1. Introduction

This chapter develops formal deformation theory in a form applicable later in the stacks project, closely following Rim [GRR72, Exposee VI] and Schlessinger [Sch68]. We strongly encourage the reader new to this topic to read the paper by Schlessinger first, as it is sufficiently general for most applications, and Schlessinger’s results are indeed used in most papers that use this kind of formal deformation theory.

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Let \( \Lambda \) be a complete Noetherian local ring with residue field \( k \), and let \( C_\Lambda \) denote the category of Artinian local \( \Lambda \)-algebras with residue field \( k \). Given a functor \( F : C_\Lambda \to \text{Sets} \) such that \( F(k) \) is a one element set, Schlessinger’s paper introduced conditions (H1)-(H4) such that:

1. \( F \) has a “hull” if and only if (H1)-(H3) hold.
2. \( F \) is prorepresentable if and only (H1)-(H4) hold.

The purpose of this chapter is to generalize these results in two ways exactly as is done in Rim’s paper:

(A) The functor \( F \) is replaced by a category \( \mathcal{F} \) cofibered in groupoids over \( \mathcal{C}_\Lambda \), see Section 3.

(B) We let \( \Lambda \) be a Noetherian ring and \( \Lambda \to k \) a finite ring map to a field. The category \( C_\Lambda \) is the category of Artinian local \( \Lambda \)-algebras \( A \) endowed with a given identification \( A/\mathfrak{m}_A = k \).

The analogue of the condition that \( F(k) \) is a one element set is that \( \mathcal{F}(k) \) is the trivial groupoid. If \( \mathcal{F} \) satisfies this condition then we say it is a predeformation category, but in general we do not make this assumption. Rim’s paper [GRR72, Exposee VI] is the original source for the results in this document. We also mention the useful paper [TV10], which discusses deformation theory with groupoids but in less generality than we do here.

An important role is played by the “completion” \( \hat{C}_\Lambda \) of the category \( C_\Lambda \). An object of \( \hat{C}_\Lambda \) is a Noetherian complete local \( \Lambda \)-algebra \( R \) whose residue field is identified with \( k \), see Section 4. On the one hand \( C_\Lambda \subset \hat{C}_\Lambda \) is a strictly full subcategory and on the other hand \( \hat{C}_\Lambda \) is a full subcategory of the category of pro-objects of \( C_\Lambda \). A functor \( C_\Lambda \to \text{Sets} \) is prorepresentable if it is isomorphic to the restriction of a representable functor \( R = \text{Mor}_{\hat{C}_\Lambda}(R, -) \) to \( C_\Lambda \) where \( R \in \text{Ob}(\hat{C}_\Lambda) \).

Categories cofibered in groupoids are dual to categories fibered in groupoids; we introduce them in Section 5. A smooth morphism of categories cofibered in groupoids over \( \mathcal{C}_\Lambda \) is one that satisfies the infinitesimal lifting criterion for objects, see Section 8. This is analogous to the definition of a formally smooth ring map, see Algebra, Definition 136.1 and is exactly dual to the notion in Criteria for Representability, Section 6. This is an important notion as we eventually want to prove that certain kinds of categories cofibered in groupoids have a smooth prorepresentable presentation, much like the characterization of algebraic stacks in Algebraic Stacks, Sections 16 and 17. A versal formal object of a category \( \mathcal{F} \) cofibered in groupoids over \( \mathcal{C}_\Lambda \) is an object \( \xi \in \hat{\mathcal{F}}(R) \) of the completion such that the associated morphism \( \xi : R \to \mathcal{F} \) is smooth.

In Section 9 we define conditions (S1) and (S2) on \( \mathcal{F} \) generalizing Schlessinger’s (H1) and (H2). The analogue of Schlessinger’s (H3)—the condition that \( \mathcal{F} \) has finite dimensional tangent space—is not given a name. A key step in the development of the theory is the existence of versal formal objects for predeformation categories satisfying (S1), (S2) and (H3), see Lemma 12.4. Schlessinger’s notion of a hull for a functor \( F : C_\Lambda \to \text{Sets} \) is, in our terminology, a versal formal object \( \xi \in \hat{\mathcal{F}}(R) \) such that the induced map of tangent spaces \( d\xi : TR \to TF \) is an isomorphism. In the literature a hull is often called a “miniversal” object. We do not do so, and here is why. It can happen that a functor has a versal formal object without having a hull. Moreover, we show in Section 13 that if a predeformation category has a
versal formal object, then it always has a minimal one (as defined in Definition 13.4) which is unique up to isomorphism, see Lemma 13.5. But it can happen that the minimal versal formal object does not induce an isomorphism on tangent spaces! (See Examples 14.3 and 14.8.)

Keeping in mind the differences pointed out above, Theorem 14.5 is the direct generalization of (1) above: it recovers Schlessinger’s result in the case that \( F \) is a functor and it characterizes minimal versal formal objects, in the presence of conditions (S1) and (S2), in terms of the map \( d_\xi : TR \to TF \) on tangent spaces.

In Section 15, we define Rim’s condition (RS) on \( F \) generalizing Schlessinger’s (H4). A deformation category is defined as a predeformation category satisfying (RS). The analogue to prorepresentable functors are the categories cofibered in groupoids over \( C_\Lambda \) which have a presentation by a smooth prorepresentable groupoid in functors on \( C_\Lambda \), see Definitions 19.1, 20.1, and 21.1. This notion of a presentation takes into account the groupoid structure of the fibers of \( F \). In Theorem 24.4 we prove that \( F \) has a presentation by a smooth prorepresentable groupoid in functors if and only if \( F \) has a finite dimensional tangent space and finite dimensional infinitesimal automorphism space. This is the generalization of (2) above: it reduces to Schlessinger’s result in the case that \( F \) is a functor. There is a final Section 25 where we discuss how to use minimal versal formal objects to produce a (unique up to isomorphism) minimal presentation by a smooth prorepresentable groupoid in functors.

We also find the following conceptual explanation for Schlessinger’s conditions. If a predeformation category \( \mathcal{F} \) satisfies (RS), then the associated functor of isomorphism classes \( \mathcal{F} : C_\Lambda \to Sets \) satisfies (H1) and (H2) (Lemmas 15.6 and 9.5). Conversely, if a functor \( F : C_\Lambda \to Sets \) arises naturally as the functor of isomorphism classes of a category \( \mathcal{F} \) cofibered in groupoids, then it seems to happen in practice that an argument showing \( F \) satisfies (H1) and (H2) will also show \( \mathcal{F} \) satisfies (RS) (see Artin’s Axioms, Section 22 for examples). Moreover, if \( \mathcal{F} \) satisfies (RS), then condition (H4) for \( \mathcal{F} \) has a simple interpretation in terms of extending automorphisms of objects of \( \mathcal{F} \) (Lemma 15.7). These observations suggest that (RS) should be regarded as the fundamental deformation theoretic glueing condition.

2. Notation and Conventions

A ring is commutative with 1. The maximal ideal of a local ring \( A \) is denoted by \( m_A \). The set of positive integers is denoted by \( \mathbb{N} = \{1, 2, 3, \ldots \} \). If \( U \) is an object of a category \( \mathcal{C} \), we denote by \( U \) the functor \( \text{Mor}_\mathcal{C}(U, -) : \mathcal{C} \to \text{Sets} \), see Remarks 5.2, 12. Warning: this may conflict with the notation in other chapters where we sometimes use \( U \) to denote \( h_U(-) = \text{Mor}_\mathcal{C}(-, U) \).

Throughout this chapter \( \Lambda \) is a Noetherian ring and \( \Lambda \to k \) is a finite ring map from \( \Lambda \) to a field. The kernel of this map is denoted \( m_\Lambda \) and the image \( k' \subset k \). It turns out that \( m_\Lambda \) is a maximal ideal, \( k' = \Lambda/m_\Lambda \) is a field, and the extension \( k' \subset k \) is finite. See discussion surrounding (3.3.1).

3. The base category

Motivation. An important application of formal deformation theory is to criteria for representability by algebraic spaces. Suppose given a locally Noetherian base \( S \) and a functor \( F : (\text{Sch}/S)^{\text{op}}_{\text{fppf}} \to \text{Sets} \). Let \( k \) be a finite type field over \( S \), i.e.,
we are given a finite type morphism $\text{Spec}(k) \to S$. One of Artin’s criteria is that for any element $x \in F(\text{Spec}(k))$ the predeformation functor associated to the triple $(S, k, x)$ should be prorepresentable. By Morphisms, Lemma 16.1 the condition that $k$ is of finite type over $S$ means that there exists an affine open $\text{Spec}(\Lambda) \subset S$ such that $k$ is a finite $\Lambda$-algebra. This motivates why we work throughout this chapter with a base category as follows.

**Definition 3.1.** Let $\Lambda$ be a Noetherian ring and let $\Lambda \to k$ be a finite ring map where $k$ is a field. We define $C_\Lambda$ to be the category with

1. objects are pairs $(A, \varphi)$ where $A$ is an Artinian local $\Lambda$-algebra and where $\varphi : A/m_A \to k$ is a $\Lambda$-algebra isomorphism, and
2. morphisms $f : (B, \psi) \to (A, \varphi)$ are local $\Lambda$-algebra homomorphisms such that $\varphi \circ (f \mod m) = \psi$.

We say we are in the classical case if $\Lambda$ is a Noetherian complete local ring and $k$ is its residue field.

Note that if $\Lambda \to k$ is surjective and if $A$ is an Artinian local $\Lambda$-algebra, then the identification $\varphi$, if it exists, is unique. Moreover, in this case any $\Lambda$-algebra map $A \to B$ is going to be compatible with the identifications. Hence in this case $C_\Lambda$ is just the category of local Artinian $\Lambda$-algebras whose residue field “is” $k$. By abuse of notation we also denote objects of $C_\Lambda$ simply $A$ in the general case. Moreover, we will often write $A/m = k$, i.e., we will pretend all rings in $C_\Lambda$ have residue field $k$ (since all ring maps in $C_\Lambda$ are compatible with the given identifications this should never cause any problems). Throughout the rest of this chapter the base ring $\Lambda$ and the field $k$ are fixed. The category $C_\Lambda$ will be the base category for the cofibered categories considered below.

**Definition 3.2.** Let $f : B \to A$ be a ring map in $C_\Lambda$. We say $f$ is a small extension if it is surjective and $\text{Ker}(f)$ is a nonzero principal ideal which is annihilated by $m_B$.

By the following lemma we can often reduce arguments involving surjective ring maps in $C_\Lambda$ to the case of small extensions.

**Lemma 3.3.** Let $f : B \to A$ be a surjective ring map in $C_\Lambda$. Then $f$ can be factored as a composition of small extensions.

**Proof.** Let $I$ be the kernel of $f$. The maximal ideal $m_B$ is nilpotent since $B$ is Artinian, say $m_B^n = 0$. Hence we get a factorization

$$B = B/Im_B^{n-1} \to B/Im_B^{n-2} \to \ldots \to B/I \cong A$$

of $f$ into a composition of surjective maps whose kernels are annihilated by the maximal ideal. Thus it suffices to prove the lemma when $f$ itself is such a map, i.e. when $I$ is annihilated by $m_B$. In this case $I$ is a $k$-vector space, which has finite dimension, see Algebra, Lemma 52.6. Take a basis $x_1, \ldots, x_n$ of $I$ as a $k$-vector space to get a factorization

$$B \to B/(x_1) \to \ldots \to B/(x_1, \ldots, x_n) \cong A$$

of $f$ into a composition of small extensions. □

The next lemma says that we can compute the length of a module over a local $\Lambda$-algebra with residue field $k$ in terms of the length over $\Lambda$. To explain the notation
in the statement, let $k' \subset k$ be the image of our fixed finite ring map $\Lambda \to k$. Note that $k/k'$ is a finite extension of rings. Hence $k'$ is a field and $k'/k$ is a finite extension, see Algebra, Lemma 35.10. Moreover, as $\Lambda \to k'$ is surjective we see that its kernel is a maximal ideal $m_\Lambda$. Thus

$$[k : k'] = [k : \Lambda/m_\Lambda] < \infty$$

and in the classical case we have $k = k'$. The notation $k' = \Lambda/m_\Lambda$ will be fixed throughout this chapter.

**Lemma 3.4.** Let $A$ be a local $\Lambda$-algebra with residue field $k$. Let $M$ be an $A$-module. Then $[k : k'] \text{length}_A(M) = \text{length}_A(M)$. In the classical case we have $\text{length}_A(M) = \text{length}_A(M)$.

**Proof.** If $M$ is a simple $A$-module then $M \cong k$ as an $A$-module, see Algebra, Lemma 51.10. In this case $\text{length}_A(M) = 1$ and $\text{length}_A(M) = [k' : k]$, see Algebra, Lemma 51.6. If $\text{length}_A(M)$ is finite, then the result follows on choosing a filtration of $M$ by $A$-submodules with simple quotients using additivity, see Algebra, Lemma 35.12. If $\text{length}_A(M)$ is infinite, the result follows from the obvious inequality $\text{length}_A(M) \leq \text{length}_A(M)$.

**Lemma 3.5.** Let $A \to B$ be a ring map in $\mathcal{C}_\Lambda$. The following are equivalent

1. $f$ is surjective,
2. $m_A/m_A^2 \to m_B/m_B^2$ is surjective, and
3. $m_A/(m_A A + m_A^2) \to m_B/(m_A B + m_B^2)$ is surjective.

**Proof.** For any ring map $f : A \to B$ in $\mathcal{C}_\Lambda$ we have $f(m_A) \subset m_B$ for example because $m_A$, $m_B$ is the set of nilpotent elements of $A$, $B$. Suppose $f$ is surjective. Let $y \in m_B$. Choose $x \in A$ with $f(x) = y$. Since $f$ induces an isomorphism $A/m_A \to B/m_B$ we see that $x \in m_A$. Hence the induced map $m_A/m_A^2 \to m_B/m_B^2$ is surjective. In this way we see that (1) implies (2).

It is clear that (2) implies (3). The map $A \to B$ gives rise to a canonical commutative diagram

$$
\begin{array}{ccc}
m_A/m_A^2 \otimes_{k'} k & \longrightarrow & m_A/m_A^2 \longrightarrow m_A/(m_A A + m_A^2) \longrightarrow 0 \\
\downarrow & & \downarrow & \downarrow \\
m_A/m_A^2 \otimes_{k'} k & \longrightarrow & m_B/m_B^2 \longrightarrow m_B/(m_A B + m_B^2) \longrightarrow 0
\end{array}
$$

with exact rows. Hence if (3) holds, then so does (2).

Assume (2). To show that $A \to B$ is surjective it suffices by Nakayama’s lemma (Algebra, Lemma 19.1) to show that $A/m_A \to B/m_A B$ is surjective. (Note that $m_A$ is a nilpotent ideal.) As $k = A/m_A = B/m_B$ it suffices to show that $m_A B \to m_B$ is surjective. Applying Nakayama’s lemma once more we see that it suffices to see that $m_A B/m_A m_B \to m_B/m_B^2$ is surjective which is what we assumed.

If $A \to B$ is a ring map in $\mathcal{C}_\Lambda$, then the map $m_A/(m_A A + m_A^2) \to m_B/(m_A B + m_B^2)$ is the map on relative cotangent spaces. Here is a formal definition.
Definition 3.6. Let \( R \to S \) be a local homomorphism of local rings. The relative cotangent space \( \Omega_{R/S} \) of \( R \) over \( S \) is the \( S/m_S \)-vector space \( m_R S / (m_R S + m_S^2) \).

If \( f_1 : A_1 \to A \) and \( f_2 : A_2 \to A \) are two ring maps, then the fiber product \( A_1 \times_A A_2 \) is the subring of \( A_1 \times A_2 \) consisting of elements whose two projections to \( A \) are equal. Throughout this chapter we will be considering conditions involving such a fiber product when \( f_1 \) and \( f_2 \) are in \( \mathcal{C}_A \). It isn’t always the case that the fibre product is an object of \( \mathcal{C}_A \).

Example 3.7. Let \( p \) be a prime number and let \( n \in \mathbb{N} \). Let \( \Lambda = \mathbb{F}_p(t_1, t_2, \ldots, t_n) \) and let \( k = \mathbb{F}_p(x_1, \ldots, x_n) \) with map \( \Lambda \to k \) given by \( t_i \mapsto x_i^p \). Let \( A = k[\epsilon] = k[x]/(x^2) \). Then \( A \) is an object of \( \mathcal{C}_1 \). Suppose that \( D : k \to k \) is a derivation of \( k \) over \( \Lambda \), for example \( D = \partial / \partial x_i \). Then the map
\[
 f_D : k \to k[\epsilon], \quad a \mapsto a + D(a) \epsilon
\]
is a morphism of \( \mathcal{C}_1 \). Let \( A_1 = A_2 = k \) and set \( f_1 = f_{\partial / \partial x_1} \) and \( f_2(a) = a \). Then \( A_1 \times_A A_2 = \{ a \in k \mid \partial / \partial x_1(a) = 0 \} \) which does not surject onto \( k \). Hence the fibre product isn’t an object of \( \mathcal{C}_1 \).

It turns out that this problem can only occur if the residue field extension \( k' \subset k \) is inseparable and neither \( f_1 \) nor \( f_2 \) is surjective.

Lemma 3.8. Let \( f_1 : A_1 \to A \) and \( f_2 : A_2 \to A \) be ring maps in \( \mathcal{C}_A \). Then:

1. If \( f_1 \) or \( f_2 \) is surjective, then \( A_1 \times_A A_2 \) is in \( \mathcal{C}_A \).
2. If \( f_2 \) is a small extension, then so is \( A_1 \times_A A_2 \to A_1 \).
3. If the field extension \( k' \subset k \) is separable, then \( A_1 \times_A A_2 \) is in \( \mathcal{C}_A \).

Proof. The ring \( A_1 \times_A A_2 \) is a \( \Lambda \)-algebra via the map \( \Lambda \to A_1 \times_A A_2 \) induced by the maps \( \Lambda \to A_1 \) and \( \Lambda \to A_2 \). It is a local ring with unique maximal ideal
\[
m_{A_1} \times_{m_A} m_{A_2} = \text{Ker}(A_1 \times_A A_2 \to k)
\]
A ring is Artinian if and only if it has finite length as a module over itself, see Algebra, Lemma \([52.6]\). Since \( A_1 \) and \( A_2 \) are Artinian, Lemma \([3.4]\) implies \( \text{length}_\Lambda(A_1) \) and \( \text{length}_\Lambda(A_2) \), and hence \( \text{length}_\Lambda(A_1 \times_A A_2) \), are all finite. As \( A_1 \times_A A_2 \subset A_1 \times A_2 \) is a \( \Lambda \)-submodule, this implies \( \text{length}_\Lambda(A_1 \times_A A_2) \leq \text{length}_\Lambda(A_1 \times_A A_2) \) is finite. So \( A_1 \times_A A_2 \) is Artinian. Thus the only thing that is keeping \( A_1 \times_A A_2 \) from being an object of \( \mathcal{C}_A \) is the possibility that its residue field maps to a proper subfield of \( k \) via the map \( A_1 \times_A A_2 \to A \to A/m_A = k \) above.

Proof of (1). If \( f_2 \) is surjective, then the projection \( A_1 \times_A A_2 \to A_1 \) is surjective. Hence the composition \( A_1 \times_A A_2 \to A_1 \to A_1/m_{A_1} = k \) is surjective and we conclude that \( A_1 \times_A A_2 \) is an object of \( \mathcal{C}_A \).

Proof of (2). If \( f_2 \) is a small extension then \( A_2 \to A \) and \( A_1 \times_A A_2 \to A_1 \) are both surjective with the same kernel. Hence the kernel of \( A_1 \times_A A_2 \to A_1 \) is a 1-dimensional \( k \)-vector space and we see that \( A_1 \times_A A_2 \to A_1 \) is a small extension.

Proof of (3). Choose \( \pi \in k \) such that \( k = k'(\pi) \) (see Fields, Lemma \([18.1]\)). Let \( P'(T) \in k'[T] \) be the minimal polynomial of \( \pi \) over \( k' \). Since \( k/k' \) is separable we see that \( dP'/dT(\pi) \neq 0 \). Choose a monic \( P \in \Lambda[T] \) which maps to \( P' \) under the

\[\text{Caution: We will see later that in our general setting the tangent space of an object } A \in \mathcal{C}_A \text{ over } \Lambda \text{ should not be defined simply as the } k\text{-linear dual of the relative cotangent space. In fact, the correct definition of the relative cotangent space is } \Omega_{S/R} \otimes_S S/m_S.\]
surjective map \( \Lambda[T] \to k'[T] \). Because \( A, A_1, A_2 \) are henselian, see Algebra, Lemma 148.10, we can find \( x, x_1, x_2 \in A, A_1, A_2 \) with \( P(x) = 0, P(x_1) = 0, P(x_2) = 0 \) and such that the image of \( x, x_1, x_2 \) in \( k \) is \( \pi \). Then \( (x_1, x_2) \in A_1 \times_A A_2 \) because \( x_1, x_2 \) map to \( x \in A \) by uniqueness, see Algebra, Lemma 148.2. Hence the residue field of \( A_1 \times_A A_2 \) contains a generator of \( k \) over \( k' \) and we win. \( \square \)

Next we define essential surjections in \( \mathcal{C}_\Lambda \). A necessary and sufficient condition for a surjection in \( \mathcal{C}_\Lambda \) to be essential is given in Lemma 3.12.

**Definition** 3.9. Let \( f : B \to A \) be a ring map in \( \mathcal{C}_\Lambda \). We say \( f \) is an *essential surjection* if it has the following properties:

1. \( f \) is surjective.
2. If \( g : C \to B \) is a ring map in \( \mathcal{C}_\Lambda \) such that \( f \circ g \) is surjective, then \( g \) is surjective.

Using Lemma 3.5, we can characterize essential surjections in \( \mathcal{C}_\Lambda \) as follows.

**Lemma 3.10.** Let \( f : B \to A \) be a ring map in \( \mathcal{C}_\Lambda \). The following are equivalent

1. \( f \) is an essential surjection,
2. the map \( B/m_B^2 \to A/m_A^2 \) is an essential surjection, and
3. the map \( B/(m_AB + m_B^2) \to A/(m_AA + m_A^2) \) is an essential surjection.

**Proof.** Assume (3). Let \( C \to B \) be a ring map in \( \mathcal{C}_\Lambda \) such that \( C \to A \) is surjective. Then \( C \to A/(m_AA + m_A^2) \) is surjective too. We conclude that \( C \to B/(m_AB + m_B^2) \) is surjective by our assumption. Hence \( C \to B \) is surjective by applying Lemma 3.5 (2 times).

Assume (1). Let \( C \to B/(m_AB + m_B^2) \) be a morphism of \( \mathcal{C}_\Lambda \) such that \( C \to A/(m_AA + m_A^2) \) is surjective. Set \( C' = C \times_B (m_AB + m_B^2) B \) which is an object of \( \mathcal{C}_\Lambda \) by Lemma 3.8. Note that \( C' \to A/(m_AA + m_A^2) \) is still surjective, hence \( C' \to A \) is surjective by Lemma 3.5. Thus \( C' \to B \) is surjective by our assumption. This implies that \( C' \to B/(m_AB + m_B^2) \) is surjective, which implies by the construction of \( C' \) that \( C \to B/(m_AB + m_B^2) \) is surjective.

In the first paragraph we proved (3) \( \Rightarrow \) (1) and in the second paragraph we proved (1) \( \Rightarrow \) (3). The equivalence of (2) and (3) is a special case of the equivalence of (1) and (3), hence we are done. \( \square \)

To analyze essential surjections in \( \mathcal{C}_\Lambda \) a bit more we introduce some notation. Suppose that \( A \) is an object of \( \mathcal{C}_\Lambda \). There is a canonical exact sequence

\[
\begin{align*}
\mathfrak{m}_A/m_A^2 & \xrightarrow{\delta_A} \Omega_{A/A} \otimes_A k \to \Omega_{k/A} \to 0
\end{align*}
\]

see Algebra, Lemma 130.9. Note that \( \Omega_{k/A} = \Omega_{k/k'} \) with \( k' \) as in (3.3.1). Let \( H_1(L_{k/A}) \) be the first homology module of the naive cotangent complex of \( k \) over \( A \), see Algebra, Definition 132.1. Then we can extend (3.10.1) to the exact sequence

\[
\begin{align*}
H_1(L_{k/A}) & \to \mathfrak{m}_A/m_A^2 \xrightarrow{\delta_A} \Omega_{A/A} \otimes_A k \to \Omega_{k/A} \to 0,
\end{align*}
\]
If $B \to A$ is a ring map in $\mathcal{C}_A$ then we obtain a commutative diagram

$$
\begin{array}{c}
H_1(L_{k/A}) & \longrightarrow & \frac{m_B}{m_B^2} & \longrightarrow & \Omega_{B/A} \otimes_B k & \longrightarrow & \Omega_{k/A} & \longrightarrow & 0 \\
\bigg\uparrow & & \downarrow d_B \bigg\uparrow & & \bigg\downarrow & & \bigg\downarrow & & \\
H_1(L_{k/A}) & \longrightarrow & \frac{m_A}{m_A^2} & \longrightarrow & \Omega_{A/A} \otimes_A k & \longrightarrow & \Omega_{k/A} & \longrightarrow & 0
\end{array}
$$

(3.10.3)

with exact rows.

**Lemma 3.11.** There is a canonical map

$$
\frac{m_A}{m_A^2} \longrightarrow H_1(L_{k/A}).
$$

If $k' \subset k$ is separable (for example if the characteristic of $k$ is zero), then this map induces an isomorphism $\frac{m_A}{m_A^2} \otimes_{k'} k = H_1(L_{k/A})$. If $k = k'$ (for example in the classical case), then $\frac{m_A}{m_A^2} = H_1(L_{k/A})$. The composition

$$
\frac{m_A}{m_A^2} \longrightarrow H_1(L_{k/A}) \longrightarrow \frac{m_A}{m_A^2}
$$

comes from the canonical map $m_A \to m_A$.

**Proof.** Note that $H_1(L_{k'/A}) = \frac{m_A}{m_A^2}$ as $A \to k'$ is surjective with kernel $m_A$. The map arises from functoriality of the naive cotangent complex. If $k' \subset k$ is separable, then $k' \to k$ is an étale ring map, see Algebra, Lemma 132.4. Thus its naive cotangent complex has trivial homology groups, see Algebra, Definition 141.1. Then Algebra, Lemma 132.4 applied to the ring maps $A \to k' \to k$ implies that $\frac{m_A}{m_A^2} \otimes_{k'} k = H_1(L_{k/A})$. We omit the proof of the final statement. □

**Lemma 3.12.** Let $f : B \to A$ be a ring map in $\mathcal{C}_A$. Notation as in (3.10.3).

1. The equivalent conditions of Lemma 3.10 characterizing when $f$ is surjective are also equivalent to
   (a) $\text{Im}(d_B) \to \text{Im}(d_A)$ is surjective, and
   (b) the map $\Omega_{B/A} \otimes_B k \to \Omega_{A/A} \otimes_A k$ is surjective.

2. The following are equivalent
   (a) $f$ is an essential surjection,
   (b) the map $\text{Im}(d_B) \to \text{Im}(d_A)$ is an isomorphism, and
   (c) the map $\Omega_{B/A} \otimes_B k \to \Omega_{A/A} \otimes_A k$ is an isomorphism.

3. If $k/k'$ is separable, then $f$ is an essential surjection if and only if the map $m_B/(m_A B + m_B^2) \to m_A/(m_A A + m_A^2)$ is an isomorphism.

4. If $f$ is a small extension, then $f$ is not essential if and only if $f$ has a section $s : A \to B$ in $\mathcal{C}_A$ with $f \circ s = \text{id}_A$.

**Proof.** Proof of (1). It follows from 3.10.3 that (1)(a) and (1)(b) are equivalent. Also, if $A \to B$ is surjective, then (1)(a) and (1)(b) hold. Assume (1)(a). Since the kernel of $d_A$ is the image of $H_1(L_{k/A})$ which also maps to $m_B/m_B^2$ we conclude that $m_B/m_B^2 \to m_A/m_A^2$ is surjective. Hence $B \to A$ is surjective by Lemma 3.5. This finishes the proof of (1).

Proof of (2). The equivalence of (2)(b) and (2)(c) is immediate from 3.10.3.

Assume (2)(b). Let $g : C \to B$ be a ring map in $\mathcal{C}_A$ such that $f \circ g$ is surjective. We conclude that $m_C/m_C^2 \to m_A/m_A^2$ is surjective by Lemma 3.5. Hence $\text{Im}(d_C) \to$
Im(d_A) is surjective and by the assumption we see that Im(d_C) → Im(d_B) is surjective. It follows that C → B is surjective by (1).

Assume (2)(a). Then f is surjective and we see that Ω_{B/A} ⊗_B k → Ω_{A/A} ⊗_A k is surjective. Let K be the kernel. Note that K = d_B(Ker(m_B/m_B^2 → m_A/m_A^2)) by (3.10.3). Choose a splitting

$$
\Omega_{B/A} ⊗_B k = \Omega_{A/A} ⊗_A k ⊕ K
$$
of k-vector space. The map d : B → Ω_{B/A} induces via the projection onto K a map D : B → K. Set C = {b ∈ B | D(b) = 0}. The Leibniz rule shows that this is a Λ-subalgebra of B. Let ι ∈ C. Choose x ∈ B mapping to ι. If D(x) ≠ 0, then we can find an element y ∈ m_B such that D(y) = D(x). Hence x − y ∈ C is an element which maps to ι. Thus C → k is surjective and C is an object of C_Λ. Similarly, pick ω ∈ Im(d_A). We can find x ∈ m_B such that d_B(x) maps to ω by (1). If D(x) ≠ 0, then we can find an element y ∈ m_B which maps to zero in m_A/m_A^2 such that D(y) = D(x). Hence z = x − y is an element of m_C whose image d_C(z) ∈ Ω_{C/k} ⊗_C k maps to ω. Hence Im(d_C) → Im(d_A) is surjective. We conclude that C → A is surjective by (1). Hence C → B is surjective by assumption. Hence D = 0, i.e., K = 0, i.e., (2)(c) holds. This finishes the proof of (2).

Proof of (3). If k'/k is separable, then H_1(L_{k/A}) = m_A/m_A^2 ⊗_k k', see Lemma 3.11. Hence Im(d_A) = m_A/(m_A A + m_A^2) and similarly for B. Thus (3) follows from (2).

Proof of (4). A section s of f is not surjective (by definition a small extension has nontrivial kernel), hence f is not essentially surjective. Conversely, assume f is a small surjection but not an essential surjection. Choose a ring map C → B in C_Λ which is not surjective, such that C → A is surjective. Let C' ⊆ B be the image of C → B. Then C' ≠ B but C' surjects onto A. Since f : B → A is a small extension, length_C(B) = length_C(A) + 1. Thus length_C(C') ≤ length_C(A) since C' is a proper subring of B. But C' → A is surjective, so in fact we must have length_C(C') = length_C(A) and C' → A is an isomorphism which gives us our section. □

**Example 3.13.** Let Λ = k[[x]] be the power series ring in 1 variable over k. Set A = k and B = Λ/(x^2). Then B → A is an essential surjection by Lemma 3.12 because it is a small extension and the map B → A does not have a right inverse (in the category C_Λ). But the map

$$
k ≅ m_B/m_B^2 → m_A/m_A^2 = 0
$$
is not an isomorphism. Thus in Lemma 3.12(3) it is necessary to consider the map of relative cotangent spaces m_B/(m_A B + m_B^2) → m_A/(m_A A + m_A^2).

### 4. The completed base category

**Definition 4.1.** Let Λ be a Noetherian ring and let Λ → k be a finite ring map where k is a field. We define C_Λ to be the category with

(1) objects are pairs (R, ϕ) where R is a Noetherian complete local Λ-algebra and where ϕ : R/m_R → k is a Λ-algebra isomorphism, and
(2) morphisms \( f : (S, \psi) \to (R, \varphi) \) are local \( \Lambda \)-algebra homomorphisms such that \( \varphi \circ (f \mod \mathfrak{m}) = \psi \).

As in the discussion following Definition 3.1 we will usually denote an object of \( \hat{\mathcal{C}}_\Lambda \) simply \( R \), with the identification \( R/\mathfrak{m}_R = k \) understood. In this section we discuss some basic properties of objects and morphisms of the category \( \hat{\mathcal{C}}_\Lambda \) paralleling our discussion of the category \( \mathcal{C}_\Lambda \) in the previous section.

Our first observation is that any object \( A \in \mathcal{C}_\Lambda \) is an object of \( \hat{\mathcal{C}}_\Lambda \) as an Artinian local ring is always Noetherian and complete with respect to its maximal ideal (which is after all a nilpotent ideal). Moreover, it is clear from the definitions that \( \mathcal{C}_\Lambda \subset \hat{\mathcal{C}}_\Lambda \) is the strictly full subcategory consisting of all Artinian rings. As it turns out, conversely every object of \( \hat{\mathcal{C}}_\Lambda \) is a limit of objects of \( \mathcal{C}_\Lambda \).

Suppose that \( R \) is an object of \( \hat{\mathcal{C}}_\Lambda \). Consider the rings \( R_n = R/\mathfrak{m}_R^n \) for \( n \in \mathbb{N} \). These are Noetherian local rings with a unique nilpotent prime ideal, hence Artinian, see Algebra, Proposition 59.6. The ring maps

\[
\cdots \to R_{n+1} \to R_n \to \cdots \to R_2 \to R_1 = k
\]

are all surjective. Completeness of \( R \) by definition means that \( R = \lim R_n \). If \( f : R \to S \) is a ring map in \( \hat{\mathcal{C}}_\Lambda \) then we obtain a system of ring maps \( f_n : R_n \to S_n \) whose limit is the given map.

**Lemma 4.2.** Let \( f : R \to S \) be a ring map in \( \hat{\mathcal{C}}_\Lambda \). The following are equivalent

1. \( f \) is surjective,
2. the map \( \mathfrak{m}_R/\mathfrak{m}_R^2 \to \mathfrak{m}_S/\mathfrak{m}_S^2 \) is surjective, and
3. the map \( \mathfrak{m}_R/(\mathfrak{m}_R \mathfrak{m}_S + \mathfrak{m}_R^2) \to \mathfrak{m}_S/(\mathfrak{m}_S \mathfrak{m}_R + \mathfrak{m}_S^2) \) is surjective.

