

# Exodromy

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July 2, 2019

## Abstract

Let  $X$  be a scheme. Let  $\mathrm{Gal}(X)$  be the topological category whose objects are geometric points of  $X$  and whose morphisms are specialisations thereof. If  $X$  is a scheme of finite type over a finitely generated field  $k$  of characteristic zero, then the category  $\mathrm{Gal}(X)$  acquires a continuous action of the absolute Galois group  $G_k$  of  $k$ . Our main result is that the resulting functor from reduced normal schemes of finite type over  $k$  to topological categories with an action of  $G_k$  and functors that preserve minimal objects is *fully faithful*.

The category  $\mathrm{Gal}(X)$  is a form of MacPherson's exit-path category for the étale topology. *Exodromy* refers to the equivalence between representations of  $\mathrm{Gal}(X)$  and constructible sheaves on  $X$ . Together with a higher categorical form of Hochster Duality, this equivalence ensures that the entire étale topos of a quasicompact quasiseparated scheme can be reconstructed from  $\mathrm{Gal}(X)$ . Voevodsky's proof of a conjecture of Grothendieck then implies our main theorem.

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## Introduction

Let  $X$  be a scheme with underling Zariski topological space  $X^{zar}$ . Consider the following category  $\text{Gal}(X)$ .

- An object is a *geometric point*  $x \rightarrow X$ , by which we mean a point whose residue field  $\kappa(x)$  is a separable closure of the residue field  $\kappa(x_0)$  of the image  $x_0 \in X^{zar}$  of  $x$ .
- For two geometric points  $x \rightarrow X$  and  $y \rightarrow X$ , a morphism  $x \rightarrow y$  is a *specialisation*  $x \leftarrow y$  – that is, a geometric point  $y \rightarrow X_{(x)}$  of the strict localisation  $X_{(x)}$  lying over  $y \rightarrow X$ .

Specialisations  $x \leftarrow y$  and  $y \leftarrow z$  compose to give a specialisation  $x \leftarrow z$ . Equivalently,  $\text{Gal}(X)$  is the category of points of the étale topos of  $X$ .

The category  $\text{Gal}(X)$  is a kind of categorification of the absolute Galois group. The assignment  $x \mapsto x_0$  is a conservative functor to the *specialisation poset* of  $X^{zar}$  – that is, the poset of points in which  $x_0 \leq y_0$  if and only if  $x_0$  lies in the closure of  $y_0$ . The fibre over a point  $x_0$  is  $BG_{\kappa(x_0)}$ , where  $G_{\kappa(x_0)}$  is the absolute Galois group of  $\kappa(x_0)$ . If  $X$  is normal, then the space of sections over a map  $x_0 \leq y_0$  is  $BD_{x_0 \leq y_0}$ , where  $D_{x_0 \leq y_0}$  is the decomposition group of  $x_0$  in the closure of  $y_0$ .

As with absolute Galois groups, there is a natural topology on the set of morphisms of  $\text{Gal}(X)$ , which is generated as follows. For any point  $u \rightarrow X$  that is finite over its image  $u_0 \in X^{zar}$ , we form the unramified extension  $A$  of the henselisation  $O_{X,u_0}^h$  with residue field the separable closure of  $\kappa(u_0)$  in  $\kappa(u)$ , and we write  $X_{(u)} := \text{Spec } A$ . Now if  $v \rightarrow X$  is finite over its image  $v_0 \in X^{zar}$ , then a *specialisation*  $u \leftarrow v$  is a point  $v \rightarrow X_{(u)}$  of  $X_{(u)}$  lying over  $v \rightarrow X$ . For any such specialisation  $u \leftarrow v$ , we define the subset  $U(u \leftarrow v)$  of the set of morphisms of  $\text{Gal}(X)$  consisting of those specialisations  $x \leftarrow y$  that lie over  $u \leftarrow v$ . We endow the morphisms of  $\text{Gal}(X)$  with the topology generated by the sets  $U(u \leftarrow v)$ . With this topology,  $\text{Gal}(X)$  becomes a *topological category*.

**A Theorem** (see [Theorem 14.4.7](#)). *Let  $k$  be a finitely generated field of characteristic zero, and let  $G_k$  be its absolute Galois group. Then the assignment  $X \mapsto \text{Gal}(X)$  is fully faithful as a functor from normal  $k$ -varieties to topological categories over  $BG_k$  and continuous functors over  $BG_k$  that carry minimal objects to minimal objects.*

Thus, for any normal  $k$ -varieties  $X$  and  $Y$ , any continuous functor  $\text{Gal}(X) \rightarrow \text{Gal}(Y)$  over  $BG_k$  that preserves minimal objects is induced by a unique morphism of schemes  $X \rightarrow Y$ . In particular, the functor  $X \mapsto \text{Gal}(X)$  is conservative for these schemes. Moreover, a  $k$ -morphism  $f: X \rightarrow Y$  is an isomorphism if and only if  $f$  induces an equivalence  $\text{Gal}(X) \rightarrow \text{Gal}(Y)$  of ordinary categories.

This theorem can be regarded as a categorical version of the *Anabelian Conjecture* of Alexander Grothendieck: in effect, it states that Galois-theoretic information, when organised carefully, provides a complete invariant of normal varieties.

The category  $\text{Gal}(X)$  is in effect an *étale exit-path category*. Bob MacPherson introduced the exit-path categories of stratified topological spaces to classify constructible sheaves in what we call the *exodromy equivalence*. Accordingly, our proof of [Theorem A](#) involves the development of a *stratification* of the *étale homotopy type* and the new theory of *exodromy* in the étale context.

## Monodromy for topological spaces

It is a truth universally acknowledged, that a local system of  $\mathbf{C}$ -vector spaces on a connected topological manifold  $X$  is completely determined by its attached *monodromy representation*, so that the choice of a point  $x \in X$  specifies an equivalence of categories

$$M_x : \mathbf{LS}(X; \mathbf{Vect}(\mathbf{C})) \simeq \mathbf{Rep}_{\mathbf{C}}(\pi_1(X, x)) .$$

If one wants to avoid selecting a point, or if one wants to drop the connectivity hypothesis on  $X$ , then one may combine the set of connected components and the various fundamental groups of  $X$  to form the *fundamental groupoid*  $\Pi_1(X)$ . Then the monodromy equivalence becomes

$$M : \mathbf{LS}(X; \mathbf{Vect}(\mathbf{C})) \simeq \mathbf{Fun}(\Pi_1(X), \mathbf{Vect}(\mathbf{C})) .$$

An early insight of Dan Kan was that in a similar fashion, *all* the homotopy groups and all the  $k$  invariants of  $X$  could, in effect, be combined to form a single combinatorial gadget – a simplicial set  $\Pi_\infty(X)$  called the *singular simplicial set* or, in contemporary parlance, the *fundamental  $\infty$ -groupoid* of  $X$  – which knows everything about the homotopy type of  $X$ .

Perhaps the clearest formulation of this insight was that of Dan Quillen, who showed that the category  $\mathbf{TSpc}$  of topological spaces and the category  $s\mathbf{Set}$  of simplicial sets each admit model structures – each with the conventional choice of weak equivalence – relative to which the functor

$$\Pi_\infty : \mathbf{TSpc} \rightarrow s\mathbf{Set}$$

is a right Quillen equivalence. Nowadays we go a step farther and think of  $\Pi_\infty$  as an equivalence  $\mathbf{S} \simeq \mathbf{Gpd}_\infty$  between the underlying  $\infty$ -category of spaces and that of  $\infty$ -groupoids.

This fundamental  $\infty$ -groupoid of  $X$  appears in derived versions of the monodromy equivalence: for instance, the monodromy of a local system of *complexes* of  $\mathbf{C}$ -vector spaces is a functor from  $\Pi_\infty(X)$  to complexes, and this induces an equivalence of  $\infty$ -categories

$$M : \mathbf{LS}(X; \mathbf{Cplx}(\mathbf{C})) \simeq \mathbf{Fun}(\Pi_\infty(X), \mathbf{Cplx}(\mathbf{C})) .$$

All of these equivalences follow from the ur-example of local systems of *spaces* on  $X$ , which are known as *parametrised homotopy types* in the homotopy theory literature [55]. These form an  $\infty$ -category  $\mathbf{LS}(X)$ , and there is a natural monodromy equivalence of  $\infty$ -categories

$$M : \mathbf{LS}(X) \simeq \tilde{\Pi}_\infty(X) := \mathbf{Fun}(\Pi_\infty(X), \mathbf{S}) .$$

## Monodromy for schemes

To replace the manifold in this story with a scheme, Grothendieck identified étale local systems on a suitable connected scheme  $X$  with representations of its étale fundamental group. Here it is not the Zariski topological space of  $X$  that is germane but its *étale topos*, and one obtains not a group but a progroup: the *extended étale fundamental group*  $\pi_1^{\text{ét}, \text{ext}}(X)$  – or, if preferred, its profinite reflection: the usual *étale fundamental group*  $\pi_1^{\text{ét}}(X)$ .

The étale fundamental group is an information-dense invariant, and Grothendieck's *Anabelian Conjectures* are roughly an investigation of the extent to which it is a *complete* invariant for certain classes of schemes. In dimension 0, the classical theorem of Neukirch and Uchida [60; 61; 76] ensures that two number fields are isomorphic if and only if their absolute Galois groups are. In dimension 1, Akio Tamagawa [74] and Shinichi Mochizuki [57] show that dominant morphisms between smooth hyperbolic curves over suitable fields of characteristic zero can be detected at the level of fundamental groups. Florian Pop [64, Theorem 1] shows that an isomorphism between two function fields over finitely generated fields can be detected at the level of Galois groups.

Eduardo Dubuc [21, §§5–6] generalised the étale fundamental group by extracting from a topos  $\mathbf{X}$  a *fundamental progroupoid*  $\Pi_1(\mathbf{X})$  and a monodromy equivalence

$$\mathbf{X}^{\text{locsys}} \simeq \text{Fun}(\Pi_1(\mathbf{X}), \mathbf{Set})$$

between the local systems of sets on  $\mathbf{X}$  and  $\mathbf{Set}$ -valued functors on the  $\Pi_1(\mathbf{X})$  (in the ‘pro’ sense). Following this, from an  $\infty$ -topos  $\mathbf{X}$ , Jacob Lurie extracted a fundamental  $\infty$ -groupoid  $\Pi_\infty(\mathbf{X})$  whose representations are monodromy representations. The caveat is again that one is forced to contend with proobjects:  $\Pi_\infty(\mathbf{X})$  is most naturally a prospace, called the *shape* of  $\mathbf{X}$ , and its profinite completion is the *homotopy type*  $\Pi_\infty^\wedge(\mathbf{X})$  of  $\mathbf{X}$ . Tom Bachmann and Marc Hoyois show [7, Proposition 10.1] that for any  $\infty$ -topos  $\mathbf{X}$ , one has a natural monodromy equivalence of  $\infty$ -categories

$$\mathbf{X}^{\text{lisce}} \simeq \text{Fun}(\Pi_\infty^\wedge(\mathbf{X}), \mathbf{S}_\pi)$$

between the *lisce* sheaves on  $\mathbf{X}$  – i.e., locally constant sheaves of  $\pi$ -finite spaces on  $\mathbf{X}$  that can be trivialised on a finite cover – and functors on  $\Pi_\infty^\wedge(\mathbf{X})$  valued in the  $\infty$ -category  $\mathbf{S}_\pi$  of  $\pi$ -finite spaces (see also Proposition 5.14.17). This monodromy equivalence is a form of *galoisian duality*. At the most abstract level, this duality arises from the fully faithful inclusion  $\mathbf{S}_\pi \hookrightarrow \mathbf{Top}_\infty$  given by  $\Pi \mapsto \widetilde{\Pi} := \text{Fun}(\Pi, \mathbf{S})$  and its proexistent left adjoint. Hoyois showed that if  $X_{\text{ét}}$  is the (1-localic) étale  $\infty$ -topos of a locally noetherian scheme  $X$ , then the profinite space  $\Pi_\infty^\wedge(X_{\text{ét}})$  coincides with the *étale homotopy type*  $\Pi_\infty^{\text{ét}, \wedge}(X)$  of Mike Artin and Barry Mazur [39, Corollary 5.6].

If the étale fundamental group  $\pi_1^{\text{ét}}$  is information-dense, then the étale homotopy type  $\Pi_\infty^{\text{ét}, \wedge}$  must be even more so. Indeed, Alexander Schmidt and Jacob Stix [70, Theorem 1.2] show that over a finitely generated field  $k$  of characteristic 0, if  $X$  and  $Y$  are smooth, geometrically connected varieties that can be embedded as locally closed subschemes of a product of hyperbolic curves, then the map

$$\text{Isom}_k(X, Y) \rightarrow \text{Isom}_{BG_k}(\Pi_\infty^{\text{ét}, \wedge}(X), \Pi_\infty^{\text{ét}, \wedge}(Y))$$

is a split injection with a natural retraction, where  $\text{Isom}_{BG_k}$  denotes the set of homotopy classes of equivalences of profinite spaces over  $BG_k$ .

## Exodromy for topological spaces

A string of results has suggested the possibility that *stratified spaces* and *constructible sheaves* might be modeled in a similarly combinatorial fashion. Bob MacPherson proved

that constructible sheaves of sets on a (suitably nice) stratified topological space  $X$  over a poset  $P$  determine and are determined by a functor from the *exit-path category*  $\Pi_{(1,1)}(X; P)$  of  $X$ , whose objects are points of  $X$  and whose morphisms are stratified homotopy equivalence classes of *exit paths* – paths from a stratum  $X_p$  to a stratum  $X_q$  for  $q \geq p$ . We call this equivalence

$$E^P : \mathbf{Sh}_{\leq 0}(X)^{P\text{-constr}} \simeq \text{Fun}(\Pi_{(1,1)}(X; P), \mathbf{Set})$$

between  $P$ -constructible sheaves of sets on  $X$  and functors  $\Pi_{(1,1)}(X; P) \rightarrow \mathbf{Set}$  the *exodromy* equivalence.<sup>1</sup> One notes that  $\Pi_{(1,1)}(X; P)$  is a category with a conservative functor to  $P$  itself. Over each point  $p \in P$ , the fibre of this functor over  $p$  is the fundamental groupoid  $\Pi_1(X_p)$  of the stratum  $X_p$ .

David Treumann [75] then extended MacPherson's result to give an exodromy equivalence between constructible *stacks* with functors from an *exit-path 2-category* of  $X$  valued in groupoids. Lurie [HA, Appendix A] extended this further to give an exodromy equivalence

$$E^P : \mathbf{Sh}(X)^{P\text{-constr}} \simeq \tilde{\Pi}_{(\infty,1)}(X; P) := \text{Fun}(\Pi_{(\infty,1)}(X; P), \mathbf{S})$$

between  $P$ -constructible sheaves of spaces on  $X$  and functors from an *exit-path category*  $\Pi_{(\infty,1)}(X; P)$ . The objects are points of  $X$ , the morphisms are exit-paths, the 2-morphisms are stratified homotopies, the 3-morphisms are stratified homotopies of homotopies, etc., etc., *ad infinitum*. One notes that  $\Pi_{(\infty,1)}(X; P)$  is an  $\infty$ -category with a conservative functor to  $P$  itself. Over each point  $p \in P$ , the fibre of this functor is the fundamental  $\infty$ -groupoid  $\Pi_{\infty}(X_p)$  of the stratum  $X_p$ .

One is led to seek an analogue of the Kan–Quillen theorem that states that the formation of the exit-path  $\infty$ -category is an equivalence of suitable homotopy theories between stratified spaces and suitable  $\infty$ -categories. A geometric form of this result was proved by David Ayala, John Francis, and Nick Rozenblyum [6], who showed that the exit-path  $\infty$ -category construction is fully faithful from a homotopy theory of *conically smooth* stratified spaces to  $\infty$ -categories.

A still closer stratified analogue of the Kan–Quillen equivalence has now been provided by the simultaneous, work of three authors:<sup>2</sup> Sylvain Douteau [20], Stephen Nand-Lal and Jon Woolf [59], and the third-named author [27; 28]. These papers each take a slightly different point of view, but for our purposes here, the salient point is this: the functor  $\Pi_{(\infty,1)}(-; P)$  is an equivalence between the following homotopy theories:

- topological spaces with a stratification over  $P$  – in which a weak equivalence of such is a weak equivalence on strata and (homotopy) links – and
- $\infty$ -categories with a conservative functor to  $P$ .

<sup>1</sup> ἔξω: outer; δρόμος: avenue.

<sup>2</sup> In his thesis [32], André Henriques conjectures that one should be able to define a model structure on  $P$ -stratified simplicial sets. In his later note [31] he defines a model structure on  $P$ -stratified simplicial sets and relates it to a model structure on  $\text{Fun}(\text{sd}(P)^{op}, \mathbf{sSet})$ . These model structures present a delocalisation of the  $\infty$ -category we're interested in.



We are thus entitled to refer to  $\infty$ -categories with a conservative functor to a poset  $P$  as *P-stratified spaces*. This makes it possible to port some of the ideas of stratified homotopy theory to the study of schemes. Importantly, if  $S$  is a spectral topological space (i.e., the underlying Zariski topological space  $X^{zar}$  of a coherent<sup>3</sup> scheme  $X$ , or equivalently a profinite poset), then we are able to extend this description to define the homotopy theory of *S-stratified spaces*.

## Exodromy for schemes

In the present paper, we define *P-stratified  $\infty$ -topoi* and more generally *S-stratified  $\infty$ -topoi*, and we study the *constructible sheaves* therein. For any  $S$ -stratified space  $\Pi$ , the  $\infty$ -topos  $\widetilde{\Pi} := \text{Fun}(\Pi, S)$  admits a natural  $S$ -stratification. This defines a functor  $\text{Str}_S \rightarrow \text{StrTop}_{\infty, S}^\wedge$ . Restricting to profinite stratified spaces, we obtain a fully faithful functor  $\text{Str}_{\pi, S}^\wedge \hookrightarrow \text{StrTop}_{\infty, S}^\wedge$  and its left adjoint  $\Pi_{(\infty, 1)}^{S, \wedge}$ .

**B Theorem (Theorem 11.1.7).** *For any  $S$ -stratified  $\infty$ -topos  $X$ , the unit  $X \rightarrow \Pi_{(\infty, 1)}^{S, \wedge}(X)$  of the adjunction to profinite stratified spaces restricts to an equivalence*

$$\text{Fun}(\Pi_{(\infty, 1)}^{S, \wedge}(X), S_\pi) \simeq X^{S\text{-constr}}$$

*between the  $\infty$ -category of functors valued in  $\pi$ -finite spaces and  $S$ -constructible sheaves  $X$ . We call this identification the exodromy equivalence for stratified  $\infty$ -topoi.*

We call the profinite  $\infty$ -category  $\Pi_{(\infty, 1)}^{S, \wedge}(X)$  the *S-stratified homotopy type of  $X$* . This is a *refinement* of the usual homotopy type of  $X$ : the classifying profinite space of  $\Pi_{(\infty, 1)}^{S, \wedge}(X)$  is precisely  $\Pi_\infty^\wedge(X)$ .

Profinite stratified spaces admit Postnikov towers  $\Pi \rightarrow \cdots \rightarrow h_2\Pi \rightarrow h_1\Pi \rightarrow h_0\Pi$ ; thus an  $S$ -stratified  $\infty$ -topos  $X$  has attached fundamental profinite  $(n, 1)$ -categories

$$\Pi_{(n, 1)}^{S, \wedge}(X) := h_n \Pi_{(\infty, 1)}^{S, \wedge}(X) .$$

Our interest in these refinements arose primarily due to the following example.

**C Example.** If  $X$  is a coherent scheme, then we have the 1-localic  $\infty$ -topos  $X_{\acute{e}t}$ , which admits a natural  $X^{zar}$ -stratification, and so we obtain the profinite  $\infty$ -category

$$\Pi_{(\infty, 1)}^{\acute{e}t, \wedge}(X) := \Pi_{(\infty, 1)}^{X^{zar}, \wedge}(X_{\acute{e}t}) ,$$

which we call the *stratified étale homotopy type of  $X$* .

For a finite ring  $\Lambda$ , the exodromy equivalence yields in particular

$$\text{Fun}(\Pi_{(\infty, 1)}^{\acute{e}t, \wedge}(X), \text{Perf}(\Lambda)) \simeq D_{\text{constr}}^b(X; \Lambda) .$$

Passing to suitable limits, we find that  $\ell$ -adic constructible sheaves on  $X$  ‘are’  $\ell$ -adic representations of the stratified étale homotopy type of  $X$ , in just the same way as  $\ell$ -adic local systems on  $X$  ‘are’  $\ell$ -adic representations of the étale homotopy type of  $X$ .

<sup>3</sup>Following the Grothendieck school we use the term ‘coherent scheme’ synonymously with ‘quasicompact quasiseparated scheme’ (0.6.1).

An important point is that the stratified étale homotopy type turns out to be 1-truncated, so that  $\Pi_{(\infty,1)}^{\text{ét},\wedge}(X) = \Pi_{(1,1)}^{\text{ét},\wedge}(X)$ . For stratified 1-types, we are able to identify them with 1-categories equipped with a suitable topology. Under this correspondence, the stratified étale homotopy type agrees with the topological category  $\text{Gal}(X)$  of points of  $X$  that we introduced just before the statement of [Theorem A](#).

## Hochster Duality for higher topoi

The main novel step in our proof of [Theorem A](#) is that the whole étale  $\infty$ -topos of any coherent scheme can be completely recovered from the stratified étale homotopy type. This is a generalisation of what we call *Hochster Duality*.

Melvin Hochster's thesis [34; 35] identifies the category of profinite posets with the category of *spectral topological spaces* – those topological spaces that underlie coherent schemes. This functions as a simultaneous generalisation of Alexandroff Duality (which identifies finite posets with finite topological spaces) and Stone Duality (which identifies profinite sets with quasicompact and totally separated topological spaces).

Lurie has already extended Stone Duality to the context of higher topoi: he proves that the functor that carries a profinite space  $\Pi$  to the  $\infty$ -topos  $\widetilde{\Pi}$  is fully faithful, and its essential image consists of bounded coherent  $\infty$ -topoi in which the truncated coherent objects coincide with the *lisse* sheaves. We call these  $\infty$ -topoi *Stone  $\infty$ -topoi*. (Lurie calls them *profinite  $\infty$ -topoi*.)

In this paper, we prove the following:

**D Theorem** ( $\infty$ -Categorical Hochster Duality; [Theorem 10.3.1](#)). *The assignment that carries a profinite stratified space  $\Pi$  to the  $\infty$ -topos  $\widetilde{\Pi}$  is fully faithful, and its essential image consists of bounded coherent  $\infty$ -topoi in which the truncated coherent objects coincide with the constructible sheaves.*

We call these  $\infty$ -topoi *spectral  $\infty$ -topoi* ([Definition 10.2.1](#)). This is partially justified by the fact that they are the natural higher categorical extension of Hochster's spectral topological spaces. Better still, we have the following.

**E Example.** Let  $X$  be a coherent scheme. Then the étale  $\infty$ -topos  $X_{\text{ét}}$  is spectral.

Thus the étale  $\infty$ -topos of a coherent scheme is of the form  $\widetilde{\Pi}$  for some profinite  $\infty$ -category  $\Pi$ , which turns out in this case to be a 1-category.

Since one may identify the constructible sheaves on  $X$  with the truncated and coherent objects of  $X_{\text{ét}}$ , we deduce that in fact  $X_{\text{ét}}$  is equivalent to the  $\infty$ -topos  $\widetilde{\Pi}_{(\infty,1)}^{\text{ét},\wedge}(X)$ . In other words, the stratified étale homotopy type of  $X$  recovers the entire étale  $\infty$ -topos attached to  $X$ .

Armed with this, [Theorem A](#) follows as soon as we know that our schemes can be recovered from their étale  $\infty$ -topoi. On this score, in his letter to Gerd Faltings, Grothendieck conjectured – and Vladimir Voevodsky proved [77] – that the assignment  $X \mapsto X_{\text{ét}}$  is a fully faithful functor from reduced, normal schemes of finite type over a finitely generated field  $k$  of characteristic 0 to  $\infty$ -topoi with an action of the absolute Galois group  $G_k$  and ‘admissible’  $G_k$ -equivariant morphisms. Combined with our results on the profinite stratified shape, we obtain our [Theorem A](#).

In effect, whereas the étale homotopy type of a scheme can only be hoped to be a complete invariant only for certain varieties constructed iteratively from hyperbolic curves, the addition of the natural stratification on the étale homotopy type turns it into a complete invariant for *all* varieties. The stratified étale homotopy type identifies reduced normal schemes over  $k$  with a subcategory of the category of profinite categories with an action of  $G_k$ .

In characteristic  $p$  and for more general arithmetic schemes, the presence of inseparable extensions forces us to give a more careful formulation of Grothendieck's conjecture ([Conjecture 14.4.4](#)), and both it and the analogue of [Theorem A](#) remain open.

## Stratified Riemann Existence

If  $X$  is a  $\mathbf{C}$ -scheme of finite type, then the Riemann Existence Theorem amounts to an equivalence between the étale homotopy type  $\Pi_{\infty}^{\text{ét},\wedge}(X)$  and the profinite completion  $\Pi_{\infty}^{\wedge}(X^{an})$  of the homotopy type of the topological space  $X^{an}$  of complex points of  $X$  with its analytic topology [[4](#), Theorem 12.9; [12](#), Proposition 4.12]. In the same vein, the *stratified* Riemann Existence Theorem provides the following.

**F Theorem** (Stratified Riemann Existence; [Proposition 13.8.3](#)). *Let  $X$  be a  $\mathbf{C}$ -scheme of finite type, and  $X \rightarrow P$  a finite constructible stratification. Then there is a natural equivalence*

$$\Pi_{\infty}^{\text{ét},\wedge}(X; P) \simeq \Pi_{\infty}^{\wedge}(X^{an}; P).$$

Combining this theorem with [Theorem A](#) above, we find that a normal  $k$ -variety can be reconstructed from the stratified homotopy type of the topological space  $(X \times_k k^a)^{an}$  along with its action of  $G_k$ . We lay this out in

## Technical overview

The first three parts of this paper reflect the three ingredients necessary to construct the stratified étale homotopy type and to prove the central Hochster Duality Theorem for higher categories ([Theorem D](#)=[Theorem 10.3.1](#)). The last part is then focused applying this machinery to the étale  $\infty$ -topoi of schemes.

The first ingredient is a small (and quite elementary) piece of abstract homotopy theory in the study of stratified spaces and profinite stratified spaces. Most of this work is relatively formal, but one important notion is that of a *spatial décollage*, which is a presheaf on the subdivision of a poset satisfying a Segal condition. We prove that the  $\infty$ -category of stratified spaces is equivalent to that of spatial décollages via a nerve construction. The upshot is that a stratified space can be recovered from its ‘unglued’ form<sup>4</sup> – a collection of strata and links, suitably organised.

On the toposic side, one wants to be able to perform the same ungluing procedure, so that one can recover an  $\infty$ -topos  $\mathbf{X}$  from the data of a closed subtopos  $\mathbf{Z}$ , its open complement  $\mathbf{U}$ , and the gluing information in the form of the *deleted tubular neighbourhood*  $\mathbf{W}$  of  $\mathbf{Z}$  in  $\mathbf{U}$ . This is the second major ingredient – *gluing squares* of  $\infty$ -topoi,

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<sup>4</sup>Whence the term ‘décollage’.

which are certain squares

$$\begin{array}{ccc} W & \xrightarrow{q_*} & U \\ p_* \downarrow & \swarrow \sigma & \downarrow j_* \\ Z & \xrightarrow{i_*} & X \end{array}$$

of geometric morphisms with a noninvertible natural transformation  $\sigma$ . In order to make sense of this, there are three nontrivial tasks:

- We must work – systematically and *ab initio* – with *bounded coherent*  $\infty$ -topoi. This involves some care, particularly as these conditions are not stable under the formation of recollements.
- We must develop the higher categorical analogue of Pierre Deligne’s *oriented fibre product* [42; 50; 63]. The *tubular neighbourhood* of  $Z$  in  $X$  is the *evanescent*  $\infty$ -topos  $Z \tilde{\times}_X X$ , and the *deleted tubular neighbourhood*  $W$  is then the open subtopos  $Z \tilde{\times}_X U \subseteq Z \tilde{\times}_X X$ .
- Finally, and most crucially, we must prove a rather delicate *Beck–Chevalley Theorem*, which ensures that the two gluing functors  $i^* j_*$  and  $p_* q^*$  agree, at least on truncated objects.

We define *stratified*  $\infty$ -topoi in a manner completely analogous to our definition of stratified topological spaces, but our study of gluing squares now permits us to prove that the  $\infty$ -category of *bounded coherent* stratified  $\infty$ -topoi are equivalent to a  $\infty$ -category of *toposic décollages* – i.e., presheaves of  $\infty$ -topoi on the subdivision of a poset that satisfy a kind of *oriented Segal condition*. This condition ensures that a string  $\{p_0 \leq \dots \leq p_n\}$  is carried to an iterated oriented fibre product  $X_{p_0} \tilde{\times}_X \dots \tilde{\times}_X X_{p_n}$  of the strata. We may also pass to profinite objects in the base, which permits us to contemplate stratified  $\infty$ -topoi over spectral topological spaces.

Among the bounded coherent stratified  $\infty$ -topoi are those in which the strata are Stone  $\infty$ -topoi. These are the *spectral*  $\infty$ -topoi. They turn out to agree with those bounded coherent stratified  $\infty$ -topoi in which the truncated coherent objects are exactly the *constructible sheaves* – i.e., those sheaves that restrict to a lisse sheaf on any stratum. If  $\Pi$  is a profinite stratified space, then the stratified  $\infty$ -topos  $\tilde{\Pi}$  is spectral in this sense. As in Lurie’s  $\infty$ -Categorical Stone Duality, there is a left adjoint to the functor  $\Pi \mapsto \tilde{\Pi}$ , which carries a stratified  $\infty$ -topos to its *stratified homotopy type*.

Now the  $\infty$ -Categorical Hochster Duality Theorem – which provides an equivalence between spectral  $\infty$ -topoi with profinite stratified spaces – follows from a sequence of three moves:

- We reduce to the case of a finite poset  $P$ . This is formal.
- We then show that the stratified homotopy type of a spectral  $\infty$ -topos can be computed by ungluing to the toposic décollage, forming the homotopy type objectwise to get a spatial décollage, and then regluing to a profinite stratified space.
- We then appeal to Lurie’s  $\infty$ -Categorical Stone Duality Theorem.

## Open problems

There are a number of questions we have not answered in this paper. Here are just a few.

**Question.** Our work here leaves [Conjecture 14.4.4](#) frustratingly open. In effect, it predicts that a large class of *absolute schemes*  $X$  (see [Definition 14.4.1](#)) can be reconstructed from  $\mathrm{Gal}(X)$ .

**Question.** We may ask whether one can recover an absolute scheme  $X$  from the profinite stratified space at a finite stage. That is, is there a finite constructible stratification  $X \rightarrow P$  such that for any absolute scheme  $Y$ , the map

$$\mathrm{Mor}_k(X, Y) \simeq \mathrm{Map}_{BG_k}(\Pi_{(\infty, 1)}^{\acute{e}t, \wedge}(Y), \Pi_{(\infty, 1)}^{\acute{e}t, \wedge}(X)) \rightarrow \pi_0 \mathrm{Map}_{BG_k}(\Pi_{(\infty, 1)}^{\acute{e}t, \wedge}(Y), \Pi_{(\infty, 1)}^{\acute{e}t, \wedge}(X; P))$$

is a bijection? (One might expect that it suffices to choose stratification in which the strata in  $X$  are strongly hyperbolic Artin neighbourhoods; at this point, we do not know.)

## Acknowledgements

The Université Montpellier has recently released a collection of notes of Alexander Grothendieck, including ‘Cote n° 151: Espaces stratifiés’, in which he develops some elements of stratified topos theory and some elements of an attached shape theory, to which he referred in his *Esquisse d’un Programme* [26, p. 36]. It is not clear to us how much of the work here he anticipated.

We have used the framework and results in Jacob Lurie’s three big books [HTT], [HA], and [SAG] everywhere here. The impact of his ideas here is obvious and extensive. We are also grateful to him for his very helpful answers to a number of technical questions we pelted him with over the course of this project.

Much of our understanding of stratified spaces is directly the result of our conversations with David Ayala, who independently developed the ‘spatial décollage’ perspective on stratified spaces. We are exceedingly grateful to him for sharing with us a portion of these ideas. Ayala’s thinking has had a tremendous influence on us, and conversations with him in the first phase of this project have been vital to our work. Additionally, he has read some early editions of this work, spotted some mistakes, and helped us improve our writing.

Dustin Clausen and Jacob Lurie have each developed a portion of the topos-theoretic material here. In particular, it seems that they were each already aware of the  $\infty$ -Categorical Hochster Duality Theorem. We are grateful to them both for sharing their insights on this matter.

We are grateful to Marc Hoyois for carefully reading a draft of this work and for providing us with helpful feedback.

We are grateful to Harry Gindi for carefully reading this work and for spotting a number of typos and pointing out some mistakes.

We thank Chang-Yeon Chough for helpful conversations on the relationship between the nonabelian proper basechange theorem in algebraic geometry and our basechange theorem for oriented fibre products.

This work was originally conceived during the Bourbon Seminar at MIT. We are grateful to our fellow participants – Marc Hoyois, Denis Nardin, Sune Precht Reeh, and Jay Shah.

The first- and third-named authors are grateful to the Isaac Newton Institute in Cambridge, whose hospitality they enjoyed while completing some of this work.

The third-named author gratefully acknowledges support from both the MIT Dean of Science Fellowship and NSF Graduate Research Fellowship. He would also like to thank Alex Sear for her generous hospitality during his visits to the University of Edinburgh during, when much of this work took place.

## o Terminology & notations

### o.1 Set theoretic conventions

**o.1.1.** Recall that if  $\delta$  is a strongly inaccessible cardinal (which we always assume to be uncountable), then the set  $V_\delta$  of all sets of rank strictly less than  $\delta$  is a Grothendieck universe of rank and cardinality  $\delta$  [SGA 4<sub>I</sub>, Exposé I, Appendix]. Conversely, if  $V$  is a Grothendieck universe that contains an infinite cardinal, then  $V = V_\delta$  for some strongly inaccessible cardinal  $\delta$ .

In order to deal precisely and simply with set-theoretic problems arising from the consideration of ‘large’ collections, we append to ZFC the Axiom of Universes (AU). This asserts that any cardinal is dominated by a strongly inaccessible cardinal.

We write  $\delta_0$  for the smallest strongly inaccessible cardinal. Now AU implies the existence of a hierarchy of strongly inaccessible cardinals

$$\delta_0 < \delta_1 < \delta_2 < \cdots,$$

in which for each ordinal  $\alpha$ , the cardinal  $\delta_\alpha$  is the smallest strongly inaccessible cardinal  $\delta_\alpha$  that dominates  $\delta_\beta$  for any  $\beta < \alpha$ .<sup>5</sup>

We certainly will not use the full strength of AU; the existence of only  $\delta_0$  and  $\delta_1$  suffices for our work here. At the cost of some circumlocutions, one could even get away with ZFC alone.

**o.1.2.** We write  $N$  for the poset of *nonnegative integers*. We write  $N^* := N \setminus \{0\}$ , and  $N^\circ := N \cup \{\infty\}$ .

### o.2 Higher categories

**o.2.1.** We use the language and tools of higher category theory, particularly in the model of *quasicategories*, as defined by Michael Boardman and Rainer Vogt and developed by André Joyal and Lurie. We will generally follow the terminological and notational conventions of Lurie’s trilogy [HTT; HA; SAG]. In particular:

- An  $\infty$ -category here will always mean *quasicategory*.

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<sup>5</sup>Thus  $V_{\delta_\alpha}$  models ZFC plus the axiom ‘the set of strongly inaccessible cardinals is order-isomorphic to  $\alpha$ ’.

- A *subcategory*  $C'$  of an  $\infty$ -category  $C$  is a simplicial subset that is stable under composition in the strong sense, so that if  $\sigma : \Delta^n \rightarrow C$  is an  $n$ -simplex of  $C$ , then  $\sigma$  factors through  $C' \subseteq C$  if and only if each of the edges  $\sigma(\Delta^{[i,i+1]})$  does so.
- An  $n$ -category here means a quasicategory with unique inner horn fillers in dimensions strictly greater than  $n$ .
- Let  $\delta$  be a strongly inaccessible cardinal. A set, group, simplicial set,  $\infty$ -category, ring, etc., will be said to be  $\delta$ -small<sup>6</sup> if it equivalent (in whatever appropriate sense) to one that lies in  $V_\delta$ . We abbreviate  $\delta_0$ -small to *small*.
- An  $\infty$ -category  $C$  is said to be *locally*  $\delta$ -small if and only if, for any objects  $x, y \in C$ , the mapping space  $\text{Map}_C(x, y)$  is  $\delta$ -small. We abbreviate *locally*  $\delta_0$ -small to *locally small*.
- Accessibility of  $\infty$ -categories and functors and presentability of  $\infty$ -categories will always refer to accessibility and presentability with respect to some  $\delta_0$ -small cardinal. Please observe that an accessible  $\infty$ -category is always essentially  $\delta_1$ -small and locally  $\delta_0$ -small.
- We will use the terms  $\infty$ -groupoid or *space* interchangeably for an  $\infty$ -category in which every morphism is invertible. If  $C$  is an  $\infty$ -category, the largest  $\infty$ -groupoid  $\iota C \subseteq C$  contained in  $C$  will be called the *interior* of  $C$ .
- Let  $\delta$  be a strongly inaccessible cardinal. Then we write  $S_\delta$  for the  $\infty$ -category of  $\delta$ -small spaces and  $\text{Cat}_{\infty, \delta}$  for the  $\infty$ -category of  $\delta$ -small  $\infty$ -categories. In particular, we shall write  $S$  and  $\text{Cat}_\infty$  for  $S_{\delta_0}$  and  $\text{Cat}_{\infty, \delta_0}$ , respectively.
- Let  $C$  be an  $\infty$ -category and  $W \subseteq C_1$  a set of morphisms of  $C$ . Then we write  $W^{-1}C$  for the result of inverting the morphisms of  $W$ . If  $\delta$  is an inaccessible cardinal for which  $C$  is  $\delta$ -small, then  $W^{-1}C$  is  $\delta$ -small as well. This  $\infty$ -category comes equipped with a functor  $C \rightarrow W^{-1}C$  that, for any  $\infty$ -category  $D$ , induces a fully faithful functor

$$\text{Fun}(W^{-1}C, D) \hookrightarrow \text{Fun}(C, D)$$

that identifies  $\text{Fun}(W^{-1}C, D)$  with the full subcategory spanned by those functors  $C \rightarrow D$  that carry the morphisms of  $W$  to equivalences in  $D$ . One can (rather inexplicitly) describe  $W^{-1}C$  by forming the model category of ( $\delta$ -small) marked simplicial sets (over  $\Delta^0$ ), and forming a fibrant replacement of the marked simplicial set  $(C, W)$ .

**o.2.2.** For any  $n \in \mathbb{N}^p$ , write  $\text{Cat}_n \subseteq \text{Cat}_\infty$  for the full subcategory spanned by those  $\infty$ -categories that are equivalent to  $n$ -categories; that is, an  $\infty$ -category  $C$  lies in  $\text{Cat}_n$  if and only if for any  $x, y \in C$ , the  $\infty$ -groupoid  $\text{Map}_C(x, y)$  is equivalent to an  $(n-1)$ -groupoid. In particular,  $\text{Cat}_0 \simeq \text{poSet}$ , the 1-category of partially ordered sets.

The inclusion  $\text{Cat}_n \subseteq \text{Cat}_\infty$  admits a left adjoint  $h_n$  [69]. If  $C$  is a  $\infty$ -category, then the unit  $C \rightarrow h_n C$  exhibits  $h_n C$  as the  $n$ -categorical truncation, so that the objects of

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<sup>6</sup>The adverb ‘essentially’ is often deployed in this situation.

$h_n C$  are exactly those of  $C$  and whose mapping spaces are defined by the condition that the map

$$\mathrm{Map}_C(x, y) \rightarrow \mathrm{Map}_{h_n C}(x, y)$$

exhibits  $\mathrm{Map}_{h_n C}(x, y)$  as the  $(n - 1)$ -truncation of  $\mathrm{Map}_C(x, y)$ . The 1-categorical truncation  $h_1 C$  is also known as the *homotopy category* of  $C$ . The 0-categorical truncation is equivalent to the poset whose elements are the equivalence classes of objects of  $C$  in which  $x \leq y$  if and only if there exists a morphism  $x \rightarrow y$ .

### 0.3 Proobjects in higher categories

**0.3.1.** We say that a  $\delta_0$ -small  $\infty$ -category  $A$  is *inverse* if and only if its opposite  $A^{op}$  is filtered. Hence an *inverse system* in an  $\infty$ -category  $C$  is a functor  $A \rightarrow C$  from an inverse  $\infty$ -category  $A$ , and an *inverse limit* is a limit of an inverse system.

For any accessible  $\infty$ -category  $C$  that admits all finite limits, a *proobject of  $C$*  is an left exact accessible functor  $C \rightarrow \mathcal{S}$ . We define  $\mathrm{Pro}(C) \subseteq \mathrm{Fun}(C, \mathcal{S})^{op}$  for the full subcategory spanned by the proobjects. We have a Yoneda embedding

$$j: C \hookrightarrow \mathrm{Pro}(C),$$

composition along which defines an equivalence

$$\mathrm{Fun}^{inv}(\mathrm{Pro}(C), D) \simeq \mathrm{Fun}(C, D)$$

for any  $\infty$ -category  $D$  with all  $\delta_0$ -small inverse limits, where  $\mathrm{Fun}^{inv}$  denotes the  $\infty$ -category of functors that preserve  $\delta_0$ -small inverse limits.

Recall that an essentially  $\delta_0$ -small  $\infty$ -category  $C$  is idempotent complete if and only if  $C$  is accessible, and every functor from  $C$  is accessible. Hence in this case, the formation of proobjects is dual to the formation of indobjects in the sense that  $\mathrm{Pro}(C)^{op} \simeq \mathrm{Ind}(C^{op})$ .

If  $X: A \rightarrow C$  is an inverse system, then its limit in  $\mathrm{Pro}(C)$  is the functor

$$Y \mapsto \mathrm{colim}_{\alpha \in A^{op}} \mathrm{Map}_C(X_\alpha, Y),$$

we will abuse notation and denote this proobject by  $X = \{X_\alpha\}_{\alpha \in A}$ . Any proobject of  $C$  can be exhibited in this manner, and for proobjects  $X = \{X_\alpha\}_{\alpha \in A}$  and  $Y = \{Y_\beta\}_{\beta \in B}$  we obtain the familiar formula

$$\mathrm{Map}_{\mathrm{Pro}(C)}(X, Y) \simeq \lim_{\beta \in B} \mathrm{colim}_{\alpha \in A^{op}} \mathrm{Map}_C(X_\alpha, Y_\beta).$$

We will thus often speak of objects of  $\mathrm{Pro}(C)$  as if they *were* inverse systems. In particular, a proobject  $X$  is said to be *constant* if and only if it lies in the essential image of  $j$ ; equivalently,  $X$  is constant if and only if, as a functor  $C \rightarrow \mathcal{S}$ , it preserves inverse limits.

**0.3.2.** Let  $\delta \geq \delta_0$  be an inaccessible cardinal,  $C$  a locally  $\delta$ -small  $\infty$ -category that admits all  $\delta_0$ -small limits,  $D$  an accessible  $\infty$ -category that admits finite limits, and  $u: D \rightarrow C$  a left exact functor. The functor  $u$  will not in general admit a left adjoint,



but passage to proobjects often repairs this. Indeed, one may extend  $u$  to a (unique) functor  $U: \text{Pro}(D) \rightarrow C$  that preserves inverse limits, and in the other direction, one may consider the composite

$$F := u^* \circ j: C \rightarrow \text{Fun}(C, \mathbf{S}_\kappa)^{op} \rightarrow \text{Fun}(D, \mathbf{S}_\kappa)^{op}$$

of the Yoneda embedding  $j$  with the restriction along  $u$ . The functor  $F$  carries an object  $c \in C$  to the assignment  $d \mapsto \text{Map}_C(c, u(d))$ . We have to make two set-theoretic assumptions:

- Assume that for any object  $c \in C$  and any object  $d \in D$ , the space  $\text{Map}_C(c, u(d))$  is  $\delta_0$ -small.
- Assume that for any object  $c \in C$ , there exists a regular cardinal  $\tau < \delta_0$  such that for any  $\tau$ -filtered diagram  $d_*: A \rightarrow D$ , the natural map

$$\text{colim}_{\alpha \in A} \text{Map}_C(c, u(d_\alpha)) \rightarrow \text{Map}_C(c, \text{colim}_{\alpha \in A} u(d_\alpha))$$

is an equivalence.

In this case, the functor  $F$  lands in  $\text{Pro}(D)$ , and  $F$  is left adjoint to  $U$ . We shall call  $F$  the *proexistent left adjoint to  $u$* . If  $u$  already admits a left adjoint  $f$ , then  $F$  lands in  $D$  and coincides with  $f$ .

## 0.4 Recollements

**0.4.1.** Given functors  $F: X \rightarrow Z$  and  $G: Y \rightarrow Z$  between  $\infty$ -categories, we write

$$X \downarrow_Z Y := X \times_{\text{Fun}(\{0\}, Z)} \text{Fun}(\Delta^1, Z) \times_{\text{Fun}(\{1\}, Z)} Y.$$

This is the *oriented fibre product* of  $\infty$ -categories.

**0.4.2.** Let  $X$  and  $Y$  be essentially  $\delta_0$ -small  $\infty$ -categories, let  $Z$  be a locally  $\delta_0$ -small  $\infty$ -category, and let  $F: X \rightarrow Z$  and  $G: Y \rightarrow Z$  be functors. Write  $Z' \subset Z$  for the full subcategory spanned by those objects in the image of  $F$  or the image of  $G$ . Then  $Z'$  is essentially  $\delta_0$ -small and the oriented fibre product  $X \downarrow_Z Y$  is equivalent to  $X \downarrow_{Z'} Y$ , whence  $X \downarrow_Z Y$  is essentially  $\delta_0$ -small.

**0.4.3** (see [HA, §A.8]). Let  $C$  be an  $\infty$ -category that admits finite limits. Then two functors  $i_*: C_Z \rightarrow C$  and  $j_*: C_U \rightarrow C$  exhibit  $C$  as a *recollement* of  $C_Z$  and  $C_U$  if and only if the following conditions are satisfied.

- Both  $i_*$  and  $j_*$  are fully faithful.
- There are left exact left adjoints  $i^*$  and  $j^*$  to the functors  $i_*$  and  $j_*$ .
- The functor  $j^* i_*$  is constant at the terminal object of  $C_U$ .
- The functor  $(i^*, j^*): C \rightarrow C_Z \times C_U$  is conservative.

We refer to the  $\infty$ -category  $C_Z$  as the *closed subcategory*, the  $\infty$ -category  $C_U$  as the *open subcategory*, and the functor  $i^* j_* : C_U \rightarrow C_Z$  as the *gluing functor*.

If  $C$  is the recollement of  $\infty$ -categories  $C_Z$  and  $C_U$ , then  $C_Z$  is canonically equivalent to the *kernel* of  $j^*$  (i.e., the full subcategory spanned by those objects  $x$  such that  $j^*(x) \simeq 1_{C_U}$ ).

If  $C_Z$  and  $C_U$  are any  $\infty$ -categories with finite limits, and if  $\phi : C_U \rightarrow C_Z$  is left exact, then we write

$$C_Z \tilde{\cup}^\phi C_U := C_Z \downarrow_{C_Z} C_U.$$

The projections  $i^* : C_Z \tilde{\cup}^\phi C_U \rightarrow C_Z$  and  $j^* : C_Z \tilde{\cup}^\phi C_U \rightarrow C_U$  admit right adjoints  $i_* : C_Z \rightarrow C_Z \tilde{\cup}^\phi C_U$  and  $j_* : C_U \rightarrow C_Z \tilde{\cup}^\phi C_U$  that together exhibit  $C_Z \tilde{\cup}^\phi C_U$  as a recollement of  $C_Z$  and  $C_U$ . Furthermore, any recollement is of this form, where  $\phi$  is the gluing functor.

If  $C_Z$  contains an initial object, then  $j^*$  admits a further left adjoint  $j_!$ , so in this case we may also write  $j^! := j^*$ . If, moreover,  $C$  contains a zero object (whence so do  $C_Z$  and  $C_U$ ), then  $i_*$  admits a further right adjoint  $i^!$ , so in this case we may also write  $i_! := i_*$ .

**o.4.4.** Let  $C$  be an  $\infty$ -category with finite limits and let  $i_* : C_Z \hookrightarrow C$  and  $j_* : C_U \hookrightarrow C$  be two functors which exhibit  $C$  as a recollement of  $C_Z$  and  $C_U$ . Then for any integer  $n \geq -2$ , since the left exact functor  $(i^*, j^*) : C \rightarrow C_Z \times C_U$  is conservative, a morphism  $f$  of  $C$  is  $n$ -truncated if and only if  $i^*(f)$  and  $j^*(f)$  are both  $n$ -truncated.

## o.5 Relative adjunctions

**o.5.1.** Given a commutative triangle of  $\infty$ -categories

$$\begin{array}{ccc} C & \xleftarrow{G} & D \\ & \searrow p & \swarrow q \\ & E & \end{array}$$

where  $p$  and  $q$  are isofibrations, we say that  $G$  *admits a left adjoint relative to  $E$*  if the following condition holds:

- There exists a functor  $F : C \rightarrow D$  and a natural transformation  $\eta : \text{id}_C \rightarrow GF$  which exhibits  $F$  as a left adjoint to  $G$  such that  $p\eta : p \rightarrow pGF \simeq qF$  is an equivalence in  $\text{Fun}(C, E)$ .

In this situation, given a functor  $E' \rightarrow E$ , define  $C_{E'} := C \times_E E'$ ,  $D_{E'} := D \times_E E'$ , and write  $G_{E'} : D_{E'} \rightarrow C_{E'}$  and  $F_{E'} : C_{E'} \rightarrow D_{E'}$  for the induced functors on pullbacks. Then the induced natural transformation  $\text{id}_{C_{E'}} \rightarrow G_{E'} F_{E'}$  exhibits  $F_{E'}$  as a left adjoint to  $G_{E'}$  relative to  $E'$ . See [HA, Proposition 7.3.2.5].

If  $p$  and  $q$  are cartesian fibrations,  $G$  admits a left adjoint relative to  $E$  if and only if the following conditions hold:

- For every object  $e \in E$ , the induced functor  $G_e : D_e \rightarrow C_e$  admits a left adjoint.
- The functor  $G$  carries  $p$ -cartesian morphisms in  $D$  to  $q$ -cartesian morphisms in  $C$ .

See [HA, Proposition 7.3.2.6]. In this case, if  $f: a \rightarrow b$  is a morphism of  $E$ , then one has a natural equivalence

$$f^* G_b \simeq G_a f^* .$$

Dually, if  $p$  and  $q$  are cocartesian fibrations,  $G$  admits a left adjoint relative to  $E$  if and only if the following (somewhat more complicated) conditions hold:

- For every object  $e \in E$ , the induced functor  $G_e: D_e \rightarrow C_e$  admits a left adjoint  $F_e$ .
- Let  $c \in C$  and  $\alpha: e \rightarrow e'$  be a morphism of  $e$  where  $e \simeq p(c)$ . Let  $\tilde{\alpha}: F_e(c) \rightarrow d$  be a  $q$ -cocartesian morphism in  $D$  lying over  $\alpha$ , and let  $\beta: c \rightarrow G(d)$  be the composite  $\beta := G(\tilde{\alpha}) \circ \eta(c)$ . Choose a factorisation of  $\beta$  as

$$\beta: c \xrightarrow{\beta'} c' \xrightarrow{\beta''} G(d) ,$$

where  $\beta'$  is a  $p$ -cocartesian morphism lifting  $\alpha$  and  $\beta''$  is a morphism in  $C_{e'}$ . Then  $\beta''$  induces an equivalence  $F_{e'}(c') \rightarrow d$  in the  $\infty$ -category  $D_{e'}$ .

See [HA, Proposition 7.3.2.11]. In this case, if  $f: a \rightarrow b$  is a morphism of  $E$ , then one has a natural equivalence

$$G_b f_! \simeq f_! G_a .$$

## o.6 Schemes

**o.6.1.** Following the Grothendieck school [SGA 4<sub>III</sub>, Exposé VI, Exemples 1.22; SGA 4<sub>III</sub>, Exposé XVII, 0.12; 42; 63], we say that scheme  $X$  is *coherent* if and only if  $X$  is quasicompact and quasiseparated.

## Part I

# Stratified spaces

## 1 Aide-mémoire on the topology of posets & profinite posets

In this section we review the topologies on posets, and stratifications of topological spaces by posets. We also recall Hochster's Theorem classifying spectral topological spaces in terms of proobjects in finite posets ([Theorem 1.3.4](#)).

### 1.1 Alexandroff Duality

First we start with topologies on posets (and, more generally preorders).

**1.1.1 Definition.** If  $P$  is a preorder (which we shall always assume to be  $\delta_0$ -small), then we endow  $P$  with the *Alexandroff topology*, in which a subset  $U \subseteq P$  is open if and only if  $U$  is a *cosieve* (i.e., if and only if, for any points  $p, q \in P$  with  $p \leq q$ , if  $p \in U$  then  $q \in U$ ), and a subset  $Z \subseteq P$  is closed if and only if  $Z$  is a *sieve* (i.e., if and only if, for any points  $p, q \in P$  with  $p \leq q$ , if  $q \in Z$  then  $p \in Z$ ). A subset  $A \subseteq P$  is locally closed if and only if  $A$  is an interval (i.e., if and only if, for any points  $p, q, r \in P$  with  $p \leq q \leq r$ , if  $p, r \in A$  then  $q \in A$ ).

In the other direction, if  $X$  is a topological space, then the preorder on  $X$  in which  $x \leq y$  if and only if  $x \in \overline{\{y\}}$  is called the *specialisation preorder*.

Alexandroff topologies admit a well-known characterisation.

**1.1.2 Proposition.** *The following are equivalent for a topological space  $X$ .*

- ▶ *The space  $X$  is finitely generated; that is, a subset  $U \subseteq X$  is open if, for any finite topological space  $A$  and any continuous map  $f : A \rightarrow X$ , the inverse image  $f^{-1}(U)$  is open.*
- ▶ *Any union of closed subsets of  $X$  is again closed.*
- ▶ *The topology on  $X$  coincides with the Alexandroff topology attached to the specialisation preorder on  $X$ .*

**1.1.3 (Alexandroff Duality).** The formation  $A$  of the Alexandroff topology and the formation  $S$  of the specialisation preorder are therefore inverse equivalences between the category of preorders and that of finitely generated topological spaces. In particular,  $A$  and  $S$  restrict to an equivalence between the category of finite preorders and that of finite topological spaces.

The functors  $A$  and  $S$  also restrict to an equivalence between:

- ▶ the category of posets and that of Kolmogoroff finitely generated topological spaces,
- ▶ the category of *noetherian* preorders (i.e., those for which every nonempty subset contains a maximal element) and that of quasi-sober finitely generated topological spaces, and thus

- the category of noetherian posets and that of sober finitely generated topological spaces.

**1.1.4 Notation.** Let  $P$  be a preorder. For any subset  $W \subseteq P$ , we write  $P_{\geq W}$  for the cosieve generated by  $W$ , which is the smallest open neighbourhood of  $W$ . Dually, we write  $P_{\leq W}$  for the sieve generated by  $W$ , which is the closure of  $W$ .

We call the sets of the form  $P_{\geq p}$  for  $p \in P$  the *principal open sets*, and we call the sets of the form  $P_{\leq p}$  the *principal ideals*.

Similarly, we write  $P_{> p} := P_{\geq p} \setminus \{p\}$  and  $P_{< p} := P_{\leq p} \setminus \{p\}$ .

**1.1.5.** A poset is quasicompact if and only if its set of minimal elements is finite and limit-cofinal. A monotone map  $f: Q \rightarrow P$  is quasicompact if and only if, for any  $p \in P$ , the poset  $f^{-1}(P_{\geq p})$  is quasicompact.

**1.1.6 Notation.** For a poset  $P$ , recall that  $\text{sd}(P)$  denotes the nerve of the poset of *strings* in  $P$  – i.e., finite, nonempty, totally ordered subsets  $\Sigma \subseteq P$  – ordered by inclusion. One has the natural forgetful functor  $\text{sd}(P) \rightarrow \Delta$ .

If  $\Sigma \subseteq P$  is a string, then a closed subset  $Z \subseteq \Sigma$  is again a string, and the inclusion is denoted  $i_{Z \subseteq \Sigma}$  (or simply  $i$  if  $Z$  and  $\Sigma$  are clear from the context). Dually, an open subset  $U \subseteq \Sigma$  is also a string, and the inclusion is denoted  $j_{U \subseteq \Sigma}$  (or again simply  $j$  if  $U$  and  $\Sigma$  are clear from the context).

In more general situations, we will generally write  $e_{W \subseteq \Sigma}: W \hookrightarrow \Sigma$  for an inclusion  $W \subseteq \Sigma$  that is not known to be either closed or open.

## 1.2 Stratifications of topological spaces

**1.2.1 Definition.** A *stratification* of a topological space  $X$  is poset  $P$  and a continuous map  $f: X \rightarrow P$ . For any point  $p \in P$ , we write

$$\begin{aligned} X_{\geq p} &:= f^{-1}(P_{\geq p}), \\ X_{> p} &:= f^{-1}(P_{> p}), \\ X_{\leq p} &:= f^{-1}(P_{\leq p}), \\ X_{< p} &:= f^{-1}(P_{< p}), \\ X_p &:= X_{\geq p} \cap X_{\leq p}. \end{aligned}$$

The subspaces  $X_{\geq p}$  and  $X_{> p}$  are open in  $X$ , and  $X_{\leq p}$  and  $X_{< p}$  are closed in  $X$ . The subspace  $X_p \subseteq X$ , which is locally closed, is called the  *$p$ -th stratum*.

We say that the stratification  $f: X \rightarrow P$  is *nondegenerate* if each stratum  $X_p$  is nonempty, and for any  $p, q \in P$ , if  $p \leq q$ , then  $X_p \subseteq \overline{X_q}$ . We say that it is *connective* if it is nondegenerate, and each stratum  $X_p$  is connected.

We say that a stratification is *finite* or *noetherian* if and only if its base poset is so. We say that the stratification  $f: X \rightarrow P$  is *constructible* if and only if, for any  $p \in P$ , the open subset  $X_{\geq p} \subseteq X$  is retrocompact – i.e., its intersection with any quasicompact open  $V \subseteq X$  is again quasicompact.

### 1.3 Hochster duality

The functor  $A$  can also be extended to *profinite posets* – i.e., proobjects in the category of finite posets. In order to study stratifications on schemes, this turns out to be convenient.

**1.3.1 Notation.** We write the  $poSet$  for 1-category of posets, and  $poSet^{fin}$  for the 1-category of finite posets. Passing to proobjects, we obtain the 1-category  $Pro(poSet)$  of proposets and the full subcategory  $Pro(poSet^{fin})$  of proobjects in the category of finite posets – which we call *profinite posets*.

**1.3.2 Definition.** For any topological space  $X$ , we write  $FC(X)$  for the 1-category of finite, nondegenerate, constructible stratifications  $X \rightarrow P$ . Please observe that  $FC(X)$  is an inverse 1-category that is (equivalent to) a poset.

A topological space  $S$  is said to be *spectral*<sup>7</sup> if and only if  $S$  is the limit of its finite, nondegenerate, constructible stratifications; that is, if and only if

$$S \simeq \lim_{P \in FC(S)} P$$

in the 1-category of topological spaces.

**1.3.3.** The formation of the Alexandroff topology extends to an equivalence of 1-categories  $A: Pro(poSet^{fin}) \simeq TSp^{spec}$ , where  $TSp^{spec}$  is the 1-category of spectral topological spaces and quasicompact continuous maps. We will therefore fail to distinguish between a spectral topological space and its corresponding profinite poset.

**1.3.4 Theorem (Hochster Duality [34; 35]).** *The following are equivalent for a topological space  $S$ .*

- ▶ *The space  $S$  is spectral.*
- ▶ *The space  $S$  is sober, quasicompact, and quasiseparated; additionally, the set of quasicompact open subsets forms a base for the topology of  $S$ .*
- ▶ *The space  $S$  is homeomorphic to  $Spec R$  for some ring  $R$ .*
- ▶ *The space  $S$  is homeomorphic to the underlying Zariski topological space  $Y^{zar}$  of some coherent scheme  $Y$ .*

**1.3.5.** On one hand, Alexandroff Duality characterises posets as finitely generated topological spaces; on the other, *Stone Duality* characterises profinite sets as *Stone spaces* – totally separated quasicompact topological spaces. Hochster duality provides a common

<sup>7</sup>Others call such topological spaces *coherent*; see for example [SAG, A.1; 48, Chapter III §3.4 & p. 78]. We use Hochster’s algebro-geometric terminology [34; 35].

extension of each of these forms of duality. The situation is summarised in the cube

$$\begin{array}{ccccc}
& \text{Set}^{fin} & \xrightarrow{\sim} & \text{TSpc}^{fin,disc} & \\
& \swarrow & \uparrow & \swarrow & \uparrow \\
\text{Pro}(\text{Set}^{fin}) & \xrightarrow{\sim} & \text{TSpc}^{Stone} & & \\
\downarrow & & \downarrow & & \downarrow \\
& \text{poSet}^{fin} & \xrightarrow{\sim} & \text{TSpc}^{fin} & \\
\downarrow & \swarrow & \downarrow & \swarrow & \\
\text{Pro}(\text{poSet}^{fin}) & \xrightarrow{\sim} & \text{TSpc}^{spec} & & 
\end{array} ,$$

where the horizontal functors marked ‘ $\sim$ ’ are equivalences of 1-categories.

One of our main technical results here – the  $\infty$ -Categorical Hochster Duality Theorem ([Theorem D=Theorem 10.3.1](#)) – will be an extension of this square of dualities to one in which the 1-category of finite sets is replaced with the  $\infty$ -category of  $\pi$ -finite spaces. Part of this extension is already established in the literature: Lurie proves [[SAG](#), §E.3] an  $\infty$ -categorical form of Stone Duality, which identifies the  $\infty$ -category  $\mathcal{S}_\pi^\wedge$  of profinite spaces with the  $\infty$ -category of what we call *Stone  $\infty$ -topoi*.<sup>8</sup>

## 1.4 Materialisation

**1.4.1 Definition.** The *materialisation* of posets is the essentially unique functor

$$\text{mat} : \text{Pro}(\text{poSet}) \rightarrow \text{poSet}$$

that preserves inverse limits and extends the identity functor  $\text{poSet} \rightarrow \text{poSet}$ . If  $\mathbf{P}$  is exhibited as an inverse system  $\{\mathbf{P}_\alpha\}_{\alpha \in A}$  of posets, then  $\text{mat}(\mathbf{P})$  is the limit  $\lim_{\alpha \in A} \mathbf{P}_\alpha$  computed in  $\text{poSet}$ .

**1.4.2 Example.** If  $S$  is a spectral topological space, then  $\text{mat}(S)$  is the specialisation poset on the set of points of  $S$ .

## 1.5 Profinite stratifications

The theory of stratifications also works well for profinite stratifications.

**1.5.1 Definition.** A *profinite stratification* of a topological space  $X$  is a spectral topological space  $S$  and a continuous map  $f : X \rightarrow S$ . We say that  $f$  is *constructible* if and only if, for any quasicompact open subset  $U \subseteq S$ , the inverse image  $f^{-1}(U) \subseteq X$  is retrocompact.

**1.5.2.** A profinite stratification with base  $S$  is the same as a compatible family of stratifications with base  $P$  for each nondegenerate, finite, constructible stratification  $S \rightarrow P$ .

<sup>8</sup>Lurie calls these *profinite  $\infty$ -topoi*.

## 2 Stratified spaces

In this section we develop the homotopy theory of stratified spaces as  $\infty$ -categories with a conservative functor to a poset.

### 2.1 Stratified spaces as conservative functors

The equivalence between the homotopy theory of topological spaces and that of simplicial sets justifies (at least partially) the treatment of the  $\infty$ -category of Kan complexes as ‘the’ homotopy theory of spaces. Analogously, the results of Nand-Lal and Woolf [59] and the third-named author [27] furnish an equivalence between the homotopy theory of stratified topological spaces and that of  $\infty$ -categories with a conservative functor to a poset. We therefore feel entitled to give the following definition.

**2.1.1 Definition.** We define the  $\infty$ -category  $\mathbf{Str}$  as the full subcategory of  $\mathrm{Fun}(\Delta^1, \mathbf{Cat}_\infty)$  spanned by those functors  $f: \Pi \rightarrow P$  in which  $P$  is a poset and  $f$  is a conservative functor. We regard the 1-category  $\mathbf{poSet}$  of posets (always  $\delta_0$ -small) and monotonic maps as a full subcategory of  $\mathbf{Cat}_\infty$ ; indeed one has  $\mathbf{poSet} \simeq \mathbf{Cat}_0$ .

The fibre  $\mathbf{Str}_P$  of the target functor  $t: \mathbf{Str} \rightarrow \mathbf{poSet}$  over a poset  $P$  is the underlying  $\infty$ -category of the third-named author’s Joyal–Kan model category  $\mathbf{sSet}_{/P}$ , whose underlying  $\infty$ -category is equivalent to the  $\infty$ -category of  $P$ -stratified topological spaces [27]. Consequently, we shall call an object of  $\mathbf{Str}$  a *stratified space* and more particularly an object of  $\mathbf{Str}_P$  a *P-stratified space*.

**2.1.2.** Please observe that if  $\Pi$  and  $\Pi'$  are two  $P$ -stratified spaces, then the  $\infty$ -category  $\mathrm{Fun}_P(\Pi, \Pi')$  of functors  $\Pi \rightarrow \Pi'$  over  $P$  is an  $\infty$ -groupoid. We regard this space of functors as the *stratified mapping space*.

### 2.2 Strata & links

**2.2.1 Definition.** If  $f: \Pi \rightarrow P$  is a stratified space, then for every point  $p \in P$ , the space

$$\Pi_p = \mathrm{Map}_P(\{p\}, \Pi)$$

will be called the *p-th stratum* of  $\Pi$ , and for every pair of points  $p, q \in P$  with  $p \leq q$ , the space

$$N_P(\Pi)\{p \leq q\} := \mathrm{Map}_P(\{p \leq q\}, \Pi)$$

will be called the *link*<sup>9</sup> from the *p-th stratum* to the *q-th stratum*.

Please observe that the link comes equipped with source and target maps

$$(s, t): N_P(\Pi)\{p \leq q\} \rightarrow \Pi_p \times \Pi_q,$$

the fibres of which over a point  $(x, y)$  is precisely the space  $\mathrm{Map}_\Pi(x, y)$ . When  $p = q$ , each of  $s$  and  $t$  is an equivalence, whence  $(s, t)$  is equivalent to the diagonal  $\Pi_p \rightarrow \Pi_p \times \Pi_p$ .

---

<sup>9</sup>Our link corresponds to what Frank Quinn and others called the *homotopy link* or *holink*. The significance of our chosen notation will become clear in [Construction 4.2.1](#).



**2.2.2.** A morphism  $\Pi' \rightarrow \Pi$  of  $\mathbf{Str}_P$  is an equivalence if and only if, for every pair of points  $p, q \in P$  with  $p \leq q$ , the map on links  $N_p(\Pi')\{p \leq q\} \rightarrow N_p(\Pi)\{p \leq q\}$  is an equivalence (whence in particular, when  $p = q$ , the map on strata  $\Pi'_p \rightarrow \Pi_p$  is an equivalence).

### 2.3 Repairing functors that are not conservative

If  $f: P \rightarrow Q$  is a morphism of posets, then the functor  $\mathbf{Cat}_{\infty, P} \rightarrow \mathbf{Cat}_{\infty, Q}$  given by postcomposition with  $f$  does not generally send  $P$ -stratified spaces to  $Q$ -stratified spaces. However, this can be easily repaired.

**2.3.1 Construction.** Let  $P$  be a poset. The forgetful functor  $\mathbf{Str}_P \rightarrow \mathbf{Cat}_{\infty, P}$  admits a left adjoint. Indeed, if  $\Pi$  is an  $\infty$ -category, and  $f: \Pi \rightarrow P$  is any functor (not necessarily conservative), we may formally invert those morphisms of  $\Pi$  that are sent to identities in  $P$  as follows. We form

$$\mathrm{Ex}_P(\Pi) := \mathrm{Ex}(\Pi) \times_{\mathrm{Ex}(P)} P,$$

so that an  $n$ -simplex of  $\mathrm{Ex}_P(\Pi)$  is a commutative square

$$\begin{array}{ccc} \mathrm{sd}(\Delta^n) & \longrightarrow & \Pi \\ \lambda \downarrow & & \downarrow f \\ \Delta^n & \longrightarrow & P \end{array}$$

where  $\lambda$  is the last vertex map. Now  $\lambda$  induces a functor  $\Pi \rightarrow \mathrm{Ex}_P(\Pi)$ , and so we are entitled to form the colimit

$$\mathrm{Ex}_P^\infty(\Pi) := \mathrm{colim}_{n \in \mathbb{N}} \mathrm{Ex}_P^n(\Pi) \cong \mathrm{Ex}^\infty(\Pi) \times_{\mathrm{Ex}^\infty(P)} P.$$

Since  $f$  is an inner fibration (as its target is the nerve of an ordinary category), so is  $\mathrm{Ex}^\infty(f)$ , whence so is the projection  $\mathrm{Ex}_P^\infty(\Pi) \rightarrow P$ ; it is also conservative, since the fibre over a point  $p \in P$  is the  $\infty$ -groupoid  $\mathrm{Ex}^\infty(\Pi_p)$ . The functor  $\Pi \rightarrow \mathrm{Ex}_P^\infty(\Pi)$ , natural in  $\Pi$ , is the unit of the desired adjunction.

**2.3.2 Proposition.** *The forgetful functor  $t: \mathbf{Str} \rightarrow \mathbf{poSet}$  is a bicartesian fibration.*

*Proof.* Let  $P$  and  $Q$  be posets, and let  $f: P \rightarrow Q$  be a monotonic map; if  $q: \Xi \rightarrow Q$  is a  $Q$ -stratified space, then one obtains a  $P$ -stratified space  $f^*(q): \Xi \times_P Q \rightarrow Q$ . The resulting square

$$\begin{array}{ccc} \Xi \times_P Q & \longrightarrow & \Xi \\ f^*(q) \downarrow & & \downarrow q \\ P & \xrightarrow{f} & Q \end{array}$$

is a cartesian edge lying over  $f$ . In the other direction, let  $p: \Pi \rightarrow P$  be a  $P$ -stratified space. Then the composite  $f \circ p$  is not in general conservative if  $f$  is not a monomorphism, but one may formally invert those morphisms of  $\Pi$  that are sent to identities by

$f \circ p$ . The square

$$\begin{array}{ccc} \Pi & \longrightarrow & \mathrm{Ex}_Q^\infty(\Pi) \\ p \downarrow & & \downarrow f_!(p) \\ P & \xrightarrow{f} & Q \end{array}$$

is a cocartesian morphism of  $\mathbf{Str}$  over  $f$ .  $\square$

**2.3.3.** To compute the limit of a diagram  $\alpha \mapsto [\Pi_\alpha \rightarrow P_\alpha]$  in  $\mathbf{Str}$ , we first form the limit  $P := \lim_\alpha P_\alpha$ ; then pulling back along the various projections  $p_\alpha: P \rightarrow P_\alpha$ , we obtain the diagram  $\alpha \mapsto p_\alpha^* \Pi_\alpha$  of  $P$ -stratified spaces. We then form the limit  $\Pi := \lim_\alpha \Pi_\alpha$  in  $\mathbf{Str}_P$ . If the diagram is *connected*, then the limit  $\lim_\alpha \Pi_\alpha$  is computed in  $\mathbf{Cat}_\infty$ .

