

MATH266: UNSTABLE MOTIVIC HOMOTOPY THEORY

Fall 2024

THOMAS BRAZELTON

ABSTRACT. Notes from MATH266: Motivic homotopy theory, taught at Harvard in Fall 2024. Last compiled: October 1, 2024

CONTENTS

About these notes	1
0. Introduction	1
1. Torsors	5
2. Torsors II: Simplicial methods	11
3. Torsors III: Sites, sheaves, and Hilbert 90	18
4. Infinity categories	20
5. Descent	26
6. Motivic spaces	34
7. Jouanolou devices and motivic equivalences	38
8. Pointed motivic spaces	40
9. \mathbb{A}^1 -homotopy classes of maps	42
10. Strong and strict \mathbb{A}^1 -invariance	43
Appendix A. More category theory	45
Appendix B. Essential smallness	46
References	47

ABOUT THESE NOTES

These are notes for a topics class taught at Harvard in Fall 2024. Notes are being updated twice a week with new lectures. Please send any and all changes to

<https://github.com/tbrazel/math266-motivic>

Thank you to Merrick Cai, Jake Levinson, Matthew Niemi, and Natalie Stewart for valuable changes and suggestions. Thank you to Liam Keenan for always letting me bother them about technical things.

0. INTRODUCTION

0.1. Overview. What sorts of things about a ring R are still true when we move to the polynomial ring $R[t]$? In other words, what sorts of things about R can't be varied in a 1-parameter family? Let's give a ton of examples! Don't stress if not all of the words are familiar, we'll break down what's happening here over the course of the semester, this is just motivation.

Example 0.1. Let R be a reduced ring. Then the inclusion $R \rightarrow R[t]$ induces an isomorphism after taking units¹

$$(2) \quad R^\times \xrightarrow{\sim} (R[t])^\times.$$

Recall that the functor sending a commutative ring to its group of units is corepresented by $\mathbb{Z}[u, u^{-1}]$, so [Equation 2](#) is equivalent to saying that the following map is a bijection

$$\mathrm{Hom}_{\mathrm{Ring}}(\mathbb{Z}[u, u^{-1}], R) \rightarrow \mathrm{Hom}_{\mathrm{Ring}}(\mathbb{Z}[u, u^{-1}], R[t]).$$

After taking Spec everywhere, this becomes

$$\mathrm{Hom}_{\mathrm{Sch}}(\mathrm{Spec}(R), \mathbb{G}_m) \rightarrow \mathrm{Hom}_{\mathrm{Sch}}(\mathrm{Spec}(R[t]), \mathbb{G}_m).$$

We therefore might rephrase [Equation 2](#) as saying that $\mathrm{Hom}_{\mathrm{Sch}}(-, \mathbb{G}_m)$ is \mathbb{A}^1 -invariant, at least when we plug in something reduced.

Example 0.3. Let k be a field. Then the functor $k \rightarrow k[t_1, \dots, t_n]$ induces an extension of scalars map

$$\begin{aligned} \mathrm{Mod}_k &\rightarrow \mathrm{Mod}_{k[t_1, \dots, t_n]} \\ M &\mapsto M \otimes_k k[t_1, \dots, t_n]. \end{aligned}$$

Serre’s Problem: Is every finitely generated $k[t_1, \dots, t_n]$ -module free?

Recall finitely generated projective R -modules are the same as “algebraic vector bundles” over $\mathrm{Spec}(R)$, so we’re asking whether every algebraic vector bundle on \mathbb{A}_k^n is trivial.

Answer: Yes (Quillen–Suslin, 1974). Quillen actually proved more— for R a PID, he proved that the every finitely generated projective $R[t]$ -module is extended from an R -module.² Lindel proved shortly thereafter that every finitely generated projective $A[t]$ -module is extended from an A -algebra, where A is a smooth algebra containing a field k . We could read this as saying that the stack of algebraic vector bundles is \mathbb{A}^1 -invariant over the category of smooth affine k -schemes.

More general: (Bass–Quillen conjecture) is it true that for every R regular Noetherian, the map

$$\begin{aligned} \mathrm{Mod}_R^{\mathrm{f.g., proj}} &\rightarrow \mathrm{Mod}_{R[t]}^{\mathrm{f.g., proj}} \\ M &\mapsto M \otimes_R R[t] \end{aligned}$$

is essentially surjective? *Still open.*

Fundamental Theorem of Algebraic K-Theory (Quillen): For R regular Noetherian, we have that $R \rightarrow R[t]$ induces an equivalence³⁴

$$K(R) \xrightarrow{\sim} K(R[t]).$$

In other K -theory is \mathbb{A}^1 -invariant for regular Noetherian rings (regular Noetherian schemes, more generally).

Example 0.4. If $X = \mathrm{Spec}(R)$ or more generally X is a scheme, then the map $\pi: X \times \mathbb{A}^1 \rightarrow X$ induces an isomorphism on Chow groups (see for instance [\[Ful98, 3.3\]](#))

$$\pi^*: \mathrm{CH}_*(X) \xrightarrow{\sim} \mathrm{CH}_{*+1}(X \times \mathbb{A}^1).$$

¹If R is not reduced, say there is some $r \in R$ so that $r^2 = 0$, then $(1 + rt)(1 - rt) = 1$, so $1 + rt \in R[t]^\times$.

²Quillen’s proof involves leveraging some previous work of Horrocks, flat descent for vector bundles, and a very clever technique he invented called *patching*. Suslin’s proof, which appeared in the same year, is almost completely linear algebraic, leveraging the theory of *unimodular rows*.

³So Bass–Quillen is really a question about *unstable* modules.

⁴The statement for K_0 is originally due to Grothendieck [\[Aso21, 5.6.1.3\]](#). The statement for K_1 is due to Bass–Heller–Swan [\[Aso21, 5.8.2.1\]](#).

Example 0.5. Let $X = \operatorname{Spec}(R)$ where R is normal and Noetherian.⁵ Then every line bundle on $X \times \mathbb{A}^1$ is extended from a line bundle on X , in other words $X \times \mathbb{A}^1 \rightarrow X$ induces an isomorphism $\operatorname{Pic}(X) \xrightarrow{\sim} \operatorname{Pic}(X \times \mathbb{A}^1)$.

Example 0.6. We can also show \mathbb{A}^1 -invariance for the Picard group over a PID. Let R be a PID, then it is a UFD, and we can show that $\operatorname{Pic}(R) = 0$, and therefore $\operatorname{Pic}(R[t_1, \dots, t_n]) = 0$.

Example 0.7. [Aso21, 3.7.1.5] Check this doesn't hold for all rings, for example $R = k[x, y]/(y^2 - x^3)$.⁶

Definition 0.8. An *inner product space* over a ring R is a finitely generated projective R -module M and a symmetric bilinear form $\beta: M \times M \rightarrow R$ for which $m \mapsto \beta(-, m)$ defines an isomorphism $M \cong M^*$.

Theorem 0.9. (Harder's Theorem, VII.3.13 in Lam's book on Serre's problem) Let k be a field. Then every inner product space over $k[t]$ is extended from an inner product space over k .

Remark 0.10. The stable analogue of this has to do with \mathbb{A}^1 -invariance of Hermitian K -theory [reference needed].

Algebraic vector bundles are GL_n -torsors (we will talk about torsors in more detail next week), so the Bass–Quillen conjecture is really asking about \mathbb{A}^1 -invariance of torsors over affine schemes. We could ask an analogous question about G -torsors for any G . Here's an example result in this direction that we'll see later in the semester:

Theorem 0.11. [AHW20, 1.3] If k is a field, and G is an isotropic reductive group scheme, then G -torsors in the Nisnevich site are \mathbb{A}^1 -invariant over any smooth affine k -scheme.