**Proof.** Note that for \( n \geq 2 \) we have the equality of relative cotangent spaces

\[
\mathfrak{m}_R/(\mathfrak{m}_R \mathfrak{m}_S + \mathfrak{m}_R^2) = \mathfrak{m}_{R_n}/(\mathfrak{m}_R \mathfrak{m}_{S_n} + \mathfrak{m}_{R_n}^2)
\]

and similarly for \( S \). Hence by Lemma 3.5 we see that \( R_n \to S_n \) is surjective for all \( n \). Now let \( K_n \) be the kernel of \( R_n \to S_n \). Then the sequences

\[
0 \to K_n \to R_n \to S_n \to 0
\]

form an exact sequence of directed inverse systems. The system \( (K_n) \) is Mittag-Leffler since each \( K_n \) is Artinian. Hence by Algebra, Lemma 85.4 taking limits preserves exactness. So \( \lim R_n \to \lim S_n \) is surjective, i.e., \( f \) is surjective. \( \square \)

**Lemma 4.3.** The category \( \hat{\mathcal{C}}_\Lambda \) admits pushouts.

**Proof.** Let \( R \to S_1 \) and \( R \to S_2 \) be morphisms of \( \hat{\mathcal{C}}_\Lambda \). Consider the ring \( C = S_1 \otimes_R S_2 \). This ring has a finitely generated maximal ideal \( \mathfrak{m} = \mathfrak{m}_{S_1} \otimes S_2 + S_1 \otimes \mathfrak{m}_{S_2} \) with residue field \( k \). Set \( C^\wedge \) equal to the completion of \( C \) with respect to \( \mathfrak{m} \). Then \( C^\wedge \) is a Noetherian ring complete with respect to the maximal ideal \( \mathfrak{m}^\wedge = \mathfrak{m}C^\wedge \) whose residue field is identified with \( k \), see Algebra, Lemma 96.5. Hence \( C^\wedge \) is an object of \( \hat{\mathcal{C}}_\Lambda \). Then \( S_1 \to C^\wedge \) and \( S_2 \to C^\wedge \) turn \( C^\wedge \) into a pushout over \( R \) in \( \hat{\mathcal{C}}_\Lambda \) (details omitted). \( \square \)

We will not need the following lemma.

**Lemma 4.4.** The category \( \hat{\mathcal{C}}_\Lambda \) admits coproducts of pairs of objects.
Proof. Let \( R \) and \( S \) be objects of \( \hat{\mathcal{C}}_\Lambda \). Consider the ring \( C = R \otimes_\Lambda S \). There is a canonical surjective map \( C \to R \otimes_\Lambda S \to k \otimes_\Lambda k \to k \) where the last map is the multiplication map. The kernel of \( C \to k \) is a maximal ideal \( m \). Note that \( m \) is generated by \( \mathfrak{m}_R C, \mathfrak{m}_S C \) and finitely many elements of \( C \) which map to generators of the kernel of \( k \otimes_\Lambda k \to k \). Hence \( m \) is a finitely generated ideal. Set \( C^\wedge \) equal to the completion of \( C \) with respect to \( m \). Then \( C^\wedge \) is a Noetherian ring complete with respect to the maximal ideal \( m^\wedge = mC^\wedge \) with residue field \( k \), see Algebra, Lemma \( \text{[96.5]} \). Hence \( C^\wedge \) is an object of \( \hat{\mathcal{C}}_\Lambda \). Then \( R \to C^\wedge \) and \( S \to C^\wedge \) turn \( C^\wedge \) into a coproduct in \( \hat{\mathcal{C}}_\Lambda \) (details omitted).

An empty coproduct in a category is an initial object of the category. In the classical case \( \hat{\mathcal{C}}_\Lambda \) has an initial object, namely \( \Lambda \) itself. More generally, if \( k' < k \), then the completion \( \Lambda^\wedge \) of \( \Lambda \) with respect to \( \mathfrak{m}_\Lambda \) is an initial object. More generally still, if \( k' < k \) is separable, then \( \hat{\mathcal{C}}_\Lambda \) has an initial object too. Namely, choose a monic polynomial \( P \in \Lambda[T] \) such that \( k \cong k'[T]/(P') \) where \( P' \in k'[T] \) is the image of \( P \). Then \( R = \Lambda^\wedge[T]/(P) \) is an initial object, see proof of Lemma \( \text{[3.8]} \).

If \( R \) is an initial object as above, then we have \( \mathcal{C}_\Lambda = C_R \) and \( \hat{\mathcal{C}}_\Lambda = \hat{C}_R \) which effectively brings the whole discussion in this chapter back to the classical case. But, if \( k' < k \) is inseparable, then an initial object does not exist.

06SC  \[ \text{Lemma 4.5.} \] Let \( S \) be an object of \( \hat{\mathcal{C}}_\Lambda \). Then \( \dim_k \text{Der}_\Lambda(S, k) < \infty \).

Proof. Let \( x_1, \ldots, x_n \in \mathfrak{m}_S \) map to a \( k \)-basis for the relative cotangent space \( \mathfrak{m}_S/(\mathfrak{m}_S S + \mathfrak{m}_S^2) \). Choose \( y_1, \ldots, y_m \in S \) whose images in \( k \) generate \( k \) over \( k' \). We claim that \( \dim_k \text{Der}_\Lambda(S, k) \leq n + m \). To see this it suffices to prove that if \( D(x_i) = 0 \) and \( D(y_j) = 0 \), then \( D = 0 \). Let \( a \in S \). We can find a polynomial \( P = \sum \lambda_j y^j \) with \( \lambda_j \in \Lambda \) whose image in \( k \) is the same as the image of \( a \) in \( k \). Then we see that \( D(a - P) = D(a) - D(P) = D(a) \) by our assumption that \( D(y_j) = 0 \) for all \( j \). Thus we may assume \( a \in \mathfrak{m}_S \). Write \( a = \sum a_i x_i \) with \( a_i \in S \). By the Leibniz rule

\[
D(a) = \sum x_i D(a_i) + \sum a_i D(x_i) = \sum x_i D(a_i)
\]

as we assumed \( D(x_i) = 0 \). We have \( \sum x_i D(a_i) = 0 \) as multiplication by \( x_i \) is zero on \( k \).

06SD  \[ \text{Lemma 4.6.} \] Let \( f : R \to S \) be a morphism of \( \hat{\mathcal{C}}_\Lambda \). If \( \text{Der}_\Lambda(S, k) \to \text{Der}_\Lambda(R, k) \) is injective, then \( f \) is surjective.

Proof. If \( f \) is not surjective, then \( \mathfrak{m}_S/(\mathfrak{m}_R S + \mathfrak{m}_S^2) \) is nonzero by Lemma \( \text{[4.2]} \). Then also \( Q = S/(f(R) + \mathfrak{m}_S S + \mathfrak{m}_S^2) \) is nonzero. Note that \( Q \) is a \( k = R/\mathfrak{m}_R \)-vector space via \( f \). We turn \( Q \) into an \( S \)-module via \( S \to k \). The quotient map \( D : S \to Q \) is an \( R \)-derivation: if \( a_1, a_2 \in S \), we can write \( a_1 = f(b_1) + a'_1 \) and \( a_2 = f(b_2) + a'_2 \) for some \( b_1, b_2 \in R \) and \( a'_1, a'_2 \in \mathfrak{m}_S \). Then \( b_i \) and \( a_i \) have the same image in \( k \) for \( i = 1, 2 \) and

\[
a_1 a_2 = (f(b_1) + a'_1)(f(b_2) + a'_2) = f(b_1) a'_2 + f(b_2) a'_1
\]

in \( Q \) which proves the Leibniz rule. Hence \( D : S \to Q \) is a \( \Lambda \)-derivation which is zero on composing with \( R \to S \). Since \( Q \neq 0 \) there also exist derivations \( D : S \to k \)
which are zero on composing with $R \to S$, i.e., $\text{Der}_A(S,k) \to \text{Der}_A(R,k)$ is not injective.

06SE **Lemma 4.7.** Let $R$ be an object of $\widehat{C}_A$. Let $(J_n)$ be a decreasing sequence of ideals such that $m^n_R \subset J_n$. Set $J = \bigcap J_n$. Then the sequence $(J_n/J)$ defines the $m_R/J$-adic topology on $R/J$.

**Proof.** It is clear that $m^n_{R/J} \subset J_n/J$. Thus it suffices to show that for every $n$ there exists an $N$ such that $J_N/J \subset m^n_{R/J}$. This is equivalent to $J_N \subset m^n_R + J$.

For each $n$ the ring $R/m^n_R$ is Artinian, hence there exists a $N_n$ such that

$$J_{N_n} + m^n_R = J_{N_n+1} + m^n_R = \ldots$$

Set $E_n = (J_{N_n} + m^n_R)/m^n_R$. Set $E = \lim E_n \subset \lim R/m^n_R = R$. Note that $E \subset J$ as for any $f \in E$ and any $m$ we have $f \in J_m + m^n_R$ for all $n > 0$, so $f \in J_m$ by Artin-Rees, see Algebra, Lemma 50.4. Since the transition maps $E_n \to E_{n-1}$ are all surjective, we see that $J$ surjects onto $E_n$. Hence for $N = N_n$ works. □

06SF **Lemma 4.8.** Let $\ldots \to A_3 \to A_2 \to A_1$ be a sequence of surjective ring maps in $C_A$. If $\text{dim}_k(m_{A_n}/m^2_{A_n})$ is bounded, then $S = \lim A_n$ is an object in $\widehat{C}_A$ and the ideals $I_n = \text{Ker}(S \to A_n)$ define the $m_S$-adic topology on $S$.

**Proof.** We will use freely that the maps $S \to A_n$ are surjective for all $n$. Note that the maps $m_{A_n+1}/m^2_{A_n+1} \to m_{A_n}/m^2_{A_n}$ are surjective, see Lemma 4.2. Hence for $n$ sufficiently large the dimension $\text{dim}_k(m_{A_n}/m^2_{A_n})$ stabilizes to an integer, say $r$. Thus we can find $x_1, \ldots, x_r \in m_S$ whose images in $A_n$ generate $m_{A_n}$. Moreover, pick $y_1, \ldots, y_n \in S$ whose images in $k$ generate $k$ over $A$. Then we get a ring map $P = A[z_1, \ldots, z_{r+t}] \to S$, $z_i \mapsto x_i$ and $z_{r+j} \mapsto y_j$ such that the composition $P \to S \to A_n$ is surjective for all $n$. Let $m \subset P$ be the kernel of $P \to k$. Let $R = P^\wedge$ be the $m$-adic completion of $P$; this is an object of $\widehat{C}_A$. Since we still have the compatible system of (surjective) maps $R \to A_n$ we get a map $R \to S$. Set $J_n = \text{Ker}(R \to A_n)$. Set $J = \bigcap J_n$. By Lemma 4.7 we see that $R/J = \lim J_n$ and that the ideals $J_n/J = I_n$ define the $m$-adic topology. (Note that for each $n$ we have $m^n_{J_n} \subset J_n$ for some $N_n$ and not necessarily $N_n = n$, so a renumbering of the ideals $J_n$ may be necessary before applying the lemma.) □

06SG **Lemma 4.9.** Let $R', R \in \text{Ob}(\widehat{C}_A)$. Suppose that $R = R' \oplus I$ for some ideal $I$ of $R$.

Let $x_1, \ldots, x_r \in I$ map to a basis of $I/m_R I$. Set $S = R'[X_1, \ldots, X_r]$ and consider the $R'$-algebra map $S \to R$ mapping $X_i$ to $x_i$. Assume that for every $n > 0$ the map $S/m^n_S \to R/m^n_R$ has a left inverse in $C_A$. Then $S \to R$ is an isomorphism.

**Proof.** As $R = R' \oplus I$ we have

$$m_R/m^n_R = m_{R'}/m^n_{R'} \oplus I/m_R I$$

and similarly

$$m_R/m^n_R = m_{R'}/m^n_{R'} \oplus \bigoplus kX_i$$

Hence for $n > 1$ the map $S/m^n_S \to R/m^n_R$ induces an isomorphism on cotangent spaces. Thus a left inverse $h_n : R/m^n_R \to S/m^n_S$ is surjective by Lemma 4.2. Since $h_n$ is injective as a left inverse it is an isomorphism. Thus the canonical surjections $S/m^n_S \to R/m^n_R$ are all isomorphisms and we win. □
5. Categories cofibered in groupoids

In developing the theory we work with categories *cofibered* in groupoids. We assume as known the definition and basic properties of categories *fibered* in groupoids, see Categories, Section 34.

**Definition 5.1.** Let \( \mathcal{C} \) be a category. A category cofibered in groupoids over \( \mathcal{C} \) is a category \( \mathcal{F} \) equipped with a functor \( p : \mathcal{F} \to \mathcal{C} \) such that \( \mathcal{C}^{opp} \) is a category fibered in groupoids over \( \mathcal{C}^{opp} \) via \( p^{opp} : \mathcal{F}^{opp} \to \mathcal{C}^{opp} \).

Explicitly, \( p : \mathcal{F} \to \mathcal{C} \) is cofibered in groupoids if the following two conditions hold:

1. For every morphism \( f : U \to V \) in \( \mathcal{C} \) and every object \( x \) lying over \( U \), there is a morphism \( x \to y \) of \( \mathcal{F} \) lying over \( f \).
2. For every pair of morphisms \( a : x \to y \) and \( b : x \to z \) of \( \mathcal{F} \) and any morphism \( f : p(y) \to p(z) \) such that \( p(b) = f \circ p(a) \), there exists a unique morphism \( c : y \to z \) of \( \mathcal{F} \) lying over \( f \) such that \( b = c \circ a \).

**Remarks 5.2.** Everything about categories fibered in groupoids translates directly to the cofibered setting. The following remarks are meant to fix notation. Let \( \mathcal{C} \) be a category.

1. We often omit the functor \( p : \mathcal{F} \to \mathcal{C} \) from the notation.
2. The fiber category over an object \( U \) in \( \mathcal{C} \) is denoted by \( \mathcal{F}(U) \). Its objects are those of \( \mathcal{F} \) lying over \( U \) and its morphisms are those of \( \mathcal{F} \) lying over \( id_U \). If \( x, y \) are objects of \( \mathcal{F}(U) \), we sometimes write \( \text{Mor}_U(x, y) \) for \( \text{Mor}_{\mathcal{F}(U)}(x, y) \).
3. The fibre categories \( \mathcal{F}(U) \) are groupoids, see Categories, Lemma 34.2. Hence the morphisms in \( \mathcal{F}(U) \) are all isomorphisms. We sometimes write \( \text{Aut}_U(x) \) for \( \text{Mor}_{\mathcal{F}(U)}(x, x) \).
4. Let \( \mathcal{F} \) be a category cofibered in groupoids over \( \mathcal{C} \), let \( f : U \to V \) be a morphism in \( \mathcal{C} \), and let \( x \in \text{Ob}({\mathcal{F}(U)}) \). A pushforward of \( x \) along \( f \) is a morphism \( x \to y \) of \( \mathcal{F} \) lying over \( f \). A pushforward is unique up to unique isomorphism (see the discussion following Categories, Definition 32.1). We sometimes write \( x \to f_* x \) for “the” pushforward of \( x \) along \( f \).
5. A choice of pushforwards for \( \mathcal{F} \) is the choice of a pushforward of \( x \) along \( f \) for every pair \((x, f)\) as above. We can make such a choice of pushforwards for \( \mathcal{F} \) by the axiom of choice.
6. Let \( \mathcal{F} \) be a category cofibered in groupoids over \( \mathcal{C} \). Given a choice of pushforwards for \( \mathcal{F} \), there is an associated pseudo-functor \( \mathcal{C} \to \text{Groupoids} \). We will never use this construction so we give no details.
7. A morphism of categories cofibered in groupoids over \( \mathcal{C} \) is a functor commuting with the projections to \( \mathcal{C} \). If \( \mathcal{F} \) and \( \mathcal{F}' \) are categories cofibered in groupoids over \( \mathcal{C} \), we denote the morphisms from \( \mathcal{F} \) to \( \mathcal{F}' \) by \( \text{Mor}_C(\mathcal{F}, \mathcal{F}') \).
8. Categories cofibered in groupoids form a \((2, 1)\)-category \( \text{Cof}(\mathcal{C}) \). Its 1-morphisms are the morphisms described in (7). If \( p : \mathcal{F} \to \mathcal{C} \) and \( p' : \mathcal{F}' \to \mathcal{C} \) are categories cofibered in groupoids and \( \varphi, \psi : \mathcal{F} \to \mathcal{F}' \) are 1-morphisms, then a 2-morphism \( \tau : \varphi \to \psi \) is a morphism of functors such that \( \tau_x = \text{id}_{p'(x)} \) for all \( x \in \text{Ob}(\mathcal{F}) \).
9. Let \( F : \mathcal{C} \to \text{Groupoids} \) be a functor. There is a category cofibered in groupoids \( \mathcal{F} \to \mathcal{C} \) associated to \( F \) as follows. An object of \( \mathcal{F} \) is a pair \((U, x)\) where \( U \in \text{Ob}(\mathcal{C}) \) and \( x \in \text{Ob}(F(U)) \). A morphism \((U, x) \to (V, y)\) is a pair
(f, a) where \( f \in \text{Mor}_C(U, V) \) and \( a \in \text{Mor}_{F(V)}(F(f)(x), y) \). The functor \( F \to C \) sends \((U, x)\) to \( U \). See Categories, Section \[36\].

Let \( F \) be cofibered in groupoids over \( C \). For \( U \in \text{Ob}(C) \) set \( \mathcal{F}(U) \) equal to the set of isomorphisms classes of the category \( \mathcal{F}(U) \). If \( f : U \to V \) is a morphism of \( C \), then we obtain a map of sets \( \mathcal{F}(U) \to \mathcal{F}(V) \) by mapping the isomorphism class of \( x \) to the isomorphism class of a pushforward \( f_*x \) of \( x \) see \[1\]. Then \( \mathcal{F} : C \to \text{Sets} \) is a functor. Similarly, if \( \varphi : F \to G \) is a morphism of cofibered categories, we denote by \( \overline{\varphi} : \mathcal{F} \to \mathcal{G} \) the associated morphism of functors.

Let \( F : C \to \text{Sets} \) be a functor. We can think of a set as a discrete category, i.e., as a groupoid with only identity morphisms. Then the construction \[\] associates to \( F \) a category cofibered in sets. This defines a fully faithful embedding of the category of functors \( C \to \text{Sets} \) to the category of categories cofibered in groupoids over \( C \). We identify the category of functors with its image under this embedding. Hence if \( F : C \to \text{Sets} \) is a functor, we denote the associated category cofibered in sets also by \( F \); and if \( \varphi : F \to G \) is a morphism of functors, we denote still by \( \varphi \) the corresponding morphism of categories cofibered in sets, and vice-versa. See Categories, Section \[37\].

Let \( U \) be an object of \( C \). We write \( \underline{U} \) for the functor \( \text{Mor}_C(U, -) : C \to \text{Sets} \). This defines a fully faithful embedding of \( C^{\text{opp}} \) into the category of functors \( C \to \text{Sets} \). Hence, if \( f : U \to V \) is a morphism, we are justified in denoting still by \( f \) the induced morphism \( V \to U \), and vice-versa.

Fiber products of categories cofibered in groupoids: If \( \mathcal{F} \to \mathcal{H} \) and \( \mathcal{G} \to \mathcal{H} \) are morphisms of categories cofibered in groupoids over \( C \), then a construction of their 2-fiber product is given by the construction for their 2-fiber product as categories over \( C \), as described in Categories, Lemma \[31.3\].

Restricting the base category: Let \( p : F \to C \) be a category cofibered in groupoids, and let \( C' \) be a full subcategory of \( C \). The restriction \( F|_{C'} \) is the full subcategory of \( F \) whose objects lie over objects of \( C' \). It is a category cofibered in groupoids via the functor \( p|_{C'} : F|_{C'} \to C' \).

6. Prorepresentable functors and predeformation categories

Our basic goal is to understand categories cofibered in groupoids over \( C \) and \( \hat{C}_A \). Since \( C_A \) is a full subcategory of \( \hat{C}_A \) we can restrict categories cofibered in groupoids over \( \hat{C}_A \) to \( C_A \), see Remarks \[5.2\] \[14\]. In particular we can do this with functors, in particular with representable functors. The functors on \( C_A \) one obtains in this way are called prorepresentable functors.

**Definition 6.1.** Let \( F : C_A \to \text{Sets} \) be a functor. We say \( F \) is prorepresentable if there exists an isomorphism \( F \cong R|_{C_A} \) of functors for some \( R \in \text{Ob}(\hat{C}_A) \).

Note that if \( F : C_A \to \text{Sets} \) is prorepresentable by \( R \in \text{Ob}(\hat{C}_A) \), then

\[ F(k) = \text{Mor}_{\hat{C}_A}(R, k) = \{\ast\} \]

is a singleton. The categories cofibered in groupoids over \( C_A \) that are arise in deformation theory will often satisfy an analogous condition.

**Definition 6.2.** A predeformation category \( \mathcal{F} \) is a category cofibered in groupoids over \( C_A \) such that \( \mathcal{F}(k) \) is equivalent to a category with a single object and a single morphism, i.e., \( \mathcal{F}(k) \) contains at least one object and there is a unique morphism
between any two objects. A morphism of predeformation categories is a morphism of categories cofibered in groupoids over $\mathcal{C}_\Lambda$.

A feature of a predeformation category is the following. Let $x_0 \in \text{Ob}(\mathcal{F}(k))$. Then every object of $\mathcal{F}$ comes equipped with a unique morphism to $x_0$. Namely, if $x$ is an object of $\mathcal{F}$ over $A$, then we can choose a pushforward $x \to q_*(x)$ where $q : A \to k$ is the quotient map. There is a unique isomorphism $q_*(x) \to x_0$ and the composition $x \to q_*(x) \to x_0$ is the desired morphism.

**Remark 6.3.** We say that a functor $F : \mathcal{C}_\Lambda \to \text{Sets}$ is a predeformation functor if the associated cofibered set is a predeformation category, i.e. if $F(k)$ is a one element set. Thus if $\mathcal{F}$ is a predeformation category, then $\mathcal{F}$ is a predeformation functor.

**Remark 6.4.** Let $p : \mathcal{F} \to \mathcal{C}_\Lambda$ be a category cofibered in groupoids, and let $x \in \text{Ob}(\mathcal{F}(k))$. We denote by $\mathcal{F}_x$ the category of objects over $x$. An object of $\mathcal{F}_x$ is an arrow $y \to x$. A morphism $(y \to x) \to (z \to x)$ in $\mathcal{F}_x$ is a commutative diagram

\[
\begin{array}{ccc}
y & \to & z \\
\downarrow & & \downarrow \\
x & \to & \\
\end{array}
\]

There is a forgetful functor $\mathcal{F}_x \to \mathcal{F}$. We define the functor $p_x : \mathcal{F}_x \to \mathcal{C}_\Lambda$ as the composition $\mathcal{F}_x \to \mathcal{F} \xrightarrow{p} \mathcal{C}_\Lambda$. Then $p_x : \mathcal{F}_x \to \mathcal{C}_\Lambda$ is a predeformation category (proof omitted). In this way we can pass from an arbitrary category cofibered in groupoids over $\mathcal{C}_\Lambda$ to a predeformation category at any $x \in \text{Ob}(\mathcal{F}(k))$.

### 7. Formal objects and completion categories

In this section we discuss how to go between categories cofibered in groupoids over $\mathcal{C}_\Lambda$ to categories cofibered in groupoids over $\mathcal{C}_\Lambda$ and vice versa.

**Definition 7.1.** Let $\mathcal{F}$ be a category cofibered in groupoids over $\mathcal{C}_\Lambda$. The category $\mathcal{F}$ of formal objects of $\mathcal{F}$ is the category with the following objects and morphisms.

1. A formal object $\xi = (R, \xi_n, f_n)$ of $\mathcal{F}$ consists of an object $R$ of $\mathcal{C}_\Lambda$, and a collection indexed by $n \in \mathbb{N}$ of objects $\xi_n$ of $\mathcal{F}(R/\mathfrak{m}_R^n)$ and morphisms $f_n : \xi_{n+1} \to \xi_n$ lying over the projection $R/\mathfrak{m}_R^{n+1} \to R/\mathfrak{m}_R^n$.
2. Let $\xi = (R, \xi_n, f_n)$ and $\eta = (S, \eta_n, g_n)$ be formal objects of $\mathcal{F}$. A morphism $a : \xi \to \eta$ of formal objects consists of a map $a_0 : R \to S$ in $\mathcal{C}_\Lambda$ and a collection $a_n : \xi_n \to \eta_n$ of morphisms of $\mathcal{F}$ lying over $R/\mathfrak{m}_R^n \to S/\mathfrak{m}_S^n$, such that for every $n$ the diagram

\[
\begin{array}{ccc}
\xi_{n+1} & \xrightarrow{f_n} & \xi_n \\
\downarrow a_{n+1} & & \downarrow a_n \\
\eta_{n+1} & \xrightarrow{g_n} & \eta_n \\
\end{array}
\]

commutes.

The category of formal objects comes with a functor $\widehat{p} : \mathcal{F} \to \mathcal{C}_\Lambda$ which sends an object $(R, \xi_n, f_n)$ to $R$ and a morphism $(R, \xi_n, f_n) \to (S, \eta_n, g_n)$ to the map $R \to S$. 
06H4 **Lemma 7.2.** Let \( p : \mathcal{F} \to \mathcal{C}_\Lambda \) be a category cofibered in groupoids. Then \( \hat{p} : \hat{\mathcal{F}} \to \hat{\mathcal{C}}_\Lambda \) is a category cofibered in groupoids.

**Proof.** Let \( R \to S \) be a ring map in \( \hat{\mathcal{C}}_\Lambda \). Let \( (R, \xi_n, f_n) \) be an object of \( \hat{\mathcal{F}} \). For each \( n \) choose a pushforward \( \xi_n \to \eta_n \) of \( \xi_n \) along \( R/I_nR \to R/I_{n+1}R \). For each \( n \) there exists a unique morphism \( g_n : \eta_{n+1} \to \eta_n \) in \( \mathcal{F} \) lying over \( S/I_{n+1}S \to S/I_nS \) such that

\[
\begin{array}{ccc}
\xi_{n+1} & \xrightarrow{f_n} & \xi_n \\
\downarrow & & \downarrow \\
\eta_{n+1} & \xrightarrow{g_n} & \eta_n
\end{array}
\]

commutes (by the first axiom of a category cofibered in groupoids). Hence we obtain a morphism \( (R, \xi_n, f_n) \to (S, \eta_n, g_n) \) lying over \( R \to S \), i.e., the first axiom of a category cofibered in groupoids holds for \( \hat{\mathcal{F}} \). To see the second axiom suppose that we have morphisms \( a : (R, \xi_n, f_n) \to (S, \eta_n, g_n) \) and \( b : (R, \xi_n, f_n) \to (T, \theta_n, h_n) \) in \( \hat{\mathcal{F}} \) and a morphism \( c_0 : S \to T \) in \( \hat{\mathcal{C}}_\Lambda \) such that \( c_0 \circ a_0 = b_0 \). By the second axiom of a category cofibered in groupoids for \( \mathcal{F} \) we obtain unique maps \( c_n : \eta_n \to \theta_n \) lying over \( S/I_nS \to T/I_nT \) such that \( c_n \circ a_n = b_n \). Setting \( c = (c_n)_{n \geq 0} \) gives the desired morphism \( c : (S, \eta_n, g_n) \to (T, \theta_n, h_n) \) in \( \hat{\mathcal{F}} \) (we omit the verification that \( h_n \circ c_{n+1} = c_n \circ g_n \)).

06H5 **Definition 7.3.** Let \( p : \mathcal{F} \to \mathcal{C}_\Lambda \) be a category cofibered in groupoids. The category cofibered in groupoids \( \hat{\mathcal{F}} \to \hat{\mathcal{C}}_\Lambda \) is called the completion of \( \mathcal{F} \).

If \( \mathcal{F} \) is a category cofibered in groupoids over \( \mathcal{C}_\Lambda \), we have defined \( \hat{\mathcal{F}}(R) \) for \( R \in \text{Ob}(\hat{\mathcal{C}}_\Lambda) \) in terms of the filtration of \( R \) by powers of its maximal ideal. But suppose \( \mathcal{I} = (I_n) \) is a filtration of \( R \) by ideals inducing the \( \mathfrak{m}_R \)-adic topology. We define \( \hat{\mathcal{F}}_{\mathcal{I}}(R) \) to be the category with the following objects and morphisms:

1. An object is a collection \( (\xi_n, f_n)_{n \in \mathbb{N}} \) of objects \( \xi_n \) of \( \mathcal{F}(R/I_n) \) and morphisms \( f_n : \xi_{n+1} \to \xi_n \) lying over the projections \( R/I_{n+1} \to R/I_n \).
2. A morphism \( a : (\xi_n, f_n) \to (\eta_n, g_n) \) consists of a collection \( a_n : \xi_n \to \eta_n \) of morphisms in \( \mathcal{F}(R/I_n) \), such that for every \( n \) the diagram

\[
\begin{array}{ccc}
\xi_{n+1} & \xrightarrow{f_n} & \xi_n \\
\downarrow & & \downarrow \\
\eta_{n+1} & \xrightarrow{g_n} & \eta_n
\end{array}
\]

commutes.

06H6 **Lemma 7.4.** In the situation above, \( \hat{\mathcal{F}}_{\mathcal{I}}(R) \) is equivalent to the category \( \hat{\mathcal{F}}(R) \).

**Proof.** An equivalence \( \hat{\mathcal{F}}_{\mathcal{I}}(R) \to \hat{\mathcal{F}}(R) \) can be defined as follows. For each \( n \), let \( m(n) \) be the least \( m \) that \( I_m \subseteq \mathfrak{m}_R^n \). Given an object \( (\xi_n, f_n) \) of \( \hat{\mathcal{F}}_{\mathcal{I}}(R) \), let \( \eta_n \) be the pushforward of \( \xi_{m(n)} \) along \( R/I_{m(n)} \to R/m^n_R \). Let \( g_n : \eta_{n+1} \to \eta_n \) be the
unique morphism of $F$ lying over $R/m_R^{n+1} \to R/m_R^n$ such that

$$
\begin{array}{ccc}
\xi_{m(n+1)} & \xrightarrow{f_{m(n+1)-1} \circ \cdots \circ f_{m(n)-1}} & \xi_{m(n)} \\
\downarrow & & \downarrow \\
\eta_{n+1} & \xrightarrow{g_n} & \eta_n
\end{array}
$$

commutes (existence and uniqueness is guaranteed by the axioms of a cofibred category). The functor $\hat{F}_I(R) \to \hat{F}(R)$ sends $(\xi_n, f_n)$ to $(R, \eta_n, g_n)$. We omit the verification that this is indeed an equivalence of categories. \hfill \square

**Remark 7.5.** Let $p : F \to C_A$ be a category cofibered in groupoids. Suppose that for each $R \in \text{Ob}(\hat{C}_A)$ we are given a filtration $I_R$ of $R$ by ideals. If $I_R$ induces the $m_R$-adic topology on $R$ for all $R$, then one can define a category $\hat{F}_I$ by mimicking the definition of $\hat{F}$. This category comes equipped with a morphism $\hat{p}_I : \hat{F}_I \to \hat{C}_A$ making it into a category cofibered in groupoids such that $\hat{F}_I(R)$ is isomorphic to $\hat{F}_{I|R}(R)$ as defined above. The categories cofibered in groupoids $\hat{F}_I$ and $\hat{F}$ are equivalent, by using over an object $R \in \text{Ob}(\hat{C}_A)$ the equivalence of Lemma 7.4.

**Remark 7.6.** Let $F : C_A \to \text{Sets}$ be a functor. Identifying functors with cofibered sets, the completion of $F$ is the functor $\hat{F} : \hat{C}_A \to \text{Sets}$ given by $\hat{F}(S) = \lim F(S/m_S^n)$. This agrees with the definition in Schlessinger’s paper [Sch68].

**Remark 7.7.** Let $F$ be a category cofibered in groupoids over $C_A$. We claim that there is a canonical equivalence

$$
can : \hat{F}|_{C_A} \longrightarrow F.
$$

Namely, let $A \in \text{Ob}(C_A)$ and let $(A, \xi_n, f_n)$ be an object of $\hat{F}|_{C_A}(A)$. Since $A$ is Artinian there is a minimal $m \in \mathbb{N}$ such that $m^n_A = 0$. Then can sends $(A, \xi_n, f_n)$ to $\xi_m$. This functor is an equivalence of categories cofibered in groupoids by Categories, Lemma 34.8 because it is an equivalence on all fibre categories by Lemma 7.4 and the fact that the $m_A$-adic topology on a local Artinian ring $A$ comes from the zero ideal. We will frequently identify $F$ with a full subcategory of $\hat{F}$ via a quasi-inverse to the functor can.

**Remark 7.8.** Let $\varphi : F \to G$ be a morphism of categories cofibered in groupoids over $C_A$. Then there is an induced morphism $\hat{\varphi} : \hat{F} \to \hat{G}$ of categories cofibered in groupoids over $\hat{C}_A$. It sends an object $\xi = (R, \xi_n, f_n)$ of $\hat{F}$ to $(R, \varphi(\xi_n), \varphi(f_n))$, and it sends a morphism $(a_0 : R \to S, a_n : \xi_n \to \eta_n)$ between objects $\xi$ and $\eta$ of $\hat{F}$ to $(a_0 : R \to S, \varphi(a_n) : \varphi(\xi_n) \to \varphi(\eta_n))$. Finally, if $t : \varphi \to \varphi'$ is a 2-morphism between 1-morphisms $\varphi, \varphi' : F \to G$ of categories cofibered in groupoids, then we obtain a 2-morphism $\hat{t} \cong \hat{\varphi} \to \hat{\varphi}'$. Namely, for $\xi = (R, \xi_n, f_n)$ as above we set $\hat{t}_\xi = (t_{\varphi(\xi_n)})$. Hence completion defines a functor between 2-categories

$$
\hat{\cdot} : \text{Cof}(C_A) \longrightarrow \text{Cof}(\hat{C}_A)
$$

from the 2-category of categories cofibered in groupoids over $C_A$ to the 2-category of categories cofibered in groupoids over $\hat{C}_A$.