## 2.4 The stratified Postnikov tower

In this subsection we investigate a Postnikov tower for stratified spaces. Importantly, the correct notion of ‘ $n$ -truncatedness’ is *not* the notion of  $n$ -truncatedness internal to the  $\infty$ -category  $\mathbf{Str}_P$  (in the sense of [HTT, §5.5.6]), but rather corresponds to the categorical level of the stratified space.

**2.4.1 Definition.** Let  $P$  be a poset and  $\Pi$  a  $P$ -stratified space. Then we obtain a tower of  $P$ -stratified spaces

$$\Pi \rightarrow \cdots \rightarrow h_3 \Pi \rightarrow h_2 \Pi \rightarrow h_1 \Pi \rightarrow h_0 \Pi \rightarrow P,$$

called the *stratified Postnikov tower*.

In particular, please observe that  $h_0 \Pi \rightarrow P$  is a monotonic map of posets.

**2.4.2.** If  $P = \{0\}$ , then the stratified Postnikov tower coincides with the usual Postnikov tower of spaces.

**2.4.3.** The following are equivalent for a poset  $P$ , a  $P$ -stratified space  $f: \Pi \rightarrow P$ , and a nonnegative integer  $n \in \mathbb{N}$ :

- the  $\infty$ -category  $\Pi$  is equivalent to an  $n$ -category;
- the natural functor  $\Pi \rightarrow h_n \Pi$  is an equivalence;
- for any objects  $x, y \in \Pi$ , the space  $\mathrm{Map}_\Pi(x, y)$  is  $(n-1)$ -truncated;
- for any pair of points  $p, q \in P$  with  $p \leq q$ , the map

$$(s, t): N_P(\Pi)\{p \leq q\} \rightarrow \Pi_p \times \Pi_q$$

is  $(n-1)$ -truncated (whence in particular, when  $p = q$ , the stratum  $\Pi_p$  is  $n$ -truncated).

**2.4.4 Definition.** Let  $P$  be a poset and  $n \in \mathbb{N}$ . We say that a  $P$ -stratified space  $\Pi$  is *n-truncated* if  $\Pi$  satisfies the equivalent conditions of (2.4.3). We write  $\mathbf{Str}_{P, \leq n} \subset \mathbf{Str}_P$  for the full subcategory spanned by the  $n$ -truncated  $P$ -stratified spaces.

We caution that an  $n$ -truncated  $P$ -stratified space is generally *not* the same thing as an  $n$ -truncated object of the  $\infty$ -category  $\mathbf{Str}_P$  in the sense of Lurie [HTT, Definition 5.5.6.1]. Nor is it the same thing as a  $P$ -stratified space whose strata are  $n$ -truncated; truncatedness in our sense involves a condition on the links as well.

**2.4.5.** Dually, the following are equivalent for a poset  $P$ , a  $P$ -stratified space  $f : \Pi \rightarrow P$ , and a nonnegative integer  $n \in \mathbb{N}$ :

- the natural functor  $h_n \Pi \rightarrow P$  is an equivalence;
- for any objects  $x, y \in \Pi$  such that  $f(x) \leq f(y)$ , the space  $\text{Map}_\Pi(x, y)$  is  $n$ -connective;
- for any pair of points  $p, q \in P$  with  $p \leq q$ , the map

$$(s, t) : N_p(\Pi) \{p \leq q\} \rightarrow \Pi_p \times \Pi_q$$

is  $n$ -connective (whence in particular, when  $p = q$ , the stratum  $\Pi_p$  is  $(n + 1)$ -connective).

**2.4.6 Definition.** Let  $P$  be a poset and  $n \in \mathbb{N}$ . We say that a  $P$ -stratified space  $\Pi$  is *n-connective* if  $\Pi$  satisfies the equivalent conditions of (2.4.5). We write  $\mathbf{Str}_{P, \geq n} \subset \mathbf{Str}_P$  for the full subcategory spanned by the  $n$ -connective  $P$ -stratified spaces.

**2.4.7 Definition.** We say that a 1-category is *layered*<sup>10</sup> if and only if every endomorphism is an isomorphism. We say that an  $\infty$ -category  $\Pi$  is *layered* if and only if its homotopy category  $h_1(\Pi)$  is a layered category. This holds if and only if the natural functor  $\Pi \rightarrow h_0(\Pi)$  is conservative. Thus a layered  $\infty$ -category  $\Pi$  is naturally an  $h_0(\Pi)$ -stratified space.

We write  $\mathbf{Lay}_\infty$  for the full subcategory of  $\mathbf{Cat}_\infty$  spanned by the layered  $\infty$ -categories.

**2.4.8.** The assignment  $[\Pi \rightarrow P] \mapsto \Pi$  defines a functor  $\mathbf{Str} \rightarrow \mathbf{Lay}_\infty$  with a fully faithful left adjoint that carries  $\Pi$  to the  $h_0(\Pi)$ -stratified space  $\Pi$ . Consequently, we obtain an identification

$$\mathbf{Lay}_\infty \simeq \mathbf{Str}_{\geq 0} ,$$

where  $\mathbf{Str}_{\geq 0} \subset \mathbf{Str}$  is the full subcategory spanned by the 0-connective stratified spaces.

## 2.5 Finite stratified spaces

We conclude this section by identifying a good finiteness property on stratified spaces.

**2.5.1 Recollection** ([SAG, Definition E.0.7.8]). An  $\infty$ -groupoid  $K$  is said to be  *$\pi$ -finite* if and only if the following conditions are satisfied.

<sup>10</sup>or *EI*, as they are more usually called

- The set  $\pi_0(K)$  is finite.
- For any point  $x \in K$  and any  $i \geq 1$ , the group  $\pi_i(K, x)$  is finite.
- The  $\infty$ -groupoid  $K$  is equivalent to an  $n$ -groupoid for some  $n \in \mathbb{N}$ .

We write  $\mathbf{S}_\pi \subset \mathbf{S}$  for the full subcategory spanned by the  $\pi$ -finite  $\infty$ -groupoids.

We caution that a  $\pi$ -finite  $\infty$ -groupoid is not the same thing as what is normally called a *finite space* – one obtained via finite colimits from  $\Delta^0$ . In fact, the overlap between these two classes of spaces is essentially trivial. In this paper, we shall never refer to finite spaces in this latter sense.

**2.5.2 Definition.** We say that a stratified space  $\Pi \rightarrow P$  is  $\pi$ -finite if and only if the following conditions are satisfied.

- The poset  $P$  is finite.
- For any point  $p \in P$ , the set  $\pi_0(\Pi_p)$  is finite.
- For any morphism  $\phi: x \rightarrow y$  of  $\Pi$ , and every  $i \geq 1$ , the group  $\pi_i(\text{Map}_\Pi(x, y), \phi)$  is finite.
- The  $\infty$ -category  $\Pi$  is equivalent to an  $n$ -category for some  $n \in \mathbb{N}$ .

In particular, a nondegenerate stratified space  $\Pi \rightarrow P$  is  $\pi$ -finite if and only if  $\Pi$  has finitely many objects up to equivalence and is *locally  $\pi$ -finite* in the sense that each mapping space  $\text{Map}_\Pi(x, y)$  is  $\pi$ -finite.

We write  $\mathbf{Str}_\pi \subset \mathbf{Str}$  for the full subcategory spanned by the  $\pi$ -finite stratified spaces, and for any finite poset  $P$ , we write  $\mathbf{Str}_{\pi, P} \subset \mathbf{Str}_P$  for the full subcategory spanned by the  $\pi$ -finite  $P$ -stratified spaces.

**2.5.3.** The forgetful functor  $t: \mathbf{Str}_\pi \rightarrow \text{poSet}^{\text{fin}}$  is a cartesian fibration, but is not a cocartesian fibration because pullback doesn't admit a left adjoint in the finite realm. However, the pullback does preserve finite limits, and there is a proexistent left adjoint, which we will discuss in the next section.

**2.5.4 Lemma.** *The full subcategory  $\mathbf{Str}_\pi \subset \mathbf{Str}$  is an accessible subcategory that is closed under finite limits.*

*Proof.* Finite limits of finite posets are finite, pullbacks of finite stratified spaces along maps of finite posets are finite, and limits of locally  $\pi$ -finite  $\infty$ -categories are locally  $\pi$ -finite. Finally,  $\mathbf{Str}_\pi$  is essentially  $\delta_0$ -small and idempotent complete.  $\square$

In light of (0.3.2), this entitles us to speak of profinite stratified spaces, to which we now turn.

### 3 Profinite stratified spaces

In this section we set up the basics of proobjects in  $\pi$ -finite stratified spaces – *profinite stratified spaces*.

### 3.1 Stratified propspaces over posets

**3.1.1 Definition.** We call objects of the  $\infty$ -category  $\text{Pro}(\mathbf{Str})$  *stratified propspaces*; the forgetful functor  $t: \mathbf{Str} \rightarrow \text{poSet}$  from stratified spaces to posets extends to a forgetful functor

$$t: \text{Pro}(\mathbf{Str}) \rightarrow \text{Pro}(\text{poSet}).$$

The fibre  $\text{Pro}(\mathbf{Str})_P$  over a poset  $P$ , regarded as a constant propset, can be identified with the  $\infty$ -category  $\text{Pro}(\mathbf{Str}_P)$  of  $P$ -stratified propspaces – i.e., of proobjects in  $\mathbf{Str}_P$ .

Similary, if  $P$  is a propset, then the fibre  $\text{Pro}(\mathbf{Str})_P$  of  $t$  over  $P$  will be called the  $\infty$ -category of  $P$ -stratified propspaces.

**3.1.2.** A stratified propspace can be exhibited as an inverse system  $\{\Pi_\alpha \rightarrow P_\alpha\}_{\alpha \in A}$  of stratified spaces. The functor  $t$  carries this stratified propspace to the propset  $\{P_\alpha\}_{\alpha \in A}$ .

**3.1.3 Example.** Our primary interest is when the base is a spectral topological space  $S$  regarded as a profinite poset, whence we obtain the  $\infty$ -category  $\text{Pro}(\mathbf{Str})_S$  of  $S$ -stratified propspaces. Still, in order to reason effectively with these, it is occasionally necessary to deal with more general stratified propspaces.

**3.1.4.** Please observe that the forgetful functor  $t: \text{Pro}(\mathbf{Str}) \rightarrow \text{Pro}(\text{poSet})$  is a cartesian fibration. Indeed, if  $\{P'_\alpha\}_{\alpha \in A} \rightarrow \{P_\alpha\}_{\alpha \in A}$  is a morphism of propsets, and if  $\{\Pi_\alpha \rightarrow P_\alpha\}_{\alpha \in A}$  is a stratified propspace, then one may form  $\{\Pi_\alpha \times_{P_\alpha} P'_\alpha\}_{\alpha \in A}$ .

**3.1.5 Construction.** Let  $\eta: P \rightarrow Q$  a morphism of propsets where  $Q$  is constant, so that  $\eta \in P(Q)$ . For a  $P$ -stratified propspace  $\Pi$ , there exists a  $t$ -cocartesian edge  $\Pi \rightarrow \eta_! \Pi$  covering  $\eta$ ; indeed, for any  $Q$ -stratified space  $X$ , one has

$$(\eta_! \Pi)(X) \simeq \Pi(X) \times_{P(Q)} \{\eta\}.$$

Equivalently, if we exhibit  $\Pi$  as an inverse system  $\{\Pi_\alpha \rightarrow P_\alpha\}_{\alpha \in A}$  in  $\mathbf{Str}$ , then the  $Q$ -stratified propspace  $\eta_! \Pi$  can be exhibited as the inverse system  $A \times_{\text{poSet}} \text{poSet}/Q \rightarrow \mathbf{Str}_Q$  given by

$$(\alpha, P_\alpha \rightarrow Q) \mapsto \text{Ex}_Q^\infty(\Pi_\alpha).$$

Note in particular that if  $P$  and  $\Pi$  are constant, then so is  $\eta_! \Pi$ .

In the  $\infty$ -category  $\text{Pro}(\mathbf{Str})$ , the inverse system  $\text{poSet}_{P/} \rightarrow \mathbf{Str}$  given by  $\eta \mapsto \eta_! \Pi$  is identified with  $\Pi$  itself.

Now if  $\theta: P' \rightarrow P$  is any morphism of propsets and if  $\Pi'$  is a  $P'$ -stratified propspace, then we may form the inverse system  $\text{poSet}_{P/} \rightarrow \mathbf{Str}$  given by  $\eta \mapsto (\eta \circ \theta)_! \Pi'$ , which defines a propset  $\theta_! \Pi'$ , and as this notation suggests, the morphism  $\Pi' \rightarrow \theta_! \Pi'$  is a  $t$ -cocartesian edge over  $\theta$ . Thus  $t: \text{Pro}(\mathbf{Str}) \rightarrow \text{Pro}(\text{poSet})$  is a cocartesian fibration.

We thus combine the previous two points:

**3.1.6 Proposition.** *The forgetful functor  $t: \text{Pro}(\mathbf{Str}) \rightarrow \text{Pro}(\text{poSet})$  is a bicartesian fibration.*

### 3.2 Profinite stratified spaces

We now turn to proobjects in  $\pi$ -finite stratified spaces.

**3.2.1 Definition.** A *profinite stratified space* is a proobject of the  $\infty$ -category  $\mathbf{Str}_\pi$ . We write  $\mathbf{Str}_\pi^\wedge := \mathrm{Pro}(\mathbf{Str}_\pi)$ . The forgetful functor  $[\mathbf{I} \rightarrow S] \mapsto S$  is a cartesian fibration

$$t : \mathbf{Str}_\pi^\wedge \rightarrow \mathbf{TSp}^{spec} \simeq \mathrm{Pro}(\mathbf{poSet}^{fin}),$$

and for any spectral topological space  $S$ , we denote by  $\mathbf{Str}_{\pi,S}^\wedge$  the fibre over  $S$ . This is the  $\infty$ -category of *profinite  $S$ -stratified spaces*.

The inclusion  $\mathbf{Str}_\pi \hookrightarrow \mathbf{Str}$  extends to a fully faithful functor  $\mathbf{Str}_\pi^\wedge \hookrightarrow \mathrm{Pro}(\mathbf{Str})$ , which admits a left adjoint  $\mathbf{I} \mapsto \mathbf{I}_\pi^\wedge$  given by restriction. We call the profinite stratified space  $\mathbf{I}_\pi^\wedge$  the *profinite completion* of  $\mathbf{I}$ .

**3.2.2.** The profinite completion functor  $\mathbf{I} \mapsto \mathbf{I}_\pi^\wedge$  is not itself a relative left adjunction over  $\mathrm{Pro}(\mathbf{poSet})$ ; however, the inclusion  $\mathbf{Str}_\pi \hookrightarrow \mathbf{Str}$  induces a fully faithful functor

$$\mathbf{Str}_\pi^\wedge \hookrightarrow \mathrm{Pro}(\mathbf{Str}) \times_{\mathrm{Pro}(\mathbf{poSet})} \mathbf{TSp}^{spec},$$

and profinite completion *does* define a relative left adjoint over  $\mathbf{TSp}^{spec}$ . In particular, if  $S$  is a spectral topological space and  $\mathbf{I}$  is an  $S$ -stratified prospace, then  $\mathbf{I}_\pi^\wedge$  is a profinite  $S$ -stratified space, and the morphism  $\mathbf{I} \rightarrow \mathbf{I}_\pi^\wedge$  lies over  $S$ .

**3.2.3 Construction.** Let  $\theta : S' \rightarrow S$  be a quasicompact continuous map of spectral topological spaces, and let  $\mathbf{I}' \rightarrow S'$  be a profinite  $S'$ -stratified space. Then following [Construction 3.1.5](#), we obtain an  $S$ -stratified prospace  $\theta_! \mathbf{I}' \rightarrow S$ , and so we may form its profinite completion  $(\theta_! \mathbf{I}')_\pi^\wedge \rightarrow S$ . The map  $\mathbf{I}' \rightarrow (\theta_! \mathbf{I}')_\pi^\wedge$  is thus a cocartesian edge over  $\theta$  for the forgetful functor  $t : \mathbf{Str}_\pi^\wedge \rightarrow \mathbf{TSp}^{spec}$ .

We thus obtain:

**3.2.4 Proposition.** *The forgetful functor  $t : \mathbf{Str}_\pi^\wedge \rightarrow \mathbf{TSp}^{spec}$  is a bicartesian fibration.*

**3.2.5 Proposition.** *Let  $S$  be a spectral topological space. Then the natural functor*

$$\mathbf{Str}_{\pi,S}^\wedge \rightarrow \lim_{P \in \mathrm{FC}(S)} \mathbf{Str}_{\pi,P}^\wedge$$

*is an equivalence.*

*Proof.* The formation of the limit in  $\mathbf{Str}_\pi^\wedge$  is an inverse. □

## 4 Spatial décollages

In this section we develop an approach to stratified spaces in the style of complete Segal spaces. Precisely, we show that a  $P$ -stratified space can be ‘glued together’ from the diagram of its strata, links, and higher-order links ([Theorem 4.2.4](#)).

## 4.1 Complete Segal spaces & spatial décollages

**4.1.1 Recollection.** An  $\infty$ -category can be modeled as a simplicial *space*. In effect, if  $C$  is an  $\infty$ -category, then one may extract a functor  $N(C): \Delta^{op} \rightarrow \mathbf{S}$  in which  $N(C)_m$  is the  $\infty$ -groupoid of functors  $\Delta^m \rightarrow C$  (the ‘moduli space of sequences of arrows in  $C$ ’). The simplicial space  $N(C)$  is what Charles Rezk [65] called a *complete Segal space* – i.e., a functor  $D: \Delta^{op} \rightarrow \mathbf{S}$  such that the following conditions obtain.

- For any  $m \in \mathbb{N}^*$ , the natural map

$$D_m \rightarrow D\{0 \leq 1\} \times_{D\{1\}} D\{1 \leq 2\} \times_{D\{2\}} \cdots \times_{D\{m-1\}} D\{m-1 \leq m\}$$

is an equivalence.

- If  $E$  denotes the unique contractible 1-groupoid with two objects, then the natural map

$$D_0 \rightarrow \text{Map}(E, D)$$

is an equivalence.

Joyal and Tierney [49] showed that the assignment  $C \mapsto N(C)$  is an equivalence between the  $\infty$ -category  $\text{Cat}_\infty$  of  $\infty$ -categories and the  $\infty$ -category  $\text{CSS}$  of complete Segal spaces.

We can isolate the  $\infty$ -groupoids in  $\text{CSS}$ : an  $\infty$ -category  $C$  is an  $\infty$ -groupoid if and only if  $N(C): \Delta^{op} \rightarrow \mathbf{S}$  is left Kan extended from  $\{0\} \subset \Delta^{op}$ .

We shall demonstrate that the homotopy theory of stratified spaces admits an analogous description.

**4.1.2 Notation.** For a poset  $P$ , write  $\text{sd}^{op}(P) := \text{sd}(P)^{op}$ .

**4.1.3 Definition.** Let  $P$  be a poset. A functor  $D: \text{sd}^{op}(P) \rightarrow \mathbf{S}$  is said to be a *spatial décollage (over  $P$ )* if and only if, for any string  $\{p_0 \leq \cdots \leq p_m\} \subseteq P$ , the map

$$D\{p_0 \leq \cdots \leq p_m\} \rightarrow D\{p_0 \leq p_1\} \times_{D\{p_1\}} D\{p_1 \leq p_2\} \times_{D\{p_2\}} \cdots \times_{D\{p_{m-1}\}} D\{p_{m-1} \leq p_m\}$$

is an equivalence. We write

$$\text{Déc}_P(\mathbf{S}) \subseteq \text{Fun}(\text{sd}^{op}(P), \mathbf{S})$$

for the full subcategory spanned by the spatial décollages.

**4.1.4 Construction.** Write  $J$  for the following 1-category. The objects are pairs  $(P, \Sigma)$  consisting of a poset  $P$  and a string  $\Sigma \subseteq P$ . A morphism  $(P, \Sigma) \rightarrow (Q, T)$  is a monotonic map  $f: P \rightarrow Q$  such that  $T \subseteq f(\Sigma)$ . The assignment  $(P, \Sigma) \mapsto P$  is a cocartesian fibration  $J \rightarrow \text{poSet}$  whose fibre over a poset  $P$  is the poset  $\text{sd}^{op}(P)$ .

We write

$$\text{Pair}_{\text{poSet}}(J, \mathbf{S})$$

for the simplicial set over  $poSet$  defined by the following universal property: for any simplicial set  $K$  over  $poSet$ , one demands a bijection

$$\text{Mor}_{sSet/poSet}(K, \text{Pair}_{poSet}(J, S)) \cong \text{Mor}_{sSet}(K \times_{poSet} J, S),$$

natural in  $K$ . By [HTT, Corollary 3.2.2.13], the functor

$$\text{Pair}_{poSet}(J, S) \rightarrow poSet$$

is a cartesian fibration whose fibre over a poset  $P$  is the  $\infty$ -category  $\text{Fun}(\text{sd}^{op}(P), S)$ . Now let

$$\mathbf{D}\acute{e}c(S) \subset \text{Pair}_{poSet}(J, S)$$

denote the full subcategory spanned by the pairs  $(P, D)$  in which  $D$  is a spatial d  collage. Since  $\mathbf{D}\acute{e}c(S)$  contains all the cartesian edges, the functor  $\mathbf{D}\acute{e}c(S) \rightarrow poSet$  is a cartesian fibration.

## 4.2 The nerve of a stratified space

We shall now show that the  $\infty$ -category  $\mathbf{Str}$  of stratified spaces and the  $\infty$ -category  $\mathbf{D}\acute{e}c(S)$  of d  collages are equivalent over  $poSet$ .

**4.2.1 Construction.** Let  $P$  be a poset. Any string contained in  $P$  can be regarded as a  $P$ -stratified space via the inclusion map. This assignment is a functor  $\text{sd}(P) \rightarrow \mathbf{Str}_P$ . Now for any  $P$ -stratified space  $\Pi$ , let us define  $N_P(\Pi) : \text{sd}^{op}(P) \rightarrow S$  to be the functor given by the assignment  $\Sigma \mapsto \text{Map}_P(\Sigma, \Pi)$ . (This is the moduli space of sections over  $\Sigma$ .) An equivalence of  $P$ -stratified spaces is carried to an objectwise equivalence of functors; hence this defines a functor

$$N_P : \mathbf{Str}_P \rightarrow \text{Fun}(\text{sd}^{op}(P), S).$$

Furthermore, the assignment  $[\Pi \rightarrow P] \mapsto (P, N_P(\Pi))$  defines a functor

$$N : \mathbf{Str} \rightarrow \text{Pair}_{poSet}(J, S).$$

**4.2.2 Example.** For any poset  $P$ , any  $P$ -stratified space  $\Pi$ , and any points  $p, q \in P$  such that  $p \leq q$ , the space

$$N_P(\Pi)\{p \leq q\} \simeq \text{Map}_P(\{p \leq q\}, \Pi)$$

is the link between the  $p$ -th and  $q$ -th strata of  $\Pi$ .

Let us demonstrate that the functor  $N$  lands in the full subcategory

$$\mathbf{D}\acute{e}c(S) \subset \text{Pair}_{poSet}(J, S).$$

**4.2.3 Lemma.** *For any poset  $P$  and any  $P$ -stratified space  $\Pi$ , the functor  $N_P(\Pi)$  is a spatial d  collage.*



*Proof.* In  $\mathbf{Cat}_{\infty/P}$ , for any string  $\{p_0 \leq \dots \leq p_n\} \subseteq P$ , one has an equivalence

$$\{p_0 \leq p_1\} \cup^{\{p_1\}} \dots \cup^{\{p_{n-1}\}} \{p_{n-1} \leq p_n\} \simeq \{p_0 \leq \dots \leq p_n\},$$

which induces an equivalence

$$\mathrm{Map}_P(\{p_0 \leq \dots \leq p_n\}, \Pi) \simeq \mathrm{Map}_P(\{p_0 \leq p_1\}, \Pi) \times_{\Pi_{p_1}} \dots \times_{\Pi_{p_{n-1}}} \mathrm{Map}_P(\{p_{n-1} \leq p_n\}, \Pi),$$

as desired.  $\square$

**4.2.4 Theorem.** *The functor  $N : \mathbf{Str} \rightarrow \mathbf{D}\acute{\mathbf{e}}\mathbf{c}(\mathbf{S})$  is an equivalence of  $\infty$ -categories over  $\mathbf{poSet}$ .*

*Proof.* Let  $P$  be a poset. The Joyal–Tierney theorem [49] implies that the functor

$$N : \mathbf{Cat}_{\infty/P} \rightarrow \mathrm{Fun}(\Delta_{/P}^{op}, \mathbf{S})_{/NP} \simeq \mathrm{Fun}(\Delta_{/P}^{op}, \mathbf{S})$$

is fully faithful, and the essential image  $\mathbf{CSS}_{/NP}$  consists of those functors  $\Delta_{/P}^{op} \rightarrow \mathbf{S}$  that satisfy both the Segal condition and the completeness condition. At the same time, the fully faithful functor  $i : \mathrm{sd}(P) \hookrightarrow \Delta_{/P}$  induces, via left Kan extension, a fully faithful functor  $\mathbf{D}\acute{\mathbf{e}}\mathbf{c}_P(\mathbf{S}) \hookrightarrow \mathbf{CSS}_{/NP}$  whose essential image consists of those complete Segal spaces  $C \rightarrow NP$  such that for any  $p \in P$ , the complete Segal space  $C_p$  is an  $\infty$ -groupoid.  $\square$

**4.2.5.** The nerve  $N$  restricts to an equivalence of  $\infty$ -categories  $\mathbf{Str}_\pi \simeq \mathbf{D}\acute{\mathbf{e}}\mathbf{c}(\mathbf{S}_\pi)$ , where  $\mathbf{D}\acute{\mathbf{e}}\mathbf{c}(\mathbf{S}_\pi)$  denotes the full subcategory of  $\mathbf{D}\acute{\mathbf{e}}\mathbf{c}(\mathbf{S})$  spanned by those pairs  $(P, D)$  where  $P$  is a finite poset and  $D$  is a spatial décollage on  $P$  whose values are all  $\pi$ -finite.

### 4.3 Profinite spatial décollages

We now extend the theory of décollages to proobjects.

**4.3.1.** We extend  $N$  to proobjects to obtain an equivalence of  $\infty$ -categories

$$N : \mathrm{Pro}(\mathbf{Str}) \simeq \mathrm{Pro}(\mathbf{D}\acute{\mathbf{e}}\mathbf{c}(\mathbf{S}))$$

over  $\mathrm{Pro}(\mathbf{poSet})$ .

**4.3.2 Recollection.** We regard  $\mathbf{S}_\pi^\wedge := \mathrm{Pro}(\mathbf{S}_\pi)$  as a full subcategory of the  $\infty$ -category  $\mathrm{Pro}(\mathbf{S})$ . Precomposition with the inclusion  $\mathbf{S}_\pi \hookrightarrow \mathbf{S}$  is *profinite completion*  $X \mapsto X_\pi^\wedge$ , which exhibits  $\mathbf{S}_\pi^\wedge$  as a localisation of  $\mathrm{Pro}(\mathbf{S})$ .

There are two monoidal structures on  $\mathrm{Pro}(\mathbf{S})$  one may contemplate. On one hand, one has the cartesian symmetric monoidal structure. On the other, the composition of two prospaces is again a prospace, whence we obtain a monoidal structure

$$(X, Y) \mapsto X \circ Y.$$

The identity functor, which is the unit for  $\circ$ , is terminal in  $\mathrm{Pro}(\mathbf{S})$ , and there certainly is a morphism  $X \circ Y \rightarrow X \times Y$  that is natural in  $X$  and  $Y$ , but it is not an equivalence in general.

However, on the  $\infty$ -category  $\mathcal{S}_\pi^\wedge$  of profinite  $\infty$ -groupoids, we can consider the profinite completion  $(X, Y) \mapsto (X \circ Y)_\pi^\wedge$ , and we claim that the morphism

$$(X \circ Y)_\pi^\wedge \rightarrow X \times Y$$

is an equivalence. Indeed, we claim that the value of the natural transformation  $X \times Y \rightarrow X \circ Y$  on any truncated space  $K$  is an equivalence.<sup>11</sup> Exhibit  $X$  and  $Y$ , respectively, as inverse systems  $\{X_\alpha\}_{\alpha \in A}$  and  $\{Y_\beta\}_{\beta \in B}$  of  $\pi$ -finite  $\infty$ -groupoids. For each  $\alpha \in A$ , the  $\infty$ -groupoid  $X_\alpha$  can be exhibited as a simplicial set with only finitely many nondegenerate simplices of each dimension, whence the functor corepresented by  $X_\alpha$  preserves filtered colimits of uniformly truncated spaces. Since  $K$  is truncated, the filtered diagram  $\beta \mapsto \text{Map}(Y_\beta, K)$  is uniformly truncated. Hence

$$\begin{aligned} (X \times Y)(K) &\simeq \text{colim}_{\alpha \in A^{op}} \text{Map}(X_\alpha, \text{colim}_{\beta \in B^{op}} \text{Map}(Y_\beta, K)) \\ &\simeq \text{colim}_{(\alpha, \beta) \in A^{op} \times B^{op}} \text{Map}(X_\alpha \times Y_\beta, K) \simeq (X \circ Y)(K), \end{aligned}$$

as desired.

This is helpful for describing fibre products in  $\mathcal{S}_\pi^\wedge$  as well: if  $p: X \rightarrow Z$  and  $q: Y \rightarrow Z$  are two morphisms of profinite  $\infty$ -groupoids, then one may identify the pullback  $X \times_Z Y$  of  $p$  along  $q$  with a cobar construction:

$$X \times_Z Y \simeq \lim_{m \in \Delta} (X \circ Z^{\circ m} \circ Y)_\pi^\wedge.$$

**4.3.3 Construction.** For any finite poset  $P$ , write  $\mathbf{D}\acute{e}c_P(\mathcal{S}_\pi^\wedge)$  for the full subcategory of  $\text{Fun}(\text{sd}^{op}(P), \mathcal{S}_\pi^\wedge)$  spanned by those functors

$$D: \text{sd}^{op}(P) \rightarrow \mathcal{S}_\pi^\wedge$$

such that for any string  $\{p_0 \leq \dots \leq p_n\} \subseteq P$ , the natural map

$$D\{p_0 \leq \dots \leq p_n\} \rightarrow \lim_{m \in \Delta} (D\{p_0 \leq p_1\} \circ D\{p_1\}^{\circ m} \circ \dots \circ D\{p_{n-1}\}^{\circ m} \circ D\{p_{n-1} \leq p_n\})_\pi^\wedge$$

is an equivalence of profinite spaces. We call objects of  $\mathbf{D}\acute{e}c_P(\mathcal{S}_\pi^\wedge)$  *profinite d\acute{e}collages over  $P$* .

Combining the equivalence

$$\text{Pro}(\text{Fun}(\text{sd}^{op}(P), \mathcal{S}_\pi)) \simeq \text{Fun}(\text{sd}^{op}(P), \mathcal{S}_\pi^\wedge)$$

furnished by [HTT, Proposition 5.3.5.15] with the equivalences (4.2.5) and (4.3.1), we obtain equivalences of  $\infty$ -categories

$$\mathbf{Str}_{\pi, P}^\wedge \simeq \text{Pro}(\mathbf{D}\acute{e}c_P(\mathcal{S}_\pi)) \simeq \mathbf{D}\acute{e}c_P(\mathcal{S}_\pi^\wedge).$$

<sup>11</sup>We are grateful to Jacob Lurie for this observation.

## Part II

# Elements of higher topos theory

## 5 Aide-mémoire on higher topoi

In this section we recall a number of important results from higher topos theory (mostly from Jacob Lurie’s [SAG, Appendices A & E]), and we develop some basic results that we’ll use throughout the rest of the paper. This section is here mostly for ease of reference, and we make no pretence to originality.

### 5.1 Higher topoi

We begin by setting our basic notational conventions for higher topoi.

**5.1.1 Notation.** We use here the theory of  $n$ -topoi for  $n \in \mathbb{N}^b$ ; see [HTT, Chapter 6]. We write  $\mathbf{Top}_n \subset \mathbf{Cat}_{\infty, \delta_1}$  for the subcategory of  $\delta_1$ -small  $n$ -topoi and geometric morphisms. All of the examples in this paper will have  $n \in \{0, 1, \infty\}$ .

For any  $\delta_0$ -small  $\infty$ -category  $C$ , we write  $\mathbf{P}(C) := \mathbf{Fun}(C^{op}, \mathbf{S})$  for the  $\infty$ -topos of presheaves of spaces on  $C$ .

**5.1.2 Example.** Recall that 0-topoi are locales (which are essentially  $\delta_0$ -small) [HTT, Proposition 6.4.2.5], and 1-topoi are topoi in the classical sense of Grothendieck [HTT, Remark 6.4.1.3].

**5.1.3 Example.** Let  $m, n \in \mathbb{N}^b$  with  $m \leq n$ . By an  $m$ -site, we mean a  $\delta_0$ -small  $m$ -category  $X$  equipped with a Grothendieck topology  $\tau$ . Attached to this  $m$ -site is the  $n$ -topos  $\mathbf{Sh}_{\tau, \leq (n-1)}(X)$  of sheaves of  $\delta_0$ -small  $(n-1)$ -groupoids on  $X$ .

Not all  $\infty$ -topoi are of the form  $\mathbf{Sh}_\tau(X)$  for some  $\infty$ -site  $X$ ; however, if  $n \in \mathbb{N}$ , then every  $n$ -topos is of the form  $\mathbf{Sh}_{\tau, \leq (n-1)}(X)$  for some  $n$ -site  $(X, \tau)$  [HTT, Theorem 6.4.1.5(1)].

**5.1.4 Example.** For any topological space  $W$ , denote by  $\widetilde{W}$  the 0-localic  $\infty$ -topos of sheaves of  $(\delta_0$ -small) spaces on  $W$ .

**5.1.5 Notation.** The  $\infty$ -topos  $\mathbf{S}$  is terminal in  $\mathbf{Top}_\infty$ . For any  $\infty$ -topos  $X$ , we write  $\Gamma_{X,*}$  or  $\Gamma_*$  for the essentially unique geometric morphism  $X \rightarrow \mathbf{S}$ ; the functor  $\Gamma_*$  is corepresented by the terminal object  $1_X \in X$ . A *point* of  $X$  is a geometric morphism  $x_* : \mathbf{S} \rightarrow X$ ; we may also write  $\tilde{x}$  for this copy of  $\mathbf{S}$ , regarded as lying over  $X$  via  $x_*$ .

**5.1.6 Recollection.** Let  $X$  and  $Y$  be  $\infty$ -topoi. A geometric morphism  $j_* : X \rightarrow Y$  is *étale* if  $j^*$  admits a further left adjoint  $j_! : X \rightarrow Y$  that exhibits  $X$  as the slice  $\infty$ -topos  $Y_{/j_!(1_X)}$ . By [HTT, Corollary 6.3.5.6], the functor

$$\mathbf{Fun}_*(Z, X) \rightarrow \mathbf{Fun}_*(Z, Y)$$

is a right fibration whose fibre over a geometric morphism  $f_* : Z \rightarrow Y$  is the (essentially  $\delta_0$ -small) Kan complex  $\mathbf{Map}_X(1_X, f^* j_!(1_X))$ .

**5.1.7 Notation.** Let  $X$  and  $Y$  be two  $n$ -topoi for some  $n \in \mathbb{N}^\flat$ . We write  $\text{Fun}_*(X, Y) \subseteq \text{Fun}(X, Y)$  for the full subcategory spanned by the geometric morphisms. We note that  $\text{Fun}_*(X, Y)$  is accessible [HTT, Proposition 6.3.1.13]. We write  $\text{Fun}^*(Y, X) \subseteq \text{Fun}(Y, X)$  for the full subcategory spanned by those functors that are left exact left adjoints, so that  $\text{Fun}^*(Y, X) \simeq \text{Fun}_*(X, Y)^{op}$ .

**5.1.8.** If  $X$  and  $Y$  are  $\infty$ -topoi, the product  $X \times Y$  in  $\mathbf{Top}_\infty$  is *not* the product of  $\infty$ -categories; rather, it can be identified with the tensor product of presentable  $\infty$ -categories.<sup>12</sup>

Similarly, if  $f_* : X \rightarrow Z$  and  $g_* : Y \rightarrow Z$  are geometric morphisms, then the pullback  $X \times_Z Y$  in  $\mathbf{Top}_\infty$  exists [HTT, Proposition 6.3.4.6], but it is not the pullback of  $\infty$ -categories.

Finally, there is an *oriented fibre product* of  $\infty$ -topoi – which we will study in detail in Section 6 – which also does not coincide with the oriented fibre product of  $\infty$ -categories. We will therefore endeavour to indicate clearly when a product, pullback, or oriented fibre product is meant to be formed in  $\mathbf{Top}_\infty$  or some  $\mathbf{Cat}_{\infty, K}$ .

We repeatedly make use of the fact that inverse limits in  $\mathbf{Top}_\infty$  are computed in  $\mathbf{Cat}_{\infty, \delta_1}$ .

**5.1.9 Theorem** ([HTT, Theorem 6.3.3.1]). *The forgetful functor  $\mathbf{Top}_\infty \rightarrow \mathbf{Cat}_{\infty, \delta_1}$  preserves inverse limits.*

## 5.2 Boundedness

We now turn to the first of two finiteness conditions that we impose on almost all of the  $\infty$ -topoi we consider in this paper.

**5.2.1 Notation.** If  $m, n \in \mathbb{N}^\flat$  with  $m < n$ , then passage to  $(m - 1)$ -truncated objects is a functor

$$\tau_{\leq m-1} : \mathbf{Top}_n \rightarrow \mathbf{Top}_m.$$

In particular, when  $m = 0$ , we write  $\text{Open}$  for  $\tau_{\leq -1}$ , and we call a  $(-1)$ -truncated object of an  $n$ -topos  $X$  an *open in  $X$* .

For any  $\infty$ -topos  $X$ , write

$$X_{<\infty} := \text{colim}_{n \in \mathbb{N}} \tau_{\leq n} X \subseteq X$$

for the full subcategory spanned by the truncated objects.

**5.2.2 Definition.** If  $m, n \in \mathbb{N}^\flat$  with  $m < n$ , then the functor  $\tau_{\leq m-1} : \mathbf{Top}_n \rightarrow \mathbf{Top}_m$  admits a fully faithful right adjoint. Write  $\mathbf{Top}_n^m \subseteq \mathbf{Top}_n$  for the essential image of this functor; this consists of those  $n$ -topoi  $X$  such that, for every  $n$ -topos  $Y$ , the functor

$$\text{Fun}_*(Y, X) \rightarrow \text{Fun}_*(\tau_{\leq m-1} Y, \tau_{\leq m-1} X)$$

is an equivalence. We call such  $n$ -topoi  *$m$ -localic* [HTT, §6.4.5].

<sup>12</sup>For this reason, Lurie writes  $X \otimes Y$  for the product in  $\mathbf{Top}_\infty$ .

**5.2.3.** If  $n \in N$ , then the proof of [HTT, Proposition 6.4.5.9] demonstrates that an  $\infty$ -topos  $X$  is  $n$ -localic if and only if  $X \simeq \mathbf{Sh}_\tau(X)$ , where  $(X, \tau)$  is a  $\delta_0$ -small  $n$ -site *with all finite limits*.

**5.2.4 Example.** If  $W$  is a topological space, then  $\widetilde{W}$  is 0-localic.

**5.2.5 Example.** If  $X$  is a scheme, then the  $\infty$ -topos  $X_{\text{ét}}$  of étale sheaves on the 1-site of étale  $X$ -schemes is 1-localic.

**5.2.6 Warning.** If  $(X, \tau)$  is an  $n$ -site and the  $n$ -category  $X$  does *not* have finite limits, then the  $\infty$ -topos  $\mathbf{Sh}_\tau(X)$  is not generally  $N$ -localic for any  $N \geq 0$ . See [SAG, Counterexample 20.4.0.1] for a basis  $B$  for the topology on the Hilbert cube  $\prod_{i \in \mathbb{Z}} [0, 1]$  for which the  $\infty$ -topos of sheaves on  $B$  is not  $N$ -localic for any  $N \geq 0$ .

**5.2.7 Example.** Let  $n \in N$  and let  $X$  be an  $n$ -localic  $\infty$ -topos. Then [SAG, Lemma 1.4.7.7] demonstrates that for an object  $U \in X$ , the over  $\infty$ -topos  $X_U$  is  $n$ -localic if and only if  $U$  is  $n$ -truncated.

**5.2.8 Definition.** Denote by  $\mathbf{Top}_\infty^\wedge$  the inverse limit of  $\infty$ -categories

$$\mathbf{Top}_\infty^\wedge := \lim_{n \in N^{op}} \mathbf{Top}_n$$

along the various truncation functors  $\tau_{\leq m-1}$ . This is the  $\infty$ -category of sequences  $\{X_n\}_{n \in N}$  in which each  $X_n$  is an  $n$ -topos, along with identifications  $X_m \simeq \tau_{\leq m-1} X_n$  whenever  $m \leq n$ . The truncation functors provide a functor

$$\tau : \mathbf{Top}_\infty \rightarrow \mathbf{Top}_\infty^\wedge,$$

which carries an  $\infty$ -topos  $X$  to the sequence  $\{\tau_{\leq n-1} X\}_{n \in N}$ .

**5.2.9 Construction.** The functor  $\tau : \mathbf{Top}_\infty \rightarrow \mathbf{Top}_\infty^\wedge$  admits a fully faithful right adjoint, which identifies  $\mathbf{Top}_\infty^\wedge$  with the full subcategory of  $\mathbf{Top}_\infty$  spanned by the *bounded  $\infty$ -topoi* [SAG, Proposition A.7.1.5]. These are the  $\infty$ -topoi that can be exhibited as inverse limits in  $\mathbf{Top}_\infty$  of a diagram of localic  $\infty$ -topoi. Equivalently, an  $\infty$ -topos  $X$  is bounded if and only if the natural geometric morphism

$$X \rightarrow \lim_{n \in N^{op}} L_n(X)$$

is an equivalence. Here  $L_n : \mathbf{Top}_\infty \rightarrow \mathbf{Top}_\infty^n$  denotes the  *$n$ -localic reflection* functor, defined as the left adjoint to the inclusion  $\mathbf{Top}_\infty^n \subset \mathbf{Top}_\infty$  of the full subcategory of  $n$ -localic  $\infty$ -topoi.

On the other hand, the functor  $\tau : \mathbf{Top}_\infty \rightarrow \mathbf{Top}_\infty^\wedge$  also admits a left adjoint, which is necessarily fully faithful. This identifies  $\mathbf{Top}_\infty^\wedge$  with the full subcategory of  $\mathbf{Top}_\infty$  spanned by the *Postnikov complete  $\infty$ -topoi* [SAG, Corollary A.7.2.8]. These are the  $\infty$ -topoi that can be exhibited in  $\mathbf{Cat}_{\infty, \delta_1}$  as the inverse limit of their truncations.

We write  $(-)^{post}$  for the right adjoint to the inclusion of the full subcategory of  $\mathbf{Top}_\infty$  spanned by the Postnikov complete  $\infty$ -topoi, and write  $(-)^b$  for the left adjoint to the inclusion of the full subcategory of  $\mathbf{Top}_\infty$  spanned by the bounded  $\infty$ -topoi. For an  $\infty$ -topos  $X$ , we call  $X^{post}$  the *Postnikov completion* of  $X$  and call  $X^b$  the *bounded reflection* of  $X$ .

5.2.10. The relationship between bounded  $\infty$ -topoi and Postnikov complete  $\infty$ -topoi is formally analogous to the relationship between  $p$ -nilpotent and  $p$ -complete abelian groups. Of course  $p$ -nilpotent and  $p$ -complete abelian groups form equivalent categories, but their embeddings into the category of all abelian groups differ.

### 5.3 Coherence

The second finiteness conditions that we impose on almost all of the  $\infty$ -topoi we consider is *coherence*.

**5.3.1 Definition.** Let  $0 \leq r \leq \infty$ , and let  $X$  be an  $r$ -topos. We say that  $X$  is *0-coherent* if and only if the 0-topos (=locale)  $\text{Open}(X)$  is quasicompact. Let  $n \in \mathbb{N}^*$ , and define  $n$ -coherence of  $r$ -topoi and their objects recursively as follows.

- An object  $U \in X$  is *n-coherent* if and only if the  $r$ -topos  $X_{/U}$  is  $n$ -coherent.
- The  $r$ -topos  $X$  is *locally n-coherent* if and only if every object  $U \in X$  admits a cover  $\{V_i \rightarrow U\}_{i \in I}$  in which each  $V_i$  is  $n$ -coherent.
- The  $r$ -topos  $X$  is *(n + 1)-coherent* if and only if  $X$  is locally  $n$ -coherent, and the  $n$ -coherent objects of  $X$  are closed under finite products.

In particular, if  $X$  is locally  $n$ -coherent, then  $U \in X$  is  $(n + 1)$ -coherent if and only if  $U$  is  $n$ -coherent and for any pair  $U', V \in X_{/U}$  of  $n$ -coherent objects, the fibre product  $U' \times_U V$  is  $n$ -coherent.

An  $r$ -topos  $X$  is *coherent* if and only if  $X$  is  $n$ -coherent for every  $n \in \mathbb{N}$ , and an object  $U$  of an  $\infty$ -topos  $X$  is *coherent* if and only if  $X_{/U}$  is a coherent  $r$ -topos. Finally, an  $r$ -topos  $X$  is *locally coherent* if and only if every object  $U \in X$  admits a cover  $\{V_i \rightarrow U\}_{i \in I}$  in which each  $V_i$  is coherent.

5.3.2. We are mostly interested in coherence for  $\infty$ -topoi, however we have introduced the notion for  $r$ -topoi in general because an  $\infty$ -topos  $X$  is  $n$ -coherent if and only if its underlying  $n$ -topos  $X_{\leq n-1}$  is  $n$ -coherent (this is the content of §5.4).

**5.3.3 Notation.** Let  $0 \leq r \leq \infty$ , and let  $X$  be an  $r$ -topos. Write  $X^{\text{coh}} \subset X$  for the full subcategory of  $X$  spanned by the coherent objects and  $X_{<\infty}^{\text{coh}} \subset X$  for the full subcategory of  $X$  spanned by the truncated coherent objects. For each integer  $n \geq 0$ , write  $X^{n\text{-coh}} \subset X$  for the full subcategory spanned by the  $n$ -coherent objects.

5.3.4. Let  $0 \leq r \leq \infty$ , let  $X$  be an  $r$ -topos, and let  $U \in X$ . Then for any integer  $n \geq 0$ , an object  $U' \rightarrow U$  of  $X_{/U}$  is  $n$ -coherent if and only if  $U'$  is  $n$ -coherent when viewed as an object of  $X$ . Thus we have canonical identifications

$$(X^{n\text{-coh}})_{/U} = (X_{/U})^{n\text{-coh}} \quad \text{and} \quad (X^{\text{coh}})_{/U} = (X_{/U})^{\text{coh}}$$

as full subcategories of  $X_{/U}$ . If  $U \in X_{<\infty}$  is a truncated object, then we have a canonical identification

$$(X_{<\infty}^{\text{coh}})_{/U} = (X_{/U})_{<\infty}^{\text{coh}}$$

as full subcategories of  $X_{/U}$ .

**5.3.5 Example.** By [SAG, Proposition A.7.5.1], if  $X$  is a bounded coherent  $\infty$ -topos, then  $X$  is also locally coherent.

**5.3.6 Definition.** Let  $X$  and  $Y$  be  $\infty$ -topoi. We say that a geometric morphism  $f_* : X \rightarrow Y$  is *coherent* if and only if, for any coherent object  $F \in Y$ , the object  $f^*(F) \in X$  is coherent as well. We write  $\mathbf{Top}_\infty^{\text{coh}}$  for the subcategory of  $\mathbf{Top}_\infty$  whose objects are coherent  $\infty$ -topoi and whose morphisms are coherent geometric morphisms.

We defer examples of coherent  $\infty$ -topoi to §5.7 where we can put all of our examples from algebraic geometry on the same footing after we develop the basic calculus of *finitary sites* in this subsection and in §5.6.

**5.3.7 Definition.** An  $\infty$ -site  $(X, \tau)$  is *finitary* if and only if  $X$  admits all fibre products, and, for every object  $U \in X$  and every covering sieve  $S \subset X_{/U}$ , there is a finite subset  $\{U_i\}_{i \in I} \subset S$  that generates a covering sieve.

Let  $(X, \tau_X)$  and  $(Y, \tau_Y)$  be finitary  $\infty$ -sites. A morphism of  $\infty$ -sites

$$f^* : (Y, \tau_Y) \rightarrow (X, \tau_X)$$

is a *morphism of finitary  $\infty$ -sites* if  $f^*$  is preserves fibre products.

**5.3.8 Proposition** ([SAG, Proposition A.3.1.3]). *Let  $(X, \tau)$  be a finitary  $\infty$ -site. Then the  $\infty$ -topos  $\mathbf{Sh}_\tau(X)$  is locally coherent, and for every object  $x \in X$ , the sheaf  $j(x)$  is a coherent object of  $\mathbf{Sh}_\tau(X)$ , where  $j : X \rightarrow \mathbf{Sh}_\tau(X)$  is the sheafified Yoneda embedding. If, in addition,  $X$  admits a terminal object, then  $\mathbf{Sh}_\tau(X)$  is coherent.*

An elementary way to construct a finitary  $\infty$ -site is to make use of an  $\infty$ -categorical analogue of the notion of pretopology on a 1-category.

**5.3.9 Definition.** An  $\infty$ -presite is a pair  $(X, E)$  consisting of an  $\infty$ -category  $X$  along with a subcategory  $E \subseteq X$  satisfying the following conditions.

- The subcategory  $E$  contains all equivalences of  $X$ .
- The  $\infty$ -category  $X$  admits finite limits, and  $E$  is stable under base change.
- The  $\infty$ -category  $X$  admits finite coproducts, which are universal, and  $E$  is closed under finite coproducts.

**5.3.10 Construction.** If  $(X, E)$  is an  $\infty$ -presite, then there exists a topology  $\tau_E$  in which the  $\tau_E$ -covering sieves are generated by finite families  $\{y_i \rightarrow x\}_{i \in I}$  such that  $\coprod_{i \in I} y_i \rightarrow x$  lies in  $E$ . The  $\infty$ -site  $(X, \tau_E)$  is finitary.

## 5.4 Coherence & $n$ -topoi

In this subsection we prove that the property that an  $\infty$ -topos  $X$  be  $n$ -coherent only depends on the underlying  $n$ -topos  $X_{\leq n-1}$  of  $(n-1)$ -truncated objects (Corollary 5.4.10).<sup>13</sup> We begin with some preliminaries on the relationship between coherence and connectivity.

<sup>13</sup>We are grateful to Jacob Lurie for conveying this observation.

**5.4.1 Proposition** ([SAG, Proposition A.2.4.1]). *Let  $\mathbf{X}$  be an  $\infty$ -topos, let  $f : X \rightarrow Y$  be a morphism in  $\mathbf{X}$ , and let  $n \in \mathbf{N}$ . Then*

(5.4.1.1) *If  $X$  is  $n$ -coherent and  $f$  is  $n$ -connective, then  $Y$  is  $n$ -coherent.*

(5.4.1.2) *If  $Y$  is  $n$ -coherent and  $f$  is  $(n + 1)$ -connective, then  $X$  is  $n$ -coherent.*

Since the natural morphism from an object in an  $\infty$ -topos to its  $n$ -truncation is  $(n + 1)$ -connective, we deduce:

**5.4.2 Corollary.** *Let  $\mathbf{X}$  be an  $\infty$ -topos and  $n \in \mathbf{N}$ . An object  $X \in \mathbf{X}$  is  $n$ -coherent if and only if  $\tau_{\leq n-1}(X)$  is an  $n$ -coherent object of  $\mathbf{X}$ .*

It is also easy to deduce the following.

**5.4.3 Corollary** ([SAG, Corollary A.2.4.4]). *Let  $\mathbf{X}$  be a coherent  $\infty$ -topos and  $n \in \mathbf{N}$ . Then for any  $n$ -coherent  $X \in \mathbf{X}$ , the  $(n - 1)$ -truncation  $\tau_{\leq n-1}(X)$  of  $X$  is a coherent object of  $\mathbf{X}$ .*

**5.4.4 Corollary.** *Let  $\mathbf{X}$  be a coherent  $\infty$ -topos. Then an object  $X \in \mathbf{X}$  is coherent if and only if for every  $n \in \mathbf{N}$ , the  $(n - 1)$ -truncation  $\tau_{\leq n-1}(X)$  of  $X$  is a coherent object of  $\mathbf{X}$ .*

**5.4.5 Corollary.** *Let  $f_* : \mathbf{X} \rightarrow \mathbf{Y}$  be a geometric morphism between coherent  $\infty$ -topoi. Then  $f_*$  is coherent if and only if  $f^*$  carries  $\mathbf{Y}_{<\infty}^{\text{coh}}$  to  $\mathbf{X}_{<\infty}^{\text{coh}}$ .*

We also deduce that coherence of a geometric morphism between coherent  $\infty$ -topoi is equivalent to the *a priori* stronger condition that the pullback functor preserve  $n$ -coherent objects for all  $n \geq 0$ :<sup>14</sup>

**5.4.6 Corollary.** *Let  $f_* : \mathbf{X} \rightarrow \mathbf{Y}$  be a geometric morphism between coherent  $\infty$ -topoi. Then  $f_*$  is coherent if and only if  $f^*$  carries  $n$ -coherent objects of  $\mathbf{Y}$  to  $n$ -coherent objects of  $\mathbf{X}$  for all  $n \in \mathbf{N}$ .*

*Proof.* It is immediate from the definition that if  $f^*$  preserves  $n$ -coherence for all  $n \geq 0$ , then  $f_*$  is coherent. Suppose that  $f^*$  is coherent, and let  $U \in \mathbf{Y}^{n\text{-coh}}$  be an  $n$ -coherent object. Since  $\mathbf{Y}$  is coherent, **Corollary 5.4.3**=[SAG, Corollary A.2.4.4] shows that  $\tau_{\leq n-1}^{\mathbf{Y}}(U)$  is an  $n$ -coherent object of  $\mathbf{Y}$ . Since  $f^*$  is coherent, we see that

$$f^* \tau_{\leq n-1}^{\mathbf{Y}}(U) \simeq \tau_{\leq n-1}^{\mathbf{X}}(f^*(U))$$

is a coherent object of  $\mathbf{X}$ . **Corollary 5.4.2** then shows that  $f^*(U)$  is an  $n$ -coherent object of  $\mathbf{X}$ .  $\square$

Before proceeding to the main results of this subsection, we need a two preliminary facts on  $m$ -connective morphisms in an  $\infty$ -topos.

**5.4.7 Lemma.** *Let  $\mathbf{X}$  be an  $\infty$ -topos and  $m \geq 0$  an integer. Let  $W \in \mathbf{X}$  and let  $u : U' \rightarrow U$  and  $v : V' \rightarrow V$  be morphisms in  $\mathbf{X}_{/W}$ . If  $u$  and  $v$  are  $m$ -connective morphisms of  $\mathbf{X}$ , then the induced morphism  $U' \times_W V' \rightarrow U \times_W V$  is  $m$ -connective.*

<sup>14</sup>This second notion is how Grothendieck and Verdier originally defined coherence for geometric morphisms between ordinary topoi [SGA 4<sub>III</sub>, Exposé VI, Définition 3.1].



*Proof.* First we treat the case where  $W = 1_X$  is the terminal object of  $X$ . In this case, since  $\tau_{\leq m-1} : X \rightarrow X$  preserves finite products [HTT, Lemma 6.5.1.2] and  $\tau_{\leq m-1}(u)$  and  $\tau_{\leq m-1}(v)$  are equivalences by assumption, we see that

$$\tau_{\leq m-1}(u \times v) \simeq \tau_{\leq m-1}(u) \times \tau_{\leq m-1}(v)$$

is an equivalence.

Now we treat the general case. In the diagram

$$\begin{array}{ccccc} U' \times_W V' & \longrightarrow & U \times_W V & \longrightarrow & W \\ \downarrow & \lrcorner & \downarrow & \lrcorner & \downarrow \Delta_W \\ U' \times V' & \xrightarrow{u \times v} & U \times V & \longrightarrow & W \times W \end{array}$$

both squares are pullbacks and  $u \times v$  is  $m$ -connective (by the preceding paragraph). This completes the proof since the class of  $m$ -connective morphisms in an  $\infty$ -topos is stable under pullback [HTT, Proposition 6.5.1.16].  $\square$

**5.4.8 Lemma.** *Let  $X$  be an  $\infty$ -topos and  $n \in \mathbb{N}$ . Let  $W \in X$  and let  $U \rightarrow W$  and  $V \rightarrow W$  be morphisms in  $X$ . If  $W$  is  $n$ -truncated, then the natural morphism*

$$\tau_{\leq n}(U \times_W V) \rightarrow \tau_{\leq n}(U) \times_W \tau_{\leq n}(V)$$

*is an equivalence.*

*Proof.* Since the natural morphisms  $U \rightarrow \tau_{\leq n}(U)$  and  $V \rightarrow \tau_{\leq n}(V)$  are  $(n+1)$ -connective, by Lemma 5.4.7 the natural morphism

$$\phi : U \times_W V \rightarrow \tau_{\leq n}(U) \times_W \tau_{\leq n}(V)$$

is  $(n+1)$ -connective. Since  $W$  is  $n$ -truncated and the  $n$ -truncated objects of an  $\infty$ -topos are closed under limits, the object  $\tau_{\leq n}(U) \times_W \tau_{\leq n}(V)$  is  $n$ -truncated. By the uniqueness of the factorization of a morphism in an  $\infty$ -topos into an  $(n+1)$ -connective morphism followed by an  $n$ -truncated morphism, we see that  $\phi$  exhibits  $\tau_{\leq n}(U) \times_W \tau_{\leq n}(V)$  as the  $n$ -truncation of  $U \times_W V$ .  $\square$

**5.4.9 Proposition.** *Let  $X$  be an  $\infty$ -topos and  $n \in \mathbb{N}$ . The following are equivalent for an  $(n-1)$ -truncated object  $W \in X$ :*

(5.4.9.1) *As an object of the  $\infty$ -topos  $X$ , the object  $W$  is  $n$ -coherent.*

(5.4.9.2) *As an object of the  $n$ -topos  $X_{\leq n-1}$ , the object  $W$  is  $n$ -coherent.*

*Proof.* Clearly (5.4.9.1) implies (5.4.9.2). We prove that (5.4.9.2) implies (5.4.9.1) by induction on  $n$ . The base case  $n = 0$  is immediate from the definition of 0-coherence.

For the induction step assume we have shown that an  $(n-1)$ -truncated object of  $X$  is  $n$ -coherent if it is  $n$ -coherent as an object of the  $n$ -topos  $X_{\leq n-1}$ . Let  $W$  be an  $n$ -truncated object of  $X$  that is  $(n+1)$ -coherent as an object of the  $(n+1)$ -topos  $X_{\leq n}$ ; we prove that  $W$  is  $(n+1)$ -coherent as an object of the  $\infty$ -topos  $X$ . First we show that  $X_{/W}$  is locally

$n$ -coherent. Let  $f : U \rightarrow W$  be a morphism in  $\mathbf{X}$ . Since  $W$  is  $n$ -truncated,  $f$  factors as a composite

$$U \twoheadrightarrow \tau_{\leq n}(U) \rightarrow W.$$

Since  $\mathbf{X}_{\leq n,/W}$  is locally  $n$ -coherent by assumption, there exists a cover  $\{U_i \rightarrow \tau_{\leq n}(U)\}_{i \in I}$  of  $\tau_{\leq n}(U)$  such that for each  $i \in I$ , the object  $U_i \in \mathbf{X}_{\leq n,/W}$  is an  $n$ -coherent object of  $\mathbf{X}_{\leq n,/W}$ , or equivalently an  $n$ -coherent object of  $\mathbf{X}_{\leq n}$  (5.3.4). Since the morphism  $U \twoheadrightarrow \tau_{\leq n}(U)$  is  $(n+1)$ -connective, Proposition 5.4.1=[SAG, Proposition A.2.4.1] and the fact that  $(n+1)$ -connective morphisms in an  $\infty$ -topos are stable under pullback [HTT, Proposition 6.5.1.16] show that the family

$$\{U_i \times_{\tau_{\leq n}(U)} U \rightarrow U\}_{i \in I}$$

is a cover of  $U$  in  $\mathbf{X}_{/W}$  by  $n$ -coherent objects. That is,  $\mathbf{X}_{/W}$  is locally  $n$ -coherent.

Now let us show that the  $n$ -coherent objects of  $\mathbf{X}_{/W}$  are stable under finite products. Let  $f : U \rightarrow W$  and  $g : V \rightarrow W$  be morphisms in  $\mathbf{X}_{/W}$ , where  $U$  and  $V$  are  $n$ -coherent. Then since the  $n$ -coherent objects of  $\mathbf{X}_{\leq n,/W}$  are stable under finite products by assumption, we see that  $\tau_{\leq n}(U) \times_W \tau_{\leq n}(V)$  is an  $n$ -coherent object of  $\mathbf{X}_{\leq n, W}$ . By the induction hypothesis and Corollary 5.4.2,  $\tau_{\leq n}(U) \times_W \tau_{\leq n}(V)$  is an  $n$ -coherent object of  $\mathbf{X}_{/W}$ . The claim now follows from the fact that the natural morphism

$$U \times_W V \rightarrow \tau_{\leq n}(U) \times_W \tau_{\leq n}(V)$$

is  $(n+1)$ -connective (Lemma 5.4.8) and Proposition 5.4.1=[SAG, Proposition A.2.4.1].  $\square$

Setting  $W = 1_{\mathbf{X}}$  in Proposition 5.4.9 we deduce:

**5.4.10 Corollary.** *Let  $n \in \mathbf{N}$ . The following are equivalent for an  $\infty$ -topos  $\mathbf{X}$ :*

(5.4.10.1) *The  $\infty$ -topos  $\mathbf{X}$  is  $n$ -coherent.*

(5.4.10.2) *The  $n$ -topos  $\mathbf{X}_{\leq n-1}$  is  $n$ -coherent.*

For the next few results, please recall the notations of Construction 5.2.9.

**5.4.11 Corollary.** *Let  $n \in \mathbf{N}$  and let  $f_* : \mathbf{X} \rightarrow \mathbf{Y}$  be a geometric morphism of  $\infty$ -topoi. If  $f_*$  induces an equivalence  $\mathbf{X}_{\leq n-1} \simeq \mathbf{Y}_{\leq n-1}$ , then  $\mathbf{X}$  is  $n$ -coherent if and only if  $\mathbf{Y}$  is  $n$ -coherent. Equivalently, if  $f_*$  induces an equivalence  $L_n(\mathbf{X}) \simeq L_n(\mathbf{Y})$  on  $n$ -localic reflections, then  $\mathbf{X}$  is  $n$ -coherent if and only if  $\mathbf{Y}$  is  $n$ -coherent.*

Corollary 5.4.11 shows that there are many different ways to check the  $n$ -coherence of an  $\infty$ -topos.

**5.4.12 Lemma.** *Let  $n \in \mathbf{N}$ . The following are equivalent for an  $\infty$ -topos  $\mathbf{X}$ :*

(5.4.12.1) *The  $\infty$ -topos  $\mathbf{X}$  is  $n$ -coherent.*

(5.4.12.2) *The  $n$ -localic reflection  $L_n(\mathbf{X})$  of  $\mathbf{X}$  is  $n$ -coherent.*

(5.4.12.3) *The hypercompletion  $\mathbf{X}^{hyp}$  of  $\mathbf{X}$  is  $n$ -coherent (see Definition 5.11.4).*

(5.4.12.4) *The Postnikov completion  $X^{post}$  of  $X$  is  $n$ -coherent.*

(5.4.12.5) *The bounded reflection  $X^b$  of  $X$  is  $n$ -coherent.*

*Proof.* The equivalence of these statements follows from repeated application of [Corollary 5.4.11](#). The equivalence of (5.4.12.1) and (5.4.12.2) follows immediately from [Corollary 5.4.11](#).

To see that (5.4.12.1)  $\iff$  (5.4.12.3), note that since truncated objects are hypercomplete, the natural fully faithful geometric morphism  $X^{hyp} \hookrightarrow X$  induces an equivalence on  $(n-1)$ -truncated objects.

To see that (5.4.12.1)  $\iff$  (5.4.12.4), note that by [SAG, Proposition A.7.3.7] the natural geometric morphism  $X^{post} \rightarrow X$  is an equivalence when restricted to  $(n-1)$ -truncated objects.

To see that (5.4.12.1)  $\iff$  (5.4.12.5), note that since the  $n$ -localic reflection functor  $L_n: \mathbf{Top}_\infty \rightarrow \mathbf{Top}_\infty$  preserves inverse limits [SAG, Lemma A.7.1.4], the natural geometric morphism

$$X \rightarrow X^b \simeq \lim_{k \in \mathbb{N}^{op}} L_k(X)$$

induces an equivalence on  $n$ -localic reflections.  $\square$

**5.4.13** (Postnikov complete coherent & bounded coherent  $\infty$ -topoi). Let

$$\begin{array}{ccc} X' & \xrightarrow{x_*} & X \\ f'_* \downarrow & & \downarrow f_* \\ Y' & \xrightarrow{y_*} & Y \end{array}$$

be a commutative square in  $\mathbf{Top}_\infty$ . [Lemma 5.4.12](#) and [Corollary 5.4.5](#) show that if  $x_*$  and  $y_*$  induce equivalences

$$X'_{<\infty} \simeq X_{<\infty} \quad \text{and} \quad Y'_{<\infty} \simeq Y_{<\infty}$$

on truncated objects, then  $f_*$  is coherent if and only if  $f'_*$  is coherent.

In particular, a geometric morphism  $f_*: X \rightarrow Y$  between bounded coherent  $\infty$ -topoi is coherent if and only if the induced geometric morphism

$$X^{post} \rightarrow X \quad \text{and} \quad Y^{post} \rightarrow Y$$

on corresponding Postnikov complete coherent  $\infty$ -topoi is coherent. Thus the equivalence between Postnikov complete  $\infty$ -topoi and bounded coherent  $\infty$ -topoi ([Construction 5.2.9](#)) restricts to an equivalence between the subcategory of Postnikov complete coherent  $\infty$ -topoi and coherent geometric morphisms and the subcategory of bounded coherent  $\infty$ -topoi and coherent geometric morphisms.

## 5.5 Coherence of morphisms & $n$ -localic $\infty$ -topoi

In this subsection we prove that coherence for an  $n$ -localic  $\infty$ -topos is equivalent to  $(n+1)$ -coherence, and may be checked on its underlying  $n$ -topos ([Proposition 5.5.6](#)). First we'll need  $\infty$ -toposic versions of a number of points from [SGA 4<sub>II</sub>, Exposé VI, §§1–3], which follow easily from [SAG, §A.2.1].

**5.5.1 Definition.** Let  $n \in \mathbb{N}$  and let  $\mathbf{X}$  be a locally  $n$ -coherent  $\infty$ -topos. A morphism  $U \rightarrow V$  in  $\mathbf{X}$  is called *relatively  $n$ -coherent* if for every  $n$ -coherent object  $V' \in \mathbf{X}$  and every morphism  $V' \rightarrow V$ , the fibre product  $U \times_V V'$  is also  $n$ -coherent.

**5.5.2 Example** ([SAG, Example A.2.1.2]). Let  $\mathbf{X}$  be a locally  $n$ -coherent  $\infty$ -topos and  $f: U \rightarrow V$  a morphism in  $\mathbf{X}$ . If  $U$  is  $n$ -coherent and  $V$  is  $(n+1)$ -coherent, then  $f$  is relatively  $n$ -coherent.

**5.5.3 Example.** As a consequence of **Proposition 5.4.1**=[SAG, Proposition A.2.4.1] and the fact that the class of  $(n+1)$ -connective morphisms in an  $\infty$ -topos is stable under pullback [HTT, Proposition 6.5.1.16], the  $(n+1)$ -connective morphism of an  $\infty$ -topos are ‘relatively  $n$ -coherent’ in a very strong sense: they satisfy the condition of relative  $n$ -coherence even without the need of local  $n$ -coherence assumptions on the  $\infty$ -topos.

**5.5.4 Lemma.** Let  $n \in \mathbb{N}$  and let  $\mathbf{X}$  be a locally  $n$ -coherent  $\infty$ -topos. Let  $u: U' \rightarrow U$  and  $v: V' \rightarrow V$  be relatively  $n$ -coherent morphisms in  $\mathbf{X}$ ,  $W \in \mathbf{X}$  an object, and  $U \rightarrow W$  and  $V \rightarrow W$  be any morphisms. Then the induced morphism  $U' \times_W V' \rightarrow U \times_W V$  is relatively  $n$ -coherent.

*Proof.* Let  $f: X \rightarrow U \times_W V$  be a morphism in  $\mathbf{X}$  where  $X$  is  $n$ -coherent. Note that we have equivalences of iterated fibre products

$$\begin{aligned} X \times_{U \times_W V} (U' \times_W V') &\simeq (X \times_U U') \times_X (X \times_V V') \\ &\simeq (X \times_U U') \times_V V'. \end{aligned}$$

First, since  $X \times_U U'$  is the pullback of  $\text{pr}_1 \circ f: X \rightarrow U$  along the relatively  $n$ -coherent morphism  $u$ , the object  $X \times_U U'$  is  $n$ -coherent. Second,  $(X \times_U U') \times_V V'$  is the pullback of the morphism  $X \times_U U' \rightarrow V$  induced by  $\text{pr}_2 \circ f: X \rightarrow V$  along the relatively  $n$ -coherent morphism  $v$ . Hence  $(X \times_U U') \times_V V'$  is an  $n$ -coherent object of  $\mathbf{X}$ , as desired.  $\square$

**5.5.5 Lemma.** Let  $\mathbf{X}$  be an  $\infty$ -topos and  $m \in \mathbb{N}$ . Let  $\mathbf{X}_0 \subset \mathbf{X}$  be a full subcategory satisfying the following conditions:

(5.5.5.1) The full subcategory  $\mathbf{X}_0 \subset \mathbf{X}$  is closed under finite products.

(5.5.5.2) Every object of  $\mathbf{X}_0$  is  $m$ -coherent.

(5.5.5.3) For every object  $U \in \mathbf{X}$ , there exists an effective epimorphism  $\coprod_{i \in I} U_i \rightarrow U$  where  $U_i \in \mathbf{X}_0$  for each  $i \in I$ .

Then the  $m$ -coherent objects of  $\mathbf{X}$  are closed under finite products.

*Proof.* Let  $\mathbf{X}'_0 \subset \mathbf{X}$  denote the closure of  $\mathbf{X}_0$  under finite coproducts. Then every object of  $\mathbf{X}'_0$  is  $m$ -coherent, and since colimits in  $\mathbf{X}$  are universal and  $\mathbf{X}_0$  is closed under finite products,  $\mathbf{X}'_0 \subset \mathbf{X}$  is closed under finite products.

Let  $U, V \in \mathbf{X}$  be  $m$ -coherent objects; we show that  $U \times V$  is  $m$ -coherent. Since  $U$  and  $V$  are quasicompact, there exist effective epimorphisms  $u: U' \rightarrow U$  and  $v: V' \rightarrow V$  where  $U', V' \in \mathbf{X}'_0$ . By [SAG, Example A.2.1.2] both  $u$  and  $v$  are relatively  $(m-1)$ -coherent. **Lemma 5.5.4** shows that

$$u \times v: U' \times V' \rightarrow U \times V$$

is a relatively  $(m-1)$ -coherent effective epimorphism. Since  $U' \times V' \in X'_0$  is  $m$ -coherent and  $X$  is locally  $m$ -coherent, [SAG, Proposition A.2.1.3] shows that  $U \times V$  is  $m$ -coherent, as desired.  $\square$

**5.5.6 Proposition.** *Let  $n \in \mathbb{N}$ . The following are equivalent for an  $n$ -localic  $\infty$ -topos  $X$ :*

(5.5.6.1) *The  $n$ -topos  $X_{\leq n-1}$  is  $(n+1)$ -coherent.*

(5.5.6.2) *The  $\infty$ -topos  $X$  is  $(n+1)$ -coherent.*

(5.5.6.3) *The  $\infty$ -topos  $X$  is coherent.*

(5.5.6.4) *The  $n$ -topos  $X_{\leq n-1}$  is coherent.*

*Proof.* Clearly (5.5.6.3)  $\implies$  (5.5.6.4) and (5.5.6.4)  $\implies$  (5.5.6.1).