0.2. \mathbb{A}^1 -homotopy theory. Recall from algebraic topology that $X \times [0, 1] \rightarrow X$ is a weak homotopy equivalence, which implies that any cohomology theory is insensitive to taking a product with an interval, e.g. for $H^*(-, \mathbb{Z})$ integral cohomology we get

$$H^*(X, \mathbb{Z}) \xrightarrow{\sim} H^*(X \times [0, 1], \mathbb{Z}).$$

In fact this type of homotopy invariance is an axiom of generalized Eilenberg–Steenrod cohomology theories.

Example 0.12. Let $k \subseteq \mathbb{C}$ be a subfield of the complex numbers. Then there is a *Betti realization* functor

$$\begin{aligned} \operatorname{Var}_k &\rightarrow \operatorname{Top} \\ X &\mapsto X(\mathbb{C}) \end{aligned}$$

sending a variety to its underlying analytic space. Note that

$$X \times \mathbb{A}_k^1 \mapsto (X \times \mathbb{A}_k^1)(\mathbb{C}) = X(\mathbb{C}) \times \mathbb{C}.$$

Therefore any homotopy invariant functor out of spaces provides another example of an \mathbb{A}^1 -invariant functor out of k -varieties, for example

$$\begin{aligned} X &\mapsto H^*(X(\mathbb{C}); \mathbb{Z}) \\ X &\mapsto \pi_*(X(\mathbb{C})). \end{aligned}$$

Q: Can we build a homotopy theory of algebraic varieties in which the affine line \mathbb{A}^1 plays the role that the interval $[0, 1]$ plays in classical topology?

⁵We can get away with weaker assumptions on this, for example in [Aso21, 3.7.13] it is only assumed that R is a locally factorial Noetherian normal domain.

⁶More generally if A is reduced, Noetherian, and has a finite normalization, then its Picard group will be \mathbb{A}^1 -invariant if and only if A is seminormal [Tra70, 3.6].

A: Yes! This is what's known as \mathbb{A}^1 -homotopy theory or *motivic homotopy theory*. This dates back to Morel and Voevodsky's seminal work in 1999, but many ideas date back to work of Karoubi–Villamayor, Jardine, Weibel in the 1980's, work of Brown, Gersten, Illusie and Joyal in the 1970's, and of Quillen and Grothendieck in the 1960's.

Q: What can we do with motivic homotopy theory?

A: Motivic homotopy theory blends algebraic geometry and topology in a beautiful way, allowing us to do many things. A short list is:

- ▷ we obtain a natural home for these kinds of \mathbb{A}^1 -invariant cohomology theories of varieties, and can study them in a method analogous to algebraic topology (e.g. we can classify cohomology operations, use fiber sequences to carry out computations, unify various spectral sequences, etc.)
- ▷ we have access to obstruction theory for classifying torsors over affine varieties — recent success in this direction is Asok–Bachmann–Hopkins' resolution of Murthy's conjecture
- ▷ we can eliminate differentials in the Adams spectral sequence via looking at their motivic depth (citation needed)

Q: What techniques will we learn in this class?

A: We should be able to do the following things:

- ▷ learn descent and torsors more thoroughly, and unify perspectives on sheaves and stacks using higher categorical language
- ▷ work with ∞ -categories at a very basic level
- ▷ learn how to work with motivic spaces and do computations
- ▷ learn motivic obstruction theory and its applications

0.3. A bit more about these notes.

Remark 0.13. (*Transparency about pedagogy*) We're going to place affine representability on the horizon and keep our eyes fixed on it in order to motivate the category of motivic spaces. This is of course ahistorical— although affine representability was one of the key early results explored by Morel, motivic spaces and spectra were developed in order to house theories such as algebraic K -theory, Bloch's higher Chow groups, and to grow new theories such as algebraic cobordism. We chose this route for a few reasons:

- (1) The Fall 2024 Thursday seminar is on the motivic Steenrod algebra, so we're hoping this class will contrast nicely and provide some foundational background in techniques in motivic obstruction theory.
- (2) In order to tailor the course to a broader audience, we'd like to unify the class around a key question which has general appeal, so we've picked the classification of torsors over affine varieties using motivic methods as such a question. This has certain advantages, for instance we can pause in the sheaf topos and discuss classifying torsors there before building motivic spaces — this vista is useful to people across many fields.
- (3) This forces us to spend a bit longer on descent and torsors, two words which strike fear in the heart of many, and are worth investing some more time in.

Remark 0.14. (*On background*) We're assuming a strong handle of algebraic geometry and category theory, and a fair bit of familiarity with commutative algebra and homotopy theory. We'll see very quickly that ∞ -categories (and/or model categories) are needed in order to develop the setting in which we wish to work. We've elected to take the ∞ -categorical approach, since it streamlines many of the constructions and key ideas, at the cost of being a high technical investment; for this reason we've done our best to make the ∞ -categorical machinery easy to black box. The reader should be aware that while the categorical language will be heavy in the first half of these notes, it will quickly fade into the background as we become familiar with the ambient setting we're working in and can set our focus towards computations.

1. TORSORS

Assumption 1.1. For this lecture, every time we say “cover” you can assume we are working with Zariski covers, or even open covers of topological spaces, since the intuition will be the same and the results here will be mostly identical. If you know about other topologies, the statements here work for any site. We will go into sheaves and sites more next week, when we will remark that everything here works for other nice sites (étale, Nisnevich, flat, etc.).

Definition 1.2. Let G be a group. Then a G -set X is called a *torsor* if its G -action is simple and transitive. Equivalently, the map

$$(3) \quad \begin{aligned} G \times X &\rightarrow X \times X \\ (g, x) &\mapsto (x, gx) \end{aligned}$$

is a bijection.

Note there are two types of G -torsors — sets of the form G/e , and the empty set. Depending on the convention, we might want to exclude the case of the empty set by including $X \neq \emptyset$ in the definition.

Intuition 1.4. A G -torsor is like a group G which has remembered its multiplication but forgotten its identity. Any choice of basepoint $x \in X$ yields a canonical bijection $G \xrightarrow{\sim} X$ by sending $g \mapsto g \cdot x$.

Example 1.5. In a locally small category \mathcal{C} , given two objects $x, y \in \mathcal{C}$, the set of isomorphisms $\text{Isom}_{\mathcal{C}}(x, y)$ is a left $\text{Aut}_{\mathcal{C}}(x)$ -torsor and a right $\text{Aut}_{\mathcal{C}}(y)$ -torsor.

Let’s try to extend this definition to the setting where G isn’t a single group, but a *sheaf of groups* \mathcal{G} on a site. What is the appropriate analogue of a torsor in this setting? By abuse of notation we will also call this a *torsor*.

Definition 1.6. [Stacks, 03AH] Let \mathcal{G} be a sheaf of groups on X , and let $\text{Shv}_{\mathcal{G}}(X)$ denote the category of \mathcal{G} -sheaves, meaning sheaves of sets equipped with a \mathcal{G} -action, and equivariant morphisms between them. We define the category of \mathcal{G} -torsors $\text{Tors}_{\mathcal{G}}(X) \subseteq \text{Shv}_{\mathcal{G}}(X)$ to be the full subcategory on those \mathcal{F} so that

- (1) if $\mathcal{F}(U)$ is non-empty then the action

$$\mathcal{G}(U) \times \mathcal{F}(U) \rightarrow \mathcal{F}(U)$$

is simply transitive.⁷

- (2) there exists a covering $\{U_i \rightarrow X\}$ over which $\mathcal{F}(U_i) \neq \emptyset$.⁸

Terminology 1.7. The choice of topology comes into play in that second point. If $\mathcal{F} \in \text{Shv}_{\mathcal{G}}(X)$, we say it is *τ -locally trivial* if \mathcal{G} is a τ -sheaf of groups, \mathcal{F} is a τ -sheaf of sets, and point (2) holds for any τ -cover.

Example 1.8. The sheaf \mathcal{G} , acting on itself by scaling, is called the *trivial* \mathcal{G} -torsor.

Example 1.9. For any group scheme G , we will refer to G -torsors, mean torsors the representable functor $\text{Hom}(-, G)$.

