$$

over S so that the obvious diagrams commute.

3.4 Coherent sheaves over $\mathcal{M}_{\mathbf{fg}}$

We would like to show that any finitely presented sheaf over $\mathcal{M}_{\mathbf{fg}}$ can be obtained by base change from $\mathcal{M}_{\mathbf{fg}}\langle n \rangle$ for some n .

Let m and n be integers $0 \leq n < m \leq \infty$ and let

$$q_{(m,n)} = q : \mathcal{M}_{\mathbf{fg}}\langle m \rangle \rightarrow \mathcal{M}_{\mathbf{fg}}\langle n \rangle$$

be the projection. I'll write q for $q_{(m,n)}$ whenever possible. Also, I'm writing $\mathcal{M}_{\mathbf{fg}}\langle \infty \rangle$ for $\mathcal{M}_{\mathbf{fg}}$ itself.

Write $\mathbf{Qmod}_{\mathbf{fg}}\langle n \rangle$ for the quasi-coherent sheaves on $\mathcal{M}_{\mathbf{fg}}\langle n \rangle$. We begin by discussing the pull-back and push-forward functors

$$q^* : \mathbf{Qmod}_{\mathbf{fg}}\langle n \rangle \rightleftarrows \mathbf{Qmod}_{\mathbf{fg}}\langle m \rangle : q_*$$

By Remark 3.4, the category of quasi-coherent sheaves on $\mathcal{M}_{\mathbf{fg}}\langle n \rangle$ is equivalent to the category of $(L\langle n \rangle, W\langle n \rangle)$ -comodules. In fact, if \mathcal{F} is a quasi-coherent sheaf, the associated comodule M is obtained by evaluating \mathcal{F} at $\mathrm{Spec}(L\langle n \rangle) \rightarrow \mathcal{M}_{\mathbf{fg}}\langle n \rangle$, and the comodule structure is obtained by evaluating \mathcal{F} on the parallel arrows

$$\mathrm{Spec}(W\langle n \rangle) \rightrightarrows \mathrm{Spec}(L\langle n \rangle) \longrightarrow \mathcal{M}_{\mathbf{fg}}\langle n \rangle.$$

We will describe the functors q_* and q^* by giving a description on comodules.

Let $\Gamma\langle n, m \rangle$ be the group scheme which assigns to each commutative ring A the invertible (under composition) power series modulo (x^{m+1})

$$x + a_n x^{n+1} + a_{n+1} x^{n+2} + \cdots + a_{m-1} x^m \quad a_i \in R.$$

Then $\Gamma\langle n, m \rangle = \mathrm{Spec}(\mathbb{Z}[a_n, a_{n+1}, \dots, a_{m-1}])$ and $\Gamma\langle n, m \rangle$ is the kernel of the projection map $\Lambda\langle m \rangle \rightarrow \Lambda\langle n \rangle$.

By Proposition 3.8 there is an equivalence of algebraic stacks

$$\mathrm{Spec}(L\langle n \rangle) \times_{\mathcal{M}_{\mathbf{fg}}\langle m \rangle} \mathcal{M}_{\mathbf{fg}}\langle m \rangle \simeq \mathbf{fgl}\langle m \rangle \times_{\Gamma\langle n, m \rangle} E\Gamma\langle n, m \rangle.$$

Let \mathcal{F} be a quasi-coherent sheaf on $\mathcal{M}_{\mathbf{fg}}\langle m \rangle$. Then the value of $q_*\mathcal{F}$ when evaluated at $\mathrm{Spec}(L\langle n \rangle) \rightarrow \mathcal{M}_{\mathbf{fg}}\langle n \rangle$ is $H^0(\mathrm{Spec}(L\langle n \rangle) \times_{\mathcal{M}_{\mathbf{fg}}\langle n \rangle} \mathcal{M}_{\mathbf{fg}}\langle m \rangle, \mathcal{F})$. If $M = \mathcal{F}(\mathrm{Spec}(L\langle m \rangle))$ is the $(L\langle m \rangle, W\langle m \rangle)$ -comodule equivalent to \mathcal{F} , then these global sections are the $(L\langle n \rangle, W\langle n \rangle)$ -comodule N defined by the equalizer diagram

$$N \longrightarrow M \rightrightarrows \mathbb{Z}[a_n, a_{n+1}, \dots, a_{m-1}] \otimes_{L\langle m \rangle} M$$

where the parallel arrows are given by left inclusion and the coaction map. The assignment $M \mapsto N$ determines $q_*\mathcal{F}$.

To describe q^* , we give the left adjoint to the functor just described on comodules. If N is a $(L\langle n \rangle, W\langle n \rangle)$ -comodule, define a $(L\langle m \rangle, W\langle m \rangle)$ comodule $M = L\langle m \rangle \otimes_{L\langle n \rangle} N$ with coaction map

$$L\langle m \rangle \otimes_{L\langle n \rangle} N \rightarrow W\langle m \rangle \otimes_{L\langle m \rangle} \otimes_{L\langle m \rangle} \otimes_{L\langle n \rangle} N \cong W\langle m \rangle \otimes_{W\langle n \rangle} W\langle n \rangle \otimes_{L\langle n \rangle} N$$

given by

$$\eta_R \otimes \psi : L\langle m \rangle \otimes_{L\langle n \rangle} N \longrightarrow W\langle m \rangle \otimes_{W\langle n \rangle} W\langle n \rangle \otimes_{L\langle n \rangle} N.$$

3.26 Proposition. *For all m and n , $0 \leq n \leq m \leq \infty$, the projection morphism*

$$q : \mathcal{M}_{\mathbf{fg}}\langle m \rangle \longrightarrow \mathcal{M}_{\mathbf{fg}}\langle n \rangle$$

is faithfully flat.

Proof. The morphism q is flat if and only if the functor $\mathcal{F} \mapsto q^*\mathcal{F}$ is exact. However, since the ring homomorphism $L\langle n \rangle \rightarrow L\langle m \rangle$ is flat, the equivalent functor $N \mapsto L\langle m \rangle \otimes_{L\langle n \rangle} N$ on comodules is evidently exact. The morphism q is now faithfully flat because it is surjective. \square

The notions of finitely presented and coherent sheaves on schemes were defined in Remark 1.2.

3.27 Definition. *Let \mathcal{F} be a quasi-coherent sheaf on an fpqc-algebraic stack \mathcal{M} . Then \mathcal{F} is **finitely presented** if there is an fpqc-presentation $q : X \rightarrow \mathcal{M}$ so that $q^*\mathcal{F}$ is finitely presented.*

By examining the definitions, we see that it is equivalent to specify that there is an fpqc-cover $p : Y \rightarrow \mathcal{M}$ and an exact sequence of sheaves

$$\mathcal{O}_Y^{(J)} \rightarrow \mathcal{O}_Y^{(I)} \rightarrow p^*\mathcal{F} \rightarrow 0.$$

with I and J finite. In many of our examples, the cover we have a cover $X \rightarrow \mathcal{M}$ with $X = \text{Spec}(A)$ with A Noetherian or, at worst, coherent. In this case, a finitely presented module sheaf is coherent (see Remark 1.2). Also \mathcal{F} is finitely presented if and only if $\mathcal{F}(\text{Spec}(A) \rightarrow \mathcal{M})$ is a finitely presented A -module.

In the following result, there is experimental evidence to show that \mathcal{F}_0 might actually be $(q_n)_*\mathcal{F}$, but I don't need this fact and couldn't find a quick proof.

3.28 Theorem. *Let \mathcal{F} be a finitely presented quasi-coherent sheaf on $\mathcal{M}_{\mathbf{fg}}$. Then there is an integer n , a quasi-coherent sheaf \mathcal{F}_0 on $\mathcal{M}_{\mathbf{fg}}\langle n \rangle$ and an isomorphism*

$$q_n^*\mathcal{F}_0 \rightarrow \mathcal{F}.$$

is an isomorphism.

Proof. Using Remark 3.14 and Remark 3.16.2, this result is equivalent to the following statement. Let M be a graded comodule over the graded Hopf algebroid $(L_*, L_*[a_1, a_2, \dots])$ which is finitely presented as an L_* -module. Then there is an integer n and a graded comodule over $(L\langle n \rangle_*, L\langle n \rangle_*[a_1, a_2, \dots, a_{n-1}])$ and an isomorphism of graded comodules $L_* \otimes_{L\langle n \rangle_*} M_0 \cong M$. This we now prove.

If N is a graded module, write $\Sigma^s N$ for the graded module with $(\Sigma^s N)_k = N_{k-s}$. Let

$$\bigoplus \Sigma^{t_j} L_* \rightarrow \bigoplus \Sigma^{s_i} L_* \rightarrow M \rightarrow 0$$

be any finite presentation. Choose an integer n greater than or equal to the maximum of the integers $|a - b|$ where

$$a, b \in \{ s_i, t_j \}.$$

Then we can complete the commutative square of $L\langle n \rangle_*$ -modules

$$\begin{array}{ccc} \oplus \Sigma^{t_j} L\langle n \rangle_* & \xrightarrow{f} & \oplus \Sigma^{s_i} L\langle n \rangle_* \\ \downarrow & & \downarrow \\ \oplus \Sigma^{t_j} L_* & \longrightarrow & \oplus \Sigma^{s_i} L \end{array}$$

and, if M_0 is the cokernel of f , a morphism of $L\langle n \rangle_*$ -modules $M_0 \rightarrow M$ so that

$$L_* \otimes_{L\langle n \rangle_*} M_0 \longrightarrow M$$

is an isomorphism. We now need only check that M_0 is a $W\langle n \rangle_{0,*}$ -comodule. But this follows from the same condition on n we used above to produce f . \square

4 Invariant derivations and differentials

4.1 The Lie algebra of a group scheme

We begin with a basic recapitulation of the notion of the Lie algebra of a group scheme G over a scheme S . The tangent scheme and the connection between the tangent scheme and differentials was discussed in §1.3.

4.1 Definition. Let $G \rightarrow S$ be a group scheme over S . Let Lie_G to be the scheme over S obtained by the pull-back diagram

$$\begin{array}{ccc} \text{Lie}_G & \longrightarrow & \mathcal{T}\text{an}_{G/S} \\ \downarrow & & \downarrow \\ S & \xrightarrow{e} & G. \end{array}$$

Let $e : S \rightarrow G$ be the inclusion of the identity, which we will assume is closed. If ω_e is the conormal sheaf of this embedding, then, by Lemma 1.24 we get a natural isomorphism

$$d : \omega_e \longrightarrow e^* \Omega_{G/S}$$

and it follows immediately from Proposition 1.23 that

$$\text{Lie}_G \cong \mathbb{V}(\omega_e).$$

In particular, $\text{Lie}(G) \rightarrow S$ is an affine morphism. See Remark 1.32 for a similar construction.

4.2 Remark. The scheme $\text{Lie}_G \rightarrow S$ has a great deal of structure; we'll emphasize those points which apply most directly here.

1.) Since $\mathcal{T}\text{an}_{G/S}$ is an abelian group scheme over G , Lie_G is an abelian group scheme over S . More than that, it is an \mathbb{A}_S^1 -module; that is, there is a multiplication morphism of schemes

$$\mathbb{A}_S^1 \times_S \text{Lie}_G \longrightarrow \text{Lie}_G$$

making Lie_G into a module over the ring scheme \mathbb{A}_S^1 . This is a coordinate free way of saying that the abelian group $\text{Lie}_G(A)$ is naturally an A -module. To get this A -module structure, let $a \in A$ and define $u_a : A(\epsilon) \rightarrow A(\epsilon)$ to be the A -algebra map determined by $u_a(\epsilon) = a\epsilon$. Then $\text{Lie}_G(u_a)$ determines the multiplication by a in $\text{Lie}_G(A)$.

2.) The zero section $s : G \rightarrow \mathcal{T}\text{an}_{G/S}$ defines an action of G on Lie_G by conjugation; if $x \in G(R)$, this action is written

$$\text{Ad}(x) : \text{Lie}_G \longrightarrow \text{Lie}_G.$$

The naturality of the semi-direct product construction shows that there is a natural isomorphism of group schemes over G

$$\mathcal{T}\text{an}_{G/S} \cong G \rtimes_S \text{Lie}_G.$$

In particular, if G is commutative we have an isomorphism

$$(4.1) \quad \mathcal{T}\text{an}_{G/S} \cong G \times_S \text{Lie}_G$$

which is natural with respect to homomorphisms of abelian group schemes.

3.) There is a Lie bracket

$$[,] : \text{Lie}_G \times_S \text{Lie}_G \longrightarrow \text{Lie}_G.$$

Thus, Lie_G is an \mathbb{A}_S^1 -Lie algebra. If G is commutative – as is our focus here – this bracket is zero, so we won't belabor it.

4.3 Remark (Invariant derivations). In Corollary 1.22 we wrote down a natural isomorphism between the module $\text{Der}_S(G, \mathcal{O}_G)$ of derivations of G over S with coefficients in \mathcal{O}_G and the module of sections of $q : \mathcal{T}\text{an}_{G/S} \rightarrow G$. If s' is a section of $\text{Lie}_G \rightarrow S$, then we get a section

$$s = s' \times G : G = S \times_S G \longrightarrow \text{Lie}_G \times_S G \cong \mathcal{T}\text{an}_{G/S}$$

of $\mathcal{T}\text{an}_{G/S} \rightarrow G$ and the assignment $s' \mapsto s$ induces an isomorphism from the module of sections of Lie_G to the module of left invariant sections of $\mathcal{T}\text{an}_{G/S}$. The inverse assigns to s the composition

$$S \xrightarrow{e} G \xrightarrow{s_0} \text{Lie}_G(S).$$

There is a sheaf version of this which defines an isomorphism from the local sections of $\text{Lie}_G \rightarrow G$ to an appropriate sheaf of invariant derivations in $\text{Der}_S(G, \mathcal{O}_G)$.

Now let $G \rightarrow S$ be a formal group over S ; we define Lie_G exactly as above:

$$\text{Lie}_G = e^* \mathcal{T}\text{an}_{G/S} \rightarrow S.$$

Let $\varepsilon : \text{Lie}_G \rightarrow \mathcal{T}\text{an}_{G/S}$ be the induced map. In Remark 1.32 we showed that $(\mathcal{T}\text{an}_{G/S}, \varepsilon)$ is a formal Lie variety over Lie_G and that there is a natural isomorphism of abelian group schemes

$$\mathbb{V}(\omega_G) \cong \text{Lie}_G$$

over S . Exactly as in Equation 4.1 we have an isomorphism (now as *fpqc* sheaves)

$$\mathcal{T}\text{an}_{G/S} \cong G \times_S \text{Lie}_G$$

over S .

4.4 Remark. Let $f : G \rightarrow H$ be homomorphism of smooth, commutative formal groups over S . In the presence of coordinates, it is possible to give a concrete formula for computing $\text{Lie}(f)$ and $\mathcal{T}\text{an}(f)$.

First suppose that we choose a coordinate y for G . Then y determines an isomorphism

$$\lambda_y : \mathbb{G}_a \rightarrow \text{Lie}_G$$

from the additive group over S to Lie_G sending $a \in \mathbb{G}_a(R)$ to $\varepsilon a \in \text{Lie}_G$.

Next suppose that we also choose a coordinate x for H . Then the image of y under f is a power series $f(x)$ and we get a commutative diagram

$$\begin{array}{ccc} G \times_S \mathbb{G}_a & \longrightarrow & H \times_S \mathbb{G}_a \\ G \times \lambda_y \downarrow & & \downarrow H \times \lambda_x \\ \mathcal{T}\text{an}_{G/S} & \xrightarrow{\mathcal{T}\text{an}(f)} & \mathcal{T}\text{an}_{H/S} \end{array}$$

where the top morphism is given pointwise by

$$(a, b) \mapsto (f(a), bf'(a)).$$

Restricting to the Lie schemes, we get a commutative diagram of schemes over S

$$\begin{array}{ccc} \mathbb{G}_a & \xrightarrow{f'(0)} & \mathbb{G}_a \\ \lambda_y \downarrow & & \downarrow \lambda_x \\ \text{Lie}_G & \xrightarrow{\text{Lie}(f)} & \text{Lie}_{H/S}. \end{array}$$

Note that we have also effectively proved the following result.

4.5 Proposition. *Let G be a smooth one-dimensional, commutative formal groups over S . Then Lie_G is a naturally a \mathbb{G}_a -torsor in the *fpqc* topology.*

Proof. The scheme $\mathrm{Lie}_G \rightarrow S$ is a \mathbb{G}_a -scheme because it is an \mathbb{A}_S^1 -module. If we choose an fpqc cover $f : T \rightarrow S$ so that f^*G can be given a coordinate, then we have just shown, in Remark 4.4, that a choice of coordinate defines an isomorphism

$$f^*\mathbb{G}_a \rightarrow \mathrm{Lie}_T(f^*G) \cong f^*\mathrm{Lie}_G.$$

□

4.2 Invariant differentials

Let $q : G \rightarrow S$ be a group scheme over S with identity $e : S \rightarrow G$. Let us assume that G is flat – and hence faithfully flat – and quasi-compact over S . Then we have a diagram

$$\begin{array}{ccc} G \times_S G & \xrightarrow[m]{p_1} & G \\ f \downarrow & & \downarrow = \\ G \times_S G & \xrightarrow[p_2]{p_1} & G \end{array}$$

where f is an isomorphism given pointwise by $f(x, y) = (x, xy)$ and m is the multiplication map. From this we conclude that we have a modified version of descent for $q : G \rightarrow S$: the category of quasi-coherent sheaves on S is equivalent to the category of quasi-coherent sheaves \mathcal{F} on G equipped with an isomorphism

$$(p_1)^*\mathcal{F} \rightarrow m^*\mathcal{F}$$

satisfying a suitable cocycle condition we leave the reader to formulate.

To apply this, we note that we have diagram

$$\begin{array}{ccc} G \times_S G & \xrightarrow[m]{p_1} & G \\ p_2 \downarrow & & \downarrow q \\ G & \xrightarrow{q} & S \end{array}$$

and both the squares are Cartesian. This supplies an isomorphism

$$(p_1)^*\Omega_{G/S} \cong \Omega_{G \times_S G/G} \cong m^*\Omega_{G/S}$$

which satisfies the necessary cocycle condition. The resulting quasi-coherent sheaf ω_G on S is the *sheaf of invariant differentials* on G . Since ω_G is already the name we've given to the conormal sheaf of the unit $e : S \rightarrow G$ we have to justify this notion. So for the next sentence, let's write ω_G for the invariant differentials and $e^*\Omega_{G/S}$ for the conormal sheaf. Then, by construction, we have that

$$(4.2) \quad q^*\omega_G \cong \Omega_{G/S}$$

from which it follows that

$$(4.3) \quad e^* \Omega_{G/S} = e^* q^* \omega_G \cong \omega_G.$$

Thus, from now on, we make no distinction between the two.

4.6 Example. This definition is less arcane that it seems. Unwinding the proof of faithfully flat descent, we see that there is an equalizer diagram of sheaves of S

$$\omega_G \longrightarrow q_* \Omega_{G/S} \xrightarrow[\cong]{dp_1/dm} q_* \Omega_{(G \times_S G)/G}$$

where I have written q for the canonical projections to S . To be even more concrete, suppose $S = \text{Spec}(R)$ and G is affine over R ; that is, $G = \text{Spec}(A)$ for some Hopf algebra A over R . Then ω_G is determined by the R -module ω_A defined by the equalizer diagram

$$\omega_A \longrightarrow \Omega_{A/R} \xrightarrow[\cong]{di_1/d\Delta} \Omega_{(A \otimes_R A)/A}.$$

For example, if $G = \mathbb{G}_m$, then $A = R[x^{\pm 1}]$ with $\Delta(x) = x \otimes x$ and we calculate that ω_A is the free R -module on dx/x .

4.7 Remark. As $\text{Lie}_G \cong \mathbb{V}(\omega_G)$, the sheaf *dual* to ω_G is the quasi-coherent sheaf which assigns to each Zariski open $U \subseteq S$ the sections of $\text{Lie}_G|_U \rightarrow U$. In particular, the global sections of this dual sheaf are exactly invariant derivations of G . If we need a name for this sheaf we will call it $\text{lie}_{G/S}$.

These notions extend to formal groups, with a little care. In this case we don't have a sheaf $\Omega_{G/S}$ defined – although we could produce it if need be. However, in Remark 1.32, we did define sheaves $(\Omega_{G/S})_n$ over G_n and we *define*

$$q^* \Omega_{G/S} \stackrel{\text{def}}{=} \lim q_*(\Omega_{G/S})_n \cong \lim q^* \Omega_{G_n/S}$$

over S , where $q : G_n \rightarrow S$ is any of the projections. Similarly

$$q_* \Omega_{G \times G/G} = \lim q_* \Omega_{G_n \times G_n/G_n}.$$

The following allows us to call ω_G the sheaf of invariant differentials for G .

4.8 Proposition. *Let $G \rightarrow S$ be a formal group over S . Then there is an equalizer diagram of sheaves on S*

$$\omega_G \longrightarrow q_* \Omega_{G/S} \xrightarrow[\cong]{dp_1/dm} q_* \Omega_{(G \hat{\times}_S G)/G}$$

4.9 Example. Suppose that $S = \text{Spec}(A)$ is affine and that G can be given a coordinate x . Then ω_G is determined by its S -module of global sections over S and we we have an equalizer diagram of A -modules

$$H^0(S, \omega_G) \longrightarrow A[[x]]dx \xrightarrow[\cong]{di_1/d\Delta} A[[x, y]]dx.$$

Let's write $F(x, y) = \Delta(x)$ for the resulting formal group law and $F_x(x, y)$ for the partial derivative of that power series with respect to x . Then an invariant differential $f(x)dx$ must satisfy the equality

$$f(x)dx = f(F(x, y))F_x(x, y)dx.$$

Setting $x = 0$ and then setting $y = x$ we get that

$$f(x) = \frac{f(0)}{F_x(0, x)}.$$

Since $F_x(0, 0) = 1$, we conclude that ω_G is the quasi-coherent sheaf on $\text{Spec}(A)$ determined by the free A -module of rank 1 with generator

$$\eta = \frac{dx}{F_x(0, x)}.$$

4.10 Example. Calculating with Lie_G and ω_G is standard, at least locally. Compare Remark 4.4. Suppose $S = \text{Spec}(A)$ and $f : G \rightarrow H$ is a homomorphism of formal groups over S . By passing to a faithfully flat extension, we may as well assume that G and H can be given coordinates x and y respectively; then f is determined by a power series $f(x) \in A[[x]]$ and the induced morphism

$$df : \omega_H \rightarrow \omega_G$$

is multiplication by $f'(0)$.

4.3 Invariant differentials in characteristic p

As a warm-up for the next section, we will isolate some of the extra phenomena that occurs when we are working over a base scheme S which is itself a scheme over $\text{Spec}(\mathbb{F}_p)$. In this case there is a Frobenius morphism $f : S \rightarrow S$. Indeed, if R is an \mathbb{F}_p algebra, the Frobenius $x \mapsto x^p$ defines a natural morphism $f_R : R \rightarrow R$ of \mathbb{F}_p algebras and

$$f_S(R) = S(f_R) : S(R) \rightarrow S(R),$$

If $X \rightarrow S$ is any scheme over S , we define $X^{(p)}$ to be the pull-back

$$\begin{array}{ccc} X^{(p)} & \longrightarrow & X \\ \downarrow & & \downarrow \\ S & \xrightarrow{f} & S \end{array}$$

and the relative Frobenius $F : X \rightarrow X^{(p)}$ to the unique morphism of schemes over S so that the following diagram commutes

$$\begin{array}{ccccc} & & f & & \\ & & \curvearrowright & & \\ X & \xrightarrow{F} & X^{(p)} & \longrightarrow & X \\ & \searrow & \downarrow & & \downarrow \\ & & S & \xrightarrow{f} & S. \end{array}$$

The following is an exercise in definitions and the universal properties of pull-backs.

4.11 Lemma. *Let $X \rightarrow S$ be a scheme over a scheme S over $\text{Spec}(\mathbb{F}_p)$.*

- 1.) *There is a natural isomorphism $\mathcal{T}\text{an}_{X/S}^{(p)} \cong \mathcal{T}\text{an}_{X^{(p)}/S}$.*
- 2.) *If $G \rightarrow S$ is a group scheme over S , then there is a natural isomorphism $\text{Lie}_G^{(p)} \cong \text{Lie}_{G^{(p)}/S}$.*
- 3.) *The relative Frobenius $F : X \rightarrow X^{(p)}$ induces the zero homomorphism $\mathcal{T}\text{an}_{X/S}(F) : \mathcal{T}\text{an}_{X/S} \rightarrow \mathcal{T}\text{an}_{X^{(p)}/S}$; that is, $\mathcal{T}\text{an}_{X/S}(F)$ can be factored*

$$\mathcal{T}\text{an}_{X/S} \longrightarrow X \xrightarrow{F} X^{(p)} \xrightarrow{s} \mathcal{T}\text{an}_{X^{(p)}/S}$$

where s is the zero section.

- 4.) *If $G \rightarrow S$ is a group scheme, the relative Frobenius $F : G \rightarrow G^{(p)}$ induces the zero homomorphism $\text{Lie}(F) : \text{Lie}_G \rightarrow \text{Lie}_{G^{(p)}/S}$; that is, $\text{Lie}(F)$ can be factored*

$$\text{Lie}_G \longrightarrow S \xrightarrow{s} \text{Lie}_{G^{(p)}/S}.$$

Proof. The first of two of these statements are an exercise in definitions and the universal properties of pull-backs. The second two follow from the fact that if R is an \mathbb{F}_p -algebra, the $f_{R(\epsilon)}(-) = (-)^p : R(\epsilon) \rightarrow R(\epsilon)$ factors

$$R(\epsilon) \xrightarrow{\epsilon=0} R \xrightarrow{f_R} R \longrightarrow R(\epsilon).$$

□

While the morphism $\text{Lie}(F)$ induced by the relative Frobenius $F : G \rightarrow G^{(p)}$ is the zero map, the relative Frobenius

$$F : \text{Lie}_G \rightarrow \text{Lie}_G^{(p)} \cong \text{Lie}_{G^{(p)}/S}$$

is not. This is the map on affine schemes over S

$$\mathbb{V}(\omega_G) \longrightarrow \mathbb{V}(\omega_G)^{(p)} \cong \mathbb{V}(\omega_{G^{(p)}})$$

induced by the Frobenius morphism on algebra sheaves

$$\text{Sym}_S(\omega_{G^{(p)}}) \rightarrow \text{Sym}_S(\omega_G).$$

By restricting to the sub- \mathcal{O}_S -module $\omega_{G^{(p)}}$ of $\text{Sym}_S(\omega_{G^{(p)}})$ we get the map needed for the following result. $\text{Sym}_p(-)$ is the p th symmetric power functor.

4.12 Lemma. *Let G be a group scheme over S and S a scheme over \mathbb{F}_p . Then the p th power map induces a natural homomorphism of quasi-coherent sheaves over S*

$$\omega_{G^{(p)}} \rightarrow \text{Sym}_p(\omega_G)$$

which, if G is smooth of dimension 1, becomes an isomorphism

$$\omega_{G^{(p)}} \cong \text{Sym}_p(\omega_G) \cong \omega_G^{\otimes p}.$$

Proof. The last statement follows because ω_G is locally free of rank 1. \square

The exact same argument now proves:

4.13 Lemma. *Let G be a formal group over S and S a scheme over \mathbb{F}_p . Then the p th power map induces a natural homomorphism of quasi-coherent sheaves over S*

$$\omega_{G^{(p)}} \rightarrow \mathrm{Sym}_p(\omega_G)$$

yields an isomorphism

$$\omega_{G^{(p)}} \cong \mathrm{Sym}_p(\omega_G) \cong \omega_G^{\otimes p}.$$

5 The height filtration

The theory of formal groups in characteristic zero is quite simple: in Corollary 3.23 we saw that over \mathbb{Q} , we are reduced to studying the additive formal group law and its automorphisms. In characteristic $p > 0$ (and hence over the integers) the story is quite different. Here formal groups are segregated by height and it is the height filtration which is at the heart of the geometry of $\mathcal{M}_{\mathbf{fg}}$. The point of this section is to spell this out in detail.

5.1 Height and the elements v_n

We are going to study formal groups G over schemes S which are themselves schemes over $\mathrm{Spec}(\mathbb{F}_p)$. In Lemma 4.11 we introduced and discussed the relative Frobenius F and its effect on tangent and Lie schemes. The following is a standard lemma for formal groups. The homomorphism $F : G \rightarrow G^{(p)}$ is the relative Frobenius.

5.1 Lemma. *Let $f : G \rightarrow H$ be a homomorphism of formal groups over S which is a scheme over $\mathrm{Spec}(\mathbb{F}_p)$. If*

$$0 = \mathrm{Lie}(f) : \mathrm{Lie}_G \rightarrow \mathrm{Lie}_H.$$

then there is a unique morphism $g : G^{(p)} \rightarrow H$ so that there is a factoring

$$\begin{array}{ccc} G & \xrightarrow{F} & G^{(p)} \\ & \searrow f & \downarrow g \\ & & H \end{array}$$

Proof. It follows immediately from the natural decomposition $\mathcal{T}\mathrm{an}_{G/S} \cong G \times \mathrm{Lie}_G$ that the induced map

$$\mathcal{T}\mathrm{an}(f) : \mathcal{T}\mathrm{an}_{G/S} \rightarrow \mathcal{T}\mathrm{an}_{H/S}$$

is the zero homomorphism as well. Because of the uniqueness of g it is sufficient to prove the result locally, so choose an fqpc-cover $q : T \rightarrow S$ so that q^*G and

q^*H can each be given a coordinate. As in Remark 4.4, we write f as a power series $f(x)$ and because $\mathcal{T}\text{an}(f) = 0$ we conclude that $f'(x) = 0$. Because we are working over \mathbb{F}_p , we may write $f(x) = g(x^p)$ for some unique $g(x)$ and we let g define the needed homomorphism $g^* : G^{(p)} \rightarrow H$. \square

Let G be a formal group over S , with S a scheme over $\text{Spec}(\mathbb{F}_p)$. Since G is commutative the p th power map

$$[p] : G \longrightarrow G$$

is a homomorphism of formal groups over S . If G can be given a coordinate, then Remark 4.4 implies that $\text{Lie}([p]) = 0$. More generally, we choose an fpqc cover $f : T \rightarrow S$ so that f^*G has a coordinate. Then, since f is faithfully flat and $f^*\text{Lie}([p]) = 0$, we have $\text{Lie}([p]) = 0$. Therefore, Lemma 5.1 implies there is a unique homomorphism $V : G^{(p)} \rightarrow G$ so that we have a factoring

$$\begin{array}{ccc} G & \xrightarrow{F} & G^{(p)} \\ & \searrow [p] & \downarrow V \\ & & G. \end{array}$$

The homomorphism V is called the *Verschiebung*. The induced morphism $\text{Lie}(V) : \text{Lie}_{G^{(p)}} \rightarrow \text{Lie}_G$ may itself be zero; if so, we obtain a factoring

$$\begin{array}{ccc} G^{(p)} & \xrightarrow{F^{(p)}} & G^{(p^2)} \\ & \searrow V & \downarrow V_2 \\ & & G. \end{array}$$

We may continue if $\text{Lie}(V_2) = 0$.