First we show that (5.5.6.1)  $\implies$  (5.5.6.2). Corollary 5.4.10 shows that  $X$  is  $n$ -coherent. Now notice that every object of  $X$  admits a cover by  $(n-1)$ -truncated  $n$ -coherent objects (so, in particular,  $X$  is locally  $n$ -coherent). This follows from the following observations:

- Since  $\infty$ -topos  $X$  is  $n$ -localic, every object of  $X$  admits a cover by  $(n-1)$ -truncated objects.
- Since the  $n$ -topos  $X_{\leq n-1}$  is locally  $n$ -coherent, Proposition 5.4.9 shows that every  $(n-1)$ -truncated object of  $X$  admits a cover by  $(n-1)$ -truncated  $n$ -coherent objects.

Moreover, since the  $(n-1)$ -truncated objects of an  $\infty$ -topos are closed under limits and  $X_{\leq n-1}$  is  $(n+1)$ -coherent, Proposition 5.4.9 shows that the  $(n-1)$ -truncated  $n$ -coherent objects of  $X$  are closed under finite products. Lemma 5.5.5 applied to the subcategory  $X_0$  of  $(n-1)$ -truncated  $n$ -coherent objects (so that  $m = n$  in the notation of Lemma 5.5.5) now shows that the  $n$ -coherent objects of  $X$  are closed under finite products.

Since an  $n$ -localic  $\infty$ -topos is  $N$ -localic for all  $N \geq n$ , to prove the implication (5.5.6.2)  $\implies$  (5.5.6.3), it suffices to prove that if  $X$  is  $(n+1)$ -coherent, then  $X$  is  $(n+2)$ -coherent. First we show that  $X$  is locally  $(n+1)$ -coherent. We have already seen that every object of  $X$  admits a cover by a  $(n-1)$ -truncated  $n$ -coherent objects, and that the subcategory  $X_0$  of  $(n-1)$ -truncated  $n$ -coherent objects is closed under finite products. Since  $X$  is  $(n+1)$ -coherent, [SAG, Corollary A.2.4.3] shows that  $(n-1)$ -truncated  $n$ -coherent objects of  $X$  are automatically  $(n+1)$ -coherent, immediately implying that  $X$  is locally  $(n+1)$ -coherent. Lemma 5.5.5 applied to the subcategory  $X_0$  of  $(n-1)$ -truncated  $(n+1)$ -coherent objects (so that  $m = n+1$  in the notation of Lemma 5.5.5) shows that the  $(n+1)$ -coherent objects of  $X$  are closed under finite products.  $\square$

## 5.6 Coherent geometric morphisms via sites & coherent ordinary topoi

In this subsection we explain the relationship between coherent ordinary topoi in the sense of [SGA 4<sub>III</sub>, Exposé VI] and their corresponding 1-localic  $\infty$ -topoi.<sup>15</sup> (See [52; 53, Appendix C, §§5–6] for an excellent accounts of coherent ordinary topoi.) We show

<sup>15</sup>The contents of this subsection originally appeared in a (partially expository) preprint of the third-named author [30].

that the  $\infty$ -category of coherent 1-localic  $\infty$ -topoi is equivalent to the 2-category of coherent ordinary topoi. In fact, the results of §5.4 allow us to show that the  $\infty$ -category of coherent  $n$ -localic  $\infty$ -topoi is equivalent to the  $(n+1)$ -category of coherent  $n$ -topoi (Proposition 5.6.11).

**5.6.1 Recollection.** A 1-topos  $\mathbf{X}$  is *coherent* in the sense of [SGA 4<sub>II</sub>, Exposé VI, Definition 2.3] if and only if  $\mathbf{X}$  is 2-coherent in the sense of Definition 5.3.1. This is true if and only if  $\mathbf{X}$  is equivalent to the 1-topos of sheaves of sets on a finitary 1-site  $(X, \tau)$  with a terminal object. Proposition 5.5.6 shows that  $\mathbf{X}$  is coherent if and only if its corresponding 1-localic  $\infty$ -topos is coherent.

A geometric morphism  $f_* : \mathbf{X} \rightarrow \mathbf{Y}$  is *coherent* [SGA 4<sub>II</sub>, Exposé VI, Definition 3.1] if and only if  $f_*$  is induced by a morphism of finitary 1-sites  $f^* : (Y, \tau_Y) \rightarrow (X, \tau_X)$ .

The content of the equivalence between coherent  $n$ -topoi and coherent  $n$ -localic  $\infty$ -topoi reduces to showing that a coherent morphism of coherent  $n$ -topoi induces a coherent morphism of corresponding  $n$ -localic  $\infty$ -topoi. This follows from the fact that coherence of a geometric morphism between locally coherent  $\infty$ -topoi can be checked on a generating set of coherent objects (Corollary 5.6.6). A particularly useful consequence is that morphisms of finitary  $\infty$ -sites induce coherent geometric morphisms (Corollary 5.6.8).

First we need a few preliminary results. For this, please recall the notion of *relative  $n$ -coherence* (Definition 5.5.1) introduced in §5.5.

**5.6.2 Lemma.** *Let  $\mathbf{X}$  be an  $\infty$ -topos. If  $e : U \rightarrowtail V$  is an effective epimorphism in  $\mathbf{X}$  and  $U$  is quasicompact, then  $V$  is quasicompact.*

*Proof.* This is a special case of [SAG, Proposition A.2.1.3], or, alternatively, Proposition 5.4.1=[SAG, Proposition A.2.4.1].  $\square$

**5.6.3 Lemma.** *Let  $n \geq 1$  be an integer and  $\mathbf{X}$  a locally  $(n-1)$ -coherent  $\infty$ -topos. Let  $U \in \mathbf{X}$  and let  $e : \coprod_{i \in I} U_i \rightarrowtail U$  be a cover of  $U$  where  $I$  is finite and  $U_i$  is  $n$ -coherent for each  $i \in I$ . The following are equivalent:*

(5.6.3.1) *The effective epimorphism  $e$  is relatively  $(n-1)$ -coherent.*

(5.6.3.2) *For all  $i, j \in I$ , the object  $U_i \times_U U_j$  is  $(n-1)$ -coherent.*

(5.6.3.3) *The object  $U$  is  $n$ -coherent.*

*Proof.* If  $e$  is relatively  $(n-1)$ -coherent, then since coproducts in  $\mathbf{X}$  are universal, the fibre product

$$\left(\coprod_{i \in I} U_i\right) \times_U \left(\coprod_{j \in I} U_j\right) \simeq \coprod_{i, j \in I} U_i \times_U U_j$$

is  $(n-1)$ -coherent. Thus  $U_i \times_U U_j$  is  $(n-1)$ -coherent for all  $i, j \in I$  [SAG, Remark A.2.0.16].

If each  $U_i \times_U U_j$  is  $(n-1)$ -coherent, then since each  $U_i$  is  $n$ -coherent the pullback of  $e$  along itself

$$\coprod_{i, j \in I} U_i \times_U U_j \rightarrowtail \coprod_{i \in I} U_i$$

is relatively  $(n - 1)$ -coherent (Example 5.5.2=[SAG, Example A.2.1.2]). Applying [SAG, Corollary A.2.1.5] we deduce that  $e: \coprod_{i \in I} U_i \twoheadrightarrow U$  is relatively  $(n - 1)$ -coherent.

To conclude, note that if  $e: \coprod_{i \in I} U_i \twoheadrightarrow U$  is relatively  $(n - 1)$ -coherent, then [SAG, Proposition A.2.1.3] shows that  $U$  is  $n$ -coherent. On the other hand, if  $U$  is  $n$ -coherent, then  $e$  is  $(n - 1)$ -coherent by Example 5.5.2=[SAG, Example A.2.1.2].  $\square$

**5.6.4 Proposition.** *Let  $f_*: X \rightarrow Y$  be a geometric morphism of  $\infty$ -topoi and  $n \in \mathbb{N}$ . Assume that:*

(5.6.4.1) *There exists a collection of  $n$ -coherent objects  $Y_0 \subset \text{Obj}(Y)$  of  $Y$  such that for every  $n$ -coherent object  $U \in Y$  there exists a cover  $\coprod_{i \in I} U_i \twoheadrightarrow U$  where  $U_i \in Y_0$  for each  $i \in I$ .*

(5.6.4.2) *The pullback functor  $f^*: Y \rightarrow X$  takes objects of  $Y_0$  to  $n$ -coherent objects of  $X$ .*

(5.6.4.3) *If  $n \geq 1$ , the  $\infty$ -topoi  $X$  and  $Y$  are locally  $(n - 1)$ -coherent and  $f^*: Y \rightarrow X$  takes  $(n - 1)$ -coherent objects of  $Y$  to  $(n - 1)$ -coherent objects of  $X$ .*

*Then  $f^*$  takes  $n$ -coherent objects of  $Y$  to  $n$ -coherent objects of  $X$ .*

*Proof.* Let  $U \in Y$  be an  $n$ -coherent object; we show that  $f^*(U)$  is  $n$ -coherent. By assumption there exists a cover

$$e: \coprod_{i \in I} U_i \twoheadrightarrow U$$

where  $U_i \in Y_0$  for each  $i \in I$  and  $I$  is finite (since  $U$  is, in particular, 0-coherent). For all  $i \in I$  the object  $f^*(U_i)$  is  $n$ -coherent by assumption, so since  $n$ -coherent objects are closed under finite coproducts [SAG, Remark A.2.0.16], the object

$$f^* \left( \coprod_{i \in I} U_i \right) \simeq \coprod_{i \in I} f^*(U_i)$$

is  $n$ -coherent.

Note that

$$f^*(e): \coprod_{i \in I} f^*(U_i) \twoheadrightarrow f^*(U)$$

is an effective epimorphism in  $X$ . If  $n = 0$ , this proves the claim (Lemma 5.6.2). If  $n \geq 1$ , then Lemma 5.6.3 shows that it suffices to show that for all  $i, j \in I$ , the object

$$f^*(U_i) \times_{f^*(U)} f^*(U_j) \simeq f^*(U_i \times_U U_j)$$

is  $(n - 1)$ -coherent. This follows from the fact that  $U_i \times_U U_j$  is  $(n - 1)$ -coherent (by Lemma 5.6.3) and the assumption that  $f^*$  sends  $(n - 1)$ -coherent objects of  $Y$  to  $(n - 1)$ -coherent objects of  $X$ .  $\square$

Proposition 5.6.4 shows that coherence of a geometric morphism between locally coherent  $\infty$ -topoi is equivalent to the *a priori* stronger condition that the pullback functor preserve  $n$ -coherent objects for all  $n \geq 0$ ; see also Corollary 5.4.6.

**5.6.5 Corollary.** *Let  $f_*: X \rightarrow Y$  be a geometric morphism between locally coherent  $\infty$ -topoi. Then  $f_*$  is coherent if and only if  $f^*$  takes  $n$ -coherent objects of  $Y$  to  $n$ -coherent objects of  $X$  for all  $n \geq 0$ .*

**Proposition 5.6.4** also shows that coherence of a geometric morphism can be checked on a generating set of coherent objects.

**5.6.6 Corollary.** *Let  $f_* : X \rightarrow Y$  be a geometric morphism between locally coherent  $\infty$ -topoi. Let  $Y_0 \subset \text{Obj}(Y^{\text{coh}})$  be a collection of coherent objects such that for every object  $U \in Y$  there exists a cover  $\coprod_{i \in I} U_i \rightarrow U$  where  $U_i \in Y_0$  for each  $i \in I$ . If for all  $U \in Y_0$  the object  $f^*(U)$  is coherent, the geometric morphism  $f_* : X \rightarrow Y$  is coherent.*

For the next result, we need the following lemma.

**5.6.7 Lemma.** *Let  $f^* : (Y, \tau_Y) \rightarrow (X, \tau_X)$  be a morphism of  $\infty$ -sites, and write  $j_Y : Y \rightarrow \text{Sh}_{\tau_Y}(Y)$  for the sheafified Yoneda embedding. If the topology  $\tau_X$  is finitary, then*

$$f^* j_Y : Y \rightarrow \text{Sh}_{\tau_X}(X)$$

*factors through  $\text{Sh}_{\tau_X}(X)^{\text{coh}} \subset \text{Sh}_{\tau_X}(X)$ .*

*Proof.* We have a commutative square

$$\begin{array}{ccc} Y & \xrightarrow{p^*} & X \\ j_Y \downarrow & & \downarrow j_X \\ \text{Sh}_{\tau_Y}(Y) & \xrightarrow{p^*} & \text{Sh}_{\tau_X}(X) \end{array}$$

where the vertical functors are sheafified Yoneda embeddings. The claim now follows from the fact that  $j_X : X \rightarrow \text{Sh}_{\tau_X}(X)$  factors through  $\text{Sh}_{\tau_X}(X)^{\text{coh}}$ , since the topology  $\tau_X$  is finitary (**Proposition 5.3.8**=[**SAG**, Proposition A.3.1.3]).  $\square$

**5.6.8 Corollary.** *Let  $f^* : (Y, \tau_Y) \rightarrow (X, \tau_X)$  be a morphism of finitary  $\infty$ -sites. Then the geometric morphism*

$$f_* : \text{Sh}_{\tau_X}(X) \rightarrow \text{Sh}_{\tau_Y}(Y)$$

*is coherent.*

*Proof.* By **Proposition 5.3.8**, both  $\text{Sh}_{\tau_X}(X)$  and  $\text{Sh}_{\tau_Y}(Y)$  are locally coherent. The image  $j_Y(Y)$  of  $Y$  under the sheafified Yoneda embedding generates  $\text{Sh}_{\tau_Y}(Y)$  under colimits, so by **Corollary 5.6.6** it suffices to check that  $f^*$  carries objects in  $j_Y(Y)$  to coherent objects of  $X$ ; this is the content of **Lemma 5.6.7**.  $\square$

**5.6.9.** **Proposition 5.5.6** and **Corollaries 5.6.6** and **5.6.8** together show that a geometric morphism of coherent 1-topoi is coherent in the sense of [**SGA 4<sub>III</sub>**, Exposé VI, Definition 3.1] if and only if the geometric morphism of corresponding 1-localic  $\infty$ -topoi is coherent if and only if the geometric morphism of coherent 1-topoi is coherent in the sense of **Definition 5.3.6**.

**5.6.10 Notation.** Let  $n \in \mathbb{N}$ . Write  $\text{Top}_{\infty}^{n, \text{coh}} \subset \text{Top}_{\infty}^{\text{coh}}$  for the full subcategory spanned by the  $n$ -localic coherent  $\infty$ -topoi. Write  $\text{Top}_n^{\text{coh}} \subset \text{Top}_n$  for the subcategory of the  $(n+1)$ -category of  $n$ -topoi with objects coherent  $n$ -topoi and morphisms coherent geometric morphisms. When  $n = 1$ , the 2-category  $\text{Top}_1^{\text{coh}}$  is the 2-category of ordinary coherent topoi and coherent geometric morphisms (both in the sense of [**SGA 4<sub>III</sub>**, Exposé VI]).



**Proposition 5.5.6** and **Corollary 5.6.6** immediately imply the following:

**5.6.11 Proposition.** *Let  $n \in \mathbb{N}$ . The equivalence of  $\infty$ -categories  $\tau_{\leq n-1} : \mathbf{Top}_{\infty}^n \simeq \mathbf{Top}_n$  restricts to an equivalence*

$$\tau_{\leq n-1} : \mathbf{Top}_{\infty}^{n,coh} \simeq \mathbf{Top}_n^{coh}$$

**5.6.12 Corollary.** *Let  $n \in \mathbb{N}$ . The following are equivalent for a geometric morphism  $f_* : X \rightarrow Y$  between  $n$ -localic coherent  $\infty$ -topoi:*

(5.6.12.1) *The geometric morphism  $f_* : X \rightarrow Y$  is coherent.*

(5.6.12.2) *The pullback functor  $f^* : Y \rightarrow X$  carries  $(n-1)$ -truncated  $n$ -coherent objects of  $Y$  to  $n$ -coherent objects of  $X$ .*

## 5.7 Examples of coherent $\infty$ -topoi from algebraic geometry

In this subsection we provide a few examples of coherent  $\infty$ -topoi from algebraic geometry that **Corollary 5.6.8** puts on the same footing.

**5.7.1 Example.** For a spectral topological space  $S$ , write  $\mathrm{Open}^{qc}(S) \subset \mathrm{Open}(S)$  for the locale of quasicompact opens in  $S$ . Since the quasicompact opens of  $S$  form a basis for the topology on  $S$  that is closed under finite intersections the  $\infty$ -topos  $\mathbf{Sh}(\mathrm{Open}^{qc}(S))$  is 0-localic. Applying [53, Proposition B.6.4] we see that the inclusion  $\mathrm{Open}^{qc}(S) \subset \mathrm{Open}(S)$  induces an equivalence of 0-localic  $\infty$ -topoi

$$\tilde{S} \simeq \mathbf{Sh}(\mathrm{Open}^{qc}(S)).$$

The Grothendieck topology on  $\mathrm{Open}^{qc}(S)$  is finitary, so the  $\infty$ -topos  $\tilde{S}$  of sheaves on  $S$  is a coherent  $\infty$ -topos. (Cf. [SAG, Lemma 2.3.4.1]).

If  $f : S \rightarrow T$  is a quasicompact continuous map of spectral topological spaces, the inverse image map  $f^{-1} : \mathrm{Open}(T) \rightarrow \mathrm{Open}(S)$  restricts to a map

$$f^{-1} : \mathrm{Open}^{qc}(T) \rightarrow \mathrm{Open}^{qc}(S).$$

**Corollary 5.6.8** shows that the induced geometric morphism  $f_* : \tilde{S} \rightarrow \tilde{T}$  is coherent. Since spectral topological spaces are sober, a continuous map  $f : S \rightarrow T$  of spectral topological spaces induces a coherent geometric morphism on the level of  $\infty$ -topoi if and only if  $f$  is quasicompact.

**5.7.2.** If  $X$  is a coherent  $\infty$ -topos, then the underlying topological space of  $X$  is spectral [48, Chapter II, §§3.3–3.4].

Combining the fact that the Zariski, Nisnevich<sup>16</sup>, étale, and proétale<sup>17</sup> topoi of a scheme all have the same underlying topological space with the fact that if a scheme  $X$  is quasicompact and quasiseparated, then the topoi of sheaves on  $X$  in each of these topologies is coherent [SAG, Proposition 2.3.4.2 & Remark 3.7.4.2; 7, Appendix A; 53, Example 7.1.7], we deduce the following:

<sup>16</sup>For background on the Nisnevich topology, see [SAG, §3.7; 37; 38; 62].

<sup>17</sup>For background on the proétale topology, see [STK, Tags 0988 & 099R; 10].

**5.7.3 Proposition.** *The following are equivalent for a scheme  $X$ :*

(5.7.3.1) *The scheme  $X$  is coherent (i.e., quasicompact and quasiseparated).*

(5.7.3.2) *The Zariski  $\infty$ -topos  $X_{zar}$  of  $X$  is a coherent  $\infty$ -topos.*

(5.7.3.3) *The Nisnevich  $\infty$ -topos  $X_{nis}$  of  $X$  is a coherent  $\infty$ -topos.*

(5.7.3.4) *The étale  $\infty$ -topos  $X_{ét}$  of  $X$  is a coherent  $\infty$ -topos.*

(5.7.3.5) *The proétale  $\infty$ -topos  $X_{proét}$  of  $X$  is a coherent  $\infty$ -topos.*

**5.7.4.** In the case of the étale topology, see also [SAG, Proposition 2.3.4.2].

**5.7.5 Example.** Let  $f : X \rightarrow Y$  be a morphism of coherent schemes and let

$$\tau \in \{zar, nis, ét, proét\}.$$

Then the induced geometric morphism  $f_* : X_\tau \rightarrow Y_\tau$  on  $\infty$ -topoi of  $\tau$ -sheaves is a coherent geometric morphism of coherent  $\infty$ -topoi. (Cf. [SAG, Proposition 2.3.5.1])

**5.7.6 Example.** Let  $X$  be a coherent scheme. Then the natural geometric morphisms

$$X_{proét} \rightarrow X_{ét}, \quad X_{ét} \rightarrow X_{nis}, \quad \text{and} \quad X_{nis} \rightarrow X_{zar}$$

are all coherent geometric morphisms of coherent  $\infty$ -topoi.

## 5.8 Classification of bounded coherent $\infty$ -topoi via $\infty$ -pretopoi

In this subsection we explain how an  $\infty$ -topos that is both bounded and coherent is *determined* by its truncated coherent objects.

**5.8.1 Notation.** Denote by  $\mathbf{Top}_\infty^{bc} \subset \mathbf{Top}_\infty^{coh}$  the full subcategory spanned by those coherent  $\infty$ -topoi that are also bounded, that is, the *bounded coherent*  $\infty$ -topoi

To a large extent, bounded coherent  $\infty$ -topoi function in much the same way as coherent 1-topoi. In particular, any bounded coherent  $\infty$ -topos is, in a canonical fashion, the  $\infty$ -category of sheaves on an  $\infty$ -site with excellent formal properties.

**5.8.2 Definition.** An  $\infty$ -category  $X$  is said to be an  $\infty$ -pretopos if and only if the following conditions are satisfied.

- The  $\infty$ -category  $X$  admits finite limits.
- The  $\infty$ -category  $X$  admits finite coproducts, which are universal and disjoint.
- Groupoid objects in  $X$  are effective, and their geometric realisations are universal.

If  $X$  and  $Y$  are  $\infty$ -pretopoi, then a functor  $f^* : Y \rightarrow X$  is a *morphism of  $\infty$ -pretopoi* if  $f^*$  preserves finite limits, finite coproducts, and effective epimorphisms. We write  $pre\mathbf{Top}_\infty \subset \mathbf{Cat}_{\infty, \delta_1}$  for the subcategory consisting of  $\infty$ -pretopoi and morphisms of  $\infty$ -pretopoi.

**5.8.3 Example.** If  $X$  is a coherent  $\infty$ -topos, then the full subcategory  $X^{\text{coh}} \subseteq X$  spanned by the coherent objects is an  $\infty$ -pretopos [SAG, Corollary A.6.1.7].

The following two useful facts are immediate from the definitions.

**5.8.4 Lemma.** *Let  $\{X_i\}_{i \in I}$  be a collection of  $\infty$ -pretopoi. Then the product  $\prod_{i \in I} X_i$  in  $\text{Cat}_{\infty, \delta_1}$  is an  $\infty$ -pretopos and for each  $j \in I$  the projection*

$$\text{pr}_j : \prod_{i \in I} X_i \rightarrow X_j$$

*is a morphism of  $\infty$ -pretopoi.*

**5.8.5 Lemma.** *Given morphisms of  $\infty$ -pretopoi  $X \rightarrow Z$  and  $Y \rightarrow Z$ , the pullback  $X \times_Z Y$  in  $\text{Cat}_{\infty, \delta_1}$  is an  $\infty$ -pretopos, and the projections*

$$\text{pr}_1 : X \times_Z Y \rightarrow X \quad \text{and} \quad \text{pr}_2 : X \times_Z Y \rightarrow Y$$

*are morphisms of  $\infty$ -pretopoi.*

**5.8.6 Notation.** If  $X$  is an  $\infty$ -pretopos, then if  $E \subseteq X$  is the collection of effective epimorphisms, then  $(X, E)$  is an  $\infty$ -presite, and we write  $\text{eff} := \tau_E$  for the resulting finitary topology, the *effective epimorphism topology* [SAG, §A.6.2], which is a subcanonical topology [SAG, Corollary A.6.2.6].

**5.8.7 Definition.** An  $\infty$ -pretopos  $X$  is *bounded* if and only if  $X$  is essentially  $\delta_0$ -small and every object of  $X$  is truncated. We write  $\text{preTop}_\infty^b \subset \text{preTop}_\infty$  for the full subcategory spanned by the bounded  $\infty$ -pretopoi.

**5.8.8 Theorem** ([SAG, Theorem A.7.5.3]). *The constructions  $X \mapsto X_{<\infty}^{\text{coh}}$  and  $X \mapsto \text{Sh}_{\text{eff}}(X)$  are mutually inverse equivalences of  $\infty$ -categories*

$$\text{Top}_\infty^{bc} \simeq \text{preTop}_\infty^{b, \text{op}}.$$

The following bounded analogue of Lemma 5.8.4 will also be useful later.

**5.8.9 Lemma.** *Let  $\{X_i\}_{i \in I}$  be a finite collection of bounded  $\infty$ -pretopoi. Then the  $\infty$ -pretopos given by the product  $\prod_{i \in I} X_i$  in  $\text{Cat}_{\infty, \delta_1}$  is a bounded  $\infty$ -pretopos.*

*Proof.* For each  $i \in I$  the  $\infty$ -category  $X_i$  is essentially  $\delta_0$ -small, so the product  $\prod_{i \in I} X_i$  is also essentially  $\delta_0$ -small. For any integer  $n \geq -2$ , an object  $F \in \prod_{i \in I} X_i$  is  $n$ -truncated if and only if  $\text{pr}_i(F) \in X_i$  is  $n$ -truncated for all  $i \in I$ . Since  $I$  is finite and every object of each of the  $\infty$ -categories  $\{X_i\}_{i \in I}$  is truncated by assumption, every object of the product  $\prod_{i \in I} X_i$  is truncated.  $\square$

## 5.9 Coherence of inverse limits

We now recall that bounded coherent  $\infty$ -topoi and coherent geometric morphisms are stable under inverse limits in  $\text{Top}_\infty$ .

**5.9.1 Proposition** ([SAG, Proposition A.8.3.1]). *The  $\infty$ -category  $\text{preTop}_\infty^b$  admits filtered colimits and the forgetful functor  $\text{preTop}_\infty^b \rightarrow \text{Cat}_{\infty, \delta_1}$  preserves filtered colimits.*

**5.9.2 Proposition** ([SAG, Proposition A.8.3.2]). *Let  $X: A \rightarrow \text{preTop}_\infty^b$  be a filtered diagram of bounded  $\infty$ -pretopoi. Then the natural geometric morphism*

$$\text{Sh}_{\text{eff}}(\text{colim}_{\alpha \in A} X_\alpha) \rightarrow \lim_{\alpha \in A^{\text{op}}} \text{Sh}_{\text{eff}}(X_\alpha)$$

*is an equivalence in  $\text{Top}_\infty$ .*

The following is immediate from the previous two propositions and [Theorem 5.1.9](#)=[HTT, Theorem 6.3.3.1].

**5.9.3 Corollary** ([SAG, Corollary A.8.3.3]). *The  $\infty$ -category  $\text{Top}_\infty^{bc}$  admits inverse limits and the inclusion  $\text{Top}_\infty^{bc} \rightarrow \text{Top}_\infty$  and forgetful functor  $\text{Top}_\infty^{bc} \rightarrow \text{Cat}_{\infty, \delta_1}$  preserves inverse limits.*

## 5.10 Coherence & preservation of filtered colimits

The goal of this subsection is to prove the appropriate  $\infty$ -toposic generalisation of the fact that a coherent geometric morphism of 1-topoi preserves filtered colimits (see [Corollary 5.10.4](#)).<sup>18</sup>

**5.10.1 Recollection.** Since filtered colimits commute with finite limits in an  $\infty$ -topos, for any  $\infty$ -topos  $\mathbf{X}$  and integer  $n \geq -2$ , the inclusion  $\tau_{\leq n} \mathbf{X} \hookrightarrow \mathbf{X}$  preserves filtered colimits. Thus  $\mathbf{X}_{\leq n}$  is an  $\omega$ -accessible localisation of  $\mathbf{X}$ .

**5.10.2 Lemma.** *Let  $(X, \tau)$  be a finitary  $\infty$ -site, write  $\mathbf{X} := \text{Sh}_\tau(X)$ , and write  $j: X \rightarrow \mathbf{X}$  for the sheafified Yoneda embedding. Then for all integers  $n \geq -2$  and  $x \in X$ , the functor*

$$\text{Map}_{\mathbf{X}}(j(x), -): \mathbf{X}_{\leq n} \rightarrow \mathcal{S}$$

*preserves filtered colimits.*

*Proof.* Write  $U := j(x)$  and let  $p_*: \mathbf{X}_{/U} \rightarrow \mathbf{X}$  denote the natural étale geometric morphism. Let  $V: A \rightarrow \mathbf{X}_{\leq n}$  be a filtered diagram. Then we have

$$\begin{aligned} \text{Map}_{\mathbf{X}}(U, \text{colim}_{\alpha \in A} V_\alpha) &\simeq \text{Map}_{\mathbf{X}}(p_!(1_{\mathbf{X}_{/U}}), \text{colim}_{\alpha \in A} V_\alpha) \\ &\simeq \text{Map}_{\mathbf{X}_{/U}}(1_{\mathbf{X}_{/U}}, \text{colim}_{\alpha \in A} p^*(V_\alpha)). \end{aligned}$$

Since  $U \in \mathbf{X}$  is coherent [Proposition 5.3.8](#)=[SAG, Proposition A.3.1.3], the global sections functor

$$\text{Map}_{\mathbf{X}_{/U}}(1_{\mathbf{X}_{/U}}, -): (\mathbf{X}_{/U})_{\leq n} \rightarrow \mathcal{S}$$

preserves filtered colimits [SAG, Proposition A.2.3.1]. Hence

$$\begin{aligned} \text{Map}_{\mathbf{X}}(U, \text{colim}_{\alpha \in A} V_\alpha) &\simeq \text{colim}_{\alpha \in A} \text{Map}_{\mathbf{X}_{/U}}(1_{\mathbf{X}_{/U}}, p^*(V_\alpha)) \\ &\simeq \text{colim}_{\alpha \in A} \text{Map}_{\mathbf{X}}(p_!(1_{\mathbf{X}_{/U}}), V_\alpha) \\ &\simeq \text{colim}_{\alpha \in A} \text{Map}_{\mathbf{X}}(U, V_\alpha). \end{aligned} \quad \square$$

<sup>18</sup>We learned how to simplify and generalize the material in this subsection from its original form through a preprint of Chang-Yeon Chough [14, Theorem 3.4].

**5.10.3 Proposition.** *Let  $f^* : (Y, \tau_Y) \rightarrow (X, \tau_X)$  be a morphism of finitary  $\infty$ -sites. Then for each integer  $n \geq -2$ , the restriction of  $f_* : \mathbf{Sh}_{\tau_X}(X) \rightarrow \mathbf{Sh}_{\tau_Y}(Y)$  to  $\mathbf{Sh}_{\tau_X}(X)_{\leq n}$  preserves filtered colimits.*

*Proof.* Write  $\mathbf{X} := \mathbf{Sh}_{\tau_X}(X)$ ,  $\mathbf{Y} := \mathbf{Sh}_{\tau_Y}(Y)$ , and  $j_X : X \rightarrow \mathbf{X}$  and  $j_Y : Y \rightarrow \mathbf{Y}$  for the sheafified Yoneda embeddings. Let  $V : A \rightarrow \mathbf{X}_{\leq n}$  be a filtered diagram. Since the essential image of  $j_Y$  generates  $\mathbf{Y}$  under colimits, to see that the natural morphism

$$\mathrm{colim}_{\alpha \in A} f_*(V_\alpha) \rightarrow f_*(\mathrm{colim}_{\alpha \in A} V_\alpha)$$

is an equivalence, it suffices to show that for all  $y \in Y$ , the induced morphism

$$\mathrm{Map}_{\mathbf{Y}}(j_Y(y), \mathrm{colim}_{\alpha \in A} f_*(V_\alpha)) \rightarrow \mathrm{Map}_{\mathbf{Y}}(j_Y(y), f_*(\mathrm{colim}_{\alpha \in A} V_\alpha))$$

is an equivalence. Applying [Lemma 5.10.2](#) to  $j_Y(y)$  and  $f^* j_Y(y) \simeq j_X(f^*(y))$  we see that

$$\begin{aligned} \mathrm{Map}_{\mathbf{Y}}(j_Y(y), \mathrm{colim}_{\alpha \in A} f_*(V_\alpha)) &\simeq \mathrm{colim}_{\alpha \in A} \mathrm{Map}_{\mathbf{Y}}(j_Y(y), f_*(V_\alpha)) \\ &\simeq \mathrm{colim}_{\alpha \in A} \mathrm{Map}_{\mathbf{Y}}(f^* j_Y(y), V_\alpha) \\ &\simeq \mathrm{Map}_{\mathbf{Y}}(f^* j_Y(y), \mathrm{colim}_{\alpha \in A} V_\alpha) \\ &\simeq \mathrm{Map}_{\mathbf{Y}}(j_Y(y), f_*(\mathrm{colim}_{\alpha \in A} V_\alpha)). \quad \square \end{aligned}$$

In light of [Theorem 5.8.8](#)=[SAG, Theorem A.7.5.3], [Proposition 5.10.3](#) specialises to the following.

**5.10.4 Corollary.** *Let  $f_* : \mathbf{X} \rightarrow \mathbf{Y}$  be a coherent geometric morphism between bounded coherent  $\infty$ -topoi. Then for any integer  $n \geq -2$ , the restriction of  $f_*$  to  $\mathbf{X}_{\leq n}$  preserves filtered colimits.*

## 5.11 Points, Conceptual Completeness, & Deligne Completeness

In this subsection we discuss points of  $\infty$ -topoi as well as the  $\infty$ -toposic generalisations of the Conceptual Completeness Theorem of Makkai–Reyes and Deligne’s Completeness Theorem.

**5.11.1 Notation.** For an  $\infty$ -topos  $\mathbf{X}$ , we write

$$\mathrm{Pt}(\mathbf{X}) := \mathrm{Fun}_*(\mathbf{S}, \mathbf{X})^{op} \simeq \mathrm{Fun}^*(\mathbf{X}, \mathbf{S})$$

of the  $\infty$ -category of *points* of  $\mathbf{X}$ .

We note that a morphism  $g_* \rightarrow f_*$  of  $\mathrm{Pt}(\mathbf{X})$  is a natural transformation  $f_* \rightarrow g_*$ . (The morphisms are the ‘geometric transformations’ usually preferred in 1-topos theory.) This choice syncs well with the direction of posets: for instance, when  $P$  is a noetherian poset, one has  $\mathrm{Pt}(\tilde{P}) \simeq P$ .

In general, the passage from an  $\infty$ -topos to its  $\infty$ -category of points loses quite a bit of information. However, the  $\infty$ -toposic version of the Conceptual Completeness Theorem of Makkai–Reyes [[54](#), Theorem 9.2] tells us that bounded coherent  $\infty$ -topoi are determined by their  $\infty$ -categories of points.

**5.11.2 Theorem** (Conceptual Completeness ; [SAG, Theorem A.9.0.6]). *A geometric morphism  $f_* : X \rightarrow Y$  between bounded coherent  $\infty$ -topoi is an equivalence if and only if  $f_*$  is coherent and the induced functor  $\mathrm{Pt}(f_*) : \mathrm{Pt}(X) \rightarrow \mathrm{Pt}(Y)$  is an equivalence of  $\infty$ -categories.*

**5.11.3 Definition.** An  $\infty$ -topos  $X$  has enough points if a morphism  $\phi$  in  $X$  is an equivalence if and only if for every point  $x_* \in \mathrm{Pt}(X)$  the stalk  $x^* \phi$  is an equivalence.

In classical topos theory, the Deligne Completeness Theorem [SGA 4<sub>III</sub>, Exposé VI, Proposition 9.0] states that a coherent ordinary topos has enough points. This is no longer true in the setting of  $\infty$ -topoi, the main obstruction being that  $\infty$ -connective morphisms in an  $\infty$ -topos need not be equivalences. For this reason the  $\infty$ -categorical version of Deligne's theorem takes place in the setting of  $\infty$ -topoi where  $\infty$ -connective morphisms are equivalences, i.e.,  $\infty$ -topoi in which Whitehead's Theorem is valid.

**5.11.4 Definition.** Let  $X$  be an  $\infty$ -topos. An object  $U \in X$  is *hypercomplete* if  $U$  is local with respect to the class of  $\infty$ -connective morphisms in  $X$ . We write  $X^{\mathrm{hyp}} \subset X$  for the full subcategory spanned by the hypercomplete objects of  $X$ . An  $\infty$ -topos is *hypercomplete* if  $X^{\mathrm{hyp}} = X$ .

**5.11.5.** The  $\infty$ -category  $X^{\mathrm{hyp}} \subset X$  is a left exact localisation of  $X$ , hence an  $\infty$ -topos [HTT, p. 699]. Moreover, the  $\infty$ -topos  $X^{\mathrm{hyp}}$  is hypercomplete [HTT, Lemma 6.5.2.12].

The  $\infty$ -topos  $X^{\mathrm{hyp}}$  is characterised by the following universal property.

**5.11.6 Proposition** ([HTT, Proposition 6.5.2.13]). *Let  $X$  be an  $\infty$ -topos. Then for every hypercomplete  $\infty$ -topos  $H$ , composition with the inclusion  $X^{\mathrm{hyp}} \subset X$  induces an equivalence*

$$\mathrm{Fun}_*(H, X^{\mathrm{hyp}}) \simeq \mathrm{Fun}_*(H, X).$$

Consequently, the assignment  $X \mapsto X^{\mathrm{hyp}}$  defines a functor right adjoint to the inclusion of hypercomplete  $\infty$ -topoi into all  $\infty$ -topoi. For this reason we call  $X^{\mathrm{hyp}}$  the *hypercompletion* of  $X$ .

**5.11.7 Example.** An  $\infty$ -topos with enough points is hypercomplete.

**5.11.8 Example.** Let  $X$  be a 1-topos with corresponding 1-localic  $\infty$ -topos  $X'$ . Then  $X$  has enough points (in the sense of [SGA 4<sub>I</sub>, Exposé IV, Définition 6.4.1]) if and only if the hypercomplete  $\infty$ -topos  $(X')^{\mathrm{hyp}}$  has enough points.

In light of **Example 5.11.7**, the following is the correct  $\infty$ -toposic generalisation of Deligne's completeness theorem.

**5.11.9 Theorem** ( $\infty$ -Categorical Deligne Completeness; [SAG, Proposition A.4.0.5]). *An  $\infty$ -topos that is locally coherent and hypercomplete has enough points.*

We have already seen that the coherence of an  $\infty$ -topos only depends on its hypercompletion (**Lemma 5.4.12**). The following proposition gives a more refined assertion about the relationship between the coherent objects of an  $\infty$ -topos and its hypercompletion.

**5.11.10 Proposition** ([SAG, Proposition A.2.2.2]). *Let  $X$  be an  $\infty$ -topos, and write  $L: X \rightarrow X^{hyp}$  for the left adjoint to the inclusion  $X^{hyp} \hookrightarrow X$ . If  $X$  is locally  $n$ -coherent for all  $n \geq 0$ , then:*

(5.11.10.1) *The  $\infty$ -topos  $X^{hyp}$  is locally  $n$ -coherent for all  $n \geq 0$ .*

(5.11.10.2) *An object  $U$  of  $X^{hyp}$  is coherent if and only if  $U$  is coherent when viewed as an object of  $X$ .*

(5.11.10.3) *An object  $U \in X$  is coherent if and only if  $L(U)$  is coherent.*

**5.11.11 Corollary.** *Let  $X$  be an  $\infty$ -topos. If  $X$  is (locally) coherent, then the hypercompletion  $X^{hyp}$  of  $X$  is (locally) coherent.*

**5.11.12 Example.** Let  $X$  be a bounded coherent  $\infty$ -topos. Then since  $X$  is also locally coherent (Example 5.3.5), the hypercompletion  $X^{hyp}$  of  $X$  is coherent and locally coherent.

**5.11.13.** Please observe that for an  $\infty$ -topos  $X$ , the hypercompletion  $X^{hyp}$  has enough points if and only if  $\infty$ -connectiveness of morphisms in  $X$  can be checked on stalks, i.e., a morphism  $\phi$  in  $X$  is  $\infty$ -connective if and only if for every point  $x_*$  of  $X$ , the stalk  $x_*^* \phi$  is an equivalence in  $\mathcal{S}$ . The Deligne Completeness Theorem (Theorem 5.11.9=[SAG, Proposition A.4.0.5]) and Corollary 5.11.11 show that  $\infty$ -connectiveness in a locally coherent  $\infty$ -topos can be checked on stalks.

## 5.12 Protruncated objects

In this subsection, we recall some facts about protruncated objects that we'll need as well as record an interesting observation (Lemma 5.12.5) which does not seem to be in the literature.

**5.12.1 Notation.** Let  $C$  be a presentable  $\infty$ -category. For each integer  $n \geq -2$ , write  $C_{\leq n} \subset C$  for the full subcategory spanned by the  $n$ -truncated objects, and  $\tau_{\leq n}: C \rightarrow C_{\leq n}$  for the  $n$ -truncation functor, which is left adjoint to the inclusion  $C_{\leq n} \subset C$  [HTT, Proposition 5.5.6.18]. Write  $C_{<\infty} \subset C$  for the full subcategory spanned by those objects which are  $n$ -truncated for some integer  $n \geq -2$ .

The *pro- $n$ -truncation* functor  $\tau_{\leq n}: \text{Pro}(C) \rightarrow \text{Pro}(C_{\leq n})$  is the extension of the  $n$ -truncation functor  $\tau_{\leq n}: C \rightarrow C_{\leq n}$  to pro-objects.

**5.12.2.** Let  $C$  be a presentable  $\infty$ -category. Then the extension to pro-objects of the functor  $C \rightarrow \text{Pro}(C_{<\infty})$  given by sending an object  $X \in C$  to the inverse system given by its Postnikov tower  $\{\tau_{\leq n}(X)\}_{n \geq -2}$  is left adjoint to the inclusion  $\text{Pro}(C_{<\infty}) \hookrightarrow \text{Pro}(C)$ . We call this left adjoint  $\tau_{<\infty}: \text{Pro}(C) \rightarrow \text{Pro}(C_{<\infty})$  *protruncation*. A morphism of pro-objects  $f: X \rightarrow Y$ , regarded as left exact accessible functors  $C \rightarrow \mathcal{S}$ , becomes an equivalence after protruncation if and only if for every truncated object  $K \in C_{<\infty}$ , the induced morphism  $f(K): X(K) \rightarrow Y(K)$  is an equivalence.

If  $C$  is an  $\infty$ -topos, then the protruncation functor  $\tau_{<\infty}$  also preserves finite products since truncations do [HTT, Lemma 6.5.1.2].

5.12.3. Isaksen's *strict model structure* on pro-simplicial sets [45] presents the  $\infty$ -category  $\text{Pro}(\mathcal{S})$  of prospaces [40, Lemma 3.1]. The model structure that Isaksen defines in [43] is the left Bousfield localisation of the strict model structure at the  $\tau_{<\infty}$ -equivalences, hence presents the  $\infty$ -category  $\text{Pro}(\mathcal{S}_{<\infty})$  of protruncated spaces [40, Remark 3.2].

5.12.4. Let  $C$  be a presentable  $\infty$ -category. The essentially unique functor

$$\text{mat}: \text{Pro}(C) \rightarrow C$$

that perserves inverse limits and restricts to the identity  $C \rightarrow C$  is right adjoint to the Yoneda embedding  $j: C \hookrightarrow \text{Pro}(C)$  [SAG, Example A.8.1.7]. Hence we have adjunctions

$$C \xrightleftharpoons[\text{mat}]{j} \text{Pro}(C) \xrightleftharpoons{\tau_{<\infty}} \text{Pro}(C_{<\infty}).$$

If Postnikov towers converge in  $C$  [SAG, Definition A.7.2.1], then the composite left adjoint is also fully faithful:

**5.12.5 Lemma.** *Let  $C$  be a Postnikov complete presentable  $\infty$ -category (e.g., a Postnikov complete  $\infty$ -topos). Then the protruncation functor*

$$\tau_{<\infty}: C \rightarrow \text{Pro}(C_{<\infty})$$

*is fully faithful. Moreover, the essential image of  $\tau_{<\infty}: C \hookrightarrow \text{Pro}(C_{<\infty})$  is the full subcategory spanned by those protruncated objects  $X$  such that for each integer  $n \geq -2$ , the pro- $n$ -truncation  $\tau_{\leq n}(X) \in \text{Pro}(C_{\leq n})$  is a constant proobject.*

*Proof.* It suffices to show that for any object  $X \in C$ , the unit morphism  $X \rightarrow \text{mat } \tau_{<\infty}(X)$  is an equivalence. This follows from the equivalence

$$\text{mat } \tau_{<\infty}(X) \simeq \lim_{n \geq -2} \tau_{\leq n}(X)$$

and the assumption that Postnikov towers converge in  $C$ .  $\square$

5.12.6. Composing the fully faithful functor  $\tau_{<\infty}: \mathcal{S} \hookrightarrow \text{Pro}(\mathcal{S}_{<\infty})$  with the inclusion  $\text{Pro}(\mathcal{S}_{<\infty}) \hookrightarrow \text{Pro}(\mathcal{S})$  gives another embedding of spaces into prospace: for a space  $K$ , the natural morphism of prospace  $j(K) \rightarrow \tau_{<\infty}(K)$  is an equivalence if and only if  $K$  is truncated. Unlike the Yoneda embedding, the functor  $\tau_{<\infty}: \mathcal{S} \hookrightarrow \text{Pro}(\mathcal{S})$  is neither a left nor a right adjoint.

## 5.13 Shape theory

We now recall the basics of *shape theory* for  $\infty$ -topoi. The shape is crucial to the study of *Stone  $\infty$ -topoi* presented in the next subsection, as well as our development of the *stratified shape* in Part III and *stratified étale homotopy type* in Part IV.

**5.13.1 Definition.** The *shape*  $\Pi_{\infty}: \mathbf{Top}_{\infty} \rightarrow \text{Pro}(\mathcal{S})$  is the left adjoint to the extension to proobjects of the fully faithful functor  $\mathcal{S} \hookrightarrow \mathbf{Top}_{\infty}$  given by  $\Pi \mapsto S_{/\Pi} \simeq \text{Fun}(\Pi, \mathcal{S})$  [SAG, §E.2.2]. The shape admits two other very useful descriptions:



- Let  $X$  be an  $\infty$ -topos, and write  $\Gamma_! : X \rightarrow \text{Pro}(\mathcal{S})$  for the proëxistent left adjoint of  $\Gamma^* : \mathcal{S} \rightarrow X$ . The shape of  $X$  is equivalent to the prospace  $\Gamma_!(1_X)$  [HA, Remark A.1.10; 39, §2].
- As a left exact accessible functor  $\mathcal{S} \rightarrow \mathcal{S}$ , the prospace  $\Pi_\infty(X)$  is the composite  $\Gamma_*\Gamma^*$  [HTT, §7.1.6; 39, §2]. Under this identification, the shape assigns to a geometric morphism  $f_* : X \rightarrow Y$  with unit  $\eta : \text{id}_Y \rightarrow f_*f^*$  the morphism of prospace corresponding to

$$\Gamma_{Y,*}\eta\Gamma_Y^* : \Gamma_{Y,*}\Gamma_Y^* \rightarrow \Gamma_{Y,*}f_*f^*\Gamma_Y^*$$

in  $\text{Pro}(\mathcal{S})^{op} \subset \text{Fun}(\mathcal{S}, \mathcal{S})$ .

**5.13.2.** The functor  $\lambda : \text{Pro}(\mathcal{S}) \rightarrow \mathbf{Top}_\infty$  given by extending the fully faithful functor  $\mathcal{S} \hookrightarrow \mathbf{Top}_\infty$  to proobjects is *not* itself fully faithful.

**5.13.3 Notation.** We write  $H : \mathbf{Cat}_\infty \rightarrow \mathcal{S}$  for the left adjoint to the inclusion, given by sending an  $\infty$ -category  $C$  to the  $\infty$ -groupoid  $H(C)$  obtained by inverting all of the morphisms of  $C$ .<sup>19</sup> The  $\infty$ -groupoid  $H(C)$  is given by the colimit  $H(C) \simeq \text{colim}_C 1_{\mathcal{S}}$  of the constant diagram  $C \rightarrow \mathcal{S}$  at the terminal object.

**5.13.4 Example.** If  $C$  is a small  $\infty$ -category, then  $\Gamma^* : \mathcal{S} \rightarrow \text{Fun}(C, \mathcal{S})$  admits a genuine left adjoint  $\Gamma_! : \text{Fun}(C, \mathcal{S}) \rightarrow \mathcal{S}$  given by taking the colimit of a diagram  $C \rightarrow \mathcal{S}$ .<sup>20</sup> The shape of the  $\infty$ -topos  $\text{Fun}(C, \mathcal{S})$  is thus given by the colimit of the constant diagram at the terminal object of  $\mathcal{S}$ :

$$\Pi_\infty(\text{Fun}(C, \mathcal{S})) = \Gamma_!(1_{\text{Fun}(C, \mathcal{S})}) = \text{colim}_C 1_{\mathcal{S}} \simeq H(C).$$

Moreover, the functor  $H : \mathbf{Cat}_\infty \rightarrow \mathcal{S}$  is equivalent to the composite

$$\mathbf{Cat}_\infty \xrightarrow{\text{Fun}(-, \mathcal{S})} \mathbf{Top}_\infty \xrightarrow{\Pi_\infty} \mathcal{S}.$$

**5.13.5 Definition.** A geometric morphism  $f_* : X \rightarrow Y$  of  $\infty$ -topoi is a *shape equivalence* if the induced morphism  $\Pi_\infty(f_*) : \Pi_\infty(X) \rightarrow \Pi_\infty(Y)$  is an equivalence in  $\text{Pro}(\mathcal{S})$ . An  $\infty$ -topos  $X$  is said to have *trivial shape* if  $\Pi_\infty(X)$  is a terminal object of  $\text{Pro}(\mathcal{S})$ .

**5.13.6.** Work of Hoyois [39, Proposition 2.6] shows that a geometric morphism  $f_*$  is a shape equivalence if and only if  $f_*$  induces an equivalence of  $\infty$ -categories of (space-valued) torsors.

**5.13.7 Warning.** The pullback (in  $\mathbf{Top}_\infty$ ) of a shape equivalence is not generally a shape equivalence, even when both morphisms are shape equivalences. As an example, consider the space  $X := [0, 1]$ , and its closed subspace  $Z := \{0\}$  and open complement  $U := (0, 1]$ . Then the  $\infty$ -topoi  $\bar{X}$ ,  $\bar{U}$ , and  $\bar{Z}$  all have trivial shape and the natural inclusions  $\bar{Z} \hookrightarrow \bar{X}$  and  $\bar{U} \hookrightarrow \bar{X}$  are both shape equivalences [HA, Example A.4.5], however the pullback  $\bar{Z} \times_{\bar{X}} \bar{U}$  is the initial  $\infty$ -topos  $\emptyset$ , which has empty shape.

<sup>19</sup>In simplicial sets the functor  $H$  can be modeled as Kan's  $\text{Ex}^\infty$  functor.

<sup>20</sup>That is to say, presheaf  $\infty$ -topoi are *locally of constant shape* [HA, Definition A.1.5 & Proposition A.1.8].

**5.13.8 Notation.** Let  $n \geq -2$  be an integer. We write

$$\Pi_n := \tau_{\leq n} \circ \Pi_\infty : \mathbf{Top}_\infty \rightarrow \mathbf{Pro}(\mathbf{S}_{\leq n})$$

for the *pro- $n$ -truncated shape* (Notation 5.12.1). We write

$$\Pi_{<\infty} := \tau_{<\infty} \circ \Pi_\infty : \mathbf{Top}_\infty \rightarrow \mathbf{Pro}(\mathbf{S}_{<\infty})$$

for the *protruncated shape* (5.12.2).

**5.13.9 Example.** Since truncated objects of an  $\infty$ -topos are hypercomplete, for any  $\infty$ -topos  $X$ , the natural geometric morphism  $X^{hyp} \hookrightarrow X$  induces an equivalence

$$\Pi_{<\infty}(X^{hyp}) \simeq \Pi_{<\infty}(X)$$

on protruncated shapes.

The remainder of this subsection is dedicated to proving that the protruncated shape preserves limits of inverse systems of bounded coherent  $\infty$ -topoi and coherent geometric morphisms (Corollary 5.13.16).<sup>21</sup> This follows from the more general fact that the protruncated shape preserves limits of systems of  $\infty$ -topoi and geometric morphisms in which the pushforward preserve filtered colimits of uniformly truncated objects. We learned this from Chang-Yeon Chough [14, §3]; though Chough's paper only states this for the profinite shape, his proof works for the protruncated shape. We fix some useful notation for the next few results.

**5.13.10 Notation.** Let  $X : I \rightarrow \mathbf{Top}_\infty$  be an inverse diagram of  $\infty$ -topoi. For each morphism  $\alpha : j \rightarrow i$  in  $I$ , we write

$$f_{\alpha,*} : X_j \rightarrow X_i$$

for the transition morphism. For each  $i \in I$ , we write

$$\pi_{i,*} : \lim_{i \in I} X_i \rightarrow X_i$$

for the projection. In addition, assume for each morphism  $\alpha : j \rightarrow i$  in  $I$  and integer  $n \geq -2$ , the restriction  $f_{\alpha,*} : X_{j,\leq n} \rightarrow X_{i,\leq n}$  of  $f_{\alpha,*}$  to  $n$ -truncated objects preserves filtered colimits.

**5.13.11 Proposition.** *Under the assumptions of Notation 5.13.10, for each  $i \in I$  and truncated object  $U \in X_{<\infty}$  we have*

$$(5.13.12) \quad \pi_i^*(U) \simeq \left\{ \operatorname{colim}_{(\alpha,\beta) \in (I_i \times I_j)^{op}} f_{\beta,*} f_\alpha^*(U) \right\}_{j \in I}.$$

*Proof.* Since inverse limits in  $\mathbf{Top}_\infty$  are computed in  $\mathbf{Cat}_{\infty,\delta_1}$  (Theorem 5.1.9=[HTT, Theorem 6.3.3.1]), the assumption that each  $f_{\alpha,*}$  preserve filtered colimits of uniformly

<sup>21</sup>A proof of this can be found in work of the third-named author [29, Proposition 2.2], but we present a better proof here.

truncated objects guarantees that the right-hand side of (5.13.12) is a well-defined object of  $\lim_{j \in I} \mathbf{X}_j$ .

For each  $i \in I$ , the forgetful functor  $I_{/i} \rightarrow I$  is limit-cofinal [HTT, Example 5.4.5.9 & Lemma 5.4.5.12], so we may without loss of generality assume that  $i \in I$  is a terminal object. In this case, a simple cofinality argument shows that

$$\operatorname{colim}_{(\alpha, \beta) \in (I_{/i} \times_I I_{/j})^{op}} f_{\beta,*} f_{\alpha}^*(U) \simeq \operatorname{colim}_{[\beta: k \rightarrow j] \in (I_{/j})^{op}} f_{\beta,*} f_k^*(U),$$

where  $f_{k,*} : \mathbf{X}_k \rightarrow \mathbf{X}_i$  is the geometric morphism induced by the essentially unique morphism  $k \rightarrow i$ . By definition, for all  $V \in \mathbf{X}$  we have

$$\begin{aligned} \operatorname{Map}_{\mathbf{X}} \left( \left\{ \operatorname{colim}_{[\beta: k \rightarrow j] \in (I_{/j})^{op}} f_{\beta,*} f_k^*(U) \right\}_{j \in I}, V \right) &\simeq \lim_{j \in I} \operatorname{Map}_{\mathbf{X}_j} \left( \operatorname{colim}_{\beta \in (I_{/j})^{op}} f_{\beta,*} f_k^*(U), \pi_{j,*}(V) \right) \\ &\simeq \lim_{j \in I} \lim_{\beta \in I_{/j}} \operatorname{Map}_{\mathbf{X}_j} (f_{\beta,*} f_k^*(U), \pi_{j,*}(V)) \\ &\simeq \lim_{j \in I} \lim_{\beta \in I_{/j}} \operatorname{Map}_{\mathbf{X}_j} (f_{\beta,*} f_k^*(U), f_{\beta,*} \pi_{k,*}(V)) \end{aligned}$$

Rewriting the limit as a limit over  $\beta \in \operatorname{Fun}(\Delta^1, I)$  and using the fact that the constant functor  $I \rightarrow \operatorname{Fun}(\Delta^1, I)$  is limit-cofinal (since it is a right adjoint), we see that

$$\begin{aligned} \operatorname{Map}_{\mathbf{X}} \left( \left\{ \operatorname{colim}_{[\beta: k \rightarrow j] \in (I_{/j})^{op}} f_{\beta,*} f_k^*(U) \right\}_{j \in I}, V \right) &\simeq \lim_{\beta \in \operatorname{Fun}(\Delta^1, I)} \operatorname{Map}_{\mathbf{X}_j} (f_{\beta,*} f_k^*(U), f_{\beta,*} \pi_{k,*}(V)) \\ &\simeq \lim_{k \in I} \operatorname{Map}_{\mathbf{X}_k} (f_k^*(U), \pi_{k,*}(V)) \\ &\simeq \lim_{k \in I} \operatorname{Map}_{\mathbf{X}} (\pi_k^* f_k^*(U), V) \\ &\simeq \lim_{k \in I} \operatorname{Map}_{\mathbf{X}} (\pi_i^*(U), V) \\ &= \operatorname{Map}_{\mathbf{X}} (\pi_i^*(U), V). \quad \square \end{aligned}$$

**5.13.13 Corollary.** *Keep the assumptions of Proposition 5.13.11. Then for each  $i \in I$  and truncated object  $U \in \mathbf{X}_{i, < \infty}$ , we have an equivalence*

$$\pi_{i,*} \pi_i^*(U) \simeq \operatorname{colim}_{\alpha \in (I_{/i})^{op}} f_{\alpha,*} f_{\alpha}^*(U)$$

*of objects of  $\mathbf{X}_i$ .*

*Proof.* For each  $i \in I$ , the forgetful functor  $I_{/i} \rightarrow I$  is limit-cofinal [HTT, Example 5.4.5.9 & Lemma 5.4.5.12], so we may without loss of generality assume that  $i \in I$  is a terminal object. Then the claim is clear from Proposition 5.13.11 and the definition of  $\pi_{i,*}$ .  $\square$

**5.13.14 Proposition.** *Keep the assumptions of Proposition 5.13.11, and in addition assume that for each  $i \in I$  and integer  $n \geq -2$  the global sections functor  $\Gamma_{\mathbf{X}_{i,*}} : \mathbf{X}_i \rightarrow \mathbf{S}$  preserves filtered colimits when restricted to  $\mathbf{X}_{\leq n}$ . Then the natural morphism*

$$\Pi_{\infty}(\mathbf{X}) \rightarrow \lim_{i \in I} \Pi_{\infty}(\mathbf{X}_i)$$

*becomes an equivalence after protruncation.*

*Proof.* For each  $i \in I$ , the forgetful functor  $I_{/i} \rightarrow I$  is limit-cofinal [HTT, Example 5.4.5.9 & Lemma 5.4.5.12], so we may without loss of generality assume that  $I$  admits a terminal object 1. Write  $\Gamma_{i,*} := \Gamma_{X_i,*}$ ,  $f_{i,*} : X_i \rightarrow X_1$  for the geometric morphism induced by the essentially unique morphism  $i \rightarrow 1$  in  $I$ , and  $\Gamma_* : \lim_{j \in I} X_j \rightarrow \mathbf{S}$  for the global sections geometric morphism.

We want to show that the natural morphism

$$\operatorname{colim}_{i \in I^{op}} \Gamma_{i,*} \Gamma_i^* \rightarrow \Gamma_* \Gamma^*$$

in  $\operatorname{Fun}(\mathbf{S}, \mathbf{S})$  is an equivalence when restricted to truncated spaces (5.12.2). For any truncated space  $K$ , we see that we have equivalences

$$\begin{aligned} \operatorname{colim}_{i \in I^{op}} \Gamma_{i,*} \Gamma_i^*(K) &\simeq \operatorname{colim}_{i \in I^{op}} \Gamma_{1,*} f_{i,*} f_i^* \Gamma_1^*(K) \\ &\simeq \Gamma_{1,*} \left( \operatorname{colim}_{i \in I^{op}} f_{i,*} f_i^* \Gamma_1^*(K) \right) && \text{(assumption on } \Gamma_{i,*} \text{)} \\ &\simeq \Gamma_{1,*} \circ \left( \operatorname{colim}_{i \in I^{op}} f_{i,*} f_i^* \right) \circ \Gamma_1^*(K) \\ &\simeq \Gamma_{1,*} \circ \pi_{1,*} \pi_1^* \circ \Gamma_1^*(K) && \text{(Proposition 5.13.11)} \\ &\simeq \Gamma_* \Gamma^*(K). \end{aligned} \quad \square$$

**5.13.15.** In particular, the assumptions of Proposition 5.13.14 are satisfied for inverse systems of coherent  $\infty$ -topoi where the transition morphisms preserve filtered colimits of uniformly truncated objects [SAG, Theorem A.2.3.1].

From Corollary 5.10.4 and Proposition 5.13.14 we deduce:

**5.13.16 Corollary.** *The protruncated shape*

$$\Pi_{<\infty} : \mathbf{Top}_{\infty}^{bc} \rightarrow \operatorname{Pro}(\mathbf{S}_{<\infty})$$

*preserves inverse limits.*

## 5.14 Profinite spaces & Stone $\infty$ -topoi

In this subsection we discuss profinite spaces and their relation to  $\infty$ -topoi, as developed in [SAG, Appendix E].

**5.14.1 Definition.** We write  $\operatorname{mat} : \mathbf{S}_{\pi}^{\wedge} \rightarrow \mathbf{S}$  for the right adjoint to  $(-)^{\wedge}_{\pi}$  and refer to  $\operatorname{mat}$  as the *materialisation* functor.

**5.14.2 Definition.** The *profinite shape* functor is the composite

$$\Pi_{\infty}^{\wedge} := (-)^{\wedge}_{\pi} \circ \Pi_{\infty} : \mathbf{Top}_{\infty} \rightarrow \mathbf{S}_{\pi}^{\wedge}$$

of the shape functor  $\Pi_{\infty}$  with the profinite completion functor  $(-)^{\wedge}_{\pi} : \operatorname{Pro}(\mathbf{S}) \rightarrow \mathbf{S}_{\pi}^{\wedge}$ .

**5.14.3 Theorem** ([SAG, Theorem E.2.4.1]). *The composite*

$$\lambda_{\pi} : \mathbf{S}_{\pi}^{\wedge} \hookrightarrow \operatorname{Pro}(\mathbf{S}) \xrightarrow{\lambda} \mathbf{Top}_{\infty}$$

*of the inclusion  $\mathbf{S}_{\pi}^{\wedge} \subset \operatorname{Pro}(\mathbf{S})$  with the functor  $\lambda$  of (5.13.2) is fully faithful and right adjoint to the profinite shape functor  $\Pi_{\infty}^{\wedge}$ .*

**5.14.4 Definition.** An  $\infty$ -topos  $X$  is *Stone*<sup>22</sup> if  $X$  lies in the essential image of  $\lambda_\pi : \mathcal{S}_\pi^\wedge \hookrightarrow \mathbf{Top}_\infty$ . We write  $\mathbf{Top}_\infty^{\text{Stone}} \subset \mathbf{Top}_\infty$  for the full subcategory spanned by the Stone  $\infty$ -topoi.

Consequently, the inclusion  $\mathbf{Top}_\infty^{\text{Stone}} \hookrightarrow \mathbf{Top}_\infty$  admits a left adjoint

$$(-)^{\text{Stone}} : \mathbf{Top}_\infty \rightarrow \mathbf{Top}_\infty^{\text{Stone}}$$

which we refer to as the *Stone reflection*.

**5.14.5 Proposition** ([SAG, Proposition E.3.1.4]). *Let  $X$  and  $Y$  be  $\infty$ -topoi. If  $Y$  is Stone, then the  $\infty$ -category  $\mathbf{Fun}_*(X, Y)$  is an (essentially small)  $\infty$ -groupoid.*

**5.14.6.** If  $Y$  is a Stone  $\infty$ -topos, then since  $\mathcal{S}$  is Stone and  $\lambda_\pi$  is fully faithful with left adjoint given by the profinite shape, we see that

$$\mathbf{Pt}(Y) \simeq \mathbf{Map}_{\mathbf{Top}_\infty}(\mathcal{S}, Y) \simeq \mathbf{mat} \Pi_\infty^\wedge(Y) .$$

Since Stone  $\infty$ -topoi are bounded and coherent, Conceptual Completeness ([Theorem 5.11.2](#)=[SAG, Theorem A.9.0.6]) implies the following ‘Whitehead theorem’ for profinite spaces.

**5.14.7 Theorem** (Whitehead’s Theorem for profinite spaces; [SAG, Theorem E.3.1.6]). *The materialisation functor  $\mathbf{mat} : \mathcal{S}_\pi^\wedge \rightarrow \mathcal{S}$  is conservative.*

**5.14.8 Proposition** ([SAG, Proposition E.4.6.1]). *Let  $n \in \mathbb{N}$ . A morphism  $f$  in  $\mathcal{S}_\pi^\wedge$  is  $n$ -truncated if and only if  $\mathbf{mat}(f)$  is an  $n$ -truncated morphism of  $\mathcal{S}$ .*

Stone  $\infty$ -topoi have a number of useful alternative characterisations. The first is that, under the assumption of bounded coherence, the conclusion of [Proposition 5.14.5](#)=[SAG, Proposition E.3.1.4] actually characterises Stone  $\infty$ -topoi.

**5.14.9 Theorem** ([SAG, Theorem E.3.4.1]). *Let  $X$  be an  $\infty$ -topos. Then  $X$  is Stone if and only if both of the following conditions are satisfied.*

- *The  $\infty$ -topos  $X$  is bounded and coherent.*
- *The  $\infty$ -category of points  $\mathbf{Pt}(X)$  of  $X$  is an  $\infty$ -groupoid.*

The next characterisation is that bounded coherent objects are in fact *lisse*.

**5.14.10 Recollection.** Let  $X$  be an  $\infty$ -topos. An object  $F \in X$  is said to be a *local system* if and only if there exists a cover  $\{U_i\}_{i \in I}$  of the terminal object of  $X$  and a corresponding family  $\{K_i\}_{i \in I}$  of spaces such that for any  $i \in I$ , one has an equivalence  $F \times U_i \simeq \Gamma_X^* K_i$ .

We say that a local system  $F$  as above is a *lisse sheaf* or *lisse object*<sup>23</sup> if, in addition, the set  $I$  can be chosen to be finite, and the spaces  $K_i$  can be chosen to be  $\pi$ -finite.

We denote by  $X^{\text{locs}} \subseteq X$  (respectively, by  $X^{\text{lisse}} \subseteq X$ ) the full subcategory spanned by the local systems (respectively, the lisse sheaves). Please note that for any geometric morphism of  $\infty$ -topoi  $f_* : X \rightarrow Y$ , the pullback  $f^* : Y \rightarrow X$  preserves lisse objects.

<sup>22</sup>Lurie calls these  $\infty$ -topoi *profinite*.

<sup>23</sup>Lurie uses the phrase *locally constant constructible*.

There is a simple characterisation of lisse sheaves as a single pullback:

**5.14.11 Lemma** ([SAG, Proposition E.2.7.7]). *Let  $\mathbf{X}$  be an  $\infty$ -topos. Then an object  $F$  of  $\mathbf{X}$  is lisse if and only if there exist: a full subcategory  $G \subset {}_{\iota}\mathcal{S}_{\pi}$  spanned by finitely many objects, an essentially unique geometric morphism  $g_* : \mathbf{X} \rightarrow \mathcal{S}_{/G}$ , and an essentially unique equivalence  $F \simeq g^*(I)$ , where  $I$  classifies the inclusion functor  $G \rightarrow \mathcal{S}$ .*

For later use, let us include the following, which is equivalent to the fact that the profinite shape  $\Pi_{\infty}^{\wedge} : \mathbf{Top}_{\infty}^{bc} \rightarrow \mathcal{S}_{\pi}^{\wedge}$  preserves inverse limits (see Corollary 5.13.16).

**5.14.12 Lemma.** *For any  $\pi$ -finite space  $G$ , the  $\infty$ -topos  $\mathcal{S}_{/G}$  is cocompact in  $\mathbf{Top}_{\infty}^{bc}$ . That is, for any inverse system  $\{X_{\alpha}\}_{\alpha \in A}$  of bounded coherent  $\infty$ -topoi with limit  $\mathbf{X}$ , the natural functor*

$$\mathrm{Fun}_*(\mathbf{X}, \mathcal{S}_{/G}) \rightarrow \lim_{\alpha \in A} \mathrm{Fun}_*(X_{\alpha}, \mathcal{S}_{/G})$$

*is an equivalence.*

**5.14.13 Proposition** ([SAG, Proposition E.3.1.1]). *Let  $\mathbf{X}$  be an  $\infty$ -topos. Then  $\mathbf{X}$  is Stone if and only if both of the following conditions are satisfied.*

- ▶ *The  $\infty$ -topos  $\mathbf{X}$  is bounded and coherent.*
- ▶ *Every truncated coherent object of  $\mathbf{X}$  is lisse.*

**5.14.14 Corollary** ([SAG, Corollary E.3.1.2]). *Let  $f_* : \mathbf{X} \rightarrow \mathbf{Y}$  be a geometric morphism between coherent  $\infty$ -topoi. If  $\mathbf{Y}$  is Stone, then  $f_*$  is coherent.*

**5.14.15 Theorem** ([SAG, Theorem E.2.3.2]). *Let  $\mathbf{X}$  be an  $\infty$ -topos. Then:*

- ▶ *The  $\infty$ -category  $\mathbf{X}^{\mathrm{lisse}}$  is a bounded  $\infty$ -pretopos and the inclusion  $\mathbf{X}^{\mathrm{lisse}} \hookrightarrow \mathbf{X}$  is a morphism of  $\infty$ -pretopoi.*
- ▶ *The inclusion  $\mathbf{X}^{\mathrm{lisse}} \hookrightarrow \mathbf{X}$  induces a geometric morphism  $\mathbf{X} \rightarrow \mathbf{Sh}_{\mathrm{eff}}(\mathbf{X}^{\mathrm{lisse}})$  which exhibits  $\mathbf{Sh}_{\mathrm{eff}}(\mathbf{X}^{\mathrm{lisse}})$  as the Stone reflection of  $\mathbf{X}$ .*

**5.14.16 Corollary** ([SAG, Corollary E.2.3.3]). *Let  $f_* : \mathbf{X} \rightarrow \mathbf{Y}$  be a geometric morphism of  $\infty$ -topoi. The following are equivalent:*

- ▶ *The induced geometric morphism  $f_*^{\mathrm{Stone}} : \mathbf{X}^{\mathrm{Stone}} \rightarrow \mathbf{Y}^{\mathrm{Stone}}$  is an equivalence of  $\infty$ -topoi.*
- ▶ *The geometric morphism  $f_*$  is a profinite shape equivalence.*
- ▶ *The morphism  $\mathrm{Pt}(f_*^{\mathrm{Stone}})$  is an equivalence of  $\infty$ -groupoids.*
- ▶ *The pullback functor  $f^*$  restricts to an equivalence of  $\infty$ -categories  $\mathbf{Y}^{\mathrm{lisse}} \simeq \mathbf{X}^{\mathrm{lisse}}$ .*

Putting together the basics about Stone  $\infty$ -topoi gives an alternative proof of the monodromy equivalence for lisse local systems proved by Bachmann and Hoyois [7, Proposition 10.1].