Proposition 1.10. A \mathcal{G} -torsor \mathcal{F} on X is trivial if and only if $\mathcal{F}(X) \neq \emptyset$, i.e. if it admits a global section.

Theorem 1.11. Every morphism in $\text{Tors}_{\mathcal{G}}(X)$ is an isomorphism.

⁷This means that in the category of $\mathcal{G}(U)$ -sets, we have that $\mathcal{F}(U) \cong \mathcal{G}(U)$, but $\mathcal{F}(U)$ doesn’t have a group structure — we might imagine that it has forgotten its identity element. Picking a basepoint $e \in \mathcal{F}(U)$ defines a group structure on $\mathcal{F}(U)$.

⁸In other words, we can find a cover in which to visualize $\mathcal{F}(U_i)$ as a group for each i .

So what are some examples of torsors, and why might we care to classify them?

Example 1.12. If L/k is a Galois field extension then $\mathrm{Spec}(L) \rightarrow \mathrm{Spec}(k)$ is a $\mathrm{Gal}(L/k)$ -torsor in the étale topology.

▷ *the inverse Galois problem*: which groups G occur as Galois groups of number fields? This is asking to scratch the surface of understanding G -torsors over $\mathrm{Spec}(\mathbb{Q})$ for all finite groups G .

Example 1.13. The associated frame bundle of an algebraic vector bundle is a GL_n -torsor (say, in the Zariski topology).

Proof. Since GL_n is affine, every torsor is representable, hence GL_n -torsors are just principal GL_n -bundles, which are precisely algebraic vector bundles. \square

▷ *Bass–Quillen conjecture*: this can be reframed as asking whether each GL_n -torsor over a regular Noetherian ring is trivial

▷ *Hartshorne’s conjecture* concerns GL_2 -torsors over \mathbb{P}^n for $n \geq 7$

Example 1.14. A PGL_n -torsor is a Brauer–Severi variety (or a central simple algebra).

▷ the *period-index conjecture* then concerns the complexity of PGL_n -torsors.

Goal 1.15. Develop methods to classify torsors.

Let’s do this, by first considering an alternative perspective on what a torsor is. We learned this from Alex Youcis’ excellent note on torsors [You].

1.1. Sheaves and stacks. Recall if \mathcal{F} is a sheaf of sets, this means for every cover $\{U_i \rightarrow U\}$, we have that the diagram is an equalizer

$$\mathcal{F}(U) \rightarrow \prod \mathcal{F}(U_i) \rightrightarrows \prod_{i,j} \mathcal{F}(U_i \times_U U_j).$$

This first map is a monomorphism (injection) because it is an equalizer. This means that if $x, y \in \mathcal{F}(U)$ are equal in $\mathcal{F}(U_i)$ for each i , then they are equal in $\mathcal{F}(U)$. In other words, the map “reflects equality” — this is literally just what it means for something to be an injection.

Let’s suppose now that $\mathcal{F}(U)$ is a *category* for every U . We’ll define this concretely soon once we have more machinery, but for now let’s just pretend that we know what this means — it means we can glue objects and morphisms along covers. Consider the analogous restriction functor:

$$\begin{aligned} \mathcal{F}(U) &\rightarrow \prod \mathcal{F}(U_i) \\ x &\mapsto (x|_{U_i})_i. \end{aligned}$$

Q: Does this map need to reflect isomorphisms?⁹

Example 1.16. Let \mathcal{F} be the functor sending U to the category of line bundles over U . If the cover is picked appropriately small, then all line bundles are isomorphic to the trivial line bundle over U_i , but they need not be isomorphic globally as line bundles over U .

A: No, by the example above. This means that we can have $x, y \in \mathcal{F}(U)$ so that $x|_{U_i} \cong y|_{U_i}$ for each i , but we *do not have* that x and y are isomorphic in the category $\mathcal{F}(U)$. In other words, the following two notions are *different*.

▷ x and y agree *globally*, meaning x and y are isomorphic in $\mathcal{F}(U)$.

▷ x and y agree *locally*, meaning there exists an open cover $\{U_i \rightarrow U\}$ for which we have isomorphisms $x|_{U_i} \xrightarrow{\sim} y|_{U_i}$ in $\mathcal{F}(U_i)$.¹⁰

⁹A functor which reflects isomorphisms is called *conservative*.

¹⁰The notation $x|_{U_i}$ is shorthand for the image of x under the restriction functor $\mathcal{F}(U) \rightarrow \mathcal{F}(U_i)$

Remark 1.17. This is a big difference between sheaves of sets (or 1-categories in general) and sheaves of categories (also called *stacks*). Equality is reflected along a cover for sheaves of sets, but isomorphism is not necessarily reflected along a cover.

Question 1.18. How many isomorphism classes of objects $y \in \mathcal{F}(U)$ are *locally isomorphic* to x along a cover, but not globally isomorphic?

We're going to build a sheaf that measures this! We'll call this sheaf $\text{Aut}_{\mathcal{F}}(x)$, and it is defined by

$$(19) \quad U_i \mapsto \text{Aut}_{\mathcal{F}(U_i)}(x).$$

Exercise 1.20. This is a priori just a presheaf of groups. Check it is actually a sheaf of groups.

Recall the following definition.

Definition 1.21. Let \mathcal{G} denote a sheaf of groups over U and $\mathcal{U} = \{U_i \rightarrow U\}$ a cover.

- (1) We define a *Čech 1-cocycle* to be a collection of elements $g_{ij} \in \mathcal{G}(U_i \times_U U_j)$ for each i, j so that

$$g_{ij}g_{jk} = g_{ik}$$

on triple overlaps.¹¹

- (2) We say two 1-cocycles (g_{ij}) and (γ_{ij}) are cohomologous if there are $\alpha_i \in \mathcal{G}(U_i)$ for each i so that

$$\alpha_i g_{ij} = \gamma_{ij} \alpha_j.$$

- (3) We define the *Čech cohomology* $\check{H}^1(U, \mathcal{G})$ to be the colimit of the Čech cohomology over covers, filtered with respect to refinement.

Theorem 1.22. There is a bijection between $H^1(U, \text{Aut}_{\mathcal{F}}(x))$ and isomorphism classes of objects $y \in \mathcal{F}(U)$ which are locally isomorphic to x .

Proof. Let's first define a map. If y is locally isomorphic to x , then there is a cover $\{U_i\}$ of U and isomorphisms $\phi_i: x|_{U_i} \xrightarrow{\sim} y|_{U_i}$ for each i . If the ϕ_i 's agreed on overlaps then they would glue to a global isomorphism $\phi: x \xrightarrow{\sim} y$ because $\text{Aut}(x)$ is a sheaf of groups, so it makes sense to look on overlaps to see what happens. Note that $\phi_i|_{U_{ij}}$ and $\phi_j|_{U_{ij}}$ will differ by an automorphism of $x|_{U_{ij}}$, call this g_{ij} :

$$g_{ij} := \left(\phi_i|_{U_{ij}} \right)^{-1} \left(\phi_j|_{U_{ij}} \right) : x|_{U_{ij}} \xrightarrow{\sim} x|_{U_{ij}}.$$

On triple overlaps, it is straightforward to verify that

$$g_{ij}g_{jk} = g_{ik}.$$

In other words we get a 1-cocycle! There was ambiguity here, since we *picked* isomorphisms $x|_{U_i} \xrightarrow{\sim} y|_{U_i}$ as our starting data. The remaining thing to prove is that any other choice of local isomorphisms gives rise to a cohomologous 1-cocycle.

Suppose we instead picked some $\psi_i: x|_{U_i} \xrightarrow{\sim} y|_{U_i}$ for each i , yielding $\gamma_{ij} = \psi_j^{-1}\psi_i$. Then ψ_i and ϕ_i differ by an automorphism of y which we call α_i :

$$\begin{array}{ccc} x|_{U_i} & \xrightarrow{\phi_i} & y|_{U_i} \\ & \searrow \alpha_i & \nearrow \psi_i \\ & x|_{U_i} & \end{array}$$

¹¹See e.g. [Mil13, §11].