**Remark 7.9.** We claim the completion functor of Remark 7.8 and the restriction functor $|_{\text{C}_A} : \text{Cof}(\hat{C}_A) \to \text{Cof}(C_A)$ of Remarks 5.2 (14) are “2-adjoint” in the following
precise sense. Let \( F \in \text{Ob}(\text{Cof}(\mathcal{C}_\Lambda)) \) and let \( G \in \text{Ob}(\text{Cof}(\widehat{\mathcal{C}}_\Lambda)) \). Then there is an equivalence of categories

\[
\Phi : \text{Mor}_{\mathcal{C}_\Lambda}(G|_{\mathcal{C}_\Lambda}, F) \to \text{Mor}_{\widehat{\mathcal{C}}_\Lambda}(G, \widehat{F})
\]

To describe this equivalence, we define canonical morphisms \( G \to \widehat{G}|_{\mathcal{C}_\Lambda} \) and \( \widehat{F}|_{\mathcal{C}_\Lambda} \to F \) as follows

(1) Let \( R \in \text{Ob}(\widehat{\mathcal{C}}_\Lambda) \) and let \( \xi \) be an object of the fiber category \( G(R) \). Choose a pushforward \( \xi \to \xi_n \) of \( \xi \) to \( R/m^n_R \) for each \( n \in \mathbb{N} \), and let \( f_n : \xi_{n+1} \to \xi_n \) be the induced morphism. Then \( G \to \widehat{G}|_{\mathcal{C}_\Lambda} \) sends \( \xi \) to \((R, \xi_n, f_n)\).

(2) This is the equivalence can : \( \widehat{F}|_{\mathcal{C}_\Lambda} \to F \) of Remark 7.7.

Having said this, the equivalence \( \Phi : \text{Mor}_{\mathcal{C}_\Lambda}(G|_{\mathcal{C}_\Lambda}, F) \to \text{Mor}_{\widehat{\mathcal{C}}_\Lambda}(G, \widehat{F}) \) sends a morphism \( \varphi : G|_{\mathcal{C}_\Lambda} \to F \) to

\[
G \to \widehat{G}|_{\mathcal{C}_\Lambda} \xrightarrow{\varphi} \widehat{F}
\]

There is a quasi-inverse \( \Psi : \text{Mor}_{\widehat{\mathcal{C}}_\Lambda}(G, \widehat{F}) \to \text{Mor}_{\mathcal{C}_\Lambda}(G|_{\mathcal{C}_\Lambda}, F) \) to \( \Phi \) which sends \( \psi : G \to \widehat{F} \) to

\[
G|_{\mathcal{C}_\Lambda} \xrightarrow{\psi|_{\mathcal{C}_\Lambda}} \widehat{F}|_{\mathcal{C}_\Lambda} \to F.
\]

We omit the verification that \( \Phi \) and \( \Psi \) are quasi-inverse. We also do not address functoriality of \( \Phi \) (because it would lead into 3-category territory which we want to avoid at all cost).

06HB \textbf{Remark 7.10.} For a category \( \mathcal{C} \) denote by \( \text{CofSet}(\mathcal{C}) \) the category of cofibered sets over \( \mathcal{C} \). It is a 1-category isomorphic the category of functors \( \mathcal{C} \to \text{Sets} \). See Remarks 5.2 (11). The completion and restriction functors restrict to functors \( \wedge : \text{CofSet}(\mathcal{C}_\Lambda) \to \text{CofSet}(\widehat{\mathcal{C}}_\Lambda) \) and \( |_{\mathcal{C}_\Lambda} : \text{CofSet}(\widehat{\mathcal{C}}_\Lambda) \to \text{CofSet}(\mathcal{C}_\Lambda) \) which we denote by the same symbols. As functors on the categories of cofibered sets, completion and restriction are adjoints in the usual 1-categorical sense: the same construction as in Remark 7.9 defines a functorial bijection

\[
\text{Mor}_{\mathcal{C}_\Lambda}(G|_{\mathcal{C}_\Lambda}, F) \to \text{Mor}_{\widehat{\mathcal{C}}_\Lambda}(G, \widehat{F})
\]

for \( F \in \text{Ob}(\text{CofSet}(\mathcal{C}_\Lambda)) \) and \( G \in \text{Ob}(\text{CofSet}(\widehat{\mathcal{C}}_\Lambda)) \). Again the map \( \widehat{F}|_{\mathcal{C}_\Lambda} \to F \) is an isomorphism.

06HE \textbf{Remark 7.11.} Let \( G : \widehat{\mathcal{C}}_\Lambda \to \text{Sets} \) be a functor that commutes with limits. Then the map \( G \to \widehat{G}|_{\mathcal{C}_\Lambda} \) described in Remark 7.9 is an isomorphism. Indeed, if \( S \) is an object of \( \mathcal{C}_\Lambda \), then we have canonical bijections

\[
\widehat{G}|_{\mathcal{C}_\Lambda}(S) = \lim_n G(S/m^n_R) = G(\lim_n S/m^n_R) = G(S).
\]

In particular, if \( R \) is an object of \( \mathcal{C}_\Lambda \) then \( R = \widehat{R}|_{\mathcal{C}_\Lambda} \) because the representable functor \( R \) commutes with limits by definition of limits.

06HC \textbf{Remark 7.12.} Let \( R \) be an object of \( \mathcal{C}_\Lambda \). It defines a functor \( R : \widehat{\mathcal{C}}_\Lambda \to \text{Sets} \) as described in Remarks 5.2 (12). As usual we identify this functor with the associated cofibered set. If \( \mathcal{F} \) is a cofibered category over \( \mathcal{C}_\Lambda \), then there is an equivalence of categories

\[
\text{Mor}_{\mathcal{C}_\Lambda}(R|_{\mathcal{C}_\Lambda}, \mathcal{F}) \to \widehat{\mathcal{F}}(R).
\]
It is given by the composition

$$\text{Mor}_{C^0}(R[c], \mathcal{F}) \xrightarrow{\Phi} \text{Mor}_{C^0}(R, \hat{\mathcal{F}}) \xrightarrow{\Psi} \hat{\mathcal{F}}(R)$$

where \( \Phi \) is as in Remark 7.9 and the second equivalence comes from the 2-Yoneda lemma (the cofibered analogue of Categories, Lemma 40.1). Explicitly, the equivalence sends a morphism \( \phi : R[c] \to \mathcal{F} \) to the formal object \( (R, \phi(R \to R/m^n_R), \varphi(f_n)) \) in \( \hat{\mathcal{F}}(R) \), where \( f_n : R/m^n_R \to R/m^{n+1}_R \) is the projection.

Assume a choice of pushforwards for \( \mathcal{F} \) has been made. Given any \( \xi \in \text{Ob} (\hat{\mathcal{F}}(R)) \) we construct an explicit \( \xi : R[c] \to \mathcal{F} \) which maps to \( \xi \) under (7.12.1). Namely, say \( \xi = (R, \xi_n, f_n) \). An object \( \alpha \) in \( R[c] \) is the same thing as a morphism \( \alpha : R \to A \) of \( \hat{C} \) with \( A \) Artinian. Let \( m \in \mathbb{N} \) be minimal such that \( m^n_A = 0 \). Then \( \alpha \) factors through a unique \( \alpha_m : R/m^m_R \to A \) and we can set \( \xi(\alpha) = \alpha_m \xi_m \). We omit the description of \( \xi \) on morphisms and we omit the proof that \( \xi \) maps to \( \xi \) via (7.12.1).

Assume a choice of pushforwards for \( \hat{\mathcal{F}} \) has been made. In this case the proof of Categories, Lemma 40.1 gives an explicit quasi-inverse

$$\iota : \hat{\mathcal{F}}(R) \to \text{Mor}_{C^0}(R, \hat{\mathcal{F}})$$

to the 2-Yoneda equivalence which takes \( \xi \) to the morphism \( \iota(\xi) : R \to \hat{\mathcal{F}} \) sending \( f \in R(S) = \text{Mor}_{C^0}(R, S) \) to \( f \xi \). A quasi-inverse to (7.12.1) is then

$$\hat{\mathcal{F}}(R) \xleftarrow{\Phi} \text{Mor}_{C^0}(R, \hat{\mathcal{F}}) \xrightarrow{\Psi} \text{Mor}_{C^0}(R[c], \mathcal{F})$$

where \( \Psi \) is as in Remark 7.9. Given \( \xi \in \text{Ob}(\hat{\mathcal{F}}(R)) \) we have \( \Psi(\iota(\xi)) \equiv \xi \) where \( \xi \) is as in the previous paragraph, because both are mapped to \( \xi \) under the equivalence of categories (7.12.1). Using \( R = R[c] \) (see Remark 7.11) and unwinding the definitions of \( \Phi \) and \( \Psi \) we conclude that \( \iota(\xi) \) is isomorphic to the completion of \( \xi \).

**Remark 7.13.** Let \( \mathcal{F} \) be a category cofibered in groupoids over \( C \). Let \( \xi = (R, \xi_i, f_n) \) and \( \eta = (S, \eta_n, g_n) \) be formal objects of \( \mathcal{F} \). Let \( a = (a_n) : \xi \to \eta \) be a morphism of formal objects, i.e., a morphism of \( \hat{\mathcal{F}} \). Let \( f = \hat{p}(a) = a_0 : R \to S \) be the projection of \( a \) in \( \hat{C} \). Then we obtain a 2-commutative diagram

$$\begin{array}{ccc}
R[c] & \xrightarrow{f} & S[c] \\
\downarrow{\xi} & \searrow{2} & \\
\mathcal{F} & & \\
\uparrow{\eta}
\end{array}$$

where \( \xi \) and \( \eta \) are the morphisms constructed in Remark 7.12. To see this let \( \alpha : S \to A \) be an object of \( S[c] \) (see loc. cit.). Let \( m \in \mathbb{N} \) be minimal such that \( m^n_A = 0 \). We get a commutative diagram

$$\begin{array}{ccc}
R & \to & R/m^m_R \\
\downarrow{f} & & \downarrow{f_m} \\
S & \to & S/m^m_R \\
\downarrow{\alpha_m} & & \downarrow{\beta_m} \\
& & A
\end{array}$$

such that the bottom arrows compose to give \( \alpha \). Then \( \eta(\alpha) = \alpha_m \circ \eta_m \) and \( \xi(\alpha \circ f) = \beta_m \circ \xi_m \). The morphism \( \alpha_m : \xi_m \to \eta_m \) lies over \( f_m \) hence we obtain a canonical morphism

$$\xi(\alpha \circ f) = \beta_m \circ \xi_m \to \eta(\alpha) = \alpha_m \circ \eta_m$$
lying over id\(_A\) such that

\[
\begin{array}{ccc}
\xi_m & \rightarrow & \beta_m, \xi_m \\
\downarrow & & \downarrow \\
\alpha_m & \rightarrow & \alpha_m, \eta_m
\end{array}
\]

commutes by the axioms of a category cofibred in groupoids. This defines a transformation of functors \(\xi \circ f \rightarrow \eta\) which witnesses the 2-commutativity of the first diagram of this remark.

06HD **Remark 7.14.** According to Remark 7.12 giving a formal object \(\xi\) of \(\mathcal{F}\) is equivalent to giving a pro-representable functor \(U : \mathcal{C}_A \rightarrow \text{Sets}\) and a morphism \(U \rightarrow \mathcal{F}\).

### 8. Smooth morphisms

06HF In this section we discuss smooth morphisms of categories cofibered in groupoids over \(\mathcal{C}_A\).

06HG **Definition 8.1.** Let \(\varphi : \mathcal{F} \rightarrow \mathcal{G}\) be a morphism of categories cofibered in groupoids over \(\mathcal{C}_A\). We say \(\varphi\) is smooth if it satisfies the following condition: Let \(B \rightarrow A\) be a surjective ring map in \(\mathcal{C}_A\). Let \(y \in \text{Ob}(\mathcal{G}(B)), x \in \text{Ob}(\mathcal{F}(A)),\) and \(y \rightarrow \varphi(x)\) be a morphism lying over \(B \rightarrow A\). Then there exists \(x' \in \text{Ob}(\mathcal{F}(B))\), a morphism \(x' \rightarrow x\) lying over \(B \rightarrow A\), and a morphism \(\varphi(x') \rightarrow y\) lying over \(\text{id} : B \rightarrow B\), such that the diagram

\[
\begin{array}{ccc}
\varphi(x') & \rightarrow & y \\
\downarrow & & \downarrow \\
\varphi(x) & \rightarrow & y
\end{array}
\]

commutes.

06HH **Lemma 8.2.** Let \(\varphi : \mathcal{F} \rightarrow \mathcal{G}\) be a morphism of categories cofibered in groupoids over \(\mathcal{C}_A\). Then \(\varphi\) is smooth if the condition in Definition 8.1 is assumed to hold only for small extensions \(B \rightarrow A\).

**Proof.** Let \(B \rightarrow A\) be a surjective ring map in \(\mathcal{C}_A\). Let \(y \in \text{Ob}(\mathcal{G}(B)), x \in \text{Ob}(\mathcal{F}(A)),\) and \(y \rightarrow \varphi(x)\) be a morphism lying over \(B \rightarrow A\). By Lemma 3.3 we can factor \(B \rightarrow A\) into small extensions \(B = B_n \rightarrow B_{n-1} \rightarrow \ldots \rightarrow B_0 = A\). We argue by induction on \(n\). If \(n = 1\) the result is true by assumption. If \(n > 1\), then denote \(f : B = B_n \rightarrow B_{n-1}\) and denote \(g : B_{n-1} \rightarrow B_0 = A\). Choose a pushforward \(y \rightarrow f_* y\) of \(y\) along \(f\), so that the morphism \(y \rightarrow \varphi(x)\) factors as \(y \rightarrow f_* y \rightarrow \varphi(x)\). By the induction hypothesis we can find \(x_{n-1} \rightarrow x\) lying over \(g : B_{n-1} \rightarrow A\) and \(a : \varphi(x_{n-1}) \rightarrow f_* y\) lying over \(\text{id} : B_{n-1} \rightarrow B_{n-1}\) such that

\[
\begin{array}{ccc}
\varphi(x_{n-1}) & \rightarrow & f_* y \\
\downarrow & & \downarrow \\
\varphi(x) & \rightarrow & y
\end{array}
\]

commutes. We can apply the assumption to the composition \(y \rightarrow \varphi(x_{n-1})\) of \(y \rightarrow f_* y\) with \(a^{-1} : f_* y \rightarrow \varphi(x_{n-1})\). We obtain \(x_n \rightarrow x_{n-1}\) lying over \(B_n \rightarrow B_{n-1}\)
and $\varphi(x_n) \to y$ lying over $\text{id}: B_n \to B_n$ so that the diagram
\[
\begin{array}{ccc}
\varphi(x_n) & \to & y \\
\downarrow & & \downarrow \\
\varphi(x_{n-1}) & \to & f_\ast y \\
\downarrow & & \downarrow \\
\varphi(x) & \to & \\
\end{array}
\]
commutes. Then the composition $x_n \to x_{n-1} \to x$ and $\varphi(x_n) \to y$ are the morphisms required by the definition of smoothness. □

**Remark 8.3.** Let $\varphi : \mathcal{F} \to \mathcal{G}$ be a morphism of categories cofibered in groupoids over $\mathcal{C}_\Lambda$. Let $B \to A$ be a ring map in $\mathcal{C}_\Lambda$. Choices of pushforwards along $B \to A$ for objects in the fiber categories $\mathcal{F}(B)$ and $\mathcal{G}(B)$ determine functors $\mathcal{F}(B) \to \mathcal{F}(A)$ and $\mathcal{G}(B) \to \mathcal{G}(A)$ fitting into a 2-commutative diagram
\[
\begin{array}{ccc}
\mathcal{F}(B) & \to & \mathcal{G}(B) \\
\downarrow & & \downarrow \\
\mathcal{F}(A) & \to & \mathcal{G}(A). \\
\end{array}
\]
Hence there is an induced functor $\mathcal{F}(B) \to \mathcal{F}(A) \times_{\mathcal{G}(A)} \mathcal{G}(B)$. Unwinding the definitions shows that $\varphi : \mathcal{F} \to \mathcal{G}$ is smooth if and only if this induced functor is essentially surjective whenever $B \to A$ is surjective (or equivalently, by Lemma 8.2 whenever $B \to A$ is a small extension).

**Remark 8.4.** The characterization of smooth morphisms in Remark 8.3 is analogous to Schlessinger’s notion of a smooth morphism of functors, cf. [Sch68, Definition 2.2.]. In fact, when $\mathcal{F}$ and $\mathcal{G}$ are cofibered in sets then our notion is equivalent to Schlessinger’s. Namely, in this case let $F,G : \mathcal{C}_\Lambda \to \text{Sets}$ be the corresponding functors, see Remarks 5.2 (11). Then $F \to G$ is smooth if and only if for every surjection of rings $B \to A$ in $\mathcal{C}_\Lambda$ the map $F(B) \to F(A) \times_{G(A)} G(B)$ is surjective.

**Remark 8.5.** Let $\mathcal{F}$ be a category cofibered in groupoids over $\mathcal{C}_\Lambda$. Then the morphism $\mathcal{F} \to \overline{\mathcal{F}}$ is smooth.

If $R \to S$ is a ring map in $\widehat{\mathcal{C}}_\Lambda$, then there is an induced morphism $\overline{S} \to \overline{R}$ between the functors $\overline{S}, \overline{R} : \widehat{\mathcal{C}}_\Lambda \to \text{Sets}$. In this situation, smoothness of the restriction $\overline{S}|_{\mathcal{C}_\Lambda} \to \overline{R}|_{\mathcal{C}_\Lambda}$ is a familiar notion:

**Lemma 8.6.** Let $R \to S$ be a ring map in $\widehat{\mathcal{C}}_\Lambda$. Then the induced morphism $\overline{S}|_{\mathcal{C}_\Lambda} \to \overline{R}|_{\mathcal{C}_\Lambda}$ is smooth if and only if $S$ is a power series ring over $R$.

**Proof.** Assume $S$ is a power series ring over $R$. Say $S = R[[x_1, \ldots, x_n]]$. Smoothness of $\overline{S}|_{\mathcal{C}_\Lambda} \to \overline{R}|_{\mathcal{C}_\Lambda}$ means the following (see Remark 8.4): Given a surjective ring map $B \to A$ in $\mathcal{C}_\Lambda$, a ring map $R \to B$, a ring map $S \to A$ such that the solid diagram
\[
\begin{array}{ccc}
S & \to & A \\
\downarrow & & \downarrow \\
R & \to & B \\
\end{array}
\]
Let $06HM$ be a dotted arrow exists making the diagram commute. (Note the similarity with Algebra, Definition 136.1) To construct the dotted arrow choose elements $b_i \in B$ whose images in $A$ are equal to the images of $x_i$ in $A$. Note that $b_i \in \mathfrak{m}_B$ as $x_i$ maps to an element of $\mathfrak{m}_A$. Hence there is a unique $R$-algebra map $R[[x_1, \ldots, x_n]] \to B$ which maps $x_i$ to $b_i$ and which can serve as our dotted arrow.

Conversely, assume $S_{|c_A} \to R_{|c_A}$ is smooth. Let $x_1, \ldots, x_n \in S$ be elements whose images form a basis in the relative cotangent space $\mathfrak{m}_S/(\mathfrak{m}_R S + \mathfrak{m}_S^2)$. Set $T = R[[X_1, \ldots, X_n]]$. Note that both

$$S/(\mathfrak{m}_R S + \mathfrak{m}_S^2) \cong R/\mathfrak{m}_R[x_1, \ldots, x_n]/(x_i x_j)$$

and

$$T/(\mathfrak{m}_R T + \mathfrak{m}_T^2) \cong R/\mathfrak{m}_R[X_1, \ldots, X_n]/(X_i X_j).$$

Let $S/(\mathfrak{m}_R S + \mathfrak{m}_S^2) \to T/(\mathfrak{m}_R T + \mathfrak{m}_T^2)$ be the local $R$-algebra isomorphism given by mapping the class of $x_i$ to the class of $X_i$. Let $f_1 : S \to T/(\mathfrak{m}_R T + \mathfrak{m}_T^2)$ be the composition $S \to S/(\mathfrak{m}_R S + \mathfrak{m}_S^2) \to T/(\mathfrak{m}_R T + \mathfrak{m}_T^2)$. The assumption that $S_{|c_A} \to R_{|c_A}$ is smooth means we can lift $f_1$ to a map $f_2 : S \to T/m_T^{-1}$, then to a map $f_3 : S \to T/m_T^2$, and so on, for all $n \geq 1$. Thus we get an induced map $f : S \to T = \lim T/m_T^n$ of local $R$-algebras. By our choice of $f_1$, the map $f$ induces an isomorphism $\mathfrak{m}_S/(\mathfrak{m}_R S + \mathfrak{m}_S^2) \to \mathfrak{m}_T/(\mathfrak{m}_R T + \mathfrak{m}_T^2)$ of relative cotangent spaces. Hence $f$ is surjective by Lemma 4.2 (where we think of $f$ as a map in $\mathcal{C}_R$). Choose preimages $y_i \in S$ of $X_i \in T$ under $f$. As $T$ is a power series ring over $R$ there exists a local $R$-algebra homomorphism $s : T \to S$ mapping $X_i$ to $y_i$. By construction $f \circ s = \text{id}$. Then $s$ is injective. But $s$ induces an isomorphism on relative cotangent spaces since $f$ does, so it is also surjective by Lemma 4.2 again. Hence $s$ and $f$ are isomorphisms.

Smooth morphisms satisfy the following functorial properties.

06HM **Lemma 8.7.** Let $\varphi : \mathcal{F} \to \mathcal{G}$ and $\psi : \mathcal{G} \to \mathcal{H}$ be morphisms of categories cofibered in groupoids over $\mathcal{C}_A$.

1. If $\varphi$ and $\psi$ are smooth, then $\psi \circ \varphi$ is smooth.
2. If $\varphi$ is essentially surjective and $\psi \circ \varphi$ is smooth, then $\psi$ is smooth.
3. If $G' \to G$ is a morphism of categories cofibered in groupoids and $\varphi$ is smooth, then $\mathcal{F} \times_G G' \to G'$ is smooth.

**Proof.** Statements (1) and (2) follow immediately from the definitions. Proof of (3) omitted. Hints: use the formulation of smoothness given in Remark 8.3 and use that $\mathcal{F} \times_G G'$ is the 2-fibre product, see Remarks 5.2 (13).

06HN **Lemma 8.8.** Let $\varphi : \mathcal{F} \to \mathcal{G}$ be a smooth morphism of categories cofibered in groupoids over $\mathcal{C}_A$. Assume $\varphi : \mathcal{F}(k) \to \mathcal{G}(k)$ is essentially surjective. Then $\varphi : \mathcal{F} \to \mathcal{G}$ and $\hat{\varphi} : \hat{\mathcal{F}} \to \hat{\mathcal{G}}$ are essentially surjective.

**Proof.** Let $y$ be an object of $\mathcal{G}$ lying over $A \in \text{Ob}(\mathcal{C}_A)$. Let $y \to y_0$ be a pushforward of $y$ along $A \to k$. By the assumption on essential surjectivity of $\varphi : \mathcal{F}(k) \to \mathcal{G}(k)$ there exist an object $x_0$ of $\mathcal{F}$ lying over $k$ and an isomorphism $y_0 \to \varphi(x_0)$. Smoothness of $\varphi$ implies there exists an object $x$ of $\mathcal{F}$ over $A$ whose image $\varphi(x)$ is isomorphic to $y$. Thus $\varphi : \mathcal{F} \to \mathcal{G}$ is essentially surjective.

Let $\eta = (R, \eta_n, g_n)$ be an object of $\hat{\mathcal{G}}$. We construct an object $\xi$ of $\hat{\mathcal{F}}$ with an isomorphism $\eta \to \varphi(\xi)$. By the assumption on essential surjectivity of $\varphi : \mathcal{F}(k) \to \mathcal{G}(k)$ which implies there exists an object $x$ of $\mathcal{F}$ over $A$ whose image $\varphi(x)$ is surjective by Lemma 4.2 again. Hence $s$ and $f$ are isomorphisms.

Smooth morphisms satisfy the following functorial properties.

06HM **Lemma 8.7.** Let $\varphi : \mathcal{F} \to \mathcal{G}$ and $\psi : \mathcal{G} \to \mathcal{H}$ be morphisms of categories cofibered in groupoids over $\mathcal{C}_A$.

1. If $\varphi$ and $\psi$ are smooth, then $\psi \circ \varphi$ is smooth.
2. If $\varphi$ is essentially surjective and $\psi \circ \varphi$ is smooth, then $\psi$ is smooth.
3. If $G' \to G$ is a morphism of categories cofibered in groupoids and $\varphi$ is smooth, then $\mathcal{F} \times_G G' \to G'$ is smooth.

**Proof.** Statements (1) and (2) follow immediately from the definitions. Proof of (3) omitted. Hints: use the formulation of smoothness given in Remark 8.3 and use that $\mathcal{F} \times_G G'$ is the 2-fibre product, see Remarks 5.2 (13).

06HN **Lemma 8.8.** Let $\varphi : \mathcal{F} \to \mathcal{G}$ be a smooth morphism of categories cofibered in groupoids over $\mathcal{C}_A$. Assume $\varphi : \mathcal{F}(k) \to \mathcal{G}(k)$ is essentially surjective. Then $\varphi : \mathcal{F} \to \mathcal{G}$ and $\hat{\varphi} : \hat{\mathcal{F}} \to \hat{\mathcal{G}}$ are essentially surjective.

**Proof.** Let $y$ be an object of $\mathcal{G}$ lying over $A \in \text{Ob}(\mathcal{C}_A)$. Let $y \to y_0$ be a pushforward of $y$ along $A \to k$. By the assumption on essential surjectivity of $\varphi : \mathcal{F}(k) \to \mathcal{G}(k)$ there exist an object $x_0$ of $\mathcal{F}$ lying over $k$ and an isomorphism $y_0 \to \varphi(x_0)$. Smoothness of $\varphi$ implies there exists an object $x$ of $\mathcal{F}$ over $A$ whose image $\varphi(x)$ is isomorphic to $y$. Thus $\varphi : \mathcal{F} \to \mathcal{G}$ is essentially surjective.

Let $\eta = (R, \eta_n, g_n)$ be an object of $\hat{\mathcal{G}}$. We construct an object $\xi$ of $\hat{\mathcal{F}}$ with an isomorphism $\eta \to \varphi(\xi)$. By the assumption on essential surjectivity of $\varphi : \mathcal{F}(k) \to \mathcal{G}(k)$ which implies there exists an object $x$ of $\mathcal{F}$ over $A$ whose image $\varphi(x)$ is...
there exists a morphism $\eta_1 \to \varphi(\xi_1)$ in $G(k)$ for some $\xi_1 \in \text{Ob}(F(k))$. The morphism $\eta_2 \xrightarrow{g_1} \eta_1 \to \varphi(\xi_1)$ lies over the surjective ring map $R/m_R^2 \to k$, hence by smoothness of $\varphi$ there exists $\xi_2 \in \text{Ob}(F(R/m_R^2))$, a morphism $f_1 : \xi_2 \to \xi_1$ lying over $R/m_R^2 \to k$, and a morphism $\eta_2 \to \varphi(\xi_2)$ such that 

$$\varphi(\xi_2) \xrightarrow{\varphi(f_1)} \varphi(\xi_1) \xleftarrow{\eta_2} \eta_1$$

commutes. Continuing in this way we construct an object $\xi = (R, \xi_n, f_n)$ of $\tilde{F}$ and a morphism $\eta \to \varphi(\xi) = (R, \varphi(\xi_n), \varphi(f_n))$ in $\tilde{G}(R)$. \qed

**Remark 8.9.** Let $p : F \to C_\Lambda$ be a category cofibered in groupoids. We can consider $\tilde{C}_\Lambda$ as the trivial category cofibered in groupoids over $C_\Lambda$, and then $p$ is a morphism of categories cofibered in groupoids over $C_\Lambda$. We say $F$ is smooth if its structure morphism $p$ is smooth. This is the “absolute” notion of smoothness for a category cofibered in groupoids over $C_\Lambda$.

**Example 8.10.** Let $R \in \text{Ob}(\tilde{C}_\Lambda)$. When is $R|_{\tilde{C}_\Lambda}$ smooth? In the classical case this means that $R$ is a power series ring over $\Lambda$, see Lemma 8.6. (Strictly speaking this uses that $\Lambda|_{\tilde{C}_\Lambda} = C_\Lambda$ because $\Lambda$ is an initial object of $\tilde{C}_\Lambda$ in the classical case.) In the general case we can construct examples as follows. Pick an integer $n \geq 0$ and a maximal ideal $m \subset \Lambda[x_1, \ldots, x_n]$ lying over $m_\Lambda$ so that

$$k' = \Lambda/m_\Lambda \to \Lambda/x_1, \ldots, x_n/m$$

is isomorphic to $k' \to k$. Fix such an identification $k = \Lambda[x_1, \ldots, x_n]/m$. Set $R = \Lambda[x_1, \ldots, x_n]$ equal to the $m$-adic completion of $\Lambda[x_1, \ldots, x_n]$. Then $R$ is an object of $\tilde{C}_\Lambda$. Namely, it is a complete local Noetherian ring (see Algebra, Lemma 96.6) and its residue field is identified with $k$. We claim that $R|_{\tilde{C}_\Lambda}$ is smooth. To see this we have to show: Given a surjection $B \to A$ in $\tilde{C}_\Lambda$ and a map $R \to A$ there exists a lift of this map to $B$. This is clear as we can first lift the composition $\Lambda[x_1, \ldots, x_n] \to B$ to a map $\Lambda[x_1, \ldots, x_n] \to B$ and then observe that this latter map factors through the completion $R$ as $B$ is complete (being Artinian). In fact, it turns out that whenever $R|_{\tilde{C}_\Lambda}$ is smooth, then $R$ is isomorphic to a completion of a smooth algebra over $\Lambda$, but we won’t use this.

**Example 8.11.** Here is a more explicit example of an $R$ as in Example 8.10. Let $p$ be a prime number and let $n \in \mathbf{N}$. Let $\Lambda = \mathbf{F}_p(t_1, t_2, \ldots, t_n)$ and let $k = \mathbf{F}_p(x_1, \ldots, x_n)$ with map $\Lambda \to k$ given by $t_i \mapsto x_i^p$. Then we can take

$$R = \Lambda[x_1, \ldots, x_n]/(x_1^p - t_1, \ldots, x_n^p - t_n)$$

We cannot do “better” in this example, i.e., we cannot approximate $\tilde{C}_\Lambda$ by a smaller smooth object of $\tilde{C}_\Lambda$ (one can argue that the dimension of $R$ has to be at least $n$ since the map $\Omega_{R/\Lambda} \otimes_R k \to \Omega_{k/\Lambda}$ is surjective). We will discuss this phenomenon later in more detail.

**Remark 8.12.** Suppose $F$ is a predeformation category admitting a smooth morphism $\varphi : \mathcal{U} \to F$ from a predeformation category $\mathcal{U}$. Then by Lemma 8.8 $\varphi$ is essentially surjective, so by Lemma 8.7 $p : F \to C_\Lambda$ is smooth if and only if the composition $\mathcal{U} \xrightarrow{\varphi} F \xrightarrow{p} C_\Lambda$ is smooth, i.e. $F$ is smooth if and only if $\mathcal{U}$ is smooth.
Later we are interested in producing smooth morphisms from prorepresentable functors to predeformation categories $\mathcal{F}$. By the discussion in Remark 7.12 these morphisms correspond to certain formal objects of $\mathcal{F}$ More precisely, these are the so-called versal formal objects of $\mathcal{F}$.

**06HR Definition 8.13.** Let $\mathcal{F}$ be a category cofibered in groupoids. Let $\xi$ be a formal object of $\mathcal{F}$ lying over $R \in \text{Ob}(\widehat{\mathcal{C}}_\Lambda)$. We say $\xi$ is versal if the corresponding morphism $\xi : R[\mathcal{C}_\Lambda] \to \mathcal{F}$ of Remark 7.12 is smooth.

**06HS Remark 8.14.** Let $\mathcal{F}$ be a category cofibered in groupoids over $\mathcal{C}_\Lambda$, and let $\xi$ be a formal object of $\mathcal{F}$. It follows from the definition of smoothness that versality of $\xi$ is equivalent to the following condition: If $\xi \to x$ is a diagram in $\widehat{\mathcal{F}}$ such that $y \to x$ lies over a surjective map $B \to A$ of Artinian rings (we may assume it is a small extension), then there exists a morphism $\xi \to y$ such that $\xi \to x$ commutes. In particular, the condition that $\xi$ be versal does not depend on the choices of pushforwards made in the construction of $\xi : R[\mathcal{C}_\Lambda] \to \mathcal{F}$ in Remark 7.12.

**06HT Lemma 8.15.** Let $\mathcal{F}$ be a predeformation category. Let $\xi$ be a versal formal object of $\mathcal{F}$. For any formal object $\eta$ of $\widehat{\mathcal{F}}$, there exists a morphism $\xi \to \eta$.

**Proof.** By assumption the morphism $\xi : R[\mathcal{C}_\Lambda] \to \mathcal{F}$ is smooth. Then $\iota(\xi) : R \to \widehat{\mathcal{F}}$ is the completion of $\xi$, see Remark 7.12. By Lemma 8.8 there exists an object $f$ of $R$ such that $\iota(\xi)(f) = \eta$. Then $f$ is a ring map $f : R \to S$ in $\widehat{\mathcal{C}}_\Lambda$. And $\iota(\xi)(f) = \eta$ means that $f_*\xi \cong \eta$ which means exactly that there is a morphism $\xi \to \eta$ lying over $f$. \qed

**9. Schlessinger’s conditions**

In the following we often consider fibre products $A_1 \times_A A_2$ of rings in the category $\mathcal{C}_\Lambda$. We have seen in Example 3.7 that such a fibre product may not always be an object of $\mathcal{C}_\Lambda$. However, in virtually all cases below one of the two maps $A_i \to A$ is surjective and $A_1 \times_A A_2$ will be an object of $\mathcal{C}_\Lambda$ by Lemma 8.8. We will use this result without further mention.

We denote by $k[e]$ the ring of dual numbers over $k$. More generally, for a $k$-vector space $V$, we denote by $k[V]$ the $k$-algebra whose underlying vector space is $k \oplus V$ and whose multiplication is given by $(a,v) \cdot (a',v') = (aa',av' + a'v)$. When $V = k$, $k[V]$ is the ring of dual numbers over $k$. For any finite dimensional $k$-vector space $V$ the ring $k[V]$ is in $\mathcal{C}_\Lambda$. 
06HW **Definition 9.1.** Let $\mathcal{F}$ be a category cofibered in groupoids over $\mathcal{C}_\Lambda$. We define conditions (S1) and (S2) on $\mathcal{F}$ as follows:

(S1) Every diagram in $\mathcal{F}$

\[
\begin{array}{ccc}
  x_2 & \xrightarrow{A_2} & A_2 \\
  \downarrow & & \downarrow \\
  x_1 & \xrightarrow{A_1} & A \\
\end{array}
\]

lying over $x$ lying over $A_1 \rightarrow A$ in $\mathcal{C}_\Lambda$ with $A_2 \rightarrow A$ surjective can be completed to a commutative diagram

\[
\begin{array}{ccc}
  y & \xrightarrow{x_2} & A_1 \times_A A_2 \\
  \downarrow & & \downarrow \\
  x_1 & \xrightarrow{A_1} & A \\
\end{array}
\]

(S2) The condition of (S1) holds for diagrams in $\mathcal{F}$ lying over a diagram in $\mathcal{C}_\Lambda$ of the form

\[
\begin{array}{ccc}
  k[e] & \xrightarrow{k} & k \\
  \downarrow & & \downarrow \\
  A & \xrightarrow{k} & A \\
\end{array}
\]

Moreover, if we have two commutative diagrams in $\mathcal{F}$

\[
\begin{array}{ccc}
  y & \xrightarrow{x_2} & x_e \\
  \downarrow & & \downarrow \\
  x & \xrightarrow{x_0} & x_0 \\
\end{array}
\quad\quad\quad
\begin{array}{ccc}
  y' & \xrightarrow{x_2'} & x_e \\
  \downarrow & & \downarrow \\
  x & \xrightarrow{x_0'} & x_0 \\
\end{array}
\]

lying over $A \times_A k[e] \rightarrow k[e]$ then there exists a morphism $b : y \rightarrow y'$ in $\mathcal{F}(A \times_A k[e])$ such that $a = a' \circ b$.