**5.14.17 Proposition.** *Let  $X$  be an  $\infty$ -topos the unit  $X \rightarrow X^{\text{Stone}}$  of the adjunction to Stone  $\infty$ -topoi restricts to an equivalence*

$$\text{Fun}(\Pi_{\infty}^{\wedge}(X), \mathcal{S}_{\pi}) \simeq X^{\text{lisse}}.$$

*Proof.* Represent the profinite shape  $\Pi_{\infty}^{\wedge}(X)$  by an inverse system  $\{\Pi_{\alpha}\}_{\alpha \in A}$  of  $\pi$ -finite spaces so that

$$\text{Fun}(\Pi_{\infty}^{\wedge}(X), \mathcal{S}_{\pi}) = \text{colim}_{\alpha \in A^{op}} \text{Fun}(\Pi_{\alpha}, \mathcal{S}_{\pi}).$$

For any  $\pi$ -finite space  $\Pi$  we have  $\text{Fun}(\Pi, \mathcal{S})_{<\infty}^{\text{coh}} = \text{Fun}(\Pi, \mathcal{S}_{\pi})$ , so

$$\begin{aligned} \text{Fun}(\Pi_{\infty}^{\wedge}(X), \mathcal{S}_{\pi}) &= \text{colim}_{\alpha \in A^{op}} \text{Fun}(\Pi_{\alpha}, \mathcal{S})_{<\infty}^{\text{coh}} \\ &\simeq (\lim_{\alpha \in A} \text{Fun}(\Pi_{\alpha}, \mathcal{S}))_{<\infty}^{\text{coh}} \\ &\simeq (X^{\text{Stone}})_{<\infty}^{\text{coh}} \\ &\simeq X^{\text{lisse}}, \end{aligned}$$

where the first equivalence follows from [Proposition 5.9.2](#)=[SAG, Proposition A.8.3.2], the second is the definition of the Stone reflection, and the last equivalence follows from [Proposition 5.14.13](#)=[SAG, Proposition E.3.1.1].  $\square$

**5.14.18 Example.** Let  $X$  be a coherent scheme, and write  $X^{\text{ét}}$  for the *finite étale site* of  $X$ : the full subcategory of the étale site  $X^{\text{ét}}$  spanned by the finite étale  $X$ -schemes, with the induced topology (see [1, §VI.9]). Since the finite étale site is a finitary site, the 1-localic finite étale  $\infty$ -topos  $X_{\text{ét}} := \text{Sh}(X^{\text{ét}})$  is coherent ([Proposition 5.3.8](#)=[SAG, Proposition A.3.1.3]). The finite étale  $\infty$ -topos  $X_{\text{ét}}$  is the classifying topos of the profinite étale fundamental groupoid of  $X$  (cf. [SGA 1, Exposé V, Proposition 5.8; 1, Lemma VI.9.11]). In particular, the finite étale  $\infty$ -topos  $X_{\text{ét}}$  is Stone.

## 6 Oriented pushouts & oriented fibre products

Deligne [SGA 7<sub>III</sub>, Exposé XIII; 50] (the latter text written by Gérard Laumon) constructed a 1-topos, called the *evanescent* or *vanishing* topos, which he identified as the natural target for the nearby cycles functor. To do so, he identified, in terms of generating sites, the *oriented fibre product* in a double category of 1-topoi (whose existence was proved first by Giraud [24]). In the  $\infty$ -categorical setting, we shall perform an analogous construction in order to describe the link between two strata in a stratified  $\infty$ -topos that satisfies suitable finiteness hypotheses.

### 6.1 Recollements of higher topoi

**6.1.1.** If  $X$  is an  $\infty$ -topos, and  $U$  is an open of  $X$ , then the overcategory  $X_{/U}$  is an  $\infty$ -topos, and the forgetful functor  $j_! : X_{/U} \rightarrow X$  admits a right adjoint  $j^*$ , which itself admits a right adjoint  $j_*$ . The functor  $j_*$  is a fully faithful geometric morphism. In this case, we write  $X_{\setminus U}$  for the closed complement, which is the full subcategory of  $X$

spanned by those objects  $F$  such that  $F \times U \simeq U$ . Write  $i_* : X_{\setminus U} \hookrightarrow X$  for the inclusion. In this case,  $X$  is a recollement (0.4.3) of  $X_{\setminus U}$  and  $X_{/U}$  with gluing functor  $i^* j_*$ , viz.,

$$X \simeq X_{\setminus U} \tilde{U}^{i^* j_*} X_{/U}.$$

**6.1.2.** Let  $X$  be an  $\infty$ -topos, and let  $i_* : Z \hookrightarrow X$  and  $j_* : U \hookrightarrow X$  be geometric morphisms of  $\infty$ -topoi that exhibit  $X$  as the recollement  $Z \tilde{U}^{i^* j_*} U$ . Then since  $i^*$  and  $j^*$  are left exact left adjoints, the natural conservative functor

$$(i^*, j^*) : X \rightarrow Z \sqcup U$$

preserves and reflects colimits and finite limits. (Here  $Z \sqcup U$  denotes the coproduct of  $Z$  and  $U$  in  $\mathbf{Top}_\infty$ , which is the *product* of  $Z$  and  $U$  in  $\mathbf{Cat}_{\infty, \delta_1}$ .) In particular, a morphism  $f$  in  $X$  is:

- an effective epimorphism if and only if both  $i^*(f)$  and  $j^*(f)$  are effective epimorphisms.
- $n$ -truncated for some integer  $n \geq -2$  if and only if both  $i^*(f)$  and  $j^*(f)$  are  $n$ -truncated (0.4.4).

**6.1.3.** A recollement of  $\infty$ -topoi is tantamount to a geometric morphism of  $\infty$ -topoi  $X \rightarrow \overline{[1]}$ . Indeed, if  $Z$  and  $U$  are  $\infty$ -topoi, and  $\phi : U \rightarrow Z$  is a left exact accessible functor, then the recollement  $X := Z \tilde{U}^\phi U$  is an  $\infty$ -topos [HA, Proposition A.8.15], and the essentially unique geometric morphisms  $Z \rightarrow S$  and  $U \rightarrow S$  now induce a geometric morphism

$$X \rightarrow S \tilde{U}^{\text{id}_S} S \simeq \overline{[1]}.$$

In the other direction, given a geometric morphism  $X \rightarrow \overline{[1]}$ , the closed subtopos  $X_0 := \{0\} \times_{\overline{[1]}} X$  and open subtopos  $X_1 := \{1\} \times_{\overline{[1]}} X$  of  $X$  form a recollement of  $X$ .

In a strong sense, the entire theory of stratified  $\infty$ -topoi (Definition 9.2.1) is a generalisation of this observation.

Since  $n$ -localic and bounded  $\infty$ -topoi (Definition 5.2.2 & Construction 5.2.9) are each closed under limits in  $\mathbf{Top}_\infty$ , we deduce the following.

**6.1.4 Lemma.** *Let  $X$  be an  $\infty$ -topos, and let  $i_* : Z \hookrightarrow X$  and  $j_* : U \hookrightarrow X$  be geometric morphisms of  $\infty$ -topoi that exhibit  $X$  as the recollement  $Z \tilde{U}^{i^* j_*} U$ . For any  $n \in \mathbb{N}$ , if  $X$  is  $n$ -localic or bounded, then both  $Z$  and  $U$  are each  $n$ -localic or bounded, respectively.*

**6.1.5 Warning.** We caution, however, that there isn't a simple converse to Lemma 6.1.4: it is not the case that the recollement of two bounded  $\infty$ -topoi is necessarily bounded. To ensure this, we need a condition on the gluing functor.

**6.1.6 Definition.** Let  $Z$  and  $U$  be two bounded  $\infty$ -topoi, and let  $\phi : U \rightarrow Z$  be a left exact accessible functor  $\phi : U \rightarrow Z$ . We say that  $\phi$  is a *bounded gluing functor* if and only if the recollement  $X := Z \tilde{U}^\phi U$  is bounded.

**6.1.7 Question.** Do bounded gluing functors admit a simple or useful intrinsic characterisation?



So much for the boundedness of recollements. Let us now turn to coherence ([Definition 5.3.1](#)). We can easily characterise the coherent objects of a coherent recollement.

**6.1.8 Proposition** ([[DAG XIII](#), Proposition 2.3.22]). *Let  $n \in \mathbb{N}$ , let  $\mathbf{X}$  be an  $(n+1)$ -coherent  $\infty$ -topos, and let  $i_* : \mathbf{Z} \hookrightarrow \mathbf{X}$  and  $j_* : \mathbf{U} \hookrightarrow \mathbf{X}$  be geometric morphisms of  $\infty$ -topoi that exhibit  $\mathbf{X}$  as the recollement  $\mathbf{Z} \tilde{\cup}^{i^* j^*} \mathbf{U}$ . If  $\mathbf{U}$  is 0-coherent, then an object  $F \in \mathbf{X}$  is  $n$ -coherent if and only if both  $i^* F$  and  $j^* F$  are  $n$ -coherent. In particular, the  $\infty$ -topoi  $\mathbf{Z}$  and  $\mathbf{U}$  are  $n$ -coherent.*

**6.1.9 Warning.** We caution again that there isn't a simple converse to [Proposition 6.1.8](#): as with boundedness, it is not the case that the recollement of two coherent  $\infty$ -topoi is necessarily coherent.

**6.1.10 Definition.** Let  $\mathbf{Z}$  and  $\mathbf{U}$  be two coherent  $\infty$ -topoi, and let  $\phi : \mathbf{U} \rightarrow \mathbf{Z}$  be a left exact accessible functor  $\phi : \mathbf{U} \rightarrow \mathbf{Z}$ . We say that  $\phi$  is a *coherent gluing functor* if and only if the recollement  $\mathbf{X} := \mathbf{Z} \tilde{\cup}^\phi \mathbf{U}$  is coherent.

**6.1.11.** Let  $\mathbf{Z}$  and  $\mathbf{U}$  be two coherent  $\infty$ -topoi, and let  $\phi : \mathbf{U} \rightarrow \mathbf{Z}$  be a left exact accessible functor. Write  $i_* : \mathbf{Z} \hookrightarrow \mathbf{X}$  and  $j_* : \mathbf{U} \hookrightarrow \mathbf{X}$  for the fully faithful functors defining the recollement. Then one can show that the gluing functor  $\phi$  is coherent if the following conditions are satisfied.

- The functor  $j_*$  is quasicompact in the sense that for any quasicompact object  $F \in \mathbf{X}$ , the object  $j^* F \in \mathbf{U}$  is also quasicompact.
- For every  $n \in \mathbb{N}$ , every object  $F \in \mathbf{U}$  admits a family  $\{G_\alpha \rightarrow F\}_{\alpha \in A}$  in which each  $G_\alpha$  is  $n$ -coherent, and the family  $\{\phi(G_\alpha) \rightarrow \phi(F)\}_{\alpha \in A}$  is a covering in  $\mathbf{Z}$ .

**6.1.12 Construction.** Let  $\mathbf{Z}$  and  $\mathbf{U}$  be bounded coherent  $\infty$ -topoi, and let  $\phi : \mathbf{U} \rightarrow \mathbf{Z}$  be a left exact accessible functor. Form the recollement

$$\mathbf{X}' := \mathbf{Z} \tilde{\cup}^\phi \mathbf{U},$$

and write  $i_* : \mathbf{Z} \hookrightarrow \mathbf{X}'$  and  $j_* : \mathbf{U} \hookrightarrow \mathbf{X}'$  for the closed and open embeddings. Consider the full subcategory  $X_0 \subseteq \mathbf{X}'$  spanned by those objects  $F$  such that  $i^* F$  and  $j^* F$  are each truncated coherent, so that  $X_0$  is the oriented fibre product (0.4.1) in  $\mathbf{Cat}_{\infty, \delta_1}$ :

$$X_0 = \mathbf{Z}_{<\infty}^{coh} \downarrow_{\mathbf{Z}} \mathbf{U}_{<\infty}^{coh}.$$

Then since  $X_0 \subset \mathbf{X}$  is closed under finite limits, finite coproducts, and the formation of geometric realisations of groupoid objects,  $X_0$  is an  $\infty$ -pretopos and the inclusion  $X_0 \hookrightarrow \mathbf{X}$  is a morphism of  $\infty$ -pretopoi ([Definition 5.8.2](#)). Moreover, by (6.1.2) every object of  $X_0$  is truncated and by (0.4.2) the  $\infty$ -category  $X_0$  is essentially  $\delta_0$ -small, hence  $X_0$  is a bounded  $\infty$ -pretopos ([Definition 5.8.7](#)). Consequently, we may form the bounded coherent  $\infty$ -topos ([Notation 5.8.6](#))

$$\mathbf{X} := \mathbf{Sh}_{eff}(X_0).$$

By [[SAG](#), Proposition A.6.4.4], the inclusion  $X_0 \hookrightarrow \mathbf{X}'$  extends (essentially uniquely) to a comparison geometric morphism  $r_* : \mathbf{X}' \rightarrow \mathbf{X}$ , which is not in general an equivalence,

but restricts to an equivalence  $r^* : X_{<\infty}^{coh} \simeq X_0$ . The geometric morphisms  $r_* i_*$  and  $r_* j_*$  are each coherent by construction. We therefore call  $X$  the *bounded coherent recollement*, and we write

$$Z \tilde{\cup}_{bc}^\phi U := X.$$

**6.1.13 Lemma.** *Let  $Z$  and  $U$  be bounded coherent  $\infty$ -topoi, and let  $\phi : U \rightarrow Z$  be an left exact accessible functor. Then the natural geometric morphism*

$$Z \tilde{\cup}^{i^* r^* r_* j_*} U \rightarrow Z \tilde{\cup}_{bc}^\phi U$$

*is an equivalence.*

*Proof.* Write  $X := Z \tilde{\cup}_{bc}^\phi U$ . The object  $j_! 1_U \in Z \tilde{\cup}^\phi U$ , is the object

$$(\emptyset_Z, 1_U, \emptyset_Z \rightarrow \phi(1_U)),$$

which is an open in  $X$  as well as an object of the  $\infty$ -pretopos  $X_0$  of [Construction 6.1.12](#). Thus  $j^* r^*$  restricts to an equivalence

$$(X_{/j_! 1_U})_{<\infty}^{coh} \simeq U_{<\infty}^{coh},$$

whence the functor  $r_* j_* : U \rightarrow X_{/j_! 1_U}$  is an equivalence. The truncated coherent objects of the closed subtopos  $X_{\setminus j_! 1_U}$  are precisely those of the form  $(F_Z, 1_U, F_Z \rightarrow \phi(1_U))$  for some truncated coherent object  $F_Z$  of  $Z$ . Hence  $i^* r^*$  restricts to an equivalence

$$(X_{\setminus j_! 1_U})_{<\infty}^{coh} \simeq Z_{<\infty}^{coh},$$

whence the functor  $i_* r_* : Z \rightarrow X_{\setminus j_! 1_U}$  is an equivalence. □

**6.1.14 Lemma.** *Let  $Z$ , and  $U$  be bounded coherent  $\infty$ -topoi, and let  $\phi : U \rightarrow Z$  be a bounded coherent gluing functor. Then  $Z \tilde{\cup}^\phi U$  is the bounded coherent recollement.*

*Proof.* This follows from [Proposition 6.1.8](#)=[[DAG XIII](#), Proposition 2.3.22] combined with [Theorem 5.8.8](#)=[[SAG](#), Theorem A.7.5.3]. □

The critical point that we use repeatedly in the sequel is the observation that the bounded coherent recollement depends only upon the restriction of the gluing functor to truncated coherent objects. More precisely, let  $Z$  and  $U$  be bounded coherent  $\infty$ -topoi, and let  $\phi : U \rightarrow Z$  and  $\phi' : U \rightarrow Z$  be two accessible, left exact functors. Let  $\eta : \phi \rightarrow \phi'$  be a natural transformation. Now  $\eta$  induces a functor

$$\eta^* : Z \tilde{\cup}^\phi U \rightarrow Z \tilde{\cup}^{\phi'} U$$

given by the assignment

$$(z, u, \alpha : z \rightarrow \phi(u)) \mapsto (z, u, \eta_u \alpha : z \rightarrow \phi'(u)).$$

The functor  $\eta^*$  preserves colimits and finite limits; consequently,  $\eta^*$  is the left adjoint of a geometric morphism  $\eta_*$ . Then since  $\eta^*$  restricts to a functor

$$\eta^* : Z_{<\infty}^{coh} \downarrow_{Z, \phi} U_{<\infty}^{coh} \simeq X_{<\infty}^{coh} \rightarrow (X')_{<\infty}^{coh} \simeq Z_{<\infty}^{coh} \downarrow_{Z, \phi'} U_{<\infty}^{coh},$$

i.e.,  $\eta^*$  preserves truncated coherent objects,  $\eta^*$  induces a geometric morphism

$$\eta_* : \mathbf{Z} \tilde{\mathcal{U}}_{bc}^{\phi'} \mathbf{U} \rightarrow \mathbf{Z} \tilde{\mathcal{U}}_{bc}^{\phi} \mathbf{U}$$

on bounded coherent recollements.

**6.1.15 Proposition.** *Let  $\mathbf{Z}$  and  $\mathbf{U}$  be bounded coherent  $\infty$ -topoi, and let  $\phi : \mathbf{U} \rightarrow \mathbf{Z}$  and  $\phi' : \mathbf{U} \rightarrow \mathbf{Z}$  be two accessible, left exact functors. Let  $\eta : \phi \rightarrow \phi'$  be a natural transformation. If  $\eta|_{\mathbf{U}_{<\infty}^{coh}}$  is an equivalence, then  $\eta$  induces an equivalence*

$$\mathbf{Z} \tilde{\mathcal{U}}_{bc}^{\phi'} \mathbf{U} \simeq \mathbf{Z} \tilde{\mathcal{U}}_{bc}^{\phi} \mathbf{U}.$$

**6.1.16 Question.** The restriction functor  $\mathrm{Fun}^{lex}(\mathbf{U}, \mathbf{Z}) \rightarrow \mathrm{Fun}^{lex}(\mathbf{U}_{<\infty}^{coh}, \mathbf{Z})$  is, as a result of this proposition, fully faithful on bounded coherent gluing functors, but what is the essential image of the bounded coherent gluing functors? It might be helpful to give a simple intrinsic characterisation.

## 6.2 Oriented squares

To speak of oriented pullbacks of  $\infty$ -topoi without finding ourselves buried under a mass of pernicious details (or unproved claims) about double  $\infty$ -categories or  $(\infty, 2)$ -categories, we express the universal property of the lax pullback in simple terms. The key kind of square we will have to contemplate is the following.

**6.2.1 Notation.** The data of geometric morphisms  $f_* : \mathbf{X} \rightarrow \mathbf{Z}$ ,  $g_* : \mathbf{Y} \rightarrow \mathbf{Z}$ ,  $p_* : \mathbf{W} \rightarrow \mathbf{X}$ , and  $q_* : \mathbf{W} \rightarrow \mathbf{Y}$ , along with a (not necessarily invertible) natural transformation  $\tau : g_* q_* \rightarrow f_* p_*$  will be exhibited by the single square

$$(6.2.2) \quad \begin{array}{ccc} \mathbf{W} & \xrightarrow{q_*} & \mathbf{Y} \\ p_* \downarrow & \searrow \tau & \downarrow g_* \\ \mathbf{X} & \xrightarrow{f_*} & \mathbf{Z} . \end{array}$$

**6.2.3 Warning.** Frustratingly, it seems that this convention for writing 2-cells is the *opposite* of what's written in some of the 1-topos theory literature (but it agrees with much of the algebro-geometric literature); we therefore emphasise that our 2-morphisms are natural transformations between the *right* adjoints.

## 6.3 Oriented pushouts

The oriented fibre product in  $\mathbf{Cat}_{\infty, \delta_1}$  of a diagram of  $\infty$ -topoi recovers not the oriented fibre product in  $\mathbf{Top}_{\infty}$ , but rather the *oriented pushout* in  $\mathbf{Top}_{\infty}$ . We shall also have to contemplate the oriented pushout in  $\mathbf{Top}_{\infty}^{bc}$ .

**6.3.1 Construction.** The  $\infty$ -category  $\mathbf{Top}_{\infty}$  is *tensored* over the  $\infty$ -category  $\mathbf{Cat}_{\infty, \delta_0}$ . Indeed, if  $\mathbf{W}$  an  $\infty$ -topos and  $\mathbf{C}$  is a  $\delta_0$ -small  $\infty$ -category, then the  $\infty$ -category  $\mathrm{Fun}(\mathbf{C}, \mathbf{W})$

is an  $\infty$ -topos, and the functor  $C \rightarrow \mathrm{Fun}_*(W, \mathrm{Fun}(C, W))$  that carries an object to the right adjoint of evaluation induces an equivalence of  $\infty$ -categories

$$\mathrm{Fun}_*(\mathrm{Fun}(C, W), Z) \simeq \mathrm{Fun}(C, \mathrm{Fun}_*(W, Z))$$

for any  $\infty$ -topos  $Z$ .

Let  $W$ ,  $Z$ , and  $U$  be three  $\infty$ -topoi, and let  $p_* : W \rightarrow Z$  and  $q_* : W \rightarrow U$  be two geometric morphisms. The recollement  $Z \tilde{\cup}^{p_*, q_*} U$  can be identified with the oriented fibre product

$$Z \downarrow_W U$$

formed in  $\mathbf{Cat}_{\infty, \delta_1}$  with respect to the *left* adjoints  $p^*$  and  $q^*$ . We note that  $Z \tilde{\cup}^{p_*, q_*} U$  is an  $\infty$ -topos. This  $\infty$ -topos enjoys the following universal property: a geometric morphism

$$\omega(f, g, \tau)_* : Z \tilde{\cup}^{p_*, q_*} U \rightarrow X$$

determines and is determined by an oriented square

$$\begin{array}{ccc} W & \xrightarrow{q_*} & U \\ p_* \downarrow & \swarrow \tau & \downarrow g_* \\ Z & \xrightarrow{f_*} & X. \end{array}$$

This universal property specifies the  $\infty$ -topos  $Z \tilde{\cup}^{p_*, q_*} U$  essentially uniquely. We write

$$Z \tilde{\cup}^W U := Z \tilde{\cup}^{p_*, q_*} U,$$

and we call this  $\infty$ -topos the *oriented pushout* of  $p_*$  and  $q_*$ . In this case, we write  $i_* : Z \hookrightarrow Z \tilde{\cup}^W U$  for the closed embedding and  $j_* : U \hookrightarrow Z \tilde{\cup}^W U$  for its open complement.

**6.3.2 Warning.** If  $Z$ ,  $U$ , and  $W$  are all bounded coherent, and if  $p_*$  and  $q_*$  are both coherent geometric morphisms, [Warning 6.1.5](#) & [Warning 6.1.9](#) still apply: we cannot ensure that the oriented pushout  $Z \tilde{\cup}^\phi U$  is either bounded or coherent (cf. [\[SGA 4<sub>II</sub>, Exposé VI, §4\]](#)).

**6.3.3 Construction.** Consider an oriented square

$$\begin{array}{ccc} W & \xrightarrow{q_*} & U \\ p_* \downarrow & \swarrow \tau & \downarrow g_* \\ Z & \xrightarrow{f_*} & X \end{array}$$

where all  $\infty$ -topoi are bounded coherent and all geometric morphisms are coherent. For any truncated coherent object  $G \in X$ , the object  $\omega(f, g, \tau)^* G$  is truncated, and the objects  $i^* \omega(f, g, \tau)^* G \simeq f^* G$  and  $j^* \omega(f, g, \tau)^* G \simeq g^* G$  are each truncated coherent,

whence  $\omega(f, g, \tau)_*$  factors through the bounded coherent recollement  $Z \tilde{\cup}_{bc}^{p_* q^*} U$  (Construction 6.1.12) in an essentially unique manner. Consequently, we write

$$Z \tilde{\cup}_{bc}^W U := Z \tilde{\cup}_{bc}^{p_* q^*} U ,$$

and call this  $\infty$ -topos the *bounded coherent oriented pushout*. This is the oriented pushout that is correct in  $\mathbf{Top}_{\infty}^{bc}$ . Accordingly, one has an equivalence of  $\infty$ -pretopoi

$$(Z \tilde{\cup}_{bc}^W U)_{<\infty}^{coh} \simeq Z_{<\infty}^{coh} \downarrow_{W_{<\infty}^{coh}} U_{<\infty}^{coh} .$$

Please observe that by construction, in the square

$$\begin{array}{ccc} W & \xrightarrow{q_*} & U \\ p_* \downarrow & \swarrow \tau & \downarrow j_* \\ Z & \xrightarrow{i_*} & Z \tilde{\cup}_{bc}^W U , \end{array}$$

the natural *Beck–Chevalley morphism*

$$\beta_\tau : i^* j_* \rightarrow p_* q^*$$

becomes an equivalence after restriction to  $U_{<\infty}^{coh}$ . A thorough study of Beck–Chevalley morphisms will occupy §8.

## 6.4 Internal homs & path $\infty$ -topoi

Oriented fibre products have the universal property that is dual to that of oriented pushouts. In order to define them, we must identify the *cotensor* of  $\mathbf{Top}_{\infty}$  over  $\mathbf{Cat}_{\infty, \delta_0}$ , or at least over  $po\mathbf{Set}$ . Partly in order to define oriented fibre products of  $\infty$ -topoi now and partly to define the nerve construction for stratified  $\infty$ -topoi later (Construction 9.4.1), we recall some facts about the internal hom in  $\infty$ -topoi. The first point to be made about the internal hom is that it doesn't always exist.

**6.4.1 Recollection.** Recall [SAG, Theorem 21.1.6.11] that an  $\infty$ -topos  $W$  is *exponentiable* if and only if the functor  $- \times W : \mathbf{Top}_{\infty} \rightarrow \mathbf{Top}_{\infty}$  admits a right adjoint  $\mathbf{Mor}(W, -)$ . If  $W$  is exponentiable, then for any  $\infty$ -topos  $Z$ , the points of the  $\infty$ -topos  $\mathbf{Mor}(W, Z)$  are precisely the geometric morphisms  $W \rightarrow Z$ . We thus call  $\mathbf{Mor}(W, Z)$  the *mapping  $\infty$ -topos*. Any compactly generated  $\infty$ -topos is exponentiable (and in fact even more is true: see [SAG, Theorem 21.1.6.12]).

In particular, for any spectral topological space  $S$ , then  $\tilde{S}$  is compactly generated [HTT, Proposition 6.5.4.4; SAG, Proposition 21.1.7.8], so for any  $\infty$ -topos  $Z$ , there exists a mapping  $\infty$ -topos  $\mathbf{Mor}(\tilde{S}, Z)$ . A point  $x \in S$  induces a geometric morphism

$$d_{x,*} : \mathbf{Mor}(\tilde{S}, Z) \rightarrow \mathbf{Mor}(\tilde{x}, Z) \simeq Z ,$$

and the geometric morphism  $\tilde{S} \rightarrow S$  induces a geometric morphism

$$\Delta_* : Z \simeq \mathbf{Mor}(S, Z) \rightarrow \mathbf{Mor}(\tilde{S}, Z) .$$

**6.4.2 Example.** If  $P$  is a finite poset, then one can identify  $\text{MOR}(\tilde{P}, -)$  with the unique limit-preserving endofunctor of  $\mathbf{Top}_\infty$  such that, for any small  $\infty$ -category  $C$ , one has

$$\text{MOR}(\tilde{P}, \text{Fun}(C, S)) \simeq \text{Fun}(\text{Fun}(P, C), S)$$

via the natural functor. In particular, if  $P$  and  $Q$  are finite posets, then

$$\text{MOR}(\tilde{P}, \tilde{Q}) \simeq \widetilde{\text{Fun}(P, Q)}.$$

**6.4.3 Definition.** For any  $\infty$ -topos  $X$ , the  $\infty$ -topos  $\text{MOR}(\widetilde{[1]}, X)$  is called the *path  $\infty$ -topos* of  $X$  [SAG, Definition 21.3.2.3]. We write  $\text{Path}(X) := \text{MOR}(\widetilde{[1]}, X)$ .

**6.4.4 Lemma.** Let  $n \in \mathbb{N}$ , and let  $Z$  be an  $n$ -localic  $\infty$ -topos. Then the path  $\infty$ -topos  $\text{Path}(Z)$  is  $n$ -localic.

*Proof.* This is a special case of [SAG, Lemma 21.1.7.3].  $\square$

**6.4.5 Construction.** Let  $(X, \tau)$  be a pair consisting of an essentially  $\delta_0$ -small  $\infty$ -category  $X$  that admits all finite limits along with a Grothendieck topology  $\tau$ . Write  $X := \mathbf{Sh}_\tau(X)$  for the  $\infty$ -topos of sheaves (of spaces) on  $X$  with respect to  $\tau$ . Then it follows from [SAG, Lemma 21.1.6.16 & Theorem 21.3.2.5] that  $\text{Path}(X)$  is naturally equivalent to the  $\infty$ -topos  $\mathbf{Sh}_{\tau'}(\text{Fun}(\Delta^{1,op}, X))$ , where  $\tau'$  is the topology on  $\text{Fun}(\Delta^{1,op}, X)$  generated by the families

$$\{f_i : v_i \rightarrow u\}_{i \in I},$$

where for each  $i \in I$ , the morphism  $f_i : \Delta^1 \times \Delta^{1,op} \rightarrow X$  is of the form

$$(6.4.6) \quad \begin{array}{ccc} v_{i,0} & \longleftarrow & v_{i,1} \\ f_{i,0} \downarrow & & \downarrow f_{i,1} \\ u_0 & \longleftarrow & u_1 \end{array}$$

in which one of the following holds:

- the family  $\{f_{i,0} : v_{i,0} \rightarrow u_0\}_{i \in I}$  generates a  $\tau$ -covering sieve, and for any  $i \in I$ , the square (6.4.6) is a pullback square;
- the family  $\{f_{i,1} : v_{i,1} \rightarrow u_1\}_{i \in I}$  generates a  $\tau$ -covering sieve, and for any  $i \in I$ , the morphism  $f_{i,0}$  is an equivalence.

When  $X$  is an  $\infty$ -pretopos equipped with the effective epimorphism topology, then  $\text{Fun}(\Delta^{1,op}, X)$  is an  $\infty$ -pretopos and the topology  $\tau'$  is the effective epimorphism topology.

## 6.5 Oriented fibre products

We are now ready to construct the oriented fibre product of  $\infty$ -topoi and to relate it to the classical oriented fibre product of 1-topoi (Lemma 6.5.13).

**6.5.1 Definition.** If  $f_* : X \rightarrow Z$  and  $g_* : Y \rightarrow Z$  are two geometric morphisms of  $\infty$ -topoi, then the *oriented fibre product* is the pullback

$$X \tilde{\times}_Z Y := X \times_{\text{MOR}(\overline{\{0\}}, Z)} \text{MOR}(\overline{\{1\}}, Z) \times_{\text{MOR}(\overline{\{1\}}, Z)} Y$$

in  $\mathbf{Top}_\infty$ . We write  $\text{pr}_{1,*} : X \tilde{\times}_Z Y \rightarrow X$  and  $\text{pr}_{2,*} : X \tilde{\times}_Z Y \rightarrow Y$  for the natural geometric morphisms.

Thus a geometric morphism

$$\psi(p, q, \tau)_* : W \rightarrow X \tilde{\times}_Z Y$$

determines and is determined by a square (6.2.2). This universal property specifies the  $\infty$ -topos  $X \tilde{\times}_Z Y$  essentially uniquely.

**6.5.2 Warning.** Please note that this is *not* the oriented/lax pullback in  $\mathbf{Cat}_{\infty, \delta_1}$ ; we will therefore take pains to express clearly where the oriented fibre product is taking place.

Additionally, in this paper, the symbol  $\tilde{\times}$  is only ever used for the oriented fibre product in  $\mathbf{Top}_\infty$ ; we only use the notation  $X \downarrow_Z Y$  for the oriented fibre product in some  $\mathbf{Cat}_{\infty, \delta}$  (see (0.4.1)).

**6.5.3.** Please observe that since the exponential functor  $\text{Path}(-) : \mathbf{Top}_\infty \rightarrow \mathbf{Top}_\infty$  is a right adjoint and limits in  $\text{Fun}(\Lambda_2^2, \mathbf{Top}_\infty)$  are computed pointwise, the functor

$$\text{Fun}(\Lambda_2^2, \mathbf{Top}_\infty) \rightarrow \mathbf{Top}_\infty$$

given by the formation of the oriented fibre product preserves limits.

**6.5.4 Example.** When  $Z = \mathbf{S}$ , the oriented fibre product reduces to the product in  $\mathbf{Top}_\infty$ :

$$X \tilde{\times}_{\mathbf{S}} Y \simeq X \times Y.$$

**6.5.5.** Let  $f_* : X \rightarrow Z$  and  $g_* : Y \rightarrow Z$  be geometric morphisms of  $\infty$ -topoi. Then under the identifications  $X \simeq X \tilde{\times}_{\mathbf{S}} \mathbf{S}$  and  $Y \simeq \mathbf{S} \tilde{\times}_{\mathbf{S}} Y$ , the projections  $\text{pr}_{1,*} : X \tilde{\times}_Z Y \rightarrow X$  and  $\text{pr}_{2,*} : X \tilde{\times}_Z Y \rightarrow Y$  are equivalent to  $\text{id}_X \tilde{\times}_{\Gamma_{Z,*}} \Gamma_{Y,*}$  and  $\Gamma_{X,*} \tilde{\times}_{\Gamma_{Z,*}} \text{id}_Y$ , respectively (Notation 5.1.5).

**6.5.6 Example.** For any  $\infty$ -topos  $X$ , the oriented fibre product  $X \tilde{\times}_X X$  is canonically identified with the path  $\infty$ -topos  $\text{Path}(X)$ .

**6.5.7.** For any  $\infty$ -topos  $E$ , the functor  $\text{Fun}_*(E, -)^{op} : \mathbf{Top}_\infty \rightarrow \mathbf{Cat}_{\infty, \delta_1}$  commutes with cotensors with  $\mathbf{Cat}_{\infty, \delta_1}$  (in particular, cotensoring with  $\Delta^1$ ) and pullbacks of  $\infty$ -topoi, hence  $\text{Fun}_*(E, -)^{op}$  carries oriented fibre products in  $\mathbf{Top}_\infty$  to oriented fibre products in  $\mathbf{Cat}_{\infty, \delta_1}$ .

Specialising to the case  $E = \mathbf{S}$ , we deduce the following.

**6.5.8 Lemma.** *The functor  $\text{Pt} : \mathbf{Top}_\infty \rightarrow \mathbf{Cat}_{\infty, \delta_1}$  carries oriented fibre products in  $\mathbf{Top}_\infty$  to oriented fibre products in  $\mathbf{Cat}_{\infty, \delta_1}$ . That is, if  $f_* : X \rightarrow Z$  and  $g_* : Y \rightarrow Z$  are geometric morphisms of  $\infty$ -topoi, then the natural functor*

$$\text{Pt}(X \tilde{\times}_Z Y) \rightarrow \text{Pt}(X) \downarrow_{\text{Pt}(Z)} \text{Pt}(Y)$$

*is an equivalence.*

**6.5.9 Example.** There is a canonical geometric morphism

$$\psi(\mathrm{pr}_1, \mathrm{pr}_2, \mathrm{id})_* : X \times_Z Y \rightarrow X \tilde{\times}_Z Y.$$

**6.5.10 Example.** The  $\infty$ -topos  $X \tilde{\times}_Z Z$  is called the *evanescent* (or *vanishing*)  $\infty$ -topos of  $f_*$ , and the natural functor

$$\Psi_{f,*} := \psi(\mathrm{id}_X, f, \mathrm{id})_* : X \rightarrow X \tilde{\times}_Z Z$$

is called the *nearby cycles functor*. Dually, the  $\infty$ -topos  $Z \tilde{\times}_Z Y$  is called the *coevanescent* (or *covanishing*)  $\infty$ -topos of  $g_*$ , and the natural functor

$$\Psi_*^g := \psi(g, \mathrm{id}_Y, \mathrm{id})_* : Y \rightarrow Z \tilde{\times}_Z Y$$

is called the *conearby cycles functor*.

One observes that the oriented fibre product can be decomposed into fibre products in  $\mathbf{Top}_\infty$  involving the evanescent and coevanescent  $\infty$ -topoi as follows: one has

$$X \tilde{\times}_Z Y \simeq (X \tilde{\times}_Z Z) \times_Z Y \quad \text{and} \quad X \tilde{\times}_Z Y \simeq X \times_Z (Z \tilde{\times}_Z Y),$$

and, more symmetrically,

$$X \tilde{\times}_Z Y \simeq (X \tilde{\times}_Z Z) \times_{\mathrm{Path}(Z)} (Z \tilde{\times}_Z Y).$$

**6.5.11 Example.** Keep the notations of [Definition 6.5.1](#), and let  $p_* : Z \hookrightarrow Z'$  be a fully faithful geometric morphism. Then  $p_*$  induces an equivalence of  $\infty$ -topoi

$$X \tilde{\times}_Z Y \simeq X \tilde{\times}_{Z'} Y.$$

To see this, simply note that  $X \tilde{\times}_Z Y$  and  $X \tilde{\times}_{Z'} Y$  have the same universal property since  $p_*$  is fully faithful. Hence for the purpose of computing oriented fibre products, we may assume that  $Z$  is a presheaf  $\infty$ -topos.

**6.5.12 Lemma.** Let  $f_* : X \rightarrow Z$  and  $g_* : Y \rightarrow Z$  be geometric morphisms of  $\infty$ -topoi. If  $X, Y$ , and  $Z$  are  $n$ -localic ([Definition 5.2.2](#)), so is the oriented fibre product  $X \tilde{\times}_Z Y$ . More generally, if  $X, Y$ , and  $Z$  are bounded ([Construction 5.2.9](#)), so is the oriented fibre product  $X \tilde{\times}_Z Y$ .

*Proof.* For the first assertion, by [Lemma 6.4.4](#) the oriented fibre product is a limit of  $n$ -localic  $\infty$ -topoi, hence  $n$ -localic. The second claim follows from the fact that formation of the oriented fibre product preserves limits ([6.5.3](#)).  $\square$

The 1-toposic oriented fibre product [[41](#); [42](#); [50](#); [58](#); [63](#)] is related to the oriented fibre product of corresponding 1-localic  $\infty$ -topoi via the following easy result.

**6.5.13 Lemma.** Let  $f_* : X \rightarrow Z$  and  $g_* : Y \rightarrow Z$  be geometric morphisms of 1-topoi, and write  $X', Y'$ , and  $Z'$  for the corresponding 1-localic  $\infty$ -topoi associated to  $X, Y$ , and  $Z$ , respectively. Then the oriented fibre product of 1-topoi  $X \tilde{\times}_Z Y$  is canonically equivalent to the 1-topos of 0-truncated objects of  $X' \tilde{\times}_{Z'} Y'$ .

*Proof.* Note equivalence of  $\infty$ -categories  $\tau_{\leq 0} : \mathbf{Top}_\infty^1 \simeq \mathbf{Top}_1$  from 1-localic  $\infty$ -topoi to 1-topoi ([Definition 5.2.2](#)) respects cotensors by the 1-category  $\Delta^1$  (this is obvious from the site-theoretic description of the path  $\infty$ -topos of [Construction 6.4.5](#)). In light of the equivalence  $\tau_{\leq 0} : \mathbf{Top}_\infty^1 \simeq \mathbf{Top}_1$ , the claim now follows from the definitions of the oriented fibre product in the setting of  $\infty$ -topoi and 1-topoi.  $\square$



## 6.6 Oriented fibre products & tubular neighbourhoods of manifolds

**6.6.1 Notation.** Let  $X$  be a smooth manifold and  $i: Z \hookrightarrow X$  the inclusion of a closed submanifold. Write  $U := X \setminus Z$  and  $j: U \hookrightarrow X$  for the inclusion of the open complement of  $Z$  in  $X$ . Let  $p: N_{Z \subset X} \rightarrow Z$  denote the normal bundle of  $Z$ , and  $z: Z \hookrightarrow N_{Z \subset X}$  its zero section. Let  $t: N_{Z \subset X} \hookrightarrow X$  be a choice of tubular neighbourhood of  $Z$  in  $X$ , so that  $tz = i$ .

**6.6.2.** Keep **Notation 6.6.1**. Since  $pz = \text{id}_Z$ , the geometric morphism

$$p_*: \tilde{N}_{Z \subset X} \rightarrow \tilde{Z}$$

exhibits the  $\infty$ -topos  $\tilde{N}_{Z \subset X}$  as local over  $\tilde{Z}$  with center  $z_*$ . In particular,  $p_*$  is a shape equivalence.

**6.6.3.** Keep **Notation 6.6.1**, and write  $\eta: \text{id}_{\tilde{Z}} \rightarrow z_* z^*$  for the unit of the adjunction  $z^* \dashv z_*$ . Then since  $tz = i$  and  $z^* \simeq p_*$ , we see that  $t_* z_* z^* \simeq i_* p_*$ . Thus  $\eta$  induces a natural transformation

$$t_* \eta: t_* \rightarrow t_* z_* z^* \simeq i_* z^* .$$

The natural transformation  $t_* \eta$  thus provides an oriented square

$$(6.6.4) \quad \begin{array}{ccc} \tilde{N}_{Z \subset X} & \xrightarrow{t_*} & \tilde{X} \\ p_* \downarrow & \swarrow_{t_* \eta} & \parallel \\ \tilde{Z} & \xrightarrow{i_*} & \tilde{X} . \end{array}$$

The square (6.6.4) induces an essentially unique geometric morphism

$$f_*^t: \tilde{N}_{Z \subset X} \rightarrow \tilde{Z} \tilde{\times}_X \tilde{X}$$

such that  $\text{pr}_{1,*} f_*^t \simeq p_*$ ,  $\text{pr}_{2,*} f_*^t \simeq t_*$ , and  $t_* \eta = f_*^t \tau$  where  $\tau: \text{pr}_{2,*} \rightarrow i_* \text{pr}_{1,*}$  is the defining natural transformation. Since  $p_*$  and  $\text{pr}_{1,*}$  are shape equivalences,  $f_*^t$  is also a shape equivalence. Moreover, note that since the geometric morphism  $t_*$  is fully faithful, the geometric morphism  $f_*^t$  is also fully faithful.

## 6.7 Generating $\infty$ -sites for oriented fibre products

We now describe a generating  $\infty$ -site for the oriented fibre product in the setting of sheaf  $\infty$ -topoi. This description is adapted from Deligne's. We employ it to deduce that the oriented fibre product of bounded coherent  $\infty$ -topoi and coherent geometric morphisms is coherent (**Lemma 6.7.6**). We begin with oriented fibre products of presheaf  $\infty$ -topoi.

**6.7.1 Construction.** Let  $X, Y$ , and  $Z$  be three essentially  $\delta_0$ -small  $\infty$ -categories, each of which admit finite limits. Let  $f^*: Z \rightarrow X$  and  $g^*: Z \rightarrow Y$  be left exact functors that induce, via precomposition, geometric morphisms

$$f_*: P(X) \rightarrow P(Z) \quad \text{and} \quad g_*: P(Y) \rightarrow P(Z)$$

on  $\infty$ -categories of presheaves of spaces.

Represent  $f^*$  and  $g^*$  as a cartesian fibration  $m: M \rightarrow \Lambda_2^2$ , so that the fibres over the vertices 0, 1, and 2 are  $X, Y$ , and  $Z$ , respectively, and  $m$  is classified by the diagram  $X \leftarrow Z \rightarrow Y$ . Now form the  $\infty$ -category

$$\vec{W}(f, g) := \mathrm{Fun}_{\Lambda_2^2}(\Lambda_2^2, M) \simeq \mathrm{Fun}(\Delta^1, X) \times_{\mathrm{Fun}(\Delta^{\{1\}}, X)} Z \times_{\mathrm{Fun}(\Delta^{\{1\}}, Y)} \mathrm{Fun}(\Delta^1, Y)$$

of sections of  $m$ . Let us write  $K_Y$  for the class of morphisms  $\phi: \Delta^1 \times \Lambda_2^2 \rightarrow M$  in  $\mathrm{Fun}_{\Lambda_2^2}(\Lambda_2^2, M)$  of the form

$$\begin{array}{ccccc} v_X & \longrightarrow & v_Z & \longleftarrow & v_Y \\ \phi_X \downarrow & & \downarrow \phi_Z & & \downarrow \phi_Y \\ u_X & \longrightarrow & u_Z & \longleftarrow & u_Y \end{array}$$

in which  $\phi_X$  is an equivalence, and the diagram above exhibits  $\phi_Y$  as the pullback of  $g^* \phi_Z$ . Dually, let us write  $K_X$  for those morphisms  $\phi$  in which  $\phi_Y$  is an equivalence, and the diagram above exhibits  $\phi_X$  as the pullback of  $f^* \phi_Z$ .

We now define two new  $\infty$ -categories by inverting these morphisms in the  $\infty$ -categorical sense (0.2.1):

$$\overleftarrow{W}(f, g) := K_Y^{-1} \vec{W}(f, g) \quad \text{and} \quad W(f, g) := K_X^{-1} \vec{W}(f, g).$$

**6.7.2.** The  $\infty$ -category  $\vec{W}(f, g)$  admits finite limits, which are computed pointwise. The sets  $K_Y$  and  $K_X$  are stable under composition and pullback. It follows that the classes  $K_Y$  and  $K_X$  each give rise to right calculi of fractions on  $\vec{W}(f, g)$  in the sense of Cisinski's book [16, Theorem 7.2.16].

Consequently, the mapping spaces in  $\vec{W}(f, g)$  admit a very simple description: for any objects  $u, v \in \vec{W}(f, g)$ , write

$$A(u, v) \subseteq \vec{W}(f, g)_{/u} \times_{\vec{W}(f, g)} \vec{W}(f, g)_{/v}$$

for the full subcategory spanned by those diagrams  $u \leftarrow w \rightarrow v$  in which the morphism  $u \leftarrow w$  lies in  $K_Y$ . Then one has a natural weak homotopy equivalence

$$\mathrm{Map}_{\vec{W}(f, g)}(u, v) \simeq \mathrm{Ex}^\infty A(u, v).$$

Furthermore, the  $\infty$ -categories  $\vec{W}(f, g)$  and  $W(f, g)$  admit finite limits, and the localisations  $\vec{W}(f, g) \rightarrow \overleftarrow{W}(f, g)$  and  $\vec{W}(f, g) \rightarrow W(f, g)$  each preserve finite limits [16, Corollary 7.1.16 & Theorem 7.2.25].

**6.7.3 Construction.** Keep the notations of Construction 6.7.1. We also have left exact functors  $p^*: X \rightarrow \vec{W}(f, g)$  and  $q^*: Y \rightarrow \vec{W}(f, g)$  defined by the assignments

$$x \mapsto [x \rightarrow 1 \leftarrow 1] \quad \text{and} \quad y \mapsto [1 \rightarrow 1 \leftarrow y].$$

We also regard these left exact functors as landing in  $\overleftarrow{W}(f, g)$  and  $W(f, g)$  by composing with the relevant localisations.

There exists a section  $\sigma: Z \rightarrow \vec{W}(f, g)$  of the natural projection that carries  $z$  to the cartesian section  $f^*(z) \rightarrow z \leftarrow g^*(z)$ . We thus have natural transformations

$$p^* f^* \xleftarrow{\theta} \sigma \xrightarrow{\xi} q^* g^*$$

where for any  $z \in Z$ , the components  $\theta_z$  and  $\xi_z$  are given by the diagram

$$\begin{array}{ccccc} f^*(z) & \longrightarrow & 1 & \longleftarrow & 1 \\ \parallel & & \uparrow ! & & \uparrow ! \\ f^*(z) & \longrightarrow & z & \longleftarrow & g^*(z) \\ ! \downarrow & & \downarrow ! & & \parallel \\ 1 & \longrightarrow & 1 & \longleftarrow & g^*(z) . \end{array}$$

In particular, note that  $\theta_z \in K_X$  and  $\xi_z \in K_Y$ . Consequently, when we pass to  $\vec{W}(f, g)$ , we obtain a natural transformation  $\theta\xi^{-1}: q^* g^* \rightarrow p^* f^*$ , and this becomes an equivalence upon passage to  $W(f, g)$ .

Now the functors  $p^*$  and  $q^*$ , along with the natural transformation  $\tau^* := \theta\xi^{-1}$ , gives rise to a square

$$(6.7.4) \quad \begin{array}{ccc} P(\vec{W}(f, g)) & \xrightarrow{q_*} & P(Y) \\ p_* \downarrow & \swarrow \tau & \downarrow g_* \\ P(X) & \xrightarrow{f_*} & P(Z) , \end{array}$$

which in turn gives rise to an identification of the oriented fibre product of presheaf  $\infty$ -topoi, viz.

$$P(X) \tilde{\times}_{P(Z)} P(Y) \simeq P(\vec{W}(f, g)) .$$

In the same manner, one obtains an identification of the oriented fibre product of presheaf  $\infty$ -topoi, viz.

$$P(X) \times_{P(Z)} P(Y) \simeq P(W(f, g)) .$$

**6.7.5 Construction.** Let  $(X, \tau_X)$ ,  $(Y, \tau_Y)$ , and  $(Z, \tau_Z)$  be three essentially  $\delta_0$ -small finitary  $\infty$ -sites (Definition 5.3.7) with all finite limits. Let  $f^*: Z \rightarrow X$  and  $g^*: Z \rightarrow Y$  be left exact functors, and assume that the two functors  $f_*: P(X) \rightarrow P(Z)$  and  $g_*: P(Y) \rightarrow P(Z)$  descend to geometric morphisms

$$f_*: X := \mathbf{Sh}_{\tau_X}(X) \rightarrow \mathbf{Sh}_{\tau_Z}(Z) =: Z \quad \text{and} \quad g_*: Y := \mathbf{Sh}_{\tau_Y}(Y) \rightarrow \mathbf{Sh}_{\tau_Z}(Z) =: Z .$$

Define the  $\infty$ -category  $\vec{W}(f, g)$  as in Construction 6.7.1. Then one has a natural equivalence of  $\infty$ -topoi

$$X \tilde{\times}_Z Y \simeq \mathbf{Sh}_{\vec{f}}(\vec{W}(f, g)) ,$$

where  $\bar{\tau}$  is the finitary topology generated by the families  $\{\phi_i : v_i \rightarrow u\}_{i \in I}$ , in which for each  $i \in I$ , the morphism  $\phi_i$  is the image of a morphism of  $\bar{W}(f, g)$  of the form

$$\begin{array}{ccccc} v_{i,X} & \longrightarrow & v_{i,Z} & \longleftarrow & v_{i,Y} \\ \phi_{i,X} \downarrow & & \downarrow \phi_{i,Z} & & \downarrow \phi_{i,Y} \\ u_X & \longrightarrow & u_Z & \longleftarrow & u_Y \end{array}$$

in which one of the following holds:

- the family  $\{\phi_{i,X} : v_{i,X} \rightarrow u_X\}_{i \in I}$  generates a  $\tau_X$ -covering sieve, and for any  $i \in I$ , the morphisms  $\phi_{i,Z}$  and  $\phi_{i,Y}$  are equivalences;
- the family  $\{\phi_{i,Y} : v_{i,Y} \rightarrow u_Y\}_{i \in I}$  generates a  $\tau_Y$ -covering sieve, and for any  $i \in I$ , the morphisms  $\phi_{i,Z}$  and  $\phi_{i,X}$  are equivalences.

The topology  $\tau_Z$  is irrelevant here, as we should expect, since  $X \tilde{\times}_Z Y \simeq X \tilde{\times}_{P(Z)} Y$  (Example 6.5.11).

Please observe that the finitary topology  $\tau$  on  $W(f, g)$  generated by these same families produces the usual (unoriented) fibre product of  $\infty$ -topoi, viz.,

$$X \times_Z Y \simeq \text{Sh}_\tau(W(f, g)) .$$

If each of  $X$ ,  $Y$ , and  $Z$  is an  $\infty$ -pretopos, each of the functors  $f^*$  and  $g^*$  is an  $\infty$ -pretopos morphism, and each of  $\tau_X$ ,  $\tau_Y$ , and  $\tau_Z$  is the effective epimorphism topology, then  $\bar{W}(f, g)$  and  $W(f, g)$  are each  $\infty$ -pretopoi, and  $\bar{\tau}$  and  $\tau$  are each the effective epimorphism topology.

**6.7.6 Lemma.** *Keep the notations of Construction 6.7.5. Then:*

- (6.7.6.1) *The oriented fibre product  $X \tilde{\times}_Z Y$  is coherent and locally coherent, and the projections  $\text{pr}_{1,*}$  and  $\text{pr}_{2,*}$  are coherent.*
- (6.7.6.2) *The pullback  $X \times_Z Y$  is coherent and locally coherent, and the projections  $\text{pr}_{1,*}$  and  $\text{pr}_{2,*}$  are coherent.*

*Proof.* Proposition 5.3.8=[SAG, Proposition A.3.1.3] ensures that the  $\infty$ -topoi  $X \tilde{\times}_Z Y$  and  $X \times_Z Y$  are coherent and locally coherent. Note that (6.7.6.1) follows from Corollary 5.6.8 since  $\text{pr}_{1,*}$  and  $\text{pr}_{2,*}$  are induced by the morphisms of finitary  $\infty$ -sites

$$(X, \tau_X) \rightarrow (\bar{W}(f, g), \bar{\tau}) \quad \text{and} \quad (Y, \tau_Y) \rightarrow (\bar{W}(f, g), \bar{\tau}) .$$

The proof of (6.7.6.2) is the same as the proof of (6.7.6.1), replacing the finitary  $\infty$ -site  $(\bar{W}(f, g), \bar{\tau})$  by  $(W(f, g), \tau)$ .  $\square$

In the setting of Lemma 6.7.6, the  $\infty$ -topos  $X \tilde{\times}_Z Y$  is *determined* by its  $\infty$ -category of points in the following sense.

**6.7.7 Proposition.** *An oriented square*

$$\begin{array}{ccc} W & \xrightarrow{q_*} & Y \\ p_* \downarrow & \lrcorner_{\tau} & \downarrow g_* \\ X & \xrightarrow{f_*} & Z, \end{array}$$

*of bounded coherent  $\infty$ -topoi and coherent geometric morphisms is an oriented fibre product square if and only if the induced oriented square*

$$\begin{array}{ccc} \mathrm{Pt}(W) & \xrightarrow{q_*} & \mathrm{Pt}(Y) \\ p_* \downarrow & \lrcorner_{\tau} & \downarrow g_* \\ \mathrm{Pt}(X) & \xrightarrow{f_*} & \mathrm{Pt}(Z), \end{array}$$

*in  $\mathbf{Cat}_{\infty, \delta_1}$  exhibits  $\mathrm{Pt}(W)$  as the oriented fibre product  $\mathrm{Pt}(X) \downarrow_{\mathrm{Pt}(Z)} \mathrm{Pt}(Y)$  (0.4.1).*

*Proof.* This follows from Conceptual Completeness ([Theorem 5.11.2](#)=[SAG, Theorem A.9.0.6]), along with the fact that the functor  $\mathrm{Pt}: \mathbf{Top}_{\infty} \rightarrow \mathbf{Cat}_{\infty, \delta_1}$  preserves oriented fibre product squares ([Lemma 6.5.8](#)).  $\square$

## 6.8 Compatibility of oriented fibre products & étale geometric morphisms

We turn to the compatibility of oriented fibre products with étale geometric morphisms. Our treatment is inspired by Illusie's discussion [[42](#), Exposé XI, 1.10(b)]. First we prove what must be a standard fact about the compatibility of ordinary pullbacks and étale geometric morphisms ([Lemma 6.8.2](#)) which we could not locate in the literature.

**6.8.1 Notation.** Let  $f_*: X \rightarrow Z$  and  $g_*: Y \rightarrow Z$  be geometric morphisms of  $\infty$ -topoi, and suppose we are given objects  $X \in X$ ,  $Y \in Y$ , and  $Z \in Z$ , along with morphisms  $\phi: X \rightarrow f^*(Z)$  and  $\psi: Y \rightarrow g^*(Z)$ . We write

$$X \times_Z Y := \mathrm{pr}_1^*(X) \times_{\mathrm{pr}_1^* f^*(Z)} \mathrm{pr}_2^*(Y) \in X \times_Z Y$$

for the pullback of  $\mathrm{pr}_1^*(X)$  and  $\mathrm{pr}_2^*(Y)$  over  $\mathrm{pr}_1^* f^*(Z) \simeq \mathrm{pr}_2^* g^*(Z)$  formed in the (un-oriented) pullback  $\infty$ -topos  $X \times_Z Y$ .

**6.8.2 Lemma.** *Keep the notations of [Notation 6.8.1](#). Then the natural geometric morphism  $p_*: X_{/X} \times_{Z_{/Z}} Y_{/Y} \rightarrow X \times_Z Y$  is étale and  $p_!(1) \simeq X \times_Z Y$ .*

*Proof.* First note that the commutative square

$$\begin{array}{ccccc} (X \times_Z Y)_{/(X \times_Z Y)} & \longrightarrow & (X \times_Z Y)_{/\mathrm{pr}_2^*(Y)} & \longrightarrow & Y_{/Y} \\ \downarrow & & & & \downarrow \\ (X \times_Z Y)_{/\mathrm{pr}_1^*(X)} & & & & \\ \downarrow & & & & \downarrow \\ X_{/X} & \longrightarrow & & \longrightarrow & Z_{/Z} \end{array}$$

defines a geometric morphism  $e_* : (X \times_Z Y)_{/(X \times_Z Y)} \rightarrow X_{/X} \times_{Z_{/Z}} Y_{/Y}$ . We claim that  $e_*$  is an equivalence of  $\infty$ -topoi. Indeed, for any  $\infty$ -topos  $E$ , consider the commutative square

$$\begin{array}{ccc} \mathrm{Fun}^*(X_{/X} \times_{Z_{/Z}} Y_{/Y}, E) & \xrightarrow{\sim} & \mathrm{Fun}^*(X_{/X}, E) \times_{\mathrm{Fun}^*(Z_{/Z}, E)} \mathrm{Fun}^*(Y_{/Y}, E) \\ \downarrow & & \downarrow \\ \mathrm{Fun}^*(X \times_Z Y, E) & \xrightarrow{\sim} & \mathrm{Fun}^*(X, E) \times_{\mathrm{Fun}^*(Z, E)} \mathrm{Fun}^*(Y, E). \end{array}$$

Now it follows from [Recollection 5.1.6](#)=[HTT, Corollary 6.3.5.6] that the functor

$$\mathrm{Fun}^*(X_{/X} \times_{Z_{/Z}} Y_{/Y}, E) \rightarrow \mathrm{Fun}^*(X \times_Z Y, E)$$

is a left fibration whose fibre over an object  $h^*$  is the space

$$\mathrm{Map}_E(1, h^* \mathrm{pr}_1^*(X)) \times_{\mathrm{Map}_E(1, h^* \mathrm{pr}_1^* f^*(Z))} \mathrm{Map}_E(1, h^* \mathrm{pr}_2^*(Y)) \simeq \mathrm{Map}_E(1, h^*(X \times_Z Y)).$$

On the other hand, again by [Recollection 5.1.6](#)=[HTT, Corollary 6.3.5.6], the natural geometric morphism  $(X \times_Z Y)_{/(X \times_Z Y)} \rightarrow X \times_Z Y$  induces a left fibration

$$\mathrm{Fun}^*((X \times_Z Y)_{/(X \times_Z Y)}, E) \rightarrow \mathrm{Fun}^*(X \times_Z Y, E)$$

whose fibre over  $h^*$  is the space  $\mathrm{Map}_E(1, h^*(X \times_Z Y))$ . Thus the geometric morphism  $e_*$  induces a fibrewise equivalence

$$\mathrm{Fun}^*((X \times_Z Y)_{/(X \times_Z Y)}, E) \rightarrow \mathrm{Fun}^*(X_{/X} \times_{Z_{/Z}} Y_{/Y}, E)$$

of left fibrations over  $\mathrm{Fun}^*(X \times_Z Y, E)$ . □

Now we turn to the compatibility of oriented fibre products and étale geometric morphisms. We can employ essentially the same reasoning as in [Lemma 6.8.2](#).

**6.8.3 Lemma.** *Let  $Z$  be an  $\infty$ -topos, and let  $Z \in \mathbf{Z}$  be an object. Then the natural geometric morphism  $p_* : \mathrm{Path}(Z_{/Z}) \rightarrow \mathrm{Path}(Z)$  is étale and  $p_!(1) \simeq \mathrm{pr}_1^*(Z)$ .*

*Proof.* We have two geometric morphisms

$$p_* : \mathrm{Path}(Z)_{/\mathrm{pr}_1^*(Z)} \rightarrow Z_{/Z} \quad \text{and} \quad q_* : \mathrm{Path}(Z)_{/\mathrm{pr}_1^*(Z)} \rightarrow \mathrm{Path}(Z)_{/\mathrm{pr}_2^*(Z)} \rightarrow Z_{/Z}$$

along with a natural transformation  $\sigma : q_* \rightarrow p_*$ . These furnish us with a geometric morphism

$$e_* : \mathrm{Path}(Z)_{/\mathrm{pr}_1^*(Z)} \rightarrow \mathrm{Path}(Z_{/Z})$$

over  $\mathrm{Path}(Z)$ . We claim that  $e_*$  is an equivalence of  $\infty$ -topoi.

First, for any  $\infty$ -topos  $E$ , consider the commutative square

$$\begin{array}{ccc} \mathrm{Fun}^*(\mathrm{Path}(Z_{/Z}), E) & \xrightarrow{\sim} & \mathrm{Fun}(\Delta^1, \mathrm{Fun}^*(Z_{/Z}, E)) \\ \downarrow & & \downarrow \\ \mathrm{Fun}^*(\mathrm{Path}(Z), E) & \xrightarrow{\sim} & \mathrm{Fun}(\Delta^1, \mathrm{Fun}^*(Z, E)). \end{array}$$

It follows from [HTT, Corollaries 2.1.2.9 & 6.3.5.6] that the functor

$$\mathrm{Fun}^*(\mathrm{Path}(\mathbf{Z}/\mathbf{Z}), \mathbf{E}) \rightarrow \mathrm{Fun}^*(\mathrm{Path}(\mathbf{Z}), \mathbf{E})$$

is a left fibration whose fibre over  $h^*$  is the space

$$\mathrm{Map}_{\mathbf{E}}(1, h^* \mathrm{pr}_1^*(\mathbf{Z})) \times_{\mathrm{Map}_{\mathbf{E}}(1, h^* \mathrm{pr}_2^*(\mathbf{Z}))} \mathrm{Map}_{\mathbf{E}}(1, h^* \mathrm{pr}_2^*(\mathbf{Z})) \simeq \mathrm{Map}_{\mathbf{E}}(1, h^* \mathrm{pr}_1^*(\mathbf{Z})) .$$

Here the map  $\mathrm{Map}_{\mathbf{E}}(1, h^* \mathrm{pr}_1^*(\mathbf{Z})) \rightarrow \mathrm{Map}_{\mathbf{E}}(1, h^* \mathrm{pr}_2^*(\mathbf{Z}))$  is induced by the natural transformation  $\hat{\tau}: \mathrm{pr}_1^* \rightarrow \mathrm{pr}_2^*$  adjoint to the defining natural transformation  $\tau: \mathrm{pr}_{2,*} \rightarrow \mathrm{pr}_{1,*}$  of the path  $\infty$ -topos  $\mathrm{Path}(\mathbf{Z})$ .

On the other hand, by **Recollection 5.1.6**=[HTT, Corollary 6.3.5.6] for any  $\infty$ -topos  $\mathbf{E}$ , the natural geometric morphism  $\mathrm{Path}(\mathbf{Z})/\mathrm{pr}_1^*(\mathbf{Z}) \rightarrow \mathrm{Path}(\mathbf{Z})$  induces a left fibration

$$\mathrm{Fun}^*(\mathrm{Path}(\mathbf{Z})/\mathrm{pr}_1^*(\mathbf{Z}), \mathbf{E}) \rightarrow \mathrm{Fun}^*(\mathrm{Path}(\mathbf{Z}), \mathbf{E})$$

whose fibre over  $h^*$  is the space  $\mathrm{Map}_{\mathbf{E}}(1, h^* \mathrm{pr}_1^*(\mathbf{Z}))$ . Thus for any  $\infty$ -topos  $\mathbf{E}$ , the geometric morphism  $e_*$  induces a fibrewise equivalence

$$\mathrm{Fun}^*(\mathrm{Path}(\mathbf{Z})/\mathrm{pr}_1^*(\mathbf{Z}), \mathbf{E}) \rightarrow \mathrm{Fun}^*(\mathrm{Path}(\mathbf{Z}/\mathbf{Z}), \mathbf{E})$$

of left fibrations over  $\mathrm{Fun}^*(\mathrm{Path}(\mathbf{Z}), \mathbf{E})$ . □

**6.8.4 Construction.** Let  $f_*: \mathbf{X} \rightarrow \mathbf{Z}$  and  $g_*: \mathbf{Y} \rightarrow \mathbf{Z}$  be geometric morphisms of  $\infty$ -topoi, and let  $X \in \mathbf{X}$ ,  $Y \in \mathbf{Y}$ , and  $Z \in \mathbf{Z}$  be objects, along with morphisms  $\phi: X \rightarrow f^*(Z)$  and  $\psi: Y \rightarrow g^*(Z)$ . Form the oriented fibre product

$$\begin{array}{ccc} X \tilde{\times}_Z Y & \xrightarrow{\mathrm{pr}_{2,*}} & Y \\ \mathrm{pr}_{1,*} \downarrow & \swarrow \tau & \downarrow g_* \\ X & \xrightarrow{f_*} & Z . \end{array}$$

Write  $X \tilde{\times}_Z Y$  for the object of  $\mathbf{X} \tilde{\times}_Z \mathbf{Y}$  defined by the pullback square

$$\begin{array}{ccc} X \tilde{\times}_Z Y & \longrightarrow & \mathrm{pr}_2^*(Y) \\ \downarrow \lrcorner & & \downarrow \mathrm{pr}_2^*(\psi) \\ \mathrm{pr}_1^*(X) & \xrightarrow{\hat{\tau}(Z) \circ \mathrm{pr}_1^*(\phi)} & \mathrm{pr}_2^*(g^*(Z)) , \end{array}$$

where

$$\hat{\tau}: \mathrm{pr}_1^* f^* \rightarrow \mathrm{pr}_2^* g^*$$

is the natural transformation adjoint to  $\tau: g_* \mathrm{pr}_{2,*} \rightarrow f_* \mathrm{pr}_{1,*}$ .

**Lemma 6.8.3** and **Lemma 6.8.2** together now imply the following.

**6.8.5 Proposition.** *Keep the notations of **Construction 6.8.4**. Then the natural geometric morphism  $p_*: \mathbf{X}/\mathbf{X} \tilde{\times}_{\mathbf{Z}/\mathbf{Z}} \mathbf{Y}/\mathbf{Y} \rightarrow \mathbf{X} \tilde{\times}_Z \mathbf{Y}$  is étale and  $p_!(1) \simeq \mathrm{pr}_1^*(X \tilde{\times}_Z Y)$ .*

*Proof.* The claim follows from [Lemma 6.8.3](#) along with [Lemma 6.8.2](#) applied to the top right, top left, and bottom left cubes in the diagram

$$\begin{array}{ccccc}
 & X_{/X} \tilde{\times}_{Z/Z} Y_{/Y} & \longrightarrow & Z_{/Z} \tilde{\times}_{Z/Z} Y_{/Y} & \longrightarrow & Y_{/Y} \\
 & \swarrow & & \swarrow & & \swarrow \\
 X \tilde{\times}_Z Y & \longrightarrow & Z \tilde{\times}_Z Y & \longrightarrow & Y & \\
 \downarrow & & \downarrow & & \downarrow & \\
 & X_{/X} \tilde{\times}_{Z/Z} Z_{/Z} & \longrightarrow & \text{Path}(Z_{/Z}) & \longrightarrow & Z_{/Z} \\
 & \swarrow & & \swarrow & & \swarrow \\
 X \tilde{\times}_Z Z & \longrightarrow & \text{Path}(Z) & \longrightarrow & Z & \\
 \downarrow & & \downarrow & & \downarrow & \\
 & X_{/X} & \longrightarrow & Z_{/Z} & \xlongequal{\quad} & Z_{/Z} \\
 \swarrow & & \swarrow & & \swarrow & \\
 X & \longrightarrow & Z & \xlongequal{\quad} & Z & ,
 \end{array}$$

where the front and back faces of the bottom right cube are oriented fibre product squares, all other squares are commutative, and the front and back faces of each of the top right, top left, and bottom left cubes are pullback squares.  $\square$

**6.8.6 Corollary.** *Keep the notations of [Construction 6.8.4](#). If the morphism*

$$\text{pr}_2^*(\psi) : \text{pr}_2^*(Y) \rightarrow \text{pr}_2^* g^*(Z)$$

*is an equivalence, then we have a natural equivalence*

$$(X \tilde{\times}_Z Y)_{/X \tilde{\times}_Z Y} \simeq (X \tilde{\times}_Z Y)_{/\text{pr}_1^*(X)} .$$

**6.8.7.** Keep the notation of [Construction 6.8.4](#) and assume, in addition, that  $X, Y$  and  $Z$  are bounded coherent, the geometric morphisms  $f_*$  and  $g_*$  are coherent, and the objects  $X, Y$ , and  $Z$  are all truncated coherent. Then the object  $X \tilde{\times}_Z Y \in X \tilde{\times}_Z Y$  is the image of the object of  $\bar{W}(f, g)$  ([Construction 6.7.5](#)) given by  $X \rightarrow Z \leftarrow Y$  under the Yoneda embedding  $j : \bar{W}(f, g) \hookrightarrow X \tilde{\times}_Z Y$ .

## 7 Local $\infty$ -topoi & localisations

In this section we generalise the basic theory of what are usually called *local geometric morphisms* and *local topoi* to the setting of  $\infty$ -topoi [[SGA 4<sub>II</sub>](#), Exposé IV, §8; [46](#), §C.3.6; [47](#)]. The  $\infty$ -toposic theory follows the 1-toposic story very closely; as such, a number of items in this section are likely known to experts.<sup>[24](#)</sup>

<sup>24</sup>Notably, Urs Schreiber has studied *local  $\infty$ -topoi* [[71](#), §3.2].



## 7.1 Quasi-equivalences

As a precursor, we begin by discussing the  $\infty$ -toposic generalisation of the notion of a *connected* geometric morphism [46, p. 525]. In the homotopical setting, the term ‘connected’ (and its variants) doesn’t seem appropriate. Instead, we elect for the distinct term *quasi-equivalence*.

**7.1.1 Definition.** A geometric morphism  $f_* : X \rightarrow Y$  of  $\infty$ -topoi is a *quasi-equivalence* if the pullback functor  $f^*$  is fully faithful.

**7.1.2.** Every geometric morphism of  $\infty$ -topoi factors as the composite of a quasi-equivalence followed by an *algebraic* geometric morphism, and this factorisation is unique up to (canonical) equivalence [HTT, Proposition 6.3.6.2].

If  $f_*$  is a quasi-equivalence, then  $f^*$  is fully faithful, whence we deduce the following.

**7.1.3 Lemma.** Let  $f_* : X \rightarrow Y$  be a quasi-equivalence of  $\infty$ -topoi. Then the canonical natural transformation  $\Gamma_{Y,*} \rightarrow \Gamma_{X,*} f^*$  is an equivalence (Notation 5.1.5).

**7.1.4.** If  $f_* : X \rightarrow Y$  is a quasi-equivalence of  $\infty$ -topoi, then by composing the canonical natural transformation  $\Gamma_{Y,*} \rightarrow \Gamma_{X,*} f^*$  with  $\Gamma_Y^*$ , Lemma 7.1.3 ensures that the canonical natural transformation

$$\Gamma_{Y,*} \Gamma_Y^* \rightarrow \Gamma_{X,*} f^* \Gamma_Y^* \simeq \Gamma_{Y,*} f_* f^* \Gamma_Y^*$$

is an equivalence in  $\text{Pro}(\mathcal{S})^{op} \subset \text{Fun}(\mathcal{S}, \mathcal{S})$ , so that  $f_*$  is a shape equivalence (Definition 5.13.5).