5.2 Definition (The height of a formal group). *Let G be a formal group over a scheme S which is itself a scheme over $\text{Spec}(\mathbb{F}_p)$. Define G to have **height at least n** if there is a factoring*

$$\begin{array}{ccccccc} G & \xrightarrow{F} & G^{(p)} & \xrightarrow{F^{(p)}} & G^{(p^2)} & \xrightarrow{F^{(p^2)}} & \dots & \xrightarrow{F^{(p^{n-1})}} & G^{(p^n)} \\ & & & & & & & & \downarrow V_n \\ & & & & & & & & G. \end{array}$$

We will define what it means for G to have exact height n below in Definition 5.5.

Note that a formal group may not have finite height; for example, if $\hat{\mathbb{G}}_a$ is the formal additive group, then $0 = [p] : \hat{\mathbb{G}}_a \rightarrow \hat{\mathbb{G}}_a$ so it must have infinite height. It follows from Lazard's uniqueness theorem (Corollary 5.26) that every infinite height formal group is locally isomorphic to the additive group.

5.3 Proposition. *Let G be a formal group over a scheme S which is itself a scheme over $\text{Spec}(\mathbb{F}_p)$. Suppose that G has height at least n . Then there is a global section*

$$v_n(G) \in H^0(S, \omega_G^{\otimes(p^n-1)})$$

*so that G has height at least $n+1$ if and only if $v_n(G) = 0$. The element $v_n(G)$ is natural; that is, if $H \rightarrow T$ is another formal group, $f : T \rightarrow S$ is a morphism of schemes and $\phi : H \rightarrow f^*G$ is an isomorphism of formal groups, then*

$$f^*v_n(G) = v_n(H).$$

Proof. Since G is of height at least n , we have the morphism $V_n : G^{(p^n)} \rightarrow G$ and G has height at least $n+1$ if and only if $\text{Lie}(V_n) = 0$. This will happen if and only if the induced map

$$dV_n : \omega_G \longrightarrow \omega_{G^{(p^n)}} \cong \omega_G^{\otimes p^n}$$

is zero. The last isomorphism uses Lemma 4.13. Since ω_G is an invertible sheaf, dV_n corresponds to a unique morphism

$$v_n(G) : \mathcal{O}_S \longrightarrow \omega_G^{\otimes(p^n-1)}.$$

This defines the global section. The naturality statement follows from the commutative diagram

$$\begin{array}{ccc} \text{Lie}_{H^{(p^n)}} & \xrightarrow{V_n} & \text{Lie}_H \\ \text{Lie}(\phi^{(p^n)}) \downarrow & & \downarrow \text{Lie}(\phi) \\ f^*\text{Lie}_{G^{(p^n)}} & \xrightarrow{V_n} & f^*\text{Lie}_G \end{array}$$

□

5.4 Remark. The global section v_n can be computed locally as follows. Let $S = \text{Spec}(R)$ be affine and suppose $G \rightarrow S$ can be given a coordinate x . Then if G is of height at least n , the power series expansion of $[p] : G \rightarrow G$ gives the p -series:

$$[p](x) = a_n x^{p^n} + a_{2n} x^{2p^n} + \dots$$

If $\eta(G, x) = dx/F_x(0, x)$ is the invariant differential associated to this coordinate, then

$$v_n(G) = a_n \eta(G, x)^{\otimes p^n - 1} \in \omega_G^{\otimes(p^n-1)}.$$

In particular, $v_n(G) = 0$ if and only if $a_n = 0$.

We wish to define a descending chain of closed substacks

$$\dots \subseteq \mathcal{M}(3) \subseteq \mathcal{M}(2) \subseteq \mathcal{M}(1) \subseteq \mathcal{M}_{\mathbf{fg}}$$

with $\mathcal{M}(n)$ the moduli stack of formal groups of height greater than or equal to n . Of course, $\mathcal{M}(n)$ will be defined by the vanishing of p, v_1, \dots, v_{n-1} , but

it's worth dwelling on the definition so that the behavior of $\mathcal{M}(n)$ under base change is transparent.

Let \mathcal{M} be an *fqc*-algebraic stack over a base scheme S . Recall that an *effective Cartier divisor* $D \subseteq \mathcal{M}$ is a closed substack so that the ideal sheaf $\mathcal{I}(D) \subseteq \mathcal{O}_{\mathcal{M}}$ defining D is locally free of rank 1.⁵ If we tensor the exact sequence

$$0 \rightarrow \mathcal{I}(D) \rightarrow \mathcal{O}_{\mathcal{M}} \rightarrow \mathcal{O}_D \rightarrow 0$$

of sheaves on \mathcal{M} with the dual sheaf $\mathcal{I}(D)^{-1}$, then we get an exact sequence

$$0 \longrightarrow \mathcal{O}_{\mathcal{M}} \xrightarrow{s} \mathcal{I}(D)^{-1} \longrightarrow \mathcal{O}_D \otimes_{\mathcal{O}_{\mathcal{M}}} \mathcal{I}(D)^{-1} \longrightarrow 0$$

with s a section of $\mathcal{I}(D)^{-1}$. Conversely, given an invertible sheaf \mathcal{L} , a section s of \mathcal{L} , and an exact sequence

$$0 \longrightarrow \mathcal{O}_{\mathcal{M}} \xrightarrow{s} \mathcal{L} \longrightarrow \mathcal{L}/\mathcal{O}_{\mathcal{M}} \longrightarrow 0$$

then the substack of zeros of s is an effective Cartier divisor with ideal sheaf defined by the image of the injection

$$s : \mathcal{L}^{-1} \longrightarrow \mathcal{O}_{\mathcal{M}}.$$

This establishes a one-to-one correspondence between effective Cartier divisors and isomorphism classes of pairs (\mathcal{L}, s) as above. We will say that the divisor is defined by the pair (\mathcal{L}, s) . For example

$$\mathcal{M}(1) \subseteq \mathcal{M}_{\mathbf{fg}}$$

is the effective Cartier divisor defined by $(\mathcal{O}_{\mathbf{fg}}, p)$. Suppose $\mathcal{M}(n)$ has been defined and classifies formal groups of height at least n .

5.5 Definition. 1.) Define the closed substack $\mathcal{M}(n+1) \subseteq \mathcal{M}(n)$ to be the effective Cartier divisor defined by the pair (ω^{p^n-1}, v_n) .

2.) Let $\mathcal{H}(n) = \mathcal{M}(n) - \mathcal{M}(n+1)$ be the open complement of $\mathcal{M}(n+1)$ in $\mathcal{M}(n)$. Then $\mathcal{H}(n)$ classifies formal groups of **exact height** n or simply of height n .

3.) Let $\mathcal{U}(n)$ be the open complement of $\mathcal{M}(n+1)$; then $\mathcal{U}(n)$ is the moduli stack of formal groups of height less than or equal to n .

Then Proposition 5.3 implies that $\mathcal{M}(n+1)$ classifies formal groups of height at least $n+1$. The inclusion $\mathcal{M}(n) \subseteq \mathcal{M}_{\mathbf{fg}}$ is closed; let $\mathcal{I}_n \subseteq \mathcal{O}_{\mathbf{fg}}$ be the ideal sheaf defining this inclusion. Thus we have an ascending sequence of ideal sheaves

$$0 \subseteq \mathcal{I}_1 = (p) \subseteq \mathcal{I}_2 \subseteq \cdots \subseteq \mathcal{O}_{\mathbf{fg}}$$

and an isomorphism

$$v_n(G) : \omega^{-(p^n-1)} \longrightarrow \mathcal{I}_{n+1}/\mathcal{I}_n$$

on $\mathcal{M}(n)$.

⁵Some authors (cf [30], Chapter 1) require also that D be flat over S . This implies that if $f : T \rightarrow S$ is a morphism of schemes, then $T \times_S D$ is an effective Cartier divisor for $T \times_S \mathcal{M}$. But it also means that if X is a scheme with \mathcal{O}_X torsion free then the closed subscheme obtained from setting $p = 0$ is not an effective Cartier divisor for X over \mathbb{Z} .

5.6 Remark. A formal group $G \rightarrow S$ has exact height n if the global section $v_n(G) \in H^0(S, \omega_G^{p^n-1})$ is invertible in the sense that

$$v_n : \omega_G^{-(p^n-1)} \longrightarrow \mathcal{O}_S$$

is an isomorphism. This makes sense even if $n = 0$, where would have p invertible in $H^0(S, \mathcal{O}_S)$. This *defines* the notion of a formal group of height 0.

5.7 Remark. We can follow up Remark 5.4 with a local description of \mathcal{I}_n and the process of defining $\mathcal{M}(n)$. If $G \rightarrow \text{Spec}(R)$ can be given a coordinate x and G has height at least n , then we can write

$$v_n(G) = u_n \eta(G, x)^{\otimes p^n - 1}$$

where $\eta(G, x) = dx/F_x(0, x)$ is the generator of ω_G . The choice of generator $\eta(G, x)^{\otimes p^n - 1}$ for $\omega_G^{p^n - 1}$ defines an isomorphism $R \cong \omega_G^{p^n - 1}$ and the section $v_n : R \rightarrow \omega_G^{p^n - 1}$ becomes isomorphic to multiplication by u_n . Thus

$$\mathcal{I}_{n+1}(G)/\mathcal{I}_n(G) = (u_n)$$

is the principal ideal generated by u_n . Note that u_n is not an isomorphism invariant, but the ideal is.

It is tempting to write, for a general formal group G with a coordinate, that there is an isomorphism

$$\mathcal{I}_n(G) = (p, u_1, \dots, u_{n-1}).$$

In general, u_{n-1} is only well-defined modulo $\mathcal{I}_{n-1}(G)$, so we must be careful with this notation. It is possible to choose a sequence p, u_1, \dots, u_{n-1} defining the ideal $\mathcal{I}_n(R)$, but the choices make the sequence unpleasant. In the presence of a p -typical coordinate, the situation improves. See the next remark.

5.8 Remark. The form v_n is defined globally only when $p = v_1 = \dots = v_{n-1} = 0$. But if G is a formal group with a coordinate over a $\mathbb{Z}_{(p)}$ algebra R , then Cartier's theorem gives a p -typical coordinate x for G . Let F be the resulting formal group law for G . Then we can write the p -series

$$[p](x) = px +_F u_1 x^p +_F u_2 x^{p^2} +_F \dots$$

Remark 5.4 implies that if $p = u_1 = \dots = u_{n-1} = 0$, then

$$v_n(H) = u_n \eta(G, x)^{\otimes p^n - 1}$$

and we really can write $\mathcal{I}_n(G) = (p, u_1, \dots, u_{n-1})$.

Note that $v_n(G) = 0$ if and only if $u_n = 0$. Since the morphism

$$\text{Spec}(\mathbb{Z}_{(p)}[u_1, u_2, \dots]) \longrightarrow \mathcal{M}_{\mathbf{fg}} \otimes \mathbb{Z}_{(p)}$$

classifying the universal p -typical formal group is an $fpqc$ -cover, this remark implies the following result.

5.9 Proposition. *For all primes p and all $n \geq 1$, there is an fpqc-cover*

$$X(n) \stackrel{\text{def}}{=} \text{Spec}(\mathbb{F}_p[u_n, u_{n+1}, \dots]) \rightarrow \mathcal{M}(n).$$

Furthermore,

$$p_1^*(p, u_1, \dots, u_{n-1}) = p_2^*(p, u_1, \dots, u_{n-1}) \subseteq \mathcal{O}_{X(n) \times_{\mathcal{M}(n)} X(n)}$$

and

$$X(n) \times_{\mathcal{M}(n)} X(n) = \text{Spec}(\mathbb{F}_p[u_n, u_{n+1}, \dots][t_0^{\pm 1}, t_1, t_2, \dots]).$$

If $q : \mathcal{N} \rightarrow \mathcal{M}$ is a representable and flat morphism of algebraic stacks and $D \subseteq \mathcal{M}$ is an effective Cartier divisor defined by (\mathcal{L}, s) , then

$$f^*D \stackrel{\text{def}}{=} D \times_{\mathcal{M}} \mathcal{N} \subseteq \mathcal{N}$$

is an effective Cartier divisor defined by $(q^*\mathcal{L}, q^*s)$. To see this, note that because f is flat, we have an exact sequence

$$0 \rightarrow f^*\mathcal{I}(D) \rightarrow f^*\mathcal{O}_{\mathcal{M}} \rightarrow f^*\mathcal{O}_D \rightarrow 0$$

which is isomorphic to

$$0 \rightarrow f^*\mathcal{I}(D) \rightarrow \mathcal{O}_{\mathcal{N}} \rightarrow \mathcal{O}_{f^*D} \rightarrow 0.$$

Thus $f^*\mathcal{I}(D) \cong \mathcal{I}(f^*D)$. From this we can immediately conclude the following.

5.10 Proposition. *Let $q : \mathcal{N} \rightarrow \mathcal{M}_{\text{fg}}$ be a representable and flat morphism of stacks and define*

$$\mathcal{N}(n) = \mathcal{M}(n) \times_{\mathcal{M}_{\text{fg}}} \mathcal{N}.$$

Then

$$\dots \subseteq \mathcal{N}(2) \subseteq \mathcal{N}(1) \subseteq \mathcal{N}$$

is a descending chain of closed substacks so that

$$\mathcal{N}(n+1) \subseteq \mathcal{N}(n)$$

is the effective Cartier divisor defined by (ω^{p^n-1}, v_n) .

This implies that for all n the section v_n defines an injection

$$v_n : \mathcal{O}_{\mathcal{N}} \rightarrow \omega^{p^n-1}.$$

If $\mathcal{N} = \text{Spec}(R) \rightarrow \mathcal{M}_{\text{fg}}$ classifies a formal group for which we can choose a coordinate, this implies that each of the ideals $\mathcal{I}_n(R)$ is generated by a regular sequence. The Landweber Exact Functor Theorem 6.19 is a partial converse to this result.

In these examples, the closed embedding $\mathcal{N}(n) \subseteq \mathcal{N}$ is a regular embedding; that is, the ideal sheaf defining the embedding is locally generated by a regular sequence.

5.2 Geometric points and reduced substacks of $\mathcal{M}_{\mathbf{fg}}$

Suppose we now work at a prime p , so that $\mathcal{M}_{\mathbf{fg}} = \mathcal{M}_{\mathbf{fg}} \otimes \mathbb{Z}_{(p)}$. We will show that $\mathcal{M}_{\mathbf{fg}}$ has exactly one geometric point for each height n , $0 \leq n \leq \infty$ and use this to show that the substacks $\mathcal{M}(n) \subseteq \mathcal{M}_{\mathbf{fg}}$ give a complete list of the reduced substacks of $\mathcal{M}_{\mathbf{fg}}$.

We begin with the following definition.

5.11 Definition. *Let \mathcal{M} be an algebraic stack.*

1.) A **geometric point** ξ of X is an equivalence class of the morphisms $x : \mathrm{Spec}(\mathbb{F}) \rightarrow \mathcal{M}$ where \mathbb{F} is a field. Two such morphisms (x', \mathbb{F}') and (x'', \mathbb{F}'') are equivalent if \mathbb{F}' and \mathbb{F}'' have a common extension \mathbb{F} and the evident diagram

$$\begin{array}{ccc} \mathrm{Spec}(\mathbb{F}) & \longrightarrow & \mathrm{Spec}(\mathbb{F}'') \\ \downarrow & & \downarrow x'' \\ \mathrm{Spec}(\mathbb{F}') & \xrightarrow{x'} & \mathcal{M} \end{array}$$

2-commutes.

2.) The set of geometric points $|X|$ has a topology with open sets $|\mathcal{U}|$ where $\mathcal{U} \subseteq \mathcal{M}$ is an open substack. When we write $|X|$ we will mean this set with this topology. This is the geometric space of the stack.

5.12 Remark. The following result implies that the topology of $|\mathcal{M}_{\mathbf{fg}}|$ is quite simple. The proof will use that over a separably closed field \mathbb{F} there is a unique isomorphism class of formal groups of a fixed height. This is proved below in Corollary 5.26 and is a consequence of the more global Theorem 5.25. But it is also simple to give a proof at this point. Let G_1 be the Honda formal group over \mathbb{F} with p -typical coordinate x so that the associated formal group law F_1 has p -series

$$[p]_{F_1}(x) = x^{p^n}.$$

Let G_2 be another formal group over \mathbb{F} and choose a p -typical coordinate and associated formal group law F_2 . To construct an isomorphism, we need to find a power series $\phi(x)$ so that

$$\phi([p]_{F_2})(x) = [p]_{F_1}(\phi(x)) = \phi(x)^{p^n}.$$

Working inductively by degree in $\phi(x)$ we obtain equations such as in Equations 5.3 and 5.4, which always have solutions over \mathbb{F} . This is the same proof as in [48], §A.2.

5.13 Proposition. *Let $\mathcal{U} \subseteq \mathcal{M}_{\mathbf{fg}}$ be an open substack and suppose that \mathcal{U} has a geometric point of height n . Then it has a geometric point of height k for all $k \leq n$.*

Proof. Let $G : \mathrm{Spec}(k) \rightarrow \mathcal{U}$ represent the geometric point of height n and $\mathrm{Spec}(L) \rightarrow \mathcal{M}_{\mathbf{fg}}$ be the cover by the Lazard ring. Then we have a 2-commutative

diagram

$$\begin{array}{ccccc}
& & \mathcal{U} \times_{\mathcal{M}_{\mathbf{fg}}} \mathrm{Spec}(L) & \xrightarrow{j} & \mathrm{Spec}(L) \\
& \nearrow F & \downarrow q & & \downarrow \\
\mathrm{Spec}(k) & \xrightarrow{G} & \mathcal{U} & \longrightarrow & \mathcal{M}_{\mathbf{fg}}
\end{array}$$

obtained by choosing a coordinate for G . The morphism j is open and the morphism q is flat, as it is the pull-back of a flat map. Choose an affine open $\mathrm{Spec}(R) \subseteq \mathcal{U} \times_{\mathcal{M}_{\mathbf{fg}}} \mathrm{Spec}(L)$ so that the morphism F factors through $\mathrm{Spec}(R)$. Let G_0 be the resulting formal group over R .

By localizing R if necessary, we may assume that $R \rightarrow k$ is onto. Choose an element $w \in R$ which reduces to $v_n(G) \in k$. Since G has height n , $v_n(G) \neq 0$; thus, w is not nilpotent. By forming $R[w^{-1}]$ if necessary, we may assume that w is a unit. From this we conclude that $\mathcal{I}_{n+1}(G_0) = R$. Since $\mathrm{Spec}(R) \rightarrow \mathcal{M}_{\mathbf{fg}}$ is flat, Proposition 5.10 implies that the ideals $\mathcal{I}_k(G_0)$, $k \leq n+1$, is generated by a regular sequence. (Note that G_0 has a canonical coordinate by construction.) Let $k \leq n$, $R_k = R/\mathcal{I}_k(G_0)$, and let $q_k : R \rightarrow R_k$ be the quotient map. We conclude immediately that $v_k(q_k^*G_0)$ is not nilpotent in R_k . Choose a prime ideal \mathfrak{p} in R_k so that $v_k(q_k^*G_0) \neq 0$ in R/\mathfrak{p} and let K be the field of fractions of R/\mathfrak{p} . Then

$$\mathrm{Spec}(K) \rightarrow \mathrm{Spec}(R) \rightarrow \mathcal{U}$$

represents a geometric point of height k . □

The importance of the closed substacks $\mathcal{M}(n)$ is underlined by the following result. Recall we are working at a prime, so that $\mathcal{M}_{\mathbf{fg}} = \mathbb{Z}_{(p)} \otimes \mathcal{M}_{\mathbf{fg}}$.

5.14 Theorem. *For all n , $1 \leq n \leq \infty$ the algebraic stack $\mathcal{M}(n)$ is reduced. Furthermore if $\mathcal{N} \subseteq \mathcal{M}_{\mathbf{fg}}$ is any closed, reduced substack, then either $\mathcal{N} = \mathcal{M}_{\mathbf{fg}}$ or there is an n so that*

$$\mathcal{M}(n) = \mathcal{N}.$$

Before proving this result, we need to recall what it means for an algebraic stack to be reduced and how to produce the reduced substack of a stack, assuming it exists.

Fix an $fpgc$ -algebraic stack \mathcal{M} . We define a diagram \mathcal{C} of closed substacks of \mathcal{M} as follows:

1. An object of \mathcal{C} is a closed substack $\mathcal{N} \subseteq \mathcal{M}$ so that the induced inclusion on geometric points $|\mathcal{N}| \rightarrow |\mathcal{M}|$ is an isomorphism;
2. A morphism $\mathcal{N}_1 \subseteq \mathcal{N}_2$ is an inclusion of closed substacks.

This diagram \mathcal{C} of closed substacks is filtered; furthermore it determines and is determined by a filtered (or cofiltered) diagram $\{\mathcal{I}_{\mathcal{N}}\}$ of quasi-coherent ideals in $\mathcal{O}_{\mathcal{M}}$. Define

$$\mathcal{I}_{\mathrm{red}} = \mathrm{colim}_{\mathcal{C}^{\mathrm{op}}} \mathcal{I}_{\mathcal{N}}.$$

The colimit is taken pointwise and, since tensor products commute the colimits, \mathcal{I}_{red} is a quasi-coherent ideal. Let

$$\mathcal{M}_{\text{red}} \subseteq \mathcal{M}$$

be the resulting closed substack. Note that \mathcal{M}_{red} is the initial closed substack $\mathcal{N} \subseteq \mathcal{M}$ so that $|\mathcal{N}| = |\mathcal{M}|$. We say that \mathcal{M} is reduced if $\mathcal{M}_{\text{red}} = \mathcal{M}$ or, equivalently, if $\mathcal{I}_{\text{red}} = 0$.

The sheaf \mathcal{I}_{red} should be closely related to the ideal of nilpotents in $\mathcal{O}_{\mathcal{M}}$. Some care is required here, however. If we define $\mathcal{N}il_{\mathcal{M}}(U) = \mathcal{N}il_U$ for any *fppc*-morphism $U \rightarrow \mathcal{M}$, the resulting ideal sheaf may not be cartesian in the *fppc*-topology; thus it is not evidently quasi-coherent. (If $R \rightarrow S$ is a faithfully flat morphism of rings, then it is not necessarily true that $\mathcal{N}il_S = S \otimes_R \mathcal{N}il_R$.) However it is a sheaf in more restrictive topologies, such as the “smooth-étale” used for the algebraic stacks of [33].

5.15 Definition. *Let \mathcal{M} be an algebraic stack in the *fppc*-topology and suppose that $X \rightarrow \mathcal{M}$ is an *fppc*-presentation so that*

$$p_1^* \mathcal{N}il_X \cong \mathcal{N}il_{X \times_{\mathcal{M}} X} \cong p_2^* \mathcal{N}il_X$$

*as ideal sheaves in $\mathcal{O}_{X \times_{\mathcal{M}} X}$. Then descent theory yields a quasi-coherent ideal sheaf $\mathcal{N}il_{\mathcal{M}} \subseteq \mathcal{O}_{\mathcal{M}}$. This is the **sheaf of nilpotents** for \mathcal{M} .*

5.16 Remark. 1.) It is not immediately clear that $\mathcal{N}il_{\mathcal{M}}$ does not depend on the choice of cover $X \rightarrow \mathcal{M}$; however, this will follow from Proposition 5.18 to follow.

2.) If \mathcal{M} has a *smooth* cover, then $\mathcal{N}il_{\mathcal{M}}$, when restricted to the smooth-étale topology, agrees with the sheaf $\mathcal{N}il_{\mathcal{M}}$ as defined in [33].

3.) In many of our standard examples, $\mathcal{N}il_X = 0 = \mathcal{N}il_{X \times_S X}$. In particular, this applies to $\mathcal{M}_{\mathbf{fg}}$ and $\mathcal{M}(n)$, by Proposition 5.9.

We need the following preliminary result before preceding.

5.17 Lemma. *Let \mathcal{M} be an algebraic stack and $\mathcal{N} \subseteq \mathcal{M}$ a closed substack. Let $X \rightarrow \mathcal{M}$ be an *fppc*-cover. Then the natural map*

$$|X \times_{\mathcal{M}} \mathcal{N}| \longrightarrow |X| \times_{|\mathcal{M}|} |\mathcal{N}|$$

is an isomorphism.

Proof. This morphism is onto for a general pull-back; that is, we don’t need $\mathcal{N} \rightarrow \mathcal{M}$ to be a closed inclusion. To see that is one-to-one, note that $X \times_{\mathcal{M}} \mathcal{N}$ is equivalent to closed subscheme $Y \subseteq X$ and that, hence, the composite

$$|Y| = |X \times_{\mathcal{M}} \mathcal{N}| \longrightarrow |X| \times_{|\mathcal{M}|} |\mathcal{N}| \rightarrow |X|$$

is an injection. □

5.18 Proposition. *Suppose that \mathcal{M} is an algebraic stack in the fpqc topology and there is an fpqc-presentation $X \rightarrow \mathcal{M}$ so that $\mathcal{N}il_{\mathcal{M}}$ is defined. Then*

$$\mathcal{N}il_{\mathcal{M}} = \mathcal{I}_{\text{red}}.$$

Proof. Let $\mathcal{M}_0 \subseteq \mathcal{M}$ be the closed substack defined by $\mathcal{N}il_X$. Then $X_{\text{red}} \rightarrow \mathcal{M}_0$ is a cover. Since $|X_{\text{red}}| = |X|$ and $|X_{\text{red}}| \rightarrow |\mathcal{M}_0|$ is surjective, we can conclude that $|\mathcal{M}_0| = |\mathcal{M}|$. This shows that $\mathcal{M}_{\text{red}} \subseteq \mathcal{M}_0$ or, equivalently, that $\mathcal{I}_{\text{red}} \subseteq \mathcal{N}il_{\mathcal{M}}$.

For the other inclusion, let $\mathcal{N} \subseteq \mathcal{M}$ be a closed inclusion defined by an ideal \mathcal{J} and suppose $|\mathcal{N}| = |\mathcal{M}|$ and let $Y = \mathcal{N} \times_{\mathcal{M}} X \rightarrow \mathcal{N}$ be the resulting cover. Then Y is the closed subscheme of X defined by $\mathcal{J}|_X$ and the natural map

$$|Y| \longrightarrow |X| \times_{|\mathcal{M}|} |\mathcal{N}|$$

is an isomorphism, by Lemma 5.17. Thus, $|Y| = |X|$, which implies that $X_{\text{red}} \subseteq Y$, or $\mathcal{N}il_X \subseteq \mathcal{J}|_X$. Since $\mathcal{N}il_X = (\mathcal{N}il_{\mathcal{M}})|_X$ and X is a cover \mathcal{M} , this implies that $\mathcal{N}il_{\mathcal{M}} \subseteq \mathcal{J}$. In particular, $\mathcal{N}il_{\mathcal{M}} \subseteq \mathcal{I}_{\text{red}}$. \square

5.19 Corollary. *Suppose that \mathcal{M} is an algebraic stack in the fpqc topology and there is an fpqc-presentation $X \rightarrow \mathcal{M}$ so that X and $X \times_{\mathcal{M}} X$ are reduced. Then \mathcal{M} is reduced.*

We next begin an investigation of the closed substacks of \mathcal{M}_{fg} . Recall that $\mathcal{M}(1) = \mathcal{M}_{\text{fg}} \otimes_{\mathbb{F}_p}$.

5.20 Proposition. *Let $\mathcal{N} \subseteq \mathcal{M}_{\text{fg},p}$ be a closed substack. If \mathcal{N} has a geometric point of height n , then*

$$\mathcal{M}(n) \subseteq \mathcal{N}.$$

Proof. We begin with the following observation: suppose that \mathcal{N}_1 and \mathcal{N}_2 are closed substacks of an algebraic stack, that \mathcal{N}_1 is reduced in the strong sense of Proposition 5.18, and that $|\mathcal{N}_1| \subseteq |\mathcal{N}_2|$. Then $\mathcal{N}_1 \subseteq \mathcal{N}_2$. For if we let $X \rightarrow \mathcal{M}$ be a cover and $Y_i \subseteq X$, $i = 1, 2$ the resulting closed subscheme which covers \mathcal{N}_i , then Y_1 is reduced and Lemma 5.17 implies that $|Y_1| \subseteq |Y_2|$. Then $Y_1 \subseteq Y_2$ and arguing as the end of the proof of Proposition 5.18, we have $\mathcal{N}_1 \subseteq \mathcal{N}_2$.

To prove the result, then, we need only show that there is an n so that $|\mathcal{M}(n)| \subseteq |\mathcal{N}|$. Thus we must prove that if $\mathcal{N} \subseteq \mathcal{M}_{\text{fg}}$ is closed and contains a geometric point of height n , then it contains a geometric point of height k for all $k \geq n$. This can be rephrased in terms of the complementary open $\mathcal{U} = \mathcal{M}_{\text{fg}} - \mathcal{N}$ as follows: if \mathcal{U} does not have a geometric point of height n , it does not have a geometric point of height k , $k \geq n$. Rephrasing this as a positive statement gives exactly Proposition 5.13. \square

5.21 Proof of the Theorem 5.14. Suppose $\mathcal{N} \subseteq \mathcal{M}_{\text{fg}}$ is closed and reduced. If $\mathcal{N} \neq \mathcal{M}_{\text{fg}}$, then we have $\mathcal{N} \subseteq \mathbb{F}_p \otimes \mathcal{M}_{\text{fg}} = \mathcal{M}(1)$. Indeed, if $\mathcal{U} = \mathcal{M}_{\text{fg}} - \mathcal{N}$ is not empty, then it must contain a geometric point of height 0, by Proposition 5.13. Let n be the smallest integer $1 \leq n \leq \infty$ so that \mathcal{N} has a geometric

point of height n . Then Proposition 5.20 implies that $\mathcal{M}(n) \subseteq \mathcal{N}$. Furthermore $|\mathcal{M}(n)| = |\mathcal{N}|$. The argument in the first paragraph of Proposition 5.20 shows that $\mathcal{M}(n) = \mathcal{N}$.

5.3 Isomorphisms and layers

We continue to work at a prime p . In this section we discuss the difference between the closed substacks $\mathcal{M}(n)$ and $\mathcal{M}(n+1)$; that is, we discuss the geometry of

$$\mathcal{H}(n) \stackrel{\text{def}}{=} \mathcal{M}(n) - \mathcal{M}(n+1).$$

and the geometry of

$$\mathcal{M}(\infty) \stackrel{\text{def}}{=} \bigcap_n \mathcal{M}(n).$$

In both case we will find that we have stacks of the form $B\Lambda$ where Λ is the group of automorphisms of some height n formal group law. The group Λ is not an algebraic group as it is not finite; however, it will pro-étale in an appropriate sense. See Theorem 5.25.

Here is a preliminary result.

5.22 Lemma. *The inclusion*

$$f_n : \mathcal{H}(n) \longrightarrow \mathcal{M}_{\mathbf{fg}}$$

is an affine morphism of algebraic stacks.