We can partly explain the meaning of conditions (S1) and (S2) in terms of fibre categories. Suppose that $f_1 : A_1 \rightarrow A$ and $f_2 : A_2 \rightarrow A$ are ring maps in $\mathcal{C}_\Lambda$ with $f_2$ surjective. Denote $p_i : A_1 \times_A A_2 \rightarrow A_i$ the projection maps. Assume a choice of pushforwards for $\mathcal{F}$ has been made. Then the commutative diagram of rings translates into a 2-commutative diagram

\[
\begin{array}{ccc}
  \mathcal{F}(A_1 \times_A A_2) & \xrightarrow{p_{2,*}} & \mathcal{F}(A_2) \\
  \downarrow & & \downarrow \\
  \mathcal{F}(A_1) & \xrightarrow{f_{2,*}} & \mathcal{F}(A) \\
\end{array}
\]

of fibre categories whence a functor

\[
\begin{array}{ccc}
  \mathcal{F}(A_1 \times_A A_2) & \rightarrow & \mathcal{F}(A_1) \times_{\mathcal{F}(A)} \mathcal{F}(A_2) \\
\end{array}
\]

into the 2-fibre product of categories. Condition (S1) requires that this functor be essentially surjective. The first part of condition (S2) requires that this functor be a essentially surjective if $f_2$ equals the map $k[e] \rightarrow k$. Moreover in this case, the second part of (S2) implies that two objects which become isomorphic in the target are isomorphic in the source (but it is not equivalent to this statement). The advantage of stating the conditions as in the definition is that no choices have to be made.
Lemma 9.2. Let $F$ be a category cofibred in groupoids over $\mathcal{C}_\Lambda$. Then $F$ satisfies (S1) if the condition of (S1) is assumed to hold only when $A_2 \to A$ is a small extension.

Proof. Proof omitted. Hints: apply Lemma 3.3 and use induction similar to the proof of Lemma 8.2.

Remark 9.3. When $F$ is cofibred in sets, conditions (S1) and (S2) are exactly conditions (H1) and (H2) from Schlessinger’s paper [Sch68]. Namely, for a functor $F : \mathcal{C}_\Lambda \to \text{Sets}$, conditions (S1) and (S2) state:

(S1) If $A_1 \to A$ and $A_2 \to A$ are maps in $\mathcal{C}_\Lambda$ with $A_2 \to A$ surjective, then the induced map $F(A_1 \times_A A_2) \to F(A_1) \times_{F(A)} F(A_2)$ is surjective.

(S2) If $A \to k$ is a map in $\mathcal{C}_\Lambda$, then the induced map $F(A \times_k k[\epsilon]) \to F(A) \times_{F(k)} F(k[\epsilon])$ is bijective.

The injectivity of the map $F(A \times_k k[\epsilon]) \to F(A) \times_{F(k)} F(k[\epsilon])$ comes from the second part of condition (S2) and the fact that morphisms are identities.

Lemma 9.4. Let $F$ be a category cofibred in groupoids over $\mathcal{C}_\Lambda$. If $F$ satisfies (S2), then the condition of (S2) also holds when $k[\epsilon]$ is replaced by $k[V]$ for any finite dimensional $k$-vector space $V$.

Proof. In the case that $F$ is cofibred in sets, i.e., corresponds to a functor $F : \mathcal{C}_\Lambda \to \text{Sets}$ this follows from the description of (S2) for $F$ in Remark 9.3 and the fact that $k[V] \cong k[\epsilon] \times_k \ldots \times_k k[\epsilon]$ with $\dim_k V$ factors. The case of functors is what we will use in the rest of this chapter.

We prove the general case by induction on $\dim(V)$. If $\dim(V) = 1$, then $k[V] \cong k[\epsilon]$ and the result holds by assumption. If $\dim(V) > 1$ we write $V = V' \oplus k\epsilon$. Pick a diagram

\[
\begin{array}{ccc}
x_V & \downarrow & k[V] \\
x \downarrow & & A \\
x_0 & \rightarrow & k
\end{array}
\]

lying over

Choose a morphism $x_V \to x_{V'}$ lying over $k[V] \to k[V']$ and a morphism $x_V \to x_\epsilon$ lying over $k[V] \to k[\epsilon]$. Note that the morphism $x_V \to x_0$ factors as $x_V \to x_{V'} \to x_0$ and as $x_V \to x_\epsilon \to x_0$. By induction hypothesis we can find a diagram

\[
\begin{array}{ccc}
y' & \rightarrow & x_{V'} \\
x \downarrow & & A \\
x_0 & \rightarrow & k
\end{array}
\]

lying over

\[
\begin{array}{ccc}
y' & \rightarrow & A \times_k k[V'] \\
x \downarrow & & A \\
x_0 & \rightarrow & k
\end{array}
\]

This gives us a commutative diagram

\[
\begin{array}{ccc}
x_\epsilon & \downarrow & k[\epsilon] \\
y' \rightarrow x_0 & & A \times_k k[V'] \rightarrow k
\end{array}
\]
Hence by (S2) we get a commutative diagram

\[
\begin{array}{ccc}
y & \rightarrow & x_e \\
y' & \rightarrow & x_0 \\
\end{array}
\]

lying over

\[
\begin{array}{ccc}
(A \times_k k[\epsilon]) \times_k k[\epsilon] & \rightarrow & k[\epsilon] \\
A \times_k k[V'] & \rightarrow & k \\
\end{array}
\]

Note that \((A \times_k k[V']) \times_k k[\epsilon] = A \times_k k[V' \oplus k\epsilon] = A \times_k k[V]\). We claim that \(y\) fits into the correct commutative diagram. To see this we let \(y \rightarrow y\) be a morphism lying over \(A \times_k k[V] \rightarrow k[V]\). We can factor the morphisms \(y \rightarrow y\) through the morphism \(y \rightarrow y\) (by the axioms of categories cofibred in groupoids). Hence we see that both \(y\) and \(x\) fit into commutative diagrams

\[
\begin{array}{ccc}
y_V & \rightarrow & x_e \\
x_V & \rightarrow & x_0 \\
\end{array}
\]

and

\[
\begin{array}{ccc}
y'_V & \rightarrow & x'_e \\
x'_V & \rightarrow & x'_0 \\
\end{array}
\]

and hence by the second part of (S2) there exists an isomorphism \(y_V \rightarrow x_V\) compatible with \(y_V \rightarrow x_V\) and \(x_V \rightarrow x_V\), and in particular compatible with the maps to \(x_0\). The composition \(y \rightarrow y_V \rightarrow x_V\) then fits into the required commutative diagram

\[
\begin{array}{ccc}
y & \rightarrow & x_V \\
x & \rightarrow & x_0 \\
\end{array}
\]

lying over

\[
\begin{array}{ccc}
A \times_k k[V] & \rightarrow & k[V] \\
A & \rightarrow & k \\
\end{array}
\]

In this way we see that the first part of (S2) holds with \(k[\epsilon]\) replaced by \(k[V]\).

To prove the second part suppose given two commutative diagrams

\[
\begin{array}{ccc}
y & \rightarrow & x_V \\
x & \rightarrow & x_0 \\
\end{array}
\]

and

\[
\begin{array}{ccc}
y' & \rightarrow & x_V \\
x & \rightarrow & x_0 \\
\end{array}
\]

lying over

\[
\begin{array}{ccc}
A \times_k k[V] & \rightarrow & k[V] \\
A & \rightarrow & k \\
\end{array}
\]

We will use the morphisms \(x_V \rightarrow x_V, \rightarrow x_0\) and \(x_V \rightarrow x, \rightarrow x_0\) introduced in the first paragraph of the proof. Choose morphisms \(y \rightarrow y'_V, y' \rightarrow y'_V, y_V \rightarrow x_V, r \rightarrow x_V\), and \(y'' \rightarrow y''_V, y'' \rightarrow y''_V, A \times_k k[V'] \rightarrow A \times_k k[V']\). The axioms of a cofibred category imply we can find commutative diagrams

\[
\begin{array}{ccc}
y_V' & \rightarrow & x_V' \\
x & \rightarrow & x_0 \\
\end{array}
\]

and

\[
\begin{array}{ccc}
y'_V & \rightarrow & x'_V \\
x & \rightarrow & x_0 \\
\end{array}
\]

lying over

\[
\begin{array}{ccc}
A \times_k k[V'] & \rightarrow & k[V'] \\
A & \rightarrow & k \\
\end{array}
\]

By induction hypothesis we obtain an isomorphism \(b : y_V' \rightarrow y'_V\) compatible with the morphisms \(y_V' \rightarrow x\) and \(y'_V \rightarrow x\), in particular compatible with the morphisms

\[
\begin{array}{ccc}
y_V' & \rightarrow & x_V' \\
x & \rightarrow & x_0 \\
\end{array}
\]

and

\[
\begin{array}{ccc}
y'_V & \rightarrow & x'_V \\
x & \rightarrow & x_0 \\
\end{array}
\]

lying over

\[
\begin{array}{ccc}
A \times_k k[V'] & \rightarrow & k[V'] \\
A & \rightarrow & k \\
\end{array}
\]
to \(x_0\). Then we have commutative diagrams

\[
\begin{array}{ccc}
y & \rightarrow & x_e \\
\downarrow & & \downarrow \\
y'_{V'} & \rightarrow & x_0
\end{array}
\quad \text{and} \quad
\begin{array}{ccc}
y' & \rightarrow & x_e \\
\downarrow & & \downarrow \\
y'_{V'} & \rightarrow & x_0
\end{array}
\]

lying over

\[
\begin{array}{ccc}
A \times_k k[e] & \rightarrow & k[e] \\
\downarrow & & \downarrow \\
A & \rightarrow & k
\end{array}
\]

where the morphism \(y \rightarrow y'_{V'}\) is the composition \(y \rightarrow y_{V'} \rightarrow y'_{V'}\) and where the morphisms \(y \rightarrow x_e\) and \(y' \rightarrow x_e\) are the compositions of the maps \(y \rightarrow x_V\) and \(y' \rightarrow x_V\) with the morphism \(x_V \rightarrow x_e\). Then the second part of (S2) guarantees the existence of an isomorphism \(y \rightarrow y'\) compatible with the maps to \(y'_{V'}\), in particular compatible with the maps to \(x\) (because \(b\) was compatible with the maps to \(x\)). \(\square\)

**Lemma 9.5.** Let \(\mathcal{F}\) be a category cofibered in groupoids over \(\mathcal{C}_A\).

1. If \(\mathcal{F}\) satisfies (S1), then so does \(\overline{\mathcal{F}}\).
2. If \(\mathcal{F}\) satisfies (S2), then so does \(\overline{\mathcal{F}}\) provided at least one of the following conditions is satisfied
   - (a) \(\mathcal{F}\) is a predeformation category,
   - (b) the category \(\mathcal{F}(k)\) is a set or a setoid, or
   - (c) for any morphism \(x_e \rightarrow x_0\) of \(\mathcal{F}\) lying over \(k[e] \rightarrow k\) the pushforward map \(\text{Aut}_{k[e]}(x_e) \rightarrow \text{Aut}_k(x_0)\) is surjective.

**Proof.** Assume \(\mathcal{F}\) has (S1). Suppose we have ring maps \(f_i : A_i \rightarrow A\) in \(\mathcal{C}_A\) with \(f_2\) surjective. Let \(x_i \in \mathcal{F}(A_i)\) such that the pushforwards \(f_1,*(x_1)\) and \(f_2,*(x_2)\) are isomorphic. Then we can denote \(x\) an object of \(\mathcal{F}\) over \(A\) isomorphic to both of these and we obtain a diagram as in (S1). Hence we find an object \(y\) of \(\mathcal{F}\) over \(A_1 \times_A A_2\) whose pushforward to \(A_1\), resp. \(A_2\) is isomorphic to \(x_1\), resp. \(x_2\). In this way we see that (S1) holds for \(\overline{\mathcal{F}}\).

Assume \(\mathcal{F}\) has (S2). The first part of (S2) for \(\overline{\mathcal{F}}\) follows as in the argument above.

The second part of (S2) for \(\overline{\mathcal{F}}\) signifies that the map

\[
\overline{\mathcal{F}}(A \times_k k[e]) \rightarrow \overline{\mathcal{F}}(A) \times_{\overline{\mathcal{F}}(k)} \overline{\mathcal{F}}(k[e])
\]

is injective for any ring \(A\) in \(\mathcal{C}_A\). Suppose that \(y, y' \in \mathcal{F}(A \times_k k[e])\). Using the axioms of cofibred categories we can choose commutative diagrams

\[
\begin{array}{ccc}
y & \rightarrow & x_e \\
\downarrow & & \downarrow \\
y' & \rightarrow & x'_e \\
\end{array}
\quad \text{and} \quad
\begin{array}{ccc}
y' & \rightarrow & x_e \\
\downarrow & & \downarrow \\
y'_{V'} & \rightarrow & x_0
\end{array}
\]

lying over

\[
\begin{array}{ccc}
A \times_k k[e] & \rightarrow & k[e] \\
\downarrow & & \downarrow \\
A & \rightarrow & k
\end{array}
\]

Assume that there exist isomorphisms \(\alpha : x \rightarrow x'\) in \(\mathcal{F}(A)\) and \(\beta : x_e \rightarrow x'_e\) in \(\mathcal{F}(k[e])\). This also means there exists an isomorphism \(\gamma : x_0 \rightarrow x'_0\) compatible with \(\alpha\). To prove (S2) for \(\overline{\mathcal{F}}\) we have to show that there exists an isomorphism \(y \rightarrow y'\) in \(\mathcal{F}(A \times_k k[e])\). By (S2) for \(\mathcal{F}\) such a morphism will exist if we can choose the isomorphisms \(\alpha\) and \(\beta\) and \(\gamma\) such that

\[
\begin{array}{ccc}
x & \rightarrow & x_0 \\
\downarrow & \downarrow & \downarrow \\
x & \rightarrow & x_e \\
\end{array}
\quad \text{and} \quad
\begin{array}{ccc}
x' & \rightarrow & x'_0 \\
\downarrow & \downarrow & \downarrow \\
x' & \rightarrow & x'_e
\end{array}
\]
Consider a commutative diagram in a predeformation category \( F \). Let \( x \) be the given map \( x : y \to x_2 \) lying over \( A \). Assume \( F \) satisfies (S2). Then there exists a morphism \( s : x \to x_0 \) with \( e \circ s = id_x \) if and only if there exists a morphism \( s_* : x \to x_0 \) with \( e \circ s_* = d \).

**Proof.** The “only if” direction is clear. Conversely, assume there exists a morphism \( s_* : x \to x_0 \) with \( e \circ s_* = d \). Note that \( p(s_*) : A \to k[\epsilon] \) is a ring map compatible with the map \( A \to k \). Hence we obtain

\[
\sigma = (id_A, p(s_*)) : A \to A \times_k k[\epsilon].
\]

Choose a pushforward \( x \to \sigma_* x \). By construction we can factor \( s_* \) as \( x \to \sigma_* x \to x_2 \). Moreover, as \( \sigma \) is a section of \( A \times_k k[\epsilon] \to A \), we get a morphism \( \sigma_* x \to x \) such that \( x \to \sigma_* x \to x \) is \( id_x \). Because \( e \circ s_* = d \) we find that the diagram

\[
x \quad \xymatrix{ \sigma_* x \ar[r]^{e} & x \ar[d]^{d} \ar[r]^{\sigma_*} & x_2 \ar[d]^{\sigma_*} \\ x & x_0 & x_0 & x_0 \} \quad \text{lying over} \quad \xymatrix{ A \times_k k[\epsilon] \ar[r]^{e} & k[\epsilon] \ar[d]^{d} \ar[r]^{\epsilon} & k[\epsilon] \ar[d]^{d} \ar[r]^{\epsilon} & k[\epsilon] \} = k[\epsilon]
\]

is commutative. Hence by (S2) we obtain a morphism \( \sigma_* x \to y \) such that \( \sigma_* x \to y \to x \) is the given map \( \sigma_* x \to x \). The solution to the problem is now to take \( a : x \to y \) equal to the composition \( x \to \sigma_* x \to y \).

**Lemma 9.7.** Let \( F \to C_\Lambda \) be a category cofibered in groupoids. Consider a diagonal of \( F \)

\[
\begin{array}{ccc}
y & \to & x \\
\downarrow^{a} & & \downarrow^{d} \\
x & \to & x_0 \\
\end{array}
\]

in \( C_\Lambda \). Assume \( F \) satisfies (S2). Then there exists a morphism \( s : x \to y \) with \( a \circ s = id_x \) if and only if there exists a morphism \( s_* : x \to x_0 \) with \( e \circ s_* = d \).

**Proof.** The “only if” direction is clear. Conversely, assume there exists a morphism \( s_* : x \to x_0 \) with \( e \circ s_* = d \). Note that \( p(s_*) : A \to k[\epsilon] \) is a ring map compatible with the map \( A \to k \). Hence we obtain

\[
\sigma = (id_A, p(s_*)) : A \to A \times_k k[\epsilon].
\]

Choose a pushforward \( x \to \sigma_* x \). By construction we can factor \( s_* \) as \( x \to \sigma_* x \to x_2 \). Moreover, as \( \sigma \) is a section of \( A \times_k k[\epsilon] \to A \), we get a morphism \( \sigma_* x \to x \) such that \( x \to \sigma_* x \to x \) is \( id_x \). Because \( e \circ s_* = d \) we find that the diagram

\[
\begin{array}{ccc}
y & \to & x_2 \\
\downarrow^{a_1} & & \downarrow^{a_2} \\
x & \to & x \\
\end{array}
\]

is commutative. Hence by (S2) we obtain a morphism \( \sigma_* x \to y \) such that \( \sigma_* x \to y \to x \) is the given map \( \sigma_* x \to x \). The solution to the problem is now to take \( a : x \to y \) equal to the composition \( x \to \sigma_* x \to y \).

**Lemma 9.8.** Consider a commutative diagram in a predeformation category \( F \)

\[
\begin{array}{ccc}
y & \to & x_2 \\
\downarrow^{a_1} & & \downarrow^{a_2} \\
x & \to & x \\
\end{array}
\]

in \( C_\Lambda \). Assume \( F \) satisfies (S2). Then there exists a morphism \( s : x \to y \) with \( a_1 \circ s = id_x \) if and only if there exists a morphism \( s_* : x \to x_0 \) with \( a_2 \circ s_* = d \).

**Proof.** The “only if” direction is clear. Conversely, assume there exists a morphism \( s_* : x \to x_0 \) with \( a_2 \circ s_* = d \). Note that \( p(s_*) : A \to k[\epsilon] \) is a ring map compatible with the map \( A \to k \). Hence we obtain

\[
\sigma = (id_A, p(s_*)) : A \to A \times_k k[\epsilon].
\]

Choose a pushforward \( x \to \sigma_* x \). By construction we can factor \( s_* \) as \( x \to \sigma_* x \to x_2 \). Moreover, as \( \sigma \) is a section of \( A \times_k k[\epsilon] \to A \), we get a morphism \( \sigma_* x \to x \) such that \( x \to \sigma_* x \to x \) is \( id_x \). Because \( e \circ s_* = d \) we find that the diagram

\[
\begin{array}{ccc}
y & \to & A_1 \\
\downarrow^{a_1} & & \downarrow^{a_2} \\
x & \to & x \\
\end{array}
\]

is commutative. Hence by (S2) we obtain a morphism \( \sigma_* x \to y \) such that \( \sigma_* x \to y \to x \) is the given map \( \sigma_* x \to x \). The solution to the problem is now to take \( a : x \to y \) equal to the composition \( x \to \sigma_* x \to y \).

**Lemma 9.9.** Let \( F \) be a category cofibered in groupoids over \( C_\Lambda \). Let \( x_0 \in F(F(k)) \). Let \( F_{x_0} \) be the category cofibered in groupoids over \( C_\Lambda \) constructed in Remark 6.2

\[
\begin{array}{ccc}
y & \to & x_2 \\
\downarrow^{a_1} & & \downarrow^{a_2} \\
x & \to & x \\
\end{array}
\]

in \( C_\Lambda \). Assume \( F \) satisfies (S2). Then there exists a morphism \( s : x_0 \to y_0 \) with \( a_1 \circ s = id_x \) if and only if there exists a morphism \( s_* : x_0 \to y_0 \) with \( a_2 \circ s_* = d \).

**Proof.** Any diagram as in Definition 9.1 in \( F_{x_0} \) gives rise to a diagram in \( F \) and the output of condition (S1) or (S2) for this diagram in \( F \) can be viewed as an output for \( F_{x_0} \) as well.
Let \( R \) be a ring. We write \( \text{Mod}_R \) for the category of \( R \)-modules and \( \text{Mod}^f_R \) for the category of finitely generated \( R \)-modules.

**Definition 10.1.** Let \( L : \text{Mod}^f_R \to \text{Mod}_R \), resp. \( L : \text{Mod}_R \to \text{Mod}_R \) be a functor. We say that \( L \) is \( R \)-linear if for every pair of objects \( M, N \) of \( \text{Mod}^f_R \), resp. \( \text{Mod}_R \) the map

\[ L : \text{Hom}(M, N) \to \text{Hom}(L(M), L(N)) \]

is a map of \( R \)-modules.

**Remark 10.2.** One can define the notion of an \( R \)-linearity for any functor between categories enriched over \( \text{Mod}_R \). We made the definition specifically for functors \( L : \text{Mod}^f_R \to \text{Mod}_R \) and \( L : \text{Mod}_R \to \text{Mod}_R \) because these are the cases that we have needed so far.

**Remark 10.3.** If \( L : \text{Mod}^f_R \to \text{Mod}_R \) is an \( R \)-linear functor, then \( L \) preserves finite products and sends the zero module to the zero module, see Homology, Lemma 3.7. On the other hand, if a functor \( \text{Mod}^f_R \to \text{Sets} \) preserves finite products and sends the zero module to a one element set, then it has a unique lift to a \( R \)-linear functor, see Lemma 10.3.

**Lemma 10.4.** Let \( L : \text{Mod}^f_R \to \text{Sets} \), resp. \( L : \text{Mod}_R \to \text{Sets} \) be a functor. Suppose \( L(0) \) is a one element set and \( L \) preserves finite products. Then there exists a unique \( R \)-linear functor \( \tilde{L} : \text{Mod}^f_R \to \text{Mod}_R \), resp. \( \tilde{L} : \text{Mod}^f_R \to \text{Mod}_R \), such that

\[ \begin{align*}
\text{forget} & \quad \text{forget} \\
\tilde{L} : \text{Mod}^f_R & \to \text{Mod}_R & \text{resp.} & \tilde{L} : \text{Mod}^f_R & \to \text{Mod}_R \\
\text{forget} & \quad \text{forget} \\
\text{Mod}^f_R & \to \text{Sets} & \text{resp.} & \text{Mod}^f_R & \to \text{Sets} \\
\end{align*} \]

commutes.
Proof. We only prove this in case $L : \text{Mod}_R^{fg} \to \text{Sets}$. Let $M$ be a finitely generated $R$-module. We define $\widetilde{L}(M)$ to be the set $L(M)$ with the following $R$-module structure.

Multiplication: If $r \in R$, multiplication by $r$ on $L(M)$ is defined to be the map $L(M) \to L(M)$ induced by the multiplication map $r \cdot : M \to M$.

Addition: The sum map $M \times M \to M : (m_1, m_2) \mapsto m_1 + m_2$ induces a map $L(M \times M) \to L(M)$. By assumption $L(M \times M)$ is canonically isomorphic to $L(M) \times L(M)$. Addition on $L(M)$ is defined by the map $L(M) \times L(M) \cong L(M \times M) \to L(M)$.

Zero: There is a unique map $0 \to M$. The zero element of $L(M)$ is the image of $L(0) \to L(M)$.

We omit the verification that this defines an $R$-module $\widetilde{L}(M)$, the unique such that is $R$-linearly functorial in $M$. □

Lemma 10.5. Let $L_1, L_2 : \text{Mod}_R^{fg} \to \text{Sets}$ be functors that take $0$ to a one element set and preserve finite products. Let $t : L_1 \to L_2$ be a morphism of functors. Then $t$ induces a morphism $\tilde{t} : \widetilde{L}_1 \to \widetilde{L}_2$ between the functors guaranteed by Lemma 10.4, which is given simply by $t_M : \widetilde{L}_1(M) \to \widetilde{L}_2(M)$ for each $M \in \text{Ob}(\text{Mod}_R^{fg})$. In other words, $t_M : \widetilde{L}_1(M) \to \widetilde{L}_2(M)$ is a map of $R$-modules.

Proof. Omitted. □

In the case $R = K$ is a field, a $K$-linear functor $L : \text{Mod}_K^{fg} \to \text{Mod}_K$ is determined by its value $L(K)$.

Lemma 10.6. Let $K$ be a field. Let $L : \text{Mod}_K^{fg} \to \text{Mod}_K$ be a $K$-linear functor. Then $L$ is isomorphic to the functor $L(K) \otimes_K - : \text{Mod}_K^{fg} \to \text{Mod}_K$.

Proof. For $V \in \text{Ob}(\text{Mod}_K^{fg})$, the isomorphism $L(K) \otimes_K V \to L(V)$ is given on pure tensors by $x \otimes v \mapsto L(f_v)(x)$, where $f_v : K \to V$ is the $K$-linear map sending $1 \mapsto v$. When $V = K$, this is the isomorphism $L(K) \otimes_K K \to L(K)$ given by multiplication by $K$. For general $V$, it is an isomorphism by the case $V = K$ and the fact that $L$ commutes with finite products (Remark 10.3). □

For a ring $R$ and an $R$-module $M$, let $R[M]$ be the $R$-algebra whose underlying $R$-module is $R \oplus M$ and whose multiplication is given by $(r, m) \cdot (r', m') = (rr', rm' + r'm)$. When $M = R$ this is the ring of dual numbers over $R$, which we denote by $R[e]$.

Now let $S$ be a ring and assume $R$ is an $S$-algebra. Then the assignment $M \mapsto R[M]$ determines a functor $\text{Mod}_R \to \text{S-Alg}/R$, where $\text{S-Alg}/R$ denotes the category of $S$-algebras over $R$. Note that $\text{S-Alg}/R$ admits finite products: if $A_1 \to R$ and $A_2 \to R$ are two objects, then $A_1 \times_R A_2$ is a product.

Lemma 10.7. Let $R$ be an $S$-algebra. Then the functor $\text{Mod}_R \to \text{S-Alg}/R$ described above preserves finite products.

Proof. This is merely the statement that if $M$ and $N$ are $R$-modules, then the map $R[M \times N] \to R[M] \times_R R[N]$ is an isomorphism in $\text{S-Alg}/R$. □
Lemma 10.8. Let $R$ be an $S$-algebra, and let $\mathcal{C}$ be a strictly full subcategory of $S\text{-Alg}/R$ containing $R[M]$ for all $M \in \text{Ob}(\text{Mod}_R^{fg})$. Let $F : \mathcal{C} \to \text{Sets}$ be a functor. Suppose that $F(R)$ is a one element set and that for any $M, N \in \text{Ob}(\text{Mod}_R^{fg})$, the induced map
\[ F(R[M] \times_R R[N]) \to F(R[M]) \times F(R[N]) \]
is a bijection. Then $F(R[M])$ has a natural $R$-module structure for any $M \in \text{Ob}(\text{Mod}_R^{fg})$.

Proof. Note that $R \cong R[0]$ and $R[M] \times_R R[N] \cong R[M \times N]$ hence $R$ and $R[M] \times_R R[N]$ are objects of $\mathcal{C}$ by our assumptions on $\mathcal{C}$. Thus the conditions on $F$ make sense. The functor $\text{Mod}_R \to S\text{-Alg}/R$ of Lemma 10.7 restricts to a functor $\text{Mod}_R^{fg} \to \mathcal{C}$ by the assumption on $\mathcal{C}$. Let $L$ be the composition $\text{Mod}_R^{fg} \to \mathcal{C} \to \text{Sets}$, i.e., $L(M) = F(R[M])$. Then $L$ preserves finite products by Lemma 10.7 and the assumption on $F$. Hence Lemma 10.4 shows that $L(M) = F(R[M])$ has a natural $R$-module structure for any $M \in \text{Ob}(\text{Mod}_R^{fg})$.

Definition 10.9. Let $\mathcal{C}$ be a category as in Lemma 10.8. Let $F : \mathcal{C} \to \text{Sets}$ be a functor such that $F(R)$ is a one element set. The tangent space $TF$ of $F$ is $F(R[e])$. When $F : \mathcal{C} \to \text{Sets}$ satisfies the hypotheses of Lemma 10.8, the tangent space $TF$ has a natural $R$-module structure.

Example 10.10. Since $\mathcal{C}_\Lambda$ contains all $k[V]$ for finite dimensional vector spaces $V$ we see that Definition 10.9 applies with $\mathcal{C} = \mathcal{C}_\Lambda$, and $F : \mathcal{C}_\Lambda \to \text{Sets}$ a predeformation functor. The tangent space is $TF = F(k[e])$.

Example 10.11. Let us work out the tangent space of Example 10.10 when $F : \mathcal{C}_\Lambda \to \text{Sets}$ is a prorepresentable functor, say $F = S|_{\mathcal{C}_\Lambda}$ for $S \in \text{Ob}(\mathcal{C}_\Lambda)$. Then $F$ commutes with arbitrary limits and thus satisfies the hypotheses of Lemma 10.8. We compute
\[ TF = F(k[e]) = \text{Mor}_{\mathcal{C}_\Lambda}(S, k[e]) = \text{Der}_\Lambda(S, k) \]
and more generally for a finite dimensional $k$-vector space $V$ we have
\[ F(k[V]) = \text{Mor}_{\mathcal{C}_\Lambda}(S, k[V]) = \text{Der}_\Lambda(S, V). \]
Explicitly, a $\Lambda$-algebra map $f : S \to k[V]$ compatible with the augmentations $q : S \to k$ and $k[V] \to k$ corresponds to the derivation $D$ defined by $s \mapsto f(s) - q(s)$. Conversely, a $\Lambda$-derivation $D : S \to V$ corresponds to $f : S \to k[V]$ in $\mathcal{C}_\Lambda$ defined by the rule $f(s) = q(s) + D(s)$. Since these identifications are functorial we see that the $k$-vector spaces structures on $TF$ and $\text{Der}_\Lambda(S, k)$ correspond (see Lemma 10.5). It follows that $\dim_k TF$ is finite by Lemma 4.5.

Example 10.12. The computation of Example 10.11 simplifies in the classical case. Namely, in this case the tangent space of the functor $F = S|_{\mathcal{C}_\Lambda}$ is simply the relative cotangent space of $S$ over $\Lambda$, in a formula $TF = T_{S/\Lambda}$. In fact, this works more generally when the field extension $k' \subset k$ is separable. See Exercises, Exercise 28.2.

Lemma 10.13. Let $F, G : \mathcal{C} \to \text{Sets}$ be functors satisfying the hypotheses of Lemma 10.8. Let $t : F \to G$ be a morphism of functors. For any $M \in \text{Ob}(\text{Mod}_R^{fg})$, the map $t_{R[M]} : F(R[M]) \to G(R[M])$ is a map of $R$-modules, where $F(R[M])$ and $G(R[M])$ are given the $R$-module structure from Lemma 10.8. In particular, $t_{R[e]} : TF \to TG$ is a map of $R$-modules.
Proof. Follows from Lemma 10.5.

Example 10.14. Suppose that $f : R \to S$ is a ring map in $\mathcal{C}_\Lambda$. Set $F = R|_{\mathcal{C}_\Lambda}$ and $G = S|_{\mathcal{C}_\Lambda}$. The ring map $f$ induces a transformation of functors $G \to F$. By Lemma 10.13 we get a $k$-linear map $TG \to TF$. This is the map $TG = \text{Der}_{\Lambda}(S,k) \to \text{Der}_{\Lambda}(R,k) = TF$ as follows from the canonical identifications $F(k[V]) = \text{Der}_{\Lambda}(R,V)$ and $G(k[V]) = \text{Der}_{\Lambda}(S,V)$ of Example 10.11 and the rule for computing the map on tangent spaces.

Lemma 10.15. Let $F : \mathcal{C} \to \text{Sets}$ be a functor satisfying the hypotheses of Lemma 10.8. Assume $R = K$ is a field. Then $F(K[V]) \cong TF \otimes_K V$ for any finite dimensional $K$-vector space $V$.

Proof. Follows from Lemma 10.6.

11. Tangent spaces of predeformation categories

We will define tangent spaces of predeformation functors using the general Definition 10.9. We have spelled this out in Example 10.10. It applies to predeformation categories by looking at the associated functor of isomorphism classes.

Definition 11.1. Let $F$ be a predeformation category. The tangent space $T_F$ of $F$ is the set $F(k[\epsilon])$ of isomorphism classes of objects in the fiber category $F(k[\epsilon])$.

Thus $T_F$ is nothing but the tangent space of the associated functor $F : \mathcal{C}_\Lambda \to \text{Sets}$. It has a natural vector space structure when $F$ satisfies (S2), or, in fact, as long as $F$ does.

Lemma 11.2. Let $F$ be a predeformation category such that $F$ satisfies (S2). Then $T_F$ has a natural $k$-vector space structure. For any finite dimensional vector space $V$ we have $F(k[V]) = TF \otimes_k V$ functorially in $V$.

Proof. Let us write $F = \mathcal{F} : \mathcal{C}_\Lambda \to \text{Sets}$. This is a predeformation functor and $F$ satisfies (S2). By Lemma 9.4 (and the translation of Remark 9.3) we see that $F(A \times_k k[V]) \to F(A) \times F(k[V])$ is a bijection for every finite dimensional vector space $V$ and every $A \in \text{Ob}(\mathcal{C}_\Lambda)$. In particular, if $A = k[W]$ then we see that $F(k[W] \times_k k[V]) = F(k[W]) \times F(k[V])$. In other words, the hypotheses of Lemma 10.8 hold and we see that $TF = T\mathcal{F}$ has a natural $k$-vector space structure. The final assertion follows from Lemma 10.15.