**7.1.5.** As noted in [HTT, Remark 7.1.6.12], an  $\infty$ -topos  $X$  has trivial shape if and only if the geometric morphism  $X \rightarrow \mathcal{S}$  is a quasi-equivalence. However, in general a shape equivalence of  $\infty$ -topoi need not be a quasi-equivalence.

**7.1.6 Example.** Let  $X$  be a scheme. By [10, Lemma 5.1.2], the natural geometric morphism  $X_{\text{proét}} \rightarrow X_{\text{ét}}$  from the proétale  $\infty$ -topos of  $X$  to the étale  $\infty$ -topos of  $X$  is a quasi-equivalence, hence a shape equivalence.

## 7.2 Local $\infty$ -topoi

Now we specialise to local  $\infty$ -topoi.

**7.2.1 Definition.** A geometric morphism  $f_* : X \rightarrow Y$  of  $\infty$ -topoi is said to be *coëssential* if  $f_*$  admits a right adjoint  $f^! : Y \rightarrow X$ . In this case, the functor  $f^!$  and its left adjoint  $f_*$  define a geometric morphism  $f^! : Y \rightarrow X$  called the *centre* of  $f_*$ .

The next definition generalises what are sometimes called *local geometric morphisms* in the 1-topos theory literature [46, §C.3.6; 47]. We instead choose terminology that syncs with the algebro-geometric terminology for local rings and doesn’t conflict with other uses of the term ‘local’ in higher category theory.

**7.2.2 Definition.** A geometric morphism  $f_* : X \rightarrow Y$  of  $\infty$ -topoi is said to exhibit  $X$  as *local over  $Y$*  if  $f_*$  is both coëssential and a quasi-equivalence.

An  $\infty$ -topos  $X$  is said to be *local* if  $X$  is local over  $\mathcal{S}$ . In this case we simply call  $\Gamma^! : \mathcal{S} \rightarrow X$  the *centre* of  $X$ .

**7.2.3.** Please observe that a geometric morphism of  $\infty$ -topoi  $f_* : X \rightarrow Y$  exhibits  $X$  as local over  $Y$  if and only if the functor  $f_*$  admits a *fully faithful* right adjoint  $f^!$ . Equivalently,  $X$  is local over  $Y$  if and only if  $f_*$  admits a section  $f^!$  in the  $(\infty, 2)$ -category  $\mathbf{Top}_\infty$ .

**7.2.4.** Let  $X$  be an  $\infty$ -topos. Note that if the global sections functor  $\Gamma_* : X \rightarrow \mathcal{S}$  admits a right adjoint  $\Gamma^! : \mathcal{S} \rightarrow X$ , then  $\Gamma^!$  is automatically fully faithful, whence  $X$  is local.

Consequently, by the Adjoint Functor Theorem and (7.2.4), an  $\infty$ -topos  $X$  is local if and only if the terminal object  $1_X \in X$  is completely compact.

**7.2.5 Lemma.** *Let  $X$  be a local  $\infty$ -topos. Then  $X$  has homotopy dimension  $\leq 0$ . In particular,  $X$  has cohomological dimension  $\leq 0$ .*

*Proof.* By [HTT, Lemma 7.2.1.7], it suffices to show that  $\Gamma_{X,*} : X \rightarrow \mathcal{S}$  preserves effective epimorphisms, which follows from the assumption that  $\Gamma_{X,*}$  is a left adjoint. The second statement is a consequence of [HTT, Corollary 7.2.2.30].  $\square$

**7.2.6 Definition.** Let  $X$  and  $Y$  be local  $\infty$ -topoi with centres  $x_*$  and  $y_*$ , respectively. A geometric morphism  $f_* : X \rightarrow Y$  is a *local geometric morphism* if  $f_* x_* \simeq y_*$ . Write  $\mathbf{Top}_\infty^{loc} \subset \mathbf{Top}_\infty$  for the (non-full) subcategory whose objects are local  $\infty$ -topoi and whose morphisms are local geometric morphisms.

If  $X$  is a local  $\infty$ -topos, then its centre is an initial object of the  $\infty$ -category  $\mathbf{Pt}(X)$ ; in fact, more is true.

**7.2.7 Notation.** Let  $f_* : X \rightarrow Y$  and  $f'_* : X' \rightarrow Y$  be two geometric morphisms of  $\infty$ -topoi. Write

$$\mathbf{Fun}_{Y,*}(X, X') := \mathbf{Fun}_*(X, X') \times_{\mathbf{Fun}_*(X, Y)} \{f_*\}$$

for the  $\infty$ -category of geometric morphisms  $X \rightarrow X'$  over  $Y$ .

**7.2.8 Lemma.** *Let  $f_* : X \rightarrow Y$  be a geometric morphism that exhibits  $X$  as local over  $Y$  with centre  $f^!$ . Then  $f^!$  is a terminal object of the  $\infty$ -category  $\mathbf{Fun}_{Y,*}(Y, X)$ .*

*Proof.* Let  $g_* : Y \rightarrow X$  be a geometric morphism over  $Y$ . Then

$$\begin{aligned} \mathbf{Map}_{\mathbf{Fun}_{Y,*}(Y, X)}(g_*, f^!) &\simeq \mathbf{Map}_{\mathbf{Fun}_{Y,*}(Y, Y)}(f_* g_*, \mathrm{id}_Y) \\ &\simeq \mathbf{Map}_{\mathbf{Fun}_{Y,*}(Y, Y)}(\mathrm{id}_Y, \mathrm{id}_Y) \simeq * . \end{aligned} \quad \square$$

Local  $\infty$ -topoi provide a convenient way to compute stalks as global sections after pulling back to an appropriate local  $\infty$ -topos. The following is immediate.

**7.2.9 Lemma.** *Let  $p_* : W \rightarrow X$  be a geometric morphism of  $\infty$ -topoi where  $W$  is local with centre  $w_*$ , and let  $x_* := p_* w_*$ . Then  $x^* \simeq \Gamma_{W,*} p^*$ .*

We shall soon see (Definition 7.3.7 and (7.3.8)) that for any  $\infty$ -topos  $X$  and any point  $x_* \in \text{Pt}(X)$ , there is a geometric morphism  $p_* : W \rightarrow X$  in which  $W$  is local with centre  $w_*$  and  $x_* \simeq p_* w_*$  (and is, moreover, universal with this property).

Local geometric morphisms are also stable under pullback, though we do not use this fact in an integral way in the present paper.

7.2.10. Consider a pullback square of  $\infty$ -topoi

$$\begin{array}{ccc} X \times_Z Y & \xrightarrow{\bar{f}_*} & Y \\ \bar{g}_* \downarrow & \lrcorner & \downarrow g_* \\ X & \xrightarrow{f_*} & Z, \end{array}$$

where  $g_*$  exhibits  $Y$  as local over  $Z$  with centre  $g^!$ . By the universal property of the pullback, the identity on  $X$  and the geometric morphism  $g^! f_* : X \rightarrow Y$  induce a geometric morphism

$$\bar{g}^! := (\text{id}_X, g^! f_*) : X \rightarrow X \times_Z Y$$

such that  $\bar{g}_* \bar{g}^! \simeq \text{id}_X$  and  $\bar{f}_* \bar{g}^! \simeq g^! f_*$ . Using the universal property of the pullback and the fact that  $g_*$  exhibits  $Y$  as local over  $Z$ , one easily checks that the functor  $\bar{g}^!$  is right adjoint to  $\bar{g}_*$ , so that  $\bar{g}_*$  exhibits  $X \times_Z Y$  as local over  $X$  with centre  $\bar{g}^!$ .

### 7.3 Nearby cycles & localisations

We now show that the evanescent  $\infty$ -topos (Example 6.5.10) provides a wealth of local  $\infty$ -topoi. Then, following Deligne as well as Peter Johnstone and Ieke Moerdijk [47, Definition 3.1], we use the evanescent  $\infty$ -topos to construct the localisation of an  $\infty$ -topos at a point.

A site-theoretic proof of the following result (originally stated without proof by Laumon [50, 3.2]) is given in [42, Exposé XI, Proposition 4.4]. The reliance on sites renders the proof given in [42, Exposé XI] inadequate in the context of  $\infty$ -topoi; luckily the work of Emily Riehl and Dominic Verity [66] permit us to employ simple 2-categorical arguments.

7.3.1 Proposition. *Let  $f_* : X \rightarrow Z$  be a geometric morphism of  $\infty$ -topoi. Then:*

(7.3.1.1) *The nearby cycles functor  $\Psi_{f,*} : X \rightarrow X \tilde{\times}_Z Z$  is right adjoint to the projection  $\text{pr}_{1,*} : X \tilde{\times}_Z Z \rightarrow X$ .*

(7.3.1.2) *The functor  $\Psi_{f,*}$  is fully faithful, hence the geometric morphism  $\text{pr}_{1,*}$  exhibits  $X \tilde{\times}_Z Z$  as local over  $X$  with centre  $\Psi_{f,*}$ .*

*Proof.* Recall that for any  $\infty$ -topos  $E$ , the functor  $\text{Fun}_*(E, -)^{op} : \mathbf{Top}_\infty \rightarrow \mathbf{Cat}_{\infty, \delta_1}$  carries oriented fibre products in  $\mathbf{Top}_\infty$  to oriented fibre products in  $\mathbf{Cat}_{\infty, \delta_1}$  (6.5.7). Thus the proof of [66, Proposition 3.4.6] works perfectly, giving the oriented fibre product in  $\mathbf{Top}_\infty$  the necessary ‘weak universal property’ (as Riehl and Verity call it) to apply [66, Lemma 3.5.8], proving both (7.3.1.1) and (7.3.1.2).  $\square$

The dual notion to being local over an  $\infty$ -topos naturally appears as the property satisfied by the second projection from the coëvanescent  $\infty$ -topos in the dual to [Proposition 7.3.1](#).

**7.3.2 Definition.** A geometric morphism  $f_* : X \rightarrow Y$  of  $\infty$ -topoi exhibits  $X$  as *colocal over Y* if  $f_*$  is a quasi-equivalence and  $f^*$  admits a left exact left adjoint  $f_! : X \rightarrow Y$ . In this case, the functor  $f^*$  and its left adjoint  $f_!$  define a geometric morphism  $f^* : Y \rightarrow X$  called the *cocentre* of  $f_*$ .

**7.3.3.** In the setting of 1-topoi, Johnstone [46, Theorem C.3.6.16] uses the term *totally connected* for what we call colocal. Again, such lingo is inapt in our context.

**7.3.4 Proposition.** Let  $g_* : Y \rightarrow Z$  be a geometric morphism of  $\infty$ -topoi. Then:

(7.3.1.1) The conearby cycles functor  $\Psi_*^g : Y \rightarrow Z \tilde{\times}_Z Y$  is left adjoint to the projection  $\text{pr}_{2,*} : Z \tilde{\times}_Z Y \rightarrow Y$ .

(7.3.1.2) The functor  $\Psi_*^g \simeq \text{pr}_2^*$  is fully faithful, whence the geometric morphism  $\text{pr}_{2,*}$  exhibits  $Z \tilde{\times}_Z Y$  as colocal over  $Y$  with cocentre  $\Psi_*^g$ .

**7.3.5.** A geometric morphism  $f_*$  that exhibits an  $\infty$ -topos as colocal over another will always satisfy the étale projection formula

$$f_!(f^*(X) \times_{f^*(Z)} Y) \simeq X \times_Z f_!(Y)$$

of [HTT, Proposition 6.3.5.11], but the geometric morphism  $f_*$  will almost never be étale as  $f_!$  is conservative if and only if  $f_*$  is an equivalence.

**7.3.6 Example.** For any  $\infty$ -topos  $X$  the diagonal functor  $\psi(\text{id}_X, \text{id}_X, \text{id})_*$  is both the nearby and conearby cycles functor

$$X \rightarrow X \tilde{\times}_X X \simeq \text{Path}(X).$$

Combining [Propositions 7.3.1](#) and [7.3.4](#), we deduce that we have a chain of (left exact) adjoints

$$\text{Path}(X) \begin{array}{c} \xleftarrow{\text{pr}_1^*} \\ \xleftarrow{\text{pr}_{1,*}} \xrightarrow{\text{pr}_2^*} \\ \xleftarrow{\text{pr}_{2,*}} \end{array} X.$$

In particular, the geometric morphisms  $\text{pr}_{1,*}, \text{pr}_{2,*} : \text{Path}(X) \rightarrow X$  are shape equivalences.

Now we define the *localisation* of an  $\infty$ -topos at a point as a evanescent  $\infty$ -topos; for this please recall [Notation 5.1.5](#).

**7.3.7 Definition.** Let  $X$  be an  $\infty$ -topos and  $x_* : S \rightarrow X$  a point of  $X$ . The *localisation* of  $X$  at  $x_*$  is the evanescent  $\infty$ -topos

$$X_{(x)} := \tilde{x} \tilde{\times}_X X.$$

We write  $\ell_{x,*} : X_{(x)} \rightarrow X$  for the second projection  $\text{pr}_{2,*} : \tilde{x} \tilde{\times}_X X \rightarrow X$ .

**7.3.8.** Let  $X$  be an  $\infty$ -topos and  $x_*$  a point of  $X$ . By [Proposition 7.3.1](#), the  $\infty$ -topos  $X_{(x)}$  is local with centre  $\Psi_{x,*} : \mathcal{S} \rightarrow X_{(x)}$ . By [Lemma 7.2.9](#), for every object  $F \in X$  we can compute the stalk at  $x$  via the familiar formula

$$F_x \simeq \Gamma(X_{(x)}; \ell_x^* F).$$

**7.3.9 Notation.** Write  $\mathbf{Top}_{\infty,*} := \mathbf{Top}_{\infty,\mathcal{S}/}$  for the  $\infty$ -category of pointed  $\infty$ -topoi. The assignment  $(X, x_*) \mapsto X_{(x)}$  defines a functor  $\mathbf{Top}_{\infty,*} \rightarrow \mathbf{Top}_{\infty}^{loc}$ .

In the other direction, the assignment  $X \mapsto (X, \Gamma^!)$  defines a fully faithful functor  $\mathbf{Top}_{\infty}^{loc} \hookrightarrow \mathbf{Top}_{\infty,*}$ .

**7.3.10 Proposition.** *Let  $X$  be a local  $\infty$ -topos with centre  $x_*$ . Then the geometric morphism  $\ell_{x,*} : X_{(x)} \rightarrow X$  is an equivalence.*

*Proof.* Let  $\eta : \mathrm{id}_X \rightarrow x_* \Gamma_{X,*}$  be the unit of the adjunction  $\Gamma_{X,*} \dashv x_*$ . Then the oriented square

$$\begin{array}{ccc} X & \xlongequal{\quad} & X \\ \downarrow & \swarrow_{\eta} & \parallel \\ \tilde{x} & \longrightarrow & X \end{array}$$

exhibits  $X$  as the oriented fibre product  $\tilde{x} \tilde{\times}_X X$ . □

**7.3.11 Corollary.** *The fully faithful functor  $\mathbf{Top}_{\infty}^{loc} \hookrightarrow \mathbf{Top}_{\infty,*}$  admits a right adjoint given by the assignment  $(X, x_*) \mapsto X_{(x)}$ .*

## 7.4 Compatibility of oriented fibre products with localisations

In this subsection we prove that the formation oriented fibre products is compatible with localisations of  $\infty$ -topoi.

**7.4.1 Lemma.** *Let  $f_* : X \rightarrow Z$  and  $g_* : Y \rightarrow Z$  be geometric morphisms of  $\infty$ -topoi. Then we have a natural equivalence*

$$\mathrm{Path}(X \tilde{\times}_Z Y) \simeq \mathrm{Path}(X) \tilde{\times}_{\mathrm{Path}(Z)} \mathrm{Path}(Y).$$

*Proof.* Since the path  $\infty$ -topos construction is a right adjoint  $\mathbf{Top}_{\infty} \rightarrow \mathbf{Top}_{\infty}$ , we have natural equivalences

$$\begin{aligned} \mathrm{Path}(X \tilde{\times}_Z Y) &= \mathrm{Path}(X \times_Z \mathrm{Path}(Z) \times_Z Y) \\ &\simeq \mathrm{Path}(X) \times_{\mathrm{Path}(Z)} \mathrm{Path}(\mathrm{Path}(Z)) \times_{\mathrm{Path}(Z)} \mathrm{Path}(Y) \\ &= \mathrm{Path}(X) \tilde{\times}_{\mathrm{Path}(Z)} \mathrm{Path}(Y). \end{aligned} \quad \square$$

**7.4.2 Proposition.** *Let  $f_* : (X, x_*) \rightarrow (Z, z_*)$  and  $g_* : (Y, y_*) \rightarrow (Z, z_*)$  be morphisms of pointed  $\infty$ -topoi, so that there is an induced point*

$$x_* \tilde{\times}_{z_*} y_* : \mathcal{S} \simeq \mathcal{S} \tilde{\times}_S \mathcal{S} \rightarrow X \tilde{\times}_Z Y.$$

*Then we have a natural equivalence*

$$(X \tilde{\times}_Z Y)_{(x_* \tilde{\times}_{z_*} y_*)} \simeq X_{(x)} \tilde{\times}_{Z_{(z)}} Y_{(y)}.$$

*Proof.* Consider the diagram  $\Lambda_2^2 \rightarrow \text{Fun}(\Lambda_2^2, \mathbf{Top}_\infty)$  defined by the diagram

$$(7.4.3) \quad \begin{array}{ccccc} \text{Path}(X) & \xrightarrow{\text{Path}(f_*)} & \text{Path}(Z) & \xleftarrow{\text{Path}(g_*)} & \text{Path}(Y) \\ \text{pr}_{1,*} \downarrow & & \downarrow \text{pr}_{1,*} & & \downarrow \text{pr}_{1,*} \\ X & \xrightarrow{f_*} & Z & \xleftarrow{g_*} & Y \\ x_* \uparrow & & \uparrow z_* & & \uparrow y_* \\ S & \xlongequal{\quad} & S & \xlongequal{\quad} & S, \end{array}$$

where we have displayed objects of  $\text{Fun}(\Lambda_2^2, \mathbf{Top}_\infty)$  horizontally, and morphisms in  $\text{Fun}(\Lambda_2^2, \mathbf{Top}_\infty)$  vertically. First taking the (vertical) limit of the diagram (7.4.3) in

$$\text{Fun}(\Lambda_2^2, \mathbf{Top}_\infty)$$

we obtain the cospan then taking the oriented fibre product of the resulting cospan yields  $X_{(x)} \tilde{\times}_{Z_{(z)}} Y_{(y)}$ . On the other hand, by Lemma 7.4.1, first forming the oriented fibre product then taking limits yields  $(X \tilde{\times}_Z Y)_{(x_* \tilde{\times}_{z_*} y_*)}$ . The claim now follows from the fact that the formation of oriented fibre products commutes with limits (6.5.3).  $\square$

## 7.5 Localisation à la Grothendieck–Verdier

In order to get our hands on geometric examples of localised  $\infty$ -topoi, we give another description of  $X_{(x)}$  that is akin to the original (1-toposic) definition of the localisation due to Grothendieck–Verdier [SGA 4<sub>III</sub>, Exposé VI, 8.4.2] as a limit over étale neighbourhoods of  $x_*$  in  $X$ .

**7.5.1 Definition.** Let  $(X, x_*)$  be a pointed  $\infty$ -topos. The  $\infty$ -category of neighbourhoods of  $x_*$  is the pullback

$$\begin{array}{ccc} \text{Nbd}(x) & \longrightarrow & S_* \\ \downarrow & \lrcorner & \downarrow \\ X & \xrightarrow{x_*} & S \end{array}$$

formed in  $\mathbf{Cat}_{\infty, \delta_1}$ .

By [HTT, Corollary 6.3.5.6 & Remark 6.3.5.7] the  $\infty$ -category  $\text{Nbd}(x)$  is equivalent to the full subcategory of  $(\mathbf{Top}_{\infty, *})_{/(X, x_*)}$  spanned by those objects  $(E, e_*) \rightarrow (X, x_*)$  with the property that the geometric morphism  $E \rightarrow X$  is étale.

Please note that  $\text{Nbd}(x)$  is an inverse  $\infty$ -category.

To provide the limit description of the localisation as well as the familiar colimit formula for the stalk at  $x$ , we must speak of limits of diagrams indexed by the (not necessarily  $\delta_0$ -small)  $\infty$ -category  $\text{Nbd}(x)$ . Happily the exact same cofinality argument given in [SGA 4<sub>III</sub>, Exposé IV, 6.8] works in the setting of higher topoi, showing that  $\text{Nbd}(x)$  admits a limit-cofinal  $\delta_0$ -small subcategory.

**7.5.2 Construction.** Let  $X$  be a  $\infty$ -topos and  $x_* \in \text{Pt}(X)$ . Then by the Yoneda lemma the stalk functor  $x^* : X \rightarrow \mathcal{S}$  can be computed as the filtered colimit

$$x^* \simeq \text{colim}_{(U,u) \in \text{Nbd}(x)^{op}} \text{Map}_X(U, -) .$$

The assignment  $(U, u) \mapsto X_{/U}$  defines a functor  $E_x : \text{Nbd}(x) \rightarrow \mathbf{Top}_{\infty, /X}$ . Moreover, the natural forgetful functor  $\mathbf{Top}_{\infty, /E_x} \rightarrow \mathbf{Top}_{\infty, /X}$  is a right fibration. We write  $\lim_{(U,u) \in \text{Nbd}(x)} X_{/U}$  for the limit in  $\mathbf{Top}_{\infty, /X}$  (equivalently, in  $\mathbf{Top}_{\infty}$ ) of the diagram  $E_x$ .

By [Recollection 5.1.6](#)=[HTT, Corollary 6.3.5.6], specifying a geometric morphism

$$X' \rightarrow \lim_{(U,u) \in \text{Nbd}(x)} X_{/U}$$

is equivalent to specifying a geometric morphism  $p_* : X' \rightarrow X$  along with a global section

$$\sigma \in \Gamma_{X', *}\left(\lim_{(U,u) \in \text{Nbd}(x)} p^* U\right) \simeq \lim_{(U,u) \in \text{Nbd}(x)} \Gamma_{X', *} p^* U .$$

Since  $X_{(x)}$  is the localisation of  $X$  at  $x_*$ , we have a natural equivalence  $x^* \simeq \Gamma_{X_{(x)}, *} \ell_x^*$  ([7.3.8](#)), whence for  $U \in X$ , we obtain a natural equivalence

$$\lim_{(U,u) \in \text{Nbd}(x)} x^*(U) \simeq \Gamma_{X_{(x)}, *}\left(\lim_{(U,u) \in \text{Nbd}(x)} \ell_x^*(U)\right) .$$

The global sections  $u \in x^*(U)$  for  $(U, u) \in \text{Nbd}(x)$  together define a global section  $s \in \lim_{(U,u) \in \text{Nbd}(x)} x^*(U)$ . This furnishes us with a geometric morphism

$$g_* : X_{(x)} \rightarrow \lim_{(U,u) \in \text{Nbd}(x)} X_{/U}$$

over  $X$ .

**7.5.3 Proposition.** *Let  $X$  be an  $\infty$ -topos and  $x_*$  a point of  $X$ . Then the geometric morphism  $g_* : X_{(x)} \rightarrow \lim_{(U,u) \in \text{Nbd}(x)} X_{/U}$  of [Construction 7.5.2](#) is an equivalence.*

*Proof.* We wish to show that  $g_* : X_{(x)} \rightarrow \lim_{(U,u) \in \text{Nbd}(x)} X_{/U}$  induces an equivalence

$$\mathbf{Top}_{\infty, /X_{(x)}} \xrightarrow{\simeq} \mathbf{Top}_{\infty, /E_x} .$$

Since both projections onto  $\mathbf{Top}_{\infty, /X}$  are right fibrations, we are reduced to showing that for every object  $p_* : X' \rightarrow X$  of  $\mathbf{Top}_{\infty, /X}$  the induced map on fibres of these right fibrations is an equivalence. By [Recollection 5.1.6](#)=[HTT, Corollary 6.3.5.6] the fibre of the right fibration  $\mathbf{Top}_{\infty, /E_x} \rightarrow \mathbf{Top}_{\infty, /X}$  over  $p_* : X' \rightarrow X$  is given by

$$\{p_*\} \times_{\mathbf{Top}_{\infty, /X}} \mathbf{Top}_{\infty, /E_x} \simeq \lim_{(U,u) \in \text{Nbd}(x)} \Gamma_{X', *} p^*(U) ,$$

On the other hand,

$$\{p_*\} \times_{\mathbf{Top}_{\infty, /X}} \mathbf{Top}_{\infty, /X_{(x)}} \simeq \text{Map}_{\text{Fun}_*(X', X)}(p_*, x_* \Gamma_{X', *}) \simeq \text{Map}_{\text{Fun}(X, \mathcal{S})}(x^*, \Gamma_{X', *} p^*) .$$

By the colimit formula for the stalk ([Construction 7.5.2](#)), we have natural equivalences

$$\begin{aligned} \mathrm{Map}_{\mathrm{Fun}(X, S)}(x^*, \Gamma_* p^*) &\simeq \mathrm{Map}_{\mathrm{Fun}(X, S)}\left(\mathrm{colim}_{(U, u) \in \mathrm{Nbd}(x)^{op}} \mathrm{Map}_X(U, -), \Gamma_{X', * p^*}\right) \\ &\simeq \lim_{(U, u) \in \mathrm{Nbd}(x)} \Gamma_{X', * p^*}(U). \end{aligned}$$

Unwinding definitions, we see that the induced map on fibres

$$\{p_*\} \times_{\mathrm{Top}_{\infty/X}} \mathrm{Top}_{\infty/X(x)} \rightarrow \{p_*\} \times_{\mathrm{Top}_{\infty/X}} \mathrm{Top}_{\infty/E_x}$$

is an equivalence.  $\square$

## 7.6 Coherence of localisations

In this subsection we use the Grothendieck–Verdier description of the localisation to deduce that  $X_{(x)}$  is bounded coherent when  $X$  is. Please note that this is not automatic from [Lemma 6.7.6](#), as points of bounded coherent  $\infty$ -topoi need not be coherent in general.

**7.6.1.** Let  $f : U \rightarrow V$  be a morphism between coherent objects of an  $\infty$ -topos  $X$ . Then the geometric morphism  $f_* : X_U \rightarrow X_V$  is coherent.

**7.6.2 Lemma.** *Let  $X$  be a bounded  $\infty$ -topos and  $U \in X_{<\infty}$  a truncated object of  $X$ . Then the over  $\infty$ -topos  $X_U$  is bounded.*

*Proof.* Indeed, if  $U$  is  $n$ -truncated, and if  $X$  is  $N$ -localic for some  $N \geq n$ , then  $X_U$  is  $N$ -localic as well. The desired result now follows by exhibiting  $X$  as an inverse limit of localic  $\infty$ -topoi.  $\square$

**7.6.3.** Let  $X$  be a bounded coherent  $\infty$ -topos and  $x_*$  a point of  $X$ . Then the full subcategory  $\mathrm{Nbd}_{<\infty}^{coh}(x) \subset \mathrm{Nbd}(x)$  consisting of those neighbourhoods  $(U, u)$  such that  $U$  is a truncated coherent object of  $X$  is limit-cofinal in  $\mathrm{Nbd}(x)$ . Thus [Proposition 7.5.3](#), [\(7.6.1\)](#), and [Lemma 7.6.2](#) together show that

$$X_{(x)} \simeq \lim_{(U, u) \in \mathrm{Nbd}_{<\infty}^{coh}(x)} X_U$$

is an inverse limit in  $\mathrm{Top}_{\infty}$  of bounded coherent  $\infty$ -topoi and coherent geometric morphisms.

From [Corollary 5.9.3](#)=[[SAG](#), Corollary A.8.3.3] we deduce the following.

**7.6.4 Lemma.** *Let  $X$  be a bounded coherent  $\infty$ -topos and  $x_*$  a point of  $X$ . Then the localisation  $X_{(x)}$  is bounded coherent and the geometric morphism  $\ell_{x,*} : X_{(x)} \rightarrow X$  is coherent.*



## 7.7 Geometric examples of localisations

**7.7.1 Example** ([47, Example 1.2(a)]). Let  $X$  be a topological space and  $s \in X$  a *special point* in the sense that the only open set of  $X$  containing  $s$  is  $X$  itself. Then it is immediate that the functor  $\tilde{X} \rightarrow \mathbf{S}$  given by taking the stalk at  $s$  is equivalent to the global sections functor, so the  $\infty$ -topos  $\tilde{X}$  is local with centre  $x_* : \mathbf{S} \rightarrow \tilde{X}$ .

**7.7.2 Subexample** ([SGA 4<sub>II</sub>, Exposé VI, 8.4.6]). In particular, when  $X = \mathrm{Spec}(A)^{\mathrm{zar}}$  is the Zariski space of the spectrum of a local ring  $A$ , and  $s = \mathfrak{m}$  is the maximal ideal, we deduce that the Zariski  $\infty$ -topos of  $A$  is local. Moreover, if  $\phi : A \rightarrow A'$  is a local homomorphism of local rings, then the induced geometric morphism of Zariski  $\infty$ -topoi  $\mathrm{Spec}(A')^{\mathrm{zar}} \rightarrow \mathrm{Spec}(A)^{\mathrm{zar}}$  is a local geometric morphism.

**7.7.3 Example** ([SGA 4<sub>II</sub>, Exposé VI, 8.4.4]). Let  $X$  be a scheme and  $x \in X$ . Then the localisation of the Zariski  $\infty$ -topos of  $X$  at the point  $x$  is the Zariski  $\infty$ -topos of  $\mathcal{O}_{X,x}$ .

**7.7.4 Example.** Let  $X$  be a scheme, and let  $x \rightarrow X$  be a point with image  $x_0 \in X^{\mathrm{zar}}$ . Suppose  $x$  is a *geometric point* in the sense that  $\kappa(x)$  is a separable closure of  $\kappa(x_0)$ . Then the localisation of the étale  $\infty$ -topos of  $X$  at  $x$  is the étale  $\infty$ -topos of the *strict localisation*  $X_{(x)} := \mathrm{Spec} \mathcal{O}_{X,x_0}^{\mathrm{sh}}$ , viz.,

$$(X_{\mathrm{\acute{e}t}})_{(x)} \simeq (X_{(x)})_{\mathrm{\acute{e}t}}.$$

More generally, for any point  $x \rightarrow X$ , the evanescent  $\infty$ -topos  $x_{\mathrm{\acute{e}t}} \tilde{\times}_{X_{\mathrm{\acute{e}t}}} X_{\mathrm{\acute{e}t}}$  can be identified with the étale  $\infty$ -topos of  $X_{(x)} := \mathrm{Spec} A$ , where  $A \supseteq \mathcal{O}_{X,x}^h$  is the unramified extension of the henselisation whose residue field is the separable closure of  $\kappa(x_0)$  in  $\kappa(x)$ .

## 8 Beck–Chevalley conditions & gluing squares

The goal of this section is to prove a basechange result for oriented fibre products of bounded coherent  $\infty$ -topoi ([Theorem 8.1.4](#)). Our result provides a nonabelian refinement of a basechange result of Ofer Gabber [42, Exposé XI, Théorème 2.4] as well as one of Moerdijk and Jacob Vermeulen [58, Theorem 2(i)]. This basechange result is essential to our *décollage* approach to *stratified higher topoi* in §9.

### 8.1 The Beck–Chevalley transformation & Beck–Chevalley conditions

We begin by recalling the *Beck–Chevalley natural transformation* associated to an oriented square of  $\infty$ -topoi.

**8.1.1 Definition.** Consider an oriented square of  $\infty$ -topoi and geometric morphisms:

$$(8.1.2) \quad \begin{array}{ccc} W & \xrightarrow{q_*} & Y \\ p_* \downarrow & \swarrow \tau & \downarrow g_* \\ X & \xrightarrow{f_*} & Z \end{array}$$

and the corresponding geometric morphism  $\psi(p, q, \tau)_* : W \rightarrow X \tilde{\times}_Z Y$  of [Definition 6.5.1](#). Write  $\eta_q : \text{id}_Y \rightarrow q_* q^*$  for the unit and  $\varepsilon_f : f^* f_* \rightarrow \text{id}_X$  for the counit. The *Beck–Chevalley transformation* is the composition

$$\beta_\tau : f^* g_* \xrightarrow{f^* g_* \eta_q} f^* g_* q_* q^* \xrightarrow{f^* \tau q^*} f^* f_* p_* q^* \xrightarrow{\varepsilon_f p_* q^*} p_* q^* .$$

We say that the square [\(8.1.2\)](#) – or equivalently the geometric morphism  $\psi(p, q, \tau)_*$  – satisfies the:

- *Beck–Chevalley condition* if the natural transformation  $\beta_\tau$  is an equivalence.
- *bounded Beck–Chevalley condition* if for every truncated object  $F \in Y_{<\infty}$ , the morphism  $\beta_\tau(F) : f^* g_*(F) \rightarrow \text{pr}_{1,*} \text{pr}_2^*(F)$  is an equivalence in  $X$ .

**8.1.3.** Please observe that given oriented squares of  $\infty$ -topoi

$$\begin{array}{ccccc} X & \longrightarrow & Y & \longrightarrow & Z \\ \downarrow & \swarrow \sigma & \downarrow & \swarrow \tau & \downarrow \\ X' & \longrightarrow & Y' & \longrightarrow & Z' , \end{array}$$

the Beck–Chevalley morphism of the outer oriented rectangle is equivalent to natural transformation given by the composite of the Beck–Chevalley morphisms

$$\begin{array}{ccccc} X & \longleftarrow & Y & \longleftarrow & Z \\ \downarrow & \swarrow \beta_\sigma & \downarrow & \swarrow \beta_\tau & \downarrow \\ X' & \longleftarrow & Y' & \longleftarrow & Z' . \end{array}$$

We now are now prepared to state our basechange result.

**8.1.4 Theorem.** *Let  $f_* : X \rightarrow Z$  and  $g_* : Y \rightarrow Z$  be coherent geometric morphisms between bounded coherent  $\infty$ -topoi. Then the oriented fibre product square*

$$(8.1.5) \quad \begin{array}{ccc} X \tilde{\times}_Z Y & \xrightarrow{\text{pr}_{2,*}} & Y \\ \text{pr}_{1,*} \downarrow & \swarrow \tau & \downarrow g_* \\ X & \xrightarrow{f_*} & Z \end{array}$$

*satisfies the bounded Beck–Chevalley condition.*

By passing to 1-localic  $\infty$ -topoi in [Theorem 8.1.4](#), we deduce Moerdijk and Vermeulen’s 1-toposic Beck–Chevalley condition [[58](#), Theorem 2(i)].

**8.1.6 Corollary.** *Let  $f_* : X \rightarrow Z$  and  $g_* : Y \rightarrow Z$  be coherent geometric morphisms between coherent 1-topoi. Then the oriented fibre product square of 1-topoi*

$$\begin{array}{ccc} X \tilde{\times}_Z Y & \xrightarrow{\text{pr}_{2,*}} & Y \\ \text{pr}_{1,*} \downarrow & \swarrow \tau & \downarrow g_* \\ X & \xrightarrow{f_*} & Z \end{array}$$

*satisfies the Beck–Chevalley condition – i.e., the Beck–Chevalley natural transformation  $f^* g_* \rightarrow \text{pr}_{1,*} \text{pr}_2^*$  is an isomorphism.*

*Proof.* Write  $X', Y'$ , and  $Z'$  for the 1-localic  $\infty$ -topoi associated to  $X, Y$ , and  $Z$ , respectively. Combining the equivalence between coherent 1-localic  $\infty$ -topoi and coherent 1-topoi (Proposition 5.6.11) with Theorem 8.1.4 shows that the oriented fibre product square of  $\infty$ -topoi

$$\begin{array}{ccc} X' \tilde{\times}_{Z'} Y' & \longrightarrow & Y' \\ \downarrow & \swarrow & \downarrow \\ X' & \longrightarrow & Z' \end{array}$$

satisfies the bounded Beck–Chevalley condition. We conclude by restricting to 0-truncated objects and applying Lemma 6.5.13.  $\square$

In the setting of derived categories, we also immediately deduce Gabber’s result [42, Exposé XI, Théorème 2.4].

The proof of Theorem 8.1.4 requires a number of preliminaries that will occupy the next few subsections. Our proof is essentially a reinterpretation of the proof of Gabber’s result that Luc Illusie presents in [42, Exposé XI, Théorème 2.4].

## 8.2 Examples of the Beck–Chevalley condition

In this subsection we provide a few examples of (oriented) squares that are easily seen to satisfy the Beck–Chevalley condition. None of these examples are used in the sequel. The first two examples are due to an observation of Gabber [42, Exposé XI, Remarque 4.9].

**8.2.1 Example.** Let  $f_* : X \rightarrow Z$  be a geometric morphism of  $\infty$ -topoi. Then from the equivalence  $\Psi_f^* \simeq \text{pr}_{1,*} : X \tilde{\times}_Z Z \rightarrow X$  and the fact that  $\text{pr}_{2,*} \Psi_{f,*} \simeq f_*$  (Proposition 7.3.1), we have equivalences

$$\text{pr}_{1,*} \text{pr}_2^* \simeq \Psi_f^* \text{pr}_2^* \simeq f^* .$$

From this we deduce the Beck–Chevalley condition for the evanescent  $\infty$ -topos square

$$\begin{array}{ccc} X \tilde{\times}_Z Z & \xrightarrow{\text{pr}_{2,*}} & Z \\ \text{pr}_{1,*} \downarrow & \swarrow & \parallel \\ X & \xrightarrow{f_*} & Z . \end{array}$$

**8.2.2 Example.** Dually, let  $g_* : Y \rightarrow Z$  be a geometric morphism of  $\infty$ -topoi. From [Proposition 7.3.4](#) we see that the defining oriented square of the coëvanescent  $\infty$ -topos  $Z \tilde{\times}_Z Y$  satisfies the Beck–Chevalley condition.

As noted by Johnstone–Moerdijk [47, Remark 2.5], pullbacks along local geometric morphisms also satisfy the Beck–Chevalley condition.

**8.2.3 Example.** Consider a pullback square of  $\infty$ -topoi

$$(8.2.4) \quad \begin{array}{ccc} X \times_Z Y & \xrightarrow{\bar{f}_*} & Y \\ \bar{g}_* \downarrow \lrcorner & & \downarrow g_* \\ X & \xrightarrow{f_*} & Z, \end{array}$$

where  $g_*$  exhibits  $Y$  as local over  $Z$  with centre  $g^!$ . Then by (7.2.10) the geometric morphism  $\bar{g}_*$  exhibits  $X \times_Z Y$  as local over  $X$  and the center  $\bar{g}^!$  of  $\bar{g}_*$  satisfies  $\bar{f}_* \bar{g}^! \simeq g^! f_*$ . We have adjunctions

$$f^* g_* \dashv g^! f_* \quad \text{and} \quad \bar{g}_* \bar{f}^* \dashv \bar{f}_* \bar{g}^!,$$

so the equivalence  $\bar{f}_* \bar{g}^! \simeq g^! f_*$  shows that  $f^* g_* \simeq \bar{g}_* \bar{f}^*$ , from which we deduce the Beck–Chevalley condition for the square (8.2.4).

**8.2.5 Example.** Let  $f_* : X \rightarrow Z$  and  $g_* : Y \rightarrow Z$  be geometric morphisms of  $\infty$ -topoi. And decompose the oriented fibre product  $X \tilde{\times}_Z Y$  as an iterated pullback

$$(8.2.6) \quad \begin{array}{ccccc} X \tilde{\times}_Z Y & \longrightarrow & Z \tilde{\times}_Z Y & \longrightarrow & Y \\ \downarrow \lrcorner & & \downarrow \lrcorner & & \downarrow g_* \\ X \tilde{\times}_Z Z & \longrightarrow & \text{Path}(Z) & \longrightarrow & Z \\ \downarrow \lrcorner & & \downarrow & \swarrow \parallel & \parallel \\ X & \xrightarrow{f_*} & Z & \xlongequal{\quad} & Z. \end{array}$$

It follows from [Example 8.2.3](#) that local geometric morphisms are *proper* [HTT, Definition 7.3.1.4]. Assume that  $g_*$  is a proper geometric morphism. Then by applying [Example 8.2.1](#) to the lower right square of (8.2.6), [Examples 7.3.6](#) and [8.2.3](#) to the lower left square of (8.2.6), and the properness of  $g_*$  to the top squares of (8.2.6), we deduce that the three pullback squares in (8.2.6) and the oriented square all satisfy the Beck–Chevalley condition, and that  $\text{pr}_{1,*} : X \tilde{\times}_Z Y \rightarrow X$  is a proper geometric morphism.

### 8.3 Localisations & the bounded Beck–Chevalley condition

In this subsection we prove the following *bounded* Beck–Chevalley condition for localisations of bounded coherent  $\infty$ -topoi.

**8.3.1 Proposition.** Let  $p_* : W \rightarrow X$  be a coherent geometric morphism between bounded coherent  $\infty$ -topoi. Then for any point  $x_*$  of  $X$ , the pullback square

$$\begin{array}{ccc} S \tilde{\times}_X W & \longrightarrow & W \\ \downarrow & \lrcorner & \downarrow p_* \\ X_{(x)} & \xrightarrow{\ell_{x,*}} & X \end{array}$$

satisfies the bounded Beck–Chevalley condition.

To do so, we use the Grothendieck–Verdier description of the localisation ([Proposition 7.5.3](#)) and the (obvious) fact that pullbacks along étale geometric morphisms satisfy Beck–Chevalley condition to reduce the problem to a general result on inverse limits ([Proposition 8.3.5](#)).

**8.3.2 Lemma.** Let  $f_* : E \rightarrow X$  and  $p_* : W \rightarrow X$  be geometric morphisms of  $\infty$ -topoi. If  $f_*$  is étale, then the pullback square

$$\begin{array}{ccc} E \times_X W & \longrightarrow & W \\ \downarrow & \lrcorner & \downarrow p_* \\ E & \xrightarrow{f_*} & X \end{array}$$

satisfies the Beck–Chevalley condition.

We fix some useful notation for the next few results.

**8.3.3 Notation.** Let  $W, X : I \rightarrow \mathbf{Top}_\infty$  be diagrams of  $\infty$ -topoi. For each morphism  $\alpha : j \rightarrow i$  in  $I$ , we write

$$e_{\alpha,*} : W_j \rightarrow W_i \quad \text{and} \quad f_{\alpha,*} : X_j \rightarrow X_i$$

for the transition morphisms. For each  $i \in I$ , we write

$$\xi_{i,*} : \lim_{i \in I} W_i \rightarrow W_i \quad \text{and} \quad \pi_{i,*} : \lim_{i \in I} X_i \rightarrow X_i$$

for the projections. In addition, we assume that for each  $\alpha : j \rightarrow i$  in  $I$  and integer  $n \geq -2$ , the functors

$$e_{\alpha,*} : W_{j,\leq n} \rightarrow W_i \quad \text{and} \quad f_{\alpha,*} : X_{j,\leq n} \rightarrow X_i$$

preserve filtered colimits.

**8.3.4.** Most importantly, the assumptions of [Notation 8.3.3](#) are valid for inverse systems of bounded coherent  $\infty$ -topoi and coherent geometric morphisms [Corollary 5.10.4](#).

**8.3.5 Proposition.** Keep the assumptions of [Notation 8.3.3](#). Let  $p : W \rightarrow X$  a natural transformation, each of whose components  $p_{i,*} : W_i \rightarrow X_i$  has the property that the functor

$p_{i,*} : W_{i \leq n} \rightarrow X_i$  preserves filtered colimits for each integer  $n \geq -2$ . If for each morphism  $\alpha : j \rightarrow i$  in  $I$  the square

$$(8.3.6) \quad \begin{array}{ccc} W_j & \xrightarrow{e_{\alpha,*}} & W_i \\ p_{j,*} \downarrow & & \downarrow p_{i,*} \\ X_j & \xrightarrow{f_{\alpha,*}} & X_i \end{array}$$

satisfies the bounded Beck–Chevalley condition, then for each  $i \in I$  the induced square

$$\begin{array}{ccc} \lim_{i \in I} W_i & \xrightarrow{\xi_{i,*}} & W_i \\ \lim_{i \in I} p_{i,*} \downarrow & & \downarrow p_{i,*} \\ \lim_{i \in I} X_i & \xrightarrow{\pi_{i,*}} & X_i \end{array}$$

satisfies the bounded Beck–Chevalley condition.

*Proof.* For each  $i \in I$ , the forgetful functor  $I_{/i} \rightarrow I$  is limit-cofinal [HTT, Example 5.4.5.9 & Lemma 5.4.5.12], so we may without loss of generality assume that  $I$  admits a terminal object 1 and that  $i = 1$ . Writing  $q_* := \lim_{i \in I} p_{i,*}$ , we see that we have reduced to showing that the square

$$(8.3.7) \quad \begin{array}{ccc} \lim_{i \in I} W_i & \xrightarrow{\xi_{1,*}} & W_1 \\ q_* \downarrow & & \downarrow p_{1,*} \\ \lim_{i \in I} X_i & \xrightarrow{\pi_{1,*}} & X_1 \end{array}$$

satisfies the bounded Beck–Chevalley condition.

Inverse limits in  $\mathbf{Top}_\infty$  are computed in  $\mathbf{Cat}_{\infty, \delta_1}$  (Theorem 5.1.9=[HTT, Theorem 6.3.3.1]), so an object of the limit of a diagram  $Y : I \rightarrow \mathbf{Top}_\infty$  is specified by a compatible system  $\{U_i\}_{i \in I}$  of objects  $U_i \in Y_i$  along with, for each  $\alpha : j \rightarrow i$  in  $I$ , an equivalence  $\phi_\alpha : g_{\alpha,*}(U_j) \simeq U_i$ , where  $g_{\alpha,*} : Y_j \rightarrow Y_i$  is the transition morphism. Thus for  $U \in W_1$  we have

$$q_* \xi_1^*(U) \simeq \{p_{i,*} \xi_{i,*} \xi_1^*(U)\}_{i \in I},$$

and

$$\pi_1^* p_{1,*}(U) \simeq \{\pi_{i,*} \pi_1^* p_{1,*}(U)\}_{i \in I}.$$

It therefore suffices to show that for each  $i \in I$ , the natural morphism

$$\pi_{i,*} \beta : \pi_{i,*} \pi_1^* p_{1,*} \rightarrow \pi_{i,*} q_* \xi_1^* \simeq p_{i,*} \xi_{i,*} \xi_1^*$$

induced by the Beck–Chevalley morphism  $\beta : \pi_1^* p_{1,*} \rightarrow q_* \xi_1^*$  is an equivalence when restricted to  $W_{1, < \infty}$ .

For  $i \in I$ , we simply write  $f_{i,*} := f_{\alpha,*}$  and  $e_{i,*} := e_{\alpha,*}$  if  $\alpha: i \rightarrow 1$ . Note that for every truncated object  $W \in \mathbf{W}_{1,<\infty}$  we have equivalences

$$\begin{aligned} \pi_{i,*} \pi_1^* p_{1,*}(U) &\simeq \pi_{i,*} \pi_i^* f_i^* p_{1,*}(U) \\ &\simeq \operatorname{colim}_{\alpha \in (I_i)^{op}} f_{\alpha,*} f_{\alpha}^* f_i^* p_{1,*}(U) && \text{(Corollary 5.13.13)} \\ &\simeq \operatorname{colim}_{[\alpha: j \rightarrow i] \in (I_i)^{op}} f_{\alpha,*} p_{j,*} e_{\alpha}^* f_i^*(U) \\ &\simeq \operatorname{colim}_{\alpha \in (I_i)^{op}} p_{i,*} e_{\alpha,*} e_{\alpha}^* e_i^*(U) \end{aligned}$$

in which the third equivalence is by assumption. In addition, Corollary 5.13.13 and the fact that  $\xi_i^* f_i^* \simeq \xi_1^*$  give equivalences

$$p_{i,*} \left( \operatorname{colim}_{\alpha \in (I_i)^{op}} e_{\alpha,*} e_{\alpha}^* e_i^*(U) \right) \simeq p_{i,*} \xi_{i,*} \xi_i^* f_i^* \simeq p_{i,*} \xi_{i,*} \xi_1^*(U).$$

for every truncated object  $U \in \mathbf{W}_{1,<\infty}$ . By assumption  $p_{i,*}$  preserves filtered colimits of uniformly truncated objects. As left exact functors preserve  $n$ -truncatedness for all  $n \geq -2$ , we see that for every truncated object  $U$  of  $\mathbf{W}_1$ , the natural morphism

$$\operatorname{colim}_{\alpha \in (I_i)^{op}} p_{i,*} e_{\alpha,*} e_{\alpha}^* e_i^*(U) \rightarrow p_{i,*} \left( \operatorname{colim}_{\alpha \in (I_i)^{op}} e_{\alpha,*} e_{\alpha}^* e_i^*(U) \right)$$

is an equivalence, which provides an equivalence

$$(8.3.8) \quad \pi_{i,*} \pi_1^* p_{1,*}(U) \simeq p_{i,*} \xi_{i,*} \xi_1^*(U).$$

To conclude, note that the equivalence (8.3.8) is homotopic to  $\pi_{1,*} \beta(U)$ .  $\square$

*Proof of Proposition 8.3.1.* Combine Lemma 8.3.2 and Proposition 8.3.5, the hypotheses of which are valid by (7.6.3) and Corollary 5.10.4 (cf. Corollary 5.9.3=[SAG, Corollary A.8.3.3]).  $\square$

## 8.4 Functoriality of oriented fibre products in oriented diagrams

In this subsection we discuss the functoriality of the oriented fibre product in oriented diagrams of cospans, and we use this additional functoriality to construct some unexpected extra adjoints to the second projection from the oriented fibre product (Proposition 8.4.6). In nice cases, this provides a way to check that the Beck–Chevalley morphism becomes an equivalence after passing to stalks (Lemma 8.4.9).

8.4.1. Suppose that we are given a diagram of  $\infty$ -topoi

$$\begin{array}{ccccc} X & \xrightarrow{f_*} & Z & \xleftarrow{g_*} & Y \\ x_* \downarrow & \eta \swarrow & z_* \downarrow & \theta \nwarrow & y_* \downarrow \\ X' & \xrightarrow{f'_*} & Z' & \xleftarrow{g'_*} & Y' \end{array}$$

Then by the universal property of the oriented fibre product  $X' \tilde{\times}_{Z'} Y'$ , the diagram

$$\begin{array}{ccccc}
 X \tilde{\times}_Z Y & \xrightarrow{\text{pr}_{2,*}} & Y & & \\
 \text{pr}_{1,*} \downarrow & \tau \swarrow & \downarrow g_* & \searrow y_* & \\
 X & \xrightarrow{f_*} & Z & & Y' \\
 x_* \searrow & \eta \swarrow & \downarrow z_* & \swarrow g'_* & \\
 X' & \xrightarrow{f'_*} & Z' & & 
 \end{array}$$

(functorially) induces a geometric morphism  $X \tilde{\times}_Z Y \rightarrow X' \tilde{\times}_{Z'} Y'$ . We simply denote the geometric morphism by  $x_* \tilde{\times}_{z_*} y_*$ , leaving the natural transformations  $\eta$  and  $\theta$  implicit. Please note that  $x_* \tilde{\times}_{z_*} y_*$  satisfies the obvious relations

$$\text{pr}_{1,*} \circ (x_* \tilde{\times}_{z_*} y_*) \simeq x_* \text{pr}_{1,*} \quad \text{and} \quad \text{pr}_{2,*} \circ (x_* \tilde{\times}_{z_*} y_*) \simeq y_* \text{pr}_{2,*} .$$

The remainder of this subsection focuses on generalising [42, Exposé XI, Proposition 2.3].

8.4.2. Suppose that we are given a diagram of  $\infty$ -topoi

$$(8.4.3) \quad \begin{array}{ccccc}
 X & \xrightarrow{f_*} & Z & \xleftarrow{g_*} & Y \\
 x_* \downarrow & & \downarrow z_* & & \downarrow y_* \\
 X' & \xrightarrow{f'_*} & Z' & \xleftarrow{g'_*} & Y' ,
 \end{array}$$

and suppose further that  $x_*$ ,  $y_*$ , and  $z_*$  are coessential with centres  $x^!$ ,  $y^!$ , and  $z^!$ , respectively. Then taking the adjoint squares in the diagram (8.4.3) with respect to the adjunctions  $x_* \dashv x^!$ ,  $y_* \dashv y^!$ , and  $z_* \dashv z^!$  [HA, Definition 4.7.4.13], we obtain a pair of oriented squares

$$(8.4.4) \quad \begin{array}{ccccc}
 X' & \xrightarrow{f'_*} & Z' & \xleftarrow{g'_*} & Y' \\
 x^! \downarrow & \swarrow & \downarrow z^! & \nwarrow & \downarrow y^! \\
 X & \xrightarrow{f_*} & Z & \xleftarrow{g_*} & Y .
 \end{array}$$

Note that the natural transformation in the left-hand square of (8.4.4) points in the *wrong* direction to apply (8.4.1).

8.4.5. Keep the notations of (8.4.2), and additionally assume that the natural transformation in the left-hand square of (8.4.4) is an equivalence, so that  $f_* x^! \simeq z^! f'_*$ . Then by the functoriality of the oriented fibre product in oriented diagrams (8.4.1), the diagram (8.4.4) defines a geometric morphism  $x^! \tilde{\times}_{z^!} y^! : X' \tilde{\times}_{Z'} Y' \rightarrow X \tilde{\times}_Z Y$ .



The following is now formal.

**8.4.6 Proposition.** *With the notations and assumptions of (8.4.5), the geometric morphism*

$$x_* \tilde{\times}_{z_*} y_* : X \tilde{\times}_Z Y \rightarrow X' \tilde{\times}_{Z'} Y'$$

*is coëssential with centre  $x^! \tilde{\times}_{z^!} y^! : X' \tilde{\times}_{Z'} Y' \rightarrow X \tilde{\times}_Z Y$ .*

We now explain a particular application of **Proposition 8.4.6** that allows us to deduce that the  $\text{pr}_{2,*} : X \tilde{\times}_Z Y \rightarrow Y$  exhibits  $X \tilde{\times}_Z Y$  as local over  $Y$  in the setting that  $f_*$  is a local geometric morphism of local  $\infty$ -topoi.

**8.4.7.** Let  $f_* : X \rightarrow Z$  be a local geometric morphism of local  $\infty$ -topoi with centres  $x_*$  and  $z_*$ , respectively, and let  $g_* : Y \rightarrow Z$  be a geometric morphism of  $\infty$ -topoi. Then since all of the vertical morphisms in the commutative diagram of  $\infty$ -topoi

$$\begin{array}{ccccc} X & \xrightarrow{f_*} & Z & \xleftarrow{g_*} & Y \\ \Gamma_{X,*} \downarrow & & \downarrow \Gamma_{Z,*} & & \parallel \\ S & \xlongequal{\quad} & S & \xleftarrow{\Gamma_{Y,*}} & Y \end{array}$$

exhibit the top  $\infty$ -topoi as local over the bottom  $\infty$ -topoi, applying the discussion of (8.4.2), the assumption that  $f_*$  is a local geometric morphism shows that we are in the situation of (8.4.5). That is to say  $x_*$ ,  $z_*$ , and  $\text{id}_Y$  induce a geometric morphism

$$x_* \tilde{\times}_{z_*} \text{id}_Y : Y \simeq S \tilde{\times}_S Y \rightarrow X \tilde{\times}_Z Y .$$

The following is our generalisation of [42, Exposé XI, Proposition 2.3]. Note that this generalisation is not just  $\infty$ -toposic: in our version we don't need to take stalks.

**8.4.8 Lemma.** *With the notations of (8.4.7), the second projection  $\text{pr}_{2,*} : X \tilde{\times}_Z Y \rightarrow Y$  exhibits  $X \tilde{\times}_Z Y$  as local over  $Y$  with centre*

$$x_* \tilde{\times}_{z_*} \text{id}_Y : Y \simeq S \tilde{\times}_S Y \rightarrow X \tilde{\times}_Z Y .$$

*Proof.* The fact that  $\text{pr}_{2,*}$  is coëssential with centre  $x_* \tilde{\times}_{z_*} \text{id}_Y$  is immediate from **Proposition 8.4.6**, and the full faithfulness of  $x_* \tilde{\times}_{z_*} \text{id}_Y$  follows from the equivalence

$$\text{pr}_{2,*} \circ (x_* \tilde{\times}_{z_*} \text{id}_Y) \simeq \text{id}_Y . \quad \square$$

In the setting of **Lemma 8.4.8**, we deduce that the Beck–Chevalley morphism becomes an equivalence after taking its stalk at the centre of  $X$ .

**8.4.9 Lemma.** *Consider an oriented square of  $\infty$ -topoi*

$$\begin{array}{ccc} W & \xrightarrow{q_*} & Y \\ P_* \downarrow & \swarrow \tau & \downarrow g_* \\ X & \xrightarrow{f_*} & Z , \end{array}$$

where  $q_*$  is a quasi-equivalence,  $X$  and  $Z$  are local with centres  $x_*$  and  $z_*$ , respectively, and  $f_*$  is a local geometric morphism. Then the natural transformation

$$x^* \beta_\tau : x^* f^* g_* \rightarrow x^* p_* q^*$$

is an equivalence.

*Proof.* We prove the stronger claim that  $x^* f^* g_* \simeq x^* p_* q^*$  and the space of natural transformations  $x^* f^* g_* \rightarrow x^* p_* q^*$  is contractible. Since  $Z$  is local we have equivalences

$$x^* f^* g_* \simeq z^* g_* \simeq \Gamma_{Z,*} g_* \simeq \Gamma_{Y,*} .$$

Since  $X$  is local and  $q_*$  is a quasi-equivalence, applying [Lemma 7.1.3](#) we have equivalences

$$x^* p_* q^* \simeq \Gamma_{X,*} p_* q^* \simeq \Gamma_{W,*} q^* \simeq \Gamma_{Y,*} .$$

Thus both  $x^* f^* g_*$  and  $x^* p_* q^*$  are equivalent to the global sections functor on  $Y$ . We are now done since  $\Gamma_{Y,*}$  is corepresented by the terminal object of  $Y$ .  $\square$

## 8.5 Proof of the Beck–Chevalley condition for oriented fibre products

This subsection is devoted to the proof of [Theorem 8.1.4](#).

*Proof of Theorem 8.1.4.* Write  $\beta : f^* g_* \rightarrow \text{pr}_{1,*} \text{pr}_2^*$  for the Beck–Chevalley natural transformation of the oriented fibre product square [\(8.1.5\)](#). Notice that since  $X$  is bounded coherent, left exact functors preserve truncated objects, and morphisms between truncated objects are truncated, [\(5.11.13\)](#) shows that to prove the claim it suffices to show that for every point  $x_* \in \text{Pt}(X)$  and truncated object  $F \in Y_{<\infty}$ , the morphism

$$x^* \beta(F) : x^* f^* g_*(F) \rightarrow x^* \text{pr}_{1,*} \text{pr}_2^*(F)$$

is an equivalence in  $\mathbf{S}$ .

Fix a point  $x_* \in \text{Pt}(X)$ , define  $z_* := f_* x_*$ , and let  $\bar{f}_* : X_{(x)} \rightarrow Z_{(z)}$  be the induced geometric morphism on localisations. To simplify notation we write  $W := X \tilde{\times}_Z Y$ ,  $W_{(x)} := X_{(x)} \times_X W$ , and  $Y_{(z)} := Z_{(z)} \times_Z Y$ . Consider the cube

$$(8.5.1) \quad \begin{array}{ccccc} & & W & \xrightarrow{\text{pr}_{2,*}} & Y \\ & \nearrow \bar{\ell}_{x,*} & \downarrow & & \nearrow \bar{\ell}_{z,*} \\ W_{(x)} & \xrightarrow{q_*} & Y_{(z)} & & \downarrow g_* \\ & \downarrow \text{pr}_{1,*} & \downarrow \bar{g}_* & & \\ & X & \xrightarrow{f_*} & Z & \\ & \nearrow \ell_{x,*} & & \nearrow \ell_{z,*} & \\ X_{(x)} & \xrightarrow{\bar{f}_*} & Z_{(z)} & & \end{array} ,$$

formed by pulling back the back face along the bottom face. In the cube (8.5.1), the front face is an oriented square, the back face is an oriented fibre product square, all other faces are commutative, and the side faces are pullback squares. Moreover, the cube satisfies the following property:

- (\*) The natural transformation between the right adjoints given by the composite of the back and left faces of (8.5.1) is equivalent to the natural transformation given by the composite of the front and right faces of (8.5.1).

We claim that the front face of (8.5.1) is an oriented fibre product square. To see this, note that by Proposition 7.5.3, the compatibility of the oriented fibre product with  $\lim$ -its (6.5.3), the compatibility of oriented fibre products with étale geometric morphisms (Proposition 6.8.5), and Corollary 6.8.6, we have equivalences

$$\begin{aligned}
X_{(x)} \tilde{\times}_{Z_{(z)}} Y_{(z)} &\simeq \left( \lim_{U \in \text{Nbd}(x)} X/U \right) \tilde{\times}_{\lim_{V \in \text{Nbd}(z)} Z/V} \left( \lim_{V \in \text{Nbd}(z)} Y/g^*(V) \right) \\
&\simeq \lim_{U \in \text{Nbd}(x)} \lim_{V \in \text{Nbd}(z)} (X/U \tilde{\times}_{Z/V} Y/g^*(V)) \\
&\simeq \lim_{U \in \text{Nbd}(x)} \lim_{V \in \text{Nbd}(z)} (X \tilde{\times}_Z Y)_{/U \tilde{\times}_V g^*(V)} \\
&\simeq \lim_{U \in \text{Nbd}(x)} \lim_{V \in \text{Nbd}(z)} (X \tilde{\times}_Z Y)_{/\text{pr}_1^*(U)} \\
&\simeq X_{(x)} \times_X W = W_{(x)} .
\end{aligned}$$

Applying Lemma 8.4.8 to the front face of (8.5.1), we deduce that  $q_* : W_{(x)} \rightarrow Y_{(z)}$  exhibits  $W_{(x)}$  as local over  $Y_{(z)}$ .

Now we define natural transformations

$$\alpha^R : x^* f^* g_* \rightarrow \Gamma_{X_{(x)},*} \bar{f}^* \bar{g}_* \bar{\ell}_z^* \quad \text{and} \quad \alpha^L : x^* \text{pr}_{1,*} \text{pr}_2^* \rightarrow \Gamma_{X_{(x)},*} p_* q^* \bar{\ell}_z^* ,$$

which are both equivalences when restricted to  $Y_{<\infty}$ , as follows. Write  $\beta^R$  for the Beck–Chevalley morphism of the right-hand face of (8.5.1) and  $\beta^L$  for the Beck–Chevalley morphism of the left-hand face. Since the bottom face of (8.5.1) commutes, under identification of left adjoints,  $\beta^R$  defines a natural transformation

$$\bar{f}^* \beta^R : \ell_x^* f^* g_* \simeq \bar{f}^* \ell_z^* g_* \rightarrow \bar{f}^* \bar{g}_* \bar{\ell}_z^* .$$

Let  $\alpha^R$  be the composite

$$\alpha^R : x^* f^* g_* \xrightarrow{\sim} \Gamma_{X_{(x)},*} \bar{f}^* \ell_z^* g_* \xrightarrow{\Gamma_{X_{(x)},*} \bar{f}^* \beta^R} \Gamma_{X_{(x)},*} \bar{f}^* \bar{g}_* \bar{\ell}_z^* ,$$

where the left-hand equivalence is by Lemma 7.2.9 and the fact that  $z^* = x^* f^*$ . By Proposition 8.3.1,  $\beta^R$  is an equivalence when restricted to  $Y_{<\infty}$ ; therefore  $\alpha^R$  is also an equivalence when restricted to  $Y_{<\infty}$ . Similarly, since the top face of (8.5.1) commutes, under identification of left adjoints,  $\beta^L$  defines a natural transformation

$$\beta^L \text{pr}_2^* : \ell_x^* \text{pr}_{1,*} \text{pr}_2^* \rightarrow p_* \bar{\ell}_x^* \text{pr}_2^* \simeq p_* q^* \bar{\ell}_z^* .$$

Let  $\alpha^L$  be the composite

$$\alpha^L : x^* \text{pr}_{1,*} \text{pr}_2^* \xrightarrow{\sim} \Gamma_{X(x),*} \ell_x^* \text{pr}_{1,*} \text{pr}_2^* \xrightarrow{\Gamma_{X(x),*} \beta^L \text{pr}_2^*} \Gamma_{X(x),*} p_* q^* \bar{\ell}_z^*,$$

where the left-hand equivalence is ensured by [Lemma 7.2.9](#). By [Proposition 8.3.1](#), the natural transformation  $\beta^L$  is an equivalence when restricted to  $W_{<\infty}$ , so since  $\text{pr}_2^*$  is left exact we see that  $\alpha^L$  is an equivalence when restricted to  $Y_{<\infty}$ .

Write  $\bar{\beta} : \bar{f}^* \bar{g}_* \rightarrow p_* q^*$  for the Beck–Chevalley morphism for the front face of the cube [\(8.5.1\)](#). Since  $q_* : W_{(x)} \rightarrow Y_{(z)}$  exhibits  $W_{(x)}$  as local over  $Y_{(z)}$ , [Lemma 8.4.9](#) shows that the natural transformation

$$\Gamma_{X(x),*} \bar{\beta} : \Gamma_{X(x),*} \bar{f}^* \bar{g}_* \rightarrow \Gamma_{X(x),*} p_* q^*$$

is an equivalence. Since  $\alpha^R$  and  $\alpha^L$  are equivalences when restricted to  $Y_{<\infty}$ , to complete the proof it suffices to show that the square

$$\begin{array}{ccc} x^* f^* g_* & \xrightarrow{\alpha^R} & \Gamma_{X(x),*} \bar{f}^* \bar{g}_* \bar{\ell}_z^* \\ x^* \beta \downarrow & & \downarrow \Gamma_{X(x),*} \bar{\beta} \bar{\ell}_z^* \\ x^* \text{pr}_{1,*} \text{pr}_2^* & \xrightarrow{\alpha^L} & \Gamma_{X(x),*} p_* q^* \bar{\ell}_z^* \end{array}$$

commutes. This is immediate from the property  $(*)$  combined with [\(8.1.3\)](#).  $\square$

## 8.6 Applications of Beck–Chevalley

**8.6.1 Example.** Let  $f_* : X \rightarrow Z$  and  $g_* : Y \rightarrow Z$  be geometric morphisms of  $\infty$ -topoi, and assume that  $X$  and  $Y$  are bounded coherent and  $Z$  is Stone. Then by [Corollary 5.14.14](#)=[[SAG](#), Corollary E.3.1.2],  $f_*$  and  $g_*$  are automatically coherent. Since  $X \bar{\times}_Z Y \simeq X \times_Z Y$  ([Proposition 10.1.1](#)), [Theorem 8.1.4](#) shows that the (unoriented) pullback square

$$(8.6.2) \quad \begin{array}{ccc} X \times_Z Y & \xrightarrow{\text{pr}_{2,*}} & Y \\ \text{pr}_{1,*} \downarrow & \lrcorner & \downarrow g_* \\ X & \xrightarrow{f_*} & Z \end{array}$$

satisfies the bounded Beck–Chevalley condition.

**8.6.3 Subexample.** Set  $Z = \mathbf{S}$  in [Example 8.6.1](#), so that  $f_* = \Gamma_{X,*}$  and  $g_* = \Gamma_{Y,*}$ . Since left exact functors preserve truncated objects, we see that for any truncated space  $K$  the natural morphism

$$\Gamma_{X,*} \Gamma_X^* \Gamma_{Y,*} \Gamma_Y^*(K) \rightarrow \Gamma_{X,*} \text{pr}_{1,*} \text{pr}_2^* \Gamma_Y^*(K)$$

in  $\mathbf{S}$  is an equivalence. Hence the natural morphism

$$\Pi_\infty(X) \circ \Pi_\infty(Y) \rightarrow \Pi_\infty(X \times Y)$$

of prospaces becomes an equivalence after protruncation. Since the composition monoidal structure and cartesian monoidal structure on  $\text{Pro}(\mathbf{S})$  coincide on the full subcategory  $\mathbf{S}_\pi^\wedge$  of profinite spaces (Recollection 4.3.2), we deduce that

$$\Pi_\infty^\wedge(X \times Y) \simeq \Pi_\infty^\wedge(X) \times \Pi_\infty^\wedge(Y).$$

Combining this with Corollary 5.13.16 we see that the profinite shape  $\Pi_\infty^\wedge : \mathbf{Top}_\infty^{bc} \rightarrow \mathbf{S}_\pi^\wedge$  preserves both inverse limits and finite products.

**8.6.4 Example.** Let  $k$  be a separably closed field and let  $X$  and  $Y$  be  $k$ -schemes. Assume that  $X$  is coherent and  $Y$  is proper over  $k$ . Then combining Chouh's work generalizing the proper basechange theorem in étale cohomology to the nonabelian setting [14, Theorem 5.3] with Subexample 8.6.3 shows that the natural geometric morphism

$$(X \times_{\text{Spec } k} Y)_{\text{ét}} \rightarrow X_{\text{ét}} \times_{(\text{Spec } k)_{\text{ét}}} Y_{\text{ét}} \simeq X_{\text{ét}} \times Y_{\text{ét}}$$

induces an equivalence on profinite shapes, or, equivalently, on lisse local systems (Corollary 5.14.16=[SAG, Corollary E.2.3.3]).

## 8.7 Gluing squares

We now use the bounded Beck–Chevalley condition for oriented fibre products to study oriented squares that are both oriented fibre product squares and oriented pushouts in the setting of bounded coherent  $\infty$ -topoi. These *gluing squares* are essential to our décollage approach to stratified higher topoi in §9.

**8.7.1 Definition.** A *gluing square* is an oriented square

$$\begin{array}{ccc} W & \xrightarrow{q_*} & U \\ p_* \downarrow & \swarrow \sigma & \downarrow j_* \\ Z & \xrightarrow{i_*} & X \end{array}$$

in which:

- every  $\infty$ -topos is bounded coherent;
- every geometric morphism is coherent;
- the natural geometric morphism  $Z \overset{W}{\underset{bc}{\smile}} U \rightarrow X$  is an equivalence (Construction 6.3.3);
- the natural geometric morphism  $W \rightarrow Z \tilde{\times}_X U$  is an equivalence (Definition 6.5.1).

We call the oriented fibre product  $W$  the *link* of the gluing square, or the *deleted tubular neighbourhood* of  $Z$  inside  $X$ .

**8.7.2 Construction.** Let  $X$  be a bounded coherent  $\infty$ -topos, along with a closed subtopos  $i_* : Z \hookrightarrow X$  and quasicompact open complement  $j_* : U \hookrightarrow X$ . Then we may form the oriented fibre product  $Z \tilde{\times}_X U$ , yielding the square

$$(8.7.3) \quad \begin{array}{ccc} Z \tilde{\times}_X U & \xrightarrow{\text{pr}_{2,*}} & U \\ \text{pr}_{1,*} \downarrow & \swarrow \tau & \downarrow j_* \\ Z & \xrightarrow{i_*} & X. \end{array}$$

The  $\infty$ -topos  $X$  is the bounded coherent recollement  $Z \tilde{\cup}_{bc}^{\text{pr}_{1,*} \text{pr}_2^*} U$ . Indeed, the bounded Beck–Chevalley condition ([Theorem 8.1.4](#)) ensures that  $\beta_\tau : i^* j_* \rightarrow \text{pr}_{1,*} \text{pr}_2^*$  becomes an equivalence after restriction to  $U_{<\infty}^{\text{coh}}$ . So [Proposition 6.1.15](#) applies, whence (8.7.3) is a gluing square.