Proof. Suppose $\text{Spec}(R) \rightarrow \mathcal{M}_{\mathbf{fg}}$ classifies a formal group G with a chosen coordinate x . Then the 2-category pull-back $\text{Spec}(R) \times_{\mathcal{M}_{\mathbf{fg}}} \mathcal{H}(n)$ is the groupoid scheme which assigns to each commutative ring S the triples (f, Γ, ϕ) where $f : R \rightarrow S$ is a morphism of commutative rings, Γ is formal group of exact height n over S and $\phi : \Gamma \rightarrow f^*G$ is an isomorphism of formal groups. An isomorphism of triples $(f, \Gamma, \phi) \rightarrow (f, \Gamma', \phi')$ is an isomorphism of formal groups $\psi : \Gamma \rightarrow \Gamma'$ so that $\phi'\psi = \phi$. Given such a triple, (f, Γ, ϕ) , the existence of ϕ forces f to factor as a composition

$$R \xrightarrow{q} R/\mathcal{I}_n(G)[u_n^{-1}] \xrightarrow{g} S$$

where $[p]_G(x) = u_n x^{p^n} + \dots$ modulo $\mathcal{I}_n(G)$. We now check that the morphism of groupoid schemes

$$\text{Spec}(R/\mathcal{I}_n(G)[u_n^{-1}]) \rightarrow \text{Spec}(R) \times_{\mathcal{M}_{\mathbf{fg}}} \mathcal{H}(n)$$

sending g to $(gq, (gq)^*G, 1)$ is an equivalence. For more general G , we use faithfully flat descent to describe the pullback as an affine scheme. \square

5.23 Remark. From this result and Proposition 5.9 we have that there is an $fpgc$ -cover

$$Y(n) \stackrel{\text{def}}{=} \text{Spec}(\mathbb{F}_p[u_n^{\pm 1}, u_{n+1}, u_{n+2}, \dots]) \rightarrow \mathcal{H}(n).$$

and that

$$Y(n) \times_{\mathcal{H}(n)} Y(n) \cong \text{Spec}(\mathbb{F}_p[u_n^{\pm 1}, u_{n+1}, u_{n+2}, \dots][t_0^{\pm 1}, t_1, t_2, \dots]).$$

Now let S be a scheme and let G_1 and G_2 be two formal groups over S . Define the scheme of isomorphisms from G_1 to G_2 by the 2-category pull-back

$$\begin{array}{ccc} \text{Iso}_S(G_1, G_2) & \longrightarrow & \mathcal{M}_{\text{fg}} \\ \downarrow & & \downarrow \Delta \\ S & \xrightarrow{G_1 \times G_2} & \mathcal{M}_{\text{fg}} \times \mathcal{M}_{\text{fg}}. \end{array}$$

Thus if $f : T \rightarrow S$ is a morphism of schemes, then a T -point of $\text{Iso}_S(G_1, G_2)$ is an isomorphism $\phi : f^*G_1 \rightarrow f^*G_2$ of formal groups over T . By Proposition 2.20, $\text{Iso}_S(G_1, G_2)$ is affine over S .

If G_3 is another formal group over S , then there is a composition

$$\text{Iso}_S(G_2, G_3) \times_S \text{Iso}_S(G_1, G_2) \longrightarrow \text{Iso}_S(G_1, G_3).$$

In particular, $\text{Aut}_S(G_1) = \text{Iso}_S(G_1, G_1)$ acts on the right on $\text{Iso}_S(G_1, G_2)$.

Because isomorphisms are locally given by power series, it is fairly clear that $\text{Iso}_S(G_1, G_2) \rightarrow S$ does not have good finiteness properties. To get well-behaved approximations, fix an integer k and let

$$\text{Iso}_S^k(G_1, G_2) \subseteq \text{Iso}_S(G_1, G_2)$$

be the normal subgroup functor which assigns to each scheme $f : T \rightarrow S$ over S the isomorphisms $\phi : f^*G_1 \rightarrow f^*G_2$ which become the identity on p^k -buds. Thus, in the presence of a coordinate $\phi(x) = x$ modulo x^{p^k+1} . Now define the quotient sheaf

$$\text{Iso}_S(G_1, G_2)_k = \text{Iso}_S(G_1, G_2) / \text{Iso}_S^k(G_1, G_2).$$

Let me emphasize that at this point $\text{Iso}_S(G_1, G_2)_k$ is only a sheaf, but we will see in Theorem 5.25 that it is actually an étale group scheme over S .

5.24 Remark. Let G_1 and G_2 be two formal groups over a scheme S and let $\text{Iso}_S((G_1)_{p^k}, (G_2)_{p^k})$ be the isomorphism scheme of the resulting p^k -buds. Thus, for $f : T \rightarrow S$, a T -point of $\text{Iso}_S((G_1)_{p^k}, (G_2)_{p^k})$ is an isomorphism of the p^k -buds $\phi : (G_1)_{p^k} \rightarrow (G_2)_{p^k}$. There is an evident map $\text{Iso}_S(G_1, G_2) \rightarrow \text{Iso}_S((G_1)_{p^k}, (G_2)_{p^k})$, but it is not onto; indeed, the image is $\text{Iso}_S(G_1, G_2)_k$.

I am very grateful to Eike Lau for pointing out this subtlety to me.

Let $\text{Iso}_S(G_1, G_2)_\infty = \text{Iso}_S(G_1, G_2)$ and let $\text{Iso}_S(G_1, G_2)_0 = S$; then there is a tower under $\text{Iso}_S(G_1, G_2)$ and over S with transition morphisms

$$\text{Iso}_S(G_1, G_2)_k \longrightarrow \text{Iso}_S(G_1, G_2)_{k-1}.$$

We have that

$$\mathrm{Iso}_S(G_1, G_2) \longrightarrow \lim \mathrm{Iso}_S(G_1, G_2)_k$$

is an isomorphism.

The following is a refined version of Lazard's uniqueness theorem. See Corollary 5.26 below.

5.25 Theorem. *Let S be a scheme over \mathbb{F}_p and let G_1 and G_2 be two formal groups of strict height n , $1 \leq n < \infty$ over S . Then*

$$\mathrm{Iso}_S(G_1, G_2)_1 \longrightarrow S$$

is a surjective and étale morphism of schemes of degree $p^n - 1$. For all $k > 1$, the morphism

$$\mathrm{Iso}_S(G_1, G_2)_k \longrightarrow \mathrm{Iso}_S(G_1, G_2)_{k-1}$$

is a surjective and étale morphism of schemes of degree p^n . Finally, the morphism

$$\mathrm{Iso}_S(G_1, G_2) \longrightarrow S$$

is surjective and pro-étale.

The proof is below in 5.29.

5.26 Corollary (Lazard's Uniqueness Theorem). *Let \mathbb{F} be a field of characteristic p and G_1 and G_2 two formal groups of strict height n . Then there is a separable extension $f : \mathbb{F} \rightarrow \mathbb{E}$ so that f^*G_1 and f^*G_2 are isomorphic. In particular, if \mathbb{F} is separably closed, then G_1 and G_2 are isomorphic.*

Proof. If the height $n < \infty$, this follows from the surjectivity statement of Theorem 5.25. If $n = \infty$, then the p -series of G_i must be zero; hence, a choice of p -typical coordinate for G_i defines an isomorphism from G_i to the additive formal group. \square

5.27 Remark. If G_1 and G_2 are two formal groups over a scheme S classified by maps $G_i : S \rightarrow \mathcal{M}_{\mathrm{fg}}$, we have a pull-back diagram

$$\begin{array}{ccc} \mathrm{Iso}_S(G_1, G_2) & \longrightarrow & S \times_{\mathcal{M}_{\mathrm{fg}}} S \\ \downarrow & & \downarrow \\ S & \xrightarrow{\Delta} & S \times S. \end{array}$$

If $S = \mathrm{Spec}(A)$ is affine and each of the formal groups G_i can be given a coordinate, then this writes (by Lemma 2.12) $\mathrm{Iso}_S(G_1, G_2)$ as the spectrum of the ring

$$A \otimes_{(A \otimes A)} A \otimes_L W \otimes_S A.$$

Thus if $x \in A$ we have (using the standard notation for Hopf algebroids)

$$x = \eta_R(x)$$

in this commutative ring. This makes it very unusual that

$$\mathrm{Iso}_S(G_1, G_2) \longrightarrow S$$

is flat, let alone étale. Thus the Theorem 5.25 is something of a surprise.

5.28 Example. We can be very concrete about the scheme $\mathrm{Aut}_{\mathbb{F}}(\Gamma_n)$ where Γ_n is of strict height n over a field \mathbb{F} . The formal group Γ_n can be given a coordinate and we can display $\mathrm{Aut}_{\mathbb{F}}(\Gamma_n)$ as

$$\mathrm{Aut}_{\mathbb{F}}(\Gamma_n) = \mathrm{Spec}(\mathbb{F} \otimes_L W \otimes_L \mathbb{F})$$

where $L \rightarrow \mathbb{F}$ classifies Γ_n with a choice of coordinate. For example, if $1 \leq n < \infty$ and if Γ_n is the Honda formal group over \mathbb{F}_p with coordinate so that $[p](x) = x^{p^n}$, then we have an isomorphism of Hopf algebras

$$(5.1) \quad \mathbb{F}_p \otimes_L W \otimes_L \mathbb{F}_p = \mathbb{F}_p[a_0^{\pm 1}, a_1, a_2, \dots] / (a_i^{p^n} - a_i).$$

This is the Hopf algebra analyzed by Ravenel in Chapter 6 of [48], where it is called the Morava stabilizer algebra. The scheme $\mathrm{Aut}_{\mathbb{F}}(\Gamma_n)_{p^k} = \mathrm{Iso}_{\mathbb{F}}(\Gamma_n, \Gamma_n)_k$ can be displayed as

$$\mathrm{Aut}_{\mathbb{F}}(\Gamma_n)_{p^k} = \mathrm{Spec}(\mathbb{F}_p[a_0^{\pm 1}, a_1, \dots, a_k] / (a_i^{p^n} - a_i)).$$

In the infinite height case, the failure to be étale can be easily seen: if we take $\Gamma_{\infty} = \hat{\mathbb{G}}_a$ with its standard coordinate, then

$$(5.2) \quad \mathbb{F}_p \otimes_L W \otimes_L \mathbb{F}_p = \mathbb{F}_p[a_0^{\pm 1}, a_1, a_2, \dots].$$

This is closely related to the mod p dual Steenrod algebra.

5.29 Proof of the Theorem 5.25. This argument is a rephrasing of an argument I learned from Neil Strickland [52]. But see also [29]. We will work inductively in k . We first note that we can reduce to the case where S is affine and both G_1 and G_2 have p -typical coordinates over S .

For example, to show that each of the sheaves $\mathrm{Iso}_S(G_1, G_2)_k$ is a scheme we can use descent. If $f : T \rightarrow S$ is any morphism, then

$$T \times_S \mathrm{Iso}_S(G_1, G_2)_k = \mathrm{Iso}_T(f^*G_1, f^*G_2)_k.$$

We will show that T is affine and G_1 and G_2 both have p -typical coordinates over T , then

$$T \times_S \mathrm{Iso}_S(G_1, G_2)_k \rightarrow T \times_S \mathrm{Iso}_S(G_1, G_2)_{k-1}$$

is an affine morphism of schemes. It then follows that there is a flat and surjective map $T \rightarrow S$ so that this morphism is affine when base-changed to T . By descent, it then follows that $\mathrm{Iso}_S(G_1, G_2)_k$ is a scheme affine over $\mathrm{Iso}_S(G_1, G_2)_{k-1}$.

Similarly, the properties listed – étale, degree, and surjectivity – are all local in the *fpqc*-topology on S ; thus, again we may assume that S is affine and that G_1 and G_2 can each be given a p -typical coordinate.

So write $S = \text{Spec}(A)$ and assume we have p -typical coordinates. Then we may write the p -series of of the formal groups

$$\begin{aligned} [p]_{G_1}(x) &= u_n x^{p^n} +_{G_1} u_{n+1} x^{p^{n+1}} + \cdots \\ [p]_{G_2}(x) &= u'_n x^{p^n} +_{G_2} u'_{n+1} x^{p^{n+1}} + \cdots \end{aligned}$$

and, hence, that the Verschiebungs may be written

$$\begin{aligned} V_{G_1}(x) &= u_n x +_{G_1} u_{n+1} x^p + \cdots \\ V_{G_2}(x) &= u'_n x +_{G_2} u'_{n+1} x^p + \cdots \end{aligned}$$

Because the formal groups have strict height n , u_n and u'_n are units.

First assume $k = 0$. Then an isomorphism $\phi : (G_1)_p \rightarrow (G_2)_p$ of p -typical formal group buds can be written $\phi(x) = b_0 x$ modulo (x^p) . Since $V_{G_2}(\phi^{(p^n)}(x)) = \phi(V_{G_1}(x))$ we have $u'_n b_0^{p^n} x = u_n b_0 x$. Since b_0 , u_n , and u'_n are all units we get an equation

$$(5.3) \quad b_0^{p^n - 1} - v = 0$$

where $v = u_n/u'_n$ is a unit. Thus,

$$\text{Iso}_S(G_1, G_2)_1 = \text{Spec}(A[b_0]/(b_0^{p^n - 1} - v)).$$

This is étale of degree $p^n - 1$ over $\text{Spec}(A)$ since b_0 is a unit in $A[b_0]/(b_0^{p^n - 1} - v)$. Surjectivity follows from the fact that $A \rightarrow A[b_0]/(b_0^{p^n - 1} - v)$ is faithfully flat.

Now assume $k > 0$ and keep the notation above. We make the inductive assumption that $\text{Iso}_S(G_1, G_2)_{k-1} = \text{Spec}(A_{k-1})$ for some A -algebra A_{k-1} . Suppose we have an isomorphism

$$\phi_0(x) : (G_1)_{p^{k-1}} \rightarrow (G_2)_{p^{k-1}}$$

of p^{k-1} -buds over some A -algebra R . We want to lift this to an isomorphism

$$\phi : (G_1)_{p^k} \rightarrow (G_2)_{p^k}$$

so that $\phi \equiv \phi_0$ as isomorphisms of $(G_1)_{p^{k-1}}$ to $(G_2)_{p^{k-1}}$. We may write $\phi(x) = \phi_0(x) +_{G_1} b_k x^{p^k}$. Then again we must have

$$V_{G_2}(\phi^{(p^n)}(x)) = \phi(V_{G_1}(x))$$

and, equating the coefficients of x^{p^k} we get an equation

$$(5.4) \quad b_k^{p^n} - v b_k + w = 0$$

where $v = u_n^{p^k}/u'_n$ is a unit. Thus,

$$\text{Iso}_S(G_1, G_2)_k = \text{Spec}(A_{k-1}[b_k]/(b_k^{p^n} - v b_k + w)).$$

This is faithfully flat, étale and of degree p^n over $\text{Spec}(A_{k-1})$. \square

If $G_1 = G_2$, we write $\text{Aut}_S(G_1)_k$ for $\text{Iso}_S(G_1, G_1)_k$; this is a étale group scheme over S if $k < \infty$. The projection morphism $\text{Iso}_S(G_1, G_2)_k \rightarrow S$ has a right action by $\text{Aut}_S(G_1)_k \rightarrow S$, $1 \leq k \leq \infty$ and this action induces a diagram of schemes over $\text{Iso}_S(G_1, G_2)$

$$\begin{array}{ccc} \text{Iso}_S(G_1, G_2)_k \times_S \text{Aut}_S(G_1)_k & \longrightarrow & \text{Iso}_S(G_1, G_2)_k \times_S \text{Iso}_S(G_1, G_2)_k \\ p_1 \downarrow & & \downarrow p_1 \\ \text{Iso}_S(G_1, G_2)_k & \xrightarrow{=} & \text{Iso}_S(G_1, G_2)_k \end{array}$$

where the top map is given pointwise by

$$(\phi, \psi) \mapsto (\phi, \phi\psi).$$

This map is evidently an isomorphism; hence we have proven the following result.

5.30 Proposition. *The morphism $\text{Iso}_S(G_1, G_2)_k \rightarrow S$ is an $\text{Aut}_S(G_1)_k$ -torsor.*

We can specialize this result even further, but first some notation and definitions.

5.31 Remark. If X is a finite set, define $X_{\mathbb{Z}}$ to be the scheme $\text{Spec}(\text{map}(X, \mathbb{Z}))$. Then for any category Y fibered in groupoids over affine schemes we get a new functor $Y \times X_{\mathbb{Z}}$. If $Y = \text{Spec}(R)$, then

$$Y \times X_{\mathbb{Z}} = \text{Spec}(\text{map}(X, R)) \stackrel{\text{def}}{=} X_R.$$

If G is a finite group, the $\mathbb{G}_{\mathbb{Z}}$ is a finite group scheme over \mathbb{Z} and the action of G on itself extends to a right action on $Y \times G_{\mathbb{Z}}$.

If $X = \lim X_k$ is a profinite set, define

$$X_{\mathbb{Z}} = \lim(X_k)_{\mathbb{Z}} = \text{Spec}(\text{colim map}(X_k, \mathbb{Z})).$$

If $G = \lim G_k$ is a profinite group, then $G_{\mathbb{Z}}$ is a profinite group scheme over \mathbb{Z} .

The notation $G_{\mathbb{Z}}$ is cumbersome; we will drop it if G is evidently a profinite group.

Now suppose $X \rightarrow S$ is a finite and étale morphism of schemes; let $\text{Aut}_S(X)$ denote the automorphisms of X over S . This is finite group. Then X is *Galois* over S if the natural map

$$\text{Aut}_S(X) \times_S X \longrightarrow X \times_S X$$

given pointwise by $(\phi, x) \mapsto (x, \phi(x))$ is an isomorphism. If $X = \lim X_k \rightarrow S$ where $\{X_k\}$ is a tower of finite and étale maps over S , then X is *pro-Galois* if there there is a coherent set of morphisms $\text{Aut}_S(X) \rightarrow \text{Aut}_S(X_k)$ so that

$$\text{Aut}_S(X) = \lim \text{Aut}_S(X_k)$$

and each of the morphism $X_k \rightarrow S$ is Galois.

5.32 Remark. Suppose that Γ is a formal group of height n over a separably closed field \mathbb{F} and let $\mathbb{G}_k(\Gamma)$ be the \mathbb{F} -points of $\text{Aut}_{\mathbb{F}}(\Gamma)_k$. If $k < \infty$, then $\mathbb{G}_k(\Gamma)$ has order $p^n k - 1$. The equations 5.3 and 5.4 imply that the natural map

$$\mathbb{G}_k(\Gamma)_{\mathbb{F}} \longrightarrow \text{Aut}_{\mathbb{F}}(\Gamma)_k, \quad k < \infty$$

is an isomorphism. Furthermore,

$$\mathbb{G}(\Gamma) \stackrel{\text{def}}{=} \mathbb{G}_{\infty}(\Gamma) \cong \lim \mathbb{G}_k(\Gamma).$$

This displays $\mathbb{G}(\Gamma)$ as a profinite group. Note that the equations 5.3 and 5.4 also imply that

$$\mathbb{G}_1(\Gamma) \cong \mathbb{F}_{p^n}^{\times} \quad \text{and} \quad \mathbb{G}_k(\Gamma)/\mathbb{G}_{k-1}(\Gamma) \cong \mathbb{F}_{p^n}.$$

5.33 Theorem. *Let S be a scheme over a separably closed field \mathbb{F} and let G_1 and G_2 be two formal groups of strict height n , $1 \leq n < \infty$ over S . Suppose that G_1 obtained by base change from a formal group Γ of height n over \mathbb{F}_p . Then for all $k < \infty$, the morphism*

$$\text{Iso}_S(G_1, G_2)_k \longrightarrow S$$

is Galois with Galois group $\mathbb{G}_k(\Gamma)$. Finally, the morphism

$$\text{Iso}_S(G_1, G_2) \longrightarrow S$$

is pro-Galois with Galois group $\mathbb{G}(\Gamma)$.

Proof. Let $f : T \rightarrow S$ be any morphism of schemes. Then

$$T \times_S \text{Iso}(G_1, G_2)_k \cong \text{Iso}_T(f^*G_1, f^*G_2)_k.$$

In particular

$$\text{Aut}_S(G_1)_k \cong S \times_{\text{Spec}(\mathbb{F})} \text{Aut}_{\mathbb{F}}(\Gamma)_k \cong \mathbb{G}_k(\Gamma)_S$$

and the result now follows from Proposition 5.30. \square

The étale extensions we produced in the proof of Theorem 5.25 were of a very particular type. See Equations 5.3 and 5.4. This can be rephrased Proposition 5.35 below, which can be proved by examining the proof just given. Here, however, we give a more conceptual proof, based on the following observation.

If R is an \mathbb{F}_p -algebra, let us write $f_R : R \rightarrow R$ for the Frobenius homomorphism sending x to x^p . If \mathcal{M} is any stack over $\text{Spec}(\mathbb{F}_p)$, we get a Frobenius homomorphism

$$f_{\mathcal{M}} : \mathcal{M} \longrightarrow \mathcal{M}$$

of stacks over $\text{Spec}(\mathbb{F}_p)$ which, upon evaluating at an \mathbb{F}_p algebra R is given by

$$f_{\mathcal{M}} = \mathcal{M}(f_R) : \mathcal{M}(R) \longrightarrow \mathcal{M}(R).$$

For example if $\mathcal{M}(1) = \mathcal{M}_{\mathbf{fg}} \otimes \text{Spec}(\mathbb{F}_p)$ is the moduli stack of formal group schemes over \mathbb{F}_p then

$$f_{\mathcal{M}}(G \rightarrow S) = G^{(p)} \rightarrow S.$$

5.34 Remark (The Frobenius trick). Let $\mathcal{H}(n)$ be the moduli stack of formal groups of exact height n , with $1 \leq n < \infty$. For all formal groups G of exact height n the *natural* factoring of the morphism $[p] : G \rightarrow G$ in Definition 5.2 yields a natural isomorphism

$$V_n = V_n^G : G^{(p^n)} \longrightarrow G.$$

Thus, if $f_{\mathcal{N}} : \mathcal{H}(n) \rightarrow \mathcal{H}(n)$ is the Frobenius – which, as we have just seen, assigns to each $G \rightarrow S$ the formal group $G^{(p)} \rightarrow S$ – we get a natural transformation

$$V_n : f_{\mathcal{N}}^n \longrightarrow 1$$

from $f_{\mathcal{N}}^n$ to the identity of $\mathcal{H}(n)$.

5.35 Proposition. *Let $0 \leq k_1 \leq k_2 \leq \infty$. Then the relative Frobenius*

$$\begin{array}{ccc} \text{Iso}_S(G_1, G_2)_{k_2} & \xrightarrow{F} & \text{Iso}_S(G_1, G_2)_{k_2}^{(p)} \\ & \searrow & \swarrow \\ & \text{Iso}_S(G_1, G_2)_{k_1} & \end{array}$$

is an isomorphism.

Proof. We will first do the absolute case of $\text{Iso}_S(G_1, G_2) \rightarrow S$ – that is, $k_1 = 0$ and $k_2 = \infty$ – and indicate at the end of the argument what changes are needed in general.

The scheme $\text{Iso}_S(G_1, G_2)^{(p)}$ over S assigns to each morphism $f : T \rightarrow S$ of schemes the set of isomorphisms

$$\psi : f^* G_1^{(p)} \longrightarrow f^* G_2^{(p)}.$$

The relative Frobenius $F : \text{Iso}_S(G_1, G_2) \rightarrow \text{Iso}_S(G_1, G_2)^{(p)}$ over S sends a T -point $\phi : f^* G_1 \rightarrow f^* G_2$ to the T -point $\phi^{(p)} : f^* G_1^{(p)} \rightarrow f^* G_2^{(p)}$. It is this we must show is an isomorphism. However, if we are given ψ , we may produce ϕ using the following commutative diagram of isomorphisms

$$\begin{array}{ccc} f^* G_1^{(p^n)} & \xrightarrow{\psi^{(p^{n-1})}} & f^* G_2^{(p^n)} \\ V_{G_1} \downarrow & & \downarrow V_{G_2} \\ f^* G_1 & \xrightarrow{\phi} & f^* G_2. \end{array}$$

As $V_{G^{(p)}} = (V_G)^{(p)}$ we may conclude that $\phi^{(p)} = \psi$ from the diagram

$$\begin{array}{ccccc} f^* G_1^{(p)} & \xleftarrow{V_{G_1}^{(p)}} & f^* G_1^{(p^{n+1})} & \xrightarrow{V_{G_1}^{(p)}} & f^* G_1^{(p)} \\ \phi^{(p)} \downarrow & & \downarrow \psi^{(p^n)} & & \downarrow \psi \\ f^* G_2^{(p)} & \xleftarrow{V_{G_2}^{(p)}} & f^* G_2^{(p^{n+1})} & \xrightarrow{V_{G_2}^{(p)}} & f^* G_2^{(p)}. \end{array}$$

The same proof works in the relative case, but the notation is more complicated, as $\text{Iso}_S(G_1, G_2)_k$ is a quotient group, and we must keep track of the cosets. \square

5.36 Proposition. *Let $\mathcal{N}(n) = \mathcal{H}(n)$ if $1 \leq n < \infty$ and let $\mathcal{N}(\infty) = \mathcal{M}(\infty)$. Let*

$$g : \text{Spec}(A) \rightarrow \mathcal{N}(n), \quad 1 \leq n \leq \infty$$

be any morphism. Then g is an fpqc-cover. In particular, g is faithfully flat.

Proof. If $g_i : \text{Spec}(A_i) \rightarrow \mathcal{H}(n)$ be any two maps. Then, by Theorem 5.25 there is a faithfully flat extension $A_1 \otimes A_2 \rightarrow B$ so that the two formal groups over the tensor product become isomorphic over B . Thus, we have a 2-commutative diagram

$$\begin{array}{ccc} \text{Spec}(B) & \xrightarrow{f_2} & \text{Spec}(A_2) \\ f_1 \downarrow & & \downarrow g_2 \\ \text{Spec}(A_1) & \xrightarrow{g_1} & \mathcal{H}(n) \end{array}$$

where both f_1 and f_2 are faithfully flat.

Now take g_1 to be faithfully flat and g_2 to be arbitrary. Then $g_1 f_1$ is faithfully flat and, since f_1 is faithfully flat, g_2 must be faithfully flat as well. Since

$$\text{Spec}(A_1) \otimes_{\mathcal{M}_{\mathbb{F}_g}} \text{Spec}(A_2) \rightarrow \text{Spec}(A_1)$$

is affine, it follows by descent that $\text{Spec}(A_2) \rightarrow \mathcal{M}(n)[v_n^{\pm 1}]$ is affine as well. In particular, it is quasi-compact. \square

The following is now immediate. We will almost always take \mathbb{F} to be an algebraic extension of \mathbb{F}_p .

5.37 Corollary. *Let $\mathcal{N}(n) = \mathcal{H}(n)$ if $1 \leq n < \infty$ and let $\mathcal{N}(\infty) = \mathcal{M}(\infty)$. Let \mathbb{F} be a field of characteristic p and $G \rightarrow \text{Spec}(\mathbb{F})$ any formal group of height n , $1 \leq n \leq \infty$. Then the classifying map for G*

$$\text{Spec}(\mathbb{F}) \longrightarrow \mathcal{N}(n)$$

is a cover in the fpqc-topology. In particular, $\mathcal{H}(n)$ and $\mathcal{M}(\infty)$ each has a single geometric point.

Now fix a formal group Γ_n over \mathbb{F}_p of height n ; for example, the Honda formal group. If $n = \infty$ we may as well fix $\Gamma_n = \hat{\mathbb{G}}_a$, the completion of the additive group. Define $\text{Aut}(\Gamma_n)$ to be the group scheme which assigns to each \mathbb{F}_p -algebra $i : \mathbb{F}_p \rightarrow A$ the automorphisms of the formal group $i^* \Gamma_n$ over A . See Example 5.28 for a concrete discussion.

5.38 Theorem. Let $\mathcal{H}(n) = \mathcal{M}(n) - \mathcal{M}(n+1)$ be the open substack of $\mathcal{M}(n)$ complementary to $\mathcal{M}(n+1)$. Then $\mathcal{H}(n)$ has a single geometric point represented by the formal group Γ_n of height n over \mathbb{F}_p . Furthermore, the map

$$\mathcal{H}(n) \longrightarrow B \operatorname{Aut}(\Gamma_n)$$

sending a formal group G of height n over an \mathbb{F}_p -algebra A to the $\operatorname{Aut}(\Gamma_n)$ -torsor $\operatorname{Iso}(\Gamma_n, G)$ is an equivalence of stacks.

5.39 Theorem. Let $\mathcal{M}(\infty) = \cap \mathcal{M}(n)$. Then $\mathcal{M}(\infty)$ has a single geometric point represented by the formal additive group $\hat{\mathbb{G}}_a$ over \mathbb{F}_p . Furthermore, the map

$$\mathcal{M}(\infty) \longrightarrow B \operatorname{Aut}(\hat{\mathbb{G}}_a)$$

sending a formal group G of infinite height over an \mathbb{F}_p -algebra A to the $\operatorname{Aut}(\hat{\mathbb{G}}_a)$ -torsor $\operatorname{Iso}(\hat{\mathbb{G}}_a, G)$ is an equivalence of stacks.

The apparent choice of the formal group Γ_n makes this result a bit puzzling. This can be rectified by coming to terms with the notion of a gerbe. Here we appeal to [33] §3.15ff.

5.40 Definition. 1.) Let S be a scheme and $X \rightarrow S$ a scheme over S . Then a **gerbe** over X is a stack $q : \mathcal{G} \rightarrow X$ over X with the properties that

- i.) for all affine $U \rightarrow S$ and all pairs of morphisms $x_1, x_2 : U \rightarrow \mathcal{G}$ so that $qx_1 = qx_2 : U \rightarrow X$, there is an faithfully flat covering $f : V \rightarrow U$ by an affine so that there is an isomorphism $f^*x_1 \cong f^*x_2$;
- ii.) for all affine $U \rightarrow S$ and all $f : U \rightarrow X$ over S , there is an faithfully flat covering $g : V \rightarrow U$ by an affine so that there is a morphism $x : V \rightarrow \mathcal{G}$ with $qx = fg$.

2.) A gerbe $q : \mathcal{G} \rightarrow X$ is **neutral** if there is a section $s : X \rightarrow \mathcal{G}$ of q .

The following is exactly Lemma 3.21 of [33]

5.41 Lemma. Suppose $q : \mathcal{G} \rightarrow X$ is a neutral gerbe over X . Then a section s of q determines an equivalence of stacks over X

$$\mathcal{G} \simeq B \operatorname{Aut}_{\mathcal{G}}(s/X)$$

where $\operatorname{Aut}(s/X)$ is the group scheme which assigns to each $f : U \rightarrow X$ the group $\operatorname{Aut}_{\mathcal{G}}(f^*s \rightarrow U)$. This equivalence sends $g \in \mathcal{G}(U)$ to the torsor $\operatorname{Iso}(sq(g), g)$.