A morphism of predeformation categories induces a map on tangent spaces.

Definition 11.3. Let $\varphi : F \to G$ be a morphism predeformation categories. The differential $d\varphi : TF \to TG$ of $\varphi$ is the map obtained by evaluating the morphism of functors $\varphi : F \to G$ at $A = k[\epsilon]$.

Lemma 11.4. Let $\varphi : F \to G$ be a morphism of predeformation categories. Assume $F$ and $G$ both satisfy (S2). Then $d\varphi : TF \to TG$ is $k$-linear.

Proof. In the proof of Lemma 11.2 we have seen that $\mathcal{F}$ and $\mathcal{G}$ satisfy the hypotheses of Lemma 10.8. Hence the lemma follows from Lemma 10.15.
Let sometimes write \( f \) generally, given a finite dimensional vector space \( \text{cofibered in groupoids over } \mathcal{C}_\Lambda \), and let \( x \in \text{Ob}(\mathcal{F}(k)) \). As in Remark 11.4, we get a predeformation category \( \mathcal{F}_x \). We define the tangent space \( T_x \mathcal{F} \) of \( \mathcal{F} \) at \( x \) to be the tangent space \( T\mathcal{F}_x \) of \( \mathcal{F}_x \). Similarly, if \( \varphi : \mathcal{F} \rightarrow \mathcal{G} \) is a morphism of categories cofibered in groupoids over \( \mathcal{C}_\Lambda \) and \( x \in \text{Ob}(\mathcal{F}(k)) \), then there is an induced morphism \( \varphi_x : \mathcal{F}_x \rightarrow \mathcal{G}_{\varphi(x)} \). We define the differential \( d_\varphi \mathcal{F} : T_x \mathcal{F} \rightarrow T_{\varphi(x)} \mathcal{G} \) of \( \varphi \) at \( x \) to be the map \( d_\varphi(x) : T\mathcal{F}_x \rightarrow T\mathcal{G}_{\varphi(x)} \). If both \( \mathcal{F} \) and \( \mathcal{G} \) satisfy (S2) then all of these tangent spaces have a natural \( k \)-vector space structure and all the differentials \( d_\varphi : T_x \mathcal{F} \rightarrow T_{\varphi(x)} \mathcal{G} \) are \( k \)-linear (use Lemmas 9.6 and 11.4).

The following observations are uninteresting in the classical case or when \( k' \subset k \) is a separable field extension, because then \( \text{Der}_\Lambda(k, k) \) and \( \text{Der}_\Lambda(k, V) \) are zero. There is a canonical identification

\[
\text{Mor}_{\mathcal{C}_\Lambda}(k, k[\epsilon]) = \text{Der}_\Lambda(k, k).
\]

Namely, for \( D \in \text{Der}_\Lambda(k, k) \) let \( f_D : k \rightarrow k[\epsilon] \) be the map \( a \mapsto a + D(a)\epsilon \). More generally, given a finite dimensional vector space \( V \) over \( k \) we have

\[
\text{Mor}_{\mathcal{C}_\Lambda}(k, k[V]) = \text{Der}_\Lambda(k, V)
\]

and we will use the same notation \( f_D \) for the map associated to the derivation \( D \). We also have

\[
\text{Mor}_{\mathcal{C}_\Lambda}(k[V], k[V]) = \text{Hom}_k(V, W) \oplus \text{Der}_\Lambda(k, V)
\]

where \((\varphi, D)\) corresponds to the map \( f_{\varphi, D} : a + w \mapsto a + \varphi(w) + D(a) \). We will sometimes write \( f_{1, D} : a + v \mapsto a + v + D(a) \) for the automorphism of \( k[V] \) determined by the derivation \( D : k \rightarrow V \). Note that \( f_{1, D} \circ f_{1, D'} = f_{1, D + D'} \).

Let \( \mathcal{F} \) be a predeformation category over \( \mathcal{C}_\Lambda \). Let \( x_0 \in \text{Ob}(\mathcal{F}(k)) \). By the above there is a canonical map

\[
\gamma_V : \text{Der}_\Lambda(k, V) \rightarrow \mathcal{F}(k[V])
\]

defined by \( D \mapsto f_{D, x_0}(x_0) \). Moreover, there is an action

\[
\alpha_V : \text{Der}_\Lambda(k, V) \times \mathcal{F}(k[V]) \rightarrow \mathcal{F}(k[V])
\]

defined by \( (D, x) \mapsto f_{1, D, x}(x) \). These two maps are compatible, i.e., \( f_{1, D, x_0} = f_{D, x_0} \) as follows from a computation of the compositions of these maps. Note that the maps \( \gamma_V \) and \( \alpha_V \) are independent of the choice of \( x_0 \) as there is a unique \( x_0 \) up to isomorphism.

\begin{lemma}
Let \( \mathcal{F} \) be a predeformation category over \( \mathcal{C}_\Lambda \). If \( \mathcal{F} \) has (S2) then the maps \( \gamma_V \) are \( k \)-linear and we have \( \alpha_V(D, x) = x + \gamma_V(D) \).
\end{lemma}

\begin{proof}
In the proof of Lemma 11.2 we have seen that the functor \( V \mapsto \mathcal{F}(k[V]) \) transforms 0 to a singleton and products to products. The same is true of the functor \( V \mapsto \text{Der}_\Lambda(k, V) \). Hence \( \gamma_V \) is linear by Lemma 10.3. Let \( D : k \rightarrow V \) be a \( \Lambda \)-derivation. Set \( D_1 : k \rightarrow V \oplus k \) equal to \( a \mapsto (D(a), 0) \). Then

\[
\begin{array}{ccc}
\kappa[V \times \kappa] & \xrightarrow{\phi} & \kappa[V] \\
\downarrow f_{1, D_1} & & \downarrow f_{1, \phi} \\
\kappa[V \times \kappa] & \xrightarrow{\phi} & \kappa[V]
\end{array}
\]

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commutes. Unwinding the definitions and using that \( F(V \times V) = F(V) \times F(V) \) this means that \( a_D(x_1) + x_2 = a_D(x_1 + x_2) \) for all \( x_1, x_2 \in F(V) \). Thus it suffices to show that \( a_V(D, 0) = 0 + \gamma_V(D) \) where \( 0 \in F(V) \) is the zero vector. By definition this is the element \( f_0,*(x_0) \). Since \( f_D = f_{1,D} \circ f_0 \) the desired result follows. \( \square \)

A special case of the constructions above are the map

\[
\text{(11.6.1)} \quad 06SV \quad \gamma : \text{Der}_A(k, k) \to TF
\]

and the action

\[
\text{(11.6.2)} \quad 06SW \quad a : \text{Der}_A(k, k) \times TF \to TF
\]

defined for any predeformation category \( F \). Note that if \( \varphi : F \to G \) is a morphism of predeformation categories, then we get commutative diagrams

\[
\begin{array}{ccc}
\text{Der}_A(k, k) & \xrightarrow{\gamma} & TF \\
\downarrow{d\varphi} & & \downarrow{d\varphi} \\
TG & \xrightarrow{1 \times d\varphi} & T\mathcal{G}
\end{array}
\quad \text{and} \quad
\begin{array}{ccc}
\text{Der}_A(k, k) \times TF & \xrightarrow{a} & TF \\
\downarrow{d\varphi} & & \downarrow{d\varphi} \\
\text{Der}_A(k, k) \times T\mathcal{G} & \xrightarrow{a} & T\mathcal{G}
\end{array}
\]

### 12. Versal formal objects

The existence of a versal formal object forces \( F \) to have property (S1).

**Lemma 12.1.** Let \( F \) be a predeformation category. Assume \( F \) has a versal formal object. Then \( F \) satisfies (S1).

**Proof.** Let \( \xi \) be a versal formal object of \( F \). Let

\[
\begin{array}{ccc}
x_2 & \xrightarrow{x_1} & x \\
\downarrow & & \downarrow \\
x & & x
\end{array}
\]

be a diagram in \( F \) such that \( x_2 \to x \) lies over a surjective ring map. Since the natural morphism \( \tilde{\mathcal{F}}|_{C^\Lambda} \to \mathcal{F} \) is an equivalence (see Remark 7.7), we can consider this diagram also as a diagram in \( \tilde{\mathcal{F}} \). By Lemma 8.15 there exists a morphism \( \xi \to x_1 \), so by Remark 8.14 we also get a morphism \( \xi \to x_2 \) making the diagram

\[
\begin{array}{ccc}
\xi & \xrightarrow{x_2} & x \\
\downarrow & & \downarrow \\
x_1 & \xrightarrow{x_1} & x
\end{array}
\]

commute. If \( x_1 \to x \) and \( x_2 \to x \) lie above ring maps \( A_1 \to A \) and \( A_2 \to A \) then taking the pushforward of \( \xi \) to \( A_1 \times_A A_2 \) gives an object \( y \) as required by (S1). \( \square \)

In the case that our cofibred category satisfies (S1) and (S2) we can characterize the versal formal objects as follows.

**Lemma 12.2.** Let \( F \) be a predeformation category satisfying (S1) and (S2). Let \( \xi \) be a formal object of \( F \) corresponding to \( \xi : R|_{C^\Lambda} \to \mathcal{F} \), see Remark 7.12. Then \( \xi \) is versal if and only if the following two conditions hold:

1. The map \( d\xi : T\tilde{\mathcal{F}}|_{C^\Lambda} \to TF \) on tangent spaces is surjective, and
(2) given a diagram in $\hat{F}$

$$
\begin{array}{ccc}
\xi & \longrightarrow & x \\
\downarrow & & \downarrow \\
B & \longrightarrow & A
\end{array}
$$

lying over $B \rightarrow A$ a small extension of Artinian rings, then there exists a ring map $R \rightarrow B$ such that

$$
\begin{array}{ccc}
B & \longrightarrow & A \\
\downarrow & & \downarrow \\
R & \longrightarrow & A
\end{array}
$$

commutes.

**Proof.** If $\xi$ is versal then (1) holds by Lemma 8.8 and (2) holds by Remark 8.14. Assume (1) and (2) hold. By Remark 8.14 we must show that given a diagram in $\hat{F}$ as in (2), there exists $\xi \rightarrow y$ such that

$$
\begin{array}{ccc}
y & \longrightarrow & y' \\
\downarrow & & \downarrow \\
\xi & \longrightarrow & x
\end{array}
$$

commutes. Let $b : R \rightarrow B$ be the map guaranteed by (2). Denote $y' = b_*\xi$ and choose a factorization $\xi \rightarrow y' \rightarrow x$ lying over $R \rightarrow B \rightarrow A$ of the given morphism $\xi \rightarrow x$. By (S1) we obtain a commutative diagram

$$
\begin{array}{ccc}
z & \longrightarrow & y \\
\downarrow & & \downarrow \\
y' & \longrightarrow & x
\end{array}
$$

lying over $B \times_A B \rightarrow B \rightarrow A$.

Set $I = \text{Ker}(k)$. Let $\tilde{g} : B \times_A B \rightarrow k[I]$ be the ring map $(u, v) \mapsto u \oplus (v - u)$, cf. Lemma 9.8. By (1) there exists a morphism $\xi \rightarrow \tilde{g}_*z$ which lies over a ring map $i : R \rightarrow k[e]$. Choose an Artinian quotient $b_1 : R \rightarrow B_1$ such that both $b : R \rightarrow B$ and $i : R \rightarrow k[e]$ factor through $R \rightarrow B_1$, i.e., giving $h : B_1 \rightarrow B$ and $i' : B_1 \rightarrow k[e]$. Choose a pushforward $y_1 = b_1_*\xi$, a factorization $\xi \rightarrow y_1 \rightarrow y'$ lying over $R \rightarrow B_1 \rightarrow B$ of $\xi \rightarrow y'$, and a factorization $\xi \rightarrow y_1 \rightarrow \tilde{g}_*z$ lying over $R \rightarrow B_1 \rightarrow k[e]$ of $\xi \rightarrow \tilde{g}_*z$. Applying (S1) once more we obtain

$$
\begin{array}{ccc}
z & \longrightarrow & y \\
\downarrow & & \downarrow \\
y_1 & \longrightarrow & x
\end{array}
$$

lying over $B_1 \times_A B \rightarrow B \times_A B \rightarrow B$.

Note that the map $g : B_1 \times_A B \rightarrow k[I]$ of Lemma 9.8 (defined using $h$) is the composition of $B_1 \times_A B \rightarrow B \times_A B$ and the map $\tilde{g}$ above. By construction there exists a morphism $y_1 \rightarrow g_*z_1 \cong \tilde{g}_*z$! Hence Lemma 9.8 applies (to the outer rectangles in the diagrams above) to give a morphism $y_1 \rightarrow y$ and precomposing with $\xi \rightarrow y_1$ gives the desired morphism $\xi \rightarrow y$. □
If $\mathcal{F}$ has property (S1) then the “largest quotient where a lift exists” exists. Here is a precise statement.

**06SZ Lemma 12.3.** Let $\mathcal{F}$ be a category cofibred in groupoids over $\mathcal{C}_\Lambda$ which has (S1). Let $B \to A$ be a surjection in $\mathcal{C}_\Lambda$ with kernel $I$ annihilated by $m_B$. Let $x \in \mathcal{F}(A)$. The set of ideals

$$\mathcal{J} = \{ J \subset I \mid \text{there exists an } y \to x \text{ lying over } B/J \to A \}$$

has a smallest element.

**Proof.** Note that $\mathcal{J}$ is nonempty as $I \in \mathcal{J}$. Also, if $J \in \mathcal{J}$ and $J \subset J' \subset I$ then $J' \in \mathcal{J}$ because we can pushforward the object $y$ to an object $y'$ over $B/J'$. Let $J$ and $K$ be elements of the displayed set. We claim that $J \cap K \in \mathcal{J}$ which will prove the lemma. Since $I$ is a $k$-vector space we can find an ideal $J \subset J' \subset I$ such that $J \cap K = J' \cap K$ and such that $J' + K = I$. By the above we may replace $J$ by $J'$ and assume that $J + K = I$. In this case

$$A/(J \cap K) = A/J \times_{A/J} A/K.$$  

Hence the existence of an element $z \in \mathcal{F}(A/(J \cap K))$ mapping to $x$ follows, via (S1), from the existence of the elements we have assumed exist over $A/J$ and $A/K$. □

We will improve on the following result later.

**06IW Lemma 12.4.** Let $\mathcal{F}$ be a category cofibred in groupoids over $\mathcal{C}_\Lambda$. Assume the following conditions hold:

1. $\mathcal{F}$ is a predeformation category.
2. $\mathcal{F}$ satisfies (S1).
3. $\mathcal{F}$ satisfies (S2).
4. $\dim_k T \mathcal{F}$ is finite.

Then $\mathcal{F}$ has a versal formal object.

**Proof.** Assume (1), (2), (3), and (4) hold. Choose an object $R \in \text{Ob}(\widehat{\mathcal{C}}_\Lambda)$ such that $R|_{\mathcal{C}_\Lambda}$ is smooth, see Example 8.10. Let $r = \dim_k T \mathcal{F}$ and put $S = R[[X_1, \ldots, X_r]]$.

We are going to inductively construct for $n \geq 2$ pairs $(J_n, f_{n-1} : \xi_n \to \xi_{n-1})$ where $J_n \subset S$ is an decreasing sequence of ideals and $f_{n-1} : \xi_n \to \xi_{n-1}$ is a morphism of $\mathcal{F}$ lying over the projection $S/J_n \to S/J_{n-1}$.

**Step 1.** Let $J_1 = m_S$. Let $\xi_1$ be the unique (up to unique isomorphism) object of $\mathcal{F}$ over $k = S/J_1 = S/m_S$.

**Step 2.** Let $J_2 = m_S^2 + m_RS$. Then $S/J_2 = k[V]$ with $V = kX_1 \oplus \ldots \oplus kX_r$. By (S2) for $\mathcal{F}$ we get a bijection

$$\mathcal{F}(S/J_2) \to T \mathcal{F} \otimes_k V,$$

see Lemmas 9.5 and 11.2. Choose a basis $\theta_1, \ldots, \theta_r$ for $T \mathcal{F}$ and set $\xi_2 = \sum \theta_i \otimes X_i \in \text{Ob}(\mathcal{F}(S/J_2))$. The point of this choice is that

$$d\xi_2 : \text{Mor}_{\mathcal{C}_\Lambda}(S/J_2, k[\epsilon]) \to T \mathcal{F}$$

is surjective. Let $f_1 : \xi_2 \to \xi_1$ be the unique morphism.

**Induction step.** Assume $(J_n, f_{n-1} : \xi_n \to \xi_{n-1})$ has been constructed for some $n \geq 2$. There is a minimal element $J_{n+1}$ of the set of ideals $J \subset S$ satisfying: (a) $m_S J_n \subset J \subset J_n$ and (b) there exists a morphism $\xi_{n+1} \to \xi_n$ lying over $S/J \to$.
Let $f_n : \xi_{n+1} \to \xi_n$ be any morphism of $\mathcal{F}$ lying over $S/J_{n+1} \to S/J_n$.

Set $J = \bigcap J_n$. Set $\mathcal{S} = S/J$. Set $\mathcal{J}_n = J_n/J$. By Lemma \ref{lem:sequence_of_ideals}, the sequence of ideals $(\mathcal{J}_n)$ induces the $m_{\mathcal{S}}$-adic topology on $\mathcal{S}$. Since $(\xi_n, f_n)$ is an object of $\hat{\mathcal{F}}(\mathcal{S})$, where $\mathcal{S}$ is the filtration $(\mathcal{J}_n)$ of $\mathcal{S}$, we see that $(\xi_n, f_n)$ induces an object $\xi$ of $\hat{\mathcal{F}}(\mathcal{S})$. See Lemma \ref{lem:versal}.

We prove $\xi$ is versal. For versality it suffices to check conditions (1) and (2) of Lemma \ref{lem:versality}. Condition (1) follows from our choice of $\xi_2$ in Step 2 above. Suppose given a diagram in $\hat{\mathcal{F}}$

\[
\begin{array}{ccc}
y & \to & B \\
\eta \downarrow & & \downarrow f \\
\mathcal{S} & \to & A
\end{array}
\]

in $\hat{\mathcal{C}}_A$ with $f : B \to A$ a small extension of Artinian rings. We have to show there is a map $\mathcal{S} \to B$ fitting into the diagram on the right. Choose $n$ such that $\mathcal{S} \to A$ factors through $\mathcal{S} \to S/J_n$. This is possible as the sequence $(\mathcal{J}_n)$ induces the $m_{\mathcal{S}}$-adic topology as we saw above. The pushforward of $\xi$ along $\mathcal{S} \to S/J_n$ is $\xi_n$. We may factor $\xi \to x$ as $\xi \to \xi_n \to x$ hence we get a diagram in $\mathcal{F}$

\[
\begin{array}{ccc}
y & \to & B \\
\eta \downarrow & & \downarrow f \\
\xi_n & \to & S/J_n \to A.
\end{array}
\]

To check condition (2) of Lemma \ref{lem:versality} it suffices to complete the diagram

\[
\begin{array}{ccc}
S/J_{n+1} & \to & B \\
\downarrow & & \downarrow f \\
S/J_n & \to & A
\end{array}
\]

or equivalently, to complete the diagram

\[
\begin{array}{ccc}
S/J_n \times_A B \\
\downarrow p_1 \\
S/J_{n+1}
\end{array}
\]

If $p_1$ has a section we are done. If not, by Lemma \ref{lem:extension_of_surjection} (2) $p_1$ is a small extension, so by Lemma \ref{lem:small_extension} (4) $p_1$ is an essential surjection. Recall that $S = R[[X_1, \ldots, X_r]]$ and that we chose $R$ such that $R_{(x)}$ is smooth. Hence there exists a map $h : R \to B$ lifting the map $R \to S \to S/J_n \to A$. By the universal property of a power series ring there is an $R$-algebra map $h : S = R[[X_1, \ldots, X_2]] \to B$ lifting the given map $S \to S/J_n \to A$. This induces a map $g : S \to S/J_n \times_A B$ making the solid square
in the diagram

\[
\begin{array}{ccc}
S & \xrightarrow{g} & S/J_n \times_A B \\
\downarrow & & \downarrow \quad p_1 \\
S/J_{n+1} & \xrightarrow{\dash} & S/J_n
\end{array}
\]

commute. Then \( g \) is a surjection since \( p_1 \) is an essential surjection. We claim the ideal \( K = \text{Ker}(g) \) of \( S \) satisfies conditions (a) and (b) of the construction of \( J_{n+1} \) in the induction step above. Namely, \( K \subseteq J_n \) is clear and \( \mathfrak{m}_S J_n \subseteq K \) as \( p_1 \) is a small extension; this proves (a). By (S1) applied to

\[
\begin{array}{cc}
y & \xrightarrow{} \\
\downarrow & \downarrow \quad \xi_n \\
x,
\end{array}
\]

there exists a lifting of \( \xi_n \) to \( S/K \cong S/J_n \times_A B \), so (b) holds. Since \( J_{n+1} \) was the minimal ideal with properties (a) and (b) this implies \( J_{n+1} \subset K \). Thus the desired map \( S/J_{n+1} \to S/K \cong S/J_n \times_A B \) exists. \( \square \)

**13. Minimal versal formal objects**

We do a little bit of work to try and understand (non)uniqueness of versal formal objects. It turns out that if a predeformation category has a versal formal object, then it has a minimal versal formal object and any two such are isomorphic. Moreover, all versal formal objects are “more or less” the same up to replacing the base ring by a power series extension.

Let \( \mathcal{F} \) be a category cofibred in groupoids over \( \mathcal{C}_\Lambda \). For every object \( x \) of \( \mathcal{F} \) lying over \( A \in \text{Ob}(\mathcal{C}_\Lambda) \) consider the category \( \mathcal{S}_x \) with objects

\[
\text{Ob}(\mathcal{S}_x) = \{ x' \to x \mid x' \to x \text{ lies over } A' \subset A \}
\]

and morphisms are morphisms over \( x \). For every \( y \to x \) in \( \mathcal{F} \) lying over \( f : B \to A \) in \( \mathcal{C}_\Lambda \) there is a functor \( f_* : \mathcal{S}_y \to \mathcal{S}_x \) defined as follows: Given \( y' \to y \) lying over \( B' \subset B \) set \( A' = f(B') \) and let \( y' \to x' \) be over \( B' \to f(B') \) be the pushforward of \( y' \). By the axioms of a category cofibred in groupoids we obtain a unique morphism \( x' \to x \) lying over \( f(B') \to A \) such that

\[
\begin{array}{ccc}
y' & \xrightarrow{f_*} & x' \\
\downarrow & & \downarrow \\
y & \xrightarrow{} & x
\end{array}
\]

commutes. Then \( x' \to x \) is an object of \( \mathcal{S}_x \). We say an object \( x' \to x \) of \( \mathcal{S}_x \) is **minimal** if any morphism \( (x'_1 \to x) \to (x' \to x) \) in \( \mathcal{S}_x \) is an isomorphism, i.e., \( x' \) and \( x'_1 \) are defined over the same subring of \( A \). Since \( A \) has finite length as a \( \Lambda \)-module we see that minimal objects always exist.

**Lemma 13.1.** Let \( \mathcal{F} \) be a category cofibred in groupoids over \( \mathcal{C}_\Lambda \) which has (S1).

1. For \( y \to x \) in \( \mathcal{F} \) a minimal object in \( \mathcal{S}_y \) maps to a minimal object of \( \mathcal{S}_x \).
2. For \( y \to x \) in \( \mathcal{F} \) lying over a surjection \( f : B \to A \) in \( \mathcal{C}_\Lambda \) every minimal object of \( \mathcal{S}_x \) is the image of a minimal object of \( \mathcal{S}_y \).
Proof. Proof of (1). Say \( y \to x \) lies over \( f : B \to A \). Let \( y' \to y \) lying over \( B' \subset B \) be as in the construction of \( f \) above. Suppose that \( (x'' \to x) \to (x' \to x) \) is a morphism of \( \mathcal{S}_x \) with \( x'' \to x' \) lying over \( A'' \subset f(B') \). By (S1) there exists \( y'' \to y' \) lying over \( B' \times_{f(B')} A'' \to B' \). Since \( y' \to y \) is minimal we conclude that \( B' \times_{f(B')} A'' \to B' \) is an isomorphism, which implies that \( A'' = f(B') \), i.e., \( x' \to x \) is minimal.

Proof of (2). Suppose \( f : B \to A \) is surjective and \( y \to x \) lies over \( f \). Let \( x' \to x \) be a minimal object of \( \mathcal{S}_x \) lying over \( A' \subset A \). By (S1) there exists \( y' \to y \) lying over \( B' = f^{-1}(A') = B \times_A A' \to B \) whose image in \( \mathcal{S}_x \) is \( x' \to x \). So \( f_*(y' \to y) = x' \to x \). Choose a morphism \( (y'' \to y) \to (y' \to y) \) in \( \mathcal{S}_x \) with \( y'' \to y \) a minimal object (this is possible by the remark on lengths above the lemma). Then \( f_*(y'' \to y) \) is an object of \( \mathcal{S}_x \) which maps to \( x' \to x \) (by functoriality of \( f_* \)) hence is isomorphic to \( x' \to x \) by minimality of \( x' \to x \). \(\square\)

Lemma 13.2. Let \( \mathcal{F} \) be a category cofibred in groupoids over \( \mathcal{C}_A \) which has (S1). Let \( \xi \) be a versal formal object of \( \mathcal{F} \) lying over \( R \). There exists a morphism \( \xi' \to \xi \) lying over \( R' \subset R \) with the following minimality properties:

1. For every \( f : R \to A \) with \( A \in \text{Ob}(\mathcal{C}_A) \) the pushforwards

\[
\begin{array}{ccc}
\xi' & \to & x' \\
\downarrow & & \downarrow \\
\xi & \to & x
\end{array}
\]

produce a minimal object \( x' \to x \) of \( \mathcal{S}_x \), and

2. For any morphism of formal objects \( \xi'' \to \xi' \) the corresponding morphism \( R'' \to R' \) is surjective.

Proof. Write \( \xi = (R, \xi_n, f_n) \). Set \( R'_1 = k \) and \( \xi'_1 = \xi_1 \). Suppose that we have constructed minimal objects \( \xi'_m \to \xi_m \) of \( \mathcal{S}_x \) lying over \( R'_m \subset R/m_R^n \) for \( m \leq n \) and morphisms \( f'_m : \xi'_{m+1} \to \xi'_m \) compatible with \( f_m \) for \( m \leq n-1 \). By Lemma 13.1 (2) there exists a minimal object \( \xi'_{n+1} \to \xi_{n+1} \) lying over \( R'_{n+1} \subset R/m_R^{n+1} \) whose image is \( \xi_n \to \xi_n \) over \( R_n' \subset R/m_R^n \). This produces the commutative diagram

\[
\begin{array}{ccc}
\xi'_{n+1} & \to & \xi'_n \\
\downarrow & & \downarrow \\
\xi_{n+1} & \to & \xi_n
\end{array}
\]

by construction. Moreover the ring map \( R'_{n+1} \to R'_n \) is surjective. Set \( R' = \lim_{\to n} R'_n \). Then \( R' \to R \) is injective.

However, it isn’t a priori clear that \( R' \) is Noetherian. To prove this we use that \( \xi \) is versal. Namely, versality implies that there exists a morphism \( \xi \to \xi'_n \) in \( \mathcal{F} \), see Lemma 8.15. The corresponding map \( R \to R'_n \) has to be surjective (as \( \xi'_n \to \xi_n \)
is minimal in $S_{\xi}$. Thus the dimensions of the cotangent spaces are bounded and Lemma 4.8 implies $R'$ is Noetherian, i.e., an object of $\hat{C}_A$. By Lemma 7.4 (plus the result on filtrations of Lemma 4.8) the sequence of elements $\xi_n$ defines a formal object $\xi'$ over $R'$ and we have a map $\xi' \to \xi$.

By construction (1) holds for $R \to R/m^n_R$ for each $n$. Since each $R \to A$ as in (1) factors through $R \to R/m^n_R \to A$ we see that (1) for $x' \to x$ over $f(R) \subset A$ follows from the minimality of $\xi_n \to \xi_n$ over $R' \to R/m^n_R$ by Lemma 13.1 (1).

If $R'' \to R'$ as in (2) is not surjective, then $R'' \to R' \to R'_n$ would not be surjective for some $n$ and $\xi_n' \to \xi_n$ wouldn’t be minimal, a contradiction. This contradiction proves (2).

06T3 Lemma 13.3. Let $\mathcal{F}$ be a category cofibred in groupoids over $C_A$ which has (S1). Let $\xi$ be a versal formal object of $\mathcal{F}$ lying over $R$. Let $\xi' \to \xi$ be a morphism of formal objects lying over $R' \subset R$ as constructed in Lemma 13.2 Then

$$R \cong R'[x_1, \ldots, x_r]$$

is a power series ring over $R'$. Moreover, $\xi'$ is a versal formal object too.

Proof. By Lemma 8.15 there exists a morphism $\xi \to \xi'$. By Lemma 13.2 the corresponding map $f : R \to R'$ induces a surjection $f|_{R'} : R' \to R'$. This is an isomorphism by Algebra, Lemma 30.8. Hence $I = \text{Ker}(f)$ is an ideal of $R$ such that $R = R' \oplus I$. Let $x_1, \ldots, x_r \in I$ be elements which form a basis for $I/m_R I$. Consider the map $S = R'[x_1, \ldots, x_r] \to R$ mapping $X_i$ to $x_i$. For every $n \geq 1$ we get a surjection of Artinian $R'$-algebras $B = S/m^n_S \to R/m^n_R = A$. Denote $y \in \text{Ob}(\mathcal{F}(B))$, resp. $x \in \text{Ob}(\mathcal{F}(A))$ the pushforward of $\xi'$ along $R' \to S \to B$, resp. $R' \to S \to A$. Note that $x$ is also the pushforward of $\xi$ along $R \to A$ as $\xi$ is the pushforward of $\xi'$ along $R' \to R$. Thus we have a solid diagram

$$\begin{array}{ccc}
S/m^n_S & \to & R/m^n_R \\
\downarrow & & \downarrow \\
R & \to & R'/m^n_R \\
\downarrow & & \downarrow \\
\xi & \to & x \text{ lying over} \\
\end{array}$$

Because $\xi$ is versal, using Remark 8.14 we obtain the dotted arrows fitting into these diagrams. In particular, the maps $S/m^n_S \to R/m^n_R$ have sections $h_n : R/m^n_R \to S/m^n_S$. It follows from Lemma 14.9 that $S \to R$ is an isomorphism.

As $\xi$ is a pushforward of $\xi'$ along $R' \to R$ we obtain from Remark 8.13 a commutative diagram

$$\begin{array}{ccc}
R|_{C_A} & \to & R'|_{C_A} \\
\downarrow & \nearrow & \downarrow \\
\xi & \to & \xi' \\
\end{array}$$

Since $R' \to R$ has a left inverse (namely $R \to R/I = R'$) we see that $R|_{C_A} \to R'|_{C_A}$ is essentially surjective. Hence by Lemma 8.7 we see that $\xi'$ is smooth, i.e., $\xi'$ is a versal formal object.

Motivated by the preceding lemmas we make the following definition.
Definition 13.4. Let \( \mathcal{F} \) be a predeformation category. We say a versal formal object \( \xi \) of \( \mathcal{F} \) is minimal if for any morphism of formal objects \( \xi' \to \xi \) the underlying map on rings is surjective. Sometimes a minimal versal formal object is called miniversal.

The work in this section shows this definition is reasonable. First of all, the existence of a versal formal object implies that \( \mathcal{F} \) has (S1). Then the preceding lemmas show there exists a minimal versal formal object. Finally, any two minimal versal formal objects are isomorphic. Here is a summary of our results (with detailed proofs).

Lemma 13.5. Let \( \mathcal{F} \) be a predeformation category which has a versal formal object. Then

1. \( \mathcal{F} \) has a minimal versal formal object,
2. minimal versal objects are unique up to isomorphism, and
3. any versal object is the pushforward of a minimal versal object along a power series ring extension.

Proof. Suppose \( \mathcal{F} \) has a versal formal object \( \xi \) over \( R \). Then it satisfies (S1), see Lemma 12.1. Let \( \xi' \to \xi \) over \( R' \subset R \) be any of the morphisms constructed in Lemma 13.2. By Lemma 13.3 we see that \( \xi' \) is versal, hence it is a minimal versal formal object (by construction). This proves (1). Also, \( R \cong R'[[x_1, \ldots, x_n]] \) which proves (3).

Suppose that \( \xi_i/R_i \) are two minimal versal formal objects. By Lemma 13.15 there exist morphisms \( \xi_1 \to \xi_2 \) and \( \xi_2 \to \xi_1 \). The corresponding ring maps \( f : R_1 \to R_2 \) and \( g : R_2 \to R_1 \) are surjective by minimality. Hence the compositions \( g \circ f : R_1 \to R_1 \) and \( f \circ g : R_2 \to R_2 \) are isomorphisms by Algebra, Lemma 30.8. Thus \( f \) and \( g \) are isomorphisms whence the maps \( \xi_1 \to \xi_2 \) and \( \xi_2 \to \xi_1 \) are isomorphisms (because \( \hat{\mathcal{F}} \) is cofibred in groupoids by Lemma 7.2). This proves (2) and finishes the proof of the lemma.

14. Miniversal formal objects and tangent spaces

The general notion of minimality introduced in Definition 13.4 can sometimes be deduced from the behaviour on tangent spaces. Let \( \xi \) be a formal object of the predeformation category \( \mathcal{F} \) and let \( \xi : R|_{\mathcal{C}} \to \mathcal{F} \) be the corresponding morphism. Then we can consider the following the condition

\[
d\xi : \text{Der}_A(R, k) \to T\mathcal{F} \text{ is bijective}
\]

and the condition

\[
d\xi : \text{Der}_A(R, k) \to T\mathcal{F} \text{ is bijective on Der}_A(k, k)-orbits.
\]

Here we are using the identification \( T\mathcal{R}|_{\mathcal{C}} = \text{Der}_A(R, k) \) of Example 11.11 and the action 11.6.2 of derivations on the tangent spaces. If \( k' \subset k \) is separable, then \( \text{Der}_A(k, k) = 0 \) and the two conditions are equivalent. It turns out that, in the presence of condition (S2) a versal formal object is minimal if and only if \( \xi \) satisfies (14.0.2). Moreover, if \( \xi \) satisfies (14.0.1), then \( \mathcal{F} \) satisfies (S2).