Dually, let  $W$ ,  $Z$ , and  $U$  be bounded coherent  $\infty$ -topoi, and let  $p_* : W \rightarrow Z$  and  $q_* : W \rightarrow U$  be geometric morphisms. Forming the bounded coherent oriented pushout  $X := Z \tilde{\cup}_{bc}^W U$ , we obtain a square

$$(8.7.4) \quad \begin{array}{ccc} W & \xrightarrow{q_*} & U \\ p_* \downarrow & \swarrow \sigma & \downarrow j_* \\ Z & \xrightarrow{i_*} & Z \tilde{\cup}_{bc}^W U. \end{array}$$

We thus obtain a geometric morphism  $\psi(p, q, \sigma)_* : W \rightarrow Z \tilde{\times}_X U$ , and if  $\psi(p, q, \sigma)_*$  is an equivalence, then the square (8.7.4) is a gluing square.

The full subcategory of  $\text{Fun}(\Delta^1 \times \Delta^1, \mathbf{Top}_{\infty}^{bc})$  spanned by the gluing squares is equivalent to the (non-full) subcategory of  $\text{Fun}(\Delta^1, \mathbf{Cat}_{\infty, \delta_1})$  whose objects are bounded coherent gluing functors between bounded coherent  $\infty$ -topoi and whose morphisms  $\phi \rightarrow \phi'$  are squares

$$\begin{array}{ccc} U & \xrightarrow{\phi} & Z \\ f_* \downarrow & & \downarrow g_* \\ U' & \xrightarrow{\phi'} & Z' \end{array}$$

in which  $f_*$  and  $g_*$  are coherent geometric morphisms.

**8.7.5 Warning.** Without some boundedness and coherence hypotheses, the notion of a gluing square would not be apposite: if  $X := [0, 1]$  is the usual closed interval,  $Z := \{0\}$ , and  $U := ]0, 1]$ , then the oriented fibre product  $\tilde{Z} \tilde{\times}_X \tilde{U}$  is the empty  $\infty$ -topos.

**8.7.6 Example.** If  $W$ ,  $Z$ , and  $U$  are profinite spaces, and if  $p : W \rightarrow Z$  and  $q : W \rightarrow U$  are morphisms, then we may form the profinite [1]-stratified space  $X$  corresponding to the profinite spatial décollage  $Z \leftarrow W \rightarrow U$ . Now we form the Stone  $\infty$ -topoi

$$W := \widetilde{W}, \quad Z := \widetilde{Z}, \quad \text{and} \quad U := \widetilde{U},$$

and we form the bounded coherent oriented pushout  $\mathbf{X} := \mathbf{Z} \mathbin{\mathbb{U}}_{bc}^{\mathbf{W}} \mathbf{U}$ :

$$\begin{array}{ccc} \mathbf{W} & \xrightarrow{q_*} & \mathbf{U} \\ p_* \downarrow & \swarrow_{\sigma} & \downarrow j_* \\ \mathbf{Z} & \xrightarrow{i_*} & \mathbf{X} . \end{array}$$

The natural geometric morphism  $\mathbf{X} \rightarrow \widetilde{\mathbf{X}}$  is now an equivalence, since  $\widetilde{\mathbf{X}}$  is the recollement of  $\mathbf{Z}$  and  $\mathbf{U}$  along  $p_*q^*$ , and  $\widetilde{\mathbf{X}}$  is bounded and coherent. Now we compute

$$\mathbf{Z} \mathbin{\mathbb{X}}_{\mathbf{X}} \mathbf{U} \simeq \mathrm{Mor}_{[\square]}(\widetilde{[1]}, \mathbf{X}) \simeq \widehat{\mathrm{Map}_{[1]}(\widetilde{[1]}, \mathbf{X})} \simeq \widetilde{\mathbf{W}} = \mathbf{W} .$$

Thus the square above is in fact a gluing square.

## Part III

# Stratified higher topos theory

## 9 Stratified higher topoi

### 9.1 Higher topoi attached to posets & proposets

**9.1.1.** A sheaf on a poset  $P$  (with its Alexandroff topology – [Definition 1.1.1](#)) is determined by its values on the principal open sets, which coincide with its stalks. Precisely since the principal opens form a basis for the topology on  $P$ , the assignment  $p \mapsto P_{\geq p}$  is a fully faithful functor  $P \hookrightarrow \text{Open}(P)^{op}$ , which induces an equivalence

$$\tilde{P} := \text{Sh}(\text{Open}(P)) \simeq \text{Fun}(P, \mathbf{S})$$

(cf. [\[5, Corollary 2.4; 53, Proposition B.6.4\]](#)). In particular, the  $\infty$ -topos  $\tilde{P}$  is both 0-localic and Postnikov complete [\[SAG, §A.7.2\]](#).

**9.1.2.** If  $P$  is a finite poset, then  $\tilde{P}$  is a coherent  $\infty$ -topos ([Example 5.7.1](#)), and a sheaf  $F$  on  $P$  is  $n$ -coherent if and only if all of the stalks of  $F$  have finite homotopy sets in degrees  $m \leq n$ .

**9.1.3.** The assignment  $P \mapsto \tilde{P}$  extends to a functor  $\text{Pro}(\text{poSet}) \rightarrow \mathbf{Top}_{\infty}$ , which we also denote by  $\mathbf{P} \mapsto \tilde{\mathbf{P}}$ . Thus if  $\mathbf{P} := \{P_{\alpha}\}_{\alpha \in A}$  is an inverse system of posets, then

$$\tilde{\mathbf{P}} \simeq \lim_{\alpha \in A} \tilde{P}_{\alpha}$$

in  $\mathbf{Top}_{\infty}$ . That is, by [\[HTT, Theorem 6.3.3.1\]](#), the  $\infty$ -category  $\tilde{\mathbf{P}}$  can be regarded as the one whose objects are collections  $\{F_{\alpha}\}_{\alpha \in A}$  of functors  $F_{\alpha} : \tilde{P}_{\alpha} \rightarrow \mathbf{S}$  along with compatible identifications of  $F_{\alpha'}$  with the right Kan extension of  $F_{\alpha}$  along  $P_{\alpha} \rightarrow P_{\alpha'}$  for any morphism  $\alpha \rightarrow \alpha'$  in  $A$ . In particular,  $\tilde{\mathbf{P}}$  is 0-localic.

**9.1.4.** If  $S$  is a spectral topological space, the 0-topos (locale)  $\text{Open}(S)$  is the limit of the 0-topoi  $\text{Open}(P)$  over  $\text{FC}(S)$ . Thus we have an equivalence of 0-localic  $\infty$ -topoi

$$\tilde{S} \simeq \lim_{P \in \text{FC}(S)} \tilde{P}.$$

Since  $\tilde{S}$  is coherent ([Example 5.7.1](#)), the  $\infty$ -pretopos  $\tilde{S}_{<\infty}^{coh}$  of truncated coherent objects of  $\tilde{S}$  can be identified with the filtered colimit  $\text{colim}_{P \in \text{FC}(S)^{op}} \tilde{P}_{<\infty}^{coh}$  over the category  $\text{FC}(S)$  of finite constructible stratifications  $S \rightarrow P$ , along the relevant restriction functors ([§5.9](#)).

Recall that if  $f : S' \rightarrow S$  is a quasicompact continuous map of spectral topological spaces, then the induced geometric morphism  $f_* : \tilde{S}' \rightarrow \tilde{S}$  is coherent ([Example 5.7.1](#)).

**9.1.5.** If  $S$  is a spectral topological space, then the  $\infty$ -category of points of  $\tilde{S}$  is equivalent to the materialisation of  $S$ , viz.,

$$\text{Pt}(\tilde{S}) \simeq \text{mat}(S).$$

Thus the points of  $\tilde{S}$  are precisely the points of  $S$  equipped with the specialisation partial ordering.



## 9.2 Stratifications over posets

There are a number of ways to describe stratified  $\infty$ -topoi, but let us focus upon the most elementary description – a straightforward generalisation of the notion of a stratified topological space ([Definition 1.2.1](#)).

**9.2.1 Definition.** For any poset  $P$  and any  $\infty$ -topos  $X$ , a *stratification of  $X$  by  $P$*  – or, more briefly, a  *$P$ -stratification of  $X$*  – is a geometric morphism of  $\infty$ -topoi  $f_* : X \rightarrow \tilde{P}$ . We define the  $\infty$ -category  $\mathbf{StrTop}_{\infty, P}$  of  *$P$ -stratified  $\infty$ -topoi* as the overcategory  $\mathbf{Top}_{\infty, / \tilde{P}}$ .

We define the  $\infty$ -category  $\mathbf{StrTop}_{\infty}$  of *stratified  $\infty$ -topoi* as the pullback

$$\mathbf{StrTop}_{\infty} := \mathrm{Fun}(\Delta^1, \mathbf{Top}_{\infty}) \times_{\mathrm{Fun}(\Delta^1, \mathbf{Top}_{\infty})} \mathbf{poSet}.$$

Since  $\mathbf{Top}_{\infty}$  admits fibre products, the projection  $\mathbf{StrTop}_{\infty} \rightarrow \mathbf{poSet}$  is a bicartesian fibration whose fibre over a poset  $P$  may be identified with the  $\infty$ -category  $\mathbf{StrTop}_{\infty, P}$ .

**9.2.2 Notation.** Let  $P$  be a poset, and let  $X$  be a  $P$ -stratified  $\infty$ -topos. For any open subset  $U \subseteq P$ , we abuse notation and write  $U$  also for the corresponding open of  $\tilde{P}$ , and we write

$$X_U := X_{/f^*U} \simeq X \times_{\tilde{P}} \tilde{U} \subseteq X$$

for the corresponding open subtopos. (Here the fibre product is formed in  $\mathbf{Top}_{\infty}$ .) Dually, if  $Z \subseteq P$  is closed, then we write

$$X_Z := X_{\setminus f^*(P \setminus Z)} \simeq X \times_{\tilde{P}} \tilde{Z} \subseteq X$$

for the corresponding closed subtopos, so that if  $U$  and  $Z$  are complementary, then one exhibits  $X$  as a recollement of  $X_Z$  and  $X_U$ .

In particular, for any point  $p \in P$ , we write

$$X_{\geq p} := X_{p_{\geq p}} \quad \text{and} \quad X_{> p} := X_{p_{> p}}$$

as well as

$$X_{\leq p} := X_{p_{\leq p}} \quad \text{and} \quad X_{< p} := X_{p_{< p}}.$$

More generally, if  $\Sigma \subseteq P$  is any subset, then we write

$$X_{\Sigma} := X \times_{\tilde{P}} \tilde{\Sigma}$$

for the fibre product formed in  $\mathbf{Top}_{\infty}$ . So we define the  $p$ -th *stratum* as the fibre product in  $\mathbf{Top}_{\infty}$ :

$$X_p := X_{\geq p} \times_X X_{\leq p},$$

which is an open subtopos of the closed subtopos  $X_{\leq p} \subseteq X$  as well as a closed subtopos of the open subtopos  $X_{\geq p} \subseteq X$ .

**9.2.3 Definition.** A stratification  $X \rightarrow \tilde{P}$  of an  $\infty$ -topos  $X$  is *finite* or *noetherian* if and only if the poset  $P$  is so. We write  $\mathbf{StrTop}_{\infty}^{\text{noeth}} \subset \mathbf{StrTop}_{\infty}$  for the full subcategory spanned by the noetherian stratifications.

Let  $P$  be a finite poset. We say that a  $P$ -stratified  $\infty$ -topos  $f_* : X \rightarrow \tilde{P}$  is *constructible* if and only if for any point  $p \in P$  and any quasicompact open  $V \in \text{Open}(X)$ , the  $\infty$ -topos  $X_{\geq p} \times_X X_{/V}$  is coherent. We say that a constructible stratification  $f_* : X \rightarrow \tilde{P}$  is *coherent constructible* if  $X$  is a coherent  $\infty$ -topos, and we say that  $f_*$  is *bounded coherent constructible* if  $X$  is a bounded coherent  $\infty$ -topos. **Proposition 6.1.8**=[DAG XIII, Proposition 2.3.22] shows that a stratification  $f_* : X \rightarrow \tilde{P}$  is coherent constructible if and only if  $X$  is coherent and the geometric morphism  $f_*$  is coherent. We write  $\mathbf{StrTop}_{\infty}^{bcc} \subset \mathbf{StrTop}_{\infty}$  for the subcategory whose objects are bounded coherent constructible stratified  $\infty$ -topoi and whose morphisms are *coherent* geometric stratified morphisms:

$$\mathbf{StrTop}_{\infty}^{bcc} := \text{Fun}(\Delta^1, \mathbf{Top}_{\infty}^{bc}) \times_{\text{Fun}(\Delta^{(1)}, \mathbf{Top}_{\infty}^{bc})} \mathbf{poSet}^{fin}.$$

**9.2.4.** Since  $\tilde{P}$  is 0-localic, it follows that a  $P$ -stratification of an  $\infty$ -topos  $X$  is tantamount to the data of a morphism of 0-topoi (locales)  $\text{Open}(X) \rightarrow \text{Open}(P)$ , where  $\text{Open}(X)$  is the 0-topos of  $(-1)$ -truncated objects of  $X$ , and  $\text{Open}(P) = \text{Open}(\tilde{P})$  is the 0-topos of open subsets of  $P$ . Thus one obtains an equivalence of  $\infty$ -categories

$$\mathbf{StrTop}_{\infty, P} \simeq \mathbf{Top}_{\infty} \times_{\mathbf{Top}_0} \mathbf{Top}_{0, / \text{Open}(P)}.$$

One may speak of a stratification of an  $n$ -topos for any  $n \in N$  (as well as the  $\infty$ -category  $\mathbf{StrTop}_n$ ), and it is tantamount to a stratification of the corresponding  $n$ -localic  $\infty$ -topos:

$$\mathbf{StrTop}_{n, P} \simeq \mathbf{Top}_n \times_{\mathbf{Top}_0} \mathbf{Top}_{0, / \text{Open}(P)}.$$

**9.2.5.** Since noetherian posets are sober, the functor  $\mathbf{poSet}^{noeth} \rightarrow \mathbf{Top}_{\infty}$  given by the assignment  $P \mapsto \tilde{P}$  is fully faithful, whence the  $\infty$ -category  $\mathbf{StrTop}_{\infty}^{noeth}$  of noetherian stratified  $\infty$ -topoi can be identified with a *full* subcategory of  $\text{Fun}(\Delta^1, \mathbf{Top}_{\infty})$ .

**9.2.6 Example.** A  $\{0\}$ -stratified  $\infty$ -topos is nothing more than an  $\infty$ -topos.

**9.2.7 Example.** Rephrasing (6.1.3), a  $[1]$ -stratified  $\infty$ -topos  $X \rightarrow \widetilde{[1]}$  is tantamount to a recollement of  $\infty$ -topoi. If  $X$  is coherent, the stratification is constructible if and only if the open subtopos  $X_1$  is quasicompact.

**9.2.8.** To generalise the previous example, let  $P$  be a poset. We claim that the data of a  $P$ -stratified  $\infty$ -topos determines and is determined by a suitable colax functor from  $P^{op}$  to a double  $\infty$ -category of  $\infty$ -topoi and left exact functors.

To make a precise assertion, we shall say that a locally cocartesian fibration  $X \rightarrow P^{op}$  is *left exact* if each fibre  $X_p$  admits all finite limits, and for any  $p \leq q$  in  $P$ , the functor  $X_q \rightarrow X_p$  is left exact. Now left exact locally cocartesian fibrations  $X \rightarrow P^{op}$  whose fibres are  $\infty$ -topoi organise themselves into a  $\infty$ -category  $\mathbf{LocCocart}_{pop}^{lex, top}$ . Then it seems likely that one can produce an equivalence of  $\infty$ -categories

$$\mathbf{LocCocart}_{pop}^{lex, top} \simeq \mathbf{StrTop}_{\infty, P},$$

natural in  $P$ . To prove this would involve a diversion into a simplicial thicket that is unnecessary for our work here; we therefore leave this matter for a later paper.

**9.2.9 Example.** The  $\infty$ -topos  $\tilde{P}$ , equipped with the identity stratification, is itself is terminal in  $\mathbf{StrTop}_{\infty, P}$ .

**9.2.10 Example.** If  $P$  is a noetherian poset, and  $\mathbf{TSpc}^{sober}$  denotes the 1-category of sober topological spaces, then the assignment  $W \mapsto \tilde{W}$  is a fully faithful functor

$$\mathbf{TSpc}_{/P}^{sober} \hookrightarrow \mathbf{StrTop}_{\infty, P}.$$

**9.2.11 Example.** Let  $P$  be a poset, and  $f : \Pi \rightarrow P$  a  $P$ -stratified space (Definition 2.1.1); i.e.,  $f$  is a conservative functor. In light of the equivalence  $\tilde{P} \simeq \mathbf{Fun}(P, \mathbf{S})$ , let us abuse notation slightly and write

$$\tilde{\Pi} := \mathbf{Fun}(\Pi, \mathbf{S})$$

for the  $\infty$ -topos of functors  $\Pi \rightarrow \mathbf{S}$ ; then right Kan extension along  $f$  is a morphism of  $\infty$ -topoi

$$f_* : \tilde{\Pi} \rightarrow \tilde{P},$$

whence  $\tilde{\Pi}$  is a  $P$ -stratified  $\infty$ -topos. For any point  $p \in P$ , the  $p$ -th stratum of  $\tilde{\Pi}$  is canonically identified the  $\infty$ -topos  $\tilde{\Pi}_p = \mathbf{Fun}(\Pi_p, \mathbf{S})$ .

The assignment  $\Pi \mapsto \tilde{\Pi}$  defines a functor  $\mathbf{Str} \rightarrow \mathbf{StrTop}_{\infty}$  over  $po\mathbf{Set}$ .

**9.2.12 Subexample.** Let  $P$  be a noetherian poset, and Let  $X$  be a conically  $P$ -stratified topological space [HA, Definition A.5.5]. Then we obtain the  $P$ -stratified space

$$\Pi_{(\infty, 1)}(X; P) := \mathbf{Sing}^P(X)$$

and thus the  $P$ -stratified  $\infty$ -topos  $\tilde{\Pi}_{(\infty, 1)}(X; P)$ . If  $X$  is hereditarily paracompact and locally of singular shape, then in light of [HA, §A.4], the stratum  $\tilde{\Pi}_{(\infty, 1)}(X; P)_p$  over any point  $p \in P$  is equivalent to the  $\infty$ -category of locally constant sheaves on  $X_p$ . In light of [HA, §A.9], the  $\infty$ -topos  $\tilde{\Pi}_{(\infty, 1)}(X; P)$  is equivalent to the  $\infty$ -category of *formally constructible* sheaves on  $X$  – i.e., those sheaves whose restrictions to each stratum  $X_p$  are locally constant.

**9.2.13 Lemma.** *Let  $P$  be a finite poset and  $\Pi$  be a  $\pi$ -finite  $P$ -stratified space. Then the stratification  $\tilde{\Pi} \rightarrow \tilde{P}$  is bounded coherent constructible.*

*Proof.* By definition  $\tilde{\Pi}$  is  $n$ -localic for some  $n \in \mathbf{N}$ . Moreover, the truncated coherent objects of  $\tilde{\Pi}$  are those functors  $\Pi \rightarrow \mathbf{S}$  that are valued in  $\pi$ -finite spaces. One concludes that  $\tilde{\Pi}$  is coherent. Since this is true for  $\Pi$ , it is true for any open therein, whence  $\tilde{\Pi} \rightarrow \tilde{P}$  is constructible.  $\square$

### 9.3 Toposic décollages

In analogy with the construction of the spatial décollage attached to a stratified space (Construction 4.2.1), we can attach to a stratified  $\infty$ -topos what we call its (*toposic*) *décollage*. Whereas a stratified  $\infty$ -topos consists of strata that are glued together, its décollage is the result of pulling these strata apart while retaining the linking information necessary to reconstruct the stratified  $\infty$ -topos.

**9.3.1 Definition.** Let  $P$  be a poset. We say that a functor  $D: \text{sd}^{op}(P) \rightarrow \mathbf{Top}_{\infty}^{bc}$  is a *décollage over  $P$*  if and only if the following conditions are satisfied.

- If  $p_0, p_1 \in P$  are two points such that  $p_0 < p_1$ , then the square

$$\begin{array}{ccc} D\{p_0, p_1\} & \xrightarrow{\quad} & D\{p_1\} \\ \downarrow & \swarrow & \downarrow j_* \\ D\{p_0\} & \xleftarrow{i_*} D\{p_0\} \tilde{\cup}_{bc}^{D\{p_0, p_1\}} D\{p_1\} \end{array}$$

is a gluing square.

- For any string  $\{p_0 \leq \dots \leq p_m\} \subseteq P$ , the geometric morphism to the fibre product of  $\infty$ -topoi

$$D\{p_0 \leq \dots \leq p_m\} \rightarrow D\{p_0 \leq p_1\}_{D\{p_1\}}^{\times} D\{p_1 \leq p_2\}_{D\{p_2\}}^{\times} \cdots D\{p_{m-1} \leq p_m\}_{D\{p_{m-1}\}}^{\times}$$

is an equivalence.

We write  $\text{D}\acute{\text{e}}\text{c}_P(\mathbf{Top}_{\infty}^{bc}) \subseteq \text{Fun}(\text{sd}^{op}(P), \mathbf{Top}_{\infty}^{bc})$  for the full subcategory spanned by the décollages over  $P$ .

It seems likely that a décollage over  $P$  can be thought of as a suitable category internal to  $\mathbf{Top}_{\infty}^{bc}$  along with a conservative functor to  $P$ . Making such an interpretation precise and helpful is a task that lies outside the scope of this work.

**9.3.2.** If  $D: \text{sd}^{op}(P) \rightarrow \mathbf{Top}_{\infty}^{bc}$  is a décollage over  $P$ , and if  $p, q \in P$  are points with  $p < q$ , then for the sake of typographical brevity, let us here write

$$D\{p\} \tilde{\cup} D\{q\} := D\{p\} \tilde{\cup}_{bc}^{D\{p \leq q\}} D\{q\}.$$

The two conditions of **Definition 9.3.1** together specify, for any string  $\{p_0 \leq \dots \leq p_m\} \subseteq P$ , an equivalence

$$D\{p_0 \leq \dots \leq p_m\} \simeq D\{p_0\} \tilde{\times}_{D\{p_0\} \tilde{\cup} D\{p_1\}}^{\tilde{\times}} D\{p_1\} \tilde{\times}_{D\{p_1\} \tilde{\cup} D\{p_2\}}^{\tilde{\times}} \cdots \tilde{\times}_{D\{p_{m-1}\} \tilde{\cup} D\{p_m\}}^{\tilde{\times}} D\{p_m\},$$

which we will call the *Segal equivalence*.

**9.3.3 Example.** The terminal object of  $\text{D}\acute{\text{e}}\text{c}_P(\mathbf{Top}_{\infty}^{bc})$  is the constant functor  $\text{sd}^{op}(P) \rightarrow \mathbf{Top}_{\infty}^{bc}$  whose value is the  $\infty$ -topos  $\mathbf{S}$ .

**9.3.4 Construction.** Consider the 1-category  $J$  of **Construction 4.1.4**, whose objects are pairs  $(P, \Sigma)$  consisting of a poset  $P$  and a string  $\Sigma \subseteq P$ , so that the assignment  $(P, \Sigma) \mapsto P$  is a cocartesian fibration  $J \rightarrow \text{poSet}$  whose fibre over a poset  $P$  is the poset  $\text{sd}^{op}(P)$ .

We write

$$\text{Pair}_{\text{poSet}}(J, \mathbf{Top}_{\infty}^{bc})$$

for the simplicial set over  $poSet$  defined by the following universal property: for any simplicial set  $K$  over  $poSet$ , one demands a bijection

$$\text{Mor}_{sSet/poSet}(K, \text{Pair}_{poSet}(J, \mathbf{Top}_{\infty}^{bc})) \cong \text{Mor}_{sSet}(K \times_{poSet} J, \mathbf{Top}_{\infty}^{bc}),$$

natural in  $K$ . By [HTT, Corollary 3.2.2.13], the functor

$$\text{Pair}_{poSet}(J, \mathbf{Top}_{\infty}^{bc}) \rightarrow poSet$$

is a cartesian fibration whose fibre over a poset  $P$  is the  $\infty$ -category  $\text{Fun}(\text{sd}^{op}(P), \mathbf{Top}_{\infty}^{bc})$ . Now let

$$\mathbf{D}\acute{e}c(\mathbf{Top}_{\infty}^{bc}) \subset \text{Pair}_{poSet}(J, \mathbf{Top}_{\infty}^{bc})$$

denote the full subcategory spanned by the pairs  $(P, D)$  in which  $D$  is a toposic d  collage over  $P$ . Since  $\mathbf{D}\acute{e}c(\mathbf{Top}_{\infty}^{bc})$  contains all the cartesian edges, the functor  $\mathbf{D}\acute{e}c(\mathbf{Top}_{\infty}^{bc}) \rightarrow poSet$  is a cartesian fibration.

## 9.4 The nerve of a stratified $\infty$ -topos

**9.4.1 Construction.** Let  $P$  be a poset, and let  $f_* : X \rightarrow \tilde{P}$  be a  $P$ -stratified  $\infty$ -topos. Then for any monotonic map  $\phi : Q \rightarrow P$ , we define the  $\infty$ -topos of sections of  $X$  over  $Q$  as the pullback of  $\infty$ -topoi

$$\text{MOR}_{\tilde{P}}(\tilde{Q}, X) := \text{MOR}(\tilde{Q}, X) \times_{\text{MOR}(\tilde{Q}, \tilde{P})} \{\phi\}.$$

The  $\infty$ -topos  $\text{MOR}_{\tilde{P}}(\tilde{Q}, X)$  depends only on the pullback  $X \times_{\tilde{P}} \tilde{Q}$ :

$$\text{MOR}_{\tilde{P}}(\tilde{Q}, X) \simeq \text{MOR}_{\tilde{Q}}(\tilde{Q}, X \times_{\tilde{P}} \tilde{Q}).$$

We thus obtain a functor  $N_P(X) : \text{sd}^{op}(P) \rightarrow \mathbf{Top}_{\infty}$  that carries a string  $\Sigma \subseteq P$  to the  $\infty$ -topos

$$N_P(X)(\Sigma) := \text{MOR}_{\tilde{P}}(\tilde{\Sigma}, X).$$

For any string  $\{p_0 \leq \dots \leq p_m\} \subseteq P$ , we thus obtain an identification

$$N_P(X)\{p_0 \leq \dots \leq p_m\} \simeq X_{p_0} \tilde{\times}_X X_{p_1} \tilde{\times}_X \dots \tilde{\times}_X X_{p_m}.$$

In particular, if  $P$  is finite and  $X$  is bounded coherent constructible (Definition 9.2.3), then the functor  $N_P(X)$  is a d  collage over  $P$ . We call  $N_P(X)$  the *nerve* of the  $P$ -stratified  $\infty$ -topos  $X$ , and we call  $N : \mathbf{StrTop}_{\infty}^{bcc} \rightarrow \mathbf{D}\acute{e}c(\mathbf{Top}_{\infty}^{bc})$  over  $poSet$  the *nerve functor*.

**9.4.2 Example.** Let  $P$  be a poset, and  $\Pi$  a  $P$ -stratified space. Then one has a identification

$$N_P(\widetilde{\Pi}) \simeq \widetilde{N_P(\Pi)},$$

natural in  $P$  and  $\Pi$ , since for any string  $\Sigma \subseteq P$ , one has

$$\text{MOR}_{\tilde{P}}(\tilde{\Sigma}, \widetilde{\Pi}) \simeq \widetilde{\text{Map}_P(\Sigma, \Pi)}$$

via the natural morphism.

We now proceed to demonstrate that the nerve is an equivalence of  $\infty$ -categories.

**9.4.3 Theorem.** *For any finite poset  $P$ , the nerve functor  $N_P : \mathbf{StrTop}_{\infty, P}^{bcc} \rightarrow \mathbf{D\acute{e}c}_P(\mathbf{Top}_{\infty}^{bc})$  is an equivalence of  $\infty$ -categories.*

*Proof.* We begin by reducing to the case in which  $P$  is a nonempty, finite, totally ordered set. To make this reduction, we note that  $P \simeq \text{colim}_{\Sigma \in \text{sd}(P)} \Sigma$ , whence  $\tilde{P}$  is the limit  $\tilde{P} \simeq \lim_{\Sigma \in \text{sd}^{op}(P)} \tilde{\Sigma}$  in  $\mathbf{Cat}_{\infty, \delta_1}$  (which is the colimit in  $\mathbf{Top}_{\infty}$ ) and moreover

$$\text{sd}^{op}(P) \simeq \text{colim}_{\Sigma \in \text{sd}(P)} \text{sd}^{op}(\Sigma).$$

From this we deduce that

$$\mathbf{StrTop}_{\infty, P}^{bcc} \simeq \text{colim}_{\Sigma \in \text{sd}(P)} \mathbf{StrTop}_{\infty, \Sigma}^{bcc} \quad \text{and} \quad \mathbf{D\acute{e}c}_P(\mathbf{Top}_{\infty}^{bc}) \simeq \text{colim}_{\Sigma \in \text{sd}(P)} \mathbf{D\acute{e}c}_{\Sigma}(\mathbf{Top}_{\infty}^{bc}),$$

which provides our reduction.

Now when  $P = [n] := \{0 \leq \dots \leq n\}$  is a nonempty totally ordered finite set, we construct an inverse  $U_n : \mathbf{D\acute{e}c}_{[n]}(\mathbf{Top}_{\infty}^{bc}) \rightarrow \mathbf{StrTop}_{\infty, [n]}^{bcc}$  to the nerve functor  $N_n := N_{[n]}$  by forming the iterated bounded coherent oriented pushout:

$$U_n(D) := D\{0\} \tilde{\cup}_{bc}^{D\{0 \leq 1\}} D\{1\} \tilde{\cup}_{bc}^{D\{1 \leq 2\}} \dots \tilde{\cup}_{bc}^{D\{n-1 \leq n\}} D\{n\},$$

equipped with its canonical geometric morphism to

$$\widehat{[n]} \simeq U_n(S),$$

which is visibly coherent.

The universal properties of the iterated bounded coherent oriented pushout and the iterated oriented pullback provide natural transformations  $U_n N_n \rightarrow \text{id}$  and  $\text{id} \rightarrow N_n U_n$ . We aim to show that these natural transformations are equivalences.

To see that  $U_n$  is an inverse to  $N_n$ , we may induct on  $n$ . The case  $n = 0$  is obvious. Assume now that  $n \geq 1$  and that  $U_{n-1}$  is an inverse to  $N_{n-1}$ . Now if  $X$  is a bounded coherent  $\infty$ -topos with a constructible stratification  $X \rightarrow \widehat{[n]}$ , then consider the recollement of  $X$  given by  $X_{\leq n-1}$  and  $X_n$ . We thus have a gluing square

$$\begin{array}{ccc} X_{\leq n-1} & \tilde{\times}_X & X_n \\ p_* \downarrow & \swarrow \sigma & \downarrow j_* \\ X_{\leq n-1} & \xleftarrow{i_*} & X. \end{array}$$

As a result, we compute:

$$U_n N_n(X) \simeq U_{n-1} N_{n-1}(X_{\leq n-1}) \tilde{\cup}_{bc}^{X_{\leq n-1} \tilde{\times}_X X_n} X_n \simeq X_{\leq n-1} \tilde{\cup}_{bc}^{X_{\leq n-1} \tilde{\times}_X X_n} X_n \simeq X,$$

as desired. In the other direction, suppose  $D : \text{sd}^{op}([n]) \rightarrow \mathbf{Top}_{\infty}^{bc}$  is a toposic d\acute{e}collage. For any  $k \in [n]$ , write  $\hat{k}$  for  $\{0, \dots, k-1, k+1, \dots, n\} \subset [n]$ ; for any string  $\Sigma \subseteq \hat{k}$ , the map  $D(\Sigma) \rightarrow N_n U_n(D)(\Sigma)$  clearly factors via equivalences

$$D(\Sigma) \simeq (D|_{\text{sd}^{op}(\hat{k})})(\Sigma) \simeq N_{\hat{k}} U_{\hat{k}}(D|_{\text{sd}^{op}(\hat{k})})(\Sigma) \simeq N_n U_n(D)(\Sigma),$$

so it remains only to contemplate the case  $\Sigma = [n]$  itself. For this, note that the morphism  $D([n]) \rightarrow N_n U_n(D)([n])$  is homotopic to the Segal equivalence

$$D\{0 \leq \dots \leq n\} \simeq D\{0\} \underset{U_n(D)}{\overset{\sim}{\times}} D\{1\} \underset{U_n(D)}{\overset{\sim}{\times}} \dots \underset{U_n(D)}{\overset{\sim}{\times}} D\{n\},$$

whence our claim.  $\square$

## 9.5 Stratifications over spectral topological spaces

**9.5.1 Definition.** For any propoet  $P$ , a  $P$ -stratified  $\infty$ -topos is a morphism of  $\infty$ -topoi  $X \rightarrow \tilde{P}$ . We write  $\mathbf{StrTop}_{\infty, P}$  for the  $\infty$ -category  $\mathbf{Top}_{\infty, \tilde{P}}$  of  $P$ -stratified  $\infty$ -topoi.

We are interested exclusively in the case where  $P$  is a spectral topological space, viewed as a profinite poset. Hence we define

$$\mathbf{StrTop}_{\infty}^{\wedge} := \mathbf{Fun}(\Delta^1, \mathbf{Top}_{\infty}) \times_{\mathbf{Fun}(\Delta^{(1)}, \mathbf{Top}_{\infty})} \mathbf{TSp}^{spec},$$

so that the fibre over  $S$  can be identified with  $\mathbf{StrTop}_{\infty, S}$ .

**9.5.2.** If  $S$  is a spectral topological space, then the  $\infty$ -topos  $\tilde{S}$  of sheaves on  $S$  coincides with the limit of  $\infty$ -topoi  $\lim_{P \in \mathbf{FC}(S)} \tilde{P}$ , so there is no ambiguity in the notation; furthermore, one has

$$\mathbf{StrTop}_{\infty, S}^{\wedge} \simeq \mathbf{Top}_{\infty} \times_{\mathbf{Top}_0} \mathbf{Top}_{0, / \mathbf{Open}(S)},$$

where  $\mathbf{Open}(S)$  is the locale of open subsets of  $S$ .

In the case of stratifications over spectral topological spaces, we employ notations as in [Notation 9.2.2](#).

**9.5.3 Notation.** Let  $S$  be a spectral topological space, and let  $X$  be a  $S$ -stratified  $\infty$ -topos. For any open subset  $U \subseteq S$ , we abuse notation and write  $U$  also for the corresponding open of  $\tilde{S}$ , and we write

$$X_U := X_{/f^*U} \simeq X \times_{\tilde{S}} \tilde{U} \subseteq X$$

for the corresponding open subtopos. (Here the fibre product is formed in  $\mathbf{Top}_{\infty}$ .) Dually, if  $Z \subseteq S$  is closed, then we write

$$X_Z := X_{\setminus f^*(S \setminus Z)} \simeq X \times_{\tilde{S}} \tilde{Z} \subseteq X$$

for the corresponding closed subtopos, so that if  $U$  and  $Z$  are complementary, then one exhibits  $X$  as a recollement of  $X_Z$  and  $X_U$ .

More generally, for any subspace  $W \subset S$ , we write

$$X_W := X \times_{\tilde{S}} \tilde{W}.$$

In particular, for any point  $s \in S$  we define the  $s$ -th *stratum* as the fibre product in  $\mathbf{Top}_{\infty}$ :

$$X_s := X \times_{\tilde{S}} \{\tilde{s}\} \subseteq X.$$

The key finiteness condition for stratifications over spectral topological spaces is *bounded coherent constructibility*.

**9.5.4 Definition.** If  $X$  is an  $\infty$ -topos and  $S$  is a spectral topological space, then a stratification  $f_* : X \rightarrow \tilde{S}$  is said to be *constructible* if and only if, for any quasicompact open  $U \subseteq S$  and any quasicompact open  $V \in \text{Open}(X)$ , the  $\infty$ -topos

$$X_U \times_X X/V \simeq X_{/(f^*(U) \times V)}$$

is coherent. We say that a constructible stratification  $f_* : X \rightarrow \tilde{S}$  is *coherent constructible* if  $X$  is a coherent  $\infty$ -topos, and we say that  $f_*$  is *bounded coherent constructible* if  $X$  is a bounded coherent  $\infty$ -topos.

**9.5.5 Lemma.** *Let  $S$  be a spectral topological space and  $f_* : X \rightarrow \tilde{S}$  be an  $S$ -stratified  $\infty$ -topos. If  $X$  is coherent, then the stratification  $f_*$  is constructible if and only if  $f_*$  is a coherent geometric morphism.*

*Proof.* If  $f_*$  is coherent, then since quasicompact opens in  $X$  are coherent [SAG, Remark A.2.3.5] and coherent objects of  $X$  are closed under finite products,  $f_*$  is a constructible stratification

For the other direction, assume that  $f_*$  is a constructible stratification. By [Corollary 5.4.5](#), to show that  $f_*$  is coherent it suffices to show that  $f^*$  carries truncated coherent objects of  $\tilde{S}$  to coherent objects of  $X$ . Let  $F \in \tilde{S}_{<\infty}^{coh}$  be a truncated coherent object; then there exists a finite constructible stratification  $S \rightarrow P$  such that  $F$  is the pullback of a truncated coherent object of  $\tilde{P}$ . Thus, for every point  $p \in P$ , the restriction  $f^*(F)|_{X_p}$  is lisse. By [Proposition 6.1.8](#)=[DAG XIII, Proposition 2.3.22] it follows that  $F$  is coherent.  $\square$

**9.5.6 Notation.** Let  $S$  be a spectral topological space. We define the  $\infty$ -category of *coherent constructible*  $S$ -stratified  $\infty$ -topoi as the overcategory

$$\mathbf{StrTop}_{\infty, S}^{\wedge, cc} := \mathbf{Top}_{\infty, /S}^{coh}.$$

We write  $\mathbf{StrTop}_{\infty, S}^{\wedge, bcc} \subset \mathbf{StrTop}_{\infty, S}^{\wedge, cc}$  for the full subcategory spanned by the *bounded coherent constructible*  $S$ -stratified  $\infty$ -topoi.

More generally, we define

$$\mathbf{StrTop}_{\infty}^{\wedge, cc} := \text{Fun}(\Delta^1, \mathbf{Top}_{\infty}^{coh}) \times_{\text{Fun}(\Delta^{\{1\}}, \mathbf{Top}_{\infty}^{coh})} \mathbf{TSp}^{spec},$$

so that the fibre over  $S$  can be identified with  $\mathbf{StrTop}_{\infty, S}^{\wedge, cc}$ . We write  $\mathbf{StrTop}_{\infty}^{\wedge, bcc} \subset \mathbf{StrTop}_{\infty}^{\wedge, cc}$  for the full subcategory spanned by those objects  $X \rightarrow \tilde{S}$  where  $X$  is a bounded  $\infty$ -topos.

## 9.6 The natural stratification of a coherent $\infty$ -topos

It turns out that *any* coherent  $\infty$ -topos  $X$  has a canonical profinite stratification: the 0-topos (=locale)  $\text{Open}(X)$  is the locale of a spectral topological space. This provides a fully faithful embedding of the  $\infty$ -category of coherent  $\infty$ -topoi into that of coherent constructible stratified  $\infty$ -topoi.

To explain this point, let us first recall the equivalence between coherent locales and spectral topological spaces.



**9.6.1 Recollection.** Let  $A$  be a locale. An object  $a \in A$  is *quasicompact*<sup>25</sup> if and only if for every subset  $S \subset A$  such that  $\coprod_{s \in S} s = a$ , there exists a finite subset  $S_0 \subset S$  such that  $\coprod_{s \in S_0} s = a$ .

One says that  $A$  is *coherent* if and only if  $A$  is coherent in the sense of [Definition 5.3.1](#). [Proposition 5.5.6](#) shows that this is the case if and only if the following conditions are satisfied:

- The quasicompact elements of  $A$  form a *sublattice* of  $A$ : the maximal element  $1_A \in A$  is quasicompact and binary products (=meets) of quasicompact elements are quasicompact.
- The quasicompact elements of  $A$  *generate*  $A$ : every element  $a \in A$  can be written as a coproduct (=join)  $a = \coprod_{s \in S} s$ , where  $S \subset A$  is a subset consisting of quasicompact elements of  $A$ .

A morphism  $A \rightarrow A'$  between coherent locales is *coherent* if and only if the corresponding map of posets  $A' \rightarrow A$  sends quasicompact elements to quasicompact elements.

We write  $\mathbf{Top}_0^{coh}$  for the category of coherent locales and coherent morphisms between them (cf. [Corollary 5.6.12](#)).

**9.6.2 Example.** Let  $X$  be an  $\infty$ -topos. Then an open  $U \in \text{Open}(X)$  is a quasicompact element of the locale  $\text{Open}(X)$  if and only if  $U$  is a quasicompact (i.e., 0-coherent) object of the  $\infty$ -topos  $X$ .

The following three results are immediate from the definitions and [Example 9.6.2](#).

**9.6.3 Lemma.** *For any 1-coherent  $\infty$ -topos  $X$ , the locale  $\text{Open}(X)$  is coherent.*

**9.6.4 Lemma.** *Let  $f_* : X \rightarrow Y$  be a coherent geometric morphism between coherent  $\infty$ -topoi. Then the induced morphism  $\text{Open}(X) \rightarrow \text{Open}(Y)$  of coherent locales is coherent.*

**9.6.5 Corollary.** *Let  $S$  be a spectral topological space and  $f_* : X \rightarrow \tilde{S}$  an  $S$ -stratified  $\infty$ -topos. If  $X$  is coherent, then  $f_*$  is a constructible stratification if and only if the induced morphism of coherent locales  $\text{Open}(X) \rightarrow \text{Open}(S)$  is coherent.*

The following classical result is an important recognition principle for coherent locales.

**9.6.6 Proposition** ([48, Chapter II, §§3.3–3.4]). *The functor  $\text{Open} : \mathbf{TSp}^{spec} \rightarrow \mathbf{Top}_0$  given by sending a spectral topological space  $S$  to its locale of opens subsets factors through  $\mathbf{Top}_0^{coh}$  and defines an equivalence of categories*

$$\text{Open} : \mathbf{TSp}^{spec} \simeq \mathbf{Top}_0^{coh}.$$

**9.6.7.** The functor  $\text{Open} : \mathbf{TSp}^{spec} \simeq \mathbf{Top}_0^{coh}$  has an explicit inverse  $\mathbf{Top}_0^{coh} \simeq \mathbf{TSp}^{spec}$  given by taking the topological space of *points* of a locale; see [48, Chapter II, §1.3].

<sup>25</sup>Such elements are sometimes called *finite*; see [48, Chapter II, §3.1].

**9.6.8 Notation.** Lemma 9.6.4 and Proposition 9.6.6 provide a functor

$$S: \mathbf{Top}_\infty^{coh} \xrightarrow{\text{Open}} \mathbf{Top}_0^{coh} \xrightarrow{\sim} \mathbf{TSpc}^{spec},$$

which we denote by  $S$ . By definition, the 0-localic reflection of a coherent  $\infty$ -topos  $X$  is given by the  $\infty$ -topos of sheaves on the spectral topological space  $S(X)$ . Thus  $X$  comes equipped with a natural  $S(X)$ -stratification  $X \rightarrow \widetilde{S(X)}$ .

The localisation  $\mathbf{Top}_\infty \rightleftarrows \mathbf{Top}_0$  thus restricts to a localisation  $\mathbf{Top}_\infty^{coh} \rightleftarrows \mathbf{Top}_0^{coh}$ .

**9.6.9 Lemma.** *For any coherent  $\infty$ -topos  $X$ , the natural stratification  $f_*: X \rightarrow \widetilde{S(X)}$  is constructible (Definition 9.5.4).*

*Proof.* Clear from Corollary 9.6.5 and the fact that  $f_*: X \rightarrow \widetilde{S(X)}$  induces an equivalence of locales

$$\text{Open}(X) \simeq \text{Open}(\widetilde{S(X)}) = \text{Open}(S(X)). \quad \square$$

**9.6.10.** The source functor  $\mathbf{StrTop}_\infty^{\wedge, cc} \rightarrow \mathbf{Top}_\infty^{coh}$  admits a fully faithful left adjoint, given by the assignment

$$X \mapsto [X \rightarrow \widetilde{S(X)}].$$

The essential image of this left adjoint is the full subcategory spanned by those coherent constructible stratified  $\infty$ -topoi  $X \rightarrow \widetilde{S}$  such that the stratification induces an equivalence of locales  $\text{Open}(X) \simeq \text{Open}(S)$ .

The source functor  $\mathbf{StrTop}_\infty^{\wedge, cc} \rightarrow \mathbf{Top}_\infty^{coh}$  also admits a fully faithful right adjoint, which carries a coherent  $\infty$ -topos  $X$  to  $X$  again, equipped with the essentially unique stratification over  $S = \{0\}$ .

## 9.7 Stratified spaces & profinite stratified spaces as stratified $\infty$ -topoi

We now extend the functor  $\mathbf{Str}_\pi \rightarrow \mathbf{StrTop}_\infty$  given by  $\Pi \mapsto \widetilde{\Pi}$  to a functor on profinite stratified spaces.

**9.7.1 Notation.** Denote by  $\lambda: \mathbf{Str} \rightarrow \mathbf{StrTop}_\infty$  the left exact functor over  $poSet$  that is defined by the assignment  $\Pi \mapsto \widetilde{\Pi}$ . For each poset  $P$ , we consider also the functor on fibres  $\lambda_P: \mathbf{Str}_P \rightarrow \mathbf{StrTop}_{\infty, P}$ .

In light of Example 9.4.2, if  $P$  is finite, then the diagram

$$\begin{array}{ccc} \mathbf{Str}_{\pi, P} & \xrightarrow{\lambda_P} & \mathbf{StrTop}_{\infty, P}^{bcc} \\ N_P \downarrow \wr & & \downarrow \wr N_P \\ \mathbf{Dec}_P(\mathbf{S}_\pi) & \xrightarrow{\lambda_{\{0\}} \circ -} & \mathbf{Dec}_P(\mathbf{Top}_\infty^{bc}) \end{array}$$

commutes, where the vertical functors are equivalences (Definition 2.5.2, (4.2.5), and Theorem 9.4.3).

We now show that the functor  $\lambda$  is fully faithful. We first describe stratified geometric morphisms  $X \rightarrow \widetilde{\Pi}$  in a more familiar fashion. Let us begin with the case in which the base poset is trivial.

**9.7.2.** In light of [Recollection 5.1.6](#)=[HTT, Corollary 6.3.5.6], if  $\Pi$  is an essentially  $\delta_0$ -small space, then one has an equivalence

$$\mathrm{Map}_{\mathrm{Pro}(\mathcal{S})}(\Pi_{\infty}(\mathbf{X}), \Pi) \simeq \mathrm{Fun}_*(\mathbf{X}, \widetilde{\Pi}),$$

where  $\Pi_{\infty}(\mathbf{X})$  is the shape prospace  $\Gamma_{\mathbf{X},*} \Gamma_{\mathbf{X}}^* : \mathcal{S} \rightarrow \mathcal{S}$  ([Definition 5.13.1](#)). In particular,  $\mathrm{Fun}_*(\mathbf{X}, \widetilde{\Pi})$  is an essentially  $\delta_0$ -small Kan complex.

In this case, one also deduces that if  $\Pi, \Pi'$  are two essentially  $\delta_0$ -small spaces, then the natural map  $\mathrm{Map}_{\mathcal{S}}(\Pi', \Pi) \rightarrow \mathrm{Map}_{\mathrm{Top}_{\infty}}(\widetilde{\Pi}', \widetilde{\Pi})$  is an equivalence.

Now we extend this result to the context of  $P$ -stratified  $\infty$ -topoi.

**9.7.3 Notation.** Let  $P$  be a finite poset, and let  $f_* : \mathbf{X} \rightarrow \bar{P}$  and  $g_* : \mathbf{Y} \rightarrow \bar{P}$  be  $P$ -stratified  $\infty$ -topoi. Let us write

$$\mathrm{Fun}_{P,*}(\mathbf{X}, \mathbf{Y}) := \mathrm{Fun}_*(\mathbf{X}, \mathbf{Y}) \times_{\mathrm{Fun}_*(\mathbf{X}, \bar{P})} \{f_*\}.$$

The mapping space  $\mathrm{Map}_{\mathrm{StrTop}_{\infty,P}}(\mathbf{X}, \mathbf{Y})$  is the interior of  $\mathrm{Fun}_{P,*}(\mathbf{X}, \mathbf{Y})$ .

If  $\mathbf{X}$  and  $\mathbf{Y}$  are bounded coherent and constructibly stratified, then in light of [Theorem 9.4.3](#), one has an equivalence of  $\infty$ -categories

$$\mathrm{Fun}_{P,*}(\mathbf{X}, \mathbf{Y}) \simeq \int_{\Sigma \in \mathrm{sd}^{op}(P)} \mathrm{Fun}_*(N_P(\mathbf{X})(\Sigma), N_P(\mathbf{Y})(\Sigma)).$$

This implies the following.

**9.7.4 Proposition.** *If  $P$  is a finite poset, and  $\mathbf{X}$  is a bounded coherent constructible  $P$ -stratified  $\infty$ -topos, then for any  $\pi$ -finite  $P$ -stratified space  $\Pi$ , one has a natural equivalence*

$$\mathrm{Fun}_{P,*}(\mathbf{X}, \widetilde{\Pi}) \simeq \int_{\Sigma \in \mathrm{sd}^{op}(P)} \mathrm{Map}_{\mathrm{Pro}(\mathcal{S})}(\Pi_{\infty}(N_P(\mathbf{X})(\Sigma)), N_P(\Pi)(\Sigma)).$$

Since the right hand side is a  $\delta_0$ -small limit of  $\delta_0$ -small Kan complexes, we obtain the following.

**9.7.5 Corollary.** *If  $P$  is a finite poset, and  $\mathbf{X}$  is a bounded coherent constructible  $P$ -stratified  $\infty$ -topos, then for any  $\pi$ -finite  $P$ -stratified space  $\Pi$ , the  $\infty$ -category  $\mathrm{Fun}_{P,*}(\mathbf{X}, \widetilde{\Pi})$  is an essentially  $\delta_0$ -small  $\infty$ -groupoid.*

Additionally, the full faithfulness of  $\lambda_{\{0\}}$  now implies the following.

**9.7.6 Corollary.** *For any finite poset and any two  $\pi$ -finite  $P$ -stratified spaces  $\Pi$  and  $\Pi'$ , the functor*

$$\mathrm{Map}_P(\Pi', \Pi) \rightarrow \mathrm{Fun}_{P,*}(\widetilde{\Pi}', \widetilde{\Pi})$$

*is an equivalence. That is, the functor  $\lambda_P$  is a fully faithful functor  $\mathrm{Str}_{\pi,P} \hookrightarrow \mathrm{StrTop}_{\infty,P}^{bcc}$ .*

Finally, we obtain:

**9.7.7 Corollary.** *If  $P$  is a finite poset, then for any bounded coherent constructible  $P$ -stratified  $\infty$ -topos  $X$  and any filtered diagram  $\Pi : A \rightarrow \mathbf{Str}$  of  $\pi$ -finite  $P$ -stratified spaces, the natural map*

$$\operatorname{colim}_{\alpha \in A} \operatorname{Map}_{\mathbf{StrTop}_{\infty}}(X, \widetilde{\Pi}_{\alpha}) \rightarrow \operatorname{Map}_{\mathbf{StrTop}_{\infty}}(X, \operatorname{colim}_{\alpha \in A} \widetilde{\Pi}_{\alpha})$$

*is an equivalence.*

**9.7.8.** Please observe that the functor  $\lambda : \mathbf{Str}_{\pi} \hookrightarrow \mathbf{StrTop}_{\infty}^{bcc}$  is left exact. This is because the functor  $\mathbf{poSet}^{fin} \rightarrow \mathbf{Top}_{\infty}^{bc}$  given by  $P \mapsto \widetilde{P}$  is left exact, and for any finite poset  $P$ , the functor

$$\lambda_P : \mathbf{Str}_{\pi, P} \rightarrow \mathbf{StrTop}_{\infty, P}^{bcc}$$

is left exact, since as a functor  $\mathbf{D\acute{e}c}_P(\mathbf{S}_{\pi}) \rightarrow \mathbf{D\acute{e}c}_P(\mathbf{Top}_{\infty}^{bc})$  it is equivalent to composition with  $\lambda_{\{0\}}$ .

**9.7.9 Construction.** Since bounded coherent constructible stratified  $\infty$ -topoi are closed under the formation of inverse limits, we can now apply (0.3.2) and extend  $\lambda$  to a functor

$$\widehat{\lambda} : \mathbf{Str}_{\pi}^{\wedge} \rightarrow \mathbf{StrTop}_{\infty}^{\wedge, bcc}$$

over  $\mathbf{TSp}^{spec}$ , which we write as the assignment  $\Pi \mapsto \widetilde{\Pi}$ .

Let us caution that if  $S$  is a spectral topological space and  $\Pi$  is a profinite  $S$ -stratified space, then although  $S$  determines and is determined by the  $\mathbf{mat}(S)$ -stratified space  $\mathbf{mat}(\Pi)$ , the  $\infty$ -topoi  $\widetilde{\Pi}$  and  $\mathbf{mat}(\Pi)$  are quite different in general. The latter is always a presheaf  $\infty$ -category, but the former is typically not.

**9.7.10 Proposition.** *The functor  $\widehat{\lambda}$  is fully faithful. In particular, if  $S$  is a spectral topological space, then we obtain a fully faithful functor  $\mathbf{Str}_{\pi, S}^{\wedge} \hookrightarrow \mathbf{StrTop}_{\infty, S}^{\wedge, bcc}$ .*

*Proof.* First we treat the case in which  $S = P$  is a finite poset. In this case, in light of the equivalences

$$\mathbf{Str}_{\pi, P}^{\wedge} \simeq \mathbf{D\acute{e}c}_P(\mathbf{S}_{\pi}^{\wedge}) \quad \text{and} \quad \mathbf{StrTop}_{\infty, P}^{bcc} \simeq \mathbf{D\acute{e}c}_P(\mathbf{Top}_{\infty}^{bc})$$

of [Construction 4.3.3](#) and [Theorem 9.4.3](#), it suffices to prove that the functor

$$\mathbf{D\acute{e}c}_P(\mathbf{S}_{\pi}^{\wedge}) \rightarrow \mathbf{D\acute{e}c}_P(\mathbf{Top}_{\infty}^{bc})$$

given by the objectwise application of  $\widehat{\lambda}_{\{0\}} : \mathbf{Str}_{\pi}^{\wedge} \rightarrow \mathbf{Top}_{\infty}^{bc}$  is fully faithful. This follows as in [Corollary 9.7.6](#) from the full faithfulness of the functor  $\mathbf{S}_{\pi}^{\wedge} \rightarrow \mathbf{Top}_{\infty}^{bc}$ .

Now for a more general spectral topological space  $S$ , the identifications

$$\mathbf{Str}_{\pi, S}^{\wedge} \simeq \lim_{P \in \mathbf{FC}(S)} \mathbf{Str}_{\pi, P}^{\wedge} \quad \text{and} \quad \mathbf{StrTop}_{\infty, S}^{\wedge, bcc} \simeq \lim_{P \in \mathbf{FC}(S)} \mathbf{StrTop}_{\infty, P}^{bcc},$$

the first of which is [Proposition 3.2.5](#) and the latter of which is obvious, together complete the proof.  $\square$

**9.7.1.1 Proposition.** *Let  $P$  be a finite poset. Then the essential image of the functor*

$$\mathbf{D}\acute{\mathbf{e}}\mathbf{c}_P(\mathbf{S}_\pi^\wedge) \rightarrow \mathbf{D}\acute{\mathbf{e}}\mathbf{c}_P(\mathbf{Top}_\infty^{bc})$$

*given by the objectwise application of  $\widehat{\lambda}_{\{0\}} : \mathbf{Str}_\pi^\wedge \rightarrow \mathbf{Top}_\infty^{bc}$  is the full subcategory  $\mathbf{D}\acute{\mathbf{e}}\mathbf{c}_P(\mathbf{Top}_\infty^{Stone}) \subset \mathbf{D}\acute{\mathbf{e}}\mathbf{c}_P(\mathbf{Top}_\infty^{bc})$  spanned by those décollages over  $P$  that carry each string to a Stone  $\infty$ -topos.*

*Proof.* The only nontrivial point to verify is that indeed  $\widehat{\lambda}$  carries décollages in profinite spaces to décollages in Stone  $\infty$ -topoi. This follows from [Example 8.7.6](#).  $\square$

The essential image of  $\widehat{\lambda}$  can be characterised as the  $\infty$ -category of *spectral*  $\infty$ -topoi, to which we shall now turn.

## 10 Spectral higher topoi

In this section, we define the notion of a *spectral*  $\infty$ -topos. The idea is that, on one hand, these are the kinds of  $\infty$ -topoi that arise as the étale  $\infty$ -topoi of coherent schemes, and on the other, these will turn out to be precisely the  $\infty$ -topoi that arise as  $\overline{\Pi}$  for some profinite stratified space  $\Pi$ .

We begin with some preliminary results on the interaction between Stone  $\infty$ -topoi and oriented fibre products.

### 10.1 Stone $\infty$ -topoi & oriented fibre products

In this subsection we prove two useful facts about oriented fibre products involving Stone  $\infty$ -topoi.

**10.1.1 Proposition.** *Let  $f_* : X \rightarrow Z$  and  $g_* : Y \rightarrow Z$  be geometric morphisms of  $\infty$ -topoi. If  $Z$  is Stone, then the natural geometric morphism  $X \times_Z Y \rightarrow X \tilde{\times}_Z Y$  is an equivalence.*

*Proof.* It suffices to show that the projections  $\mathrm{pr}_{1,*}, \mathrm{pr}_{2,*} : \mathrm{Path}(Z) \rightarrow Z$  are equivalences. Since  $Z$  is Stone, by [Lemma 6.7.6](#) the  $\infty$ -topos  $\mathrm{Path}(Z)$  is bounded coherent, and [Theorem 5.14.9](#)=[SAG, Theorem E.3.4.1] shows that the  $\infty$ -category  $\mathrm{Pt}(Z)$  is an  $\infty$ -groupoid. Thus

$$\mathrm{Pt}(\mathrm{Path}(Z)) \simeq \mathrm{Fun}(\Delta^1, \mathrm{Pt}(Z))$$

is an  $\infty$ -groupoid as well, and again appealing to [Theorem 5.14.9](#)=[SAG, Theorem E.3.4.1] we conclude that  $\mathrm{Path}(Z)$  is Stone. The claim now follows from the fact that  $\mathrm{pr}_{1,*}$  and  $\mathrm{pr}_{2,*}$  are shape equivalences ([Example 7.3.6](#)).  $\square$

**10.1.2 Proposition.** *Let  $X$  and  $Y$  be Stone  $\infty$ -topoi,  $Z$  a bounded coherent  $\infty$ -topos, and  $f_* : X \rightarrow Z$  and  $g_* : Y \rightarrow Z$  coherent geometric morphisms. Then the oriented fibre product  $X \tilde{\times}_Z Y$  is a Stone  $\infty$ -topos.*

*Proof.* By [Lemma 6.7.6](#) the  $\infty$ -topos  $X \tilde{\times}_Z Y$  is bounded coherent, so by [Theorem 5.14.9](#) = [\[SAG, Theorem E.3.4.1\]](#) it suffices to prove that the  $\infty$ -category  $\mathrm{Pt}(X \tilde{\times}_Z Y)$  is an  $\infty$ -groupoid. In light of [Lemma 6.5.8](#) we have  $\mathrm{Pt}(X \tilde{\times}_Z Y) \simeq \mathrm{Pt}(X) \downarrow_{\mathrm{Pt}(Z)} \mathrm{Pt}(Y)$ , so the fact that  $\mathrm{Pt}(X)$  and  $\mathrm{Pt}(Y)$  are  $\infty$ -groupoids implies that the  $\infty$ -category  $\mathrm{Pt}(X \tilde{\times}_Z Y)$  is as well.  $\square$

## 10.2 Spectral $\infty$ -topoi & toposic décollages

In this subsection we define the  $\infty$ -toposic generalization of spectral topological spaces relevant for our  $\infty$ -Categorical Hochster Duality Theorem ([Theorem 10.3.1](#)).

**10.2.1 Definition.** Let  $S$  be a spectral topological space. An  $S$ -stratified  $\infty$ -topos  $X \rightarrow \tilde{S}$  is a *spectral*  $S$ -stratified  $\infty$ -topos if and only if the following conditions are satisfied.

- The  $\infty$ -topos  $X$  is bounded and coherent.
- The stratification by  $S$  is constructible.
- For every point  $s \in S$ , the stratum  $X_s$  is a Stone  $\infty$ -topos.

We write  $\mathbf{StrTop}_{\infty, S}^{\mathrm{spec}} \subset \mathbf{StrTop}_{\infty, S}^{\wedge, \mathrm{bcc}}$  for the full subcategory spanned by the spectral  $S$ -stratified  $\infty$ -topoi.

More generally, write

$$\mathbf{StrTop}_{\infty}^{\mathrm{spec}} \subset \mathbf{StrTop}_{\infty}^{\wedge, \mathrm{bcc}}$$

for the full subcategory whose objects are spectral  $\infty$ -topoi and whose morphisms are squares

$$\begin{array}{ccc} X' & \longrightarrow & X \\ \downarrow & & \downarrow \\ \tilde{S}' & \longrightarrow & \tilde{S} \end{array}$$

of coherent geometric morphisms. We observe that the pullback of a spectral  $\infty$ -topos along the geometric morphism induced by a quasicompact continuous map is again spectral, whence the functor  $\mathbf{StrTop}_{\infty}^{\mathrm{spec}} \rightarrow \mathbf{TSp}^{\mathrm{spec}}$  is a cartesian fibration.

**10.2.2 Example.** Let  $\Pi \rightarrow S$  be a profinite stratified space ([Definition 3.2.1](#)). Then  $\tilde{\Pi}$  is a spectral  $\infty$ -topos, as the fibres  $\tilde{\Pi}_s \simeq \tilde{\Pi}_s$  are Stone  $\infty$ -topoi.

**10.2.3.** In [Theorem 10.3.1](#), we will prove the central  $\infty$ -Categorical Hochster Duality Theorem, which states that *every* spectral  $\infty$ -topos is of the form  $\tilde{\Pi}$  for some profinite stratified space.

**10.2.4 Example.** Let  $X$  be a coherent scheme. Write  $X^{\mathrm{zar}}$  for its underlying Zariski spectral topological space, and let  $X_{\acute{\mathrm{e}}\mathrm{t}}$  denote its coherent, 1-localic étale  $\infty$ -topos. The identification  $\mathrm{Open}(X_{\acute{\mathrm{e}}\mathrm{t}}) \cong \mathrm{Open}(X^{\mathrm{zar}})$  provides a canonical  $X^{\mathrm{zar}}$ -stratification of  $X_{\acute{\mathrm{e}}\mathrm{t}}$ . For any point  $x \in X^{\mathrm{zar}}$ , the stratum  $(X_{\acute{\mathrm{e}}\mathrm{t}})_x$  is identified with  $(\mathrm{Spec} \kappa(x))_{\acute{\mathrm{e}}\mathrm{t}}$ , which is the Stone  $\infty$ -topos  $\widehat{BG_{\kappa(x)}}$ . Consequently  $X_{\acute{\mathrm{e}}\mathrm{t}}$  is a spectral  $\infty$ -topos.

**10.2.5 Proposition.** *Let  $S$  be a spectral topological space, and let  $X$  be a bounded coherent constructible  $S$ -stratified  $\infty$ -topos. Then  $X$  is spectral if and only if the functor*

$$\mathrm{Pt}(X) \rightarrow \mathrm{Pt}(\bar{S}) \simeq \mathrm{mat}(S)$$

*exhibits  $\mathrm{Pt}(X)$  as a  $\mathrm{mat}(S)$ -stratified space.*

*Proof.* This follows directly from [Theorem 5.14.9](#)=[SAG, Theorem E.3.4.1].  $\square$

**10.2.6.** Let  $P$  be a finite poset. We now consider the nerve of a spectral  $P$ -stratified  $\infty$ -topos  $X \rightarrow \bar{P}$ . Since each stratum  $X_p$  is Stone, it follows from [Proposition 10.1.2](#) that for any string  $\{p_0 \leq \dots \leq p_n\} \subseteq P$ , the value

$$N_P(X)\{p_0 \leq \dots \leq p_n\} \simeq X_{p_0} \tilde{\times}_X X_{p_1} \tilde{\times}_X \dots \tilde{\times}_X X_{p_n}$$

is a Stone  $\infty$ -topos. Consequently, we deduce that the equivalence

$$N_P : \mathrm{StrTop}_{\infty, P}^{bcc} \xrightarrow{\sim} \mathrm{D\acute{e}c}_P(\mathrm{Top}_{\infty}^{bc})$$

restricts to an equivalence between the  $\infty$ -category of spectral  $P$ -stratified  $\infty$ -topoi and the full subcategory  $\mathrm{D\acute{e}c}_P(\mathrm{Top}_{\infty}^{\mathrm{Stone}}) \subset \mathrm{D\acute{e}c}_P(\mathrm{Top}_{\infty}^{bc})$  spanned by those décollages over  $P$  that carry each string to a Stone  $\infty$ -topos.

**10.2.7 Lemma.** *Let  $P$  be a finite poset. Then the nerve equivalence*

$$N_P : \mathrm{StrTop}_{\infty, P}^{bcc} \xrightarrow{\sim} \mathrm{D\acute{e}c}_P(\mathrm{Top}_{\infty}^{bc})$$

*restricts to an equivalence  $\mathrm{StrTop}_{\infty, P}^{\mathrm{spec}} \xrightarrow{\sim} \mathrm{D\acute{e}c}_P(\mathrm{Top}_{\infty}^{\mathrm{Stone}})$ .*

### 10.3 Hochster duality for higher topoi

In [\(1.3.5\)](#) we described Hochster duality as a cube of dualities: the equivalence of 1-categories between profinite posets and spectral topological spaces restricts on one hand to an equivalence of 1-categories between profinite sets and Stone spaces, and on the other to an equivalence of 1-categories between finite posets and finite topological spaces. Our objective now is to exhibit the analogous cube for higher topoi:

$$\begin{array}{ccccc} & & S_{\pi} & \xrightarrow{\sim} & \mathrm{Top}_{\infty}^{\mathrm{fin}} \\ & \swarrow & \uparrow & & \swarrow \\ S_{\pi}^{\wedge} & \xrightarrow{\sim} & \mathrm{Top}_{\infty}^{\mathrm{Stone}} & & \downarrow \\ \downarrow & & \downarrow & & \downarrow \\ & \swarrow & \mathrm{Str}_{\pi} & \xrightarrow{\sim} & \mathrm{StrTop}_{\infty}^{\mathrm{fin}} \\ \downarrow & & \downarrow & & \downarrow \\ \mathrm{Str}_{\pi}^{\wedge} & \xrightarrow{\sim} & \mathrm{StrTop}_{\infty}^{\mathrm{spec}} & & \end{array},$$

where the vertical fully faithful functors are given by equipping an object with the trivial stratification. The top face of this cube was established by Lurie [\[SAG, Appendix E\]](#). We must now address the bottom face, more precisely the equivalence  $\mathrm{Str}_{\pi}^{\wedge} \simeq \mathrm{StrTop}_{\infty}^{\mathrm{spec}}$ .

**10.3.1 Theorem** ( $\infty$ -Categorical Hochster Duality). *Let  $S$  be a spectral topological space. Then the functor*

$$\widehat{\lambda}_S : \mathbf{Str}_{\pi, S}^{\wedge} \rightarrow \mathbf{StrTop}_{\infty, S}^{spec}$$

*given by the assignment  $\Pi \mapsto \widetilde{\Pi}$  is an equivalence of  $\infty$ -categories. Consequently, the functor*

$$\widehat{\lambda} : \mathbf{Str}_{\pi}^{\wedge} \rightarrow \mathbf{StrTop}_{\infty}^{spec}$$

*is an equivalence of  $\infty$ -categories.*

*Proof.* Since  $\widehat{\lambda}$  is fully faithful ([Proposition 9.7.10](#)) and preserves inverse limits, it suffices to prove that for any finite poset  $P$ , the fully faithful functor  $\widehat{\lambda} : \mathbf{Str}_{\pi, P}^{\wedge} \hookrightarrow \mathbf{StrTop}_{\infty, P}^{spec}$  is essentially surjective.

This now follows from the conjunction of [Lemma 10.2.7](#) and [Proposition 9.7.11](#).  $\square$

The back face of the cube is now just a restriction of the front face: we define  $\mathbf{Top}_{\infty}^{fin}$  as the full subcategory of  $\mathbf{Top}_{\infty}^{Stone}$  spanned by the essential image of the fully faithful functor  $S_{\pi} \hookrightarrow \mathbf{Top}_{\infty}^{Stone}$  given by  $\Pi \mapsto S_{/\Pi} \simeq \text{Fun}(\Pi, S)$ . Then  $\mathbf{StrTop}_{\infty}^{fin}$  is the  $\infty$ -category of bounded coherent constructible  $\infty$ -topoi over a finite poset  $P$  such that for every point  $p \in P$ , the  $\infty$ -topos  $X_p$  is in  $\mathbf{Top}_{\infty}^{fin}$ .

## 10.4 Constructible sheaves

The truncated coherent objects of a Stone  $\infty$ -topos are exactly the *lisse sheaves* ([Recollection 5.14.10](#)). This turns out to be a defining property of Stone  $\infty$ -topoi ([Proposition 5.14.13](#)=[[SAG](#), Proposition E.3.1.1]). In the same manner, the truncated coherent objects of a spectral  $\infty$ -topos are exactly the *constructible sheaves*, to which we now turn.

**10.4.1 Definition.** Let  $P$  be a noetherian poset and  $X$  a  $P$ -stratified  $\infty$ -topos. An object  $F \in X$  is said to be *formally constructible* (or *formally  $P$ -constructible* if disambiguation is called for) if and only if, for any point  $p \in P$ , the restriction  $F|_{X_p} := e_p^* F \in X_p$  is a local system, where  $e_{p,*} : X_p \hookrightarrow X$  is the inclusion of the  $p$ -th stratum.

We say that  $F$  is *constructible* (or  *$P$ -constructible*) if and only if the following pair of conditions is satisfied:

- The object  $F$  is formally constructible.
- For any point  $p \in P$ , the restriction  $F|_{X_p} \in X_p$  is lisse.

**10.4.2.** This notion of constructibility depends upon the whole structure of the stratified  $\infty$ -topos, not only upon the underlying  $\infty$ -topos.

**10.4.3.** For any noetherian poset  $P$  and  $P$ -stratified  $\infty$ -topos  $X \rightarrow \bar{P}$ , the  $\infty$ -category of constructible sheaves on  $X$  is given by the pullback of  $\infty$ -categories:

$$\begin{array}{ccc} \mathbf{X}^{P\text{-constr}} & \xrightarrow{\quad} & \prod_{p \in P} \mathbf{X}_p^{lisse} \\ \downarrow & \lrcorner & \downarrow \\ \mathbf{X} & \xrightarrow{\prod_{p \in P} e_p^*} & \prod_{p \in P} \mathbf{X}_p \end{array} ,$$



where here  $\prod_{p \in P} X_p$  is the product in  $\mathbf{Cat}_{\infty, \delta_1}$ . [Lemmas 5.8.4](#) and [5.8.5](#) now show that  $X^{P\text{-constr}}$  is an  $\infty$ -pretopos ([Definition 5.8.2](#)) and the inclusion  $X^{P\text{-constr}} \hookrightarrow X$  is a morphism of  $\infty$ -pretopoi.

**10.4.4.** If  $P$  is a nonnoetherian poset, [Definition 10.4.1](#) is insufficient, and one needs to assume also the following convergence condition:

- for any ideal  $A \subseteq P$ , if we write  $i_{A,*} : X_A \hookrightarrow X$  for the closed immersion, then the natural morphism

$$i_A^* F \rightarrow \lim_{p \in A^{op}} i_{p,*} i_p^* F$$

is an equivalence, where  $i_{p,*} : X_{\leq p} \hookrightarrow X_A$  is the inclusion of the closed subtopos.