5.42 Proof of Theorems 5.38 and 5.39. Let $\mathcal{N}(n) = \mathcal{H}(n)$ if $1 \leq n < \infty$ and let $\mathcal{N}(\infty) = \mathcal{M}(\infty)$. We claim that $\mathcal{N}(n) \rightarrow \operatorname{Spec}(\mathbb{F}_p)$ is a neutral gerbe. Then the result follows from Lemma 5.41. The two conditions to be gerbe are easily satisfied in this case: (1) any two height n formal groups over an \mathbb{F}_p -algebra A become isomorphic after a faithfully flat extension and (2) every \mathbb{F}_p algebra A has a height n formal group over it. Finally the choice of Γ_n shows that we have a neutral gerbe.

5.43 Remark. The *Morava stabilizer group* \mathbb{S}_n is defined to be the $\overline{\mathbb{F}}_p$ points of the algebraic group $\text{Aut}(\Gamma_n)$; that is, if $i : \mathbb{F}_p \rightarrow \overline{\mathbb{F}}_p$ is the inclusion, then \mathbb{S}_n is the automorphisms over $\overline{\mathbb{F}}_p$ of the formal group $i^*\Gamma_n$. By Theorem 5.26, this is independent of the choice of Γ_n . The *big Morava stabilizer group* \mathbb{G}_n is the group of 2-commuting diagrams

$$\begin{array}{ccc} \text{Spec}(\overline{\mathbb{F}}_p) & \longrightarrow & \text{Spec}(\overline{\mathbb{F}}_p) \\ & \searrow^{i^*\Gamma_n} & \swarrow_{i^*\Gamma_n} \\ & \mathcal{M}_{\text{fg}} & \end{array}$$

There is a semi-direct product decomposition

$$\mathbb{G}_n \cong \text{Gal}(\overline{\mathbb{F}}_p/\mathbb{F}_p) \rtimes \mathbb{S}_n.$$

6 Localizing sheaves at a height n point

In this section we define and discuss the sheaves $\mathcal{F}[v_n^{-1}]$ when \mathcal{F} is an \mathcal{I}_n -torsion quasi-coherent sheaf on the moduli stack \mathcal{M}_{fg} of formal groups. This is largely groundwork for the results on chromatic convergence to be proved later, but we do revisit the Landweber Exact Functor Theorem here, using a proof due to Mike Hopkins [18]. We begin with a discussion of the derived tensor product and derived completions, which – by results of Hovey [22] – have a particularly nice form for the stacks under consideration here.

6.1 Derived tensor products and derived completion

We will want to control the derived tensor product of two quasi-coherent sheaves on an algebraic stack \mathcal{M} . While this works particularly well if \mathcal{M} is quasi-compact and separated, for the stacks encountered in homotopy theory we can do even better: by using results of Mark Hovey, it is possible to give completely functorial construction using resolutions by locally free sheaves. This is because we will be able to assume that the category $\mathbf{Qmod}_{\mathcal{M}}$ of quasi-coherent sheaves is generated by the finitely generated locally free sheaves on \mathcal{M} . There is no reason to expect this assumption to hold in great generality, of course, but it holds when \mathcal{M} is one the stacks that arises in the chromatic picture. We will discuss this below in Proposition 6.7.

The following is a restatement of some of the results of [22] §2, especially Theorem 2.13 of that paper. Indeed, that result is a statement about the cofibrant objects in a model category structure on chain complexes of quasi-coherent sheaves. Weak equivalences can be deduced from point (2) of the next statement.

6.1 Proposition. *Let \mathcal{M} be an algebraic stack so that the finitely generated locally free sheaves generate the category of $\mathbf{Qmod}_{\mathcal{M}}$ of quasi-coherent sheaves*

on \mathcal{M} . Then for any chain complex of quasi-coherent sheaves \mathcal{F} on \mathcal{M} there is a natural quasi-isomorphism of chain complexes

$$\mathcal{P}_\bullet^{\mathcal{M}}(\mathcal{F}) = \mathcal{P}_\bullet \rightarrow \mathcal{F}_\bullet$$

with the properties that

1. for all n , the sheaf \mathcal{P}_n is a coproduct of finitely generated locally free sheaves;
2. for all finitely generated locally free sheaves \mathcal{V} on \mathcal{M} the morphism of function complexes

$$\mathrm{Hom}(\mathcal{V}, \mathcal{P}_\bullet) \longrightarrow \mathrm{Hom}(\mathcal{V}, \mathcal{F}_\bullet)$$

is a quasi-isomorphism.

Let \mathcal{F} be a sheaf on \mathcal{M} . In much of the sequel we will write $\mathcal{F}(R)$ for $\mathcal{F}(\mathrm{Spec}(R) \rightarrow \mathcal{M})$. We note that the tensor product of quasi-coherent sheaves behaves particularly well.

6.2 Lemma. *Let \mathcal{E} and \mathcal{F} be two quasi-coherent sheaves in the fpqc-topology on an algebraic stack \mathcal{M} . Then presheaf $\mathcal{E} \otimes \mathcal{F} = \mathcal{E} \otimes_{\mathcal{O}} \mathcal{F}$ which assigns to each flat and quasi-compact morphism $\mathrm{Spec}(R) \rightarrow \mathcal{M}$ the tensor product*

$$\mathcal{E}(R) \otimes_R \mathcal{F}(R)$$

is a quasi-coherent sheaf.

Proof. To see that we actually have a sheaf, let $R \rightarrow S$ be faithfully flat extension. Then

$$\mathcal{E}(R) \otimes_R \mathcal{F}(R) \longrightarrow \mathcal{E}(S) \otimes_S \mathcal{F}(S) \rightrightarrows \mathcal{E}(S \otimes_R S) \otimes_{(S \otimes_R S)} \mathcal{F}(S \otimes_R S)$$

is, up to isomorphism,

$$\mathcal{E}(R) \otimes_R \mathcal{F}(R) \longrightarrow S \otimes_R (\mathcal{E}(R) \otimes_R \mathcal{F}(R)) \rightrightarrows S \otimes_R S \otimes_R (\mathcal{E}(R) \otimes_R \mathcal{F}(R)).$$

If we apply $S \otimes_R (-)$ to the later sequence it becomes exact, as it has a retraction. Since $R \rightarrow S$ is faithfully flat, it was exact to begin with. This proves we have a sheaf; it is quasi-coherent because (as we have already noted)

$$S \otimes_R \mathcal{E}(R) \otimes_R \mathcal{F}(R) \xrightarrow{\cong} \mathcal{E}(S) \otimes_S \mathcal{F}(S).$$

□

6.3 Definition. *Suppose \mathcal{M} is an algebraic stack in the fpqc-topology so that the finitely generated locally free sheaves generated $\mathbf{Qmod}_{\mathcal{M}}$. Let \mathcal{E} and \mathcal{F} be two quasi-coherent sheaves on \mathcal{M} . Define their **derived tensor product** $\mathcal{E} \otimes^L \mathcal{F} = \mathcal{E} \otimes_{\mathcal{O}_{\mathcal{M}}}^L \mathcal{F}$ to be the chain complex of quasi-coherent sheaves (for the fpqc-topology) with values at $\mathrm{Spec}(R) \rightarrow \mathcal{M}$ given by*

$$\mathcal{E}(R) \otimes_R \mathcal{P}_\bullet(R)$$

where $\mathcal{P}_\bullet \rightarrow \mathcal{F}$ is the natural resolution of Proposition 6.1.

Many of the usual properties of tensor product apply to this construction. For example, if

$$0 \rightarrow \mathcal{E}_1 \rightarrow \mathcal{E}_2 \rightarrow \mathcal{E}_3 \rightarrow 0$$

is a short exact sequence of quasi-coherent sheaves, then we get a distinguished triangle in the derived category of quasi-coherent sheaves

$$\mathcal{E}_1 \otimes^L \mathcal{F} \rightarrow \mathcal{E}_2 \otimes_{\mathcal{O}_{\mathcal{M}}}^L \mathcal{F} \rightarrow \mathcal{E}_3 \otimes_{\mathcal{O}_{\mathcal{M}}}^L \mathcal{F} \rightarrow (\mathcal{E}_1 \otimes_{\mathcal{O}_{\mathcal{M}}}^L \mathcal{F})[-1].$$

This definition and the distinguished triangle generalize to the case when \mathcal{E} and \mathcal{F} are bounded below complex chain complexes of quasi-coherent sheaves.

Closely related to the derived tensor product is the derived completion.

6.4 Definition. *Let $\mathcal{Z} \subseteq \mathcal{M}$ be a closed substack defined by a quasi-coherent ideal sheaf \mathcal{I} . Let \mathcal{F} be a quasi-coherent sheaf on \mathcal{M} . Then the **derived completion** of \mathcal{F} at \mathcal{Z} by*

$$L(\mathcal{F})_{\mathcal{Z}}^{\wedge} = L(\mathcal{F})_{\mathcal{Z}}^{\wedge} = \text{holim}(\mathcal{O}/\mathcal{I}^n \otimes^L \mathcal{F}).$$

Thus, if $\text{Spec}(R) \rightarrow \mathcal{M}$ is faithfully flat and quasi-compact, we can set

$$L(\mathcal{F})_{\mathcal{Z}}^{\wedge}(R) = \lim P_{\bullet}(R)/\mathcal{I}^n(R)\mathcal{P}_{\bullet}(R).$$

This is an \mathcal{O} -module sheaf, but not necessarily quasi-coherent, as inverse limit and tensor product need not commute. If $j_n : \mathcal{Z}^{(n)} \subseteq \mathcal{M}$ are the infinitesimal neighborhoods of \mathcal{Z} defined by the powers of \mathcal{I} , then

$$L(\mathcal{F})_{\mathcal{Z}}^{\wedge} = \text{holim}(j_n)_*(Lj_n)^*\mathcal{F}$$

where $(Lj_n)^*$ is the total left derived functor of j_n^* .

We now turn to the question of when the hypotheses of Proposition 6.1 apply. There is a classical and useful notion from stable homotopy theory which guarantees that the finitely generated locally free sheaves generate the category of quasi-coherent sheaves.

6.5 Definition. 1.) *A Hopf algebroid (A, Λ) is an **Adams Hopf algebroid** if the left unit $A \rightarrow \Lambda$ is flat and the (A, Λ) -comodule Λ can be written as a filtered colimit of comodules Λ_i each of which is a finitely generated projective A -module.*

2.) *An algebraic stack \mathcal{M} will be an **Adams stack** if there is an *fpqc*-presentation $\text{Spec}(A) \rightarrow \mathcal{M}$ so that*

$$\text{Spec}(A) \times_{\mathcal{M}} \text{Spec}(A) \cong \text{Spec}(\Lambda)$$

is itself affine and the resulting Hopf algebroid (A, Λ) is an Adams Hopf algebroid.

6.6 Remark. 1.) Definition 6.5 has a curious and unfortunate feature. We would like to assert that if \mathcal{M} has one *fpqc*-presentation $\text{Spec}(A) \rightarrow \mathcal{M}$ so that (A, Λ) is an Adams Hopf algebroid then any other *fpqc* presentation would have

the same property. But this is not known. See [22], Question 1.4.2.⁶ However, we do have the following rephrasing of Proposition 1.4.4 of [22].

2.) More generally, one can ask whether the category of quasi-coherent sheaves on an algebraic stack has the property that its category of quasi-coherent sheaves can be generated by the finitely generated locally free sheaves. Results of Thomason [54] imply that this will be the case if for homotopy orbit stacks of the form $X \times_G EG$, at least under appropriate finiteness hypotheses. Totaro [55] has considered the converse. Section 2 of that paper has a history of this problem as well.

6.7 Proposition. *Let \mathcal{M} be an Adams stack. Then the finitely generated locally free sheaves generate the category $\mathbf{Qmod}_{\mathcal{M}}$ of quasi-coherent sheaves on \mathcal{M} .*

We now make good on our claim that most of the stacks in this monograph are of this kind.

6.8 Proposition. *For all n , $0 \leq n \leq \infty$, the moduli stack $\mathcal{M}_{\mathbf{fg}}\langle n \rangle$ of n -buds of formal groups is an Adams stack.*

Proof. We show that the evident presentation

$$\mathrm{Spec}(L\langle n \rangle) \longrightarrow \mathcal{M}_{\mathbf{fg}}\langle n \rangle$$

has the desired property. Recall from Proposition 3.1 that

$$\mathrm{Spec}(L\langle n \rangle) \times_{\mathcal{M}_{\mathbf{fg}}\langle n \rangle} \mathrm{Spec}(L_n) \cong \mathrm{Spec}(W\langle n \rangle) \cong \mathbf{fgl}\langle n \rangle \times \Lambda\langle n \rangle.$$

We use the gradings of Remark 3.14 and, especially, Remark 3.16.2.

Let

$$A_{n,i} \subseteq \mathbb{Z}[a_1, \dots, a_{n-1}] \subseteq \mathbb{Z}[a_0^{\pm 1}, a_1, \dots, a_{n-1}]$$

be the elements of degree less than or equal to i , let

$$B_{n,i} = \bigoplus_{-i \leq s \leq i} A_{n,i} a_0^s \subseteq \mathbb{Z}[a_0^{\pm 1}, \dots, a_{n-1}]$$

and let

$$W\langle n, i \rangle = L\langle n \rangle \otimes B_{n,i}.$$

Then $W\langle n, i \rangle$ is a finitely generated free $L\langle n \rangle$ module, a sub-comodule of $W\langle n \rangle$, and $\mathrm{colim}_i W\langle n, i \rangle = W\langle n \rangle$. \square

6.9 Proposition. *The following stacks are Adams stacks.*

1. $\mathcal{M}(n)$, the closed substack of $\mathcal{M}_{\mathbf{fg}} \otimes \mathbb{Z}_{(p)}$ of formal groups of height at least n ;
2. $\mathcal{H}(n) = \mathcal{M}(n)[v^{-1}]$, the open substack of $\mathcal{M}(n)$ of formal groups of exactly height n ;

⁶This problem could be avoided by working with resolutions by appropriately flat modules; these exist over any quasi-compact and separated stack. See [1] §1. I have chosen to use the Adams condition only because it fits better with the culture of homotopy theory.

3. $\mathcal{U}(n)$, the open substack of $\mathcal{M}_{\mathbf{fg}} \otimes \mathbb{Z}_{(p)}$ of formal groups of height at most n .

Proof. Because we have base-changed over $\mathbb{Z}_{(p)}$, we can choose the morphism

$$\mathrm{Spec}(\mathbb{Z}_{(p)}[u_1, u_2, \dots]) \rightarrow \mathcal{M}_{\mathbf{fg}} \otimes \mathbb{Z}_{(p)}$$

representing the universal p -typical formal group as the presentation. Then we have presentations

$$\mathrm{Spec}(\mathbb{F}_p[u_n, u_{n-1}, \dots]) \rightarrow \mathcal{M}(n)$$

and

$$\mathrm{Spec}(\mathbb{F}_p[u_n^{\pm 1}, u_{n-1}, \dots]) \rightarrow \mathcal{H}(n)$$

and

$$\mathrm{Spec}(\mathbb{Z}_{(p)}[u_1, \dots, u_{n-1}, u_n^{\pm 1}]) \rightarrow \mathcal{U}(n).$$

Then we appeal to Theorem 1.4.9 and Proposition 1.4.11. of [22]. \square

6.2 Torsion modules and inverting v_n

In the next section on Landweber exactness, and later when we discuss chromatic convergence, we are going to need some technical lemmas about inverting v_n for \mathcal{I}_n -torsion sheaves on $\mathcal{M}_{\mathbf{fg}}$. We begin with some definitions so that we can work in some generality with algebraic stacks \mathcal{N} flat over $\mathcal{M}_{\mathbf{fg}}$. The following definition generalizes the definition of regular scale given in [37].

6.10 Definition. Let \mathcal{N} be an algebraic stack and

$$0 = \mathcal{J}_0 \subseteq \mathcal{J}_1 \subseteq \mathcal{J}_2 \subseteq \dots \subseteq \mathcal{O}_{\mathcal{N}}$$

be an ascending sequence of ideal sheaves. Then the sequence $\{\mathcal{J}_n\}$ forms a **regular scale** for \mathcal{N} if for all n , the ideal sheaf $\mathcal{J}_{n+1}/\mathcal{J}_n$ is locally free of rank 1 as a $\mathcal{O}/\mathcal{J}_n$ module. A regular scale is a **finite** if $\mathcal{J}_n = \mathcal{O}$ for some n .

6.11 Remark. Given a regular scale on \mathcal{N} , let $\mathcal{N}(n)$ denote that closed substack defined by \mathcal{J}_n . Then $\mathcal{N}(n) \subseteq \mathcal{N}(n-1)$ is an effective Cartier divisor for $\mathcal{N}(n-1)$. An embedding $\mathcal{Z} \subseteq \mathcal{N}$ of a closed substack is called *regular* if the ideal defining the embedding is locally generated by a regular sequence. Thus a regular scale produces regular embeddings $\mathcal{N}(n) \subseteq \mathcal{N}$, but it does more: it specifies the terms in the regular sequence modulo the lower terms.

6.12 Example. Fix a prime p , let $\mathcal{M} = \mathcal{M}_{\mathbf{fg}}$ and let

$$0 \subseteq \mathcal{I}_1 \subseteq \mathcal{I}_2 \subseteq \dots \subseteq \mathcal{O}_{\mathbf{fg}}$$

be the ascending chain of ideals giving the closed substacks $\mathcal{M}(n) \subseteq \mathcal{M}_{\mathbf{fg}}$ classifying formal groups of height greater than or equal to n . This, of course, is the basic example of a regular scale. This scale is not finite; however, if we let

$i_n : \mathcal{U}(n) \rightarrow \mathcal{M}_{\mathbf{fg}}$ be the open substack classifying formal groups of height less than or equal to n , then

$$i_n^* \mathcal{I}_0 \subseteq i_n^* \mathcal{I}_1 \subseteq i_n^* \mathcal{I}_2 \subseteq \cdots \subseteq i_n^* \mathcal{O}_{\mathbf{fg}} = \mathcal{O}_{\mathcal{U}(n)}$$

is a finite regular scale as $i_n^* \mathcal{I}_n = i_n^* \mathcal{I}_k = \mathcal{O}_{\mathcal{U}(n)}$ for $k \geq n$.

This example can be generalized to stacks \mathcal{N} representable and flat over $\mathcal{M}_{\mathbf{fg}}$. See Proposition 5.10.

We now come to torsion modules and inverting v_n . Let \mathcal{N} be an algebraic stack and let $\{\mathcal{J}_n\}$ be a scale for \mathcal{N} . Let $j_n : \mathcal{N}(n) \subseteq \mathcal{N}$ be the closed inclusion defined by \mathcal{J}_n and let $i_{n-1} : \mathcal{V}(n-1) \rightarrow \mathcal{N}$ be the open complement. (The numerology is chosen to agree with case of $\mathcal{I}_n \subseteq \mathcal{O}_{\mathbf{fg}}$.) Let's write \mathcal{O} for $\mathcal{O}_{\mathcal{N}}$.

6.13 Definition. An \mathcal{O} -module sheaf \mathcal{F} is **supported on $\mathcal{N}(n)$** if $i_{n-1}^* \mathcal{F} = 0$. We also say that \mathcal{F} is **\mathcal{J}_n -torsion** if for any flat and quasi-compact morphism $\mathrm{Spec}(R) \rightarrow \mathcal{M}_{\mathbf{fg}}$, the R -module $\mathcal{F}(R)$ is $\mathcal{I}_n(R)$ -torsion.

In Definition 6.13 we do not assume that \mathcal{F} is quasi-coherent; however, the next result shows that the two notions defined there are equivalent for quasi-coherent sheaves.

6.14 Lemma. Let \mathcal{F} be a quasi-coherent \mathcal{O} -module sheaf. Then \mathcal{F} is supported on $\mathcal{N}(n)$ if and only if \mathcal{F} is \mathcal{J}_n -torsion.

Proof. This is a consequence of the fact that \mathcal{J}_n defines a regular embedding. For each flat and quasi-compact morphism $\mathrm{Spec}(R) \rightarrow \mathcal{M}_{\mathbf{fg}}$, choose – by passing to a faithfully flat extension if necessary – generators (p, u_1, \dots, u_{n-1}) of $\mathcal{J}_n(R)$.

First suppose \mathcal{F} is supported on $\mathcal{N}(n)$. Then there are commutative diagrams

$$\begin{array}{ccc} \mathrm{Spec}(R[u_i^{-1}]) & \xrightarrow{\subseteq} & \mathrm{Spec}(R) \\ \downarrow & & \downarrow \\ V(n-1) & \xrightarrow{\subseteq} & \mathcal{N}. \end{array}$$

Thus $R[u_i^{-1}] \otimes_R \mathcal{F}(R) \cong \mathcal{F}(R[u_i^{-1}]) = 0$, and we may conclude that $\mathcal{F}(R)$ is $\mathcal{J}_n(R)$ -torsion.

Conversely, suppose \mathcal{F} is \mathcal{J}_n -torsion and $\mathrm{Spec}(R) \rightarrow V(n-1)$ is any flat and quasi-compact morphism. Then $\mathcal{J}_n(R) = R$, so $\mathcal{J}_n(R)^k = R$ for all $k > 0$. If $x \in \mathcal{F}(R)$, then $Rx = \mathcal{J}_n(R)^k x = 0$ for some k , whence $x = 0$. Thus $i_{n-1}^* \mathcal{F} = 0$. \square

In the following result, let hom denote the sheaf of homomorphisms.

6.15 Lemma. Let \mathcal{F} be a quasi-coherent \mathcal{J}_n -torsion sheaf. Then evaluation defines a natural isomorphism

$$\mathrm{colim} \mathrm{hom}_{\mathcal{O}}(\mathcal{O}/\mathcal{J}_n^k, \mathcal{F}) \xrightarrow{\cong} \mathcal{F}.$$

If $f_k : \mathcal{N}(n)_k \subseteq \mathcal{N}$ is the inclusion of the k th infinitesimal neighborhood of $\mathcal{N}(n)$ defined by the vanishing of \mathcal{I}_n^k , then there is a quasi-coherent sheaf \mathcal{F}_k on $\mathcal{N}(n)_k$ and a natural isomorphism

$$(f_k)_* \mathcal{F}_k \cong \mathrm{hom}_{\mathcal{O}}(\mathcal{O}/\mathcal{I}_n^k, \mathcal{F}).$$

Proof. The first statement can be checked locally, and there it follows from the fact that \mathcal{J}_n is finitely generated. For the second statement, we use the fact that any closed inclusion is affine (see 1.15). From this it follows that $(f_k)_*$ induces an equivalence between the categories of quasi-coherent $\mathcal{O}/\mathcal{J}_n^k$ -modules on \mathcal{N} and the category of quasi-coherent modules on $\mathcal{N}(n)_k$. See Proposition 1.16. \square

Suppose \mathcal{F} is a quasi-coherent \mathcal{J}_n -torsion sheaf. The Lemma 6.14 implies that $i_{n-1}^* \mathcal{F} = 0$. We next consider $i_n^* \mathcal{F}$ or, more exactly, the resulting push-forward $(i_n)_* i_n^* \mathcal{F}$, which is a sheaf on \mathcal{N} . The next result shows that the natural map

$$(i_n)_* i_n^* \mathcal{F} \rightarrow R(i_n)_* i_n^* \mathcal{F}$$

is an equivalence and gives a local description of $(i_n)_* i_n^* \mathcal{F}$.

6.16 Proposition. *Let \mathcal{F} be a quasi-coherent \mathcal{J}_n -torsion sheaf on \mathcal{N} . Let $\mathrm{Spec}(R) \rightarrow \mathcal{N}$ be any flat and quasi-compact morphism so that $\mathcal{J}_n(R)/\mathcal{J}_{n-1}(R)$ is free of rank one over $R/\mathcal{J}_{n-1}(R)$. Then we have an isomorphism*

$$[(i_n)_* i_n^* \mathcal{F}](R) \cong \mathcal{F}[u_n^{-1}]$$

where $u_n \in \mathcal{J}_n(R)$ is any element so that $u_n + \mathcal{J}_{n-1}(R)$ generates the R -module $\mathcal{J}_n(R)/\mathcal{J}_{n-1}(R)$. Furthermore,

$$R^s(i_n)_* i_n^* \mathcal{F} = 0, \quad s > 0.$$

Proof. By Lemma 6.15 and a colimit argument, we may assume that $\mathcal{F} = f_* \mathcal{E}$ for some quasi-coherent sheaf \mathcal{E} on the k th infinitesimal neighborhood $f : \mathcal{N}(n)_k \rightarrow \mathcal{N}$ of $\mathcal{N}(n)$.

Consider the pull-back square⁷

$$\begin{array}{ccc} \mathcal{N}(n)_k \times_{\mathcal{N}} \mathcal{V}(n) & \xrightarrow{p_2} & \mathcal{V}(n) \\ p_1 \downarrow & & \downarrow i_n \\ \mathcal{N}(n)_k & \xrightarrow{f} & \mathcal{N}. \end{array}$$

Then $i_n^* f_* \mathcal{E} = (p_2)_* p_1^* \mathcal{E}$; thus, we may conclude that we have an equivalence in the derived category

$$(6.1) \quad R(i_n)_* i_n^* f_* \mathcal{E} \simeq f_* R(p_1)_* p_1^* \mathcal{E}.$$

⁷In the case where $\mathcal{N} = \mathcal{M}_{\mathbf{fg}}$ and $\mathcal{J}_n = \mathcal{I}_n$, we have that $\mathcal{N}(n)_k \times_{\mathcal{N}} \mathcal{V}(n)$ is the k th infinitesimal neighborhood of $\mathcal{H}(n)$.

The open inclusion $\mathcal{N}(n)_k \times_{\mathcal{N}} \mathcal{V}(n) \subseteq \mathcal{N}(n)_k$ is the complement of the closed inclusion $\mathcal{N}(n+1) \subseteq \mathcal{N}(n)_k$. Locally, this closed inclusion is defined by the vanishing of u_n . We see that this implies

$$(6.2) \quad R(p_1)_* p_1^* \mathcal{E} \simeq (p_1)_* p_1^* \mathcal{E} \cong \mathcal{E}[u_n^{-1}].$$

The result now follows because f_* is exact. \square

6.17 Remark. Now let $f : \mathcal{N} \rightarrow \mathcal{M}_{\mathbf{fg}}$ be a representable and flat morphism of algebraic stacks and let $\{\mathcal{J}_n\} = \{f^* \mathcal{I}_n\}$ be the resulting scale. See Proposition 5.10. Regard v_n as a global section of ω^{p^n-1} considered as a sheaf over $\mathcal{N}(n)$. Suppose \mathcal{F} is actually an $\mathcal{O}/\mathcal{J}_n$ -module sheaf; that is, suppose $\mathcal{F} = (j_n)_* \mathcal{E}$ for some quasi-coherent sheaf \mathcal{E} on $\mathcal{N}(n)$. Then we can form the colimit sheaf $\mathcal{F}[v_n^{-1}]$ of the sequence

$$\mathcal{F} \xrightarrow{v_n} \mathcal{F} \otimes \omega^{p^n-1} \xrightarrow{v_n} \mathcal{F} \otimes \omega^{2(p^n-1)} \xrightarrow{v_n} \dots$$

We claim that $\mathcal{F}[v_n^{-1}] \cong (i_n)_* i_n^* \mathcal{F}$.

By Equations 6.1 and 6.2, and because $(j_n)_*$ is exact, it is sufficient to show

$$\mathcal{E}[v_n^{-1}] \cong (p_1)_* p_1^* \mathcal{E}.$$

Since multiplication by v_n is invertible for sheaves on

$$\mathcal{N}(n) \times_{\mathcal{N}} \mathcal{V}(n) \cong \mathcal{H}(n) \times_{\mathcal{M}_{\mathbf{fg}}} \mathcal{N},$$

the natural map $\mathcal{E} \rightarrow (p_1)_* p_1^* \mathcal{E}$ factors as a map $\mathcal{E}[v_n^{-1}] \rightarrow (p_1)_* p_1^* \mathcal{E}$. To show this is an isomorphism we need only work locally. Let

$$G : \text{Spec}(R) \longrightarrow \mathcal{M}(n)$$

be a flat and quasi-compact morphism classifying a formal group G . Taking a faithfully flat extension if needed, we may choose an invariant derivation $u \in \omega_G^{-1}$ for G generating the free R -module ω_G^{-1} ; then the element

$$u_n \stackrel{\text{def}}{=} u^{(p^n-1)} v_n(G) \in R = \omega_G^0$$

generates $\mathcal{J}_n(R) = \mathcal{J}_n(R)/\mathcal{J}_{n-1}(R)$. Then we have a commutative diagram

$$\begin{array}{ccccccc} \mathcal{E}(G) & \xrightarrow{v_n} & \mathcal{E}(G) \otimes \omega^{p^n-1} & \xrightarrow{v_n} & \mathcal{E}(G) \otimes \omega^{2(p^n-1)} & \xrightarrow{v_n} & \dots \\ \downarrow = & & \downarrow u^{p^n-1} & & \downarrow u^{2(p^n-1)} & & \\ \mathcal{E}(G) & \xrightarrow{u_n} & \mathcal{E}(G) & \xrightarrow{u_n} & \mathcal{E}(G) & \xrightarrow{u_n} & \dots \end{array}$$

Since the vertical maps are isomorphisms, the claim follows from Proposition 6.16.

This observation can easily be generalized to the case where \mathcal{F} is an $\mathcal{O}/\mathcal{J}_n^k$ -module sheaf for any $k \geq 1$ because a power of v_n is a global section of the appropriate power of ω .

Because of the previous remark, the following definition does not create an ambiguity.

6.18 Definition. *Let $f : \mathcal{N} \rightarrow \mathcal{M}_{\mathbf{fg}}$ be a representable and flat morphism of algebraic stacks and let $\{\mathcal{J}_n\} = \{f^*\mathcal{I}_n\}$ be the resulting scale for \mathcal{N} . If \mathcal{F} is a quasi-coherent \mathcal{J}_n -torsion sheaf on \mathcal{N} define*

$$\mathcal{F}[v_n^{-1}] = (i_n)_*i_n^*\mathcal{F}.$$

6.3 LEFT: A condition for flatness

Let $f : \mathcal{N} \rightarrow \mathcal{M}_{\mathbf{fg}}$ be a representable morphism of algebraic stacks. We would like to give a concrete and easily checked condition on this morphism to guarantee that it be flat. This condition is a partial converse to Proposition 5.10 and a version of the Landweber Exact Functor Theorem (LEFT). This theorem has a variety of avatars; the one we give here is due to Hopkins and Miller. See [18] and [37]. The original source is [32].

In this section we will work over $\mathcal{M}_{\mathbf{fg}}$ over $\mathrm{Spec}(\mathbb{Z})$, rather than at a given prime.