\( ^2 \)This may be nonstandard terminology. Many authors tie this notion in with properties of tangent spaces. We will make the link in Section 14.
Lemma 14.1. Let $F$ be a predeformation category. Let $\xi$ be a versal formal object of $F$ such that (14.0.2) holds. Then $\xi$ is a minimal versal formal object. In particular, such $\xi$ are unique up to isomorphism.

Proof. If $\xi$ is not minimal, then there exists a morphism $\xi' \to \xi$ lying over $R' \to R$ such that $R = R'[x_1, \ldots, x_n]$ with $n > 0$, see Lemma 13.5. Thus $d\xi$ factors as

$$\text{Der}_\Lambda(R, k) \to \text{Der}_\Lambda(R', k) \to \mathcal{F}$$

and we see that (14.0.2) cannot hold because $D : f \mapsto \partial/\partial x_1(f) \mod m_R$ is an element of the kernel of the first arrow which is not in the image of $\text{Der}_\Lambda(k, k) \to \text{Der}_\Lambda(R, k)$.

Lemma 14.2. Let $F$ be a predeformation category. Let $\xi$ be a versal formal object of $F$ such that (14.0.1) holds. Then

1. $F$ satisfies (S1).
2. $F$ satisfies (S2).
3. $\dim_k T\mathcal{F}$ is finite.

Proof. Condition (S1) holds by Lemma 12.1. The first part of (S2) holds since (S1) holds. Let

$$\begin{array}{ccc}
y & \xrightarrow{c} & x_e \\
\downarrow a & & \downarrow e \\
x & \xrightarrow{d} & x_0
\end{array} \quad \text{and} \quad \begin{array}{ccc}
y' & \xrightarrow{c'} & x_e \\
\downarrow a' & & \downarrow e \\
x & \xrightarrow{d} & x_0
\end{array} \quad \text{lying over} \quad \begin{array}{ccc}
A \times_k k[\epsilon] & \xrightarrow{\pi} & k[\epsilon] \\
\downarrow & & \downarrow \\
A & \xrightarrow{\pi} & k
\end{array}$$

be diagrams as in the second part of (S2). As above we can find morphisms $b : \xi \to y$ and $b' : \xi \to y'$ such that

$$\begin{array}{ccc}
\xi & \xrightarrow{b} & y' \\
\downarrow b & & \downarrow a' \\
y & \xrightarrow{a} & x
\end{array}$$

commutes. Let $p : F \to C_\Lambda$ denote the structure morphism. Say $\tilde{p}(\xi) = R$, i.e., $\xi$ lies over $R \in \text{Ob}(C_\Lambda)$. We see that the pushforward of $\xi$ via $p(c) \circ p(b)$ is $x_e$ and that the pushforward of $\xi$ via $p(c') \circ p(b')$ is $x_e$. Since $\xi$ satisfies (14.0.1), we see that $p(c) \circ p(b) = p(c') \circ p(b')$ as maps $R \to k[\epsilon]$. Hence $p(b) = p(b')$ as maps from $R \to A \times_k k[\epsilon]$. Thus we see that $y$ and $y'$ are isomorphic to the pushforward of $\xi$ along this map and we get a unique morphism $y \to y'$ over $A \times_k k[\epsilon]$ compatible with $b$ and $b'$ as desired.

Finally, by Example 10.11 we see $\dim_k T\mathcal{F} = \dim_k TR|_{C_\Lambda}$ is finite.

Example 14.3. There exist predeformation categories which have a versal formal object satisfying (14.0.2) but which do not satisfy (S2). A quick example is to take $F = k[\epsilon]/G$ where $G \subset \text{Aut}_{C_\Lambda}(k[\epsilon])$ is a finite nontrivial subgroup. Namely, the map $k[\epsilon] \to F$ is smooth, but the tangent space of $F$ does not have a natural $k$-vector space structure (as it is a quotient of a $k$-vector space by a finite group).

Lemma 14.4. Let $F$ be a predeformation category satisfying (S2) which has a versal formal object. Then its minimal versal formal object satisfies (14.0.2).
Proof. Let $\xi$ be a minimal versal formal object for $\mathcal{F}$, see Lemma 13.5. Say $\xi$ lies over $R \in \text{Ob}(\tilde{\mathcal{C}})$. In order to parse (14.0.2) we point out that $T\mathcal{F}$ has a natural $k$-vector space structure (see Lemma 11.2), that $d\xi : \text{Der}_\Lambda(R, k) \to T\mathcal{F}$ is linear (see Lemma 11.4), and that the action of $\text{Der}_\Lambda(k, k)$ is given by addition (see Lemma 11.6). Consider the diagram

\[
\begin{array}{ccc}
\text{Hom}_k(m_R/m_R^2, k) & \rightarrow & \text{Der}_\Lambda(R, k) \\
K & \xrightarrow{d\xi} & T\mathcal{F} \rightarrow \text{Der}_\Lambda(k, k)
\end{array}
\]

The vector space $K$ is the kernel of $d\xi$. Note that the middle column is exact in the middle as it is dual to the sequence (3.10.1). If (14.0.2) fails, then we can find a nonzero element $D \in K$ which does not map to zero in $\text{Hom}_k(m_R/m_R^2, k)$. Note that the middle column is exact in the middle as it is dual to the sequence (3.10.1). If (14.0.2) fails, then we can find a nonzero element $D \in K$ which does not map to zero in $\text{Hom}_k(m_R/m_R^2, k)$. This means there exists an $t \in m_R$ such that $D(t) = 1$. Set $R' = \{ a \in R \mid D(a) = 0 \}$. As $D$ is a derivation this is a subring of $R$. Since $D(t) = 1$ we see that $R' \rightarrow k$ is surjective (compare with the proof of Lemma 3.12). Note that $m_R' = \text{Ker}(D : m_R \rightarrow k)$ is an ideal of $R$ and $m_R'^2 \subset m_R'$. Hence

\[m_R/m_R^2 = m_R'/m_R'^2 + k\]

which implies that the map

\[R'/m_R'^2 \times_k k[\epsilon] \rightarrow R/m_R^2 \]

sending $\epsilon$ to $t$ is an isomorphism. In particular there is a map $R/m_R^2 \rightarrow R'/m_R'^2$.

Let $\xi \rightarrow y$ be a morphism lying over $R \rightarrow R/m_R^2$. Let $y \rightarrow x$ be a morphism lying over $R/m_R^2 \rightarrow R'/m_R'^2$. Let $y \rightarrow x_\epsilon$ be a morphism lying over $R/m_R^2 \rightarrow k[\epsilon]$. Let $x_0$ be the unique (up to unique isomorphism) object of $\mathcal{F}$ over $k$. By the axioms of a category cofibred in groupoids we obtain a commutative diagram

\[
\begin{array}{ccc}
y & \xrightarrow{x_\epsilon} & R'/m_R'^2 \times_k k[\epsilon] \\
x & \xrightarrow{x_0} & m_R/m_R^2 \rightarrow k[\epsilon]
\end{array}
\]

lying over

\[
\begin{array}{ccc}
R'/m_R'^2 & \rightarrow & k[\epsilon] \\
R'/m_R'^2 \rightarrow k
\end{array}
\]

Because $D \in K$ we see that $x_\epsilon$ is isomorphic to $0 \in \mathcal{F}(k[\epsilon])$, i.e., $x_\epsilon$ is the pushforward of $x_0$ via $k \rightarrow k[\epsilon], a \mapsto a$. Hence by Lemma 0.7 we see that there exists a morphism $x \rightarrow y$. Since $\text{length}_\Lambda(R'/m_R'^2) < \text{length}_\Lambda(R/m_R^2)$ the corresponding ring map $R'/m_R'^2 \rightarrow R/m_R^2$ is not surjective. This contradicts the minimality of $\xi/R$, see part (1) of Lemma 13.2. This contradiction shows that such a $D$ cannot exist, hence we win. □

06IX Theorem 14.5. Let $\mathcal{F}$ be a predeformation category. Consider the following conditions

1. $\mathcal{F}$ has a minimal versal formal object satisfying (14.0.1),
2. $\mathcal{F}$ has a minimal versal formal object satisfying (14.0.2),
3. the following conditions hold:
   a. $\mathcal{F}$ satisfies (S1).
(b) $F$ satisfies (S2).
(c) $\dim_k TF$ is finite.

We always have

$$ (1) \Rightarrow (3) \Rightarrow (2). $$

If $k' \subset k$ is separable, then all three are equivalent.

**Proof.** Lemma 14.2 shows that $(1) \Rightarrow (3)$. Lemmas 12.4 and 14.4 show that $(3) \Rightarrow (2)$. If $k' \subset k$ is separable then $\text{Der}_\Lambda(k, k) = 0$ and we see that $(14.0.1) = (14.0.2)$, i.e., $(1)$ is the same as $(2)$.

An alternative proof of $(3) \Rightarrow (1)$ in the classical case is to add a few words to the proof of Lemma 12.4 to see that one can right away construct a versal object which satisfies $(14.0.1)$ in this case. This avoids the use of Lemma 12.4 in the classical case. Details omitted. 

□

**Remark 14.6.** When $F$ is a predeformation functor, the condition $\dim_k TF < \infty$ is precisely condition (H3) from Schlessinger’s paper. In the classical case (or the case where $k' \subset k$ is separable), Theorem 14.5 recovers Schlessinger’s theorem on the existence of “hulls”. In our terminology a hull is a versal formal object $\xi$ for a predeformation functor such that $d\xi$ is an isomorphism.

**Remark 14.7.** Let $F$ be a predeformation category satisfying (S1), (S2), and $\dim_k TF < \infty$. Then $\overline{F}$ also satisfies (S1), (S2), and $\dim_k T\overline{F} < \infty$, see Lemma 9.5. Thus, if $k' \subset k$ is separable, then $\overline{F}$ has a hull (see Remark 14.6). In fact, if $\xi$ is a minimal versal object for $F$ lying over $R$, then the composition $R|_{C_\Lambda} \to F \to \overline{F}$ is smooth and identifies tangent spaces, i.e., the image $\overline{\xi}$ of $\xi$ in $\overline{F}$ is a hull. This follows from the fact that $F \to \overline{F}$ identifies tangent spaces.

**Example 14.8.** In Example 8.10 we constructed objects $R \in \hat{C}_\Lambda$ such that $R|_{C_\Lambda}$ is smooth. We can reformulate this as follows. Let $F = C_\Lambda$ considered as cofibred in groupoids via the identity functor. In other words, $F$ is the category cofibred in sets corresponding to the functor $F : A \mapsto \{*\}$ (this is the final object in the category of functors $C_\Lambda \to \text{Sets}$). The condition that $R|_{C_\Lambda}$ is smooth means exactly that $R|_{C_\Lambda} \to F$ is smooth, i.e., that $\xi = *$ is a formal versal object of $F$ over $R$. Hence $F$ has a versal formal object. In fact, it is easy to see that $F$ satisfies condition (3) of Theorem 14.5. The theorem implies that (2) holds. This means we can find a minimal versal formal object $* \in \hat{F}(S)$ over some $S \in \hat{C}_\Lambda$ such that $d*: \text{Der}_\Lambda(S, k) \to 0$ is bijective on $\text{Der}_\Lambda(k, k)$-orbits. Clearly this means that the injection $\text{Der}_\Lambda(k, k) \to \text{Der}_\Lambda(S, k)$ is also surjective. In other words, the exact sequence $(3.10.2)$ turns into a pair of isomorphisms

$$ H_1(L_{k/\Lambda}) = m_S/m_S^2 \quad \text{and} \quad \Omega_{S/\Lambda} \otimes_S k = \Omega_{k/\Lambda}. $$

(The first arrow is injective because of the formal smoothness of $S$ over $\Lambda$; details omitted.) Of course the existence of such a ring $S$ can be proved directly by judiciously slicing the ring $R$ constructed in Example 8.10.
15. Rim-Schlessinger conditions and deformation categories

There is a very natural property of categories fibred in groupoids over $\mathcal{C}_\Lambda$ which is easy to check in practice and which implies Schlessinger’s properties (S1) and (S2) we have introduced earlier.

**Definition 15.1.** Let $\mathcal{F}$ be a category cofibered in groupoids over $\mathcal{C}_\Lambda$. We say that $\mathcal{F}$ satisfies condition (RS) if for every diagram in $\mathcal{F}$

$$
\begin{array}{ccc}
x_2 & \longrightarrow & A_2 \\
\downarrow & & \downarrow \\
x_1 & \longrightarrow & A_1
\end{array}
$$

lying over

$$
\begin{array}{ccc}
A_1 & \longrightarrow & A \\
\downarrow & & \downarrow \\
x & \longrightarrow & x
\end{array}
$$

in $\mathcal{C}_\Lambda$ with $A_2 \to A$ surjective, there exists a fiber product $x_1 \times_x x_2$ in $\mathcal{F}$ such that the diagram

$$
\begin{array}{ccc}
x_1 \times_x x_2 & \longrightarrow & x_2 \\
\downarrow & & \downarrow \\
x_1 & \longrightarrow & x
\end{array}
$$

lies over

$$
\begin{array}{ccc}
A_1 \times_A A_2 & \longrightarrow & A_2 \\
\downarrow & & \downarrow \\
A_1 & \longrightarrow & A
\end{array}
$$


**Lemma 15.2.** Let $\mathcal{F}$ be a category cofibered in groupoids over $\mathcal{C}_\Lambda$ satisfying (RS). Given a commutative diagram in $\mathcal{F}$

$$
\begin{array}{ccc}
y & \longrightarrow & x_2 \\
\downarrow & & \downarrow \\
x_1 & \longrightarrow & x
\end{array}
$$

$$
\begin{array}{ccc}
A_1 \times_A A_2 & \longrightarrow & A_2 \\
\downarrow & & \downarrow \\
A_1 & \longrightarrow & A
\end{array}
$$

with $A_2 \to A$ surjective, then it is a fiber square.

**Proof.** Since $\mathcal{F}$ satisfies (RS), there exists a fiber product diagram

$$
\begin{array}{ccc}
x_1 \times_x x_2 & \longrightarrow & x_2 \\
\downarrow & & \downarrow \\
x_1 & \longrightarrow & x
\end{array}
$$

lying over

$$
\begin{array}{ccc}
A_1 \times_A A_2 & \longrightarrow & A_2 \\
\downarrow & & \downarrow \\
A_1 & \longrightarrow & A
\end{array}
$$

The induced map $y \to x_1 \times_x x_2$ lies over $\text{id} : A_1 \times_A A_1 \to A_1 \times_A A_1$, hence it is an isomorphism.

**Lemma 15.3.** Let $\mathcal{F}$ be a category cofibered in groupoids over $\mathcal{C}_\Lambda$. Then $\mathcal{F}$ satisfies (RS) if the condition in Definition 15.1 is assumed to hold only when $A_2 \to A$ is a small extension.

**Proof.** Apply Lemma 3.3. The proof is similar to that of Lemma 8.2.

**Lemma 15.4.** Let $\mathcal{F}$ be a category cofibered in groupoids over $\mathcal{C}_\Lambda$. The following are equivalent

1. $\mathcal{F}$ satisfies (RS),
2. the functor $\mathcal{F}(A_1 \times_A A_2) \to \mathcal{F}(A_1) \times_{\mathcal{F}(A)} \mathcal{F}(A_2)$ see (9.1.1) is an equivalence of categories whenever $A_2 \to A$ is surjective, and
3. same as in (2) whenever $A_2 \to A$ is a small extension.
Let $F$ be a category cofibered in groupoids over $C \Lambda$. The condition (RS) for $F$ implies both (S1) and (S2) for $F$.

**Proof.** Using the reformulation of Lemma 15.4 and the explanation of (S1) following Definition 9.1 it is immediate that (RS) implies (S1). This proves the first part of (S2). The second part of (S2) follows because Lemma 15.2 tells us that $y = x_1 \times_{d, x_0, e} x_2 = y'$ if $y, y'$ are as in the second part of the definition of (S2) in Definition 9.1. (In fact the morphism $y \to y'$ is compatible with both $a, a'$ and $c, c'$.)

The following lemma is the analogue of Lemma 15.5. Recall that if $F$ is a category cofibered in groupoids over $C \Lambda$ and $x$ is an object of $F$ lying over $A$, then we denote $\text{Aut}_A(x) = \text{Mor}_A(x, x) = \text{Mor}_F(A)(x, x)$. If $x' \to x$ is a morphism of $F$ lying over $A' \to A$ then there is a well defined map of groups $\text{Aut}_A(x') \to \text{Aut}_A(x)$.

**Remark 15.5.** When $F$ is cofibered in sets, condition (RS) is exactly condition (H4) from Schlessinger’s paper [Sch68, Theorem 2.11]. Namely, for a functor $F : C \Lambda \to \text{Sets}$, condition (RS) states: If $A_1 \to A$ and $A_2 \to A$ are maps in $C \Lambda$ with $A_2 \to A$ surjective, then the induced map $F(A_1 \times_A A_2) \to F(A_1) \times_{F(A)} F(A_2)$ is bijective.

**Lemma 15.6.** Let $F$ be a category cofibered in groupoids over $C \Lambda$. The condition (RS) for $F$ implies both (S1) and (S2) for $F$.

**Proof.** Assume (1). By Lemma 15.2 we see that every object of $F(A_1 \times_A A_2)$ is of the form $x_1 \times x_2$. Moreover

$$\text{Mor}_{A_1 \times_A A_2}(x_1 \times x_2, y_1 \times y_2) = \text{Mor}_{A_1}(x_1, y_1) \times \text{Mor}_{A_2}(x_2, y_2).$$

Hence we see that $F(A_1 \times_A A_2)$ is a 2-fibre product of $F(A_1)$ with $F(A_2)$ over $F(A)$ by Categories, Remark 30.5. In other words, we see that (2) holds.

The implication (2) $\Rightarrow$ (3) is immediate.

Assume (3). Let $q_1 : A_1 \to A$ and $q_2 : A_2 \to A$ be given with $q_2$ a small extension. We will use the description of the 2-fibre product $F(A_1) \times_{F(A)} F(A_2)$ from Categories, Remark 30.5. Hence let $y \in F(A_1 \times_A A_2)$ correspond to $(x_1, x_2, x, a_1 : x_1 \to x, a_2 : x_2 \to x)$. Let $z$ be an object of $F$ lying over $C$. Then

$$\text{Mor}_F(z, y) = \{(f, \alpha) \mid f : C \to A_1 \times A_2, \alpha : f_* z \to y\} = \{(f_1, f_2, \alpha_1, \alpha_2) \mid f_i : C \to A_i, \alpha_i : f_i_* z \to x_i, q_1 \circ f_1 = q_2 \circ f_2, q_1_* \alpha_1 = q_2_* \alpha_2\} = \text{Mor}_F(z, x_1) \times \text{Mor}_F(z, x_2) \times \text{Mor}_F(z, y)$$

whence $y$ is a fibre product of $x_1$ and $x_2$ over $x$. Thus we see that $F$ satisfies (RS) in case $A_2 \to A$ is a small extension. Hence (RS) holds by Lemma 15.3.

**Lemma 15.7.** Let $F$ be a category cofibered in groupoids over $C \Lambda$ satisfying (RS). The following conditions are equivalent:

1. $F$ satisfies (RS).
2. Let $f_1 : A_1 \to A$ and $f_2 : A_2 \to A$ be ring maps in $C \Lambda$ with $f_2$ surjective. The induced map of sets of isomorphism classes

$$\overline{F}(A_1) \times_{\overline{F}(A)} \overline{F}(A_2) \to \overline{F}(A_1) \times_{\overline{F}(A)} \overline{F}(A_2)$$

is injective.
3. For every morphism $x' \to x$ in $F$ lying over a surjective ring map $A' \to A$, the map $\text{Aut}_{A'}(x') \to \text{Aut}_A(x)$ is surjective.
Definition 15.8. A deformation category is a predeformation category \( \mathcal{F} \) satisfying (RS). A morphism of deformation categories is a morphism of categories over \( \mathcal{C}_A \).

Proof. We prove that (1) is equivalent to (2) and (2) is equivalent to (3). The equivalence of (3) and (4) follows from Lemma 3.3.

Let \( f_1 : A_1 \to A \) and \( f_2 : A_2 \to A \) be ring maps in \( \mathcal{C}_A \) with \( f_2 \) surjective. By Remark 15.5, we see \( \mathcal{F} \) satisfies (RS) if and only if the map
\[
\mathcal{F}(A_1 \times A A_2) \to \mathcal{F}(A_1) \times_{\mathcal{F}(A)} \mathcal{F}(A_2)
\]
is bijective for any such \( f_1, f_2 \). This map is at least surjective since that is the condition of (S1) and \( \mathcal{F} \) satisfies (S1) by Lemmas 15.6 and 9.5. Moreover, this map factors as
\[
\mathcal{F}(A_1 \times A A_2) \to \mathcal{F}(A_1) \times_{\mathcal{F}(A)} \mathcal{F}(A_2) \to \mathcal{F}(A_1) \times_{\mathcal{F}(A)} \mathcal{F}(A_2),
\]
where the first map is a bijection since
\[
\mathcal{F}(A_1 \times A A_2) \to \mathcal{F}(A_1) \times_{\mathcal{F}(A)} \mathcal{F}(A_2)
\]
is an equivalence by (RS) for \( \mathcal{F} \). Hence (1) is equivalent to (2).

Assume (2) holds. Let \( x' \to x \) be a morphism in \( \mathcal{F} \) lying over a surjective ring map \( f : A' \to A \). Let \( a \in \text{Aut}_A(x) \). The objects
\[
(x', x', a : x \to x), (x', x', \text{id} : x \to x)
\]
of \( \mathcal{F}(A') \times_{\mathcal{F}(A)} \mathcal{F}(A') \) have the same image in \( \mathcal{F}(A') \times_{\mathcal{F}(A)} \mathcal{F}(A') \). By (2) there exists maps \( b_1, b_2 : x' \to x' \) such that
\[
\begin{array}{ccc}
x & \xrightarrow{a} & x \\
\downarrow{f_1b_1} & & \downarrow{f_1b_2} \\
x & \xrightarrow{\text{id}} & x
\end{array}
\]
commutes. Hence \( b_2^{-1} \circ b_1 \in \text{Aut}_{A'}(x') \) has image \( a \in \text{Aut}_A(x) \). Hence (3) holds.

Assume (3) holds. Suppose
\[
(x_1, x_2, a : (f_1)_*x_1 \to (f_2)_*x_2), (x'_1, x'_2, a' : (f_1)_*x'_1 \to (f_2)_*x'_2)
\]
are objects of \( \mathcal{F}(A_1) \times_{\mathcal{F}(A)} \mathcal{F}(A_2) \) with the same image in \( \mathcal{F}(A_1) \times_{\mathcal{F}(A)} \mathcal{F}(A_2) \).

Then there are morphisms \( b_1 : x_1 \to x'_1 \) in \( \mathcal{F}(A_1) \) and \( b_2 : x_2 \to x'_2 \) in \( \mathcal{F}(A_2) \). By (3) we can modify \( b_2 \) by an automorphism of \( x_2 \) over \( A_2 \) so that the diagram
\[
\begin{array}{ccc}
(f_1)_*x_1 & \xrightarrow{a} & (f_2)_*x_2 \\
(f_1)_*b_1 & & (f_2)_*b_2 \\
(f_1)_*x'_1 & \xrightarrow{a'} & (f_2)_*x'_2
\end{array}
\]
commutes. This proves \((x_1, x_2, a) \cong (x'_1, x'_2, a') \) in \( \mathcal{F}(A_1) \times_{\mathcal{F}(A)} \mathcal{F}(A_2) \). Hence (2) holds.

Finally we define the notion of a deformation category.
Remark 15.9. We say that a functor $F : \mathcal{C} \to \text{Sets}$ is a deformation functor if the associated cofibered set is a deformation category, i.e. if $F(k)$ is a one element set and $F$ satisfies (RS). If $\mathcal{F}$ is a deformation category, then $\mathcal{F}$ is a predeformation functor but not necessarily a deformation functor, as Lemma 15.7 shows.

Example 15.10. A prorepresentable functor $F$ is a deformation functor. Namely, suppose $R \in \text{Ob}(\mathcal{C})$ and $F(A) = \text{Mor}_{\mathcal{C}}(R, A)$. There is a unique morphism $R \to k$, so $F(k)$ is a one element set. Since $\text{Hom}_{\mathcal{C}}(R, A_1 \times_A A_2) = \text{Hom}_{\mathcal{C}}(R, A_1) \times_{\text{Hom}_{\mathcal{C}}(R, A)} \text{Hom}_{\mathcal{C}}(R, A_2)$ the same is true for maps in $\mathcal{C}$ and we see that $F$ has (RS).

The following is one of our typical remarks on passing from a category cofibered in groupoids to the predeformation category at a point over $k$: it says that this process preserves (RS).

Lemma 15.11. Let $F$ be a category cofibered in groupoids over $\mathcal{C}$. Let $x_0 \in \text{Ob}(F(k))$. Let $F_{x_0}$ be the category cofibered in groupoids over $\mathcal{C}$ constructed in Remark 6.4. If $F$ satisfies (RS), then so does $F_{x_0}$. In particular, $F_{x_0}$ is a deformation category.

Proof. Any diagram as in Definition 15.1 in $F_{x_0}$ gives rise to a diagram in $F$ and the output of (RS) for this diagram in $F$ can be viewed as an output for $F_{x_0}$ as well.

The following lemma is the analogue of the fact that 2-fibre products of algebraic stacks are algebraic stacks.

Lemma 15.12. Let

$$
\begin{array}{ccc}
\mathcal{H} \times_{\mathcal{F}} \mathcal{G} & \longrightarrow & \mathcal{G} \\
\downarrow & & \downarrow \scriptstyle{g} \\
\mathcal{H} & \underset{f}{\longrightarrow} & \mathcal{F}
\end{array}
$$

be 2-fibre product of categories cofibered in groupoids over $\mathcal{C}$. If $\mathcal{F}, \mathcal{G}, \mathcal{H}$ all satisfy (RS), then $\mathcal{H} \times_{\mathcal{F}} \mathcal{G}$ satisfies (RS).

Proof. If $A$ is an object of $\mathcal{C}$, then an object of the fiber category of $\mathcal{H} \times_{\mathcal{F}} \mathcal{G}$ over $A$ is a triple $(u, v, a)$ where $u \in \mathcal{H}(A)$, $v \in \mathcal{G}(A)$, and $a : f(u) \to g(v)$ is a morphism in $\mathcal{F}(A)$. Consider a diagram in $\mathcal{H} \times_{\mathcal{F}} \mathcal{G}$

$$
\begin{array}{ccc}
(u_2, v_2, a_2) & \longrightarrow & A_2 \\
\downarrow & & \downarrow \\
(u_1, v_1, a_1) & \longrightarrow & (u, v, a) \\
\downarrow & & \downarrow \\
(u_1, v_1) & \longrightarrow & A_1 \\
\downarrow & & \downarrow \\
(u) & \longrightarrow & A
\end{array}
$$

in $\mathcal{C}$ with $A_2 \to A$ surjective. Since $\mathcal{H}$ and $\mathcal{G}$ satisfy (RS), there are fiber products $u_1 \times_u u_2$ and $v_1 \times_v v_2$ lying over $A_1 \times_A A_2$. Since $\mathcal{F}$ satisfies (RS), Lemma 15.2 shows

$$
\begin{array}{ccc}
f(u_1 \times_u u_2) & \longrightarrow & f(u_2) \\
\downarrow & & \downarrow \\
f(u_1) & \longrightarrow & f(u)
\end{array}
\quad \text{and} \quad
\begin{array}{ccc}
g(v_1 \times_v v_2) & \longrightarrow & g(v_2) \\
\downarrow & & \downarrow \\
g(v_1) & \longrightarrow & g(v)
\end{array}
$$
are both fiber squares in $\mathcal{F}$. Thus we can view $a_1 \times_a a_2$ as a morphism from $f(u_1 \times_u u_2)$ to $g(v_1 \times_v v_2)$ over $A_1 \times_A A_2$. It follows that

\[
\begin{array}{ccc}
(u_1 \times_u u_2, v_1 \times_v v_2, a_1 \times_a a_2) & \longrightarrow & (u_2, v_2, a_2) \\
\downarrow & & \downarrow \\
(u_1, v_1, a_1) & \longrightarrow & (u, v, a)
\end{array}
\]

is a fiber square in $\mathcal{H} \times_{\mathcal{F}} \mathcal{G}$ as desired. \qed

16. Lifts of objects

06JD The content of this section is that the tangent space has a principal homogeneous action on the set of lifts along a small surjection in the case of a deformation category.

06JE **Definition 16.1.** Let $\mathcal{F}$ be a category cofibered in groupoids over $\mathcal{C}_A$. Let $f : A' \to A$ be a map in $\mathcal{C}_A$. Let $x \in \mathcal{F}(A)$. The category Lift$(x, f)$ of lifts of $x$ along $f$ is the category with the following objects and morphisms.

1. Objects: A lift of $x$ along $f$ is a morphism $x' \to x$ lying over $f$.
2. Morphisms: A morphism of lifts from $a_1 : x_1' \to x_2'$ to $a_2 : x_2' \to x$ is a morphism $b : x_1' \to x_2'$ in $\mathcal{F}(A')$ such that $a_2 = a_1 \circ b$.

The set Lift$(x, f)$ of lifts of $x$ along $f$ is the set of isomorphism classes of Lift$(x, f)$.

06JF **Remark 16.2.** When the map $f : A' \to A$ is clear from the context, we may write Lift$(x, A')$ and Lift$(x, f)$ in place of Lift$(x, f)$ and Lift$(x, f)$.

06JG **Remark 16.3.** Let $\mathcal{F}$ be a category cofibered in groupoids over $\mathcal{C}_A$. Let $x_0 \in \text{Ob}(\mathcal{F}(k))$. Let $V$ be a finite dimensional vector space. Then Lift$(x_0, k[V])$ is the set of isomorphism classes of $\mathcal{F}_{x_0}(k[V])$ where $\mathcal{F}_{x_0}$ is the predeformation category of objects in $\mathcal{F}$ lying over $x_0$, see Remark 6.4. Hence if $\mathcal{F}$ satisfies (S2), then so does $\mathcal{F}_{x_0}$ (see Lemma 9.6) and by Lemma 11.2 we see that

\[\text{Lift}(x_0, k[V]) = T\mathcal{F}_{x_0} \otimes_k V\]

as $k$-vector spaces.

06JH **Remark 16.4.** Let $\mathcal{F}$ be a category cofibered in groupoids over $\mathcal{C}_A$ satisfying (RS). Let

\[
\begin{array}{ccc}
A_1 \times_A A_2 & \longrightarrow & A_2 \\
\downarrow & & \downarrow \\
A_1 & \longrightarrow & A
\end{array}
\]

be a fibre square in $\mathcal{C}_A$ such that either $A_1 \to A$ or $A_2 \to A$ is surjective. Let $x \in \text{Ob}(\mathcal{F}(A))$. Given lifts $x_1 \to x$ and $x_2 \to x$ of $x$ to $A_1$ and $A_2$, we get by (RS) a lift $x_1 \times x_2 \to x$ of $x$ to $A_1 \times_A A_2$. Conversely, by Lemma 15.2 any lift of $x$ to $A_1 \times_A A_2$ is of this form. Hence a bijection

\[\text{Lift}(x, A_1) \times \text{Lift}(x, A_2) \longrightarrow \text{Lift}(x, A_1 \times_A A_2)\]

Similarly, if $x_1 \to x$ is a fixed lifting of $x$ to $A_1$, then there is a bijection

\[\text{Lift}(x_1, A_1 \times_A A_2) \longrightarrow \text{Lift}(x, A_2).\]
Now let

\[
\begin{array}{ccc}
A'_1 \times_A A_2 & \longrightarrow & A_1 \times_A A_2 \\
\downarrow & & \downarrow \\
A'_1 & \longrightarrow & A_1
\end{array}
\]

be a composition of fibre squares in \(C_A\) with both \(A'_1 \to A_1\) and \(A_1 \to A\) surjective. Let \(x_1 \to x\) be a morphism lying over \(A_1 \to A\). Then by the above we have bijections

\[
\text{Lift}(x_1, A'_1 \times_A A_2) = \text{Lift}(x_1, A'_1) \times \text{Lift}(x_1, A_1 \times_A A_2) \\
= \text{Lift}(x_1, A'_1) \times \text{Lift}(x, A_2).
\]

**Lemma 16.5.** Let \(F\) be a deformation category. Let \(A' \to A\) be a surjective ring map in \(C_A\) whose kernel \(I\) is annihilated by \(m_A\). Let \(x \in \text{Ob}(F(A))\). If \(\text{Lift}(x, A')\) is nonempty, then there is a free and transitive action of \(TF \otimes_k I\) on \(\text{Lift}(x, A')\).