This condition is automatically satisfied for noetherian stratifications, which are our sole concern in this text.

The pullback of a geometric morphism of  $\infty$ -topoi preserves lisse objects (see [Recollection 5.14.10](#)); in the same manner, the pullback of a morphism of stratified  $\infty$ -topoi preserves constructible objects.

**10.4.5 Lemma.** *Let  $f : P' \rightarrow P$  be a morphism of noetherian posets, and let  $X' \rightarrow \tilde{P}'$  and  $X \rightarrow \tilde{P}$  be stratified  $\infty$ -topoi. Then for any geometric morphism  $q_* : X' \rightarrow X$  over  $f_* : \tilde{P}' \rightarrow \tilde{P}$ , the pullback  $q^* : X \rightarrow X'$  sends  $P$ -constructible objects of  $X$  to  $P'$ -constructible objects of  $X'$ . Hence  $q^*$  restricts to a morphism of  $\infty$ -pretopoi*

$$q^* : X^{P\text{-constr}} \rightarrow (X')^{P'\text{-constr}}.$$

*Proof.* Let  $F \in X^{P\text{-constr}}$  be a  $P$ -constructible object of  $X$ . Then for any point  $p \in P'$ , the restriction  $F|_{X_{f(p)}}$  is lisse, so since the pullback in a geometric morphism preserves lisse objects, we see that  $q^*(F)|_{X'_p}$  is lisse. Hence  $q^*(F)$  is  $P'$ -constructible.

The fact that  $q^* : X^{P\text{-constr}} \rightarrow (X')^{P'\text{-constr}}$  is a morphism of  $\infty$ -pretopoi is immediate from [\(10.4.3\)](#).  $\square$

**10.4.6 Proposition.** *Let  $P$  be a finite poset and  $X \rightarrow \tilde{P}$  a  $P$ -stratified  $\infty$ -topos. Then the  $\infty$ -pretopos  $X^{P\text{-constr}}$  is bounded ([Definition 5.8.7](#)).*

*Proof.* If  $P = \emptyset$ , then the claim is obvious, so assume that  $P$  is nonempty. We prove the claim by induction on the rank of  $P$ .

In the base case where  $P$  has rank 0,  $P$  is discrete, so  $X$  is finite the coproduct of  $\infty$ -topoi  $\coprod_{p \in P} X_p$  (which is the product  $\prod_{p \in P} X_p$  in  $\mathbf{Cat}_{\infty, \delta_1}$ ). Thus  $X^{P\text{-constr}}$  is the product of  $\infty$ -categories:

$$X^{P\text{-constr}} = \prod_{p \in P} X_p^{\text{lisse}}.$$

By [Theorem 5.14.15](#)=[SAG, Theorem E.2.3.2], for all  $p \in P$  the  $\infty$ -pretopos  $X_p^{\text{lisse}}$  is bounded; the finiteness of  $P$  and [Lemma 5.8.9](#) now show that  $X^{P\text{-constr}}$  is also bounded.

For the induction step, let  $n \geq 0$  be a natural number and assume that the claim holds for all finite posets  $P$  of rank  $n$  and  $P$ -stratified  $\infty$ -topoi  $X \rightarrow \tilde{P}$ . Let  $P$  be a finite poset of rank  $n + 1$ , and write  $M \subset P$  for the full subposet spanned by the minimal elements

of  $P$ . Then  $M$  is discrete and closed in  $P$ . Write  $U := P \setminus M$  for the open complement of  $M$  in  $P$ . Then  $U$  is a poset of rank  $n$ . Moreover, since  $\tilde{P}$  is the recollement of  $\tilde{M}$  and  $\tilde{U}$ , the  $P$ -stratified  $\infty$ -topos  $X$  is the recollement of  $X_M$  and  $X_U$ . An object  $F \in X$  is  $P$ -constructible if and only if  $F|_{X_M}$  and  $F|_{X_U}$  are both constructible, from which we deduce that  $X^{P\text{-constr}}$  is the oriented fibre product of  $\infty$ -categories

$$X^{P\text{-constr}} \simeq X_M^{M\text{-constr}} \downarrow_{X_M} X_U^{U\text{-constr}}.$$

Since  $M$  is a poset of rank 0 and  $U$  is a poset of rank  $n$ , by the induction hypothesis both  $X_M^{M\text{-constr}}$  and  $X_U^{U\text{-constr}}$  are bounded  $\infty$ -pretopoi. To conclude that the  $\infty$ -pretopos  $X^{P\text{-constr}}$  is a bounded, note that by (6.1.2) every object of  $X^{P\text{-constr}}$  is truncated and by (0.4.2) the  $\infty$ -category  $X^{P\text{-constr}}$  is essentially  $\delta_0$ -small.  $\square$

**10.4.7 Definition.** Let  $S$  be a spectral topological space and  $X$  an  $S$ -stratified  $\infty$ -topos. We say that an object  $F \in X$  is *formally constructible* (or *formally  $S$ -constructible*) if and only if there exist a finite poset  $P$  and a constructible stratification  $S \rightarrow P$  of posets such that  $F$  is formally  $P$ -constructible. We say that  $F$  is *constructible* (or  *$S$ -constructible*) if and only if there exist a poset  $P$  and a finite constructible stratification  $S \rightarrow P$  of posets such that  $F$  is  $P$ -constructible.

For any spectral topological space  $S$  and any  $S$ -stratified  $\infty$ -topos  $X \rightarrow \tilde{S}$ , we denote by  $X^{S\text{-fconstr}} \subseteq X$  (respectively, by  $X^{S\text{-constr}} \subseteq X$ ) the full subcategory spanned by the formally constructible objects (respectively, the constructible objects).

**10.4.8.** For any spectral topological space  $S$  and  $S$ -stratified  $\infty$ -topos  $X \rightarrow \tilde{S}$ , the  $\infty$ -category of constructible sheaves on  $X$  is thus a filtered colimit of  $\infty$ -categories:

$$X^{S\text{-constr}} \simeq \operatorname{colim}_{P \in \operatorname{FC}(S)^{op}} X^{P\text{-constr}}.$$

Thus Lemma 10.4.5 and Proposition 10.4.6 combined with Proposition 5.9.1=[SAG, Proposition A.8.3.1] show that  $X^{S\text{-constr}}$  is a bounded  $\infty$ -pretopos. Moreover, (10.4.3) shows that the inclusion  $X^{S\text{-constr}} \hookrightarrow X$  is a morphism of  $\infty$ -pretopoi.

From Lemma 10.4.5 we now immediately deduce the following.

**10.4.9 Lemma.** *Let  $f : S' \rightarrow S$  be a quasicompact continuous map of spectral topological spaces, and let  $X' \rightarrow \tilde{S}'$  and  $X \rightarrow \tilde{S}$  be stratified  $\infty$ -topoi. Then for any geometric morphism  $q_* : X' \rightarrow X$  over  $f_* : \tilde{S}' \rightarrow \tilde{S}$ , the pullback  $q^* : X \rightarrow X'$  sends  $S$ -constructible objects of  $X$  to  $S'$ -constructible objects of  $X'$ . Hence  $q^*$  restricts to a morphism of  $\infty$ -pretopoi*

$$q^* : X^{S\text{-constr}} \rightarrow (X')^{S'\text{-constr}}.$$

We now turn to the relationship between coherence and constructibility in  $\infty$ -topoi stratified by a spectral topological space.

**10.4.10 Lemma.** *Let  $S$  be a spectral topological space, and let  $X$  be an  $S$ -stratified  $\infty$ -topos. Then an object  $F$  of  $X$  is constructible if and only if, for every point  $s \in S$ , there exists a constructible subset  $W \subseteq S$  containing  $s$  such that  $F|_{X_W}$  is lisse.*

*Proof.* The ‘only if’ direction is clear. Conversely, assume that every point of  $S$  is contained in such a constructible set. Hence the collection  $\{W_\alpha\}_{\alpha \in A}$  of constructible subsets of  $S$  such that  $F|_{X_{W_\alpha}}$  is lisse is a cover of  $S$  by constructible subsets. Since the constructible topology on  $S$  is quasicompact, it follows that there exists a finite subcover  $\{W_\alpha\}_{\alpha \in A'}$ . Select a finite constructible stratification  $S \rightarrow P$  of  $S$  such that for every  $p \in P$ , there exists an  $\alpha \in A'$  such that the stratum  $S_p \subseteq W_\alpha$ . Now  $F$  is  $P$ -constructible.  $\square$

**10.4.11 Lemma.** *Let  $S$  be a spectral topological space, and  $X \rightarrow \tilde{S}$  a coherent coherent constructible  $S$ -stratified  $\infty$ -topos. Then every constructible object of  $X$  is truncated and coherent. If  $X$  is also bounded and every truncated and coherent object of  $X$  is constructible, then  $X$  is spectral.*

*Proof.* For the first statement, let  $F \in X^{S\text{-constr}}$ , and let  $S \rightarrow P$  be a finite constructible stratification such that for every point  $p \in P$ , the restriction  $F|_{X_p}$  is lisse. By **Proposition 6.1.8**=[**DAG XIII**, Proposition 2.3.22] it follows that  $F$  is coherent. If each  $F|_{X_p}$  is  $N$ -truncated, then  $F$  is  $N$ -truncated.

For the second statement, if every truncated coherent object of  $X$  is constructible and  $X$  is bounded, then  $X \simeq \mathbf{Sh}_{\text{eff}}(X^{S\text{-constr}})$ . For any point  $s \in S$ , one thus has an equivalence  $X_s \simeq \mathbf{Sh}_{\text{eff}}(X_s^{\text{lisse}})$ , which is a Stone  $\infty$ -topos. Thus  $X$  is spectral.  $\square$

**10.4.12 Proposition.** *If  $S$  is a spectral topological space, and  $X$  is a spectral  $S$ -stratified  $\infty$ -topos  $X$ , then every truncated and coherent object of  $X$  is constructible.*

*Proof.* Let  $F$  be a truncated coherent object of  $X$ , and  $s \in S$  a point. We wish to show that there exists a constructible subset of  $W \subset S$  containing  $s$  such that  $F|_{X_W}$  is lisse (**Lemma 10.4.10**). Passing to the closure of  $s$ , it suffices to assume that  $S$  is irreducible, and  $s$  is its generic point.

Since  $F|_{X_s}$  is lisse, it follows from **Lemma 5.14.11**=[**SAG**, Proposition E.2.7.7] that there exists a full subcategory  $E \subset \mathbf{S}_\pi$  spanned by finitely many  $\pi$ -finite spaces and a unique geometric morphism  $g_* : X_s \rightarrow \mathbf{S}_{/IE}$  and an equivalence  $\varepsilon_s : F|_{X_s} \simeq g^*(I)$ , where  $I$  is the inclusion functor  $E \hookrightarrow \mathbf{S}$ . Now since  $\mathbf{S}_{/IE}$  is cocompact as an object of  $\mathbf{Top}_\infty^{bc}$  (**Lemma 5.14.12**) and  $X_s$  is identified with the limit  $\lim_W X_W$  over constructible subsets  $W \subset S$  containing  $s$ , it follows that for some such  $W$ , one may factor  $g_*$  through a geometric morphism  $g_{W,*} : X_W \rightarrow \mathbf{S}_{/IE}$ . Now since  $X_{s,<\infty}^{\text{coh}} \simeq \text{colim}_W X_{W,<\infty}^{\text{coh}}$ , we shrink  $W$  as needed to ensure that there exists an equivalence  $\varepsilon_s : F|_{X_W} \simeq g_W^*(I)$ , and conclude that  $F$  is lisse on  $W$ .  $\square$

**10.4.13 Example.** If  $X$  is a coherent scheme, then the truncated coherent objects of  $X_{\text{ét}}$  are precisely the constructible sheaves of spaces. This is the nonabelian analogue of the well-known result that for a finite ring  $\Lambda$ , the compact objects of  $\mathbf{Sh}_{\text{ét}}(X; D(\Lambda))$  coincide with the bounded derived  $\infty$ -category of constructible  $\Lambda$ -sheaves.

We have shown that the  $\infty$ -category  $\mathbf{Str}_\pi^\wedge$  of profinite stratified spaces is equivalent to the  $\infty$ -category  $\mathbf{StrTop}_\infty^{\text{spec}}$ , which is in turn a full subcategory of  $\mathbf{StrTop}_\infty^{\wedge, bcc}$  of bounded coherent constructible stratified  $\infty$ -topoi. This last  $\infty$ -category is a *non-full* subcategory of  $\mathbf{StrTop}_\infty^\wedge$ , however. Just as how every geometric morphism between Stone  $\infty$ -topoi is coherent (**Corollary 5.14.14**=[**SAG**, Corollary E.3.1.2]), the subcategory  $\mathbf{StrTop}_\infty^{\text{spec}} \subset \mathbf{StrTop}_\infty^\wedge$  is full, as we shall now explain.

**10.4.14 Proposition.** *Let  $f : S' \rightarrow S$  be a quasicompact continuous map of spectral topological spaces, let  $X' \rightarrow \tilde{S}'$  be a coherent constructible stratified  $\infty$ -topos, and let  $X \rightarrow \tilde{S}$  be a spectral  $\infty$ -topos. Then any geometric morphism  $q_* : X' \rightarrow X$  over  $f_* : \tilde{S}' \rightarrow \tilde{S}$  is coherent.*

*Proof.* By [Corollary 5.4.5](#) it suffices to show that if  $F \in X$  is truncated and coherent, then  $p^*F$  is coherent. By [Proposition 10.4.12](#)

$$X^{S\text{-constr}} = X_{<\infty}^{\text{coh}},$$

so the claim now follows from the facts that  $q^*$  preserves constructibility ([Lemma 10.4.9](#)) and the  $S'$ -constructible objects of  $X'$  are truncated coherent ([Lemma 10.4.11](#)).  $\square$

**10.4.15 Corollary.** *The subcategory  $\mathbf{StrTop}_{\infty}^{\text{spec}} \subset \mathbf{StrTop}_{\infty}^{\wedge}$  is full.*

**10.4.16 Construction.** Let  $S$  be a spectral topological space, and  $X$  an  $S$ -stratified  $\infty$ -topos. By [\[SAG, Proposition A.6.4.4\]](#), the fully faithful inclusion  $X^{S\text{-constr}} \hookrightarrow X$  of  $\infty$ -pre-topoi extends (essentially uniquely) to a geometric morphism  $X \rightarrow \mathbf{Sh}_{\text{eff}}(X^{S\text{-constr}})$  over  $\tilde{S}$ . By construction, the  $S$ -stratified  $\infty$ -topos

$$X^{S\text{-spec}} := \mathbf{Sh}_{\text{eff}}(X^{S\text{-constr}})$$

is spectral. Furthermore,  $X^{S\text{-spec}}$  is the universal spectral  $S$ -stratified  $\infty$ -topos receiving a geometric morphism over  $\tilde{S}$  from  $X$ . Thus the assignment

$$X \mapsto X^{S\text{-spec}}$$

provides a relative left adjoint to the inclusion  $\mathbf{StrTop}_{\infty}^{\text{spec}} \hookrightarrow \mathbf{StrTop}_{\infty}^{\wedge}$  over  $\mathbf{TSp}^{\text{spec}}$ , which we call the *spectrification*. This is the stratified analogue of the Stone reflection ([Theorem 5.14.15](#)).

**10.4.17 Example.** When  $S = [n]$ , the spectrification of a bounded coherent  $\infty$ -topos  $X$  equipped with a constructible stratification by  $[n]$  can be identified as an iterated bounded coherent oriented pushout:

$$X^{[n]\text{-spec}} \simeq X_0^{\text{Stone}} \mathrel{\mathop{\smash{\rightarrow}}\limits_{bc}}^{(X_0 \times_X X_1)^{\text{Stone}}} \dots \mathrel{\mathop{\smash{\rightarrow}}\limits_{bc}}^{(X_{n-1} \times_X X_n)^{\text{Stone}}} X_n^{\text{Stone}}.$$

**10.4.18 Construction.** Thanks to the existence of the spectrification functor, we deduce the forgetful functor  $\mathbf{StrTop}_{\infty}^{\text{spec}} \rightarrow \mathbf{TSp}^{\text{spec}}$  is a cocartesian fibration (as well as a cartesian fibration): for any quasicompact continuous map  $f : S' \rightarrow S$  and any spectral  $S'$ -stratified  $\infty$ -topos  $X$ , the stratified geometric morphism  $X \rightarrow X^{S\text{-spec}}$  is a cocartesian edge over  $f$ .

**10.4.19 Lemma.** *Let  $S$  be a spectral topological space. Then the natural functor*

$$\mathbf{StrTop}_{\infty, S}^{\text{spec}} \rightarrow \lim_{P \in \mathbf{FC}(S)} \mathbf{StrTop}_{\infty, P}^{\text{spec}}$$

*is an equivalence of  $\infty$ -categories.*

*Proof.* The formation of the limit is an inverse.  $\square$

## 11 Profinite stratified shape

In this section we investigate the inverse to the equivalence of  $\infty$ -categories

$$\widehat{\lambda}: \mathbf{Str}_{\pi}^{\wedge} \simeq \mathbf{StrTop}_{\infty}^{spec}$$

provided by  $\infty$ -Categorical Hoshster Duality. This inverse equivalence provides a stratified refinement of the profinite shape (Example 11.1.6).

### 11.1 The definition of the profinite stratified shape

**11.1.1 Construction.** We have constructed (Theorem 10.3.1) an equivalence of  $\infty$ -categories  $\widehat{\lambda}: \mathbf{Str}_{\pi}^{\wedge} \simeq \mathbf{StrTop}_{\infty}^{spec}$  over  $\mathbf{TSp}^{spec}$ , given by the assignment  $\Pi \mapsto \widetilde{\Pi}$ . The further inclusion  $\mathbf{StrTop}_{\infty}^{spec} \hookrightarrow \mathbf{StrTop}_{\infty}^{\wedge}$  admits a left adjoint, given by spectrification (Construction 10.4.16). We therefore obtain an adjunction

$$\Pi_{(\infty,1)}^{\wedge}: \mathbf{StrTop}_{\infty}^{\wedge} \rightleftarrows \mathbf{Str}_{\pi}^{\wedge}: \widehat{\lambda}$$

in which the left adjoint carries a stratified  $\infty$ -topos  $X \rightarrow \widetilde{S}$  to the profinite  $S$ -stratified space that as a left exact accessible functor  $\mathbf{Str}_{\pi} \rightarrow \mathbf{S}$  is given by

$$\Pi \mapsto \mathrm{Map}_{\mathbf{StrTop}_{\infty}^{\wedge}}(X, \widetilde{\Pi}).$$

Over any spectral topological space  $S$ , we obtain an adjunction

$$\Pi_{(\infty,1)}^{S,\wedge}: \mathbf{StrTop}_{\infty,S}^{\wedge} \rightleftarrows \mathbf{Str}_{\pi,S}^{\wedge}: \widehat{\lambda}_S$$

over  $S$ .

**11.1.2 Example.** For any spectral topological space  $S$  and any profinite  $S$ -stratified space  $\Pi$ , we have  $\Pi_{(\infty,1)}^{S,\wedge}(\widetilde{\Pi}) \simeq \Pi$ .

**11.1.3 Example.** The functor  $\Pi_{(\infty,1)}^{\{0\},\wedge}$  is the profinite shape of Definition 5.14.2.

**11.1.4 Definition.** Let  $S$  be a spectral topological space, and let  $X \rightarrow \widetilde{S}$  be an  $S$ -stratified  $\infty$ -topos. Then we call the profinite  $S$ -stratified space  $\Pi_{(\infty,1)}^{S,\wedge}(X)$  the *S-stratified homotopy type* of  $X$ .

**11.1.5.** Since left adjoints compose, if  $\eta: S' \rightarrow S$  is a quasicompact continuous map of spectral topological spaces, then there is a natural equivalence

$$\eta! \Pi_{(\infty,1)}^{S',\wedge} \simeq \Pi_{(\infty,1)}^{S,\wedge}.$$

**11.1.6 Example.** For any bounded coherent constructible  $S$ -stratified  $\infty$ -topos  $X$ , the homotopy type  $\Pi_{\infty}^{\wedge}(X)$  is the classifying profinite space of the profinite  $\infty$ -category  $\Pi_{(\infty,1)}^{S,\wedge}(X)$ ; thus the stratification on  $X$  gives rise to a delocalisation of its homotopy type.

Combining  $\infty$ -Categorical Hochster Duality (Theorem 10.3.1) with Proposition 10.4.12 we deduce the *Exodromy Equivalence* stated as Theorem B in the introduction.

**11.1.7 Theorem** (Exodromy Equivalence for Stratified  $\infty$ -Topoi ). *Let  $S$  be a spectral topological space and  $X$  an  $S$ -stratified  $\infty$ -topos. Then the unit  $X \rightarrow \tilde{\Pi}_{(\infty,1)}^{S,\wedge}(X)$  of the adjunction to profinite stratified spaces restricts to an equivalence*

$$\mathrm{Fun}(\Pi_{(\infty,1)}^{S,\wedge}(X), S_\pi) \simeq X^{S\text{-constr}}.$$

## 11.2 Recovering the protruncated shape from the profinite stratified shape

In [Example 11.1.6](#) we saw how to recover the the profinite shape  $\Pi_\infty^\wedge(X)$  of a spectral stratified  $\infty$ -topos  $X$  from its profinite stratified shape  $\Pi_{(\infty,1)}^\wedge(X)$  by ‘inverting all morphisms’ in a suitable sense. This delocalisation result essentially comes for free from the functoriality of the profinite stratified shape. In this subsection prove a stronger delocalisation result ([Theorem 11.2.3](#)): the profinite stratified shape is a delocalisation of the *protruncated* shape.<sup>26</sup>

The equivalence  $\mathbf{Str}_\pi^\wedge \simeq \mathbf{StrTop}_\infty^{spec}$  provided by  $\infty$ -categorical Hochster Duality ([Theorem 10.3.1](#)) provides a way to recover the shape of a spectral  $\infty$ -topos from its profinite stratified shape, via the composite

$$\mathbf{Str}_\pi^\wedge \xrightarrow{\sim} \mathbf{StrTop}_\infty^{spec} \longrightarrow \mathbf{Top}_\infty^{bc} \xrightarrow{\Pi_\infty} \mathrm{Pro}(S),$$

where the middle functor forgets the stratification. There is another functor  $H: \mathbf{Str}_\pi^\wedge \rightarrow \mathrm{Pro}(S)$  that doesn’t require the use of  $\infty$ -topoi, namely, the extension to proobjects of the composite

$$\mathbf{Str}_\pi \longrightarrow \mathbf{Cat}_\infty \xrightarrow{H} S,$$

where the first functor forgets the stratification and the second functor sends an  $\infty$ -category  $C$  to the  $\infty$ -groupoid  $H(C)$  obtained by inverting every morphism in  $C$  ([Notation 5.13.3](#)). It follows formally that these two functors agree on  $\mathbf{Str}_\pi$ :

**11.2.1 Lemma.** *The square*

$$\begin{array}{ccc} \mathbf{Str}_\pi & \xleftarrow{\hat{\lambda}} & \mathbf{StrTop}_\infty^{spec} \\ H \downarrow & & \downarrow \Pi_\infty \\ S & \xleftarrow{j} & \mathrm{Pro}(S) \end{array}$$

*commutes.*

*Proof.* By the definition of the equivalence  $\hat{\lambda}: \mathbf{Str}_\pi^\wedge \simeq \mathbf{StrTop}_\infty^{spec}$  ([Theorem 10.3.1](#)), the following square commutes

$$\begin{array}{ccc} \mathbf{Str}_\pi & \xleftarrow{\hat{\lambda}} & \mathbf{StrTop}_\infty^{spec} \\ \downarrow & & \downarrow \\ \mathbf{Cat}_\infty & \xrightarrow{\mathrm{Fun}(-,S)} & \mathbf{Top}_\infty \end{array},$$

<sup>26</sup>The contents of this subsection originally appeared in a short preprint by the third-named author [29].

where the vertical functors forget stratifications. Combining this with [Example 5.13.4](#) proves the claim.  $\square$

**11.2.2.** Since the functor  $H: \mathbf{Str}_\pi^\wedge \rightarrow \mathbf{Pro}(\mathbf{S})$  preserves inverse limits, [Lemma 11.2.1](#) provides a natural transformation

$$\theta: \Pi_\infty \circ \hat{\lambda} \rightarrow H.$$

**11.2.3 Theorem.** *The natural transformation*

$$\tau_{<\infty}\theta: \Pi_{<\infty} \circ \hat{\lambda} \rightarrow \tau_{<\infty}H$$

*of functors  $\mathbf{Str}_\pi^\wedge \rightarrow \mathbf{Pro}(\mathbf{S}_{<\infty})$  is an equivalence.*

*Proof.* Since the forgetful functor  $\mathbf{StrTop}_\infty^{spec} \rightarrow \mathbf{Top}_\infty^{bc}$  preserves inverse limits, [Corollary 5.13.16](#) implies that the protruncated shape  $\Pi_{<\infty}: \mathbf{StrTop}_\infty^{spec} \rightarrow \mathbf{Pro}(\mathbf{S}_{<\infty})$  preserves inverse limits. Both  $\tau_{<\infty}$  and  $H$  preserve inverse limits, hence their composite  $\tau_{<\infty}H: \mathbf{Str}_\pi^\wedge \rightarrow \mathbf{Pro}(\mathbf{S}_{<\infty})$  preserves inverse limits. The claim now follows from the fact that  $\theta$  is an equivalence when restricted to  $\mathbf{Str}_\pi$  ([Lemma 11.2.1](#)) and the universal property of the  $\infty$ -category  $\mathbf{Str}_\pi^\wedge$  of profinite stratified spaces.  $\square$

### 11.3 Points & materialisation

We now provide a stratified refinement of [\(5.14.6\)](#), which allows us to prove a ‘Whitehead Theorem’ for profinite stratified spaces, and effectively speak of *n-truncated* profinite stratified spaces via materialisation.

**11.3.1.** Let  $\mathbf{S}$  be a spectral topological space, and let  $\mathbf{X}$  be an  $\mathbf{S}$ -stratified  $\infty$ -topos. The  $\infty$ -category of points of  $\mathbf{X}$  is

$$\mathrm{Pt}(\mathbf{X}) = \mathrm{Fun}_*(\mathbf{S}, \mathbf{X})^{op} \simeq \mathrm{Fun}_{\mathbf{StrTop}_\infty^\wedge, *}(\widetilde{\{0\}}, \mathbf{X})^{op}.$$

Since  $\Pi_{(\infty,1)}^\wedge(\widetilde{\{0\}}) \simeq *$ , applying  $\Pi_{(\infty,1)}^\wedge$  yields a natural functor

$$\mathrm{Pt}(\mathbf{X}) \rightarrow \mathrm{Fun}_{\mathbf{Str}_\pi^\wedge}(*, \Pi_{(\infty,1)}^\wedge(\mathbf{X})) \simeq \mathrm{mat} \Pi_{(\infty,1)}^\wedge(\mathbf{X}).$$

In the case where  $\mathbf{X}$  is a spectral  $\infty$ -topos, then  $\infty$ -Categorical Hochster Duality ([Theorem 10.3.1](#)) implies the following stratified refinement of [\(5.14.6\)](#).

**11.3.2 Lemma.** *If  $\mathbf{X}$  is a spectral  $\infty$ -topos, then the natural morphism*

$$\mathrm{Pt}(\mathbf{X}) \rightarrow \mathrm{mat} \Pi_{(\infty,1)}^\wedge(\mathbf{X})$$

*of stratified spaces is an equivalence.*

Now we can deduce a stratified refinement of Whitehead’s Theorem for profinite spaces ([Theorem 5.14.7](#)=[[SAG](#), Theorem E.3.1.6]).

**11.3.3 Theorem** (Profinite Stratified Whitehead Theorem). *The materialisation functor  $\mathrm{mat}: \mathbf{Str}_\pi^\wedge \rightarrow \mathbf{Str}$  is conservative.*

*Proof.* Let  $f: \mathbf{I} \rightarrow \mathbf{I}'$  be a morphism in  $\mathbf{Str}_\pi^\wedge$  and assume that  $\text{mat}(f)$  is an equivalence in  $\mathbf{Str}$ . Write  $f_*: \widetilde{\mathbf{I}} \rightarrow \widetilde{\mathbf{I}'}$  for the induced morphism of spectral  $\infty$ -topoi. From [Lemma 11.3.2](#) we deduce that

$$\text{Pt}(f_*): \text{Pt}(\widetilde{\mathbf{I}}) \rightarrow \text{Pt}(\widetilde{\mathbf{I}'})$$

is an equivalence of  $\infty$ -categories. Conceptual Completeness ([Theorem 5.11.2](#)=[SAG, Theorem A.9.0.6]) implies that  $f_*$  is an equivalence of  $\infty$ -topoi. The full faithfulness of the functor  $\mathbf{I} \mapsto \widetilde{\mathbf{I}}$  completes the proof.  $\square$

We can employ the Profinite Stratified Whitehead Theorem to study the Postnikov tower of profinite stratified spaces.

**11.3.4 Definition.** Let  $n \in \mathbb{N}$ . A profinite stratified space  $\mathbf{I} \rightarrow S$  is said to be *n-truncated* if and only if  $\mathbf{I}$  can be exhibited as an inverse limit of finite  $n$ -truncated  $\pi$ -finite stratified spaces. Equivalently, if we extend  $h_n: \mathbf{Str}_\pi \rightarrow \mathbf{Str}_\pi$  to an inverse-limit preserving functor  $h_n: \mathbf{Str}_\pi^\wedge \rightarrow \mathbf{Str}_\pi^\wedge$ , then an  $n$ -truncated profinite space is one in the essential image of  $h_n$ .

We write  $(\mathbf{Str}_\pi^\wedge)_{\leq n} \subset \mathbf{Str}_\pi^\wedge$  for the full subcategory spanned by the  $n$ -truncated profinite stratified spaces.

**11.3.5 Lemma.** Let  $n \in \mathbb{N}$ , and let  $S$  be a spectral topological space. Then a profinite stratified space  $\mathbf{I} \rightarrow S$  is  $n$ -truncated if and only if, for all  $s, t \in \text{mat}(S)$  with  $s \leq t$ , the induced morphism

$$N_{\text{mat}(S)}(\mathbf{I})\{s, t\} \rightarrow \mathbf{I}_s \times \mathbf{I}_t$$

is an  $(n-1)$ -truncated morphism of  $\mathbf{S}_\pi^\wedge$ .

*Proof.* If  $\mathbf{I}$  is exhibited as a sequence  $\{\Pi_\alpha \rightarrow P_\alpha\}_{\alpha \in A}$  of  $\pi$ -finite  $n$ -truncated stratified spaces, then express  $s$  and  $t$  as sequences  $\{s_\alpha\}_{\alpha \in A}$  and  $\{t_\alpha\}_{\alpha \in A}$  of points. So the sequence

$$\{N_{P_\alpha}(\Pi_\alpha)\{s_\alpha, t_\alpha\} \rightarrow \Pi_{s_\alpha} \times \Pi_{t_\alpha}\}_{\alpha \in A},$$

which exhibits the morphism  $N_{\text{mat}(S)}(\mathbf{I})\{s, t\} \rightarrow \mathbf{I}_s \times \mathbf{I}_t$  of  $\mathbf{S}_\pi^\wedge$ , is  $(n-1)$ -truncated.

Conversely, assume that  $\mathbf{I}$  is exhibited as a sequence  $\{\Pi_\alpha \rightarrow P_\alpha\}_{\alpha \in A}$  of  $\pi$ -finite stratified spaces, and that for any  $s, t \in \text{mat}(S)$  with  $s \leq t$ , the morphism  $N_{\text{mat}(S)}(\mathbf{I})\{s, t\} \rightarrow \mathbf{I}_s \times \mathbf{I}_t$  of  $\mathbf{S}_\pi^\wedge$  is  $(n-1)$ -truncated. Now consider  $h_n \mathbf{I} := \{h_n \Pi_\alpha \rightarrow P_\alpha\}_{\alpha \in A}$  and the natural morphism  $\mathbf{I} \rightarrow h_n \mathbf{I}$ . To see that this morphism is an equivalence, we may pass to the materialisation by [Theorem 11.3.3](#), where it is obvious.  $\square$

**11.3.6 Lemma.** Let  $n \in \mathbb{N}$ . A profinite stratified space  $\mathbf{I} \rightarrow S$  is  $n$ -truncated if and only if  $\text{mat}(\mathbf{I}) \in \mathbf{Str}$  is  $n$ -truncated in the sense of [Definition 2.4.4](#).

*Proof.* For  $s, t \in \text{mat}(S)$  with  $s \leq t$ , we have

$$\text{mat}(N_{\text{mat}(S)}(\mathbf{I})\{s, t\}) \simeq N_{\text{mat}(S)}(\text{mat}(\mathbf{I}))\{s, t\}.$$

By [Proposition 5.14.8](#)=[SAG, Proposition E.4.6.1] and the fact that materialisation is a right adjoint, we see that a profinite stratified space  $\mathbf{I}$  is  $n$ -truncated if and only if the morphism

$$N_{\text{mat}(S)}(\text{mat}(\mathbf{I}))\{s, t\} \rightarrow \text{mat}(\mathbf{I})_s \times \text{mat}(\mathbf{I})_t$$

is an  $(n-1)$ -truncated morphism of spaces, which is true if and only if  $\text{mat}(\mathbf{I})$  is  $n$ -truncated in the sense of [Definition 2.4.4](#).  $\square$



Under  $\infty$ -Categorical Hochster Duality ([Theorem 10.3.1](#))  $n$ -localic spectral stratified  $\infty$ -topoi correspond to  $n$ -truncated profinite stratified spaces:

**11.3.7 Proposition.** *Let  $X$  be a spectral  $\infty$ -topos and  $n \in \mathbb{N}$ . Then the following are equivalent:*

- *The  $\infty$ -topos  $X$  is  $n$ -localic.*
- *The  $\infty$ -category  $\mathrm{Pt}(X)$  of points of  $X$  is an  $n$ -category.*
- *The profinite stratified shape  $\Pi_{(\infty,1)}^\wedge(X)$  is an  $n$ -truncated profinite stratified space.*

*Proof.* If  $X$  is  $n$ -localic, then the  $\infty$ -category  $\mathrm{Pt}(X)$  is an  $n$ -category, which shows that

$$\mathrm{mat} \Pi_{(\infty,1)}^\wedge(X) \simeq \mathrm{Pt}(X)$$

is an  $n$ -category ([Lemma 11.3.2](#)). Applying [Lemma 11.3.6](#) we see that  $\Pi_{(\infty,1)}^\wedge(X)$  is an  $n$ -truncated profinite stratified space.

If  $\Pi_{(\infty,1)}^\wedge(X)$  is an  $n$ -truncated profinite stratified space, then  $\Pi_{(\infty,1)}^\wedge(X)$  can be exhibited as an inverse system  $\{\Pi_\alpha\}_{\alpha \in A}$  of  $n$ -truncated  $\pi$ -finite stratified spaces. Thus

$$X \simeq \widetilde{\Pi}_{(\infty,1)}^\wedge(X) \simeq \lim_{\alpha \in A} \widetilde{\Pi}_\alpha$$

is an  $n$ -localic  $\infty$ -topos. □

**11.3.8.** Combining the preceding with ordinary Stone Duality between profinite sets and Stone topological spaces, the functor  $\mathrm{Pt}: (\mathrm{Str}_\pi^\wedge)_{\leq 1} \rightarrow \mathbf{Cat}_1$  factors through a fully faithful functor  $(\mathrm{Str}_\pi^\wedge)_{\leq 1} \hookrightarrow \mathbf{Cat}(\mathbf{TSp}^{\mathrm{Stone}})$  from the 2-category of 1-truncated profinite stratified spaces to the 2-category of category objects in the category of Stone topological spaces. The essential image of this functor is spanned by the *layered* category objects – i.e., the ones in which every endomorphism is an isomorphism.

## 11.4 Stratified homotopy types via décollages

To identify the functor  $\Pi_{(\infty,1)}^\wedge$  in terms of the usual homotopy type  $\Pi_\infty^\wedge$ , we can pass to the décollage over  $P$ .

**11.4.1 Construction.** Let  $P$  be a finite poset. Let us consider the functor

$$\widehat{\lambda}_P^{\mathrm{déc}}: \mathbf{Déc}_P(\mathbf{S}_\pi^\wedge) \rightarrow \mathbf{Déc}_P(\mathbf{Top}_\infty^{bc})$$

given by composition with  $\lambda_{\{0\}}$ , so that a profinite spatial décollage  $D: \mathrm{sd}^{op}(P) \rightarrow \mathbf{S}_\pi^\wedge$  is carried to the toposic décollage  $\Sigma \mapsto \widehat{D}(\Sigma)$ . We have seen ([Proposition 9.7.11](#)) that this is a fully faithful functor whose essential image is  $\mathbf{Déc}_P(\mathbf{Top}_\infty^{\mathrm{Stone}})$ .

In the other direction, let us consider the functor

$$\Pi_\infty^{\mathrm{predéc}, P, \wedge}: \mathbf{Déc}_P(\mathbf{Top}_\infty^{bc}) \rightarrow \mathrm{Fun}(\mathrm{sd}^{op}(P), \mathbf{S}_\pi^\wedge)$$

given by composition with the profinite shape functor  $\Pi_\infty^\wedge$ , so that a toposic décollage  $D: \mathrm{sd}^{op}(P) \rightarrow \mathbf{Top}_\infty^{bc}$  is carried to the functor  $\Sigma \mapsto \Pi_\infty^\wedge D(\Sigma)$ . We can then compose

this with the Segalification functor – that is, the left adjoint to the fully faithful functor  $\mathbf{D}\acute{\mathbf{e}}\mathbf{c}_P(\mathbf{S}_\pi^\wedge) \hookrightarrow \mathbf{Fun}(\mathbf{sd}^{op}(P), \mathbf{S}_\pi^\wedge)$  – to obtain a functor

$$\Pi_\infty^{d\acute{e}c, P, \wedge} : \mathbf{D}\acute{\mathbf{e}}\mathbf{c}_P(\mathbf{Top}_\infty^{bc}) \rightarrow \mathbf{D}\acute{\mathbf{e}}\mathbf{c}_P(\mathbf{S}_\pi^\wedge)$$

that is left adjoint to  $\widehat{\lambda}_P^{d\acute{e}c}$ .

The difficulty here is that the functor  $\Pi_\infty^{d\acute{e}c, P, \wedge}$  is very inexplicit, because it involves Segalification. To address this, we have the following.

**11.4.2 Theorem.** *Let  $P$  be a finite poset. If  $\mathbf{X} \rightarrow \tilde{P}$  is a spectral  $P$ -stratified  $\infty$ -topos, then the functor  $\Sigma \mapsto \Pi_\infty^\wedge \mathbf{D}(\Sigma)$  is already a profinite spatial décollage; that is, the Segalification morphism*

$$\Pi_\infty^{pred\acute{e}c, P, \wedge}(\mathbf{X}) \rightarrow \Pi_\infty^{d\acute{e}c, P, \wedge}(\mathbf{X})$$

*is an equivalence in  $\mathbf{Fun}(\mathbf{sd}^{op}(P), \mathbf{S}_\pi^\wedge)$ .*

*Proof.* It suffices to prove that for every string  $\Sigma := \{p_0 \leq \dots \leq p_n\} \subset P$ , the natural morphism

$$f_\Sigma : \Pi_\infty^\wedge(\mathbf{X}_{p_0} \tilde{\times}_\mathbf{X} \dots \tilde{\times}_\mathbf{X} \mathbf{X}_{p_n}) = \Pi_\infty^\wedge \mathbf{Mor}_{\tilde{P}}(\tilde{\Sigma}, \mathbf{X}) \rightarrow \mathbf{Map}_P(\Sigma, \Pi_{(\infty, 1)}^\wedge(\mathbf{X}))$$

in  $\mathbf{S}_\pi^\wedge$  an equivalence. By Whitehead's Theorem for profinite spaces ([Theorem 5.14.7](#) = [\[SAG, Theorem E.3.1.6\]](#)), it suffices to prove that the materialisation  $\mathbf{mat}(f_\Sigma)$  is an equivalence. Since  $\mathbf{X}$  is spectral, we have a natural equivalence

$$\mathbf{mat} \Pi_\infty^\wedge(\mathbf{X}_{p_0} \tilde{\times}_\mathbf{X} \dots \tilde{\times}_\mathbf{X} \mathbf{X}_{p_n}) \simeq \mathbf{Pt}(\mathbf{X}_{p_0} \tilde{\times}_\mathbf{X} \dots \tilde{\times}_\mathbf{X} \mathbf{X}_{p_n}).$$

Similarly, since  $\Sigma$  is constant as a proobject and  $\mathbf{X}$  is spectral, by Whitehead's Theorem for profinite stratified spaces ([Theorem 11.3.3](#)) we have natural equivalences

$$\begin{aligned} \mathbf{mat} \mathbf{Map}_P(\Sigma, \Pi_{(\infty, 1)}^\wedge(\mathbf{X})) &\simeq \mathbf{Map}_P(\Sigma, \mathbf{mat} \Pi_{(\infty, 1)}^\wedge(\mathbf{X})) \\ &\simeq \mathbf{Map}_P(\Sigma, \mathbf{Pt}(\mathbf{X})). \end{aligned}$$

By the universal property of the iterated oriented fibre product  $\mathbf{X}_{p_0} \tilde{\times}_\mathbf{X} \dots \tilde{\times}_\mathbf{X} \mathbf{X}_{p_n}$ , we have a natural identification

$$(11.4.3) \quad \mathbf{Map}_P(\Sigma, \mathbf{Pt}(\mathbf{X})) \simeq \mathbf{Pt}(\mathbf{X}_{p_0} \tilde{\times}_\mathbf{X} \dots \tilde{\times}_\mathbf{X} \mathbf{X}_{p_n}).$$

To complete the proof, note that the materialisation  $\mathbf{mat}(f_\Sigma)$  is equivalent to the morphism [\(11.4.3\)](#).  $\square$

**11.4.4 Example.** Let  $P$  be a finite poset, and let  $\mathbf{X} \rightarrow \tilde{P}$  be a spectral  $P$ -stratified  $\infty$ -topos. It follows from [Theorem 11.4.2](#) that, for any point  $p \in P$ , the  $p$ -th stratum  $\Pi_{(\infty, 1)}^{P, \wedge}(\mathbf{X})_p$  is equivalent to the homotopy type  $\Pi_\infty^\wedge(\mathbf{X}_p)$ .

**11.4.5 Example.** Let  $P$  be a finite poset, and let  $\mathbf{X} \rightarrow \tilde{P}$  be a spectral  $P$ -stratified  $\infty$ -topos. It follows from [Theorem 11.4.2](#) that, for any points  $p, q \in P$  with  $p < q$ , the link  $\mathbf{Map}_P(\{p \leq q\}, \Pi_{(\infty, 1)}^{P, \wedge}(\mathbf{X}))$  between the  $p$ -th and  $q$ -th strata of  $\Pi_{(\infty, 1)}^{P, \wedge}(\mathbf{X})$  is equivalent to the homotopy type  $\Pi_\infty^\wedge(\mathbf{X}_p \tilde{\times}_\mathbf{X} \mathbf{X}_q)$  of the link.

**11.4.6 Example.** Let  $P$  be a finite poset, and  $X$  a spectral  $P$ -stratified  $\infty$ -topos. For any points  $p, q \in P$  with  $p \leq q$ , write

$$i_{pq,*} : X_p \hookrightarrow X_{\{p \leq q\}} \quad \text{and} \quad j_{pq,*} : X_q \hookrightarrow X_{\{p \leq q\}}$$

for the closed and open immersions of strata, respectively. Then the Beck–Chevalley Theorem ([Theorem 8.1.4](#)) ensures that the décollage

$$\Pi_{\infty}^{\text{déc}, P, \wedge}(X) : \text{sd}^{op}(P) \rightarrow \mathbf{S}_{\pi}^{\wedge}$$

carries any string  $\{p_0 \leq \dots \leq p_n\} \subseteq P$  to the profinite space  $\mathbf{S}_{\pi}^{\wedge} \rightarrow \mathbf{S}$  given by the composite

$$\Gamma_{X_{p_0},*} i_{p_0 p_1}^* j_{p_0 p_1,*} i_{p_1 p_2}^* j_{p_1 p_2,*} \dots i_{p_{n-1} p_n}^* j_{p_{n-1} p_n,*} \Gamma_{X_{p_n}}^* .$$

## 11.5 Van Kampen theorem

If  $P$  is a poset and  $\eta : P \rightarrow \{0\}$  then the ‘invert everything’ functor  $\Pi \mapsto \Pi^+ \simeq \eta_! \Pi$  from  $P$ -stratified spaces to spaces, regarded as a functor from spatial décollages to spaces, is given by the formation of the colimit. That is, if  $\Pi \rightarrow P$  is a  $P$ -stratified space, then one has

$$\Pi^+ \simeq \text{colim}_{\Sigma \in \text{sd}^{op}(P)} N_P(\Pi)(\Sigma) .$$

The ‘invert everything’ functor extends to a functor  $\Pi \mapsto \Pi^+$  from profinite  $P$ -stratified spaces to profinite spaces, and this formula is precisely the same in that context. The compatibility ([11.1.5](#)) therefore provides a colimit description of the homotopy type of a stratified  $\infty$ -topos:

**11.5.1 Proposition** (van Kampen Theorem). *Let  $P$  be a finite poset, and let  $X \rightarrow \tilde{P}$  be a spectral  $P$ -stratified  $\infty$ -topos. Then the homotopy type of  $X$  is equivalent to the colimit*

$$\Pi_{\infty}^{\wedge}(X) \simeq \text{colim}_{\Sigma \in \text{sd}^{op}(P)} \Pi_{\infty}^{\wedge}(N_P(X)(\Sigma))$$

in profinite spaces.

**11.5.2 Example.** If  $X$  is a spectral  $\infty$ -topos exhibited as a recollement  $\mathbf{Z} \overset{\phi}{\cup} \mathbf{U}$  of Stone  $\infty$ -topoi  $\mathbf{Z}$  and  $\mathbf{U}$ , then one has the formula

$$\Pi_{\infty}^{\wedge}(X) \simeq \Pi_{\infty}^{\wedge}(\mathbf{Z}) \cup^{\Pi_{\infty}^{\wedge}(\mathbf{Z} \tilde{\times}_X \mathbf{U})} \Pi_{\infty}^{\wedge}(\mathbf{U})$$

in profinite spaces.

**11.5.3 Example.** Let  $n \in \mathbf{N}$ , and let  $X \rightarrow \widetilde{[n]}$  be a spectral  $[n]$ -stratified  $\infty$ -topos. Then  $\Pi_{\infty}^{\wedge}(X)$  can be exhibited as the colimit of a punctured  $(n+1)$ -cube  $\text{sd}^{op}([n]) \rightarrow \mathbf{S}_{\pi}^{\wedge}$  given by

$$\{p_0, \dots, p_k\} \mapsto \Pi_{\infty}^{\wedge}(X_{p_0} \tilde{\times}_X X_{p_1} \tilde{\times}_X \dots \tilde{\times}_X X_{p_k}) .$$

## Part IV

# Stratified étale homotopy theory

## 12 Aide-mémoire on étale homotopy types

In this section we recall how to situate the *étale homotopy type* of Artin–Mazur–Friedlander in the  $\infty$ -categorical setting, as well as provide some example computations of the étale homotopy type.

### 12.1 Artin & Mazur’s étale homotopy types of schemes

From an  $\infty$ -categorical perspective, there are *a priori* four étale shapes to contemplate:

**12.1.1 Definition.** Let  $X$  be a scheme  $X$ . We define:

- ▶ the shape  $\Pi_{\infty}^{\text{ét}}(X) := \Pi_{\infty}(X_{\text{ét}})$  of the 1-localic étale  $\infty$ -topos,
- ▶ the shape  $\Pi_{\infty}^{\text{ét},\text{hyp}}(X) := \Pi_{\infty}(X_{\text{ét}}^{\text{hyp}})$  of the hypercomplete étale  $\infty$ -topos,
- ▶ the homotopy type  $\Pi_{\infty}^{\text{ét},\wedge}(X) := \Pi_{\infty}^{\wedge}(X_{\text{ét}})$  of the 1-localic  $\infty$ -topos, and
- ▶ the homotopy type  $\Pi_{\infty}^{\text{ét},\text{hyp},\wedge}(X) := \Pi_{\infty}^{\wedge}(X_{\text{ét}}^{\text{hyp}})$  of the hypercomplete étale  $\infty$ -topos.

**12.1.2.** As a special case of [Example 5.13.9](#), we see that the natural morphism

$$\Pi_{\infty}^{\text{ét},\text{hyp}}(X) \rightarrow \Pi_{\infty}^{\text{ét}}(X)$$

becomes an equivalence after protruncation. In particular, we obtain an equivalence  $\Pi_{\infty}^{\text{ét},\text{hyp},\wedge}(X) \simeq \Pi_{\infty}^{\text{ét},\wedge}(X)$ . We simply write

$$\Pi_{<\infty}^{\text{ét}}(X) := \Pi_{\infty}^{\text{ét},\text{hyp}}(X) \simeq \Pi_{\infty}^{\text{ét}}(X)$$

for the protruncated étale shape.

For a locally noetherian scheme  $X$ , Artin and Mazur [4, §9] constructed a proobject in the homotopy category of spaces called the *étale homotopy type* of  $X$ . Friedlander [23, §4] later refined this construction, producing a proobject in simplicial sets called the *étale topological type* of  $X$  whose image in  $\text{Pro}(h\mathbf{S})$  agrees with the étale homotopy type of Artin–Mazur [23, Proposition 4.5]. Hoyois [39, §5] has shown that Friedlander’s étale topological type corepresents the shape of the hypercomplete étale  $\infty$ -topos of  $X$ :

**12.1.3 Theorem** ([39, Corollary 5.6]). *Let  $X$  be a locally noetherian scheme. Then the étale topological type of  $X$ , as defined by Friedlander, corepresents the shape  $\Pi_{\infty}^{\text{ét},\text{hyp}}(X)$  of the hypercomplete étale  $\infty$ -topos.*

In certain cases, the étale topological type is already profinite.

**12.1.4 Theorem** ([4, Theorem 11.1; 23, Theorem 7.3; DAG XIII, Theorem 3.6.5]). *Let  $X$  be a connected noetherian scheme that is geometrically unibranch. Then the protruncation of  $\Pi_{\infty}^{\acute{e}t}(X)$  is profinite, that is,*

$$\Pi_{<\infty}^{\acute{e}t}(X) \simeq \Pi_{\infty}^{\acute{e}t,\wedge}(X) .$$

**12.1.5 Question.** Let  $X$  be a connected noetherian scheme that is geometrically unibranch. Even in simple cases, we do not at this point have a very good understanding of the kind of information that is contained in the étale shape  $\Pi_{\infty}^{\acute{e}t}(X)$  but not in the other invariants. In this paper, we are content to focus our attention on the profinite homotopy types (and their stratified variants, of course).

## 12.2 Examples

In this subsection we provide some example computations of étale shapes and homotopy types.

**12.2.1 Example.** For any field  $k$  one has a noncanonical identification

$$\Pi_{\infty}^{\acute{e}t,\wedge}(\mathrm{Spec} k) \simeq BG_k ,$$

where  $G_k$  is the absolute Galois group of  $k$ .

**12.2.2 Example.** Since  $\mathrm{Spec} \mathbf{Z}$  has no unramified étale covers, the étale fundamental group of the  $\mathrm{Spec} \mathbf{Z}$  is trivial. Moreover, for all integers  $i \geq 1$  and  $n \geq 2$ , the étale cohomology group  $H_{\acute{e}t}^i(\mathrm{Spec} \mathbf{Z}; \mathbf{Z}/n)$  is trivial (see [68; 56]). The Universal Coefficient Theorem and Hurewicz Theorem imply that the étale homotopy type  $\Pi_{\infty}^{\acute{e}t,\wedge}(\mathrm{Spec} \mathbf{Z})$  of  $\mathrm{Spec} \mathbf{Z}$  is trivial (cf. [4, §4]). Since  $\mathbf{Z}$  is a noetherian domain, **Theorem 12.1.4** applies, hence the protruncated shape  $\Pi_{<\infty}^{\acute{e}t}(\mathrm{Spec} \mathbf{Z})$  of  $\mathrm{Spec} \mathbf{Z}$  is trivial.

**12.2.3 Example.** Let  $k$  be an algebraically closed field of characteristic 0 and

$$C = \mathrm{Spec}(k[x, y]/(y^2 - x^3 - x^2))$$

the nodal cubic. Then one has a noncanonical identification  $\Pi_{\infty}^{\acute{e}t}(C) \simeq B\mathbf{Z}$ , whereas the étale homotopy type is given by  $\Pi_{\infty}^{\acute{e}t,\wedge}(C) \simeq B\widehat{\mathbf{Z}}$ .

**12.2.4 Example.** If  $C$  is a smooth irreducible curve over a field  $k$  with Euler characteristic  $\chi(C) < 2$ , then we have a noncanonical identification  $\Pi_{\infty}^{\acute{e}t,\wedge}(C) \simeq B\pi_1^{\acute{e}t}(C)$ .

**12.2.5 Example** (see **Theorem 12.5.3**). We have an equivalence  $\Pi_{\infty}^{\acute{e}t,\wedge}(P_C^1) \simeq (S^2)_{\pi}^{\wedge}$ , where  $S^2$  denotes the 2-sphere.

**12.2.6 Example** ([36, Theorem 1]). Let  $k$  be an algebraically closed field of positive characteristic and let  $X$  be a smooth  $k$ -variety. Then  $\Pi_{\infty}^{\acute{e}t, hyp}(X) \simeq *$  if and only if  $X$  is isomorphic to  $\mathrm{Spec} k$ .

### 12.3 Monodromy

Specialising [Proposition 5.14.17](#) to the case of the étale  $\infty$ -topos of a scheme shows that lisse étale sheaves are the same as representations of the étale homotopy type:

**12.3.1 Proposition.** *Let  $X$  be a scheme the unit  $X_{\text{ét}} \rightarrow X_{\text{ét}}^{\text{Stone}}$  restricts to an equivalence*

$$\text{Fun}(\Pi_{\infty}^{\text{ét}, \wedge}(X), \mathbf{S}_{\pi}) \simeq X_{\text{ét}}^{\text{lisse}}.$$

This generalizes the classical fact that the profinite étale fundamental groupoid

$$\Pi_1^{\text{ét}, \wedge}(X) \simeq \tau_{\leq 1} \Pi_{\infty}^{\text{ét}, \wedge}(X)$$

classifies lisse étale sheaves of *sets* (see [Example 5.14.18](#)).

### 12.4 Friedlander's étale homotopy of simplicial schemes

Attached to a simplicial scheme  $Y_*$  is the étale topological type of  $Y_*$  as constructed by Eric Friedlander [[23](#), §4] and refined by David Cox [[19](#)], Daniel Isaksen [[44](#)], Ilan Barnea and Tomer Schlank [[8](#)], David Carchedi [[12](#)], and Chang-Yeon Chough [[13](#); [15](#)]. Thanks to work of Cox [[19](#), Theorem III.8], Isaksen [[44](#), §3, Theorem 11], and Chough [[15](#), Proposition 3.2.13], the étale topological type of  $Y_*$  can be defined as the colimit in prospaces of the simplicial object that carries  $m \in \Delta$  to the étale shape of  $Y_m$ . Again, from an  $\infty$ -categorical perspective, there are variations on this notion:

**12.4.1 Definition.** Let  $Y_*$  be a simplicial scheme. We define:

► *The étale topological type*

$$\Pi_{\infty}^{\text{ét}}(Y_*) := \text{colim}_{m \in \Delta^{op}} \Pi_{\infty}^{\text{ét}}(Y_m)$$

to be the geometric realization of the simplicial prospace  $m \mapsto \Pi_{\infty}^{\text{ét}}(Y_m)$ .

► *Friedlander's étale topological type*

$$\Pi_{\infty}^{\text{ét}, \text{hyp}}(Y_*) := \text{colim}_{m \in \Delta^{op}} \Pi_{\infty}^{\text{ét}, \text{hyp}}(Y_m)$$

to be the geometric realization of the simplicial prospace  $m \mapsto \Pi_{\infty}^{\text{ét}, \text{hyp}}(Y_m)$ .

**12.4.2.** Since protuncation is a left adjoint, from [\(12.1.2\)](#) we deduce that the natural morphism of prospaces

$$\Pi_{\infty}^{\text{ét}, \text{hyp}}(Y_*) \rightarrow \Pi_{\infty}^{\text{ét}}(Y_*)$$

becomes an equivalence after protruncation, and hence after profinite completion as well.

**12.4.3.** We can extend the functor that assigns a scheme its étale  $\infty$ -topos to simplicial schemes by left Kan extension, so that the étale  $\infty$ -topos of a simplicial scheme  $Y_*$  is given by the geometric realization

$$Y_{*, \text{ét}} := \text{colim}_{m \in \Delta^{op}} Y_{m, \text{ét}}$$

in  $\mathbf{Top}_\infty$ . Since the shape is a left adjoint, we see that the shape of the  $\infty$ -topos  $Y_{*,\acute{e}t}$  coincides with the étale topological type  $\Pi_\infty^{\acute{e}t}(Y_*)$ . Likewise, Friedlander's étale topological type coincides with the shape of the hypercomplete  $\infty$ -topos given by the geometric realization of the simplicial hypercomplete  $\infty$ -topos  $m \mapsto Y_{m,\acute{e}t}^{hyp}$ .

## 12.5 Riemann Existence Theorem

In this subsection we recall the Artin–Mazur–Friedlander Riemann Existence Theorem ([Theorem 12.5.3](#)), which states that the étale homotopy type of a scheme of finite type over the complex numbers agrees with the homotopy type of its underlying analytic space, up to profinite completion.

**12.5.1 Notation.** Write  $\mathbf{C}$  for the field of complex numbers and  $\mathbf{Sch}_{/\mathbf{C}}^{ft}$  for category of schemes of finite type over  $\mathbf{C}$  and finite type morphisms between them. We write

$$(-)^{an} : \mathbf{Sch}_{/\mathbf{C}}^{ft} \rightarrow \mathbf{TSpc}$$

for the *analytification* functor, which carries a scheme  $X$  of finite type over  $\mathbf{C}$  to  $X(\mathbf{C})$  equipped with the complex analytic topology.

**12.5.2 Recollection.** Let  $X$  be a scheme finite type over  $\mathbf{C}$ . In [[SGA 4<sub>III</sub>](#), Exposé XI, 4.0], Artin defines a natural geometric morphism of 1-topoi  $\varepsilon_* : \tau_{\leq 0} \widehat{X}^{an} \rightarrow \tau_{\leq 0} X_{\acute{e}t}$  from the 1-topos of sheaves of sets on  $X^{an}$  to the 1-topos of sheaves of sets on the étale site of  $X$ . The geometric morphism  $\varepsilon_*$  extends to a natural geometric morphism of 1-localic  $\infty$ -topoi

$$\varepsilon_* : \widehat{X}^{an} \rightarrow X_{\acute{e}t}.$$

The naturality can be encoded as a functor  $\mathbf{Sch}_{/\mathbf{C}}^{ft} \rightarrow \mathbf{Fun}(\Delta^1, \mathbf{Top}_\infty)$ , so that if  $f : X \rightarrow Y$  is a finite type morphism of finite type  $\mathbf{C}$ -schemes, then one has an equivalence  $f_*^{\acute{e}t} \varepsilon_* \simeq \varepsilon_* f_*^{an}$ .

In light of [Theorem 12.1.3](#), the Riemann Existence Theorem proved by Artin–Mazur [[4](#), Theorem 12.9] and later Friedlander [[23](#), Theorem 8.6] asserts that  $\widehat{X}^{an}$  and  $X_{\acute{e}t}$  have the same profinite shape, when regarded as proobjects of the homotopy category of spaces. One may refine the Artin–Mazur–Friedlander equivalence to an equivalence in the  $\infty$ -category of profinite spaces (cf. [[12](#), Proposition 4.12; [15](#), §4]). Indeed, the Théorème de Comparaison [[SGA 4<sub>III</sub>](#), Exposé XI, Théorèmes 4.3 & 4.4] can be employed to provide an equivalence between the  $\infty$ -category of lisse étale sheaves of spaces on  $X$  and that of lisse sheaves of spaces on  $X^{an}$ , whence we obtain the following.

**12.5.3 Theorem (Riemann Existence).** *Let  $X$  be a scheme finite type over  $\mathbf{C}$ . Then  $\varepsilon^*$  induces an equivalence  $X_{\acute{e}t}^{lisse} \simeq (\widehat{X}^{an})^{lisse}$  of  $\infty$ -categories of lisse sheaves. Consequently,  $\varepsilon_*$  induces an equivalence of profinite spaces*

$$(X^{an})_\pi^\wedge \simeq \Pi_\infty^\wedge(\widehat{X}^{an}) \simeq \Pi_\infty^\wedge(X_{\acute{e}t}).$$

## 12.6 Van Kampen Theorem for étale homotopy types

## 13 Galois categories

In this section we use the profinite shape to define a stratified refinement of the étale homotopy type and provide a number of example computations of this *stratified étale homotopy type*.

### 13.1 Galois categories of schemes

**13.1.1 Notation.** Recall that for a coherent scheme  $X$ , we let  $\mathbf{FC}(X)$  denote the 1-category of nondegenerate, finite, constructible stratifications of the spectral topological space  $X^{\text{zar}}$ . We abuse notation and write merely  $P$  for an object  $X^{\text{zar}} \rightarrow P$  of this category, leaving the structure morphism implicit. The 1-category  $\mathbf{FC}(X)$  is, up to equivalence, a poset in which  $P \leq Q$  if and only if  $P$  refines  $Q$ ; that is,  $P \leq Q$  if and only if  $X^{\text{zar}} \rightarrow Q$  factors through  $X^{\text{zar}} \rightarrow P$ . The spectral topological space  $X^{\text{zar}}$  corresponds under Hochster Duality to the profinite poset  $\{P\}_{P \in \mathbf{FC}(X)}$ .

We write  $\Phi_X$  for the set of *filters* on  $\mathbf{FC}(X)$  – i.e., open subsets that are inverse as 1-categories – equipped with the partial ordering given by inclusion. One has a natural injection  $\mathbf{FC}(X)^{\text{op}} \hookrightarrow \Phi_X$  that carries  $P$  to the *principal filter*  $F_{X, \geq P}$ .

**13.1.2 Notation.** We write  $\mathbf{Sch}$  for the 1-category of *coherent* schemes (0.6.1).

**13.1.3 Definition.** Let  $X$  be a coherent scheme. Then we write

$$\text{Gal}(X) := \Pi_{(\infty, 1)}^{X^{\text{zar}}, \wedge}(X_{\text{ét}}).$$

We call this the *Galois category* of  $X$ . This is a functor  $\text{Gal}: \mathbf{Sch} \rightarrow \mathbf{Str}_{\pi}^{\wedge}$ .

More generally, if  $F \in \Phi_X$  is a filter, then  $F$  is an inverse system of finite posets, and we have a constructible stratification  $p: X^{\text{zar}} \rightarrow F$ . We may therefore define

$$\text{Gal}(X/F) := \Pi_{(\infty, 1)}^{F, \wedge}(X_{\text{ét}}).$$

**13.1.4.** We obtain a diagram

$$\text{Gal}(X/-): \Phi_X^{\text{op}} \rightarrow \mathbf{Str}_{\pi}^{\wedge}$$

of localisations.

In particular, for any nondegenerate, finite, constructible stratification  $P \in \mathbf{FC}(X)$ , we define

$$\text{Gal}(X/P) := \text{Gal}(X/F_{X, \geq P}) \simeq \Pi_{(\infty, 1)}^{P, \wedge}(X_{\text{ét}}).$$

### 13.2 Examples

**13.2.1 Example.** If  $X$  is any (coherent) scheme, we may consider  $X$  with its trivial  $\{0\}$ -stratification. In this case, one recovers the usual étale homotopy type: one has a canonical equivalence

$$\text{Gal}(X/\{0\}) \simeq \Pi_{\infty}^{\text{ét}, \wedge}(X).$$



**13.2.2 Example.** Let  $S = \operatorname{Spec} A$  be the spectrum of a discrete valuation ring  $A$ , with closed point  $s$  and generic point  $\eta$ . Then  $S^{\text{zar}} \cong [1]$ , so  $S_{\text{ét}}$  is a spectral  $\infty$ -topos that is naturally  $[1]$ -stratified, with closed stratum  $s_{\text{ét}}$  and open stratum  $\eta_{\text{ét}}$ .

Write  $S^h$  and  $S^{sh}$  for the spectra of the henselisation  $A^h$  and the strict henselisation  $A^{sh}$  of  $A$ , and write  $\eta^h$  and  $\eta^{sh}$  for the spectra of the fraction field  $K^h$  of  $A^h$  and the fraction field  $K^{sh}$  of  $A^{sh}$ .

In this case, please observe that the evanescent  $\infty$ -topos  $s_{\text{ét}} \tilde{\times}_{S_{\text{ét}}} S_{\text{ét}}$  can be identified with the étale  $\infty$ -topos  $S_{\text{ét}}^h$  (Example 7.7.4), and the oriented fibre product  $s_{\text{ét}} \tilde{\times}_{S_{\text{ét}}} \eta_{\text{ét}}$  can be identified with the étale  $\infty$ -topos  $\eta_{\text{ét}}^h$ .

Now we have the following (noncanonical) identifications of profinite spaces:

$$\Pi_{\infty}^{\wedge}(\eta) \simeq BG_K, \quad \Pi_{\infty}^{\wedge}(\eta^h) \simeq BD_A, \quad \Pi_{\infty}^{\wedge}(\eta^{sh}) \simeq BI_A, \quad \text{and} \quad \Pi_{\infty}^{\wedge}(S^h) \simeq BG_k,$$

where  $G_K$  and  $G_k$  are the absolute Galois groups of  $K$  and  $k$ , the subgroup  $D_A \subseteq G_K$  is the decomposition group, and  $I_A \subseteq D_A$  is the inertia group.

We thus identify, noncanonically, the corresponding profinite décollage  $N_{[1]}(\operatorname{Gal}(S))$  over  $[1]$  as the functor  $\operatorname{sd}^{op}([1]) \rightarrow \mathcal{S}_{\pi}^{\wedge}$  given by the diagram

$$BG_k \leftarrow BD_A \rightarrow BG_K.$$

**13.2.3 Example (Knots and primes).** If  $A$  is a number ring with fraction field  $K$ , then  $\operatorname{Gal}(\operatorname{Spec} A)$  is a category with (isomorphism classes of) objects the prime ideals of  $A$ . For each nonzero prime ideal  $\mathfrak{p} \in \operatorname{Spec} A$ , the automorphisms of  $\mathfrak{p}$  can be identified with the absolute Galois group  $G_{\kappa(\mathfrak{p})}$  of the finite field  $\kappa(\mathfrak{p})$ . Thus the étale homotopy type of  $\operatorname{Spec} A$  is stratified by the various closed strata, each of which is an embedded circle – i.e., a knot  $BG_{\kappa(\mathfrak{p})}$ . The open complement of each  $BG_{\kappa(\mathfrak{p})}$  is a  $BG_{\mathfrak{p}}$ , where

$$G_{\mathfrak{p}} := \pi_1^{\text{ét}}(\operatorname{Spec}(A) \setminus \mathfrak{p})$$

is the automorphism group of the maximal Galois extension of  $K$  that is ramified at most only at  $\mathfrak{p}$  and the infinite primes. Enveloping each knot is a tubular neighbourhood, given by  $\operatorname{Gal}(\operatorname{Spec} A_{\mathfrak{p}}^{sh})$ , so that the deleted tubular neighbourhood of  $BG_{\kappa(\mathfrak{p})}$  is a  $BG_{K_{\mathfrak{p}}}$ .

### 13.3 Sieves & cosieves of Galois categories

**13.3.1 Proposition.** *A monomorphism  $U \hookrightarrow X$  of schemes is an open immersion if and only if the induced functor  $\operatorname{Gal}(U) \rightarrow \operatorname{Gal}(X)$  is equivalent to the inclusion of a cosieve.*

*Dually, a monomorphism  $Z \hookrightarrow X$  of schemes is a closed immersion if and only if  $\operatorname{Gal}(Z) \rightarrow \operatorname{Gal}(X)$  is equivalent to the inclusion of a sieve.*

An *interval* in an  $\infty$ -category  $C$  is a full subcategory  $D \subseteq C$  such that a morphism  $P \rightarrow Q$  of  $D$  factors through an object  $R$  of  $C$  only if  $R$  lies in  $D$ .

**13.3.2 Corollary.** *A monomorphism  $W \hookrightarrow X$  of schemes is a locally closed immersion if and only if the induced functor  $\operatorname{Gal}(W) \rightarrow \operatorname{Gal}(X)$  is equivalent to the inclusion of an interval.*

**13.3.3 Corollary.** *A scheme  $X$  is local if and only if  $\text{Gal}(X)$  contains a weakly initial object – i.e., an object from which every object receives a morphism. Dually, a scheme  $X$  is irreducible if and only if  $\text{Gal}(X)$  contains a weakly terminal object – i.e., an object to which every object sends a morphism.*

**13.3.4.** For any scheme  $X$  and any point  $x_0 \in X^{\text{zar}}$ , the Galois category of the localisation is the fibre product

$$\text{Gal}(X_{(x_0)}) \simeq \text{Gal}(X) \times_{X^{\text{zar}}} X_{x_0}^{\text{zar}}.$$

Dually, for any point  $y_0 \in X^{\text{zar}}$ , the Galois category of the closure  $X^{(y_0)}$  of  $y_0$  (with the reduced subscheme structure, say) is the fibre product

$$\text{Gal}(X^{(y_0)}) \simeq \text{Gal}(X) \times_{X^{\text{zar}}} X_{/y}^{\text{zar}}.$$

### 13.4 Undercategories & overcategories of Galois categories

**13.4.1 Notation.** If  $x \rightarrow X$  is a point of a scheme  $X$ , then we write  $O_{X,x_0}^h$  for the henselisation of the local ring  $O_{X,x_0}$ , and we write  $O_{X,x}^h \supseteq O_{X,x_0}^h$  for the unique extension of henselian local rings that on residue fields reduces to the field extension  $\kappa \supseteq \kappa(x_0)$ , where  $\kappa$  is the separable closure of  $\kappa(x_0)$  in  $\kappa(x)$ . We will also write

$$X_{(x)} := \text{Spec}(O_{X,x}^h).$$

We call  $X_{(x)}$  the *localisation of  $X$  at  $x$* . It is the limit of the factorisations  $x \rightarrow U \rightarrow X$  in which  $U \rightarrow X$  is étale.

If  $x \rightarrow X$  is a geometric point, then  $O_{X,x}^h$  is the strict henselisation of  $O_{X,x_0}$ , and  $X_{(x)}$  is the strict localisation of  $X$  at  $x$ .

Dually, if  $y \rightarrow X$  is a point, then we write  $X^{(y_0)}$  for the reduced subscheme structure on the Zariski closure of  $y_0$ , and we write  $X^{(y)}$  for the normalisation of  $X^{(y_0)}$  under  $\text{Spec } \kappa$ , where  $\kappa$  is the separable closure of  $\kappa(y_0)$  in  $\kappa(y)$ . We call  $X^{(y)}$  the *normalisation of  $X$  at  $y$* .

If  $y \rightarrow X$  is a geometric point, then we call  $X^{(y)}$  the *strict normalisation of  $X$  at  $y$* . It is the limit of the factorisations  $y \rightarrow Z \rightarrow X$  in which  $Z \rightarrow X$  is finite.