Now let $f : \mathcal{N} \rightarrow \mathcal{M}_{\mathbf{fg}}$ be a representable, quasi-compact, and quasi-separated morphism of stacks. The hypotheses on the morphism guarantee that if \mathcal{F} is a quasi-coherent sheaf on \mathcal{N} , then $f_*\mathcal{F}$ is a quasi-coherent sheaf on $\mathcal{M}_{\mathbf{fg}}$. Compare Proposition 1.6. Let $\mathcal{J}_n \subseteq \mathcal{O}_{\mathcal{N}}$ be the kernel of the morphism

$$\mathcal{O}_{\mathcal{N}} = f^*\mathcal{O}_{\mathbf{fg}} \rightarrow f^*(\mathcal{O}_{\mathbf{fg}}/\mathcal{I}_n).$$

Thus \mathcal{J}_n defines the closed inclusion

$$j_n : \mathcal{N}(n) = \mathcal{M}(n) \times_{\mathcal{M}_{\mathbf{fg}}} \mathcal{N} \xrightarrow{\subseteq} \mathcal{N}.$$

Thus there is a surjection $f^*\mathcal{I}_n \rightarrow \mathcal{J}_n$ which becomes an isomorphism if f is flat. Also note that

$$(j_n)_*\mathcal{O}_{\mathcal{N}(n)} = \mathcal{O}_{\mathcal{N}}/\mathcal{J}_n = \mathcal{O}_{\mathcal{N}}/f^*\mathcal{I}_n.$$

From this we can conclude that the global section $v_n \in H^0(\mathcal{M}(n), \omega^{p^n-1})$ defines a surjection

$$v_n : \mathcal{O}_{\mathcal{N}}/\mathcal{J}_{n-1} \rightarrow \mathcal{J}_n/\mathcal{J}_{n-1} \otimes \omega^{p^n-1}.$$

This includes the case $n = 0$; we set $v_0 = p$. The basic criterion of flatness is the following. Note that if \mathcal{N} is a stack over $\mathbb{Z}_{(\ell)}$ for some prime ℓ , then the hypotheses are automatically true for all prime $p \neq \ell$. This remark will have a variant for all our other versions of Landweber exactness below.

6.19 Theorem (Landweber Exactness I). *Let $f : \mathcal{N} \rightarrow \mathcal{M}_{\mathbf{fg}}$ be a representable, quasi-compact, and quasi-separated morphism of stacks. Suppose that for all primes p ,*

1. $v_n : \mathcal{O}_{\mathcal{N}}/\mathcal{J}_{n-1} \rightarrow \mathcal{J}_n/\mathcal{J}_{n-1} \otimes \omega^{p^n-1}$ is an isomorphism, and

2. $\mathcal{I}_n = \mathcal{O}_{\mathcal{N}}$ for large n .

Then f is flat. Conversely, if for all primes p , $\mathcal{I}_n = \mathcal{O}_{\mathcal{N}}$ for some n , then f is flat only if condition (1) holds.

6.20 Remark. The hypotheses of Theorem 6.19 imply, in particular, that the ideals \mathcal{I}_n form a finite regular scale for \mathcal{N} ; in particular, in the descending chain of closed substacks

$$\cdots \subseteq \mathcal{N}(n) \subseteq \mathcal{N}(n-1) \subseteq \cdots \subseteq \mathcal{N}(1) \subseteq \mathcal{N}$$

each of the inclusions is that of an effective Cartier divisor and that there is an n so that $\mathcal{N}(k)$ is empty for $k > n$. Furthermore, an inductive argument shows that the natural surjections $f^*\mathcal{I}_n \rightarrow \mathcal{I}_n$ are, in fact, isomorphisms. Indeed, if $f^*\mathcal{I}_{n-1} \cong \mathcal{I}_{n-1}$, then we obtain a diagram

$$\begin{array}{ccc} & & f^*\mathcal{I}_n/f^*\mathcal{I}_{n-1} \\ & \nearrow v_n & \downarrow \\ \mathcal{O}_{\mathcal{N}}/f^*\mathcal{I}_{n-1} & & \mathcal{I}_n/f^*\mathcal{I}_{n-1} \\ & \searrow v_n & \\ & & \mathcal{I}_n/f^*\mathcal{I}_{n-1} \end{array}$$

and we can conclude $f^*\mathcal{I}_n/f^*\mathcal{I}_{n-1} \rightarrow \mathcal{I}_n/\mathcal{I}_{n-1}$ is an isomorphism.

By specializing to the affine case and using Remark 5.7, we obtain a more classical version of Landweber exactness.

6.21 Corollary. Let $g : \text{Spec}(A) \rightarrow \mathcal{M}_{\mathbf{fg}}$ classify a formal group G with a coordinate x . For all primes p , let p, u_1, u_2, \dots be elements of A so that the p -series can be written

$$[p](x) = u_k x^{p^k} + \cdots$$

modulo (p, u_1, \dots, u_{k-1}) . Suppose the elements p, u_1, \dots form a regular sequence and suppose there is some n so that

$$(p, u_1, \dots, u_{n-1}) = A$$

Then g is flat.

In Landweber's original paper [32] the hypothesis that $\mathcal{I}_n(G) = A$ for some n was not required. This finiteness condition was removed by Naumann in [41] using some ideas of Mark Behrens. I believe Hollander also has a way to remove this hypothesis. See [15].

6.22 Remark. We can reformulate the hypotheses of Theorem 6.19 as conditions on the quasi-coherent algebra sheaf $f_*\mathcal{O}_{\mathcal{N}}$ on $\mathcal{M}_{\mathbf{fg}}$. As a matter of notation, let's write

$$\mathcal{F}/\mathcal{I}_n \stackrel{\text{def}}{=} (j_n)_* j_n^* \mathcal{F}$$

for any \mathcal{F} be a quasi-coherent sheaf on $\mathcal{M}_{\mathbf{fg}}$. We will say that the regular scale $\{\mathcal{I}_n\}$ acts **regularly and finitely** on \mathcal{F} if for all n

$$v_n : \mathcal{F}/\mathcal{I}_n \longrightarrow \mathcal{F}/\mathcal{I}_n \otimes \omega^{p^n-1}$$

is injective and $\mathcal{F}/\mathcal{I}_n = 0$ for large n . Because have a pull-back square for all n

$$\begin{array}{ccc} \mathcal{M}(n) \times_{\mathcal{M}_{\mathbf{fg}}} \mathcal{N} & \longrightarrow & \mathcal{N} \\ \downarrow & & \downarrow f \\ \mathcal{M}(n) & \xrightarrow{j_n} & \mathcal{M}_{\mathbf{fg}} \end{array}$$

we have that $f_*(\mathcal{O}_{\mathcal{N}}/\mathcal{J}_n) = (f_*\mathcal{O}_{\mathcal{N}})/\mathcal{I}_n$.

Suppose the hypotheses of Theorem 6.19 hold. Then

$$v_n : \mathcal{O}_{\mathcal{N}}/\mathcal{J}_{n-1} \rightarrow \mathcal{O}_{\mathcal{N}}/\mathcal{J}_{n-1} \otimes \omega^{p^n-1}$$

is injective and $\mathcal{O}_{\mathcal{N}}/\mathcal{J}_n = 0$ for large n . Since f_* is left exact, we have that $\{\mathcal{I}_n\}$ acts regularly and finitely on $f_*\mathcal{O}_{\mathcal{N}}$.

Conversely, suppose $\{\mathcal{I}_n\}$ acts regularly and finitely on $f_*\mathcal{O}_{\mathcal{N}}$. We will see below in Theorem 6.26 that this implies that f is a flat morphism, which in turn implies that $f^*\mathcal{I}_n = \mathcal{J}_n$ and, hence, that

$$f^*(\mathcal{I}_n/\mathcal{I}_{n-1}) = \mathcal{J}_n/\mathcal{J}_{n-1}.$$

This, in its turn, implies that the hypotheses of Theorem 6.19 hold. Thus, Theorem 6.19 is equivalent to the following result.

6.23 Theorem (Landweber Exactness II). *Let $f : \mathcal{N} \rightarrow \mathcal{M}_{\mathbf{fg}}$ be a representable, quasi-compact, and quasi-separated morphism of stacks. Suppose that for all primes, the set of ideals $\{\mathcal{I}_n\}$ acts regularly and finitely on $f_*\mathcal{O}_{\mathcal{N}}$. Then f is flat.*

Conversely, if for all primes p , $f_\mathcal{O}_{\mathcal{N}}/\mathcal{I}_n = 0$ for some n , then f is flat only if the set of ideals $\{\mathcal{I}_n\}$ acts regularly and finitely on $f_*\mathcal{O}_{\mathcal{N}}$.*

This, in turn, is a corollary Proposition 5.10 and the following result. Here and in what follows the higher torsion sheaves are defined by

$$\mathrm{Tor}_s^{\mathcal{O}}(\mathcal{F}, \mathcal{E}) = H_s(\mathcal{F} \otimes_{\mathcal{O}}^L \mathcal{E}).$$

6.24 Theorem (Landweber Exactness III). *Let \mathcal{F} be a quasi-coherent sheaf on $\mathcal{M}_{\mathbf{fg}}$. Suppose that for all primes p , the set of ideals $\{\mathcal{I}_n\}$ acts regularly and finitely on \mathcal{F} . Then \mathcal{F} is flat as an $\mathcal{O}_{\mathbf{fg}}$ module; that is,*

$$\mathrm{Tor}_s^{\mathcal{O}}(\mathcal{F}, \mathcal{E}) = 0, \quad s > 0.$$

Conversely, if for all primes p , $\mathcal{F}/\mathcal{I}_n\mathcal{F} = 0$ for some n , then \mathcal{F} is flat only if the set of ideals $\{\mathcal{I}_n\}$ acts regularly and finitely on \mathcal{F} .

Theorem 6.24 was proved by Mike Hopkins in [18]; the proofs here are the same.

Let $j_n : \mathcal{M}(n) \rightarrow \mathcal{M}_{\mathbf{fg}}$ be the inclusion. The first result is this. The argument requires careful organization of exact sequences.

6.25 Proposition. *Suppose that for each prime p , the scale $\{\mathcal{I}_n\}$ acts regularly and finitely on \mathcal{F} and that for each n ,*

$$\mathrm{Tor}_s^{\mathcal{O}}((\mathcal{F}/\mathcal{I}_n)[v_n^{-1}], -) = 0, \quad s > n.$$

Then \mathcal{F} is a flat $\mathcal{O}_{\mathbf{fg}}$ -module sheaf.

Proof. By hypothesis, we have that for all large k ,

$$\mathrm{Tor}_s^{\mathcal{O}}(\mathcal{F}/\mathcal{I}_k, -) = 0.$$

This begins a downward induction, where the induction hypothesis is that

$$\mathrm{Tor}_s^{\mathcal{O}}((\mathcal{F}/\mathcal{I}_{n+1}), -) = 0, \quad s > n + 1.$$

The final result is the case $n = -1$.

We make the argument for the induction step, using the following fact: if \mathcal{L} is any locally free sheaf, then

$$\mathrm{Tor}_s^{\mathcal{O}}(\mathcal{E} \otimes \mathcal{L}, \mathcal{E}') \cong \mathrm{Tor}_s^{\mathcal{O}}(\mathcal{E}, \mathcal{E}') \otimes \mathcal{L}$$

for any quasi-coherent sheaves \mathcal{E} and \mathcal{E}' .

Since the scale $\{\mathcal{I}_n\}$ acts regularly, we have an exact sequence

$$0 \rightarrow \mathcal{F}/\mathcal{I}_n \otimes \omega^{-(p^n-1)} \xrightarrow{v_n} \mathcal{F}/\mathcal{I}_n \rightarrow \mathcal{F}/\mathcal{I}_{n+1} \rightarrow 0.$$

The induction hypothesis implies that for any quasi-coherent sheaf \mathcal{E}

$$v_n : \mathrm{Tor}_s^{\mathcal{O}}(\mathcal{F}/\mathcal{I}_n, \mathcal{E}) \rightarrow \mathrm{Tor}_s^{\mathcal{O}}(\mathcal{F}/\mathcal{I}_n, \mathcal{E}) \otimes \omega^{p^n-1}$$

is an injection for $s > n$.

Now recall that in Remark 6.17 we showed that $\mathcal{F}/\mathcal{I}_n[v_n^{-1}]$ can be written as the colimit of the sequence

$$\mathcal{F}/\mathcal{I}_n \xrightarrow{v_n} \mathcal{F}/\mathcal{I}_n \otimes \omega^{p^n-1} \xrightarrow{v_n} \mathcal{F}/\mathcal{I}_n \otimes \omega^{2(p^n-1)} \xrightarrow{v_n} \dots$$

Thus, we have for $s > n$,

$$0 = \mathrm{Tor}_s(\mathcal{F}/\mathcal{I}_n[v_n^{-1}], \mathcal{E}) \cong \mathrm{colim} \mathrm{Tor}_s(\mathcal{F}/\mathcal{I}_n, \mathcal{E}) \otimes \omega^{t(p^n-1)}.$$

Since each of the maps in the sequence is an injection, the induction step follows. \square

Now we must check the hypothesis of Proposition 6.25 in order to prove Theorem 6.24. Recall from Definition 6.18, that if \mathcal{E} is any \mathcal{I}_n -torsion sheaf, then

$$\mathcal{E}[v_n^{-1}] = (i_n)_* i_n^* \mathcal{E}$$

where $i_n : \mathcal{U}(n) \rightarrow \mathcal{M}_{\mathbf{fg}}$ is the inclusion. In the case where $\mathcal{E} = \mathcal{F}/\mathcal{I}_n$, we have that \mathcal{E} is the push-forward of the sheaf $j_n^* \mathcal{F}$ on $\mathcal{M}(n)$. Since there is a pull-back diagram

$$\begin{array}{ccc} \mathcal{H}(n) & \xrightarrow{g_n} & \mathcal{M}(n) \\ k_n \downarrow & & \downarrow j_n \\ \mathcal{U}(n) & \xrightarrow{i_n} & \mathcal{M}_{\mathbf{fg}} \end{array}$$

we have

$$i_n^* \mathcal{F}/\mathcal{I}_n = (k_n)_* g_n^* j_n^* \mathcal{F}.$$

Write $f_n : \mathcal{H}(n) \rightarrow \mathcal{M}_{\mathbf{fg}}$ for the inclusion. Thus we can conclude that

$$\mathcal{F}/\mathcal{I}_n[v_n^{-1}] = (f_n)_* (f_n)^* \mathcal{F}.$$

The next result then verifies the hypothesis of Proposition 6.25.

6.26 Proposition. *Let \mathcal{F} be any quasi-coherent sheaf on $\mathcal{H}(n)$ and let \mathcal{E} be any quasi-coherent sheaf on $\mathcal{M}_{\mathbf{fg}}$. Then*

$$\mathrm{Tor}_s^{\mathcal{O}}((f_n)_* \mathcal{F}, \mathcal{E}) = 0, \quad s > n.$$

Proof. Recall from Lemma 5.22, that the inclusion $f_n : \mathcal{H}(n) \rightarrow \mathcal{M}_{\mathbf{fg}}$ is affine. This implies that the category of quasi-coherent sheaves on $\mathcal{H}(n)$ is equivalent, via the the push-forward $(f_n)_*$, to the category of quasi-coherent $(f_n)_* \mathcal{O}_{\mathcal{H}(n)}$ modules on $\mathcal{M}_{\mathbf{fg}}$. (Compare Proposition 1.16.) In particular, $(f_n)_*$ is exact on quasi-coherent sheaves. Also, for all quasi-coherent sheaves \mathcal{E} on $\mathcal{M}_{\mathbf{fg}}$, there is a natural isomorphism

$$(f_n)_* f_n^* \mathcal{E} \cong (f_n)_* \mathcal{O}_{\mathcal{H}(n)} \otimes_{\mathcal{O}_{\mathbf{fg}}} \mathcal{E}.$$

It follows that there is a natural isomorphism

$$(6.3) \quad (f_n)_* (\mathcal{F}) \otimes \mathcal{E} \cong (f_n)_* (\mathcal{F} \otimes_{\mathcal{O}_{\mathcal{H}(n)}} f_n^* \mathcal{E})$$

which becomes an equivalence of derived sheaves

$$(f_n)_* (\mathcal{F}) \otimes^L \mathcal{E} \cong (f_n)_* (\mathcal{F} \otimes_{\mathcal{O}_{\mathcal{H}(n)}}^L L(f_n^*) \mathcal{E}).$$

By Theorem 5.38 we have that the morphism $\Gamma_n : \mathrm{Spec}(\mathbb{F}_p) \rightarrow \mathcal{H}(n)$ classifying any height n formal group over \mathbb{F}_p is an *fqc*-cover; hence, the category of quasi-coherent sheaves on $\mathcal{H}(n)$ is equivalent to the category of $(\mathbb{F}_p, \mathcal{O}_{\mathrm{Aut}(\Gamma_n)})$ comodules. Here we have written $\mathrm{Spec}(\mathcal{O}_{\mathrm{Aut}(\Gamma_n)}) = \mathrm{Spec}(\mathbb{F}_p) \times_{\mathcal{H}(n)} \mathrm{Spec}(\mathbb{F}_p)$.

From this we have that the functor $\mathcal{F} \otimes_{\mathcal{H}(n)} (-)$ is exact, since the corresponding functor on comodules is simply

$$\mathcal{F}(\Gamma_n : \text{Spec}(\mathbb{F}_p) \rightarrow \mathcal{H}(n)) \otimes_{\mathbb{F}_p} (-).$$

Thus we need only show that

$$H_s L(f_n^*) \mathcal{E} = 0$$

for $s > n$. Since $(f_n)_*$ is exact, we need only check that $H_s(f_n)_* L(f_n^*) \mathcal{E} = 0$ for $s > n$. We need only check this equation locally, thus we may evaluate at any morphism

$$G : \text{Spec}(R) \longrightarrow \mathcal{M}_{\mathbf{fg}}$$

classifying a formal group with a coordinate. Applying the formula of Equation 6.3 we see that locally these homology sheaves are given by

$$\text{Tor}_s^R(u_n^{-1} R / \mathcal{I}_n(G), \mathcal{E}(G)).$$

The result now follows from the fact that $\mathcal{I}_n(G)$ is locally generated by a regular sequence of length n . \square

6.27 Remark. Almost all of the argument for Theorem 6.24 uses only that we have a sequence of regularly embedded closed substacks $\{\mathcal{M}(n)\}$ of $\mathcal{M}_{\mathbf{fg}}$. However, in the proof Proposition 6.26 we used Theorem 5.38 which, in turn, ultimately depends on Lazard's proof of the result that, over a separably closed field of characteristic p , all formal groups of height n are isomorphic. Thus, it does not appear to me that the Landweber exact functor theorem is a generality – it seems quite specific to formal groups.

6.28 Remark (Presentations of $\mathcal{U}(n)$). Let R be a $\mathbb{Z}_{(p)}$ -algebra and $G \rightarrow \text{Spec}(R)$ a formal group so that the classifying map

$$G : \text{Spec}(R) \rightarrow \mathcal{M}_{\mathbf{fg}} \otimes \mathbb{Z}_{(p)}$$

is flat and so that $v_n(G)$ is invertible in the sense of Remark 5.6. For simplicity, let's assume G has a coordinate. Given a choice of p -typical coordinate, the conditions on G amount to saying the element p, u_1, \dots (See Corollary 6.21.) form a regular sequence and u_n is invertible. Then the induced map

$$G : \text{Spec}(R) \longrightarrow \mathcal{U}(n)$$

is a presentation, by Proposition 5.13. In particular, the resulting category of comodules over the Hopf algebroid $(R, R \otimes_L W \otimes_L R)$ is equivalent to the category of quasi-coherent sheaves over $\mathcal{U}(n)$; thus, as a consequence, any two such pairs (R, G) produce equivalent categories of comodules. This point has been discussed in further detail in [25] and [41]. From such pairs (R, G) we get a homology theory $E(R, G)_*(-) = R \otimes_L MUP_*(-)$, where MUP_* is the 2-periodic version of complex cobordism. We call these theories *Landweber exact* of height n .

7 The formal neighborhood of a height n point

In this section we make the following slogan precise: the formal neighborhood in $\mathcal{M}_{\mathbf{fg}}$ of a height n formal group Γ over a perfect field of characteristic p is the Lubin-Tate space of the deformations of Γ . This is not quite true as stated; a more precise statement is that Lubin-Tate space is a universal cover the formal neighborhood and the automorphisms of the formal group are the covering transformations. The exact result is given in Theorem 7.22 below.

Let $\mathcal{U}_{\mathbf{fg}}(n) = \mathcal{M}_{\mathbf{fg}} - \mathcal{M}(n+1)$ be the open substack of $\mathcal{M}_{\mathbf{fg}}$ classifying formal groups of height less than or equal to n . Then

$$\mathcal{H}(n) = \mathcal{U}_{\mathbf{fg}}(n) - \mathcal{U}_{\mathbf{fg}}(n-1)$$

is a closed substack of $\mathcal{U}_{\mathbf{fg}}(n)$ defined by the vanishing of the ideal \mathcal{I}_n . Recall the $\mathcal{H}(n)$ has a single geometric point, but that this point has plenty of automorphisms. See Theorem 5.38. We wish to write down a description of the formal neighborhood $\widehat{\mathcal{H}}(n)$ of $\mathcal{H}(n) \subseteq \mathcal{U}_{\mathbf{fg}}(n)$.

By definition, $\widehat{\mathcal{H}}(n)$ is the category fibered in groupoids over $\mathbf{Aff}_{\mathbb{Z}(p)}$ which assigns to each $\mathbb{Z}(p)$ -algebra B the groupoid with objects the formal groups G over B so that

1. $\mathcal{I}_n(G) \subseteq B$ is nilpotent; and
2. $\mathcal{I}_{n+1}(G) = B$.

Thus, if $q : B \rightarrow B/\mathcal{I}_n(G)$ is the quotient map, the formal group q^*G has strict height n in the sense that $v_i(G) = 0$ for $i < n$ and $v_n(G)$ is invertible. A great many examples of such formal groups can be obtained as deformations of a height n formal group; thus, we now discuss deformations and Lubin-Tate space.

7.1 Deformations of height n formal groups over a field

Fix a formal group Γ of height n over a perfect field \mathbb{F} of characteristic p . (In practice, \mathbb{F} will be an algebraic extension of a the prime field \mathbb{F}_p). Recall that an Artin local ring is a Noetherian commutative ring with a unique nilpotent maximal ideal. Let $\mathbf{Art}_{\mathbb{F}}$ denote the category of Artin local rings (A, \mathfrak{m}) so that we can choose an isomorphism $A/\mathfrak{m} \cong \mathbb{F}$ from the residue field of A to \mathbb{F} . The isomorphism is not part of the data. Morphisms in $\mathbf{Art}_{\mathbb{F}}$ are ring homomorphisms which induce an isomorphism on residue fields.

7.1 Definition. A deformation of the pair (\mathbb{F}, Γ) to an object A of $\mathbf{Art}_{\mathbb{F}}$ is a Cartesian square

$$\begin{array}{ccc} \Gamma & \longrightarrow & G \\ \downarrow & & \downarrow \\ \mathrm{Spec}(\mathbb{F}) & \xrightarrow{f} & \mathrm{Spec}(A) \end{array}$$

where G is a formal group over A and f induces an isomorphism $\mathrm{Spec}(\mathbb{F}) \cong \mathrm{Spec}(A/\mathfrak{m})$.

Deformations become a category $\mathbf{Def}(\mathbb{F}, \Gamma)$ fibered in groupoids over $\mathbf{Art}_{\mathbb{F}}$ by setting a morphism to be a commutative cube

$$\begin{array}{ccccc}
 & & \Gamma & \longrightarrow & G' \\
 & \nearrow = & \downarrow & & \downarrow \\
 \Gamma & \longrightarrow & G & & \\
 \downarrow & & \downarrow & & \downarrow \\
 & \nearrow = & \mathrm{Spec}(\mathbb{F}) & \longrightarrow & \mathrm{Spec}(A') \\
 \mathrm{Spec}(\mathbb{F}) & \longrightarrow & \mathrm{Spec}(A) & &
 \end{array}$$

where the right face is also a Cartesian.

7.2 Remark. We can rephrase this as follows. A deformation of Γ to A is a triple (G, i, ϕ) where G is a formal group over A , $i : \mathrm{Spec}(\mathbb{F}) \rightarrow \mathrm{Spec}(A/\mathfrak{m})$ is an isomorphism and $\phi : \Gamma \rightarrow i^*G_0$ is an isomorphism of formal groups over \mathbb{F} . Here and always we write G_0 for the *special fiber* of G ; that is, the induced formal group over A/\mathfrak{m} . There is an isomorphism of deformations $\psi : (G, i, \phi) \rightarrow (G', i', \phi')$ to A if $i = i'$ and $\psi : G \rightarrow G'$ is an isomorphism of formal groups so that

$$\begin{array}{ccc}
 & & i^*G_0 \\
 & \nearrow \phi & \downarrow i^*\psi_0 \\
 \Gamma & & i^*G'_0 \\
 & \searrow \phi' &
 \end{array}$$

commutes.

In either formulation of a deformation, we note that if G is a deformation of Γ to (A, \mathfrak{m}) , then $\mathcal{I}_n(G) \subseteq \mathfrak{m}$ and $\mathcal{I}_{n+1}(G) = A$.

7.3 Remark. Let $R = (R, \mathfrak{m}_R)$ be a complete local ring so that $R/\mathfrak{m}_R \cong \mathbb{F}$. We write $\mathrm{Spf}(R)$ equally for the resulting formal scheme and for the the category fibered in groupoids over $\mathbf{Art}_{\mathbb{F}}$ that assigns to each object (A, \mathfrak{m}) of $\mathbf{Art}_{\mathbb{F}}$ the discrete groupoid of all ring homomorphisms which induce an isomorphism $R/\mathfrak{m}_R \cong A/\mathfrak{m}$; so, in particular, $f(\mathfrak{m}_R) \subseteq \mathfrak{m}$. This is an abuse of notation, but a mild one, and should cause no confusion. Indeed, the formal scheme $\mathrm{Spf}(R)$ is the left Kan extension of the functor $\mathrm{Spf}(R)$ on $\mathbf{Art}_{\mathbb{F}}$ along the inclusion of $\mathbf{Art}_{\mathbb{F}}$ into all rings.

7.4 Theorem (Lubin-Tate). *The category fibered in groupoids $\mathbf{Def}(\mathbb{F}, \Gamma)$ is discrete and representable; that is, there is a complete local ring $R(\mathbb{F}, \Gamma)$ and a deformation*

$$\begin{array}{ccc}
 \Gamma & \longrightarrow & H \\
 \downarrow & & \downarrow \\
 \mathrm{Spec}(\mathbb{F}) & \longrightarrow & \mathrm{Spf}(R(\mathbb{F}, \Gamma))
 \end{array}$$

of Γ to $R(\mathbb{F}, \Gamma)$ so that the induced morphism

$$\mathrm{Spf}(R(\mathbb{F}, \Gamma)) \longrightarrow \mathbf{Def}(\mathbb{F}, \Gamma)$$

is an equivalence of categories fibered in groupoids over $\mathbf{Art}_{\mathbb{F}}$.

The formal spectrum $\mathrm{Spf}(R(\mathbb{F}, \Gamma))$ is called *Lubin-Tate space*.

7.5 Remark. The induced morphism $\mathrm{Spf}(R(\mathbb{F}, \Gamma)) \longrightarrow \mathbf{Def}(\mathbb{F}, \Gamma)$ is not completely trivial to define. Given a homomorphism $R(\mathbb{F}, \Gamma) \rightarrow A$ to an Artin local ring which induces an isomorphism of residue fields, we are asserting there is a unique way to complete the back square of the following diagram so that it commutes.

$$\begin{array}{ccccc}
 & & \Gamma & \longrightarrow & f^*H \\
 & \swarrow & \downarrow & & \downarrow \\
 \Gamma & \xrightarrow{=} & \Gamma & \longrightarrow & H \\
 \downarrow & & \downarrow & & \downarrow \\
 & & \mathrm{Spec}(\mathbb{F}) & \longrightarrow & \mathrm{Spec}(A) \\
 \downarrow & \swarrow & \downarrow & & \downarrow \\
 \mathrm{Spec}(\mathbb{F}) & \xrightarrow{=} & \mathrm{Spf}(R(\mathbb{F}, \Gamma)) & &
 \end{array}$$

Thus, given $f : \mathrm{Spec}(A) \rightarrow \mathrm{Spf}(R(\mathbb{F}, \Gamma))$, the universal deformation (H, j, ϕ_u) gets sent to

$$f^*(H, j, \phi_u) \stackrel{\mathrm{def}}{=} (f^*H, f_0^{-1}j, \phi_u)$$

where $f_0 : \mathrm{Spec}(A/\mathfrak{m}_A) \rightarrow \mathrm{Spf}(R(\mathbb{F}, \Gamma)/\mathfrak{m})$ is the induced isomorphism and we have written ϕ_u for both the universal isomorphism

$$\phi_u : \Gamma \longrightarrow j^*H_0$$

and the induced isomorphism

$$\phi_u : \Gamma \longrightarrow (f_0^{-1}j)^*(f^*H)_0 \cong j^*H_0.$$

In this language, the theorem of Lubin and Tate reads as follows: given a deformation (G, i, ϕ) of Γ to $A \in \mathbf{Art}_{\mathbb{F}}$, there is a homomorphism $f : R(\mathbb{F}, \Gamma) \rightarrow A$ inducing an isomorphism on residue fields and a unique isomorphism of deformations

$$\psi : (G, i, \phi) \longrightarrow f^*(H, j, \phi_u).$$

The main lemma of Lubin and Tate is to calculate the deformations of Γ to the ring of dual numbers $\mathbb{F}[\epsilon]$, where $\epsilon^2 = 0$. Indeed, they show for that ring there is a non-canonical isomorphism

$$\pi_0 \mathbf{Def}(\mathbb{F}, \Gamma)_{\mathbb{F}[\epsilon]} \cong (\mathbb{F}\epsilon)^{n-1}$$

where $(-)^k$ means the k th Cartesian power and

$$\pi_1(\mathbf{Def}(\mathbb{F}, \Gamma), G)_{\mathbb{F}[\epsilon]} = \{1\}$$

for any deformation G . The general theory of deformations (see [50], Proposition 3.12) then shows that there is a (non-canonical) isomorphism

$$(7.1) \quad \pi_0 \mathbf{Def}(\mathbb{F}, \Gamma) \cong \mathfrak{m}^{n-1}$$

where we write \mathfrak{m} for the functor which assigns to an Artin local ring A its maximal ideal \mathfrak{m}_A . For any deformation G ,

$$(7.2) \quad \pi_1(\mathbf{Def}(\mathbb{F}, \Gamma), G) = \{1\}.$$

It immediately follows that the ring $R(\mathbb{F}, \Gamma)$ is a power series ring. More explicitly, since $R(\mathbb{F}, \Gamma)$ is local, Noetherian, and p -complete, the universal deformation H can be given a p -typical coordinate x for which the p -series of H becomes

$$[p]_H(x) = px +_H u_1 x^p +_H \cdots +_H u_{n-1} x^{p^{n-1}} +_H u_n x^{p^n} +_H \cdots.$$

Then there is an isomorphism

$$(7.3) \quad R(\mathbb{F}, \Gamma) \cong W(\mathbb{F})[[u_1, \dots, u_{n-1}]]$$

where $W(\mathbb{F})$ is the Witt vectors of \mathbb{F} and the maximal ideal $\mathfrak{m} = \mathcal{I}_n(H) = (p, u_1, \dots, u_{n-1})$. Note that u_n is a unit. This isomorphism is non-canonical as it depends on a choice of p -typical coordinate.