Then on U_{ij} we have

$$g_{ij} = \phi_i^{-1} \phi_j = (\psi_i \alpha_i)^{-1} (\psi_j \alpha_j) = \alpha_i^{-1} \psi_i^{-1} \psi_j \alpha_j.$$

Hence

$$\alpha_i g_{ij} = \gamma_{ij} \alpha_j$$

And we get cohomologous 1-cocycles. \square

Theorem 1.23. There is a bijection between isomorphism classes of \mathcal{G} -torsors and $\check{H}^1(U, \mathcal{G})$.

Sketch. Let \mathcal{F} be a \mathcal{G} -torsor, and pick $s_i \in \mathcal{F}(U_i)$ for each i . Then on the overlap $U_i \times_U U_j$, we have that s_i and s_j differ by a unique element $g_{ij} \in \mathcal{G}(U_i \times_U U_j)$. We run basically an identical argument. \square

So if $\mathcal{G} = \text{Aut}_{\mathcal{F}}(x)$ then we have a bijection

$$\left\{ \begin{array}{l} \text{iso classes of } y \in \mathcal{F}(U) \\ \text{locally isomorphic to } x \end{array} \right\} \leftrightarrow \check{H}^1(U, \text{Aut}_{\mathcal{F}}(x)) \leftrightarrow \{\text{Aut}_{\mathcal{F}}(x)\text{-torsors}\}.$$

These sorts of arguments are compatible with refinement of the cover, and since Čech and sheaf cohomology agree we see that G -torsors are in bijection with the first sheaf cohomology $H^1(U, G)$.

Exercise 1.24. Show that every sheaf of groups \mathcal{G} is of the form $\text{Aut}_{\mathcal{F}}(x)$ for some sheaf of categories \mathcal{F} .

Intuition 1.25. A \mathcal{G} -torsor is an object whose automorphisms locally look like $\mathcal{G}(U_i)$.

1.2. Interlude: representable G -torsors. When both the presheaf \mathcal{G} and the sheaf of sets \mathcal{F} are representable, we get a slightly different characterization.

Setup 1.26. Suppose $\mathcal{C} = \text{Sch}_X$ is a site of schemes over X , and let $G \in \text{Grp}(\text{Sch}_X)$ be a group scheme over X . Suppose $\mathcal{G} = \text{Hom}_X(-, G)$ is a representable sheaf of groups, and let $\mathcal{F} = \text{Hom}_X(-, Y)$ for some $Y \in \text{Sch}_X$, where Y comes equipped with a G -action.

In this setup, what does it mean in this case for \mathcal{F} to be a \mathcal{G} -torsor?

Condition (1) from [Definition 1.6](#) asks that

$$\text{Hom}_X(U, G) \times \text{Hom}_X(U, Y) \rightarrow \text{Hom}_X(U, Y)$$

to be simply transitive for every $U \in \text{Sch}_X$. This seems a bit tedious to check, but the following result gives us a cleaner characterization of it, which is a sheafy version of [Equation 3](#).

Proposition 1.27. [[Stacks](#), 0499] In [Setup 1.26](#) the following two conditions are equivalent:

(1) The map

$$\begin{aligned} G \times_X Y &\rightarrow Y \times_X Y \\ (g, y) &\mapsto (y, gy) \end{aligned}$$

is an isomorphism of X -schemes.

(2) For every $U \in \text{Sch}_X$, the induced action

$$\text{Hom}_X(U, G) \times \text{Hom}_X(U, Y) \rightarrow \text{Hom}_X(U, Y)$$

is simply transitive.

What about condition (2) from [Definition 1.6](#)? This condition translates, in [Setup 1.26](#), to asking for a cover $\{U_i \rightarrow X\}$ for which $\text{Hom}_X(U_i, Y) \neq \emptyset$ for each i . Pick any $s_i \in \text{Hom}_X(U_i, Y)$, then it makes the diagram commute:

$$\begin{array}{ccc} & & Y \\ & \nearrow s & \downarrow \\ U_i & \longrightarrow & X. \end{array}$$

Then the pullback torsor $Y \times_X U_i \rightarrow U_i$ admits a section, which implies it is trivial by [Proposition 1.10](#):

$$\begin{array}{ccc} Y \times_X U_i & \longrightarrow & X \\ \uparrow \downarrow & \lrcorner & \downarrow \\ U_i & \longrightarrow & X. \end{array}$$

We summarize these observations in the following proposition.

Proposition 1.28. Let X be a scheme, let G be a group scheme over X , and let

$$f: Y \rightarrow X$$

be an X -scheme equipped with a G -action. Then Y is a G -torsor if and only if

- (1) The map $G \times_X Y \rightarrow Y \times_X Y$ is an isomorphism of X -schemes.
- (2) There exists a cover $\{U_i \rightarrow X\}$ for which $Y \times_X U_i \rightarrow U_i$ is isomorphic to the trivial G -torsor over U_i .

In this setting, we call $Y \rightarrow X$ a *principal G -bundle*.

Example 1.29. Let's double back to [Example 1.12](#) and actually prove that $\mathrm{Spec} L \rightarrow \mathrm{Spec} k$ is a principal $\mathrm{Gal}(L/k)$ -bundle in the étale site when L/k is a Galois field extension.

Proof. We check the conditions from [Proposition 1.28](#). The first condition asks that

$$\left(\coprod_{g \in G} \mathrm{Spec}(k) \right) \times_{\mathrm{Spec}(k)} \mathrm{Spec}(L) \rightarrow \mathrm{Spec}(L) \times_{\mathrm{Spec} k} \mathrm{Spec}(L)$$

is an equivalence. Since everything in sight is affine, we can rephrase this as asking for the map

$$\begin{aligned} \prod_{g \in G} L &\leftarrow L \otimes_k L \\ (x \cdot g(y))_{g \in G} &\leftarrow x \otimes y \end{aligned}$$

to be an equivalence, which we recall is the *normal basis theorem* from Galois theory. The second condition from [Proposition 1.28](#) asks us to find a cover of $\mathrm{Spec}(k)$ trivializing $\mathrm{Spec}(L) \rightarrow \mathrm{Spec}(k)$, but if we work in the étale site, then $\mathrm{Spec}(L) \rightarrow \mathrm{Spec}(k)$ is itself a cover, and it is clear that the product induces a section

$$\begin{array}{ccc} \mathrm{Spec}(L \otimes_k L) & \longrightarrow & \mathrm{Spec}(L) \\ \uparrow \downarrow & \lrcorner & \downarrow \\ \mathrm{Spec}(L) & \longrightarrow & \mathrm{Spec}(k). \end{array}$$

Hence we have a trivialization, and hence a principal $\mathrm{Gal}(L/k)$ -bundle (a $\mathrm{Gal}(L/k)$ -torsor). \square

Often it's just enough to assume the sheaf of groups is representable to get all torsors are representable.

Proposition 1.30. Let G be an affine group scheme over X , and let $\tau \leq \mathrm{fppf}$. Then every G -torsor is representable. (see [\[Stacks, 0497\]](#), [\[You, 3.25\]](#))

Sketch. Every G -torsor is an algebraic space, and algebraic spaces which are locally affine are schemes. Since a G -torsor is locally isomorphic to G , which was assumed to be affine, then we conclude every torsor is actually a scheme. \square

Terminology 1.31. A representable fpqc-torsor for G is called a *principal homogeneous space*.

Remark 1.32. If $t \leq \tau$, then every t -cover is a τ -cover, hence if we can find a t -cover trivializing a G -torsor, then it also trivializes it in the τ -topology. hence

$$t \leq \tau \Rightarrow \{t\text{-torsors}\} \subseteq \{\tau\text{-torsors}\}.$$

So a very natural question is *how do we tell when a τ -torsor is also a t -torsor?* We'll discuss this next week.