**Proof.** Consider the ring map \(g : A' \times_A A' \to k[I]\) defined by the rule \(g(a_1, a_2) = \pi_1 \oplus a_2 - a_1\) (compare with Lemma 9.8). There is an isomorphism

\[
A' \times_A A' \sim A' \times_k k[I]
\]

given by \((a_1, a_2) \mapsto (a_1, g(a_1, a_2))\). This isomorphism commutes with the projections to \(A'\) on the first factor, and hence with the projections of \(A' \times_A A'\) and \(A' \times_k k[I]\) to \(A\). Thus there is a bijection

**06TA** (16.5.1) \(\text{Lift}(x, A' \times_A A') \longrightarrow \text{Lift}(x, A' \times_k k[I])\)

By Remark 16.4 there is a bijection

**06TB** (16.5.2) \(\text{Lift}(x, A') \times \text{Lift}(x, A') \longrightarrow \text{Lift}(x, A' \times_A A')\)

There is a commutative diagram

\[
\begin{array}{ccc}
A' \times_k k[I] & \longrightarrow & A \times_k k[I] \\
\downarrow & & \downarrow \\
A' & \longrightarrow & A \\
\end{array}
\]

Thus if we choose a pushforward \(x \to x_0\) of \(x\) along \(A \to k\), we obtain by the end of Remark 16.4 a bijection

**06TC** (16.5.3) \(\text{Lift}(x, A' \times_k k[I]) \longrightarrow \text{Lift}(x, A') \times \text{Lift}(x_0, k[I])\)

Composing 16.5.2, 16.5.1, and 16.5.3 we get a bijection

\[
\Phi : \text{Lift}(x, A') \times \text{Lift}(x, A') \longrightarrow \text{Lift}(x, A') \times \text{Lift}(x_0, k[I]).
\]

This bijection commutes with the projections on the first factors. By Remark 16.3 we see that \(\text{Lift}(x_0, k[I]) = TF \otimes_k I\). If \(pr_2\) is the second projection of \(\text{Lift}(x, A') \times \text{Lift}(x, A')\), then we get a map

\[
a = pr_2 \circ \Phi^{-1} : \text{Lift}(x, A') \times (TF \otimes_k I) \longrightarrow \text{Lift}(x, A').
\]

Unwinding all the above we see that \(a(x' \to x, \theta)\) is the unique lift \(x'' \to x\) such that \(g_* (x', x'') = \theta\) in \(\text{Lift}(x_0, k[I]) = TF \otimes_k I\). To see this is an action of \(TF \otimes_k I\) on \(\text{Lift}(x, A')\) we have to show the following: if \(x', x'', x'''\) are lifts of \(x\) and \(g_*(x', x'') = \theta\), then \(g_*(x', x''') = \theta\).
\[ \theta, g_*(x'', x'''') = \theta', \text{ then } g_*(x', x''') = \theta + \theta'. \] This follows from the commutative diagram
\[
\begin{array}{ccc}
A' \times_A A' \times_A A' & \longrightarrow & k[I] \times_k k[I] = k[I] \\
\downarrow & & \downarrow + \\
& \longrightarrow & k[I]
\end{array}
\]

The action is free and transitive because \( \Phi \) is bijective. \( \square \)

**Remark 16.6.** The action of Lemma 16.5 is functorial. Let \( \varphi : \mathcal{F} \to \mathcal{G} \) be a morphism of deformation categories. Let \( A \to A \) be a surjective ring map whose kernel \( I \) is annihilated by \( \mathfrak{m}_A \). Let \( x \in \text{Ob}(\mathcal{F}(A)) \). In this situation \( \varphi \) induces the vertical arrows in the following commutative diagram
\[
\begin{array}{ccc}
\text{Lift}(x, A') \times (T\mathcal{F} \otimes_k I) & \longrightarrow & \text{Lift}(x, A') \\
(\varphi, d\varphi \otimes \text{id}_I) \downarrow & & \downarrow \varphi \\
\text{Lift}(\varphi(x), A') \times (T\mathcal{G} \otimes_k I) & \longrightarrow & \text{Lift}(\varphi(x), A')
\end{array}
\]

The commutativity follows as each of the maps \([16.5.2], [16.5.3]\), and \([16.5.3]\) of the proof of Lemma 16.5 gives rise to a similar commutative diagram.

17. Schlessinger’s theorem on prorepresentable functors

**Lemma 17.1.** Let \( F, G : \mathcal{C}_A \to \text{Sets} \) be deformation functors. Let \( \varphi : F \to G \) be a smooth morphism which induces an isomorphism \( d\varphi : T\mathcal{F} \to T\mathcal{G} \) of tangent spaces. Then \( \varphi \) is an isomorphism.

**Proof.** We prove \( F(A) \to G(A) \) is a bijection for all \( A \in \text{Ob}(\mathcal{C}_A) \) by induction on \( \text{length}_A(A) \). For \( A = k \) the statement follows from the assumption that \( F \) and \( G \) are deformation functors. Suppose that the statement holds for rings of length less than \( n \) and let \( A' \) be a ring of length \( n \). Choose a small extension \( f : A' \to A \). We have a commutative diagram
\[
\begin{array}{ccc}
F(A') & \longrightarrow & G(A') \\
F(f) \downarrow & & \downarrow G(f) \\
F(A) \longrightarrow & \sim & G(A)
\end{array}
\]

where the map \( F(A) \to G(A) \) is a bijection. By smoothness of \( F \to G \), \( F(A') \to G(A') \) is surjective (Lemma 8.8). Thus we can check bijectivity by checking it on fibers \( F(f)^{-1}(x) \to G(f)^{-1}(\varphi(x)) \) for \( x \in F(A) \) such that \( F(f)^{-1}(x) \) is nonempty. These fibers are precisely \( \text{Lift}(x, A') \) and \( \text{Lift}(\varphi(x), A') \) and by assumption we have an isomorphism \( d\varphi \otimes \text{id} : T\mathcal{F} \otimes_k \text{Ker}(f) \to T\mathcal{G} \otimes_k \text{Ker}(f) \). Thus, by Lemma 16.5 and Remark 16.6 for \( x \in F(A) \) such that \( F(f)^{-1}(x) \) is nonempty the map \( F(f)^{-1}(x) \to G(f)^{-1}(\varphi(x)) \) is a map of sets commuting with free transitive actions by \( T\mathcal{F} \otimes_k \text{Ker}(f) \). Hence it is bijective. \( \square \)

Note that in case \( k' \subset k \) is separable condition (c) in the theorem below is empty.
Theorem 17.2. Let $F : C_A \to \text{Sets}$ be a functor. Then $F$ is prorepresentable if and only if (a) $F$ is a deformation functor, (b) dim$_k TF$ is finite, and (c) $\gamma : \text{Der}_A(k,k) \to TF$ is injective.

Proof. Assume $F$ is prorepresentable by $R \in \hat{C}_A$. We see $F$ is a deformation functor by Example 15.10. We see dim$_k TF$ is finite by Example 10.11. Finally, Der$_A(k,k) \to TF$ is identified with Der$_A(k,k) \to \text{Der}_A(R,k)$ by Example 10.14, which is injective because $R \to k$ is surjective.

Conversely, assume (a), (b), and (c) hold. By Lemma 15.6 we see that (S1) and (S2) hold. Hence by Theorem 14.5 there exists a minimal versal formal object $x$ of $F$ such that (14.0.2) holds. Say $x$ lies over $R$. The map

$$d\xi : \text{Der}_A(R,k) \to TF$$

is bijective on Der$_A(k,k)$-orbits. Since the action of Der$_A(k,k)$ on the left hand side is free by (c) and Lemma 11.6 we see that the map is bijective. Thus we see that $\xi$ is an isomorphism by Lemma 17.1.

18. Infinitesimal automorphisms

Let $F$ be a category cofibered in groupoids over $C_A$. Given a morphism $x' \to x$ in $F$ lying over $A' \to A$, there is an induced homomorphism

$$\text{Aut}_{A'}(x') \to \text{Aut}_A(x).$$

Lemma 15.7 says that the cokernel of this homomorphism determines whether condition (RS) on $F$ passes to $F$. In this section we study the kernel of this homomorphism. We will see that it also gives a measure of how far $F$ is from $\hat{F}$.

Definition 18.1. Let $F$ be a category cofibered in groupoids over $C_A$. Let $x' \to x$ be a morphism in $F$ lying over $A' \to A$. The group of infinitesimal automorphisms of $x'$ over $x$ is the kernel of $\text{Aut}_{A'}(x') \to \text{Aut}_A(x)$. Notation Inf$_{x'}(x) = \text{Ker}(\text{Aut}_{A'}(x') \to \text{Aut}_A(x))$.

Definition 18.2. Let $F$ be a category cofibered in groupoids over $C_A$. Let $x_0 \in \text{Ob}(F(k))$. Assume a choice of pushforward $x_0 \to x_0'$ of $x_0$ along the map $k \to k[e], a \mapsto a$ has been made. Then there is a unique map $x_0' \to x_0$ such that $x_0 \to x_0' \to x_0$ is the identity on $x_0$. The group of infinitesimal automorphisms of $x_0$ is Inf$_{x_0}(F) := \text{Inf}(x_0'/x_0)$.

Remark 18.3. Up to isomorphism, Inf$_{x_0}(F)$ does not depend on the choice of pushforward $x_0 \to x_0'$. Moreover, if $y_0 \in F(k)$ and $x_0 \cong y_0$ in $F(k)$, then Inf$_{x_0}(F) \cong$ Inf$_{y_0}(F)$.

Remark 18.4. When $F$ is a predeformation category, $\text{Aut}_k(x_0)$ is trivial and hence Inf$_{x_0}(F) = \text{Aut}_{k[e]}(x_0')$.

We will see that Inf$_{x_0}(F)$ has a natural $k$-vector space structure when $F$ satisfies (RS). At the same time, we will see that if $F$ satisfies (RS), then the infinitesimal automorphisms Inf$_{x'/x}$ of a morphism $x' \to x$ lying over a small extension are governed by Inf$_{x_0}(F)$, where $x_0$ is a pushforward of $x$ to $F(k)$. In order to do this, we introduce the automorphism functor for any object $x \in \text{Ob}(F)$ as follows.
Definition 18.5. Let \(p : \mathcal{F} \to \mathcal{C}\) be a category cofibered in groupoids over an arbitrary base category \(\mathcal{C}\). Assume a choice of pushforwards has been made. Let \(x \in \text{Ob}(\mathcal{F})\) and let \(U = p(x)\). Let \(\mathcal{U}/\mathcal{C}\) denote the category of objects under \(U\). The automorphism functor of \(x\) is the functor \(\text{Aut}(x) : \mathcal{U}/\mathcal{C} \to \text{Sets}\) sending an object \(f : U \to V\) to \(\text{Aut}_V(f, x)\) and sending a morphism

\[
\begin{array}{ccc}
V' & \xrightarrow{f'} & V \\
& V \xleftarrow{f} & \end{array}
\]

to the homomorphism \(\text{Aut}_{V'}(f'_*x) \to \text{Aut}_V(f_*x)\) coming from the unique morphism \(f'_*x \to f_*x\) lying over \(V' \to V\) and compatible with \(x \to f'_*x\) and \(x \to f_*x\).

We will be concerned with the automorphism functors of objects in a category cofibered in groupoids \(\mathcal{F}\) over \(\mathcal{C}_\Lambda\). If \(A \in \text{Ob}(\mathcal{C}_\Lambda)\), then the category \(A/\mathcal{C}_\Lambda\) is nothing but the category \(\mathcal{C}_A\), i.e. the category defined in Section 3 where we take \(\Lambda = A\) and \(k = A/\mathfrak{m}_A\). Hence the automorphism functor of an object \(x \in \text{Ob}(\mathcal{F}(A))\) is a functor \(\text{Aut}(x) : \mathcal{C}_A \to \text{Sets}\).

The following lemma could be deduced from Lemma 18.6 by thinking about the “inertia” of a category cofibered in groupoids, see for example Stacks, Section 7 and Categories, Section 33. However, it is easier to see it directly.

Lemma 18.6. Let \(\mathcal{F}\) be a category cofibered in groupoids over \(\mathcal{C}_\Lambda\) satisfying (RS). Let \(x \in \text{Ob}(\mathcal{F}(A))\). Then \(\text{Aut}(x) : \mathcal{C}_A \to \text{Sets}\) satisfies (RS).

Proof. It follows that \(\text{Aut}(x)\) satisfies (RS) from the fully faithfulness of the functor \(\mathcal{F}(A_1 \times_A A_2) \to \mathcal{F}(A_1) \times_{\mathcal{F}(A)} \mathcal{F}(A_2)\) in Lemma 15.4.

Lemma 18.7. Let \(\mathcal{F}\) be a category cofibered in groupoids over \(\mathcal{C}_\Lambda\) satisfying (RS). Let \(x \in \text{Ob}(\mathcal{F}(A))\). Let \(x_0\) be a pushforward of \(x\) to \(\mathcal{F}(k)\).

1. \(T_{id_{x_0}} \text{Aut}(x)\) has a natural \(k\)-vector space structure such that addition agrees with composition in \(T_{id_{x_0}} \text{Aut}(x)\). In particular, composition in \(T_{id_{x_0}} \text{Aut}(x)\) is commutative.

2. There is a canonical isomorphism \(T_{id_{x_0}} \text{Aut}(x) \to T_{id_{x_0}} \text{Aut}(x_0)\) of \(k\)-vector spaces.

Proof. We apply Remark 6.4 to the functor \(\text{Aut}(x) : \mathcal{C}_A \to \text{Sets}\) and the element \(id_{x_0} \in \text{Aut}(x)(k)\) to get a predeformation functor \(F = \text{Aut}(x)_{id_{x_0}}\). By Lemmas 18.6 and 15.11, \(F\) is a deformation functor. By definition \(T_{id_{x_0}} \text{Aut}(x) = TF = F(k[\epsilon])\), which has a natural \(k\)-vector space structure specified by Lemma 10.8.

Addition is defined as the composition \(F(k[\epsilon]) \times F(k[\epsilon]) \to F(k[\epsilon] \times_k k[\epsilon]) \to F(k[\epsilon])\) where the first map is the inverse of the bijection guaranteed by (RS) and the second is induced by the \(k\)-algebra map \(k[\epsilon] \times_k k[\epsilon] \to k[\epsilon]\) which maps \((0, \epsilon)\) and \((0, \epsilon)\) to \(\epsilon\).

If \(A \to B\) is a ring map in \(\mathcal{C}_A\), then \(F(A) \to F(B)\) is a homomorphism where \(F(A) = \text{Aut}(x)_{id_{x_0}}(A)\) and \(F(B) = \text{Aut}(x)_{id_{x_0}}(B)\) are groups under composition. We conclude that \(+ : F(k[\epsilon]) \times F(k[\epsilon]) \to F(k[\epsilon])\) is a homomorphism where \(F(k[\epsilon])\) is regarded as a group under composition. With \(id \in F(k[\epsilon])\) the unit element we see that \(+ (v, id) = +(id, v) = v\) for any \(v \in F(k[\epsilon])\) because \((id, v)\) is the pushforward.
of \( v \) along the ring map \( k[\epsilon] \to k[\epsilon] \times_k k[\epsilon] \) with \( \epsilon \mapsto (\epsilon, 0) \). In general, given a group \( G \) with multiplication \( \circ \) and \( + : G \times G \to G \) is a homomorphism such that \( + (g, 1) = + (1, g) = g \), where 1 is the identity of \( G \), then \( + = \circ \). This shows addition in the \( k \)-vector space structure on \( F(k[\epsilon]) \) agrees with composition.

Finally, (2) is a matter of unwinding the definitions. Namely \( T_{\text{id}_x} \text{Aut}(x) \) is the set of automorphisms \( \alpha \) of the pushforward of \( x \) along \( A \to k \to k[\epsilon] \) which are trivial modulo \( \epsilon \). On the other hand \( T_{\text{id}_x} \text{Aut}(x_0) \) is the set of automorphisms of the pushforward of \( x_0 \) along \( k \to k[\epsilon] \) which are trivial modulo \( \epsilon \). Since \( x_0 \) is the pushforward of \( x \) along \( A \to k \) the result is clear. \( \square \)

**Remark 18.8.** We point out some basic relationships between infinitesimal automorphism groups, liftings, and tangent spaces to automorphism functors. Let \( \mathcal{F} \) be a category cofibered in groupoids over \( \mathcal{C}_\Lambda \). Let \( x' \to x \) be a morphism lying over a ring map \( A' \to A \). Let \( x_0 \) be a pushforward of \( x \) to \( \mathcal{F}(k) \). Then from the definitions we have an equality

\[
\text{Inf}(x'/x) = \text{Lift}(\text{id}_x, A')
\]

where the liftings are of \( \text{id}_x \) as an object of \( \text{Aut}(x') \). If \( x_0 \in \text{Ob}(\mathcal{F}(k)) \) and \( x'_0 \) is the pushforward to \( \mathcal{F}(k[\epsilon]) \), then applying this to \( x'_0 \to x_0 \) we get

\[
\text{Inf}_{x_0}(\mathcal{F}) = \text{Lift}(\text{id}_{x_0}, k[\epsilon]) = T_{\text{id}_x} \text{Aut}(x_0),
\]

the last equality following directly from the definitions.

**Lemma 18.9.** Let \( \mathcal{F} \) be a category cofibered in groupoids over \( \mathcal{C}_\Lambda \) satisfying (RS). Let \( x_0 \in \text{Ob}(\mathcal{F}(k)) \). Then \( \text{Inf}_{x_0}(\mathcal{F}) \) is equal as a set to \( T_{\text{id}_x} \text{Aut}(x_0) \), and so has a natural \( k \)-vector space structure such that addition agrees with composition of automorphisms.

**Proof.** The equality of sets is as in the end of Remark 18.8 and the statement about the vector space structure follows from Lemma 18.7. \( \square \)

**Lemma 18.10.** Let \( \varphi : \mathcal{F} \to \mathcal{G} \) be a morphism of categories cofibered in groupoids over \( \mathcal{C}_\Lambda \) satisfying (RS). Let \( x_0 \in \text{Ob}(\mathcal{F}(k)) \). Then \( \varphi \) induces a \( k \)-linear map \( \text{Inf}_{x_0}(\mathcal{F}) \to \text{Inf}_{\varphi(x_0)}(\mathcal{G}) \).

**Proof.** It is clear that \( \varphi \) induces a morphism from \( \text{Aut}(x_0) \to \text{Aut}(\varphi(x_0)) \) which maps the identity to the identity. Hence this follows from the result for tangent spaces, see Lemma 11.4. \( \square \)

**Lemma 18.11.** Let \( \mathcal{F} \) be a category cofibered in groupoids over \( \mathcal{C}_\Lambda \) satisfying (RS). Let \( x' \to x \) be a morphism lying over a surjective ring map \( A' \to A \) with kernel \( I \) annihilated by \( \mathfrak{m}_{A'} \). Let \( x_0 \) be a pushforward of \( x \) to \( \mathcal{F}(k) \). Then \( \text{Inf}(x'/x) \) has a free and transitive action by \( T_{\text{id}_x} \text{Aut}(x') \otimes_k I = \text{Inf}_{x_0}(\mathcal{F}) \otimes_k I \).

**Proof.** This is just the analogue of Lemma 16.5 in the setting of automorphism sheaves. To be precise, we apply Remark 6.4 to the functor \( \text{Aut}(x') : \mathcal{C}_{A'} \to \text{Sets} \) and the element \( \text{id}_{x_0} \in \text{Aut}(x(k)) \) to get a predeformation functor \( F = \text{Aut}(x')_{\text{id}_{x_0}} \). By Lemmas 18.6 and 15.11 \( F \) is a deformation functor. Hence Lemma 16.5 gives a free and transitive action of \( TF \otimes_k I \) on \( \text{Lift}(\text{id}_x, A') \), because as \( \text{Lift}(\text{id}_x, A') \) is a group it is always nonempty. Note that we have equalities of vector spaces

\[
TF = T_{\text{id}_{x_0}} \text{Aut}(x') \otimes_k I = \text{Inf}_{x_0}(\mathcal{F}) \otimes_k I
\]
by Lemma \[18.7\]. The equality $\text{Inf}(x'/x) = \text{Lift}(id_x, A')$ of Remark \[18.8\] finishes the proof. \[\square\]

\textbf{Lemma 18.12.} Let $\mathcal{F}$ be a category cofibered in groupoids over $\mathcal{C}_\Lambda$ satisfying $(RS)$. Let $x' \to x$ be a morphism in $\mathcal{F}$ lying over a surjective ring map. Let $x_0$ be a pushforward of $x$ to $\mathcal{F}(k)$. If $\text{Inf}_{x_0}(\mathcal{F}) = 0$ then $\text{Inf}(x'/x) = 0$.

\textbf{Proof.} Follows from Lemmas \[3.3\] and \[18.11\]. \[\square\]

\textbf{Lemma 18.13.} Let $\mathcal{F}$ be a category cofibered in groupoids over $\mathcal{C}_\Lambda$ satisfying $(RS)$. Let $x_0 \in \text{Ob}(\mathcal{F}(k))$. Then $\text{Inf}_{x_0}(\mathcal{F}) = 0$ if and only if the natural morphism $\mathcal{F}_{x_0} \to \widetilde{\mathcal{F}}_{x_0}$ of categories cofibered in groupoids is an equivalence.

\textbf{Proof.} The morphism $\mathcal{F}_{x_0} \to \widetilde{\mathcal{F}}_{x_0}$ is an equivalence if and only if $\mathcal{F}_{x_0}$ is fibered in setoids, cf. Categories, Section \[38\] (a setoid is by definition a groupoid in which the only automorphism of any object is the identity). We prove that $\text{Inf}_{x_0}(\mathcal{F}) = 0$ if and only if this condition holds for $\mathcal{F}_{x_0}$. Obviously if $\mathcal{F}_{x_0}$ is fibered in setoids then $\text{Inf}_{x_0}(\mathcal{F}) = 0$. Conversely assume $\text{Inf}_{x_0}(\mathcal{F}) = 0$. Let $A$ be an object of $\mathcal{C}_\Lambda$. Then by Lemma \[18.12\] $\text{Inf}(x/x_0) = 0$ for any object $x \to x_0$ of $\mathcal{F}_{x_0}(A)$. Since by definition $\text{Inf}(x/x_0)$ equals the group of automorphisms of $x \to x_0$ in $\mathcal{F}_{x_0}(A)$, this proves $\mathcal{F}_{x_0}(A)$ is a setoid. \[\square\]

\textbf{Lemma 18.14.} Let $f : \mathcal{H} \to \mathcal{F}$ and $g : \mathcal{G} \to \mathcal{F}$ be 1-morphisms of deformation categories. Then

1. $\mathcal{W} = \mathcal{H} \times_\mathcal{F} \mathcal{G}$ is a deformation category.
2. let $w_0 \in \text{Ob}(\mathcal{W}(k))$ and let $x_0, y_0, z_0$ be the image of $w_0$ in $\mathcal{F}, \mathcal{H}, \mathcal{G}$. Then we have a 6-term exact sequence of vector spaces

$$0 \to \text{Inf}_{w_0}(\mathcal{W}) \to \text{Inf}_{y_0}(\mathcal{H}) \oplus \text{Inf}_{z_0}(\mathcal{G}) \to \text{Inf}_{x_0}(\mathcal{F}) \to \mathcal{T}\mathcal{W} \to \mathcal{T}\mathcal{H} \oplus \mathcal{T}\mathcal{G} \to \mathcal{T}\mathcal{F}$$

\textbf{Proof.} Part (1) follows from Lemma \[15.12\] and the fact that $\mathcal{W}(k)$ is the fibre product of two setoids with a unique isomorphism class over a setoid with a unique isomorphism class.

Part (2). We apply Lemmas \[11.4\] and \[18.10\] to get all the linear maps except for the “boundary map” $\delta : \text{Inf}_{x_0}(\mathcal{F}) \to \mathcal{T}\mathcal{W}$. We will insert suitable signs later.

Construction of $\delta$. Choose a pushforward $w_0 \to w'_0$ along $k \to k[e]$. Denote $x'_0, y'_0, z'_0$ the images of $w'_0$ in $\mathcal{F}, \mathcal{H}, \mathcal{G}$. In particular we obtain isomorphisms $b' : f(y'_0) \to x'_0$ and $c' : x'_0 \to g(z'_0)$. Denote $b : f(y_0) \to x_0$ and $c : x_0 \to g(z_0)$ the pushforwards along $k[e] \to k$. Observe that this means $w'_0 = (k[e], y'_0, z'_0, c' \circ b')$ and $w_0 = (k, y_0, z_0, c \circ b)$ in terms of the explicit form of the fibre product of categories, see Remarks \[5.2\] \[13\]. Given $\alpha : x'_0 \to x_0$ we set $\delta(\alpha) = (k[e], y'_0, z'_0, c' \circ \alpha \circ b')$ which is indeed an object of $\mathcal{W}$ over $k[e]$ and comes with a morphism $(k[e], y'_0, z'_0, c' \circ \alpha \circ b') \to w_0$ over $k[e] \to k$ as $\alpha$ pushes forward to the identity over $k$. More generally, for any $k$-vector space $V$ we can define a map

$$\text{Lift}(id_{x_0}, k[V]) \to \text{Lift}(w_0, k[V])$$

using exactly the same formulae. This construction is functorial in the vector space $V$ (details omitted). Hence $\delta$ is $k$-linear by an application of Lemma \[10.5\].

Having constructed these maps it is straightforward to show the sequence is exact. Injectivity of the first map comes from the fact that $f \times g : \mathcal{W} \to \mathcal{F} \times \mathcal{G}$ is faithful. If $(\beta, \gamma) \in \text{Inf}_{y_0}(\mathcal{H}) \oplus \text{Inf}_{z_0}(\mathcal{G})$ map to the same element of $\text{Inf}_{x_0}(\mathcal{F})$ then $(\beta, \gamma)$ defines
an automorphism of \( w'_0 = (k[x], y'_0, z'_0, c' \circ b') \) whence exactness at the second spot.

If \( \alpha \) as above gives the trivial deformation \( (k[e], y'_0, z'_0, c' \circ \alpha \circ b') \) of \( w_0 \), then the isomorphism \( w'_0 = (k[e], y'_0, z'_0, c' \circ \alpha \circ b') \to (k[e], y'_0, z'_0, c' \circ b') \) produces a pair \( (\beta, \gamma) \) which is a preimage of \( \alpha \). If \( w = (k[e], y, z, \phi) \) is a deformation of \( w_0 \) such that \( y'_0 \cong y \) and \( z \cong z'_0 \) then the map

\[
    f(y'_0) \to f(y) \overset{\phi}{\to} g(z) \to g(z'_0)
\]

is an \( \alpha \) which maps to \( w \) under \( \delta \). Finally, if \( y \) and \( z \) are deformations of \( y_0 \) and \( z_0 \) and there exists an isomorphism \( \phi : f(y) \to g(z) \) of deformations of \( f(y'_0) = x_0 = g(z_0) \) then we get a preimage \( w = (k[e], y, z, \phi) \) of \((x, y)\) in \( TW \). This finishes the proof. \( \square \)

19. Groupoids in functors on an arbitrary category

We begin with generalities on groupoids in functors on an arbitrary category. In the next section we will pass to the category \( \mathcal{C}_A \). For clarity we shall sometimes refer to an ordinary groupoid, i.e., a category whose morphisms are all isomorphisms, as a groupoid category.

**Definition 19.1.** Let \( \mathcal{C} \) be a category. The *category of groupoids in functors on \( \mathcal{C} \)* is the category with the following objects and morphisms.

1. **Objects:** A *groupoid in functors on \( \mathcal{C} \)* is a quintuple \((U, R, s, t, c)\) where \( U, R : \mathcal{C} \to \text{Sets} \) are functors and \( s, t : R \to U \) and \( c : R \times_{s, U, t} R \to R \) are morphisms with the following property: For any object \( T \) of \( \mathcal{C} \), the quintuple

\[
    (U(T), R(T), s, t, c)
\]

is a groupoid category.

2. **Morphisms:** A *morphism* \((U, R, s, t, c) \to (U', R', s', t', c')\) of groupoids in functors on \( \mathcal{C} \) consists of morphisms \( U \to U' \) and \( R \to R' \) with the following property: For any object \( T \) of \( \mathcal{C} \), the induced maps \( U(T) \to U'(T) \) and \( R(T) \to R'(T) \) define a functor between groupoid categories

\[
    (U(T), R(T), s, t, c) \to (U'(T), R'(T), s', t', c').
\]

**Remark 19.2.** A groupoid in functors on \( \mathcal{C} \) amounts to the data of a functor \( \mathcal{C} \to \text{Groupoids} \), and a morphism of groupoids in functors on \( \mathcal{C} \) amounts to a morphism of the corresponding functors \( \mathcal{C} \to \text{Groupoids} \). However, for our purposes it is more convenient to use the terminology of groupoids in functors. In fact, thinking of a groupoid in functors as the corresponding functor \( \mathcal{C} \to \text{Groupoids} \), or equivalently as the category cofibered in groupoids associated to that functor, can lead to confusion (Remark 21.2).

**Remark 19.3.** Let \((U, R, s, t, c)\) be a groupoid in functors on a category \( \mathcal{C} \). There are unique morphisms \( e : U \to R \) and \( i : R \to R \) such that for every object \( T \) of \( \mathcal{C} \), \( e : U(T) \to R(T) \) sends \( x \in U(T) \) to the identity morphism on \( x \) and \( i : R(T) \to R(T) \) sends \( a \in U(T) \) to the inverse of \( a \) in the groupoid category \((U(T), R(T), s, t, c)\). We will sometimes refer to \( s, t, c, e, \) and \( i \) as “source”, “target”, “composition”, “identity”, and “inverse”.

**Definition 19.4.** Let \( \mathcal{C} \) be a category. A groupoid in functors on \( \mathcal{C} \) is *representable* if it is isomorphic to one of the form \((U, R, s, t, c)\) where \( U \) and \( R \) are objects of \( \mathcal{C} \) and the pushout \( R \amalg_{s, U, t} R \) exists.
06K7 **Remark 19.5.** Hence a representable groupoid in functors on $C$ is given by objects $U$ and $R$ of $C$ and morphisms $s,t : U \to R$ and $c : R \to R \amalg_{s,t} R$ such that $(U,R,s,t,c)$ satisfies the condition of Definition 19.1. The reason for requiring the existence of the pushout $R \amalg_{s,t} R$ is so that the composition morphism $c$ is defined at the level of morphisms in $C$. This requirement will always be satisfied below when we consider representable groupoids in functors on $\hat{C}_\Lambda$, since by Lemma 4.3 the category $\hat{C}_\Lambda$ admits pushouts.

06K8 **Remark 19.6.** We will say “let $(U,R,s,t,c)$ be a groupoid in functors on $C$” to mean that we have a representable groupoid in functors. Thus this means that $U$ and $R$ are objects of $C$, there are morphisms $s,t : U \to R$, the pushout $R \amalg_{s,t} R$ exists, there is a morphism $c : R \to R \amalg_{s,t} R$, and $(U,R,s,t,c)$ is a groupoid in functors on $C$.

We introduce notation for restriction of groupoids in functors. This will be relevant below when we consider representable groupoids in functors on $\hat{C}_\Lambda$.

06K9 **Definition 19.7.** Let $(U,R,s,t,c)$ be a groupoid in functors on a category $C$. Let $C'$ be a subcategory of $C$. The restriction $(U,R,s,t,c)|_{C'}$ of $(U,R,s,t,c)$ to $C'$ is the groupoid in functors on $C'$ given by $(U|_{C'},R|_{C'},s|_{C'},t|_{C'},c|_{C'})$.

06KA **Remark 19.8.** In the situation of Definition 19.7 we often denote $s|_{C'},t|_{C'},c|_{C'}$ simply by $s,t,c$.

06KB **Definition 19.9.** Let $(U,R,s,t,c)$ be a groupoid in functors on a category $C$.

1. The assignment $T \mapsto (U(T),R(T),s,t,c)$ determines a functor $C \to \text{Groupoids}$. The quotient category cofibered in groupoids $[U/R] \to C$ is the category cofibered in groupoids over $C$ associated to this functor (as in Remarks 5.2 (9)).

2. The quotient morphism $U \to [U/R]$ is the morphism of categories cofibered in groupoids over $C$ defined by the rules

   a. $x \in U(T)$ maps to the object $(T,x) \in \text{Ob}([U/R](T))$, and

   b. $x \in U(T)$ and $f : T \to T'$ give rise to the morphism $(f,\text{id}_{U(f)(x)}) : (T,x) \to (T,U(f)(x))$ lying over $f : T \to T'$.

20. Groupoids in functors on the base category

06KC In this section we discuss groupoids in functors on $\hat{C}_\Lambda$. Our eventual goal is to show that prorepresentable groupoids in functors on $\hat{C}_\Lambda$ serve as “presentations” for well-behaved deformation categories in the same way that smooth groupoids in algebraic spaces serve as presentations for algebraic stacks, cf. Algebraic Stacks, Section 10.

06KD **Definition 20.1.** A groupoid in functors on $\hat{C}_\Lambda$ is prorepresentable if it is isomorphic to $(R_0,R_1,s,t,c)|_{\hat{C}_\Lambda}$ for some representable groupoid in functors $(R_0,R_1,s,t,c)$ on the category $\hat{C}_\Lambda$.

Let $(U,R,s,t,c)$ be a groupoid in functors on $\hat{C}_\Lambda$. Taking completions, we get a quintuple $(\hat{U},\hat{R},\hat{s},\hat{t},\hat{c})$. By Remark 7.10 completion as a functor on $\text{ColSet}(\hat{C}_\Lambda)$ is a right adjoint, so it commutes with limits. In particular, there is a canonical isomorphism

\[
R \times_{s,t} U \to \hat{R} \times_{\hat{s},\hat{t}} \hat{R},
\]
so \( \tilde{c} \) can be regarded as a functor \( \tilde{R} \times_{\tilde{s}, \tilde{t}} \tilde{R} \to \tilde{R} \). Then \( (\tilde{U}, \tilde{R}, \tilde{s}, \tilde{t}, \tilde{c}) \) is a groupoid in functors on \( \tilde{C}_\Lambda \), with identity and inverse morphisms being the completions of those of \((U, R, s, t, c)\).

06KE **Definition 20.2.** Let \((U, R, s, t, c)\) be a groupoid in functors on \( C_\Lambda \). The completion \((U, R, s, t, c)^\wedge\) of \((U, R, s, t, c)\) is the groupoid in functors \((\tilde{U}, \tilde{R}, \tilde{s}, \tilde{t}, \tilde{c})\) on \( \tilde{C}_\Lambda \) described above.

06KF **Remark 20.3.** Let \((U, R, s, t, c)\) be a groupoid in functors on \( C_\Lambda \). Then there is a canonical isomorphism \((U, R, s, t, c)^\wedge|_{C_\Lambda} \cong (U, R, s, t, c)\), see Remark 7.7. On the other hand, let \((U, R, s, t, c)\) be a groupoid in functors on \( \hat{C}_\Lambda \) such that \( U, R : \hat{C}_\Lambda \to Sets \) both commute with limits, e.g. if \( U, R \) are representable. Then there is a canonical isomorphism \(((U, R, s, t, c)|_{\Lambda})^\wedge \cong (U, R, s, t, c)\). This follows from Remark 7.11.

06KG **Lemma 20.4.** Let \((U, R, s, t, c)\) be a groupoid in functors on \( C_\Lambda \).

1. \((U, R, s, t, c)\) is prorepresentable if and only if its completion is representable as a groupoid in functors on \( \tilde{C}_\Lambda \).

2. \((U, R, s, t, c)\) is prorepresentable if and only if \( U \) and \( R \) are prorepresentable.

**Proof.** Part (1) follows from Remark 20.3. For (2), the “only if” direction is clear from the definition of a prorepresentable groupoid in functors. Conversely, assume \( U \) and \( R \) are prorepresentable, say \( U \cong R_0|_{\Lambda} \) and \( R \cong R_1|_{\Lambda} \) for objects \( R_0 \) and \( R_1 \) of \( \tilde{C}_\Lambda \). Since \( R_0 \cong R_0|_{\Lambda} \) and \( R_1 \cong R_1|_{\Lambda} \) by Remark 7.11 we see that the completion \((U, R, s, t, c)^\wedge\) is a groupoid in functors of the form \((R_0, R_1, \hat{s}, \hat{t}, \hat{c})\). By Lemma 4.3 the pushout \( R_1 \times_{\hat{s}, \hat{t}} R_1 \) exists. Hence \((R_0, R_1, \hat{s}, \hat{t}, \hat{c})\) is a representable groupoid in functors on \( \tilde{C}_\Lambda \). Finally, the restriction \((R_0, R_1, s, t, c)|_{\Lambda}\) gives back \((U, R, s, t, c)\) by Remark 20.3 hence \((U, R, s, t, c)\) is prorepresentable by definition.