Equation 7.2 can be deduced from the following result.

7.6 Lemma. *Let (A, \mathfrak{m}) be an Artin local ring with A/\mathfrak{m} of characteristic p . Let G_1 and G_2 be two formal groups over B so that $(G_1)_0$ and $(G_2)_0$ are of height $n < \infty$. Then the affine morphism*

$$\mathrm{Iso}_B(G_1, G_2) \longrightarrow \mathrm{Spec}(A)$$

is unramified. In particular, if we are given a choice of isomorphism

$$\phi : (G_1)_0 \longrightarrow (G_2)_0$$

over (A/\mathfrak{m}) , then there is at most one isomorphism $\psi : G_1 \rightarrow G_2$ over A so that $(\psi)_0 = \phi$.

Proof. By Theorem 5.25 the morphism

$$\mathrm{Iso}_{A/\mathfrak{m}}((G_1)_0, (G_2)_0) \longrightarrow \mathrm{Spec}(A/\mathfrak{m})$$

is pro-étale; that is, flat and unramified. Since $\mathrm{Spec}(A/\mathfrak{m}) \rightarrow \mathrm{Spec}(A)$ is the unique point of $\mathrm{Spec}(A)$, the main statement follows. (See Proposition I.3.2 of

[39].) The statement about the unique lifting follows from one of the characterizations of unramified: there is at most one way to complete the diagram

$$\begin{array}{ccc}
 \mathrm{Spec}(A/\mathfrak{m}) & \xrightarrow{\phi} & \mathrm{Iso}_B(G_1, G_2) \\
 \downarrow & \nearrow \text{---} & \downarrow \\
 \mathrm{Spec}(A) & \xrightarrow{=} & \mathrm{Spec}(A)
 \end{array}$$

so that both triangles commute. \square

7.7 Remark. We can give an alternate description of deformations in terms of formal group laws. Fix a coordinate x for Γ and let F_Γ be the resulting formal group law over \mathbb{F} . Define $\mathbf{Def}_*(\mathbb{F}, \Gamma)$ to be the groupoid valued functor on $\mathbf{Art}_{\mathbb{F}}$ which assigns to each Artin local ring (A, \mathfrak{m}) of $\mathbf{Art}_{\mathbb{F}}$ the groupoid with objects all pairs (i, F) where $i : A/\mathfrak{m} \rightarrow \mathbb{F}$ is an isomorphism and F is a formal group law over A so that

$$i^*F_0(x, y) = F_\Gamma(x, y) \in \mathbb{F}[[x, y]].$$

Here we've written $F_0(x, y)$ for the reduction of F to A/\mathfrak{m} . There is a morphism $\psi : (i, F) \rightarrow (i', F')$ if $i = i'$ and $\psi : F \rightarrow F'$ is an isomorphism of formal group laws so that

$$i^*\psi_0(x) = x \in \mathbb{F}[[x]].$$

The set $\pi_0\mathbf{Def}_*(\mathbb{F}, \Gamma)$ is the the set of \star -isomorphism classes of deformations of the formal group law F_Γ .

There is a natural transformation of groupoid functors

$$\mathbf{Def}_*(\mathbb{F}, \Gamma) \longrightarrow \mathbf{Def}(\mathbb{F}, \Gamma).$$

This is a equivalence. It is obviously full and faithful, so we need only show that every object in the target is isomorphic to some object from the source.

To see this, we'll use the notation of Remark 7.2. Let (A, \mathfrak{m}) be an Artin local ring over \mathbb{F} and G a deformation of Γ to A . Since \mathbb{F} is a field, G_0 can be given a coordinate; since A is local Noetherian, G can be given a coordinate which reduces to a chosen coordinate for G_0 . The isomorphism $\phi : \Gamma \rightarrow G_0$ determines an isomorphism of formal group laws

$$\phi : F_{G_0}(x, y) \longrightarrow (i^*)^{-1}F_\Gamma(x, y).$$

Lift the power series $\phi(x)$ to a power series $\psi(x) \in A[[x]]$ so that $\psi_0(x) = \phi(x)$ and define a formal group law $F(x, y)$ over A by requiring that

$$\psi(x) : F_G(x, y) \longrightarrow F(x, y)$$

is an isomorphism. Then $F(x, y)$ is the required formal group law.

7.8 Remark. Following the example of Remark 7.3 we extend the notion of deformations to all commutative rings by left Kan extensions along the forgetful functor from $\mathbf{Art}_{\mathbb{F}}$ to rings. In more detail, let B be a commutative ring. Define the category $\mathbf{Art}_{\mathbb{F}}/B$ to have objects the morphisms

$$A \longrightarrow B$$

of commutative rings where (A, \mathfrak{m}) is an Artin local ring in $\mathbf{Art}_{\mathbb{F}}$. Morphisms in \mathbf{Art}/B are commutative triangles. The category $\mathbf{Art}_{\mathbb{F}}/B$ has a cofinal subcategory consisting of those morphisms which are injections. It is also filtered, at least if \mathbb{F} is an algebraic extension of \mathbb{F}_p . To see this, let

$$f_i : A_i \longrightarrow B, \quad i = 1, 2$$

be two morphism from Artin local rings in \mathbf{Art}/\mathbb{F} into B . If we choose isomorphisms $\lambda_i : \mathbb{F} \rightarrow A_i/\mathfrak{m}_i$, then the induced maps

$$f_i \lambda_i : \mathbb{F} \longrightarrow B/[\mathfrak{m}_1 B + \mathfrak{m}_2 B]$$

may not be equal. However, there will be an automorphism σ of \mathbb{F} so that $f_i \lambda_i = f_1 \lambda_1 \sigma$. Replacing λ_2 by $\lambda_2 \sigma$, we now use the universal property of Witt vectors to obtain a commutative diagram

$$\begin{array}{ccc} W(\mathbb{F}) & \longrightarrow & A_2 \\ \downarrow & & \downarrow f_2 \\ A_1 & \xrightarrow{f_1} & B. \end{array}$$

The ring $A_1 \otimes_{W(\mathbb{F})} A_2$ is again in \mathbf{Art}/\mathbb{F} ; from this we can conclude that \mathbf{Art}/\mathbb{F} is indeed filtered.

Since the tensor product $A \otimes_{\mathbb{Z}} A'$ of Artin local rings is an Artin local ring, the category $\mathbf{Art}_{\mathbb{F}}/B$ is filtered and has a cofinal subcategory consisting of those morphisms which are injections.

Define the groupoid $\mathbf{Def}(\mathbb{F}, \Gamma)_B$ of deformations of Γ over B to be the colimit

$$\mathbf{Def}(\mathbb{F}, \Gamma)_B = \operatorname{colim}_{\mathbf{Art}_{\mathbb{F}}/B} \mathbf{Def}(\mathbb{F}, \Gamma)_A.$$

Thus a generalized deformation of Γ to B is a deformation of Γ to an Artin local subring $A \subseteq B$. This is probably easiest to understand using formal group laws.

Fix a coordinate of Γ and let $\mathbf{Def}_*(\mathbb{F}, \Gamma)$ be the groupoid defined in Remark 7.7. Then by that remark, there is an equivalence

$$\operatorname{colim}_{\mathbf{Art}_{\mathbb{F}}/B} \mathbf{Def}_*(\mathbb{F}, \Gamma)_A \rightarrow \mathbf{Def}(\mathbb{F}, \Gamma)_B$$

and the elements of the source are easily described. The objects are equivalence classes of pairs (F, i) where F is a formal group law

$$F(x, y) = \sum a_{ij} x^i y^j \in B[[x, y]]$$

so that the coefficients a_{ij} lie in an Artin local subring $A \subseteq B$ and so that the pair $(F|_A, i) \in \mathbf{Def}_*(\mathbb{F}, \Gamma)_A$. Isomorphisms in $\mathbf{Def}(\mathbb{F}, \Gamma)_B$ must similarly lie over Artin local subrings.

The following result extends and follows immediately from Remark 7.3 and Theorem 7.4.

7.9 Theorem. *The natural isomorphism of functors on commutative rings*

$$\mathrm{Spf}(R(\mathbb{F}, \Gamma)) \longrightarrow \pi_0 \mathbf{Def}(\mathbb{F}, \Gamma)$$

is an isomorphism and for all deformation G of Γ over B

$$\pi_1(\mathbf{Def}(\mathbb{F}, \Gamma)_B, G) = \{ 1 \}.$$

Now let $\mathcal{H}(n) \subseteq \mathcal{U}_{\mathrm{fg}}(n)$ be the closed substack of formal groups of exact height n and let $\widehat{\mathcal{H}}(n)$ denote its formal neighborhood. There is a 1-morphism of groupoid schemes

$$\mathbf{Def}(\mathbb{F}, \Gamma) \longrightarrow \widehat{\mathcal{H}}(n)$$

which sends a deformation $(G/B, \phi)$ to the formal group G .

Given a formal group G over B so that $\mathcal{I}_n(G)$ is nilpotent and $\mathcal{I}_{n+1}(G) = B$, it is not necessarily true that G arises from a deformation; that would amount to a choice of 2-commuting diagram

$$\begin{array}{ccc} & & \mathbf{Def}(\mathbb{F}, \Gamma) \\ & \nearrow & \downarrow \\ \mathrm{Spec}(B) & \xrightarrow{G} & \widehat{\mathcal{H}}(n). \end{array}$$

Nonetheless, we have the following two results. Recall from Corollary 5.37 that if Γ is a height n formal group over a field \mathbb{F} , then the induced map $\mathrm{Spec}(\mathbb{F}) \rightarrow \mathcal{H}(n)$ is a presentation. Such a formal group also defines a trivial deformation; that is, Γ is itself a deformation of Γ to \mathbb{F} .

7.10 Proposition. *Let Γ be a height n formal group law over an algebraic extension of \mathbb{F}_p . Then the 2-commuting square*

$$\begin{array}{ccc} \mathrm{Spec}(\mathbb{F}) & \longrightarrow & \mathbf{Def}(\mathbb{F}, \Gamma) \\ \downarrow & & \downarrow \\ \mathcal{H}(n) & \longrightarrow & \widehat{\mathcal{H}}(n) \end{array}$$

is 2-category pull-back square.

Proof. Write P for the 2-category pull-back. By Theorem 7.9, an object in P over a ring B is a triple (G, f, ϕ) where G is formal group of exact height n over B , $f : R(\mathbb{F}, \Gamma) \rightarrow B$ is a ring homomorphism so that $B \cdot f(\mathfrak{m})$ is nilpotent, and

$\phi : G \rightarrow f^*H$ is an isomorphism of formal groups. Here H is the universal deformation as in Theorem 7.4 and $\mathfrak{m} \subseteq R(\mathbb{F}, \Gamma)$ is the maximal ideal. A morphism $\psi : (G, f, \phi) \rightarrow (G', f, \phi')$ is an isomorphism $\psi : G \rightarrow G'$ so that $\phi'\psi = \phi$. In particular, such a triple has no non-identity automorphisms and P is discrete.

Given a triple (G, f, ϕ) , we have that

$$0 = \mathcal{I}_n(G) = \mathcal{I}_n(f^*H) = B \cdot f(\mathfrak{m});$$

hence, the morphism $f : R(\mathbb{F}, \Gamma) \rightarrow B$ factors through \mathbb{F} . Furthermore ϕ itself defines an isomorphism

$$(G, f, \phi) \rightarrow (f^*H, f, 1).$$

It follows that there is an equivalence $\text{Spec}(\mathbb{F}) \rightarrow P$ sending $g : \mathbb{F} \rightarrow B$ to the triple $(f^*H, f, 1)$ with f the composite $R(\mathbb{F}, \Gamma) \rightarrow \mathbb{F} \rightarrow B$. \square

7.11 Proposition. *The morphism $q : \text{Def}(\mathbb{F}, \Gamma) \rightarrow \widehat{\mathcal{H}}(n)$ is representable, flat, and surjective.*

Proof. We first show it is representable; in fact, we will show that given a diagram

$$\text{Spec}(B) \xrightarrow{G} \widehat{\mathcal{H}}(n) \longleftarrow \text{Spf}(R(\mathbb{F}, \Gamma))$$

then

$$p_1 : \text{Spec}(B) \times_{\widehat{\mathcal{H}}(n)} \text{Spf}(R(\mathbb{F}, \Gamma)) \rightarrow \text{Spec}(B)$$

is a formal affine scheme over B . By a descent argument, we may assume that G has a coordinate. Then, arguing as in Lemma 2.11, we see that the pull-back is equivalent to

$$\text{Spf}(B \otimes_L W \otimes_L R(\mathbb{F}, \Gamma)),$$

the formal neighborhood of $B \otimes_L W \otimes_L R(\mathbb{F}, \Gamma)$ at the ideal $\mathcal{I}_n(p_1^*G) = \mathcal{I}_n(p_2^*H)$ where $p_i, i = 1, 2$ are the projections onto the two factors.

To see that q is flat, we apply Theorem 6.19 (the Landweber Exact Functor Theorem) and the description of $R(\mathbb{F}, \Gamma)$ given in Equation 7.3.

For surjectivity, note that if k is any field and $g : \text{Spec}(k) \rightarrow \widehat{\mathcal{H}}(n)$ classifies a formal group G , then $\mathcal{I}_n(G) = 0$ and G is a height n ; that is, g factors through $\mathcal{H}(n)$. The result now follows from the first part and the fact that $\text{Spec}(\mathbb{F}) \rightarrow \mathcal{H}(n)$ is surjective – see Corollary 5.37. \square

7.2 The action of the automorphism group

Let $\mathbb{G}(\mathbb{F}, \Gamma) = \text{Aut}(\mathbb{F}, \Gamma)$, the automorphism of the pair (\mathbb{F}, Γ) . An element of $\mathbb{G}(\mathbb{F}, \Gamma)$ is a pull-back diagram

$$\begin{array}{ccc} \Gamma & \xrightarrow{g} & \Gamma \\ \downarrow & & \downarrow \\ \text{Spec}(\mathbb{F}) & \xrightarrow{\sigma} & \text{Spec}(\mathbb{F}). \end{array}$$

where σ is induced by a field automorphism. For historical and topological reasons we call this the *Morava stabilizer group* of the pair (\mathbb{F}, Γ) . We may write such a diagram as a pair (σ, λ) where $\lambda : \Gamma \rightarrow \sigma^* \Gamma$ is the isomorphism induced by g . If \mathbb{F} is an algebraic extension of \mathbb{F}_p and Γ is defined over \mathbb{F}_p , this yields an isomorphism

$$\mathbb{G}(\mathbb{F}, \Gamma) \cong \text{Gal}(\mathbb{F}/\mathbb{F}_p) \ltimes \text{Aut}(\Gamma)$$

where $\text{Aut}(\Gamma)$ is the group of automorphisms of Γ defined over \mathbb{F} .

The group $\mathbb{G}(\mathbb{F}, \Gamma)$ acts on the groupoid functor $\mathbf{Def}(\mathbb{F}, \Gamma)$ on the right by sending a diagram

$$\begin{array}{ccc} \Gamma & \longrightarrow & G \\ \downarrow & & \downarrow \\ \text{Spec}(\mathbb{F}) & \longrightarrow & \text{Spec}(A) \end{array}$$

to the outer square of the diagram

$$\begin{array}{ccccc} \Gamma & \xrightarrow{g} & \Gamma & \longrightarrow & G \\ \downarrow & & \downarrow & & \downarrow \\ \text{Spec}(\mathbb{F}) & \xrightarrow{\sigma} & \text{Spec}(\mathbb{F}) & \longrightarrow & \text{Spec}(A) \end{array}$$

This action commutes with the isomorphisms in $\mathbf{Def}(\mathbb{F}, \Gamma)$; thus we obtain a right action on $\pi_0 \mathbf{Def}(\mathbb{F}, \Gamma)$ and hence a left action on $R(\mathbb{F}, \Gamma)$.

7.12 Remark. If, following Remark 7.2, we think of a deformation of Γ to A as a triple, (G, i, ϕ) and an element of $\mathbb{G}(\mathbb{F}, \Gamma)$ as a pair (σ, λ) as above, then the action of (σ, λ) on (G, i, ϕ) yields the triple

$$(G, i\sigma, (\sigma^* \phi)\lambda).$$

Because $\pi_0 \mathbf{Def}(\mathbb{F}, \Gamma)$ is a set of equivalence classes, we must take a little care in interpreting this action on $R(\mathbb{F}, \Gamma)$. See, for example, [6].

The following is the key lemma about this action.

7.13 Lemma. *Let A be a Artin local ring with residue field isomorphic to \mathbb{F} and let (G, i, ϕ) and (G', i', ϕ') be two deformations of (\mathbb{F}, Γ) . Suppose there is an isomorphism of formal groups $\psi : G \rightarrow G'$ over A . Then there is a unique pair $(\sigma, \lambda) \in \text{Aut}(\mathbb{F}, \Gamma)$ so that ψ induces an isomorphism*

$$\psi : (G, i\sigma, (\sigma^* \phi)\lambda) \longrightarrow (G', i', \phi').$$

Proof. This is simply the assertion that there is a unique way to fill in left face

of the following diagram so that it commutes

$$\begin{array}{ccccc}
 & & \Gamma & \xrightarrow{\quad} & G_0 \\
 & \swarrow g & \downarrow & & \swarrow \psi_0 \\
 \Gamma & \xrightarrow{\quad} & G'_0 & & \downarrow \\
 \downarrow & & \downarrow & & \downarrow \\
 \text{Spec}(\mathbb{F}) & \xrightarrow{i} & \text{Spec}(A/\mathfrak{m}) & & \\
 \downarrow \sigma & & \downarrow & & \swarrow \\
 \text{Spec}(\mathbb{F}) & \xrightarrow{i'} & \text{Spec}(A/\mathfrak{m}) & &
 \end{array}$$

Alternatively, writing down the equations provides both the pair (σ, λ) and its uniqueness. Indeed, we need an equality of isomorphisms from $\text{Spec}(\mathbb{F})$ to $\text{Spec}(A/\mathfrak{m})$

$$i\sigma = i'$$

and a commutative diagram of isomorphisms of formal groups

$$\begin{array}{ccc}
 & & i^*G_0 \\
 \sigma^*(\phi)\lambda & \nearrow & \downarrow (i\sigma)^*\psi_0 \\
 \Gamma & & i^*G'_0 \\
 & \searrow \phi' &
 \end{array}$$

□

The action of the Morava stabilizer group is actually continuous in a sense we now make precise. Assume now that \mathbb{F} is an algebraic extension of \mathbb{F}_p . First we notice that the extended automorphism group $\mathbb{G}(\mathbb{F}, \Gamma)$ is profinite. Define normal subgroups $\mathbb{G}_k(\mathbb{F}, \Gamma)$ of $\mathbb{G}(\mathbb{F}, \Gamma)$ as follows. The group $\mathbb{G}(\mathbb{F}, \Gamma)$ is the set of Cartesian squares

$$\begin{array}{ccc}
 \Gamma & \xrightarrow{\lambda} & \Gamma \\
 \downarrow & & \downarrow \\
 \text{Spec}(\mathbb{F}) & \xrightarrow{\sigma} & \text{Spec}(\mathbb{F})
 \end{array}$$

under composition. The subgroup $\mathbb{G}_i(\mathbb{F}, \Gamma)$ is the set of those squares so that σ is the identity and λ induces the identity on the p^k -bud of the formal group Γ . Then $\mathbb{G}_0(\mathbb{F}, \Gamma) = \text{Aut}_{\mathbb{F}}(\Gamma)$,

$$\mathbb{G}(\mathbb{F}, \Gamma)/\mathbb{G}_0(\mathbb{F}, \Gamma) = \text{Gal}(\mathbb{F}, \mathbb{F}_p)$$

and

$$\mathbb{G}(\mathbb{F}, \Gamma) \cong \lim \mathbb{G}_k(\mathbb{F}, \Gamma).$$

If $\mathbb{F} \rightarrow \mathbb{F}'$ is an extension of subfields of $\bar{\mathbb{F}}_p$, then we get an injection of groups $\mathbb{G}_0(\mathbb{F}, \Gamma) \rightarrow \mathbb{G}_0(\mathbb{F}', \Gamma)$ which preserves the subgroups above. Thus the following result displays $\mathbb{G}(\mathbb{F}, \Gamma)$ as a profinite group. In Remark 5.32 we made the

following calculation. There is an isomorphism

$$\mathbb{G}_0(\bar{\mathbb{F}}_p, \Gamma)/\mathbb{G}_1(\bar{\mathbb{F}}_p, \Gamma) \cong \mathbb{F}_{p^n}^\times$$

and for $k > 0$ a non-canonical isomorphism

$$\mathbb{G}_k(\bar{\mathbb{F}}_p, \Gamma)/\mathbb{G}_{k+1}(\bar{\mathbb{F}}_p, \Gamma) \cong \mathbb{F}_{p^n}$$

7.14 Remark (The continuity of the action). Define $\mathbf{Def}_k(\mathbb{F}, \Gamma)$ to be the groupoid of triples (G, i, ϕ) where G is a formal group over an Artin local ring A , $i : \text{Spec}(\mathbb{F}) \rightarrow \text{Spec}(A/\mathfrak{m})$ is an isomorphism and

$$\phi : \Gamma_{p^k} \longrightarrow i^*(G_0)_{p^k}$$

is an isomorphism of p^k -buds. The morphisms in $\mathbf{Def}_k(\mathbb{F}, \Gamma)$ are isomorphisms $\psi : G \rightarrow G'$ which induce the appropriate commutative triangle over \mathbb{F} . (Note that $\mathbf{Def}_f(\mathbb{F}, \mathbb{G})$ is *not* the deformation of the buds, as these isomorphisms are defined over the whole group.) Since every isomorphism of buds over a Noetherian local ring can be lifted to an isomorphism of the formal groups, we have that the evident map

$$\mathbf{Def}(\mathbb{F}, \Gamma) \longrightarrow \mathbf{Def}_k(\mathbb{F}, \Gamma)$$

is surjective on objects and $\mathbb{G}(\mathbb{F}, \Gamma)$ -equivariant; furthermore, the induced map

$$(7.4) \quad \mathbf{Def}(\mathbb{F}, \Gamma) \longrightarrow \lim \mathbf{Def}_k(\mathbb{F}, \Gamma)$$

is an isomorphism. The action of $\mathbb{G}(\mathbb{F}, \Gamma)$ on $\mathbf{Def}_k(\mathbb{F}, \Gamma)$ factors through the quotient group $\mathbb{G}(\mathbb{F}, \Gamma)/\mathbb{G}_k(\mathbb{F}, \Gamma)$. If we give $\mathbf{Def}_k(\mathbb{F}, \Gamma)$ the discrete topology and $\mathbf{Def}(\mathbb{F}, \Gamma)$ the topology defined by the natural isomorphism 7.4, then the action of $\mathbb{G}(\mathbb{F}, \Gamma)$ on $\mathbf{Def}(\mathbb{F}, \Gamma)$ is continuous.

7.15 Lemma. *There is a natural isomorphism of functors on Artin local rings*

$$[\pi_0 \mathbf{Def}(\mathbb{F}, \Gamma)]/\mathbb{G}_k(\mathbb{F}, \Gamma) \xrightarrow{\cong} \pi_0 \mathbf{Def}_k(\mathbb{F}, \Gamma)$$

and for all (G, i, ϕ) in $\mathbf{Def}_k(\mathbb{F}, \Gamma)_A$,

$$\pi_1(\mathbf{Def}_k(\mathbb{F}, \Gamma)_A, G) = \mathbb{G}_k(\mathbb{F}, \Gamma).$$

Proof. This is a direct consequence of Lemma 7.13. The natural transformation

$$\pi_0 \mathbf{Def}(\mathbb{F}, \Gamma)/\mathbb{G}_k(\mathbb{F}, \Gamma) \longrightarrow \pi_0 \mathbf{Def}_k(\mathbb{F}, \Gamma)$$

is onto. If (G, i, ϕ) and (G', i, ϕ') are two deformations and

$$\psi : (G, i, \phi) \longrightarrow (G', i, \phi')$$

is an isomorphism in the $\mathbf{Def}_k(\mathbb{F}, \Gamma)$ there is a *unique* automorphism λ of Γ over \mathbb{F} so that

$$\psi : (G, i, \phi\lambda) \longrightarrow (G', i, \phi')$$

is an isomorphism in $\mathbf{Def}(\mathbb{F}, \Gamma)$. Note that λ is necessarily in $\mathbb{G}_k(\mathbb{F}, \Gamma)$.

Almost the same proof gives the statement about π_1 . Indeed, if $(G, i, \bar{\phi})$ is any lift of (G, i, ϕ) to $\mathbf{Def}(\mathbb{F}, \Gamma)$, then an automorphism $\psi : (G, i, \phi) \rightarrow (G, i, \phi)$ determines a unique element in $\mathbb{G}_k(\mathbb{F}, \Gamma)$ so that ψ induces an isomorphism

$$\psi : (G, i, \bar{\phi}\lambda) \longrightarrow (G, i, \bar{\phi}).$$

The assignment $\psi \mapsto \lambda$ induces the requisite isomorphism. \square

The functor $\mathbf{Def}_k(\mathbb{F}, \Gamma)$ from Artin rings to groupoids can be extended to all commutative rings using a left Kan extension as in Remark 7.8. Since we are taking a filtered colimit, the natural transformation $\mathbf{Def}(\mathbb{F}, \Gamma) \rightarrow \mathbf{Def}_k(\mathbb{F}, \Gamma)$ remains onto for all commutative rings. We get a natural sequence of maps

$$\pi_0 \mathbf{Def}(\mathbb{F}, \Gamma)_B \longrightarrow \lim \pi_0 \mathbf{Def}(\mathbb{F}, \Gamma)_B / \mathbb{G}_k(\mathbb{F}, \Gamma) \xrightarrow{\cong} \lim \mathbf{Def}_k(\mathbb{F}, \Gamma)_B.$$

The first map, which is an isomorphism for Artin rings, is not immediately an isomorphism in this generality because colimits don't commute with limits in general; however it is continuous and, as a result, an injection.

7.3 Deformations are the universal cover

We now prove the main result – that Lubin-Tate space is the universal cover of $\widehat{\mathcal{H}}(n)$. The notion of the group scheme defined by a profinite group G was covered in Remark 5.31. In the following result $\mathbb{G}(\Gamma, \mathbb{F})$ is the profinite group of automorphisms of the pair (Γ, \mathbb{F}) ; that is, the big Morava stabilizer group.

7.16 Theorem. *The natural transformations of groupoids over Artin local rings*

$$\mathbf{Def}(\mathbb{F}, \Gamma) \times \mathbb{G}(A, \mathbb{F}) \longrightarrow \mathbf{Def}(\mathbb{F}, \Gamma) \times_{\widehat{\mathcal{H}}(n)} \mathbf{Def}(\mathbb{F}, \Gamma)$$

given by

$$((G, i, \phi), (\sigma, \lambda)) \mapsto ((G, i, \phi), (G, i\sigma, \phi\lambda), 1 : G \rightarrow G)$$

is an equivalence.

Proof. A typical element in the pull-back is a triple

$$(7.5) \quad ((G, i, \phi), (G', i', \phi'), \psi : G \rightarrow G')$$

where the first two terms are deformations and ψ is any isomorphism of formal groups. A morphism in the pull-back

$$(\gamma, \gamma') : ((G_1, i, \phi), (G'_1, i', \phi'), \psi_1 : G_1 \rightarrow G'_1) \rightarrow ((G_2, j, \phi), (G'_2, i', \phi'), \psi_2 : G_2 \rightarrow G'_2)$$

are isomorphisms γ and γ' of deformations so that $\psi_2\gamma = \gamma'\psi_1$. Now we apply Lemma 7.13. Given the typical element, as in 7.5, we get a unique pair (σ, λ) in $\mathbb{G}(\mathbb{F}, \Gamma)$ so that

$$(7.6) \quad (1, \psi) : ((G, i, \phi), (G, i\sigma, \phi\lambda), 1_G) \rightarrow ((G, i, \phi), (G', i', \phi'), \psi)$$

is an isomorphism in the pull-back. The assignment

$$((G, i, \phi), (G', i', \phi'), \psi) \mapsto ((G, i, \phi), (G, i\sigma, \phi\lambda), 1_G)$$

becomes a natural transformation of groupoids sending a morphism (γ, γ') to (γ, γ) . Then 7.6 displays the necessary contraction. \square

7.17 Definition. Let $q : Y \rightarrow X$ be a morphism of categories fibered in groupoids over some base category. The group $\text{Aut}_Y(X)$ of automorphisms of Y over X consists of equivalence classes pairs (f, ψ) where $f : Y \rightarrow Y$ is a 1-morphism of groupoids and $\psi : q \rightarrow qf$ is a 2-morphism. Two such pairs (f, ψ) and (f', ψ') are equivalent if there is a 2-morphism $\phi : f \rightarrow f'$ so that $\psi'\phi = \psi$. The composition law reads

$$(g, \psi)(f, \phi) = (gf, (f^*\psi)\phi).$$

There is a homomorphism

$$\mathbb{G}(\mathbb{F}, \Gamma) \longrightarrow \text{Aut}_{\widehat{\mathcal{H}}(n)}(\mathbf{Def}(\mathbb{F}, \Gamma))$$

sending (σ, λ) to the pair $(f_{(\sigma, \lambda)}, 1)$ where $f_{(\sigma, \lambda)}$ is the transformation

$$(G, i, \phi) \mapsto (G, i\sigma, \phi\lambda).$$

7.18 Theorem. This homomorphism

$$\mathbb{G}(\mathbb{F}, \Gamma) \longrightarrow \text{Aut}_{\widehat{\mathcal{H}}(n)}(\mathbf{Def}(\mathbb{F}, \Gamma)).$$

is an isomorphism.

Proof. That the map is an injection is clear from the definitions. We now prove that it's surjective. Let (f, ψ) be an element of the automorphisms of $\mathbf{Def}(\mathbb{F}, \Gamma)$ over $\widehat{\mathcal{H}}(n)$. Let's write

$$f(G, i, \phi) = (G_f, i_f, \phi_f).$$

Then ψ gives isomorphism of formal groups $\psi_G : G \rightarrow G_f$. By Lemma 7.13 there is a unique pair $(\sigma, \lambda) \in \mathbb{G}(\mathbb{F}, \Gamma)$ so that

$$\psi_G : (G, i\sigma, \phi\lambda) \rightarrow (G_f, i_f, \phi_f)$$

is an isomorphism of deformations. The uniqueness of (σ, λ) and this equation give us the needed 2-morphism

$$\phi : f_{(\sigma, \lambda)} \longrightarrow f$$

\square

We wish to show that the isomorphism of Theorem 7.18 is appropriately continuous.