1.3. Interlude: representability of torsors in topology. So it's a very reasonable goal to ask for any tools that could help us try to classify torsors. A natural idea, by analogy, is to look to homotopy theory, where we have a suite of tools for studying torsors.

Definition 1.33. Let X be a compact Hausdorff topological space and G a group. Then a *principal G -bundle* (or we might just say a G -torsor) is a fiber bundle $\pi: Y \rightarrow X$ so that G acts freely and transitively on the fibers.

In topology there is a *universal G -torsor*, which is denoted $EG \rightarrow BG$. This is universal in the sense that, given any map $f: X \rightarrow BG$, we can consider the fiber product

$$\begin{array}{ccc} f^*EG & \longrightarrow & EG \\ \downarrow & \lrcorner & \downarrow \\ X & \xrightarrow{f} & BG. \end{array}$$

Then $f^*EG \rightarrow X$ is a principal G -bundle, and all principal G -bundles are obtained in this way. Not only that, but isomorphic principal G -bundles are given by homotopic classifying maps. In other words we have a bijection

$$\text{Prin}_G(X) \leftrightarrow [X, BG].$$

So the data of a principal G -bundle is the data of a map $X \rightarrow BG$, and an isomorphism of principal G -bundles is equivalent to a homotopy between two maps $f, g: X \rightarrow BG$.

Example 1.34. We have that $B(\mathbb{Z}/2) = \mathbb{RP}^\infty$ and $E\mathbb{Z}/2 = S^\infty$, so that $\mathbb{Z}/2$ -torsors are real line bundles. Similarly $BC^\times = \mathbb{CP}^\infty$.

A big example comes from quotienting out by a compact subgroup:

Theorem 1.35. (Samelson, 1941) If $H \leq G$ is a compact subgroup of a Lie group, then $G \rightarrow G/H$ is a Serre fibration and principal H -bundle.

Corollary 1.36. We have fiber sequences

$$\begin{aligned} H &\rightarrow G \rightarrow G/H \\ G/H &\rightarrow BH \rightarrow BG. \end{aligned}$$

Example 1.37. For the inclusions $O(n) \subseteq O(n+1)$ and $U(n) \subseteq U(n+1)$ we get fiber sequences

$$\begin{aligned} S^{2n+1} &\rightarrow \text{BU}(n) \rightarrow \text{BU}(n+1) \\ S^n &\rightarrow \text{BO}(n) \rightarrow \text{BO}(n+1). \end{aligned}$$

This is how Bott periodicity is proved.

1.4. Why we like representability of torsors. This has a number of huge applications:

- ▷ Given any cohomology theory E^* and any class $c \in E^*(BG)$, if $f^*(c) \neq g^*(c)$ in $E^*(X)$, this means that f and g correspond to non-isomorphic torsors. This is the basic idea of characteristic classes.

Example 1.38. If $G = \text{GL}_n(\mathbb{C})$, then $\text{BGL}_n(\mathbb{C}) = \text{BU}(n) = \text{Gr}_{\mathbb{C}}(n, \infty)$ is a Grassmannian of n -planes in \mathbb{C}^∞ . A map $f: X \rightarrow \text{Gr}_{\mathbb{C}}(n, \infty)$ gives a complex n -dimensional vector space by pullback.

Theorem 1.39. (Pontryagin–Steenrod) There is a bijection

$$\text{Vect}_{\mathbb{C}}^n(X) \cong [X, \text{BU}(n)].$$

Since $H^*(\text{BU}(n); \mathbb{Z}) = \mathbb{Z}[c_1, \dots, c_n]$, if $E \rightarrow X$ is any rank n vector bundle classified by a map $f: X \rightarrow \text{BU}(n)$, then its Chern classes are by definition $c_i(E) = f^*c_i$.

▷ We have access to *obstruction theory* – this lets us break down lifting problems into smaller manageable stages.

Example 1.40. If X is a complex n -dimensional manifold, and $E \rightarrow X$ is a rank n complex vector bundle, then it splits off a free summand if and only if $c_n(E) = 0$.

Example 1.41. If we fix $c_1, \dots, c_n \in H^*(X; \mathbb{Z})$, we can ask how many isomorphism classes of complex rank n vector bundles on X have these given Chern classes. Since $c_i \in H^{2i}(X; \mathbb{Z}) = [X, K(\mathbb{Z}, 2i)]$ this is equivalent to asking how many lifts there are for

$$\begin{array}{ccc} & & \text{BU}(n) \\ & \nearrow & \downarrow \\ X & \xrightarrow{c_1, \dots, c_n} & \prod_i K(\mathbb{Z}, 2i). \end{array}$$

If X is a finite CW complex, there are only finitely many such lifts by basic obstruction theory.

▷ Suppose we have two groups G and K , and we want to study natural ways to create K -torsors out of G -torsors over any space. Then representability, combined with the Yoneda lemma, allows us to completely classify all the ways to do this.

Example 1.42. There is one and only one natural non-trivial function

$$\{\text{GL}_n(\mathbb{R})\text{-torsors}\} \rightarrow \{(\mathbb{Z}/2)\text{-torsors}\},$$

given by the nonzero class in $[\text{BGL}_n(\mathbb{R}), B\mathbb{Z}/2] = \mathbb{Z}/2$. This is called the *determinant bundle* or the *first Stiefel–Whitney class*.

1.5. Motivation of what’s to come.

Question 1.43. By analogy to homotopy theory, we might ask, for a group scheme G , the following questions:

- (1) Is there an analogous universal space BG in algebraic geometry which classifies G -torsors?
- (2) If so, can we classify G -torsors over X via some “homotopy classes” of maps from X to BG ?

The answer to both will be yes, but *not in the category of varieties*. We need more machinery than is available to us there.

2. TORSORS II: SIMPLICIAL METHODS

Definition 2.1. We denote by Δ the category whose objects are finite ordered sets of the form $[n] = \{0 < 1 < \dots < n\}$, and whose morphisms $[n] \rightarrow [m]$ are order-preserving maps.

Notation 2.2. Let \mathcal{C} be a category. Then we refer to a functor $\Delta \rightarrow \mathcal{C}$ as a *cosimplicial object* of \mathcal{C} , and a functor $\Delta^{\text{op}} \rightarrow \mathcal{C}$ as a *simplicial object* of \mathcal{C} .

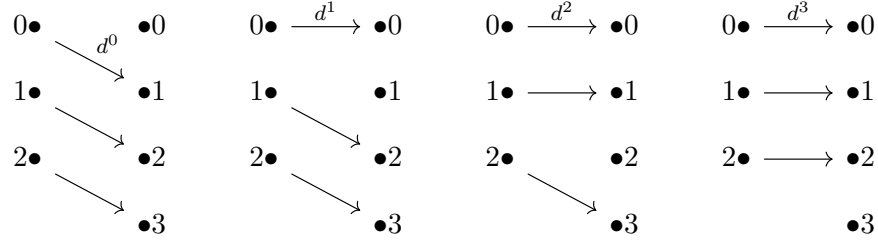
Intuition 2.3. We should think about a (co)simplicial object as a *data type* — it is a combinatorial gadget that is surprisingly convenient for bookkeeping and appears frequently in nature. We’ll see quite a few examples, but let’s first see how to compress this data.

There are a priori a lot of order-preserving functions $[n] \rightarrow [m]$, so we’d like a nice class of easy-to-manage morphisms in Δ so that any morphism factors into nice morphisms. These fall in two classes:

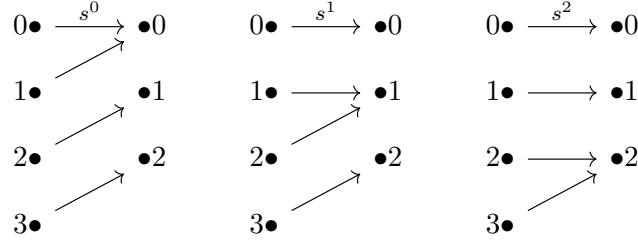
Terminology 2.4.