21. Smooth groupoids in functors on the base category

06KH The notion of smoothness for groupoids in functors on \( C_\Lambda \) is defined as follows.

06KI **Definition 21.1.** Let \((U, R, s, t, c)\) be a groupoid in functors on \( C_\Lambda \). We say \((U, R, s, t, c)\) is smooth if \( s, t : R \to U \) are smooth.

06KJ **Remark 21.2.** We note that this terminology is potentially confusing: if \((U, R, s, t, c)\) is a smooth groupoid in functors, then the quotient \([U/R]\) need not be a smooth category cofibered in groupoids as defined in Remark 8.9. However smoothness of \((U, R, s, t, c)\) does imply (in fact is equivalent to) smoothness of the quotient morphism \( U \to [U/R] \) as we shall see in Lemma 21.4.

06KK **Remark 21.3.** Let \((R_0, R_1, s, t, c)|_{\Lambda}\) be a prorepresentable groupoid in functors on \( C_\Lambda \). Then \((R_0, R_1, s, t, c)|_{\Lambda}\) is smooth if and only if \( R_1 \) is a power series over \( R_0 \) via both \( s \) and \( t \). This follows from Lemma 8.6.

06KL **Lemma 21.4.** Let \((U, R, s, t, c)\) be a groupoid in functors on \( C_\Lambda \). The following are equivalent:

1. The groupoid in functors \((U, R, s, t, c)\) is smooth.
2. The morphism \( s : R \to U \) is smooth.
3. The morphism \( t : R \to U \) is smooth.
(4) The quotient morphism $U \to [U/R]$ is smooth.

**Proof.** Statement (2) is equivalent to (3) since the inverse $i : R \to R$ of $(U, R, s, t, c)$ is an isomorphism and $t = s \circ i$. By definition (1) is equivalent to (2) and (3) together, hence it is equivalent to either of them individually.

Finally we prove (2) is equivalent to (4). Unwinding the definitions:

(2) Smoothness of $s : R \to U$ amounts to the following condition: If $f : B \to A$ is a surjective ring map in $C_A$, $a \in R(A)$, and $y \in U(B)$ such that $s(a) = U(f)(y)$, then there exists $a' \in R(B)$ such that $R(f)(a') = a$ and $s(a') = y$.

(4) Smoothness of $U \to [U/R]$ amounts to the following condition: If $f : B \to A$ is a surjective ring map in $C_A$ and $(f, a) : (B, y) \to (A, x)$ is a morphism of $[U/R]$, then there exists $x' \in U(B)$ and $b \in R(B)$ with $s(b) = x'$, $t(b) = y$ such that $e(a, R(f)(b)) = e(x)$. Here $e : U \to R$ denotes the identity and the notation $(f, a)$ is as in Remarks 5.2 (9); in particular $a \in R(A)$ with $s(a) = U(f)(y)$ and $t(a) = x$.

If (4) holds and $f, a, y$ as in (2) are given, let $x = t(a)$ so that we have a morphism $(f, a) : (B, y) \to (A, x)$. Then (4) produces $x' = b$ and $a' = i(b)$ satisfies the requirements of (2). Conversely, assume (2) holds and let $(f, a) : (B, y) \to (A, x)$ as in (4) be given. Then (2) produces $a' \in R(B)$, and $x' = t(a')$ and $b = t(a')$ satisfy the requirements of (4).

22. Deformation categories as quotients of groupoids in functors

**Lemma 22.1.** Let $(U, R, s, t, c)$ be a smooth groupoid in functors on $C_A$. Assume $U$ and $R$ satisfy (RS). Then $[U/R]$ satisfies (RS).

**Proof.** Let

$$
\begin{array}{ccc}
(A_2, x_2) & \xrightarrow{(f_2, a_2)} & (A, x) \\
(A_1, x_1) & \xleftarrow{(f_1, a_1)} & \end{array}
$$

be a diagram in $[U/R]$ such that $f_2 : A_2 \to A$ is surjective. The notation is as in Remarks 5.2 (9). Hence $f_1 : A_1 \to A$, $f_2 : A_2 \to A$ are maps in $C_A$, $x \in U(A)$, $x_1 \in U(A_1)$, $x_2 \in U(A_2)$, and $a_1, a_2 \in R(A)$ with $s(a_1) = U(f_1)(x_1)$, $t(a_1) = x$ and $s(a_2) = U(f_2)(x_2)$, $t(a_2) = x$. We construct a fiber product lying over $A_1 \times_A A_2$ for this diagram in $[U/R]$ as follows.

Let $a = c(i(a_1), a_2)$, where $i : R \to R$ is the inverse morphism. Then $a \in R(A)$, $x_2 \in U(A_2)$ and $s(a) = U(f_2)(x_2)$. Hence an element $(a, x_2) \in R(A) \times_{s, U(A), U(f_2)} U(A_2)$.

By smoothness of $s : R \to U$ there is an element $\tilde{a} \in R(A_2)$ with $R(f_2)(\tilde{a}) = a$ and $s(\tilde{a}) = x_2$. In particular $U(f_2)(t(\tilde{a})) = t(a) = U(f_1)(x_1)$. Thus $x_1$ and $t(\tilde{a})$ define an element

$$(x_1, t(\tilde{a})) \in U(A_1) \times_{U(A)} U(A_2).$$

By the assumption that $U$ satisfies (RS), we have an identification $U(A_1) \times_{U(A)} U(A_2) = U(A_1 \times_A A_2)$. Let us denote $x_1 \times t(\tilde{a}) \in U(A_1 \times_A A_2)$ the element
corresponding to \((x_1,t(\bar{a}))\) \(\in U(A_1) \times_{U(A)} U(A_2)\). Let \(p_1, p_2\) be the projections of \(A_1 \times_A A_2\). We claim
\[
(A_1 \times_A A_2, x_1 \times t(\bar{a})) \xrightarrow{(p_1,e(x_1))} (A_2, x_2) \quad \xrightarrow{(f_1,a_1)} \quad (A, x)
\]
is a fiber square in \([U/R]\). (Note \(e : U \to R\) denotes the identity.)

The diagram is commutative because \(c(a_2,R(f_2)(i(\bar{a}))) = c(a_2,i(a)) = a_1\). To check it is a fiber square, let
\[
(B, z) \quad \xrightarrow{(g_1,b_1)} \quad (A_2, x_2) \quad \xrightarrow{(f_1,a_1)} \quad (A, x)
\]
be a commutative diagram in \([U/R]\). We will show there is a unique morphism \((g, b) : (B, z) \to (A_1 \times_A A_2, x_1 \times t(\bar{a}))\) compatible with the morphisms to \((A_1, x_1)\) and \((A_2, x_2)\). We must take \(g = (g_1, g_2) : B \to A_1 \times_A A_2\). Since by assumption \(R\) satisfies (RS), we have an identification \(R(A_1 \times_A A_2) = R(A_1) \times_{R(A)} R(A_2)\).

Hence we can write \(b = (b'_1, b'_2)\) for some \(b'_1 \in R(A_1), b'_2 \in R(A_2)\) which agree in \(R(A)\). Then \(((g_1,g_2),(b'_1,b'_2)) : (B, z) \to (A_1 \times_A A_2, x_1 \times t(\bar{a}))\) will commute with the projections if and only if \(b'_1 = b_1\) and \(b'_2 = c(a_2, b_2)\) proving unicity and existence.

06KU **Lemma 22.2.** Let \((U, R, s, t, c)\) be a smooth groupoid in functors on \(\mathcal{C}_A\). Assume \(U\) and \(R\) are deformation functors. Then:

1. The quotient \([U/R]\) is a deformation category.
2. The tangent space of \([U/R]\) is
\[
T[U/R] = \text{Coker}(ds - dt : TR \to TU).
\]
3. Let \(x_0\) be the unique object of \([U/R](k)\). The space of infinitesimal automorphisms of \([U/R]\) is
\[
\text{Inf}_{x_0}(U/R) = \text{Ker}(ds \oplus dt : TR \to TU \oplus TU).
\]

**Proof.** Since \(U\) and \(R\) are deformation functors \([U/R]\) is a predeformation category. Since (RS) holds for deformation functors by definition we see that (RS) holds for \([U/R]\) by Lemma 22.1. Hence \([U/R]\) is a deformation category. Statements (2) and (3) follow directly from the definitions. \(\square\)

23. Presentations of categories cofibered in groupoids

06KW A presentation is defined as follows.

06KK **Definition 23.1.** Let \(\mathcal{F}\) be a category cofibered in groupoids over a category \(\mathcal{C}\). Let \((U, R, s, t, c)\) be a groupoid in functors on \(\mathcal{C}\). A presentation of \(\mathcal{F}\) by \((U, R, s, t, c)\) is an equivalence \(\varphi : [U/R] \to \mathcal{F}\) of categories cofibered in groupoids over \(\mathcal{C}\).

The following two general lemmas will be used to get presentations.
**Lemma 23.2.** Let $\mathcal{F}$ be category cofibered in groupoids over a category $\mathcal{C}$. Let $U : \mathcal{C} \to \text{Sets}$ be a functor. Let $f : U \to \mathcal{F}$ be a morphism of categories cofibered in groupoids over $\mathcal{C}$. Define $R, s, t, c$ as follows:

1. $R : \mathcal{C} \to \text{Sets}$ is the functor $U \times_{f, \mathcal{F}, f} U$.
2. $t, s : R \to U$ are the first and second projections, respectively.
3. $c : R \times_{s, U, t} R \to R$ is the morphism given by projection onto the first and last factors of $U \times_{f, \mathcal{F}, f} U \times_{f, \mathcal{F}, f} U$ under the canonical isomorphism $R \times_{s, U, t} R \to U \times_{f, \mathcal{F}, f} U \times_{f, \mathcal{F}, f} U$.

Then $(U, R, s, t, c)$ is a groupoid in functors on $\mathcal{C}$.

**Proof.** Omitted. □

**Lemma 23.3.** Let $\mathcal{F}$ be category cofibered in groupoids over a category $\mathcal{C}$. Let $U : \mathcal{C} \to \text{Sets}$ be a functor. Let $f : U \to \mathcal{F}$ be a morphism of categories cofibered in groupoids over $\mathcal{C}$. Let $(U, R, s, t, c)$ be the groupoid in functors on $\mathcal{C}$ constructed from $f : U \to \mathcal{F}$ in Lemma 23.2. Then there is a natural morphism $[f] : [U/R] \to \mathcal{F}$ such that:

1. $[f] : [U/R] \to \mathcal{F}$ is fully faithful.
2. $[f] : [U/R] \to \mathcal{F}$ is an equivalence if and only if $f : U \to \mathcal{F}$ is essentially surjective.

**Proof.** Omitted. □

### 24. Presentations of deformation categories

According to the next lemma, a smooth morphism from a predeformation functor to a predeformation category $\mathcal{F}$ gives rise to a presentation of $\mathcal{F}$ by a smooth groupoid in functors.

**Lemma 24.1.** Let $\mathcal{F}$ be a category cofibered in groupoids over $\mathcal{C}_{\Lambda}$. Let $U : \mathcal{C}_{\Lambda} \to \text{Sets}$ be a functor. Let $f : U \to \mathcal{F}$ be a smooth morphism of categories cofibered in groupoids. Then:

1. If $(U, R, s, t, c)$ is the groupoid in functors on $\mathcal{C}_{\Lambda}$ constructed from $f : U \to \mathcal{F}$ in Lemma 23.2, then $(U, R, s, t, c)$ is smooth.
2. If $f : U(k) \to \mathcal{F}(k)$ is essentially surjective, then the morphism $[f] : [U/R] \to \mathcal{F}$ of Lemma 23.3 is an equivalence.

**Proof.** From the construction of Lemma 23.2 we have a commutative diagram

$$
\begin{array}{ccc}
R = U \times_{f, \mathcal{F}, f} U & \xrightarrow{s} & U \\
\downarrow t & & \downarrow f \\
U & \xrightarrow{f} & \mathcal{F}
\end{array}
$$

where $t, s$ are the first and second projections. So $t, s$ are smooth by Lemma 8.7. Hence (1) holds.

If the assumption of (2) holds, then by Lemma 8.8 the morphism $f : U \to \mathcal{F}$ is essentially surjective. Hence by Lemma 23.3 the morphism $[f] : [U/R] \to \mathcal{F}$ is an equivalence. □
Lemma 24.2. Let $\mathcal{F}$ be a deformation category. Let $U : \mathcal{C}_\Lambda \to \text{Sets}$ be a deformation functor. Let $f : U \to \mathcal{F}$ be a morphism of categories cofibered in groupoids. Let $u_0$ be the unique element of $U(k)$. Then $U \times_{f, \mathcal{F}, f} U$ is a deformation functor with tangent space fitting into an exact sequence of $k$-vector spaces

$$0 \to \text{Inf}_{f(u_0)}(\mathcal{F}) \to T(U \times_{f, \mathcal{F}, f} U) \to TU \oplus TU$$

Proof. Follows from Lemma 18.14 and the fact that $\text{Inf}_{u_0}(U) = (0)$. □

Lemma 24.3. Let $\mathcal{F}$ be a deformation category. Let $U : \mathcal{C}_\Lambda \to \text{Sets}$ be a prorepresentable functor. Let $f : U \to \mathcal{F}$ be a morphism of categories cofibered in groupoids. Let $(U, R, s, t, c)$ be the groupoid in functors on $\mathcal{C}_\Lambda$ constructed from $f : U \to \mathcal{F}$ in Lemma 23.2. Assume $\dim_k \text{Inf}_{x_0}(\mathcal{F})$ is finite for some $x_0 \in \text{Ob}(\mathcal{F}(k))$. Then $(U, R, s, t, c)$ is prorepresentable.

Proof. Note that $U$ is a deformation functor by Example 15.10. By Lemma 24.2 we see that $R = U \times_{f, \mathcal{F}, f} U$ is a deformation functor whose tangent space $TR = T(U \times_{f, \mathcal{F}, f} U)$ sits in an exact sequence $0 \to \text{Inf}_{x_0}(\mathcal{F}) \to TR \to TU \oplus TU$. Since we have assumed the first space has finite dimension and since $TU$ has finite dimension by Example 10.11 we see that $\dim TR < \infty$. The map $\gamma : \text{Der} \Lambda(k, k) \to TR$ see (11.6.1) is injective because its composition with $TR \to TU$ is injective by Theorem 17.2 for the prorepresentable functor $U$. Thus $R$ is prorepresentable by Theorem 17.2. It follows from Lemma 20.4 that $(U, R, s, t, c)$ is prorepresentable. □

Theorem 24.4. Let $\mathcal{F}$ be a category cofibered in groupoids over $\mathcal{C}_\Lambda$. Then $\mathcal{F}$ admits a presentation by a smooth prorepresentable groupoid in functors on $\mathcal{C}_\Lambda$ if and only if the following conditions hold:

1. $\mathcal{F}$ is a deformation category.
2. $\dim_k TF$ is finite.
3. $\dim_k \text{Inf}_{x_0}(\mathcal{F})$ is finite for some $x_0 \in \text{Ob}(\mathcal{F}(k))$.

Proof. Recall that a prorepresentable functor is a deformation functor, see Example 15.10. Thus if $\mathcal{F}$ is equivalent to a smooth prorepresentable groupoid in functors, then conditions (1), (2), and (3) follow from Lemma 22.2 (1), (2), and (3).

Conversely, assume conditions (1), (2), and (3) hold. Condition (1) implies that (S1) and (S2) are satisfied, see Lemma 15.6. By Lemma 12.4 there exists a versal formal object $\xi$. Setting $U = U|_{\mathcal{C}_\Lambda}$ the associated map $\xi : U \to \mathcal{F}$ is smooth (this is the definition of a versal formal object). Let $(U, R, s, t, c)$ be the groupoid in functors constructed in Lemma 23.2 from the map $\xi$. By Lemma 24.1 we see that $(U, R, s, t, c)$ is a smooth groupoid in functors and that $[U/R] \to \mathcal{F}$ is an equivalence. By Lemma 24.3 we see that $(U, R, s, t, c)$ is prorepresentable. Hence $[U/R] \to \mathcal{F}$ is the desired presentation of $\mathcal{F}$. □

25. Remarks regarding minimality

The main theorem of this chapter is Theorem 24.4 above. It describes completely those categories cofibered in groupoids over $\mathcal{C}_\Lambda$ which have a presentation by a smooth prorepresentable groupoid in functors. In this section we briefly discuss how the minimality discussed in Sections 13 and 14 can be used to obtain a “minimal” smooth prorepresentable presentation.
06KM **Definition 25.1.** Let \((U, R, s, t, c)\) be a smooth prorepresentable groupoid in functors on \(\mathcal{C}_\Lambda\).

1. We say \((U, R, s, t, c)\) is *normalized* if the groupoid \((U(k[\epsilon]), R(k[\epsilon]), s, t, c)\) is totally disconnected, i.e., there are no morphisms between distinct objects.
2. We say \((U, R, s, t, c)\) is *minimal* if the \(U \to [U/R]\) is given by a minimal versal formal object of \([U/R]\).

The difference between the two notions is related to the difference between conditions (14.0.1) and (14.0.2) and disappears when \(k' \subset k\) is separable. Also a normalized smooth prorepresentable groupoid in functors is minimal as the following lemma shows. Here is a precise statement.

06KN **Lemma 25.2.** Let \((U, R, s, t, c)\) be a smooth prorepresentable groupoid in functors on \(\mathcal{C}_\Lambda\).

1. \((U, R, s, t, c)\) is normalized if and only if the morphism \(U \to [U/R]\) induces an isomorphism on tangent spaces, and
2. \((U, R, s, t, c)\) is minimal if and only if the kernel of \(TU \to T[U/R]\) is contained in the image of \(\text{Der}_{\Lambda}(k, k) \to TU\).

**Proof.** Part (1) follows immediately from the definitions. To see part (2) set \(F = [U/R]\). Since \(F\) has a presentation it is a deformation category, see Theorem 24.4. In particular it satisfies (RS), (S1), and (S2), see Lemma 15.6. Recall that minimal versal formal objects are unique up to isomorphism, see Lemma 13.5. By Theorem 14.5 a minimal versal object induces a map \(\xi : R|_{\mathcal{C}_\Lambda} \to F\) satisfying (14.0.2). Since \(U \cong R|_{\mathcal{C}_\Lambda}\) over \(F\) we see that \(TU \to T\mathcal{F} = T[U/R]\) satisfies the property as stated in the lemma. \(\square\)

The quotient of a minimal prorepresentable groupoid in functors on \(\mathcal{C}_\Lambda\) does not admit autoequivalences which are not automorphisms. To prove this, we first note the following lemma.

06KP **Lemma 25.3.** Let \(U : \mathcal{C}_\Lambda \to \text{Sets}\) be a prorepresentable functor. Let \(\varphi : U \to U\) be a morphism such that \(d\varphi : TU \to TU\) is an isomorphism. Then \(\varphi\) is an isomorphism.

**Proof.** If \(U \cong R|_{\mathcal{C}_\Lambda}\) for some \(R \in \text{Ob}(\mathcal{C}_\Lambda)\), then completing \(\varphi\) gives a morphism \(R \to R\). If \(f : R \to R\) is the corresponding morphism in \(\mathcal{C}_\Lambda\), then \(f\) induces an isomorphism \(\text{Der}_{\Lambda}(R, k) \to \text{Der}_{\Lambda}(R, k)\), see Example 10.14. In particular \(f\) is a surjection by Lemma 4.6. As a surjective endomorphism of a Noetherian ring is an isomorphism (see Algebra, Lemma 30.8) we conclude \(f\), hence \(R \to R\), hence \(\varphi : U \to U\) is an isomorphism. \(\square\)

06KQ **Lemma 25.4.** Let \((U, R, s, t, c)\) be a minimal smooth prorepresentable groupoid in functors on \(\mathcal{C}_\Lambda\). If \(\varphi : [U/R] \to [U/R]\) is an equivalence of categories cofibered in groupoids, then \(\varphi\) is an isomorphism.

**Proof.** A morphism \(\varphi : [U/R] \to [U/R]\) is the same thing as a morphism \(\varphi : (U, R, s, t, c) \to (U, R, s, t, c)\) of groupoids in functors over \(\mathcal{C}_\Lambda\) as defined in Definition 19.1. Denote \(\phi : U \to U\) and \(\psi : R \to R\) the corresponding morphisms. Because
The diagram

\[
\begin{array}{ccc}
T(U) & \xrightarrow{\gamma} & T(U) \\
\downarrow{d\phi} & & \downarrow{d\phi} \\
T[U/R] & \xrightarrow{d\phi} & T[U/R]
\end{array}
\]

is commutative, since \(d\phi\) is bijective, and since we have the characterization of minimality in Lemma 25.2 we conclude that \(d\phi\) is injective (hence bijective by dimension reasons). Thus \(\phi : U \to U\) is an isomorphism by Lemma 25.3. We can use a similar argument, using the exact sequence

\[
0 \to \text{Inf}_x(T[U/R]) \to TR \to TU \oplus TU
\]

of Lemma 24.2 to prove that \(\psi : R \to R\) is an isomorphism. But is also a consequence of the fact that \(R = U \times_{[U/R]} U\) and that \(\varphi\) and \(\phi\) are isomorphisms.

\[\square\]

**Lemma 25.5.** Let \((U, R, s, t, c)\) and \((U', R', s', t', c')\) be minimal smooth prorepresentable groupoids in functors on \(\mathcal{C}_\Lambda\). If \(\varphi : [U/R] \to [U'/R']\) is an equivalence of categories cofibered in groupoids, then \(\varphi\) is an isomorphism.

**Proof.** Let \(\psi : [U'/R'] \to [U/R]\) be a quasi-inverse to \(\varphi\). Then \(\psi \circ \varphi\) and \(\varphi \circ \psi\) are isomorphisms by Lemma 25.4, hence \(\varphi\) and \(\psi\) are isomorphisms. \(\square\)

The following lemma summarizes some of the things we have seen earlier in this chapter.

**Lemma 25.6.** Let \(F\) be a deformation category such that \(\dim_k TF < \infty\) and \(\dim_k \text{Inf}_{x_0}(F) < \infty\) for some \(x_0 \in \text{Ob}(F(k))\). Then there exists a minimal versal formal object \(\xi\) of \(F\). Say \(\xi\) lies over \(R \in \text{Ob}(\widehat{\mathcal{C}}_\Lambda)\). Let \(U = R|_{\mathcal{C}_\Lambda}\). Let \(f = \xi : U \to F\) be the associated morphism. Let \((U, R, s, t, c)\) be the groupoid in functors on \(\mathcal{C}_\Lambda\) constructed from \(f : U \to F\) in Lemma 23.4. Then \((U, R, s, t, c)\) is a minimal smooth prorepresentable groupoid in functors on \(\mathcal{C}_\Lambda\) and there is an equivalence \([U/R] \to F\).

**Proof.** As \(F\) is a deformation category it satisfies (S1) and (S2), see Lemma 15.6. By Lemma 12.4 there exists a versal formal object. By Lemma 13.5 there exists a minimal versal formal object \(\xi/R\) as in the statement of the lemma. Setting \(U = R|_{\mathcal{C}_\Lambda}\) the associated map \(\xi : U \to F\) is smooth (this is the definition of a versal formal object). Let \((U, R, s, t, c)\) be the groupoid in functors constructed in Lemma 23.2. By Lemma 24.1 we see that \((U, R, s, t, c)\) is a smooth groupoid in functors and that \([U/R] \to F\) is an equivalence. By Lemma 24.3 we see that \((U, R, s, t, c)\) is prorepresentable. Finally, \((U, R, s, t, c)\) is minimal because \(U \to [U/R] = F\) corresponds to the minimal versal formal object \(\xi\). \(\square\)

Presentations by minimal prorepresentable groupoids in functors satisfy the following uniqueness property.

**Lemma 25.7.** Let \(F\) be category cofibered in groupoids over \(\mathcal{C}_\Lambda\). Assume there exist presentations of \(F\) by minimal smooth prorepresentable groupoids in functors \((U, R, s, t, c)\) and \((U', R', s', t', c')\). Then \((U, R, s, t, c)\) and \((U', R', s', t', c')\) are isomorphic.
Proof. Follows from Lemma 25.5 and the observation that a morphism \([U/R] \to [U'/R']\) is the same thing as a morphism of groupoids in functors (by our explicit construction of \([U/R]\) in Definition 19.9). □

In summary we have proved the following theorem.

06TE Theorem 25.8. Let \(\mathcal{F}\) be a category cofibred in groupoids over \(\mathcal{C}_\Lambda\). Consider the following conditions

(1) \(\mathcal{F}\) admits a presentation by a normalized smooth prorepresentable groupoid in functors on \(\mathcal{C}_\Lambda\),
(2) \(\mathcal{F}\) admits a presentation by a smooth prorepresentable groupoid in functors on \(\mathcal{C}_\Lambda\),
(3) \(\mathcal{F}\) admits a presentation by a minimal smooth prorepresentable groupoid in functors on \(\mathcal{C}_\Lambda\), and
(4) \(\mathcal{F}\) satisfies the following conditions
   (a) \(\mathcal{F}\) is a deformation category,
   (b) \(\dim_k T\mathcal{F}\) is finite.
   (c) \(\dim_k \text{Inf}^x_{\mathcal{O}_0}(\mathcal{F})\) is finite for some \(x_0 \in \text{Ob}(\mathcal{F}(k))\).

Then (2), (3), (4) are equivalent and are implied by (1). If \(k' \subset k\) is separable, then (1), (2), (3), (4) are all equivalent. Furthermore, the minimal smooth prorepresentable groupoids in functors which provide a presentation of \(\mathcal{F}\) are unique up to isomorphism.

Proof. We see that (1) implies (3) and is equivalent to (3) if \(k' \subset k\) is separable from Lemma 25.2. It is clear that (3) implies (2). We see that (2) implies (4) by Theorem 24.4. We see that (4) implies (3) by Lemma 25.6. This proves all the implications. The final uniqueness statement follows from Lemma 25.7. □

26. Change of residue field

07W7 In this section we quickly discuss what happens if we replace the residue field \(k\) by a finite extension. Let \(\Lambda\) be a Noetherian ring and let \(\Lambda \to k\) be a finite ring map where \(k\) is a field. Throughout this whole chapter we have used \(\mathcal{C}_\Lambda\) to denote the category of Artinian local \(\Lambda\)-algebras whose residue field is identified with \(k\), see Definition 3.1. However, since in this section we will discuss what happen when we change \(k\) we will instead use the notation \(\mathcal{C}_{\Lambda,k}\) to indicate the dependence on \(k\).

07W8 Situation 26.1. Let \(\Lambda\) be a Noetherian ring and let \(\Lambda \to k \to l\) be a finite ring maps where \(k\) and \(l\) are fields. Thus \(k \subset l\) is a finite extensions of fields. A typical object of \(\mathcal{C}_{\Lambda,l}\) will be denoted \(B\) and a typical object of \(\mathcal{C}_{\Lambda,k}\) will be denoted \(A\). We define

(26.1.1) \[ \mathcal{C}_{\Lambda,l} \longrightarrow \mathcal{C}_{\Lambda,k}, \quad B \longmapsto B \times_k l \]

Given a category cofibred in groupoids \(p : \mathcal{F} \to \mathcal{C}_{\Lambda,k}\) we obtain an associated category cofibred in groupoids

\[ p_{l/k} : \mathcal{F}_{l/k} \longrightarrow \mathcal{C}_{\Lambda,l} \]

by setting \(\mathcal{F}_{l/k}(B) = \mathcal{F}(B \times_k l)\).
The functor \((26.1.1)\) makes sense: because \(B \times_1 k \subset B\) we have
\[
[k : k'] \; \text{length}_{B \times_1 k}(B \times_1 k) = \text{length}_k(B \times_1 k) \\
\leq \text{length}_k(B) \\
= [l : k'] \; \text{length}_B(B) < \infty
\]
(see Lemma \(3.4\)) hence \(B \times_1 k\) is Artinian (see Algebra, Lemma \(52.6\)). Thus \(B \times_1 k\) is an Artinian local ring with residue field \(k\). Note that \((26.1.1)\) commutes with fibre products
\[(B_1 \times_B B_2) \times_1 k = (B_1 \times_1 k) \times_{(B \times_1 k)} (B_2 \times_1 k)\]
and transforms surjective ring maps into surjective ring maps. We use the “expensive” notation \(\mathcal{F}_{l/k}\) to prevent confusion with the construction of Remark \(6.4\). Here are some elementary observations.

**Lemma 26.2.** With notation and assumptions as in Situation \(26.1\)

1. We have \(\mathcal{F}_{l/k} = (\mathcal{F})_{l/k}\).
2. If \(\mathcal{F}\) is a predeformation category, then \(\mathcal{F}_{l/k}\) is a predeformation category.
3. If \(\mathcal{F}\) satisfies (S1), then \(\mathcal{F}_{l/k}\) satisfies (S1).
4. If \(\mathcal{F}\) satisfies (S2), then \(\mathcal{F}_{l/k}\) satisfies (S2).
5. If \(\mathcal{F}\) satisfies (RS), then \(\mathcal{F}_{l/k}\) satisfies (RS).

**Proof.** Part (1) is immediate from the definitions.
Since \(\mathcal{F}_{l/k}(l) = \mathcal{F}(k)\) part (2) follows from the definition, see Definition \(6.2\).

Part (3) follows as the functor \((26.1.1)\) commutes with fibre products and transforms surjective maps into surjective maps, see Definition \(9.1\).

Part (4). To see this consider a diagram
\[
\begin{array}{ccc}
l[\epsilon] & \downarrow \\
B & \longrightarrow & l
\end{array}
\]
in \(\mathcal{C}_{\Lambda, l}\) as in Definition \(9.1\). Applying the functor \((26.1.1)\) we obtain
\[
\begin{array}{ccc}
k[l[\epsilon]] & \downarrow \\
B \times_1 k & \longrightarrow & k
\end{array}
\]
where \(l[\epsilon]\) denotes the finite dimensional \(k\)-vector space \(l[\epsilon] \subset l[\epsilon]\). According to Lemma \(9.4\) the condition of (S2) for \(\mathcal{F}\) also holds for this diagram. Hence (S2) holds for \(\mathcal{F}_{l/k}\).

Part (5) follows from the characterization of (RS) in Lemma \(15.4\) part (2) and the fact that \((26.1.1)\) commutes with fibre products.

The following lemma applies in particular when \(\mathcal{F}\) satisfies (S2) and is a predeformation category, see Lemma \(9.5\).
Lemma 26.3. With notation and assumptions as in Situation 26.1. Assume \( \mathcal{F} \) is a predeformation category and \( \mathcal{F} \) satisfies (S2). Then there is a canonical \( l \)-vector space isomorphism
\[
T \mathcal{F} \otimes_k l \to T \mathcal{F}_{l/k}
\]
of tangent spaces.

Proof. By Lemma 26.2 we may replace \( \mathcal{F} \) by \( \mathcal{F} \). Moreover we see that \( T \mathcal{F}_{l/k} \) has a canonical \( k \)-vector space structure, resp. \( l \)-vector space structure, see Lemma 11.2. Then
\[
T \mathcal{F}_{l/k} = \mathcal{F}_{l/k}(l[\epsilon]) = \mathcal{F}(k[\epsilon]) = T \mathcal{F} \otimes_k l
\]
the last equality by Lemma 11.2. More generally, given a finite dimensional \( l \)-vector space \( V \) we have
\[
\mathcal{F}_{l/k}(l[V]) = \mathcal{F}(k[V]) = T \mathcal{F} \otimes_k V_k
\]
where \( V_k \) denotes \( V \) seen as a \( k \)-vector space. We conclude that the functors \( V \mapsto \mathcal{F}_{l/k}(l[V]) \) and \( V \mapsto T \mathcal{F} \otimes_k V_k \) are canonically identified as functors to the category of sets. By Lemma 10.4 we see there is at most one way to turn either functor into an \( l \)-linear functor. Hence the isomorphisms are compatible with the \( l \)-vector space structures and we win. \( \square \)

Lemma 26.4. With notation and assumptions as in Situation 26.1. Assume \( \mathcal{F} \) is a deformation category. Let \( x_0 \in \text{Ob}(\mathcal{F}(k)) \) and denote \( x_{l,0} \) the corresponding object of \( \mathcal{F}_{l/k} \) over \( l \). Then there is a canonical \( l \)-vector space isomorphism
\[
\text{Inf}_{x_0}(\mathcal{F}) \otimes_k l \to \text{Inf}_{x_{l,0}}(\mathcal{F}_{l/k})
\]
of infinitesimal automorphism spaces.

Proof. Recall that the vector space structure on \( \text{Inf}_{x_0}(\mathcal{F}) \) comes from identifying it with the tangent space of the functor \( \text{Aut}(x_0) \) which is defined on the category \( \mathcal{C}_{k,k} \) of Artinian local \( k \)-algebras with residue field \( k \). Similarly, \( \text{Inf}_{x_{l,0}}(\mathcal{F}_{l/k}) \) is the tangent space of \( \text{Aut}(x_{l,0}) \) which is defined on the category \( \mathcal{C}_{l,l} \) of Artinian local \( l \)-algebras with residue field \( l \). Unwinding the definitions we see that \( \text{Aut}(x_{l,0}) \) is the restriction of \( \text{Aut}(x_0)_{l/k} \) (which lives on \( \mathcal{C}_{k,l} \)) to \( \mathcal{C}_{l,l} \). Since there is no difference between the tangent space of \( \text{Aut}(x_0)_{l/k} \) seen as a functor on \( \mathcal{C}_{k,l} \) or \( \mathcal{C}_{l,l} \), the lemma follows from Lemma 26.3 and the fact that \( \text{Aut}(x_0) \) satisfies (RS) by Lemma 18.6 (whence we have (S2) by Lemma 15.6). \( \square \)

Lemma 26.5. With notation and assumptions as in Situation 26.1. If \( \mathcal{F} \to \mathcal{G} \) is a smooth morphism of categories cofibred in groupoids over \( \mathcal{C}_{\Lambda,k} \), then \( \mathcal{F}_{l/k} \to \mathcal{G}_{l/k} \) is a smooth morphism of categories cofibred in groupoids over \( \mathcal{C}_{\Lambda,l} \).

Proof. This follows immediately from the definitions and the fact that (26.1.1) preserves surjections.

There are many more things you can say about the relationship between \( \mathcal{F} \) and \( \mathcal{F}_{l/k} \) (in particular about the relationship between versal deformations) and we will add these here as needed.

27. Other chapters

Preliminaries

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