7.19 Lemma. *There is a surjective homomorphism of groups*

$$q_k : \text{Aut}_{\widehat{\mathcal{H}}(n)}(\mathbf{Def}(\mathbb{F}, \Gamma)) \rightarrow \text{Aut}_{\widehat{\mathcal{H}}(n)}(\mathbf{Def}_k(\mathbb{F}, \Gamma))$$

which induces a commutative diagram of groups

$$\begin{array}{ccc} \mathbb{G}(\mathbb{F}, \Gamma) & \longrightarrow & \text{Aut}_{\widehat{\mathcal{H}}(n)}(\mathbf{Def}(\mathbb{F}, \Gamma)) \\ \downarrow & & \downarrow q_k \\ \mathbb{G}(\mathbb{F}, \Gamma)/\mathbb{G}_{k+1}(\mathbb{F}, \Gamma) & \longrightarrow & \text{Aut}_{\widehat{\mathcal{H}}(n)}(\mathbf{Def}_k(\mathbb{F}, \Gamma)). \end{array}$$

Proof. We use Theorem 7.18. Any automorphism of $\mathbf{Def}(\mathbb{F}, \Gamma)$ of the form $f_{(\sigma, \lambda)}$ immediately induces an automorphism of $\mathbf{Def}_k(\mathbb{F}, \Gamma)$. This defines a morphism

$$\mathbb{G}(\mathbb{F}, \Gamma) \longrightarrow \text{Aut}_{\widehat{\mathcal{H}}(n)}(\mathbf{Def}_k(\mathbb{F}, \Gamma))$$

which factors through $\mathbb{G}(\mathbb{F}, \Gamma)/\mathbb{G}_{k+1}(\mathbb{F}, \Gamma)$. It remains only to show that it's onto. To show this, we use a variant of the argument in the proof of Theorem 7.18. If (f, ψ) is an automorphism of $\mathbf{Def}_k(\mathbb{F}, \Gamma)$ over $\widehat{\mathcal{H}}(n)$, we again write

$$f(G, i, \phi) = (G_f, i_f, \phi_f).$$

choose isomorphisms $\bar{\phi}$ and $\bar{\phi}_f$ lifting ϕ and ϕ_f respectively. Then Lemma 7.13 supplies an element $(\sigma, \lambda) \in \mathbb{G}(\mathbb{F}, \Gamma)$ so that

$$\psi_G : (G, i\sigma, \bar{\phi}\lambda) \rightarrow (G_f, i_f, \bar{\phi}_f).$$

The class of (σ, λ) in $\mathbb{G}(\mathbb{F}, \Gamma)/\mathbb{G}_{k+1}(\mathbb{F}, \Gamma)$ is independent of the choice and ψ supplies the needed 2-morphism to show surjectivity. \square

The groupoid $\mathbf{Def}_0(\mathbb{F}, \Gamma)$ has a simple description. Indeed, $\mathbf{Def}_0(\mathbb{F}, \Gamma)$ assigns to each Artin local ring A the pairs (G, i) where $i : \mathbb{F} \rightarrow \mathbb{A}/\mathfrak{m}$ is an isomorphism. Since \mathbb{F} is perfect, the universal property of Witt vectors ([5] §III.3) implies there is a unique homomorphism of rings $W(\mathbb{F}) \rightarrow A$ which reduces to \mathbb{F} modulo maximal ideals. Thus, we conclude that $\mathbf{Def}_0(\mathbb{F}, \Gamma)$ is the functor from groupoids to which assigns to each Artin local $W(\mathbb{F})$ -algebra A so that

$$W(\mathbb{F})/(p) \longrightarrow A/\mathfrak{m}$$

is an isomorphism the groupoid of formal groups G over A so that $\mathcal{I}_n(G) \subseteq \mathfrak{m}$ and $\mathcal{I}_{n+1}(G) = A$. Thus we have proved:

7.20 Lemma. *There is a natural isomorphism of categories fibered in groupoids over $\mathbf{Art}_{\mathbb{F}}$*

$$\mathbf{Def}_0(\mathbb{F}, \Gamma) \xrightarrow{\cong} W(\mathbb{F}) \otimes_{\mathbb{Z}_p} \widehat{\mathcal{H}}(n).$$

We now define what it means for a morphism to be Galois in this setting. Galois morphisms of schemes were defined in Remark 5.31.

7.21 Definition. A representable morphism $q : X \rightarrow Y$ of sheaves of groupoids in the fpqc-topology is **Galois** if q faithfully flat, and if the natural map

$$X \times \text{Aut}_Y(X) \longrightarrow X \times_Y X$$

is an equivalence of groupoids over X .

The main result of the section is now as follows.

7.22 Theorem. Let $\mathbb{F} = \bar{\mathbb{F}}_p$ be the algebraic closure of the prime field and let Γ be any height n -formal group over \mathbb{F}_p . Then

$$q : \mathbf{Def}(\mathbb{F}, \Gamma) \longrightarrow \widehat{\mathcal{H}}(n)$$

is Galois with Galois group

$$\mathbb{G}(\mathbb{F}, \Gamma) = \text{Gal}(\mathbb{F}/\mathbb{F}_p) \times \text{Aut}_{\bar{\mathbb{F}}_p}(\Gamma).$$

The discrete groupoid $\mathbf{Def}(\mathbb{F}, \Gamma) \simeq \text{Spf}(R(\mathbb{F}, \Gamma))$ itself has no non-trivial étale covers, so the morphism q is the universal cover.

Proof. To get that q is Galois, combine Proposition 7.11, Theorem 7.16, Theorem 7.18, Lemma 7.19, and Lemma 7.20. That $R(\mathbb{F}, \Gamma)$ has no non-trivial étale extensions follows from the fact that this ring is complete, local, and has an algebraically closed residue field. \square

7.23 Remark. All of these results can be rewritten in terms of the Lubin-Tate ring $R(\mathbb{F}, \Gamma)$ of Theorem 7.4 if we wish. For example, we can define a homomorphism

$$\mathbb{G}(\mathbb{F}, \Gamma) \longrightarrow \text{Aut}_{\widehat{\mathcal{H}}(n)}(\text{Spf}(R(\mathbb{F}, \Gamma)))$$

as follows. We refer to Remark 7.5. Let (H, j, ϕ_u) be the universal deformation over $\text{Spf}(R(\mathbb{F}, \Gamma))$ and let (σ, λ) be in $\mathbb{G}(\mathbb{F}, \Gamma)$. Then we get a new deformation $(H, j\sigma, \phi_u\lambda)$ over $\text{Spf}(R(\mathbb{F}, \Gamma))$, classified by a map

$$f = f_{(\sigma, \lambda)} : \text{Spf}(R(\mathbb{F}, \Gamma)) \rightarrow \text{Spf}(R(\mathbb{F}, \Gamma)).$$

Thus there is a unique isomorphism of deformations

$$\psi = \psi_{(\sigma, \lambda)} : (H, j, \phi_u) \rightarrow f^*(H, j, \phi_u).$$

The pair $(f_{(\sigma, \lambda)}, \psi_{(\sigma, \lambda)})$ now produces the 2-commuting diagram

$$\begin{array}{ccc} \text{Spf}(R(\mathbb{F}, \Gamma)) & \xrightarrow{f_{(\sigma, \lambda)}} & \text{Spf}(R(\mathbb{F}, \Gamma)) \\ & \searrow & \swarrow \\ & \widehat{\mathcal{H}}(n) & \end{array}$$

and the assignment

$$(\sigma, \lambda) \longmapsto (f_{(\sigma, \lambda)}, \psi_{(\sigma, \lambda)})$$

defines a group homomorphism

$$\mathbb{G}(\mathbb{F}, \Gamma) \longrightarrow \text{Aut}_{\widehat{\mathcal{H}}(n)}(\text{Spf}(R(\mathbb{F}, \Gamma))).$$

Theorem 7.18 then becomes the following result.

7.24 Proposition. *This homomorphism*

$$\mathbb{G}(\mathbb{F}, \Gamma) \longrightarrow \text{Aut}_{\widehat{\mathcal{H}}(n)}(\text{Spf}(R(\mathbb{F}, \Gamma))).$$

is an isomorphism.

Theorem 7.22 then reads as follows:

7.25 Theorem. *Let Γ be a formal group of height n over \mathbb{F}_p and let*

$$q : \text{Spf}(R(\overline{\mathbb{F}}_p, \Gamma)) \longrightarrow \widehat{\mathcal{H}}(n)$$

classify a universal deformation of Γ regarded as a formal group over $\overline{\mathbb{F}}_p$. Then q is the universal cover of the formal neighborhood $\widehat{\mathcal{H}}(n)$ of Γ ; specifically, q is pro-étale and Galois with Galois group the big Morava stabilizer group

$$\mathbb{G}(\overline{\mathbb{F}}_p, \Gamma) \cong \text{Gal}(\overline{\mathbb{F}}_p/\mathbb{F}_p) \rtimes \text{Aut}_{\overline{\mathbb{F}}_p}(\Gamma).$$

7.4 Morava modules

We add two remarks intended to clarify what it means to be a comodule over Morava E -theory

$$E_n \stackrel{\text{def}}{=} E(\mathbb{F}_{p^n}, \Gamma_n).$$

The conceptual difficulty is that we define

$$(E_n)_* E_n = \pi_* L_{K(n)}(E_n \wedge E_n)$$

where $L_{K(n)}$ is localization at Morava K -theory. As such, the usual translation from homotopy theory to comodules needs some modification. The appropriate concept is that of a Morava module, and we will give some exposition of this in Remark 7.27. To simplify matters we pass to $E(\overline{\mathbb{F}}_p, \Gamma)$.

7.26 Remark. Theorem 7.16 is the restatement of the well-known calculation of the homology cooperations in Lubin-Tate theory. There is a 2-periodic homology theory $E(\overline{\mathbb{F}}_p, \Gamma)$ with $E(\overline{\mathbb{F}}_p, \Gamma)_0 = R(\overline{\mathbb{F}}_p, \Gamma)$ and whose associated formal group is a choice of universal deformation of Γ . Then $E(\overline{\mathbb{F}}_p, \Gamma)$ is Landweber exact and

$$\begin{aligned} E(\overline{\mathbb{F}}_p, \Gamma)_0 E(\overline{\mathbb{F}}_p, \Gamma) &\stackrel{\text{def}}{=} \pi_0 L_{K(n)}(E(\overline{\mathbb{F}}_p, \Gamma) \wedge E(\overline{\mathbb{F}}_p, \Gamma)) \\ &\cong \text{map}(\mathbb{G}(\overline{\mathbb{F}}_p, \Gamma), R(\overline{\mathbb{F}}_p, \Gamma)) \end{aligned}$$

where $\text{map}(-, -)$ is the set of continuous maps. Proofs of this statement can be found in [53] and [23]; indeed, the argument given here for Theorem 7.16 is very similar to Hovey's.

7.27 Remark (Morava modules). Theorem 7.25 allows us to interpret quasi-coherent sheaves on $\widehat{\mathcal{H}}(n)$ as quasi-coherent sheaves on $\mathrm{Spf}(R(\overline{\mathbb{F}}_p, \Gamma))$ with a suitable $\mathbb{G}(\overline{\mathbb{F}}_p, \Gamma)$ action. Let's spell this out in more detail.

Let $\mathfrak{m} = \mathcal{I}_n(H) \subseteq R(\overline{\mathbb{F}}_p, \Gamma)$, where H is any choice of the universal deformation. Recall that a quasi-coherent sheaf on $\mathrm{Spf}(R(\overline{\mathbb{F}}_p, \Gamma))$ is determined by a tower

$$\cdots \rightarrow M_k \rightarrow M_{k-1} \rightarrow \cdots \rightarrow M_1$$

where M_k is an $R(\overline{\mathbb{F}}_p, \Gamma)/\mathfrak{m}^k$ -module, $M_k \rightarrow M_{k-1}$ is a $R(\overline{\mathbb{F}}_p, \Gamma)/\mathfrak{m}^k$ -module homomorphism and

$$R(\overline{\mathbb{F}}_p, \Gamma)/\mathfrak{m}^{k-1} \otimes_{R(\overline{\mathbb{F}}_p, \Gamma)/\mathfrak{m}^k} M_k \longrightarrow M_{k-1}$$

is an isomorphism. Under appropriate finiteness conditions, this tower is determined by its inverse limit $\lim M_k$ regarded as a continuous $R(\overline{\mathbb{F}}_p, \Gamma)$ -module.

A quasi-coherent sheaf on

$$\mathrm{Spf}(R(\overline{\mathbb{F}}_p, \Gamma)) \times_{\widehat{\mathcal{H}}(n)} \mathrm{Spf}(R(\overline{\mathbb{F}}_p, \Gamma)) \cong \mathrm{Spf}(\mathrm{map}(\mathbb{G}(\overline{\mathbb{F}}_p, \Gamma), R(\overline{\mathbb{F}}_p, \Gamma)))$$

has a similar description as modules over the tower

$$\{\mathrm{map}(\mathbb{G}(\overline{\mathbb{F}}_p, \Gamma), R(\overline{\mathbb{F}}_p, \Gamma)/\mathfrak{m}^n)\}.$$

A *Morava module* is a tower of $R(\overline{\mathbb{F}}_p, \Gamma)$ -modules

$$\cdots \rightarrow M_k \rightarrow M_{k-1} \rightarrow \cdots \rightarrow M_1$$

so that

1. M_k is an $R(\overline{\mathbb{F}}_p, \Gamma)/\mathfrak{m}^k$ -module and the induced map

$$R(\overline{\mathbb{F}}_p, \Gamma)/\mathfrak{m}^{k-1} \otimes_{R(\overline{\mathbb{F}}_p, \Gamma)/\mathfrak{m}^k} M_k \longrightarrow M_{k-1}$$

is an isomorphism;

2. M_k has a continuous $\mathbb{G}(\overline{\mathbb{F}}_p, \Gamma)$ -action, where M_k has the discrete topology;
3. the action of $\mathbb{G}(\overline{\mathbb{F}}_p, \Gamma)$ is twisted over $R(\overline{\mathbb{F}}_p, \Gamma)$ in the sense that if $a \in R(\overline{\mathbb{F}}_p, \Gamma)$, $x \in M_k$, and $g \in \mathbb{G}(\overline{\mathbb{F}}_p, \Gamma)$, then

$$g(ax) = g(a)g(x).$$

Now Theorem 7.25 implies there is an equivalence of categories between quasi-coherent sheaves on $\widehat{\mathcal{H}}(n)$ and Morava modules.

8 Completion and chromatic convergence

In this section we give the recipe for recovering a coherent sheaf on $\mathcal{M}_{\mathbf{fg}}$ (over $\mathbb{Z}_{(p)}$) from its restrictions to each of the open substacks of formal groups of height less than or equal to n . This has two steps: passing from one height to the next via a fracture square (Theorem 8.18) and then taking a derived inverse limit (Theorem 8.22). The latter theorem has particular teeth as the union of the open substacks of finite height is not all of $\mathcal{M}_{\mathbf{fg}}$.

Students of the homotopy theory literature will see that, in the end, our arguments are not so different from the Hopkins–Ravenel Chromatic Convergence of [49]. Much of the algebra here can be reworked in the language of comodules and, as such, it can be deduced from the work of Hovey and Strickland [25].

8.1 Local cohomology and scales

We begin by recalling some notation from Definition 6.10 and Proposition 5.10. Let $f : \mathcal{N} \rightarrow \mathcal{M}_{\mathbf{fg}}$ be a representable, separated, and flat morphism of algebraic stacks. We will confuse the ideal sheaves \mathcal{I}_n defining the height filtration with the pull-backs $f^*\mathcal{I}_n$, which induce the height filtration on \mathcal{N} . Thus, we let

$$0 = \mathcal{I}_0 \subseteq \mathcal{I}_1 \subseteq \mathcal{I}_2 \subseteq \cdots \subseteq \mathcal{O}_{\mathcal{N}}$$

denote the resulting scale on \mathcal{N} . Let $\mathcal{N}(n) = \mathcal{M}(n) \times_{\mathcal{M}_{\mathbf{fg}}} \mathcal{N} \subseteq \mathcal{N}$ be the closed substack defined by \mathcal{I}_n and let $\mathcal{V}(n-1)$ be the open complement. We will write $i_n : \mathcal{V}(n) \rightarrow \mathcal{N}$ and $j_n : \mathcal{N}(n) \rightarrow \mathcal{N}$ for the inclusions. Finally, let's write \mathcal{O} for $\mathcal{O}_{\mathcal{N}}$.

If \mathcal{F} is a quasi-coherent \mathcal{I}_n -torsion sheaf, we defined (in 6.18)

$$\mathcal{F}[v_n^{-1}] = (i_n)_* i_n^* \mathcal{F}.$$

The notation was justified in Remark 6.17. A local description of this sheaf was given in Proposition 6.16.

We wish to recursively define quasi-coherent sheaves $\mathcal{O}/\mathcal{I}_n^\infty$ on \mathcal{N} by setting $\mathcal{O}/\mathcal{I}_0^\infty = \mathcal{O}$ and then defining $\mathcal{O}/\mathcal{I}_{n+1}^\infty$ by the short exact sequence

$$(8.1) \quad 0 \rightarrow \mathcal{O}/\mathcal{I}_n^\infty \rightarrow \mathcal{O}/\mathcal{I}_n^\infty[v_n^{-1}] \rightarrow \mathcal{O}/\mathcal{I}_{n+1}^\infty \rightarrow 0.$$

In order to do this, we must prove the following lemma. In the process, we give local descriptions on these sheaves. See Equations 8.2 and 8.3.

8.1 Lemma. *For all $n \geq 0$, the sheaf $\mathcal{O}/\mathcal{I}_n^\infty$ is an \mathcal{I}_n -torsion sheaf and the unit of the adjunction*

$$\mathcal{O}/\mathcal{I}_n^\infty \rightarrow (i_n)_* i_n^* \mathcal{O}/\mathcal{I}_n^\infty = \mathcal{O}/\mathcal{I}_n^\infty[v_n^{-1}]$$

is injective.

Proof. Both statements are local, so can be proved by evaluating on an affine morphism $\text{Spec}(R) \rightarrow \mathcal{M}$ which is flat and quasi-compact. By taking a faithfully flat extension if necessary, we may assume that there are elements $u_n \in R$ so that

$$u_n + \mathcal{I}_n(R) \in \mathcal{O}/\mathcal{I}_n(R) \cong R/(u_0, \dots, u_{n-1})$$

is a generator of $\mathcal{I}_n(R)/\mathcal{I}_{n-1}(R)$. Since we have a scale, multiplication by u_n on $R/(u_0, \dots, u_{n-1})$ is injective. Define R -modules $R/(u_0^\infty, \dots, u_{n-1}^\infty)$ inductively by beginning with R and by insisting there be a short exact sequence

$$0 \rightarrow R/(u_0^\infty, \dots, u_{n-1}^\infty) \rightarrow R/(u_0^\infty, \dots, u_{n-1}^\infty)[u_n^{-1}] \rightarrow R/(u_0^\infty, \dots, u_n^\infty) \rightarrow 0.$$

Then inductively we have, using Proposition 6.16

$$(8.2) \quad \mathcal{O}/\mathcal{I}_n^\infty(R) = R/(u_0^\infty, \dots, u_{n-1}^\infty)$$

and

$$(8.3) \quad (i_n)_* i_n^* \mathcal{O}/\mathcal{I}_n^\infty(R) = R/(u_0^\infty, \dots, u_{n-1}^\infty)[u_n^{-1}].$$

The result now follows. \square

We note that Proposition 6.16 also implies:

8.2 Lemma. *For all $n > 0$ and all $s > 0$*

$$R^s (i_n)_* i_n^* \mathcal{O}/\mathcal{I}_n^\infty = 0.$$

8.3 Remark (Triangles and fiber sequences). In the rest of the section, we are going to use a shift functor on (co-)chain complexes of sheaves determined by the following equation. If C is a cochain complex and n is an integer, then

$$H^s C[n] = H^{s+n} C.$$

If C is a chain complex, then we regard it as a cochain complex by the equation $H^s C = H_{-s} C$; thus, $H_s C[n] = H_{s-n} C$. A distinguished triangle of cochain complexes

$$A \rightarrow B \rightarrow C \rightarrow A[1]$$

induces a long exact sequence in cohomology

$$\dots \rightarrow H^s A \rightarrow H^s B \rightarrow H^s C \rightarrow H^s A[1] = H^{s+1} A \rightarrow \dots$$

To shorten notation we may revert to the homotopy theory conventions and say that $A \rightarrow B \rightarrow C$ is a fiber sequence in cochain complexes.

If M is a sheaf, we may regard it as a cochain complex in degree zero; hence

$$H^s M[-n] = \begin{cases} M, & s = n; \\ 0, & s \neq n. \end{cases}$$

We now introduce local cohomology, which will be an important tool for the rest of this section.

8.4 Definition. Let $Z \subseteq \mathcal{N}$ be any closed substack with open complement $i : U \rightarrow \mathcal{N}$. If \mathcal{F} is a quasi-coherent sheaf on \mathcal{N} , define the derived **local cohomology sheaf** of \mathcal{F} by the distinguished triangle

$$(8.4) \quad R\Gamma_Z(\mathcal{N}, \mathcal{F}) \rightarrow \mathcal{F} \rightarrow Ri_*i^*\mathcal{F} \rightarrow R\Gamma_Z(\mathcal{N}, \mathcal{F})[1].$$

Put another way, $R\Gamma_Z(\mathcal{N}, \mathcal{F})$ is the homotopy fiber of the map $\mathcal{F} \rightarrow Ri_*i^*\mathcal{F}$.

If \mathcal{N} is understood, we may write $R\Gamma_Z\mathcal{F}$ for $R\Gamma_Z(\mathcal{N}, \mathcal{F})$; if Z is defined by an ideal sheaf $\mathcal{I} \subseteq \mathcal{O}$, we may write $R\Gamma_{\mathcal{I}}\mathcal{F}$ for $R\Gamma_Z(\mathcal{N}, \mathcal{F})$.

The *local cohomology* of \mathcal{F} at Z is then the graded cohomology sheaf

$$H_Z^*(\mathcal{N}, \mathcal{F}) \stackrel{\text{def}}{=} H^*R\Gamma_Z(\mathcal{N}, \mathcal{F}).$$

If $V \rightarrow \mathcal{N}$ is an open morphism in our topology, then

$$\Gamma_Z(\mathcal{N}, \mathcal{F})(V) = H_Z^0(\mathcal{N}, \mathcal{F})(V)$$

is the set of sections $s \in \mathcal{F}(V)$ which vanish when restricted to $\mathcal{F}(U \times_{\mathcal{N}} V)$. If \mathcal{I} is locally generated by a regular sequence, then we can give the following local description of $\Gamma_Z(\mathcal{N}, \mathcal{F})$. Let $\text{Spec}(R) \rightarrow \mathcal{N}$ be any morphism so that $\mathcal{I}(R)$ is generated by a regular sequence u_0, \dots, u_{n-1} . Then there is an exact sequence

$$(8.5) \quad \Gamma_Z(\mathcal{N}, \mathcal{F})(R) \rightarrow \mathcal{F}(R) \rightarrow \prod_i \mathcal{F}(R)[u_i^{-1}].$$

This has the following consequence. See Corollary 3.2.4 of [1] for a generalization.

In the next result and what follows, hom denotes the sheaf of homomorphisms and Hom denotes its global sections.

8.5 Lemma. Suppose that the ideal $\mathcal{I} \subseteq \mathcal{O}_{\mathcal{N}} = \mathcal{O}$ defining the closed substack $Z \subseteq \mathcal{N}$ is locally generated by a regular sequence. Then for any quasi-coherent sheaf \mathcal{F} on \mathcal{N} there is a natural equivalence

$$\text{colim}_k R \text{hom}(\mathcal{O}/\mathcal{I}^k, \mathcal{F}) \xrightarrow{\simeq} R\Gamma_Z(\mathcal{N}, \mathcal{F}).$$

Proof. Before taking derived functors, we note that there is certainly a natural map

$$\text{colim}_k \text{Hom}(\mathcal{O}/\mathcal{I}^k, \mathcal{F}) \longrightarrow \Gamma_Z(\mathcal{N}, \mathcal{F})$$

given by evaluating at the unit. We first prove that this is an isomorphism; for this it is sufficient to work locally. Let $\text{Spec}(R) \rightarrow \mathcal{M}$ where $\mathcal{I}(R)$ is generated by the regular sequence u_0, \dots, u_{k-1} . Then the exact sequence of 8.5 implies that $x \in \mathcal{F}(R)$ is in $\Gamma_Z(\mathcal{M}, \mathcal{F})(R)$ if and only if for all i there is a t_i so that $u_i^{t_i}x = 0$. This yields the desired (underived) isomorphism. Since colimit is exact on filtered diagrams, the derived version follows. \square

We now set $Z = \mathcal{N}(n+1)$, defined by \mathcal{I}_{n+1} , so that $\mathcal{V}(n) = \mathcal{N} - \mathcal{N}(n+1)$ and there is a distinguished triangle

$$R\Gamma_{\mathcal{N}(n+1)}\mathcal{F} \rightarrow \mathcal{F} \rightarrow R(i_n)_*i_n^*\mathcal{F} \rightarrow R\Gamma_{\mathcal{N}(n+1)}\mathcal{F}[1].$$

If \mathcal{F} is a quasi-coherent \mathcal{I}_n -torsion sheaf, then Proposition 6.16 applies and $(i_n)_*i_n^*\mathcal{F} = \mathcal{F}[v_n^{-1}]$.

The exact sequence defining $\mathcal{O}/\mathcal{I}_n^\infty$ and Lemmas 8.1 and 8.2 imply following result.

8.6 Lemma. *For all $n \geq 1$ there is an isomorphism in the derived category*

$$R\Gamma_{\mathcal{N}(n)}(\mathcal{N}, \mathcal{O}/\mathcal{I}_{n-1}^\infty) \cong \mathcal{O}/\mathcal{I}_n^\infty[-1].$$

We also have the following key calculation.

8.7 Proposition. *For all $n \geq 1$ there is an equivalence in the derived category of quasi-coherent sheaves*

$$R\Gamma_{\mathcal{N}(n)}(\mathcal{N}, \mathcal{O}) \simeq \mathcal{O}/\mathcal{I}_n^\infty[-n].$$

That is,

$$H_{\mathcal{N}(n)}^s(\mathcal{N}, \mathcal{O}) \cong \begin{cases} 0, & s \neq n; \\ \mathcal{O}/\mathcal{I}_n^\infty, & s = n. \end{cases}$$

Proof. We proceed by induction to show that

$$R\Gamma_{\mathcal{N}(n)}(\mathcal{N}, \mathcal{O}/\mathcal{I}_{n-k}^\infty) \simeq \mathcal{O}/\mathcal{I}_n^\infty[-k].$$

Lemma 8.6 is the case $k = 1$. To get the inductive case, we have an exact sequence

$$0 \rightarrow \mathcal{O}/\mathcal{I}_{n-(k+1)}^\infty \rightarrow (i_{n-k})_*i_{n-k}^*\mathcal{O}/\mathcal{I}_{n-(k+1)}^\infty \rightarrow \mathcal{O}/\mathcal{I}_{n-k}^\infty \rightarrow 0.$$

Hence we need to show that

$$R\Gamma_{\mathcal{N}(n)}((i_{n-k})_*i_{n-k}^*\mathcal{O}/\mathcal{I}_{n-(k+1)}^\infty) = 0,$$

or equivalently that

$$(i_{n-k})_*i_{n-k}^*\mathcal{O}/\mathcal{I}_{n-(k+1)}^\infty \rightarrow R(i_{n-1})_*i_{n-1}^*(i_{n-k})_*i_{n-k}^*\mathcal{O}/\mathcal{I}_{n-(k+1)}^\infty$$

is an equivalence. Consider the sequence of inclusions

$$\mathcal{V}(n-k) \xrightarrow{f} \mathcal{V}(n-1) \xrightarrow{i_{n-1}} \mathcal{N}$$

$\underbrace{\hspace{10em}}_{i_{n-k}}$

We easily check that $i_{n-1}^*(i_{n-k})_* = f_*$; since i_{n-1}^* is exact we have an equivalence

$$R(i_{n-k})_*i_{n-k}^*\mathcal{O}/\mathcal{I}_{n-(k+1)}^\infty \rightarrow R(i_{n-1})_*i_{n-1}^*(i_{n-k})_*i_{n-k}^*\mathcal{O}/\mathcal{I}_{n-(k+1)}^\infty$$

The result now follows from Lemma 8.2. \square

8.8 Theorem. *Let \mathcal{F} be a quasi-coherent sheaf on \mathcal{N} . Then there are natural equivalences in the derived category*

$$R\Gamma_{\mathcal{N}(n)}(\mathcal{N}, \mathcal{F}) \simeq \mathcal{O}/\mathcal{I}_n^\infty[-n] \otimes_{\mathcal{O}}^L \mathcal{F}$$

Proof. This follows immediately from Lemma 8.5 and Proposition 8.7; indeed, since $\mathcal{O}/\mathcal{I}_n^k$ is locally finitely presented

$$\begin{aligned} R\Gamma_{\mathcal{N}(n)}(\mathcal{N}, \mathcal{F}) &\simeq \operatorname{colim} R\operatorname{hom}(\mathcal{O}/\mathcal{I}_n^k, \mathcal{F}) \\ &\simeq \operatorname{colim} R\operatorname{hom}(\mathcal{O}/\mathcal{I}_n^k, \mathcal{O}) \otimes^L \mathcal{F} \\ &\simeq R\Gamma_{\mathcal{N}(n)}(\mathcal{N}, \mathcal{O}) \otimes^L \mathcal{F}. \end{aligned}$$

□

Another consequence of Lemma 8.5 and Proposition 8.7 is the following result.

8.9 Proposition. *There is an equivalence*

$$\operatorname{colim}_k R\operatorname{hom}(\mathcal{O}/\mathcal{I}_n^k, \mathcal{O}) \xrightarrow{\cong} \mathcal{O}/\mathcal{I}_n^\infty[-n].$$

We also will be interested in what happens if we vary n . Consider the sequence of inclusions

$$\begin{array}{ccc} \mathcal{V}(n-1) & \xrightarrow{f} & \mathcal{V}(n) & \xrightarrow{i_n} & \mathcal{N} \\ & & \searrow & \nearrow & \\ & & & & \mathcal{N} \\ & & & & \uparrow \\ & & & & \mathcal{V}(n-1) \end{array}$$

Recall that $\mathcal{V}(n)$ is the complement of $\mathcal{N}(n+1)$. In the case where $\mathcal{N} = \mathcal{M}_{\mathbf{fg}}$, $\mathcal{N}(n) = \mathcal{M}(n)$ classifies formal groups of height at least n , $\mathcal{V}(n) = \mathcal{U}(n)$ classifies formal groups of height at most n and $\mathcal{H}(n) = \mathcal{M}(n) \cap \mathcal{U}(n)$ classifies formal groups of exact height n .