- (1) We have *coface* maps $d^i: [n] \rightarrow [n+1]$ for $0 \leq i \leq n+1$ which are defined by the property that they miss the element $i \in [n+1]$.
- (2) We have *codegeneracy* maps $s^j: [n] \rightarrow [n-1]$ for $0 \leq j \leq n-1$ defined by the property that they are surjective and that $s^j(j) = s_j(j+1)$.

Example 2.5. The coface maps $d^i: [2] \rightarrow [3]$ look like



Example 2.6. The codegeneracy maps $[3] \rightarrow [2]$ look like



Terminology 2.7. Let $X_\bullet: \Delta^{\text{op}} \rightarrow \mathcal{C}$ denote a simplicial object.

- (1) We use the notation X_n to denote the object $X_\bullet([n])$ in \mathcal{C} .
- (2) We denote by $d_i: X_n \rightarrow X_{n-1}$ for $0 \leq i \leq n$ the image of the coface map d^i . We call d_i a *face map*.
- (3) Similarly we denote by $s_i: X_n \rightarrow X_{n+1}$ for $0 \leq i \leq n$ the image of the codegeneracy map s^i , and call s_i a *degeneracy map*.

Exercise 2.8. Convince yourself that every map in Δ factors into face and degeneracy maps, and therefore any simplicial object X_\bullet in \mathcal{C} can be described by the data of X_n for each n , and its face and degeneracy maps.¹²

Definition 2.9. If \mathcal{C} is a locally small category with all finite products (binary products and a terminal object), then a *group object* in \mathcal{C} is the data of an object $G \in \mathcal{C}$ together with morphisms

$$\begin{aligned} m: G \times G &\rightarrow G \\ e: 1 &\rightarrow G \\ i: G &\rightarrow G \end{aligned}$$

called multiplication, identity, and inverse, such that the following diagrams commute.

$$\begin{array}{ccc} G \times G \times G & \xrightarrow{\text{id} \times m} & G \times G \\ m \times \text{id} \downarrow & & \downarrow m \\ G \times G & \xrightarrow{m} & G \end{array} \quad \begin{array}{ccc} G & \xrightarrow{e \times \text{id}} & G \times G \\ \text{id} \times e \downarrow & \searrow \text{id} & \downarrow m \\ G \times G & \xrightarrow{m} & G \end{array} \quad \begin{array}{ccc} G & \xrightarrow{i \times \text{id}} & G \times G \\ \text{id} \times i \downarrow & \searrow e & \downarrow m \\ G \times G & \xrightarrow{m} & G \end{array}$$

Example 2.10. Let G be a group object in a category \mathcal{C} as above. Then we can define a simplicial object

$$\begin{aligned} B_\bullet G: \Delta^{\text{op}} &\rightarrow \mathcal{C} \\ [n] &\mapsto G^{\times n}, \end{aligned}$$

as:

$$* \begin{array}{c} \xleftarrow{\quad} \\ \xrightarrow{\quad} \end{array} G \begin{array}{c} \xleftarrow{\quad} \\ \xrightarrow{\quad} \end{array} G \times G$$

¹²Any time we define a simplicial object via this compressed data, we should check that the simplicial identities hold, although we'll mostly omit these arguments here.

Explicitly, $B_n G = G^{\times n}$, with face maps $d_i: G^{\times n} \rightarrow G^{\times(n-1)}$ given by

$$d_i(g_1, \dots, g_n) = \begin{cases} (g_2, \dots, g_n) & i = 0 \\ (g_1, \dots, g_i g_{i+1}, g_{i+2}, \dots, g_n) & 1 \leq i \leq n-1 \\ (g_1, \dots, g_{n-1}) & i = n, \end{cases}$$

and degeneracies $s_i: G^{\times n} \rightarrow G^{\times(n+1)}$ given by

$$s_i(g_1, \dots, g_n) = \begin{cases} (e, g_1, \dots, g_n) & i = 0 \\ (g_1, \dots, g_i, e, g_{i+1}, \dots, g_n) & 1 \leq i \leq n. \end{cases}$$

Note that $d_1: G^{\times 2} \rightarrow G$ is precisely the group multiplication, while $s_0: * \rightarrow G$ is the identity on the group.

Exercise 2.11. Check the simplicial identities hold *precisely* because of the group axioms. In particular, observe that we didn't use anything special about spaces — if G is a group object in any category \mathcal{C} we obtain an associated bar construction which is a simplicial object in \mathcal{C} that we call $B_\bullet G$.

Example 2.12. (Important) For the formal categorical reason in [Exercise 2.11](#), any group scheme G gives rise to a simplicial scheme $B_\bullet G \in \text{Fun}(\Delta^{\text{op}}, \text{Sch})$. This dates back at least to work of Friedlander [[Fri82](#), Example 1.2]. We'll use this object frequently.

Example 2.13. Simplicial objects appeared crucially in Deligne's work on resolution of singularities and mixed Hodge structures. Let X be a complete¹³ singular variety. Then we can “replace” X with a simplicial variety

$$\cdots \quad X_2 \begin{matrix} \xrightarrow{\quad} \\ \xleftarrow{\quad} \\ \xrightarrow{\quad} \\ \xleftarrow{\quad} \end{matrix} X_1 \begin{matrix} \xrightarrow{\quad} \\ \xleftarrow{\quad} \end{matrix} X_0,$$

where each X_i is smooth and projective. There is a cohomological descent spectral sequence computing the cohomology of X in terms of the cohomology of the X_n 's. This dates back to SGA 4. Additionally, this replacement is the core idea of *resolution of singularities*. Deligne uses these simplicial methods to endow singular varieties with Hodge structures, so-called *mixed Hodge structures* [[Del74](#)].

Example 2.14. Let $A_\bullet: \Delta^{\text{op}} \rightarrow \text{Ab}$ be a simplicial abelian group. Then by taking the alternating sum of the face maps, we obtain a chain complex, purely by the simplicial identities. This assignment is functorial:

$$\begin{aligned} \text{sAb} &\rightarrow \text{Ch}_{\geq 0}(\text{Ab}) \\ A_\bullet &\mapsto \left(A_n, \partial = \sum_{i=0}^n (-1)^i d_i \right). \end{aligned}$$

The associated chain complex is called the *Moore complex* of the simplicial abelian group. Two quick remarks about this:

- (1) This works if we replace Ab by any abelian category.
- (2) This process is invertible — this implies that simplicial objects and connective chain complexes in any abelian category are equivalent.¹⁴ We will use this later, as we will want to construct certain simplicial objects in sheaves of abelian groups, and it will be more direct to construct them first as chain complexes, then pass through this equivalence.

¹³ X is *complete* if it is proper over the base [[Har77](#), p. 105]. This is a slightly more general notion than projective.

¹⁴There's a small lie here, the actual functor exhibiting the equivalence is not the Moore complex but the *normalized chains complex*, although the normalized chain complex maps to the Moore complex in a natural way, and this is a chain homotopy equivalence [[GJ99](#), III.2.4], so they are essentially the same. This equivalence is the *Dold–Kan theorem*. For more detail see [[GJ99](#), §III.2].

Example 2.15 (Čech nerve $N_\bullet(U)$). A simplicial object can conveniently encode the data of an open cover, its intersections, triple intersections, etc.¹⁵ For this, given an open cover $\{U_i \rightarrow X\}$ of a variety X , denote by $U_{ij} := U_i \times_X U_j$ the double overlaps, by $U_{ijk} := U_i \times_X U_j \times_X U_k$ the triple overlaps, and so on. We define a simplicial object

$$\coprod_i U_i \begin{array}{c} \xleftarrow{\quad} \\ \xrightarrow{\quad} \end{array} \coprod_{i,j} U_{ij} \begin{array}{c} \xleftarrow{\quad} \\ \xrightarrow{\quad} \end{array} \coprod_{i,j,k} U_{ijk} \quad \cdots$$

The face maps are defined by omitting the j th index

$$d_j: U_{i_1 \dots i_n} \rightarrow U_{i_1 \dots \widehat{i_j} \dots i_n},$$

and the degeneracy maps repeat the j th index

$$s_j: U_{i_1 \dots i_n} \rightarrow U_{i_1 \dots i_{j-1} i_j i_j i_{j+1} \dots i_n}.$$

We call this the *Čech nerve* associated to the cover, and we denote it by $N(\mathcal{U})$.