**13.4.2.** Stefan Schröer [72] has brought us *totally separably closed* schemes, which are integral normal schemes whose function field is separably closed. In other words, a totally separably closed scheme is one of the form  $X^{(y)}$  for some geometric point  $y \rightarrow X$ . (In the language of Schröer,  $X^{(y)}$  is the total separable closure of the Zariski closure of  $y_0$  – with the reduced subscheme structure – under  $y$ .) Schröer has shown that this class of schemes has a number of curious properties:

- If  $Z$  is totally separably closed, then for any point  $z_0 \in Z^{\text{zar}}$ , the local ring  $O_{Z,z_0}$  is strictly henselian [72, Proposition 2.6].
- If  $Z$  is totally separably closed, then the étale topos and the Zariski topos of  $Z$  coincide, so that  $\text{Gal}(Z) \simeq Z^{\text{zar}}$  [72, Corollary 2.5]. In other words,  $\text{Gal}(Z)$  is a profinite poset with a terminal object.

- If  $Z$  is totally separably closed and  $W$  is irreducible, then any integral morphism  $W \rightarrow Z$  is radicial [72, Lemma 2.3]. Thus any integral surjection  $W \rightarrow Z$  is a universal homeomorphism.
- If  $Z$  is totally separably closed, then the poset  $\text{Gal}(Z) \simeq Z^{\text{zar}}$  has all finite nonempty joins [73, Theorem 2.1].

Here now is the basic observation, which follows more or less immediately from the limit descriptions of the strict localisation and the strict normalisation:

**13.4.3 Proposition.** *Let  $X$  be a scheme, and let  $x \rightarrow X$  and  $y \rightarrow X$  be two geometric points thereof. The following profinite sets are in (canonical) bijection:*

- the set  $\text{Map}_{\text{Gal}(X)}(x, y)$  of morphisms  $x \rightarrow y$  in  $\text{Gal}(X)$ ;
- the set  $\text{Mor}_X(y, X_{(x)})$  of lifts of  $y$  to the strict localisation  $X_{(x)}$ ;
- the set  $\text{Mor}_X(x, X^{(y)})$  of lifts of  $y$  to the strict normalisation  $X^{(y)}$ .

We may thus describe the over- and undercategories of Galois categories:

**13.4.4 Corollary.** *Let  $X$  be a scheme, and let  $x \rightarrow X$  and  $y \rightarrow X$  be two geometric points thereof. Then we have*

$$\text{Gal}(X)_{x/} \simeq \text{Gal}(X_{(x)}) \quad \text{and} \quad \text{Gal}(X)_{/y} \simeq \text{Gal}(X^{(y)}).$$

The first sentence is originally due to Grothendieck [SGA 4<sub>III</sub>, Exposé VIII, Corollaire 7.6].

**13.4.5 Corollary.** *Let  $X$  be a scheme. Then  $\text{Gal}(X)$  is equivalent to both of the following full subcategories of  $X$ -schemes:*

- the one spanned by the strict localisations of  $X$ , and
- the one spanned by the strict normalisations of  $X$ .

Since  $\text{Gal}(X^{(y)}) \simeq X^{(y), \text{zar}}$ , it follows that Galois categories are of a very particular sort:

**13.4.6 Corollary.** *Let  $X$  be a scheme. For any geometric point  $y \rightarrow X$ , the overcategory  $\text{Gal}(X)_{/y}$  is a profinite poset with all finite nonempty joins. In particular, every morphism of  $\text{Gal}(X)$  is a monomorphism.*

**13.4.7 Definition.** Let  $X$  be a scheme. Then a *witness* is a totally separably closed valuation ring  $V$  and a morphism  $\gamma: \text{Spec } V \rightarrow X$ . If  $p_0$  is the initial object of  $\text{Gal}(V)$  and  $p_\infty$  is the terminal object of  $\text{Gal}(V)$ , then we say that  $\gamma$  *witnesses* the map  $\gamma(p_0) \rightarrow \gamma(p_\infty)$  of  $\text{Gal}(X)$ .

**13.4.8.** Any morphism  $x \rightarrow y$  of  $\text{Gal}(X)$  has a witness: you can always find a local morphism  $\text{Spec } V \rightarrow (X^{(y)})_{(x)}$  that induces an isomorphism of function fields.

### 13.5 Recovering the protruncated étale homotopy type

Since  $\mathrm{Gal}(X)$  is the profinite stratified shape of a coherent topos, the fact that the profinite stratified shape is a delocalisation of the protruncated shape ([Theorem 11.2.3](#)) immediately implies the following:

**13.5.1 Theorem.** *Let  $X$  be a coherent scheme. Then there is a natural map of prospaces*

$$\theta_X : \Pi_{\infty}^{\mathrm{ét}}(X) \rightarrow H(\mathrm{Gal}(X)).$$

Moreover,  $\theta_X$  induces an equivalence on protruncations. As a consequence:

- For each integer  $n \geq 1$  and geometric point  $x \rightarrow X$ , we have canonical isomorphisms of progroups

$$\pi_n^{\mathrm{ét}}(X, x) \simeq \pi_n(H(\mathrm{Gal}(X)), x),$$

where  $\pi_n^{\mathrm{ét}}(X, x)$  is the  $n^{\mathrm{th}}$  homotopy progroup of the étale shape  $\Pi_{\infty}^{\mathrm{ét}}(X)$  of  $X$ .

- For any ring  $R$ , there is an equivalence of  $\infty$ -categories between local systems of  $R$ -modules on  $X$  that are uniformly bounded both below and above and continuous functors  $\mathrm{Gal}(X) \rightarrow D^b(R)$  that carry every morphism to an equivalence.

The progroups  $\pi_n^{\mathrm{ét}}(X, x)$  are what we call the *extended étale homotopy groups* of  $X$ . Note that the progroup  $\pi_1^{\mathrm{ét}}(X, x)$  is the *groupe fondamentale élargi* of [\[SGA 3<sub>III</sub>, Exposé X, §6\]](#); the usual étale fundamental group of [\[SGA 1, Exposé V, §7\]](#) is the profinite completion of  $\pi_1^{\mathrm{ét}}(X, x)$ .

### 13.6 Fibred Galois categories

In this subsection we extend our notion of Galois categories to simplicial schemes.

**13.6.1 Definition.** Let  $S$  be an  $\infty$ -category. A *bounded coherent topos fibration*  $X \rightarrow S$  is a topos fibration in which each fibre  $X_s$  is bounded coherent, and for any morphism  $f : t \rightarrow s$  of  $S$ , the induced geometric morphism  $f_* : X_s \rightarrow X_t$  is coherent. A *spectral topos fibration*  $X \rightarrow S$  is a bounded coherent topos fibration in which each fibre  $X_s$  is a spectral topos (for the canonical profinite stratification of [§9.6](#)).

**13.6.2.** The usual straightening/unstraightening equivalence restricts to an equivalence between the  $\infty$ -category of bounded coherent (respectively, spectral) topos fibrations  $X \rightarrow S$  and the  $\infty$ -category of functors from  $S^{\mathrm{op}}$  to the  $\infty$ -category of bounded coherent (resp., spectral) topoi (cf. [\[HTT, Proposition 6.3.1.7\]](#)).

For a bounded coherent topos fibration  $X \rightarrow S$  we write  $X_{<\infty}^{\mathrm{coh}} \subseteq X$  for the full subcategory spanned by the objects that are truncated and coherent in their fibre [\[9, Definition 5.18\]](#). Then  $X_{<\infty}^{\mathrm{coh}} \rightarrow S$  is a cocartesian fibration that is classified by a functor from  $S$  to the category of bounded  $\infty$ -pretopoi [\[SAG, Definition A.7.4.1 & Theorem A.7.5.3\]](#).

**13.6.3 Example.** If  $X_*$  is a simplicial coherent scheme, then the fibred topos  $X_{*,\mathrm{ét}} \rightarrow \Delta$  is a spectral topos fibration.

A fibred form of  $\infty$ -Categorical Hochster Duality is what allows us to construct fibred Galois categories. To define it, we need to make sense categories fibred in profinite stratified spaces.

**13.6.4 Definition.** Let  $S$  be an  $\infty$ -category. A functor  $f : \Pi \rightarrow S$  will be said to be *an  $\infty$ -category over  $S$  fibred in layered  $\infty$ -categories* if  $f$  is a catesian fibration whose fibres are layered  $\infty$ -categories. We write  $\mathbf{Lay}_{/S}^{cart}$  for the  $\infty$ -category of  $\infty$ -categories over  $S$  fibred in layered  $\infty$ -categories.

**13.6.5 Construction.** There is a monad  $T$  on the  $\infty$ -category  $\mathbf{Lay}$  of small layered  $\infty$ -categories given by sending a layered category  $\Pi$  to the limit over the  $\pi$ -finite layered  $\infty$ -categories to which it maps.<sup>27</sup> The  $\infty$ -category of  $T$ -algebras is equivalent to the  $\infty$ -category of profinite layered  $\infty$ -categories. If  $S$  is an  $\infty$ -category, this monad can be applied fibrewise to give a monad  $T_S$  on the  $\infty$ -category  $\mathbf{Lay}_{/S}^{cart}$  of categories fibred in layered  $\infty$ -categories.

Under the straightening/unstraightening identification

$$\mathbf{Lay}_{/S}^{cart} \simeq \mathbf{Fun}(S^{op}, \mathbf{Lay}),$$

the monad  $T_S$  corresponds to the monad on  $\mathbf{Fun}(S^{op}, \mathbf{Lay})$  given by applying  $T$  objectwise. Consequently, the  $\infty$ -category of  $T_S$ -algebras is equivalent to the  $\infty$ -category of functors from  $S^{op}$  to the  $\infty$ -category of profinite layered  $\infty$ -categories.

**13.6.6 Definition.** Let  $S$  be an  $\infty$ -category. An  $\infty$ -category over  $S$  fibred in profinite layered  $\infty$ -categories is a  $T_S$ -algebra. If  $\Pi \rightarrow S$  is an  $\infty$ -category fibred in layered  $\infty$ -categories, then a *fibrewise profinite structure* on  $\Pi \rightarrow S$  is a  $T_S$ -algebra structure on  $\Pi \rightarrow S$ . We write  $\mathbf{Lay}_{\pi, S}^{cart, \wedge}$  for the  $\infty$ -category of  $T_S$ -algebras.

**13.6.7 Warning.** One might also contemplate the  $\infty$ -category  $\mathbf{Pro}(\mathbf{Lay}_{\pi, S}^{cart})$  of pro-objects in the full subcategory

$$\mathbf{Lay}_{\pi, S}^{cart} \subseteq \mathbf{Lay}_{/S}^{cart}$$

spanned by those cartesian fibrations whose fibres are  $\pi$ -finite layered  $\infty$ -categories. This is generally *not* equivalent to the  $\infty$ -category of categories over  $S$  fibred in profinite layered  $\infty$ -categories. Under straightening/unstraightening, the  $\infty$ -category  $\mathbf{Lay}_{\pi, S}^{cart, \wedge}$  is equivalent to the  $\infty$ -category  $\mathbf{Fun}(S^{op}, \mathbf{Lay}_{\pi}^{\wedge})$ , whereas  $\mathbf{Pro}(\mathbf{Lay}_{\pi, S}^{cart})$  is equivalent to the  $\infty$ -category  $\mathbf{Pro}(\mathbf{Fun}(S^{op}, \mathbf{Lay}_{\pi}))$ . These coincide when  $S$  is a finite poset [HTT, Proposition 5.3.5.15], but otherwise typically do not coincide.

**13.6.8.** Let  $S$  be an  $\infty$ -category. Then the  $\infty$ -category of spectral topos fibrations over  $S$  is equivalent to the  $\infty$ -category  $\mathbf{Lay}_{\pi, S}^{cart, \wedge}$ . Let us make the equivalence explicit. If  $X \rightarrow S$  is a spectral topos fibration, then we define an  $\infty$ -category over  $S$  fibred in layered  $\infty$ -categories

$$\Pi_{(\infty, 1)}^{S, \wedge}(X) \rightarrow S$$

as follows. An object of  $\Pi_{(\infty, 1)}^{S, \wedge}(X)$  is a pair  $(s, \nu)$ , where  $s \in S$  and  $\nu_* : \mathbf{S} \rightarrow \mathbf{X}_s$  is a point. A morphism  $(s, \nu) \rightarrow (t, \xi)$  is a morphism  $f : s \rightarrow t$  of  $S$  and a natural transformation

<sup>27</sup>That is,  $T$  is the right Kan extension of the inclusion  $\mathbf{Lay}_{\pi} \hookrightarrow \mathbf{Lay}$  of  $\pi$ -finite layered  $\infty$ -categories along itself.

$v_* \rightarrow f_* \xi_*$ . The  $\infty$ -category  $\Pi_{(\infty,1)}^{S,\wedge}(X)$  fibred in layered  $\infty$ -categories admits a canonical fibrewise profinite structure; the fibre  $\Pi_{(\infty,1)}^{S,\wedge}(X)_s$  over an object  $s \in S$  is the profinite stratified shape  $\Pi_{(\infty,1)}^\wedge(X_s)$ .

In the other direction, if  $\Pi \rightarrow S$  is an  $\infty$ -category over  $S$  fibred in profinite layered  $\infty$ -categories, then let  $X_0 \rightarrow S$  denote the cocartesian fibration in which the objects are pairs  $(s, F)$  consisting of an object  $s \in S$  and a functor  $F: \Pi_s \rightarrow S_\pi$ , and a morphism  $(f, \phi): (s, F) \rightarrow (t, G)$  consists of a morphism  $f: s \rightarrow t$  of  $S$  and a natural transformation  $\phi: f_! F \rightarrow G$ . Then  $(\widetilde{\Pi})_{<\infty}^{coh}$  is equivalent to the subcategory of  $X_0$  whose objects are those pairs  $(s, F)$  in which  $F$  is continuous and whose morphisms are those pairs  $(f, \phi)$  in which  $\phi$  is continuous.

**13.6.9 Construction.** If  $S$  is an  $\infty$ -category and  $Y$  is a bounded coherent topos, then the projection  $Y \times S \rightarrow S$  is a bounded coherent topos fibration. The assignment  $Y \mapsto Y \times S$  defines a functor from the  $\infty$ -category of bounded coherent topoi to the  $\infty$ -category of bounded coherent topos fibrations over  $S$ . This functor admits a left adjoint, which we denote by  $|-|_S$ . At the level of  $\infty$ -pretopoi,  $(|X|_S)_{<\infty}^{coh}$  is equivalent to the  $\infty$ -category of cocartesian sections of  $X_{<\infty}^{coh} \rightarrow S$ , i.e., the limit of the corresponding functor from  $S$  to bounded  $\infty$ -pretopoi.

Now we arrive at the main topos-theoretic result.

**13.6.10 Proposition.** *Let  $S$  be an  $\infty$ -category, and let  $X \rightarrow S$  be a spectral topos fibration. Then the  $\infty$ -pretopos  $(|X|_S)_{<\infty}^{coh}$  is equivalent to the  $\infty$ -category of functors  $F: \Pi_{(\infty,1)}^{S,\wedge}(X) \rightarrow S_\pi$  with the following properties.*

- *$F$  carries any cartesian edge to an equivalence.*
- *For any object  $s \in S$ , the restriction  $F|_{\Pi_{(\infty,1)}^\wedge(X_s)}$  is continuous.*
- *$F$  is uniformly truncated in the sense that there exists an  $N \in \mathbf{N}$  such that for any object  $(s, v) \in \Pi_{(\infty,1)}^{S,\wedge}(X)$ , the space  $F(s, v)$  is  $N$ -truncated.*

*Proof.* The  $\infty$ -pretopos  $(|X|_S)_{<\infty}^{coh}$  can be identified with the  $\infty$ -category of cocartesian sections of  $X_{<\infty}^{coh} \rightarrow S$ . The description of (13.6.8) completes the proof.  $\square$

Please note that the last condition of **Proposition 13.6.10** is automatic if  $S$  has only finitely many connected components (e.g.,  $S = \Delta$ ).

**13.6.11 Example.** If  $X_*$  is a simplicial scheme, then the  $\infty$ -category over  $\Delta$  fibred in profinite layered  $\infty$ -categories  $\Pi_{(\infty,1)}^{\Delta,\wedge}(X_{*,\acute{e}t})$  associated to the spectral topos fibration  $X_{*,\acute{e}t} \rightarrow \Delta$  is the 1-category  $\text{Gal}^\Delta(X_*)$  of **Construction 13.7.6**. In this case, **Proposition 13.6.10** implies that  $(|X_{*,\acute{e}t}|_\Delta)_{<\infty}^{coh}$  is equivalent to the  $\infty$ -category of functors

$$\text{Gal}^\Delta(X_*) \rightarrow S_\pi$$

that carry cartesian edges to equivalences and restrict to continuous functors  $\text{Gal}^\Delta(X_m) \rightarrow S_\pi$  for all  $m \in \Delta$ .

Finally, since the profinite stratified shape is a delocalisation of the protruncated shape (**Theorem 11.2.3**) we deduce the following:

**13.6.12 Proposition.** *Let  $S$  be an  $\infty$ -category, and let  $X \rightarrow S$  be a spectral topos fibration. Then the protruncated shape of  $|X|_S$  is equivalent to the protruncated homotopy type of  $\Pi_{(\infty,1)}^{S,\wedge}(X)$ .*

**13.6.13 Example.** If  $X_*$  is a simplicial scheme, then the protruncated homotopy type of the fibrewise profinite category  $\mathrm{Gal}^\Delta(X_*)$  is equivalent to the Friedlander étale topological type of  $X_*$  [Theorem 13.5.1](#).

### 13.7 Exodromy for schemes and simplicial schemes

In this subsection we explain the *Exodromy Equivalence* of [Theorem B](#) in the context of schemes and simplicial schemes.

**13.7.1 Construction.** Let  $X$  be a coherent scheme. The  $X^{\mathrm{zar}}$ -stratified  $\infty$ -topos  $X_{\mathrm{\acute{e}t}}$  is spectral. Our  $\infty$ -Categorical Hochster Duality Theorem ([Theorem 10.3.1](#)) implies that  $X_{\mathrm{\acute{e}t}} \simeq \widehat{\mathrm{Gal}(X)}$ , and thus

$$X_{\mathrm{\acute{e}t}}^{\mathrm{constr}} \simeq \mathrm{Fun}(\mathrm{Gal}(X), S_\pi).$$

Here, at last, is the *Exodromy Equivalence*. If  $X$  and  $Y$  are coherent schemes, then the natural map

$$\mathrm{Map}_{\mathrm{Top}_\infty}(X_{\mathrm{\acute{e}t}}, Y_{\mathrm{\acute{e}t}}) \rightarrow \mathrm{Map}_{\mathrm{Str}_\pi^\wedge}(\mathrm{Gal}(X), \mathrm{Gal}(Y))$$

is an equivalence.

We also have an equivalence

$$\mathrm{mat}(\mathrm{Gal}(X)) \simeq \mathrm{Pt}(X_{\mathrm{\acute{e}t}}),$$

and this category can be described in the following manner: an object is a geometric point  $x \rightarrow X$ , and for any geometric points  $x \rightarrow X$  and  $y \rightarrow X$ , the space  $\mathrm{Map}_{\mathrm{Pt}(X_{\mathrm{\acute{e}t}})}(x, y)$  is identified with the space of points  $\mathrm{Pt}(x \tilde{\times}_X y) \simeq \mathrm{mat}(\Pi_\infty^\wedge(x \tilde{\times}_X y))$ . This is a discrete space whose components are specialisations  $x \leftarrow y$ . In other words,  $\mathrm{mat}(\mathrm{Gal}(X))$  agrees with the underlying 1-category denoted  $\mathrm{Gal}(X)$  in the Introduction preceding [Theorem A](#).

The profinite stratified space  $\mathrm{Gal}(X)$  is thus 1-truncated; that is, it is a profinite 1-category, and so in light of [\(11.3.8\)](#), it can be regarded as a category object in the category of Stone topological spaces. The topology on  $\mathrm{Gal}(X)$  is precisely the one described in the introduction.

**13.7.2 Construction.** Write  $\mathbf{Aff}$  for the 1-category of affine schemes. We employ [\[HTT, Corollary 3.2.2.13\]](#) to construct an  $\infty$ -category  $\mathbf{PSh}_{\mathrm{\acute{e}t}}$  and a cocartesian fibration

$$\mathbf{PSh}_{\mathrm{\acute{e}t}} \rightarrow \mathbf{Aff}^{\mathrm{op}}$$

in which the objects of  $\mathbf{PSh}_{\mathrm{\acute{e}t}}$  are pairs  $(S, F)$  consisting of an affine scheme  $S$  and a presheaf (of spaces) on the small étale site of  $S$ , and a morphism  $(S, F) \rightarrow (T, G)$  is a pair  $(f, \phi)$  consisting of a morphism  $f: T \rightarrow S$  and a morphism of presheaves  $\phi: f^{-1}F \rightarrow G$  on the small étale site of  $T$ . Define  $\mathbf{Sh}_{\mathrm{\acute{e}t}} \subset \mathbf{PSh}_{\mathrm{\acute{e}t}}$  to be the full subcategory spanned by those pairs  $(S, F)$  in which  $F$  is a sheaf; then  $\mathbf{Sh}_{\mathrm{\acute{e}t}} \rightarrow \mathbf{Aff}^{\mathrm{op}}$  is a topos fibration. Define

$\mathbf{Constr}_{\acute{e}t} \subset \mathbf{Sh}_{\acute{e}t}$  to be the further full subcategory spanned by those pairs  $(S, F)$  in which  $F$  is a (nonabelian) constructible sheaf [9, Definition 10.11]; then  $\mathbf{Constr}_{\acute{e}t} \rightarrow \mathbf{Aff}^{op}$  is a cocartesian fibration.

**13.7.3 Definition.** Let  $X \rightarrow \mathbf{Aff}$  be a stack, i.e., a right fibration that is classified by an accessible fpqc sheaf  $\mathbf{Aff}^{op} \rightarrow \mathbf{S}$ . A (nonabelian) constructible sheaf on  $X$  is a cocartesian section

$$F: X^{op} \rightarrow \mathbf{Constr}_{\acute{e}t}$$

over  $\mathbf{Aff}^{op}$ . We write  $\mathbf{Constr}_{\acute{e}t}(X)$  for the  $\infty$ -category of constructible sheaves on  $X$ .

**13.7.4 Warning.** This can only be expected to be a reasonable definition for coherent stacks.

**13.7.5.** Informally, a constructible sheaf  $F$  on  $X$  assigns to every affine scheme  $S$  over  $X$  a constructible sheaf  $F_S$  and to every morphism  $f: S \rightarrow T$  of affine schemes an equivalence  $F_S \simeq f^* F_T$ . In other words, the  $\infty$ -category of constructible sheaves on  $X$  is the limit of the diagram  $X^{op} \rightarrow \mathbf{Cat}_{\infty}$  given by the assignment  $S \mapsto \mathbf{Constr}_{\acute{e}t}(S)$ .

Of course, since  $X$  is not a small category, it is not obvious that this limit exists in  $\mathbf{Cat}_{\infty}$ . However, if  $X$  contains a small limit-cofinal full subcategory  $Y$ , then the desired limit exists.

**13.7.6 Construction.** Let  $Y_*$  be a simplicial scheme. Denote by  $\mathrm{Gal}^{\Delta}(Y_*)$  the following 1-category. The objects are pairs  $(m, \nu)$  consisting of an object  $m \in \Delta$  and a geometric point  $\nu \rightarrow Y_m$ . A morphism  $(m, \nu) \rightarrow (n, \xi)$  of  $\mathrm{Gal}^{\Delta}(Y_*)$  is a morphism  $\sigma: m \rightarrow n$  of  $\Delta$  and a specialisation  $\nu \leftarrow \sigma^*(\xi)$ . This category has an obvious forgetful functor  $\mathrm{Gal}^{\Delta}(Y_*) \rightarrow \Delta$ , which is a cartesian fibration. A morphism  $(m, \nu) \rightarrow (n, \xi)$  is cartesian over  $\sigma: m \rightarrow n$  in  $\Delta$  if and only if the specialisation  $\nu \leftarrow \sigma^*(\xi)$  is an isomorphism.

The fibre over  $m \in \Delta$  is the category  $\mathrm{Gal}(Y_m)$ , which we regard as a profinite category. (See Definition 13.6.4 for the precise notion of categories fibred in profinite categories.)

Now we conclude:

**13.7.7 Proposition.** *If  $p: X \rightarrow \mathbf{Aff}$  is a stack, and if  $X$  is presented by a simplicial scheme  $Y_*$ , then we obtain an equivalence between the  $\infty$ -category  $\mathbf{Constr}_{\acute{e}t}(X)$  and the  $\infty$ -category of functors*

$$\mathrm{Gal}^{\Delta}(Y_*) \rightarrow \mathbf{S}_{\pi}$$

*that carry cartesian edges to equivalences and for all  $m \in \Delta$  restrict to a continuous functor  $\mathrm{Gal}(Y_m) \rightarrow \mathbf{S}_{\pi}$ .*

Recall that the protruncated étale topological type of a simplicial scheme  $Y_*$  can be identified with the colimit in protruncated spaces of the simplicial object that carries  $m \in \Delta$  to the protruncated étale homotopy type of  $Y_m$  ((12.4.2)). Since the protruncated homotopy type of the fibres of the cartesian fibration  $\mathrm{Gal}^{\Delta}(Y_*) \rightarrow \Delta$  agree with the protruncated étale homotopy type of the schemes  $Y_m$ , it follows from Proposition 13.6.12 that the protruncated homotopy type of the total category  $\mathrm{Gal}^{\Delta}(Y_*)$  is the colimit of this simplicial diagram. In other words:



**13.7.8 Theorem.** *The classifying protruncated space of  $\mathrm{Gal}^\Delta(Y_*)$  recovers the protruncated étale topological type of  $Y_*$ .*

Combining this with **Proposition 13.7.7** we obtain:

**13.7.9 Corollary.** *Let  $n \in \mathbf{N}$  and let  $X$  be an Artin  $n$ -stack. If  $Y_*$  is a presentation  $X$ , then the localisation of  $\mathrm{Gal}^\Delta(Y_*)$  at the cartesian edges classifies constructible sheaves on  $X$ .*

**Corollary 13.7.9** speaks only of Artin  $n$ -stacks, but of course applies just as well to any coherent fpqc stack with a presentation as a simplicial scheme.

**13.7.10 Example.** Let  $G$  be an affine group scheme over a ring  $k$ , and let  $X$  be a  $k$ -scheme with an action of  $G$ . Then we have the usual simplicial  $k$ -scheme  $B_{k,*}(X, G, k)$  whose  $n$ -simplices are  $X \times_{\mathrm{Spec} k} G^n$ ; this presents the quotient stack  $X/G$ .

Thus the category of  $G$ -equivariant (nonabelian) constructible sheaves on  $X$  is equivalent to the category of continuous functors

$$\mathrm{Gal}^\Delta(B_{k,*}(X, G, k)) \rightarrow \mathbf{S}_\pi$$

that carry the cartesian edges to equivalences. If  $\Lambda$  is a ring, then the derived category of  $G$ -equivariant constructible sheaves of  $\Lambda$ -modules on  $X$  is equivalent to the category of continuous functors

$$\mathrm{Gal}^\Delta(B_{k,*}(X, G, k)) \rightarrow \mathbf{Perf}(\Lambda)$$

that carry cartesian edges to equivalences.

The objects of the category  $\mathrm{Gal}^\Delta(B_{k,*}(X, G, k))$  can be thought of as tuples

$$(m, \Omega, x_0, g_1, \dots, g_m)$$

in which  $m \in \Delta$  is an object,  $\Omega$  is a separably closed field, and  $x_0: \mathrm{Spec} \Omega \rightarrow X$  and  $g_1, \dots, g_m: \mathrm{Spec} \Omega \rightarrow G$  are points with the property that  $(x_0, g_1, \dots, g_m)$  is a geometric point of  $X \times_{\mathrm{Spec} k} G^m$ , so that  $\Omega$  is the separable closure of the residue field of the image of the  $(x_0, g_1, \dots, g_m)$  in the Zariski space of  $X \times_{\mathrm{Spec} k} G^m$ .

## 13.8 Stratified Riemann Existence Theorem

We now use the Artin Comparison Theorem to prove a stratified refinement of the Riemann Existence Theorem of Artin–Mazur–Friedlander (**Theorem 12.5.3**), giving a comparison between étale and analytic stratified homotopy types for schemes of finite type over the complex numbers. To do so, we invoke the critical basechange result of Artin. A straightforward Postnikov argument permits us to reformulate Artin's theorem as follows.

**13.8.1 Theorem** (Artin Comparison; [SGA 4<sub>III</sub>, Exposé XVI, Théorème 4.1]). *Let  $f: X \rightarrow Y$  be a finite type morphism of finite type  $\mathbf{C}$ -schemes, and let  $F \in X_{\mathrm{ét}}$  be a constructible sheaf. Then the natural Beck–Chevalley morphism*

$$\varepsilon^* f_*^{\mathrm{ét}} F \rightarrow f_*^{\mathrm{an}} \varepsilon^* F$$

*is an equivalence, where  $\varepsilon_*: \widetilde{X}^{\mathrm{an}} \rightarrow X_{\mathrm{ét}}$  is the geometric morphism of **Recollection 12.5.2**.*

**13.8.2 Construction.** If  $X$  is a scheme of finite type over  $\mathbf{C}$ , then the topological space  $X^{an}$  admits the evident profinite stratification  $X^{an} \rightarrow X^{zar}$ , and  $\varepsilon_*$  is an  $X^{zar}$ -stratified geometric morphism.

If  $X^{zar} \rightarrow P$  is a finite constructible stratification, then the topological space  $X^{an}$  also inherits a stratification  $X^{an} \rightarrow P$ , which is conical.

On each stratum  $X_p$ , the functor  $\varepsilon^*$  restricts to a functor  $X_{p,\acute{e}t}^{lisse} \rightarrow (\widetilde{X_p^{an}})^{lisse}$  (which is an equivalence by [Theorem 12.5.3](#)), whence we obtain a functor

$$\varepsilon^* : X_{\acute{e}t}^{P\text{-constr}} \rightarrow (\widetilde{X^{an}})^{P\text{-constr}}$$

which in turn induces a  $P$ -stratified geometric morphism

$$\varepsilon_*^{P\text{-constr}} : \mathbf{Sh}_{\text{eff}}((\widetilde{X^{an}})^{P\text{-constr}}) \rightarrow \mathbf{Sh}_{\text{eff}}(X_{\acute{e}t}^{P\text{-constr}})$$

of spectral  $P$ -stratified  $\infty$ -topoi.

Please note that we also have the Exodromy Equivalence for stratified topological spaces ([Subexample 9.2.12](#)), which provides an equivalence

$$\Pi_{(\infty,1)}^\wedge(X^{an}; P) \simeq \Pi_{(\infty,1)}^\wedge(\mathbf{Sh}_{\text{eff}}((\widetilde{X^{an}})^{P\text{-constr}}); P)$$

between the profinite completion (in the stratified sense) of the exit-path  $\infty$ -category of  $X^{an}$  and the profinite stratified shape of  $\mathbf{Sh}_{\text{eff}}((\widetilde{X^{an}})^{P\text{-constr}})$ .

**13.8.3 Proposition** (Stratified Riemann Existence). *Let  $X$  be a scheme of finite type over  $\mathbf{C}$ , and let  $X^{zar} \rightarrow P$  be a finite stratification. Then the geometric morphism  $\varepsilon_*^{P\text{-constr}}$  is an equivalence. Consequently,  $\varepsilon_*$  induces an equivalence*

$$\Pi_{(\infty,1)}^\wedge(X^{an}; P) \simeq \Pi_{(\infty,1)}^\wedge(\widetilde{X^{an}}; P) \simeq \Pi_{(\infty,1)}^{\acute{e}t,\wedge}(X; P)$$

of profinite  $P$ -stratified homotopy types.

*Proof.* On strata,  $\varepsilon_*^{P\text{-constr}}$  is an equivalence by the Riemann Existence Theorem. For any point  $p \in P$ , let us write  $X_p^L$  for the Stone  $\infty$ -topos  $\mathbf{Sh}_{\text{eff}}((\widetilde{X_p^{an}})^{lisse}) \simeq \mathbf{Sh}_{\text{eff}}(X_{p,\acute{e}t}^{lisse})$ . For any points  $p < q$ , the geometric morphism  $\varepsilon_*^{P\text{-constr}}$  on the link from  $p$  to  $q$  is a geometric morphism of Stone  $\infty$ -topoi

$$X_p^L \xrightarrow{\widetilde{\varepsilon}}_{\mathbf{Sh}_{\text{eff}}((\widetilde{X^{an}})^{P\text{-constr}})} X_q^L \rightarrow X_p^L \xrightarrow{\widetilde{\varepsilon}}_{\mathbf{Sh}_{\text{eff}}(X_{\acute{e}t}^{P\text{-constr}})} X_q^L.$$

To see that this is an equivalence, since the oriented fibre product is invariant under localisations of the corner ([Example 6.5.11](#)), we may assume that  $P = \{p \leq q\}$ , in which case  $\mathbf{Sh}_{\text{eff}}((\widetilde{X^{an}})^{P\text{-constr}})$  and  $\mathbf{Sh}_{\text{eff}}(X_{\acute{e}t}^{P\text{-constr}})$  are each bounded coherent recollements of  $X_p^L$  and  $X_q^L$ . Therefore it suffices to prove that the gluing functors coincide on truncated coherent objects. That is, one needs to confirm that the natural transformation

$$\varepsilon^* i_{*,*}^{\acute{e}t,*} j_*^{\acute{e}t} \rightarrow i^{an,*} j_*^{an} \varepsilon^*$$

is an equivalence when restricted to  $(X_q^L)^{coh}_{<\infty} \simeq X_{q,\acute{e}t}^{lisse}$ . This now follows from the Artin Comparison Theorem ([Theorem 13.8.1](#)) and naturality of  $\varepsilon^*$ .  $\square$

Passing to the limit over finite stratifications, we obtain the following.

**13.8.4 Corollary.** *Let  $X$  be a scheme of finite type over  $\mathbf{C}$ . Then  $\varepsilon_*$  induces an equivalence*

$$\Pi_{(\infty,1)}^\wedge(\widetilde{X^{an}}; X^{zar}) \simeq \Pi_{(\infty,1)}^{\acute{e}t,\wedge}(X).$$

### 13.9 Van Kampen

Let  $X$  be a coherent scheme. A nonempty closed subset  $Z \subset X$  with dense, quasicompact open complement  $U \subset X$  specifies a nondegenerate constructible stratification  $X^{\text{zar}} \rightarrow [1]$ , and we may – in an overindulgence of abusive notation – write

$$\text{Gal}(X; Z) := \text{Gal}(X/[1]) ,$$

which is a profinite  $[1]$ -stratified space. Its décollage is the functor  $\text{sd}^{\text{op}}([1]) \rightarrow \mathcal{S}_\pi^\wedge$  given by the diagram

$$\Pi_\infty^{\text{ét}, \wedge}(Z) \leftarrow \Pi_\infty^\wedge(Z_{\text{ét}} \tilde{\times}_{X_{\text{ét}}} U_{\text{ét}}) \rightarrow \Pi_\infty^{\text{ét}, \wedge}(U) .$$

(Note that any subscheme structure on  $Z$  will do, as nilimmersions don't affect the étale  $\infty$ -topos.) The profinite space  $\Pi_\infty^\wedge(Z_{\text{ét}} \tilde{\times}_{X_{\text{ét}}} U_{\text{ét}})$  is the *deleted tubular neighbourhood* of  $\Pi_\infty^{\text{ét}, \wedge}(Z)$  in  $\Pi_\infty^{\text{ét}, \wedge}(X)$ .

When  $Z = \{z\}$  with  $\kappa(z)$  separably closed, one may identify the deleted tubular neighbourhood of  $\Pi_\infty^{\text{ét}, \wedge}(Z) \simeq *$  in  $\Pi_\infty^{\text{ét}, \wedge}(X)$  with the étale homotopy type of the punctured Milnor ball  $X_{(z)}^{\text{sh}} \setminus \{z\}$ .

When  $X$  is a curve over a field  $k$  and  $Z = \{z\}$  is a rational point, we obtain an identification of the deleted tubular neighbourhood with the classifying space of ‘the’ profinite decomposition group  $D_z \subseteq \pi_1^{\text{ét}}(U)$ . More generally, we may regard the deleted tubular neighbourhood  $\Pi_\infty^\wedge(Z_{\text{ét}} \tilde{\times}_{X_{\text{ét}}} U_{\text{ét}})$  as a kind of generalised ‘decomposition homotopy type’.

Our van Kampen theorem ([Proposition 11.5.1](#)) exhibits an equivalence of profinite spaces

$$\Pi_\infty^{\text{ét}, \wedge}(X) \simeq \Pi_\infty^{\text{ét}, \wedge}(Z) \cup^{\Pi_\infty^\wedge(Z_{\text{ét}} \tilde{\times}_{X_{\text{ét}}} U_{\text{ét}})} \Pi_\infty^{\text{ét}, \wedge}(U) ,$$

which functions in the same manner as Friedlander’s van Kampen theorem [[23](#), Proposition 15.6].

**13.9.1 Question.** Cox [[17](#); [18](#)] also developed a deleted tubular neighbourhood for schemes, which is what appears in Friedlander’s formulation of van Kampen. One is tempted to believe, therefore, that Cox’s deleted tubular neighbourhood and our toposic version have, at the very least, equivalent profinite homotopy types. At this point, unfortunately, we do not know.

We can answer!

## 14 Perfectly reduced schemes & reconstruction of absolute schemes

We have shown that the étale  $\infty$ -topos  $X_{\text{ét}}$  of a coherent scheme  $X$  can be reconstructed from the profinite  $\infty$ -category  $\Pi_{(\infty, 1)}^{\text{ét}, \wedge}(X)$ . Following Grothendieck’s *Brief an Faltings* [[25](#), (8)], we can ask to what extent  $X$  itself can be recovered from  $X_{\text{ét}}$ . We first note that there are three easily-spotted obstacles to the *conservativity* of the functor  $X \mapsto X_{\text{ét}}$ .

- One must restrict attention to schemes over a base with suitable finiteness conditions: for example, a nontrivial extension  $\Omega \subset \Omega'$  of algebraically closed fields will give an equivalence of étale  $\infty$ -topoi (which are of course each trivial).

- The base must be sufficiently small: over  $\mathbf{C}$ , for example, any two smooth proper curves of the same genus have equivalent étale  $\infty$ -topoi.
- One must account for universal homeomorphisms: for example, the normalisation of the cuspidal cubic induces an equivalence of étale  $\infty$ -topoi. In fact, any universal homeomorphism induces an equivalence of étale  $\infty$ -topoi; this is the *invariance topologique* of the étale  $\infty$ -topos [SGA 1, Exposé IX, 4.10] and [SGA 4<sub>III</sub>, Exposé VIII, 1.1].

The first two points compel us to impose serious finiteness conditions on our schemes, and this last point compels us to consider the  $\infty$ -category obtained from the 1-category  $\mathbf{Sch}$  of coherent schemes by inverting universal homeomorphisms. Fortunately, it is not necessary to do something excessively abstract: there is a 1-categorical colocalisation that performs this function; this is the *perfection* or *absolute weak normalisation*.

### 14.1 Universal homeomorphisms and equivalences of Galois categories

Now we arrive at a sensitive question: under which circumstances does a morphism of schemes induce an equivalence of étale topoi or, equivalently, of Galois categories? The well-known theorem here is Grothendieck's *invariance topologique* of the étale topoi [SGA 4<sub>III</sub>, Exposé VIII, 1.1], which states that a universal homeomorphism induces an equivalence on étale topoi. Let us reprove this result with the aid of Galois categories; this will also provide us with a partial converse.

**14.1.1 Proposition.** *Let  $f : X \rightarrow Y$  be a morphism of schemes. If  $f$  is radicial, then every fibre of  $\mathrm{Gal}(X) \rightarrow \mathrm{Gal}(Y)$  is either empty or a singleton.<sup>28</sup> Conversely, if  $f$  is of finite type, and if every fibre of  $\mathrm{Gal}(X) \rightarrow \mathrm{Gal}(Y)$  is either empty or a singleton, then  $f$  is radicial.*

*Proof.* If  $f$  is radicial, then the map  $X^{\mathrm{zar}} \rightarrow Y^{\mathrm{zar}}$  is an injection, and for any point  $x_0 \in X^{\mathrm{zar}}$ , the map  $BG_{\kappa(x_0)} \rightarrow BG_{\kappa(f(x_0))}$  on fibres is an equivalence since  $\kappa(f(x_0)) \subseteq \kappa(x_0)$  is purely inseparable. So for any geometric point  $y$  with image  $y_0$ , the fibre over  $y$  is a singleton.

Conversely, if  $f$  is of finite type, and if every fibre of  $\mathrm{Gal}(X) \rightarrow \mathrm{Gal}(Y)$  is either empty or a singleton, then certainly the map  $X^{\mathrm{zar}} \rightarrow Y^{\mathrm{zar}}$  is an injection, whence  $f$  is in particular quasifinite. For any point  $x_0 \in X^{\mathrm{zar}}$ , the fibres of the map  $BG_{\kappa(x_0)} \rightarrow BG_{\kappa(f(x_0))}$  are each a singleton, whence it is an equivalence. Now since  $\kappa(f(x_0)) \subseteq \kappa(x_0)$  is a finite extension, it is purely inseparable.  $\square$

**14.1.2 Example.** The finite type hypothesis in the second half of **Proposition 14.1.1** is of course necessary, as any nontrivial extension  $E \subset F$  of separably closed fields induces the identity on trivial Galois categories.

**14.1.3 Corollary.** *Let  $f : X \rightarrow Y$  be a morphism of schemes. If  $f$  is radicial and surjective, then every fibre of  $\mathrm{Gal}(X) \rightarrow \mathrm{Gal}(Y)$  is a singleton. Conversely, if  $f$  is of finite type, and if every fibre of  $\mathrm{Gal}(X) \rightarrow \mathrm{Gal}(Y)$  is a singleton, then  $f$  is radicial and surjective.*

<sup>28</sup>By *singleton* we mean *contractible groupoid*.

The following is the Valuative Criterion, along with a simple argument [STK, Tag 03K8] that allows one to extend the fraction field of the valuation ring therein.

**14.1.4 Lemma.** *Let  $f : X \rightarrow Y$  be a morphism of schemes. Then the following are equivalent.*

- *The morphism  $f$  is universally closed.*
- *For any witness  $\gamma : \text{Spec } V \rightarrow Y$  and any diagram*

$$\begin{array}{ccc} \text{Spec } K & \longrightarrow & X \\ \downarrow & & \downarrow f \\ \text{Spec } V & \xrightarrow{\gamma} & Y \end{array}$$

*in which  $K$  is the fraction field of  $V$ , there exists a lift  $\bar{\gamma} : \text{Spec } V \rightarrow X$ .*

**14.1.5 Recollection.** A functor  $f : C \rightarrow D$  is a right fibration if and only if, for any object  $x \in C$ , the induced functor  $C_{/x} \rightarrow D_{/f(x)}$  is an equivalence of categories. Dually,  $f$  is a left fibration if and only if  $f^{op}$  is a right fibration, so that for any object  $x \in C$ , the induced functor  $C_{x/} \rightarrow D_{f(x)/}$  is an equivalence of categories.

**14.1.6 Proposition.** *Let  $f : X \rightarrow Y$  be a morphism of schemes. If  $f$  is an integral morphism, then  $\text{Gal}(X) \rightarrow \text{Gal}(Y)$  is a right fibration. Conversely, if  $\text{Gal}(X) \rightarrow \text{Gal}(Y)$  is a right fibration, then  $f$  is universally closed.*

*Proof.* Assume that  $f$  is integral. Then for every geometric point  $x \rightarrow X$ , the induced morphism  $X^{(x)} \rightarrow Y^{(f(x))}$  is also integral, and by Schröer's result [72, Lemma 2.3], it is radicial as well. Hence at the level of Zariski topological spaces,  $X^{(x),zar} \rightarrow Y^{(f(x)),zar}$  is an inclusion of a closed subset; since source and target are each irreducible, and the inclusion carries the generic point to the generic point, it is a homeomorphism. (In fact,  $X^{(x)} \rightarrow Y^{(f(x))}$  is a universal homeomorphism.) Thus

$$\text{Gal}(X)_{/x} \simeq \text{Gal}(X^{(x)}) \simeq X^{(x),zar} \rightarrow Y^{(f(x)),zar} \simeq \text{Gal}(Y^{(f(x))}) \simeq \text{Gal}(Y)_{/f(x)}$$

is an equivalence, whence  $\text{Gal}(X) \rightarrow \text{Gal}(Y)$  is a right fibration.

Conversely, assume that  $f$  is of finite type and that  $\text{Gal}(X) \rightarrow \text{Gal}(Y)$  is a right fibration. We employ Lemma 14.1.4 to show that  $f$  is universally closed; consider a witness  $\gamma : \text{Spec } V \rightarrow Y$  along with a diagram

$$\begin{array}{ccc} \text{Spec } K & \xrightarrow{\xi} & X \\ \downarrow & & \downarrow f \\ \text{Spec } V & \xrightarrow{\gamma} & Y \end{array}$$

in which  $K$  is the fraction field of  $V$ . Let  $\psi : y \rightarrow f(\xi)$  be the morphism of  $\text{Gal}(Y)$  witnessed by  $\gamma$ , and let  $\phi : x \rightarrow \xi$  be a lift thereof to  $\text{Gal}(X)$ . We obtain a square

$$\begin{array}{ccc} \mathcal{O}_{Y,y}^{sh} & \xrightarrow{\gamma} & V \\ \downarrow & & \downarrow \\ \mathcal{O}_{X,x}^{sh} & \xrightarrow{\xi} & K, \end{array}$$

and since  $O_{Y,y}^{sh} \rightarrow O_{X,x}^{sh}$  is local, we obtain a lift  $\bar{\gamma}: O_{X,x}^{sh} \rightarrow V$ , as required.  $\square$

A universal homeomorphism is a morphism that is radicial, surjective, and universally closed. An equivalence of categories is a right fibration with fibres contractible groupoids. We thus deduce:

**14.1.7 Proposition.** *Let  $f: X \rightarrow Y$  be a morphism of schemes. If  $f$  is a universal homeomorphism, then  $\text{Gal}(X) \rightarrow \text{Gal}(Y)$  is an equivalence. Conversely, if  $f$  is of finite type, and if  $\text{Gal}(X) \rightarrow \text{Gal}(Y)$  is an equivalence, then  $f$  is a universal homeomorphism (which is necessarily finite).*

## 14.2 Perfectly reduced schemes

The notion of a perfect scheme is elsewhere defined only for  $F_p$ -schemes. Here, we extend this notion to arbitrary reduced schemes in a way that restricts to the usual familiar notion on schemes in characteristic  $p$ .

Just as a reduced scheme receives no nontrivial nilimmersions, a perfect scheme receives no nontrivial universal homeomorphisms. This is in fact a local condition that can be expressed in very concrete terms:

**14.2.1 Lemma.** *The following are equivalent for a coherent scheme  $X$ .*

- Any universal homeomorphism  $X' \rightarrow X$  in which  $X'$  is reduced is an isomorphism.
- Any universal homeomorphism  $X' \rightarrow X$  admits a section.
- There exists an affine open covering  $\{\text{Spec } A_i\}_{i \in I}$  of  $X$  such that for every  $i \in I$ , the following conditions obtain:
  - for any  $f, g \in A_i$ , if  $f^2 = g^3$ , then there is a unique  $h \in A_i$  such that  $f = h^3$  and  $g = h^2$ ; and
  - for any prime number  $p$  and any  $f, g \in A_i$ , if  $f^p = p^p g$ , then there is a unique element  $h \in A_i$  such that  $f = ph$  and  $g = h^p$ .

This is discussed in [STK, Tag 0EUK]. See also [51, 1.4 and 1.7; 67, Appendix B; 78, Theorem 1].

**14.2.2 Definition.** A coherent scheme  $X$  is said to be *perfectly reduced* – or, in the language of [67, B.1], *absolutely weakly normal* – if  $X$  satisfies the equivalent conditions of Lemma 14.2.1. Denote by  $\text{Sch}_{\text{perf}} \subset \text{Sch}$  the full subcategory spanned by the perfectly reduced schemes.

A coherent scheme  $X$  is said to be *seminormal* if and only if there exists an affine open covering  $\{\text{Spec } A_i\}_{i \in I}$  of  $X$  such that for every  $i \in I$  and any  $f, g \in A_i$ , if  $f^2 = g^3$ , then there is a unique  $h \in A_i$  such that  $f = h^3$  and  $g = h^2$ .

**14.2.3 Example.** A  $\mathbf{Q}$ -scheme is perfectly reduced if and only if it is seminormal.

Let  $p$  be a prime number. A reduced  $F_p$ -scheme is perfectly reduced if and only if it is perfect.

### 14.3 Perfection

We now show that  $\mathbf{Sch}_{perf}$  is the result of inverting the universal homeomorphisms in  $\mathbf{Sch}$ . More precisely, we show that the inclusion  $\mathbf{Sch}_{perf} \hookrightarrow \mathbf{Sch}$  admits a right adjoint  $X \mapsto X_{perf}$  in which the counit  $X_{perf} \rightarrow X$  is a universal homeomorphism. We first check that inverse limits of universal homeomorphisms are universal homeomorphisms.

**14.3.1 Lemma.** *Let  $X$  be a scheme. Let  $A$  be an inverse category, and  $W : A \rightarrow \mathbf{Sch}/_X$  a diagram of  $X$ -schemes such that for any object  $\alpha \in A$ , the structure morphism  $p_\alpha : W_\alpha \rightarrow X$  is a universal homeomorphism. Then the natural morphism*

$$p : W' := \lim_{\alpha \in A^{op}} W_\alpha \rightarrow X$$

*is a universal homeomorphism.*

*Proof.* All the bonding morphisms  $W_\alpha \rightarrow W_{\alpha'}$  are universal homeomorphisms. It follows from [EGA IV<sub>3</sub>, 8.3.8(i)] that  $p$  is surjective. For any field  $k$ , the diagram  $W'(k) : A^{op} \rightarrow \mathbf{Set}$  is a diagram of injections, whence for any  $\alpha \in A^{op}$ , the map  $W'(k) \rightarrow W_\alpha(k)$  is an injection; thus  $p$  is a universal injection. It thus remains to show that  $p$  is integral. Since  $W'$  is a diagram of affine  $X$ -schemes, it is enough to observe that the filtered colimit  $\text{colim}_{\alpha \in A} p_{\alpha,*} \mathcal{O}_{W_\alpha}$  is an integral  $\mathcal{O}_X$ -algebra.  $\square$

**14.3.2 Proposition.** *The inclusion  $\mathbf{Sch}_{perf} \hookrightarrow \mathbf{Sch}$  admits a right adjoint, and the counit  $X_{perf} \rightarrow X$  is a universal homeomorphism.*

*Proof.* For any coherent scheme  $X$ , let  $U_X \subset \mathbf{Sch}/_X$  be the full subcategory spanned by the universal homeomorphisms  $p : Y \rightarrow X$ . Limit-cofinal therein is the full subcategory  $U_X^f$  spanned by the finite universal homeomorphisms. Hence the limit of this diagram of  $X$ -schemes exists and is a universal homeomorphism  $\varepsilon : X_{perf} \rightarrow X$ . Any universal homeomorphism  $Y \rightarrow X_{perf}$  admits a section, whence  $X_{perf}$  is perfect. Moreover, if  $Z$  is perfect, then for any morphism  $f : Z \rightarrow X$ , the pullback  $Z \cong Z \times_X X_{perf} \rightarrow X_{perf}$  provides an inverse to the natural map  $\text{Mor}(Z, X_{perf}) \rightarrow \text{Mor}(Z, X)$ , whence  $\varepsilon$  is a colocalisation of  $\mathbf{Sch}$  relative to  $\mathbf{Sch}_{perf}$ .  $\square$

**14.3.3 Corollary.** *The  $\infty$ -category obtained from the 1-category  $\mathbf{Sch}$  by inverting universal homeomorphisms is equivalent to  $\mathbf{Sch}_{perf}$ .*

**14.3.4 Definition.** We call the right adjoint  $X \mapsto X_{perf}$  the *perfection functor* or the *absolute weak normalisation*.

**14.3.5.** David Rydh [67, Appendix B] presented an alternative description of this functor: if  $X$  is a reduced coherent scheme whose set of irreducible components is finite, or, respectively, an affine scheme, then one may form ‘the’ *absolute integral closure*  $\overline{X}$  of  $X$  [3] or, respectively, ‘the’ *total integral closure*  $\overline{X}$  of  $X$  [22; 33]. In either case, one can show that  $X_{perf}$  is isomorphic to the weak normalisation of  $X$  (in the sense of Andreotti–Bombieri [2, Teorema 2]) under  $\overline{X} \rightarrow X$ .

**14.3.6 Example.** For reduced  $\mathbf{Q}$ -schemes, the perfection is the seminormalisation [STK, Tag 0EUT].

**14.3.7 Example.** Let  $p$  be a prime number. If  $X$  is a reduced  $F_p$ -scheme then we have [11, Lemma 3.8]

$$X_{perf} \cong \lim \left( \cdots \xrightarrow{\phi_X} X \xrightarrow{\phi_X} X \right),$$

where  $\phi_X$  is the absolute Frobenius.

**14.3.8 Definition.** A *topological morphism* from a scheme  $X$  to a scheme  $Y$  is an morphism  $\phi: X_{perf} \rightarrow Y$ . If  $\phi$  induces an isomorphism  $X_{perf} \xrightarrow{\sim} Y_{perf}$ , then it is said to be a *topological equivalence* from  $X$  to  $Y$ .

**14.3.9.** Let  $X$  and  $Y$  be schemes. Consider the following category  $T(X, Y)$ . The objects are diagrams

$$X \leftarrow X' \rightarrow Y$$

in which  $X \leftarrow X'$  is a universal homeomorphism. A morphism

$$\text{from } X \leftarrow X' \rightarrow Y \quad \text{to} \quad X \leftarrow X'' \rightarrow Y$$

is a commutative diagram

$$\begin{array}{ccccc} & & X' & & \\ & \swarrow & \downarrow & \searrow & \\ X & & & & Y \\ & \nwarrow & \downarrow & \nearrow & \\ & & X'' & & \end{array}$$

in which the vertical morphism is (of necessity) a universal homeomorphism. The nerve of the category  $T(X, Y)$  is equivalent to the set  $\text{Mor}(X_{perf}, Y) \cong \text{Mor}(X_{perf}, Y_{perf})$  of topological morphisms from  $X$  to  $Y$ .

**14.3.10.** The point now is that  $\text{Gal}$ , viewed as a functor from  $\text{Sch}_{perf}$  to categories, is *conservative*.

**14.3.11 Definition.** Let  $P$  be a property of morphisms of schemes that is stable under base change and composition. We will say that a morphism  $f: X \rightarrow Y$  is *topologically  $P$*  if and only if it is topologically equivalent to a morphism of schemes  $f': X' \rightarrow Y'$  with property  $P$ .

**14.3.12.** Let  $P$  be a property of morphisms of schemes that is stable under base change and composition. The class of topologically  $P$  morphisms is the smallest class of morphisms  $P^t$  that contains  $P$  and satisfies the following condition: for any commutative diagram

$$\begin{array}{ccc} X & \xrightarrow{f} & Y \\ \phi \downarrow & & \downarrow \psi \\ X' & \xrightarrow{f'} & Y' \end{array}$$

in which  $\phi$  and  $\psi$  are universal homeomorphisms, the morphism  $f$  lies in  $P^t$  if and only if  $f'$  does.

A morphism  $f: X \rightarrow Y$  of perfectly reduced schemes is topologically  $P$  precisely when it factors as a universal homeomorphism  $X \rightarrow X'$  followed by a morphism  $X' \rightarrow Y$  with property  $P$ .



**14.3.13 Example.** A morphism  $f : X \rightarrow Y$  of perfectly reduced schemes is topologically radicial, surjective, universally closed, or integral if and only if it is radicial, surjective, universally closed, or integral (respectively).

**14.3.14 Example.** A morphism  $f : X \rightarrow Y$  of perfectly reduced schemes is topologically étale if and only if it is étale. Indeed, if  $f' : X' \rightarrow Y$  is étale, then  $X'$  is perfectly reduced [67, B.6(ii)].

#### 14.4 Grothendieck's conjecture and the proof of **Theorem A**

In this subsection we discuss the relationship between the Galois category of a coherent scheme and Grothendieck's anabelian programme.

**14.4.1 Definition.** By an *absolute scheme*, we shall mean a perfectly reduced scheme  $X$  such that  $X \rightarrow \text{Spec } \mathbf{Z}$  is topologically essentially of finite type over  $\text{Spec } \mathbf{Z}$ . Denote by  $\text{Sch}_{abs} \subset \text{Sch}_{perf}$  the subcategory whose objects are absolute schemes and whose morphisms are of finite type.

Chevalley's theorem ensures that any morphism of finite presentation between coherent schemes carries constructible sets to constructible sets. We codify this topological condition.

**14.4.2 Definition.** If  $S$  and  $T$  are spectral topological spaces, then a quasicompact continuous map  $f : S \rightarrow T$  is said to be *admissible* if and only if the image of any constructible subset of  $S$  under  $f$  is constructible.

Accordingly, if  $\Pi'$  and  $\Pi$  are profinite stratified spaces, then a morphism  $\Pi' \rightarrow \Pi$  is said to be *admissible* if and only if the induced quasicompact continuous map of spectral topological spaces  $h_0\Pi' \rightarrow h_0\Pi$  is admissible. We write  $\text{Str}_\pi^{\wedge, adm} \subset \text{Str}_\pi^{\wedge}$  for the subcategory whose objects are profinite stratified spaces and whose morphisms are admissible morphisms.

Likewise, if  $X$  and  $Y$  are bounded coherent  $\infty$ -topoi, then a coherent geometric morphism  $f_* : X \rightarrow Y$  is said to be *admissible* if and only if the induced quasicompact continuous map of spectral topological spaces  $S(X) \rightarrow S(Y)$  is admissible (**Notation 9.6.8**). We write

$$\text{Top}_\infty^{bc, adm} \subset \text{Top}_\infty^{bc}$$

for the subcategory whose objects are bounded coherent  $\infty$ -topoi and whose morphisms are admissible geometric morphisms.

**14.4.3.** If  $S$  and  $T$  are Jacobson spectral topological spaces, then a quasicompact continuous map  $f : S \rightarrow T$  is admissible if and only if  $f$  carries closed points to closed points. Similarly, if  $\Pi'$  and  $\Pi$  are profinite stratified spaces such that  $h_0\Pi'$  and  $h_0\Pi$  are Jacobson spectral topological spaces, then a morphism  $f : \Pi' \rightarrow \Pi$  is admissible if and only if  $f$  carries minimal objects to minimal objects.

Here is the 'tantalising conjecture' of Grothendieck in his letter to Faltings [25, p. 7]:

**14.4.4 Conjecture.** *The functor*

$$\text{Sch}_{abs} \rightarrow (\text{Top}_\infty^{bc, adm})_{/(\text{Spec } \mathbf{Z})_{\text{ét}}}$$

given by the assignment  $X \mapsto X_{\text{ét}}$  is fully faithful. In particular, if  $X$  and  $Y$  are absolute schemes, then any admissible geometric morphism  $X_{\text{ét}} \rightarrow Y_{\text{ét}}$  is induced by some morphism  $X \rightarrow Y$  of finite type.

From this conjecture we may deduce a stratified anabelian result:

**14.4.5 Corollary.** Assume [Conjecture 14.4.4](#); then the functor

$$\mathbf{Sch}_{\text{abs}} \rightarrow (\mathbf{Str}_{\pi}^{\wedge, \text{adm}})_{/\Pi_{(\infty, 1)}^{\text{ét}, \wedge}(\text{Spec } \mathbb{Z})}$$

given by the assignment  $X \mapsto \Pi_{(\infty, 1)}^{\text{ét}, \wedge}(X)$  is fully faithful. In particular, if  $X$  and  $Y$  are absolute schemes, then any admissible profinite functor  $\Pi_{(\infty, 1)}^{\text{ét}, \wedge}(X) \rightarrow \Pi_{(\infty, 1)}^{\text{ét}, \wedge}(Y)$  is induced by a morphism  $X \rightarrow Y$  of finite type.

An early paper of Voevodsky [77] provides a proof of [Conjecture 14.4.4](#) for normal absolute schemes in characteristic 0.

**14.4.6 Theorem** ([77, Theorem 3.1]). Let  $k$  be a finitely generated field of characteristic 0, and write  $\mathbf{Sch}_{\text{norm}, k}$  for the category of reduced normal schemes of finite type over  $k$ . Then the functor

$$\mathbf{Sch}_{\text{norm}, k} \rightarrow (\mathbf{Top}_{\infty}^{bc, \text{adm}})_{/(\text{Spec } k)_{\text{ét}}}$$

given by the assignment  $X \mapsto X_{\text{ét}}$  is fully faithful.

Voevodsky also claims that his proof – with some modifications – will work when  $k$  is a finitely generated field of characteristic  $p$  and of transcendence degree  $\geq 1$ .

Voevodsky’s result combined with Conceptual Completeness ([Theorem 5.11.2](#)=[[SAG](#), Theorem A.9.0.6]) show that a morphism  $f: X \rightarrow Y$  of such schemes is an isomorphism if and only if  $f$  induces an equivalence on categories of points  $\text{Pt}(X_{\text{ét}}) \rightarrow \text{Pt}(Y_{\text{ét}})$  of the corresponding étale topoi. Combining our  $\infty$ -categorical Hochster Duality Theorem with Voevodsky’s Theorem and our identification of  $\Pi_{(\infty, 1)}^{\text{ét}, \wedge}(X)$  with the topological category  $\text{Gal}(X)$  ([Construction 13.7.1](#)), we can upgrade this conservativity result to the following strong reconstruction theorem for these schemes:

**14.4.7 Theorem.** Let  $k$  be a finitely generated field of characteristic 0. Then for any reduced normal  $k$ -schemes  $X$  and  $Y$  of finite type, the natural map

$$\text{Mor}_k(X, Y) \rightarrow \text{Mor}_{BG_k}(\text{Gal}(X), \text{Gal}(Y))$$

identifies  $\text{Mor}_k(X, Y)$  with the subgroupoid of continuous functors  $\text{Gal}(X) \rightarrow \text{Gal}(Y)$  that carry minimal objects to minimal objects.

In particular, if  $X$  and  $Y$  are reduced normal  $k$ -schemes of finite type, and  $\text{Gal}(X)$  and  $\text{Gal}(Y)$  are equivalent as topological categories over  $BG_k$ , then  $X$  and  $Y$  are isomorphic.

Thus the category of reduced normal  $k$ -schemes of finite type can be embedded as a subcategory of profinite categories with an action of  $G_k$ , as asserted in [Theorem A](#).

The data of the map  $\text{Gal}(X) \rightarrow BG_k$  is the same as a continuous  $G_k$  action on the fibre, which is  $\text{Gal}(X_{\bar{k}})$  for some algebraic closure  $\bar{k} \supset k$ . Thus by [Corollary 13.8.4](#), a normal  $k$ -variety  $X$  can be reconstructed from  $\Pi_{(\infty, 1)}^{\wedge}(\widehat{X_{\bar{k}}}^{\text{an}}; X_{\bar{k}}^{\text{zar}})$  with its  $G_k$ -action.

## 14.5 Example: Curves

In this section, we illustrate our main theorem by making explicit how one may reconstruct a connected, smooth, complete curve over  $k$  from a combination of stratified-homotopy-theoretic and Galois-theoretic data.

**14.5.1 Construction.** Let  $n \geq 2$  be an integer. Let  $X_n$  be the poset  $\{0, 1, \dots, n-1, \infty\}$ , where  $0, 1, \dots, n-1$  are pairwise incomparable, and for each  $i \in \{0, 1, \dots, n-1\}$  one has  $i < \infty$ . Let  $p_n: X_{n+1} \rightarrow X_n$  be the monotonic map defined by

$$p_n(i) := \begin{cases} i, & i \in \{0, 1, \dots, n-1\} \\ \infty, & i \in \{n, \infty\}. \end{cases}$$

We thus obtain an inverse system of posets

$$\dots \rightarrow X_4 \rightarrow X_3 \rightarrow X_2$$

whose limit  $X$  in stratified topological spaces is the underlying Zariski topological space of any connected, normal curve.

Now let  $g \geq 0$  be an integer. Let  $C_{g,n}: \text{sd}^{op}(X_n) \rightarrow \mathcal{S}$  be the following profinite spatial décollage over  $X_n$ . For any  $i \in \{0, 1, \dots, n-1\}$ , set  $C_{g,n}\{i\} := \{i\}$ , and let  $C_{g,n}\{\infty\}$  be the classifying space of the free group on generators

$$a_1, b_1, a_2, b_2, \dots, a_g, b_g, c_1, c_2, \dots, c_{n-1}.$$

For any  $i \in \{0, 1, \dots, n-1\}$ , let  $C_{g,n}\{i < \infty\}$  be the classifying space of the free group on a single generator  $\xi_i$ . The morphisms  $C_{g,n}\{i < \infty\} \rightarrow C_{g,n}\{\infty\}$  carry the generator  $\xi_i$  to

$$\begin{cases} ([a_1, b_1][a_2, b_2] \cdots [a_g, b_g])(c_1 c_2 \cdots c_{n-1})^{-1}, & i = 0 \\ c_i, & i \neq 0. \end{cases}$$

Thus  $C_{g,n}$  – or rather the corresponding  $X_n$ -stratified space – is the exit-path  $\infty$ -category of a closed smooth 2-manifold of genus  $g$  relative to an  $X_n$ -stratification in which the closed strata are all points. Define a morphism of stratified spaces  $f_n: C_{g,n+1} \rightarrow C_{g,n}$  over  $p_n$  by carrying  $a_j \mapsto a_j$ ,  $b_j \mapsto b_j$ ,  $c_i \mapsto c_i$  for  $i \in \{0, 1, \dots, n-1\}$ , and  $c_n$  to the identity. This defines an inverse system of stratified spaces

$$\dots \rightarrow C_{g,4} \rightarrow C_{g,3} \rightarrow C_{g,2}.$$

After profinite completion, we obtain an inverse system of profinite stratified spaces

$$\dots \rightarrow \widehat{C}_{g,4} \rightarrow \widehat{C}_{g,3} \rightarrow \widehat{C}_{g,2}$$

whose limit is an  $X$ -profinite stratified space that we will call  $\widehat{C}_g$ .

For the remainder of this subsection we fix a finitely generated field  $k$  of characteristic 0 and an algebraic closure  $\bar{k} \supset k$  of  $k$ . The following is immediate from [Proposition 13.8.3](#).

**14.5.2 Proposition.** *Let  $C$  be a connected, smooth, complete curve over  $k$  of genus  $g$ . Then  $\text{Gal}(C_{\bar{k}})$  is equivalent to  $\widehat{C}_g$ .*

**Theorem 14.4.7** says that the curve  $C$  can be reconstructed from the profinite stratified space  $\text{Gal}(C_{\bar{k}}) \simeq \widehat{C}_g$  with its action of  $G_k$ .

To explain this point in more detail, let us make the following slightly tongue-in-cheek definition.

**14.5.3 Definition.** An *incorporeal field extension* of  $k$  is a finite transitive  $G_k$ -set.

Galois theory shows that the assignment  $E \mapsto \text{Gal}(E \otimes_k \bar{k})$  defines an equivalence from the category of finite extensions of  $k$  to the category of incorporeal field extensions of  $k$ . We partially extend this to curves.

**14.5.4 Definition.** An *incorporeal curve over  $k$  of genus  $g$*  is a continuous action of  $G_k$  on  $\widehat{C}_g$ .

A  *$k$ -morphism* from an incorporeal curve  $(\widehat{C}_{g_1}, \alpha_1)$  of genus  $g_1$  to an incorporeal curve  $(\widehat{C}_{g_2}, \alpha_2)$  of genus  $g_2$  is a  $G_k$ -equivariant functor

$$\widehat{C}_{g_1} \rightarrow \widehat{C}_{g_2}.$$

Let  $S$  be an incorporeal field extension of  $k$ . An  *$S$ -point* of an incorporeal curve  $(\widehat{C}_g, \alpha)$  over  $k$  is a  $G_k$ -equivariant functor  $S \rightarrow \widehat{C}_g$ .

Incorporeal curves are completely group-theoretic objects. They amount to inverse families of free profinite groups along with actions of  $G_k$ .

**14.5.5. Theorem 14.4.7** implies that the assignment  $C \mapsto \text{Gal}(C_{\bar{k}})$  defines a fully faithful functor from connected, smooth, complete curves over  $k$  to incorporeal curves over  $k$ .

Additionally, it allows one to reconstruct the points of  $C$  from the corresponding incorporeal curve. For any finite extension  $E \supset k$ , we have a natural bijection between the set of  $E$ -points of  $C$  and the set of  $\text{Gal}(E \otimes_k \bar{k})$ -points of  $\text{Gal}(C_{\bar{k}})$ .

## 14.6 Fibrations of Galois categories

We have already seen (**Proposition 14.1.6**) that an integral morphism of schemes induces a right fibration of Galois categories and that a morphism that induces a right fibration of Galois categories must be universally closed. Let us complete this picture.

Let us begin with an obvious characterisation of quasifinite morphisms. We will say that a functor has *finite fibres* if each of its fibres is equivalent to a finite set.

**14.6.1 Lemma.** *Let  $f: X \rightarrow Y$  be a morphism that is of finite type. Then  $f$  is quasifinite if and only if  $\text{Gal}(X) \rightarrow \text{Gal}(Y)$  has finite fibres.*

Since proper quasifinite morphisms are finite, **Proposition 14.1.6** now yields:

**14.6.2 Proposition.** *Let  $f: X \rightarrow Y$  be a morphism that is separated and of finite type. Then  $f$  is finite if and only if  $\text{Gal}(X) \rightarrow \text{Gal}(Y)$  is a right fibration with finite fibres.*

**14.6.3 Proposition.** *Let  $f : X \rightarrow Y$  be a morphism of schemes. If  $f$  is weakly étale, then  $\text{Gal}(X) \rightarrow \text{Gal}(Y)$  is equivalent to a left fibration. Conversely, if  $X$  and  $Y$  are perfectly reduced, if  $f$  is of finite presentation, and if  $\text{Gal}(X) \rightarrow \text{Gal}(Y)$  is a left fibration with finite fibres, then  $f$  is étale.*

*Proof.* Assume that  $f$  is weakly étale. Then for any geometric point  $x \rightarrow X$ , the morphism  $X_{(x)} \rightarrow Y_{(f(x))}$  is an isomorphism, whence the functor

$$\text{Gal}(X)_{x/} \simeq \text{Gal}(X_{(x)}) \rightarrow \text{Gal}(Y_{(f(x))}) \simeq \text{Gal}(Y)_{f(x)/}$$

is an equivalence, whence  $\text{Gal}(X) \rightarrow \text{Gal}(Y)$  is a left fibration.

Conversely, assume that  $X$  and  $Y$  are perfectly reduced, that  $f$  is of finite presentation, and that  $\text{Gal}(X) \rightarrow \text{Gal}(Y)$  is a left fibration with finite fibres. So the functor  $\text{Gal}(X) \rightarrow \text{Gal}(Y)$  is classified by a continuous functor  $\text{Gal}(Y) \rightarrow \mathbf{Set}^{fin}$ , which in turn corresponds to a constructible étale sheaf of finite sets on  $Y$ , which in particular coincides with the sheaf represented by  $X$ . Since the sheaf represented by  $X$  is constructible, there exists an étale map  $U \rightarrow Y$  and an effective epimorphism  $U \rightarrow X$  of étale sheaves on  $Y$ . By descent,  $X \rightarrow Y$  is étale.  $\square$

We may as well combine the last two entries in our dictionary.

**14.6.4 Recollection.** A *Kan fibration* is a functor that induces a Kan fibration on nerves. Equivalently, it is a functor that is both a left and right fibration. Equivalently, it is a functor  $C \rightarrow D$  that is equivalent to the Grothendieck construction applied to a diagram of groupoids indexed on  $D^{op}$  that carries every morphism to an equivalence of groupoids.

**14.6.5 Proposition.** *Let  $f : X \rightarrow Y$  be a morphism of perfectly reduced schemes that is separated and of finite presentation. Then  $f$  is finite étale if and only if  $\text{Gal}(X) \rightarrow \text{Gal}(Y)$  is a Kan fibration with finite fibres.*

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