8.10 Lemma. *For all quasi-coherent \mathcal{F} on \mathcal{N} , there are fiber sequences of cochain complexes of quasi-coherent sheaves*

$$R(i_n)_* i_n^* R\Gamma_{\mathcal{N}(n)} \mathcal{F} \rightarrow R(i_n)_* (i_n)^* \mathcal{F} \rightarrow R(i_{n-1})_* (i_{n-1})^* \mathcal{F}$$

and

$$R\Gamma_{\mathcal{N}(n+1)} \mathcal{F} \rightarrow R\Gamma_{\mathcal{N}(n)} \mathcal{F} \rightarrow R(i_n)_* i_n^* R\Gamma_{\mathcal{N}(n)} \mathcal{F}$$

Proof. The fiber sequence which defines local cohomology (see Definition 8.4) yields that these sequences are equivalent; so, we prove the first.

For any quasi-coherent sheaf on \mathcal{N} , we have a fiber sequence

$$(8.6) \quad R\Gamma_{\mathcal{H}(n)}(\mathcal{V}(n), i_n^* \mathcal{F}) \rightarrow i_n^* \mathcal{F} \rightarrow Rf_* i_{n-1}^* \mathcal{F}.$$

Here we have taken the liberty of writing $\mathcal{H}(n)$ for $\mathcal{V}(n) \cap \mathcal{N}(n)$ and we have used $f^* i_n^* \cong i_{n-1}^*$.

Next note that the adjoint to the equivalence $R(i_{n-1})_* \cong R(i_n)_* Rf_*$ yields a commutative diagram

$$\begin{array}{ccccc} i_n^* R\Gamma_{\mathcal{N}(n)}(\mathcal{N}, \mathcal{F}) & \longrightarrow & i_n^* \mathcal{F} & \longrightarrow & i_n^* R(i_{n-1})_* i_{n-1}^* \mathcal{F} \\ \downarrow & & \downarrow = & & \downarrow \\ R\Gamma_{H(n)}(\mathcal{V}(n), i_n^* \mathcal{F}) & \longrightarrow & i_n^* \mathcal{F} & \longrightarrow & Rf_* i_{n-1}^* \mathcal{F}. \end{array}$$

Finally, for all quasi-coherent sheaves \mathcal{E} on $\mathcal{V}(n-1)$, the natural map

$$i_n^* R(i_{n-1}^*) \mathcal{E} \longrightarrow Rf_* \mathcal{E}$$

is an equivalence; indeed, we easily check that $i_n^*(i_{n-1})_* \mathcal{E} \rightarrow f_* \mathcal{E}$ is an isomorphism and then we use that i_n^* is exact. From this we conclude that

$$R\Gamma_{H(n)}(\mathcal{V}(n), i_n^* \mathcal{F}) \longrightarrow i_n^* R\Gamma_{\mathcal{N}(n)}(\mathcal{N}, \mathcal{F})$$

is an equivalence. We feed this into Equation 8.6 and apply $R(i_n)_*$ to get the result. \square

Applying the second of the fiber sequences of Lemma 8.10 to $\mathcal{F} = \mathcal{O}$ itself and using Theorem 8.8, we get the fiber sequence

$$(8.7) \quad \mathcal{O}/\mathcal{I}_{n+1}^\infty[-n-1] \rightarrow \mathcal{O}/\mathcal{I}_n^\infty[-n] \rightarrow \mathcal{O}/\mathcal{I}_n^\infty[v^{-1}][-n]$$

which is the evident shift of the defining sequence 8.1. From this we obtain the following result.

8.11 Lemma. *There is a natural commutative diagram*

$$\begin{array}{ccc} R\Gamma_{\mathcal{N}(n+1)}(\mathcal{N}, \mathcal{F}) & \longrightarrow & R\Gamma_{\mathcal{N}(n)}(\mathcal{N}, \mathcal{F}) \\ \cong \downarrow & & \downarrow \cong \\ \mathcal{O}/\mathcal{I}_{n+1}^\infty[-n-1] \otimes_{\mathcal{O}}^L \mathcal{F} & \longrightarrow & \mathcal{O}/\mathcal{I}_n^\infty[-n] \otimes_{\mathcal{O}}^L \mathcal{F} \end{array}$$

where the bottom morphism is the boundary morphism induced by the short exact sequence

$$0 \rightarrow \mathcal{O}/\mathcal{I}_n^\infty \rightarrow \mathcal{O}/\mathcal{I}_n^\infty[v_n^{-1}] \rightarrow \mathcal{O}/\mathcal{I}_{n+1}^\infty \rightarrow 0.$$

8.2 Greenlees-May duality

There is a remarkable duality between local cohomology and completion first noticed by Greenlees and May [12] and globalized in [1]. Similar results appear in [4], which also has the general version of the fracture square we will write down below in Theorem 8.17. The techniques of [1] apply directly to the case of a quasi-compact and separated stack \mathcal{N} and the closed substacks $\mathcal{N}(n) \subseteq \mathcal{N}$ arising from a scale. The main result we'll use is the following. Derived completion was defined in Definition 6.4.

8.12 Proposition. *For all quasi-coherent sheaves \mathcal{F} on \mathcal{N} there is a natural equivalence*

$$L(\mathcal{F})_{\mathcal{N}(n)}^{\wedge} \simeq R\mathrm{hom}(\mathcal{O}/\mathcal{I}_n^{\infty}[-n], \mathcal{F}).$$

This result is actually equivalent to an apparently stronger result – *Greenlees-May duality*:

8.13 Theorem. *Let \mathcal{E} and \mathcal{F} be two chain complexes of quasi-coherent sheaves on \mathcal{N} . Then there is a natural equivalence*

$$R\mathrm{hom}(R\Gamma_{\mathcal{N}(n)}\mathcal{E}, \mathcal{F}) \simeq R\mathrm{hom}(\mathcal{E}, L(\mathcal{F})_{\mathcal{N}(n)}^{\wedge}).$$

Certainly Theorem 8.13 implies Proposition 8.12 by setting $\mathcal{E} = \mathcal{O}_{\mathcal{N}}$ and applying Proposition 8.7. Conversely, Theorem 8.8 gives a natural isomorphism

$$\begin{aligned} R\mathrm{hom}(R\Gamma_{\mathcal{N}(n)}\mathcal{E}, \mathcal{F}) &\cong R\mathrm{hom}(\mathcal{O}/\mathcal{I}_n^{\infty}[-n] \otimes^L \mathcal{E}, \mathcal{F}) \\ &\cong R\mathrm{hom}(\mathcal{E}, R\mathrm{hom}(\mathcal{O}/\mathcal{I}_n^{\infty}[-n], \mathcal{F})). \end{aligned}$$

Hence Theorem 8.13 follows from Proposition 8.12.

The argument to prove Proposition 8.12 goes exactly as in [1]; hence we will content ourselves with giving an outline.

Lemma 8.5 allows us to define a natural map

$$\Phi : L(\mathcal{F})_{\mathcal{N}(n)}^{\wedge} \longrightarrow R\mathrm{hom}(R\Gamma_{\mathcal{N}(n)}(\mathcal{N}, \mathcal{O}), \mathcal{F})$$

as follows. First note that for \mathcal{O} -module sheaves \mathcal{E} and \mathcal{F} , there is a natural map

$$(8.8) \quad \mathcal{E} \otimes \mathcal{F} \longrightarrow \mathrm{Hom}(\mathrm{Hom}(\mathcal{E}, \mathcal{O}), \mathcal{F})$$

given pointwise by sending $x \otimes y$ to the homomorphism $\phi_{x \otimes y}$ with

$$\phi_{x \otimes y}(f) = f(x)y.$$

The morphism of Equation 8.8 can be derived to an morphism

$$\mathcal{E} \otimes^L \mathcal{F} \longrightarrow R\mathrm{Hom}(R\mathrm{Hom}(\mathcal{E}, \mathcal{O}), \mathcal{F}).$$

Now Φ is defined as the composition

$$\begin{aligned} L(\mathcal{F})_{\mathcal{N}(n)}^{\wedge} &= \mathrm{holim}(\mathcal{F} \otimes^L \mathcal{O}/\mathcal{I}_n^k) \rightarrow \mathrm{holim} R\mathrm{hom}(R\mathrm{hom}(\mathcal{O}/\mathcal{I}_n^k, \mathcal{O}), \mathcal{F}) \\ &\cong R\mathrm{hom}(\mathrm{colim} R\mathrm{hom}(\mathcal{O}/\mathcal{I}_n^k, \mathcal{O}), \mathcal{F}) \\ &\cong R\mathrm{hom}(R\Gamma_{\mathcal{N}(n)}(\mathcal{N}, \mathcal{O}), \mathcal{F}). \end{aligned}$$

Proposition 8.12 now can be restated as

8.14 Proposition. *For all quasi-coherent sheaves \mathcal{F} , the natural map*

$$\Phi : L(\mathcal{F})_{\mathcal{N}(n)}^{\wedge} \longrightarrow R\mathrm{hom}(R\Gamma_{\mathcal{N}(n)}(\mathcal{N}, \mathcal{O}), \mathcal{F})$$

is an equivalence.

The first observation is that the question is local; that is, it is sufficient to show that Φ is an equivalence when evaluated at any flat and quasi-compact morphism $\text{Spec}(R) \rightarrow \mathcal{M}$ for which $\mathcal{I}_n(R)$ is generated by a regular sequence. This follows readily from the definition of completion (6.4) and the remarks immediately afterwards. If we write $I = \mathcal{I}_n(R)$ and $M = \mathcal{F}(R)$, then we are asking that the map

$$\Phi_V : L(M)_I^\wedge \rightarrow R \text{hom}(R\Gamma_I(R), M)$$

be an equivalence. This is exactly what Greenlees and May prove. There is a finiteness condition in the argument which is worth emphasizing: for all i , the R -module $R/(u_0^i, \dots, u_{n-1}^i)$ has a finite resolution by finitely generated free R -modules. The usual such resolution is the Koszul complex, which we now review.

Let R be a commutative ring and let $u \in R$. Define $K(u)$ to be the chain complex

$$R \xrightarrow{u} R$$

concentrated in degrees 0 and 1. If $\mathbf{u} = (u_0, \dots, u_{n-1})$ is an ordered n -tuple of elements in R , define the *Koszul complex* to be

$$K(\mathbf{u}) = K(u_0) \otimes \cdots \otimes K(u_{n-1}).$$

Note that if \mathbf{u} is a regular sequence in R and I is the ideal generated by u_0, \dots, u_{n-1} , then $K(\mathbf{u})$ is the Koszul resolution of R/I and

$$H_s(K(\mathbf{u}) \otimes M) \cong \text{Tor}_s^R(R/I, M).$$

Now fix the n -tuple \mathbf{u} and define $\mathbf{u}^i = (u_0^i, \dots, u_{n-1}^i)$. The commutative squares

$$\begin{array}{ccc} R & \xrightarrow{u_j^i} & R \\ u_j \downarrow & & \downarrow \\ R & \xrightarrow{u_j^{i-1}} & R \end{array} =$$

combine to give morphisms $f_i : K(\mathbf{u}^i) \rightarrow K(\mathbf{u}^{i-1})$. Thus if the elements of \mathbf{u} form a regular sequence,⁸ then a simple bicomplex argument shows that for any R -module M there is an homology isomorphism

$$L(M)_I^\wedge \simeq \text{holim}_j(K(\mathbf{u}^j) \otimes M).$$

This equivalence is natural in M , although it doesn't look very natural in R or I .

The dual complex

$$K^*(\mathbf{u}) \stackrel{\text{def}}{=} \text{Hom}_R(K(\mathbf{u}), R)$$

⁸Or, more generally, if the elements of \mathbf{u} are *pro-regular* as in [12].

is a chain complex concentrated in degrees s , $-n \leq s \leq 0$. Note that if the u_i form a regular sequence

$$(8.9) \quad H_s K^*(\mathbf{u}) = \text{Ext}_R^{-s}(R/(u_0, \dots, u_{n-1}), R) \cong \begin{cases} R/(u_0, \dots, u_{n-1}), & s = -n; \\ 0, & s \neq -n. \end{cases}$$

The dual of the maps f_i give maps $f_i^* : K^*(\mathbf{u}^{i-1}) \rightarrow K^*(\mathbf{u}^i)$. Define

$$K^*(\mathbf{u}^\infty) = \text{colim } K^*(\mathbf{u}^i).$$

We have natural homology equivalences, assuming the elements in \mathbf{u} form a regular sequence:

$$\begin{aligned} K^*(\mathbf{u}^\infty) \otimes M &\simeq \text{colim } K^*(\mathbf{u}^i) \otimes M \\ &\simeq \text{colim } \text{Hom}_R(K(\mathbf{u}^i), M) \\ &\simeq \text{colim } R \text{hom}_R(R/(x_0^i, \dots, x_{n-1}^i), M) \\ &\simeq R\Gamma_I(M). \end{aligned}$$

More is true, because $K(\mathbf{u}^i)$ is finitely generated as a chain complex of R -modules we have that the map of Equation 8.8

$$K(\mathbf{u}^i) \otimes M \longrightarrow \text{Hom}(K^*(\mathbf{u}^i), M)$$

is an isomorphism, natural in M . Then the local version of Greenlees-May duality follows:

$$\begin{aligned} L(M)_I^\wedge &\simeq \text{holim}(K(\mathbf{u}^j) \otimes R) \\ &\simeq \text{holim } \text{Hom}(K^*(\mathbf{u}^i), M) \\ &\simeq R \text{hom}(\text{colim } K^*(\mathbf{u}^i), M) \\ &\simeq R \text{hom}(R\Gamma_I(R), M). \end{aligned}$$

It is an exercise in bicomplexes to show that this is, up to natural homology equivalence, the map Φ of Proposition 8.14.

8.15 Remark. The isomorphism

$$H_{-s}(K^*(\mathbf{u}^\infty) \otimes M) \cong H_I^s(R, M)$$

developed above extends the exact sequence of Equation 8.5. Indeed, $K^*(\mathbf{u}^\infty) \otimes_R M$ is exactly the chain complex

$$M \rightarrow \prod_i M[u_i^{-1}] \rightarrow \prod_{i_1 < i_2} M[u_{i_1}^{-1} u_{i_2}^{-1}] \rightarrow \dots \rightarrow M[u_0^{-1} \dots u_{k-1}^{-1}] \rightarrow 0 \dots$$

8.3 Algebraic chromatic convergence

We now supply the two results we promised: a fracture square for reconstructing quasi-coherent sheaves for the completions and a decomposition of a coherent sheaf as a homotopy inverse limit.

We begin with a preliminary calculation. Compare Corollary 5.1.1 of [1].

8.16 Theorem. *Let \mathcal{F} be a quasi-coherent sheaf on \mathcal{N} . Then the natural map*

$$R\Gamma_{\mathcal{N}(n)}\mathcal{F} \longrightarrow R\Gamma_{\mathcal{N}(n)}L(\mathcal{F})_{\mathcal{N}(n)}^{\wedge}$$

is an equivalence.

Proof. The question is local (again) and, therefore, reduces to the following assertion. Let $\mathbf{u} = (u_0, \dots, u_{n-1})$ be a regular sequence in R , let I be the ideal generated by this regular sequence, and let P be a projective R -module. Then

$$K^*(\mathbf{u}^{\infty}) \otimes P \longrightarrow K^*(\mathbf{u}^{\infty}) \otimes (P)_I^{\wedge}$$

is an equivalence. Indeed, if we apply homology to the map

$$K^*(\mathbf{u}^i) \otimes P \longrightarrow K^*(\mathbf{u}^i) \otimes (P)_I^{\wedge}$$

then, by Equation 8.9 we obtain the maps

$$\mathrm{Ext}_R^s(R/(u_0^i, \dots, u_{n-1}^i), P) \longrightarrow \mathrm{Ext}_R^s(R/(u_0^i, \dots, u_{n-1}^i), (P)_I^{\wedge}).$$

Both source and target are zero if $s \neq n$ and if $s = n$ we have the map

$$P/(u_0^i, \dots, u_{n-1}^i) \rightarrow (P)_I^{\wedge}/(u_0^i, \dots, u_{n-1}^i)$$

which is an isomorphism. \square

This result has the following fracture square as a consequence. Recall that the open inclusion $i_{n-1} : \mathcal{V}(n-1) \rightarrow \mathcal{N}$ is complementary to the closed inclusion $j_n : \mathcal{N}(n) \rightarrow \mathcal{N}$.

8.17 Theorem (The fracture squares). *Let \mathcal{F} be a quasi-coherent sheaf on \mathcal{N} . Then there is a homotopy cartesian square in the derived category*

$$\begin{array}{ccc} \mathcal{F} & \longrightarrow & L(\mathcal{F})_{\mathcal{N}(n)}^{\wedge} \\ \downarrow & & \downarrow \\ R(i_{n-1})_* i_{n-1}^* \mathcal{F} & \longrightarrow & R(i_{n-1})_* i_{n-1}^* L(\mathcal{F})_{\mathcal{N}(n)}^{\wedge}. \end{array}$$

Proof. The induced morphisms on fibers of the vertical maps is exactly

$$R\Gamma_{\mathcal{N}(n)}\mathcal{F} \longrightarrow R\Gamma_{\mathcal{N}(n)}L(\mathcal{F})_{\mathcal{N}(n)}^{\wedge}$$

which is an equivalence by Proposition 8.16. \square

8.18 Remark. An important special case is worth isolating. Let \mathcal{F} be a quasi-coherent sheaf on \mathcal{N} and consider the sequence of inclusions

$$\mathcal{V}(n-1) \xrightarrow{f} \mathcal{V}(n) \xrightarrow{i_n} \mathcal{N}$$

$\underbrace{\hspace{10em}}_{i_{n-1}}$

Applying Theorem 8.17 to a complex of sheaves of the form $R(i_n)_*i_n^*\mathcal{F}$ where \mathcal{F} is quasi-coherent on \mathcal{N} , we get a homotopy cartesian square

$$(8.10) \quad \begin{array}{ccc} R(i_n)_*i_n^*\mathcal{F} & \longrightarrow & L(R(i_n)_*i_n^*\mathcal{F})_{\mathcal{N}(n)}^\wedge \\ \downarrow & & \downarrow \\ R(i_{n-1})_*i_{n-1}^*\mathcal{F} & \longrightarrow & R(i_{n-1})_*i_{n-1}^*L(R(i_n)_*i_n^*\mathcal{F})_{\mathcal{N}(n)}^\wedge. \end{array}$$

The right hand vertical column of this diagram seems excessively complicated, but expected to those familiar with the results of [24] §7.3. The topological analog of these calculations supplies a fracture square of spectra

$$\begin{array}{ccc} L_n X & \longrightarrow & L_{K(n)} X \\ \downarrow & & \downarrow \\ L_{n-1} X & \longrightarrow & L_{n-1} L_{K(n)} X. \end{array}$$

The connection to completion is somewhat less than straightforward and given by the equations

$$L_{K(n)} X \simeq L_{K(n)} L_n X = \text{holim } S/I \wedge L_n X$$

where $\{S/I\}$ is a suitable family of type n complexes.

Despite the unwieldy nature of the diagram of 8.10, the induced map on the homotopy fibers of the vertical map actually simplifies somewhat, as the following result shows. Compare Proposition 8.16.

8.19 Proposition. *For all quasi-coherent sheaves \mathcal{F} on \mathcal{N} , the natural map*

$$R\Gamma_{\mathcal{N}(n)} \mathcal{F} \rightarrow R\Gamma_{\mathcal{N}(n)} R(i_n)_*i_n^*\mathcal{F}$$

is an equivalence.

Proof. This follows from the fact that

$$R(i_{n-1})_*i_{n-1}^*\mathcal{F} \rightarrow R(i_{n-1})_*i_{n-1}^*R(i_n)_*i_n^*\mathcal{F}$$

is an equivalence, which in turn follows from the fact that

$$i_{n-1}^*(i_n)_* = f^*$$

and the fact that i_{n-1}^* is exact. □

Now let's specialize to the case where $\mathcal{N} = \mathcal{M}_{\mathbf{fg}}$ itself and $i_n : \mathcal{U}(n) \rightarrow \mathcal{M}_{\mathbf{fg}}$ be the inclusion of the open moduli substack of formal groups of height at most n . Then we will show that if \mathcal{F} is a *coherent* sheaf on $\mathcal{M}_{\mathbf{fg}}$, then the natural map

$$\mathcal{F} \rightarrow \operatorname{holim} R(i_n)_* i_n^* \mathcal{F}$$

is an isomorphism in the derived category of quasi-coherent sheaves. This is an algebraic analog of chromatic convergence. There is something to prove here as the open substacks $\mathcal{U}(n)$ do not exhaust $\mathcal{M}_{\mathbf{fg}}$; indeed, the morphism

$$\mathbb{G}_a : \operatorname{Spec}(\mathbb{F}_p) \longrightarrow \mathcal{M}_{\mathbf{fg}}$$

classifying the additive formal group (which has infinite height) does not factor through $\mathcal{U}(n)$ for any n .

The proof is below in Theorem 8.22. The observation that drives the argument in this: recall from Theorem 3.28 that if \mathcal{F} is a coherent sheaf on $\mathcal{M}_{\mathbf{fg}}$, then there is an integer r and a coherent sheaf \mathcal{F}_0 on the moduli stack of buds $\mathcal{M}_{\mathbf{fg}}\langle p^r \rangle$ so that $\mathcal{F} \cong q^* \mathcal{F}_0$. Thus we begin with the next computation.

8.20 Theorem. *Let \mathcal{F} be a quasi-coherent sheaf on $\mathcal{M}_{\mathbf{fg}}\langle p^r \rangle$. Then for all $n > r$ and all s , the map on local cohomology groups*

$$H_{\mathcal{M}(n+1)}^s(\mathcal{M}_{\mathbf{fg}}, q^* \mathcal{F}) \rightarrow H_{\mathcal{M}(n)}^s(\mathcal{M}_{\mathbf{fg}}, q^* \mathcal{F})$$

is zero.

Proof. We apply Lemma 8.11 and show that the induced map

$$\mathcal{O}/\mathcal{I}_{n+1}^\infty \otimes_{\mathcal{O}}^L \mathcal{F} \rightarrow \mathcal{O}/\mathcal{I}_n^\infty[1] \otimes_{\mathcal{O}}^L \mathcal{F}$$

is zero in homology. It is sufficient to prove this after evaluation at any affine presentation $f : X \rightarrow \mathcal{M}_{\mathbf{fg}}$. Let

$$X = \operatorname{Spec}(\mathbb{Z}_{(p)}[u_1, u_2, \dots]) \stackrel{\text{def}}{=} \operatorname{Spec}(V)$$

and let f classify the formal group obtained from the universal p -typical formal group law. Similarly, let

$$X_r = \operatorname{Spec}(\mathbb{Z}_{(p)}[u_1, u_2, \dots, u_r]) \stackrel{\text{def}}{=} \operatorname{Spec}(V_r) \rightarrow \mathcal{M}_{\mathbf{fg}}\langle p^r \rangle$$

classify the resulting bud. This, too, is a presentation, by Lemma 3.24. Let $M = \mathcal{F}(X_r \rightarrow \mathcal{M}_{\mathbf{fg}}\langle p^r \rangle)$. Then

$$V \otimes_{V_r} M \cong (q^* \mathcal{F})(X \rightarrow \mathcal{M}_{\mathbf{fg}})$$

and we are trying to calculate

$$\operatorname{Tor}_s^V(V/(p^\infty, \dots, u_n^\infty), V \otimes_{V_r} M) \rightarrow \operatorname{Tor}_{s-1}^V(V/(p^\infty, \dots, u_{n-1}^\infty), V \otimes_{V_r} M).$$

Since V is a free V_r -module, to see this homomorphism is zero it is sufficient to note that

$$V/(p^\infty, \dots, u_{n-1}^\infty) \rightarrow V/(p^\infty, \dots, u_{n-1}^\infty)[u_n^{-1}]$$

is split injective as a V_r -module as long as $n > r$. \square

8.21 Corollary. *Let \mathcal{F} be a quasi-coherent sheaf on $\mathcal{M}_{\mathbf{fg}}\langle p^r \rangle$. Then*

$$H_s(\mathcal{O}/\mathcal{I}_n^\infty \otimes^L q^* \mathcal{F}) = 0$$

for $s > r$.

Proof. Again one can work locally, using the presentations of the previous proof. We prove the result by induction on n . If $n \leq r$ the chain complex $K^*(\mathbf{u}^\infty)$ of V -modules supplies a resolution of length n of $V/(p^\infty, \dots, u_{n-1}^\infty)$ by flat V -modules; therefore,

$$H_s(\mathcal{O}/\mathcal{I}_n^\infty \otimes^L q^* \mathcal{F}) = 0, \quad s > n.$$

So we may assume $n > r$. Then the previous result and the induction hypothesis imply that

$$H_s(R(i_n)_* i_n^* \mathcal{O}/\mathcal{I}_{n-1}^\infty \otimes^L q^* \mathcal{F}) \cong H_s(\mathcal{O}/\mathcal{I}_n^\infty \otimes^L q^* \mathcal{F})$$

for $s > r$. Evaluated at $\mathrm{Spec}(V) \rightarrow \mathcal{M}_{\mathbf{fg}}$ this is an isomorphism

$$\mathrm{Tor}_s^V(V/(p^\infty, \dots, u_{n-1}^\infty)[u_n^{-1}], V \otimes_{V_r} M) \cong \mathrm{Tor}_s^V(V/(p^\infty, \dots, u_n^\infty), V \otimes_{V_r} M).$$

Since $n > r$, we have

$$\begin{aligned} \mathrm{Tor}_s^V(V/(p^\infty, \dots, u_{n-1}^\infty)[u_n^{-1}], V \otimes_{V_r} M) \\ \cong \mathrm{Tor}_s^V(V/(p^\infty, \dots, u_{n-1}^\infty), V \otimes_{V_r} M)[u_n^{-1}]. \end{aligned}$$

Since $s > r$, the latter group is zero by the induction hypothesis. \square

8.22 Theorem (Chromatic Convergence). *Let \mathcal{F} be a coherent sheaf on $\mathcal{M}_{\mathbf{fg}}$. Then the natural map*

$$\mathcal{F} \longrightarrow \mathrm{holim} R(i_n)_* i_n^* \mathcal{F}$$

is a quasi-isomorphism.

Proof. There are distinguished triangles

$$R\Gamma_{\mathcal{M}(n)} \mathcal{F} \rightarrow \mathcal{F} \rightarrow R(i_n)_* i_n^* \mathcal{F} \rightarrow R\Gamma_{\mathcal{M}(n)} \mathcal{F}[1];$$

therefore, it is sufficient to show that

$$\mathrm{holim} R\Gamma_{\mathcal{M}(n)} \mathcal{F} \simeq 0.$$

But this follows from Theorem 8.20. \square

8.23 Remark. The chromatic convergence result holds in slightly greater generality: if \mathcal{F}_0 is any quasi-coherent sheaf on $\mathcal{M}_{\mathbf{fg}}\langle p^r \rangle$ for some $r < \infty$, then the natural map

$$q^* \mathcal{F}_0 \longrightarrow \mathrm{holim} R(i_n)_* i_n^* q^* \mathcal{F}_0$$

is a quasi-isomorphism. I also point out that Hollander [17] has a proof that works if we only assume the the quasi-coherent sheaf \mathcal{F} has finite projective dimension in an appropriate sense.

8.24 Remark. The Hopkins-Ravenel chromatic convergence theorem [49] says that if X is a p -local finite spectrum, then the natural map

$$X \longrightarrow \operatorname{holim} L_n X$$

is an equivalence, where $L_n(-)$ denotes localization at the Johnson-Wilson homology theory $E(n)_*$ or, indeed, any Landweber exact homology theory of height n in the sense of 6.28. Translating Theorem 8.22 into a statement about (BP_*, BP_*BP) comodules, using Corollary 2.46 and Remark 3.14 and appealing to results of Hovey and Strickland [25], we see that we have proved that if X is a p -local finite spectrum, there is an isomorphism of comodules

$$BP_* X \cong \lim BP_* L_n X$$

and, further, that the higher right derived functors of limit in comodules all vanish:

$$\lim^s BP_* L_n X = 0.$$

Thus, if an appropriate homology spectral sequence converges, topological chromatic convergence will follow. Such spectral sequences are notorious for *not* converging, so some serious homotopy theoretic input is needed. In [49] this takes the form of a vanishing line argument.

8.25 Theorem. *Let \mathcal{F}_0 be a quasi-coherent sheaf on $\mathcal{M}_{\mathbf{fg}}\langle p^r \rangle$ and let $\mathcal{F} = q^* \mathcal{F}_0$ be the pull-back to $\mathcal{M}_{\mathbf{fg}}$. Then the natural map*

$$H^s(\mathcal{M}_{\mathbf{fg}}, \mathcal{F}) \longrightarrow H^s(\mathcal{U}(n), i_n^* \mathcal{F})$$

is an isomorphism for $s < n - r$ and injective for $s = n - r - 1$.

Proof. The failure of this map to be an isomorphism is measured by the long exact sequence

$$\begin{aligned} \cdots \rightarrow H^s(\mathcal{M}_{\mathbf{fg}}, R\Gamma_{\mathcal{M}(n+1)} \mathcal{F}) &\rightarrow H^s(\mathcal{M}_{\mathbf{fg}}, \mathcal{F}) \\ &\rightarrow H^s(\mathcal{U}(n), i_n^* \mathcal{F}) \rightarrow H^{s+1}(\mathcal{M}_{\mathbf{fg}}, R\Gamma_{\mathcal{M}(n+1)} \mathcal{F}) \rightarrow \cdots \end{aligned}$$

where $H^*(\mathcal{M}_{\mathbf{fg}}, R\Gamma_{\mathcal{M}(n+1)} \mathcal{F})$ is the hyper-cohomology of the derived local cohomology sheaf $R\Gamma_{\mathcal{M}(n+1)} \mathcal{F}$. This can be computed via the spectral sequence

$$H^p(\mathcal{M}_{\mathbf{fg}}, H^q R\Gamma_{\mathcal{M}(n+1)} \mathcal{F}) \implies H^{p+q}(\mathcal{M}_{\mathbf{fg}}, R\Gamma_{\mathcal{M}(n+1)} \mathcal{F}).$$

The isomorphism of Theorem 8.8

$$H^q R\Gamma_{\mathcal{M}(n+1)} \mathcal{F} \cong H_{n+1-q}(\mathcal{O}/\mathcal{L}_{n+1}^\infty \otimes^L \mathcal{F})$$

and Corollary 8.21 now give the result. \square

8.26 Remark. The Hopkins-Ravenel chromatic convergence results of [49] says that if X is a p -local finite complex, then there is a natural weak equivalence

$$X \xrightarrow{\simeq} \text{holim } L_n X$$

where $L_n X$ is the localization at the Johnson-Wilson theory $E(n)_*$. For such X , $BP_* X$ is a finitely presented comodule and, as in [25], we can interpret Theorem 8.22 as saying that there is an isomorphism

$$BP_* X \cong R \lim BP_* L_n X$$

where $R \lim$ is an appropriate total derived functor of inverse limit in comodules. Because homology and inverse limits do not necessarily commute, this is not, in itself, enough to prove the Hopkins-Ravenel result; some more homotopy theoretic data is needed.

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Department of Mathematics, Northwestern University, Evanston IL 60208
 pgoerss@math.northwestern.edu