2.1. More on simplicial sets. We denote by

$$\mathbf{sSet} := \mathbf{Fun}(\Delta^{\mathrm{op}}, \mathbf{Set})$$

the category of *simplicial sets*. Given a simplicial set

$$X_\bullet: \Delta^{\mathrm{op}} \rightarrow \mathbf{Set}$$

$$[n] \mapsto X_n,$$

we call X_n the set of n -*simplices*.

Example 2.16. Any set Y gives rise to a constant simplicial set \underline{Y} , given by sending $[n] \mapsto Y$, and every morphism in Δ to the identity on Y .

Example 2.17. We denote by Δ^n the simplicial set

$$\Delta^n := \mathbf{Hom}_\Delta(-, [n]): \Delta^{\mathrm{op}} \rightarrow \mathbf{Set}.$$

By the Yoneda lemma, we have a natural bijection

$$\mathbf{Hom}_{\mathbf{sSet}}(\Delta^n, X_\bullet) \cong X_n$$

for any $X_\bullet \in \mathbf{sSet}$.

There is a functor called *geometric realization*, which “assembles” a simplicial set into a topological space: Let Δ_{top}^n denote the *topological n -simplex*¹⁶

$$|-|: \mathbf{sSet} \rightarrow \mathbf{Top}$$

$$X_\bullet \mapsto \coprod_{n \geq 0} X_n \times \Delta_{\mathrm{top}}^n / \sim,$$

where \sim is

$$\begin{aligned} (x, d_i u) &\sim (d_i x, u) & x \in X_n, u \in \Delta_{\mathrm{top}}^{n-1} \\ (y, s_i v) &\sim (s_i y, v) & y \in X_{n-1}, v \in \Delta_{\mathrm{top}}^n. \end{aligned}$$

Remark 2.18. We discussed this universal space BG classifying principal G -bundles last week. We can define this as $BG := |B_\bullet G|$, i.e. it is the geometric realization of the bar construction for the group.¹⁷

Definition 2.19. We say two maps $f, g: X_\bullet \rightarrow Y_\bullet$ are *simplicially homotopic* if there is a map

$$H: \Delta^1 \times X_\bullet \rightarrow Y_\bullet$$

so that $H|_{\{0\} \times X_\bullet} = f$ and $H|_{\{1\} \times X_\bullet} = g$.

¹⁵Technically it should be an *augmented simplicial object* since we’d also like to remember the data of the maps $U_i \rightarrow X$.

¹⁶This is the locus $\Delta_{\mathrm{top}}^n := \{(x_0, \dots, x_{n+1}) \in \mathbb{R}^{n+1}: \sum x_i = 1, x_i \geq 0\}$.

¹⁷If G is a discrete group this is literally correct. If G is a topological group we have to modify the domain of geometric realization to be $|-|: \mathbf{Fun}(\Delta^{\mathrm{op}}, \mathbf{Top}) \rightarrow \mathbf{Top}$ in order to get the correct definition.

Remark 2.20. Unpacking this data, we can verify it is the same as asking for maps for every n :

$$H_i^n: X_n \rightarrow Y_{n+1} \quad 0 \leq i \leq n,$$

so that $d_0 H_0^n = f_n$, and $d_{n+1} H_n^n = g_n$, and so that they satisfy the following relations with face and degeneracy maps:¹⁸

$$d_i H_j^n = \begin{cases} H_{j-1}^{n-1} d_i & i < j \\ d_i H_{j-1}^n & i = j \neq 0 \\ d_{j+1} H_{j+1}^n & i = j + 1, j \neq n \\ H_j^{n-1} d_{i-1} & i > j + 1. \end{cases}$$

$$s_i H_j^n = \begin{cases} H_{j+1}^{n+1} s_i & i \leq j \\ H_j^{n+1} s_{i-1} & i > j. \end{cases}$$

This notion makes sense for maps between simplicial objects in any category, and it is called a *simplicial homotopy*.

- (1) A priori we should be careful calling it a homotopy, since it doesn't require us to have any notion of a model structure or higher-categorical structure in order to state, however we will see this won't be a problem.
- (2) In the context of simplicial sets, this coincides with [Definition 2.19](#), as we can check (see e.g. [\[Wei94, 8.3.12\]](#)).
- (3) It is not true (even in simplicial sets) that this is an equivalence relation, and indeed it isn't. Nevertheless it generates one, so when we say “up to simplicial homotopy” we often mean with respect to the transitive closure of this relation.

Theorem 2.21. Geometric realization preserves products.

Corollary 2.22. Simplicial homotopies become honest homotopies of spaces after geometric realization.

Remark 2.23. We can study simplicial sets up to homotopy or spaces up to homotopy, and in a sense that can be made precise, these are essentially the same theory.

Remark 2.24. Historically this connection between simplicial sets and spaces was part of a research program which used to be called “combinatorial homotopy theory,” led by Kan in the 1950's.

2.2. Torsors via simplicial maps. The big takeaway of this entire section is the following:

Theorem 2.25. Let $\mathcal{U} = \{U_i \rightarrow X\}$ be a cover, and let G be a group scheme over X . To any map from the Čech nerve to the bar construction, we can assign a Čech 1-cocycle

$$\mathrm{Hom}_{\mathrm{Fun}(\Delta^{\mathrm{op}}, \mathrm{Var}_k)}(N(\mathcal{U}), B_\bullet G) \rightarrow H^1(\mathcal{U}, G),$$

and this assignment is surjective.

Proof. We'll figure out some what's happening in lower degrees first and use this to see how to define maps in general.

Low-degree intuition: To specify a map, we need to know what happens on each level, so let's consider the diagram:

$$\begin{array}{ccccc} N(\mathcal{U}) = & \coprod_i U_i & \rightrightarrows & \coprod_{i,j} U_{ij} & \cdots \\ & \downarrow & & \downarrow & \\ BG = & * & \rightrightarrows & G & \cdots \end{array}$$

¹⁸This is in [\[Wei94, 8.3.11\]](#).

On 0-simplices, there is no data, and on 1-simplices, we are obtaining elements we will call $(g_{ij} \in \text{Hom}(U_{ij}, G))$. For each i , the degeneracy maps require the following diagram to commute.

$$\begin{array}{ccc} U_i & \xrightarrow{s_0} & U_{ii} \\ \downarrow & & \downarrow g_{ii} \\ * & \xrightarrow{e} & G, \end{array}$$

which tells us that $g_{ii} = e$. That's about all we can learn from degeneracies. What happens on 2-cells? Let's consider the inner and outermost face maps $N_2(U) \rightarrow N_1(U)$:

$$\begin{array}{ccc} U_{jk} & \xleftarrow{d_0} & U_{ijk} \\ g_{jk} \downarrow & & \downarrow \\ G & \xleftarrow{d_0=\text{proj}_2} & G \times G \end{array} \quad \begin{array}{ccc} U_{ij} & \xleftarrow{d_2} & U_{ijk} \\ g_{ij} \downarrow & & \downarrow \\ G & \xleftarrow{d_2=\text{proj}_1} & G \times G \end{array}$$

We've decorated the face maps on the bar construction to recall whether they are projection or multiplication. By the universal property of the product, $U_{ijk} \rightarrow G \times G$ is determined by its post-composition with the projections, hence it makes sense to call this map (g_{ij}, g_{jk}) . The d_1 relation gives us

$$\begin{array}{ccc} U_{ik} & \xleftarrow{d_1} & U_{ijk} \\ g_{ik} \downarrow & & \downarrow (g_{ij}, g_{jk}) \\ G & \xleftarrow{d_1=\text{mult}} & G \times G \end{array}$$

This implies that

$$g_{ik} = g_{ij}g_{jk}.$$

This is *exactly the 1-cocycle condition* from [Definition 1.21](#). We claim that the remaining data of the map $N(\mathcal{U})_\bullet \rightarrow B_\bullet G$ is completely determined by this relation. In particular, every Čech 1-cocycle can be extracted from a map $N_\bullet(\mathcal{U}) \rightarrow B_\bullet G$ by the above process.

In general: It is now clear how to define the map $N_n \mathcal{U} \rightarrow B_n G$ — its component on $U_{i_0 \dots i_n}$ is given by the tuples of maps

$$\prod_{j=0}^{n-1} g_{i_j i_{j+1}} : U_{i_0 \dots i_n} \rightarrow G^{\times n}.$$

This clearly commutes with degeneracies, and commutes with face maps by universal property of the product and by the 1-cocycle relation. We see in fact that this map is well-defined if and only if the 1-cocycle condition holds. \square

Theorem 2.26. Two 1-cocycles for the cover \mathcal{U} are cohomologous if and only if they are simplicially homotopic.

Proof sketch. Let $f, g : N(\mathcal{U})_\bullet \rightarrow B_\bullet G$ be two maps corresponding to 1-cocycles (f_{ij}) and (g_{ij}) , respectively. Recall simplicial homotopy requires us to define maps $H_i^n : N(\mathcal{U})_n \rightarrow B_{n+1} G$ for $0 \leq i \leq n$ so that $d_0 H_0 = f_n$, $d_{n+1} H_n = g_n$, and various other relations hold. Again let's start in low degrees to gain some intuition and then prove the theorem directly.

Low-degree intuition: Let's see what H_0^0 looks like:

$$\begin{array}{ccccc} \coprod_i U_i & \xrightleftharpoons{\quad} & \coprod_{i,j} U_{ij} & \xrightleftharpoons{\quad} & \coprod_{i,j,k} U_{ijk} & \cdots \\ \downarrow & \searrow H_0^0 & \downarrow & \searrow H_0^1, H_1^1 & \downarrow & \searrow H_0^2, H_1^2, H_2^2 \\ * & \xrightleftharpoons{\quad} & G & \xrightleftharpoons{\quad} & G \times G & \cdots \end{array}$$

At level zero, the map H_0^0 specifies an element $\alpha_i \in G(U_i)$. Let's see what the degeneracy relations tell us at level one:

$$\begin{array}{ccc} \coprod_i U_i & \xleftarrow{d^0} \coprod_{i,j} U_{ij} & \\ & \xleftarrow{d^1} & \\ & \searrow H_0^0 & \downarrow \\ & & G \end{array} \quad \begin{array}{c} \xrightarrow{H_0^1, H_1^1} \\ \xleftarrow{d_0} \\ \xleftarrow{d_1} \\ \xleftarrow{d_2} \end{array} \quad \begin{array}{c} G \times G \\ \dots \end{array}$$

Since H_i^1 is mapping into a product, it is determined by its projections, which are post-composing with d_2 and d_0 , respectively. From the relations and the simplicial homotopy condition, we get

$$d_0 H_0^1 = f_{ij}$$

$$d_2 H_0^1 = H_0^0 d_1 = \alpha_i,$$

so H_0^1 is the tuple $(\alpha_i, f_{ij}): U_{ij} \rightarrow G \times G$.¹⁹ Similarly we compute

$$d_0 H_1^1 = H_0^0 d_0 = \alpha_j$$

$$d_2 H_1^1 = g_{ij},$$

so $H_1^1 = (g_{ij}, \alpha_j): U_{ij} \rightarrow G \times G$. The remaining relation states that

$$d_1 H_1^1 = d_1 H_0^1,$$

and since d_1 is the multiplication $G \times G \rightarrow G$, this tells us that $\alpha_i f_{ij} = g_{ij} \alpha_j$, which is the coboundary condition.

Exercise: Show that, as maps $U_{i_0 i_1 i_2} \rightarrow G \times G \times G$, we have

$$H_0^2 = (\alpha_{i_0}, f_{i_0 i_1}, f_{i_1 i_2})$$

$$H_1^2 = (g_{i_0 i_1}, \alpha_{i_1}, f_{i_1 i_2})$$

$$H_2^2 = (g_{i_0 i_1}, g_{i_1 i_2}, \alpha_{i_2}).$$

In general: We define

$$H_j^n: U_{i_0 i_1 \dots i_n} \rightarrow G^{\times(n+1)}$$

by

$$(g_{i_0 i_1}, \dots, g_{i_{j-1} i_j}, \alpha_{i_j}, f_{i_j i_{j+1}}, \dots, f_{i_{n-1} i_n}).$$

We verify that the relevant relations hold if and only if the coboundary condition $\alpha_i f_{ij} = g_{ij} \alpha_j$ holds for every i, j . \square

Motivation 2.27. Last week we asked for a universal space BG so that homotopy classes of maps $X \rightarrow BG$ classifies G -torsors, and we're getting close! We now have a fantastic candidate for BG , namely the bar construction $B_\bullet G$ above. However we (1) didn't have a notion of homotopy of maps to witness two torsors being equivalent, and (2) we were mapping from $N(\mathcal{U})$, *not* from X . To that end, let's write down what we're looking for.

Wishlist: We want some nice category \mathcal{C} where both X and $B_\bullet G$ live (so our category should contain simplicial varieties), and we want our category to have a notion of *equivalence* with the following properties:

- (1) Two maps $N(\mathcal{U}) \rightarrow B_\bullet G$ are homotopic in \mathcal{C} if and only if they classify cohomologous G -torsors. We want to make this notion of homotopy precise.
- (2) In \mathcal{C} , we have that $X \simeq N(\mathcal{U})$, i.e. a variety is equivalent to the Čech nerve of any cover over it, so that up to homotopy, we can classify torsors via maps $X \rightarrow B_\bullet G$.

Let's preview how this is going to go — the category Var_k of k -varieties doesn't support a nice homotopy theory, nor does simplicial varieties $\text{Fun}(\Delta^{\text{op}}, \text{Var}_k)$. So what we could do instead is

¹⁹There's abuse of notation here with α_i .

replace each variety by its representable presheaf (functor of points, for the algebraic geometers). The Yoneda embedding $\mathrm{Var}_k \rightarrow \mathrm{Fun}(\mathrm{Var}_k^{\mathrm{op}}, \mathrm{Set})$ then induces a functor

$$\mathrm{Fun}(\Delta^{\mathrm{op}}, \mathrm{Var}_k) \rightarrow \mathrm{Fun}(\Delta^{\mathrm{op}}, \mathrm{Fun}(\mathrm{Var}_k^{\mathrm{op}}, \mathrm{Set})).$$

Doing some adjoint business, we get that this latter category is equivalent to

$$\mathrm{Fun}(\mathrm{Var}_k^{\mathrm{op}}, \mathrm{Fun}(\Delta^{\mathrm{op}}, \mathrm{Set})) = \mathrm{Fun}(\mathrm{Var}_k^{\mathrm{op}}, \mathrm{sSet}).$$

So altogether we get a Yoneda embedding

$$\mathrm{Var}_k \hookrightarrow \mathrm{Fun}(\mathrm{Var}_k^{\mathrm{op}}, \mathrm{sSet}).$$

This latter category is called the category of *simplicial presheaves*, or in higher category language it is just denoted $\mathrm{PSh}(\mathrm{Var}_k)$, and called the ∞ -category of (∞) -presheaves. It comes with a notion of homotopy coming from simplicial homotopy theory. We'll see that this was not only a nice well-behaved way to access homotopy theory starting from Var_k , it was actually the *universal* way to do this (see e.g. [Dug01]).

This category $\mathrm{PSh}(\mathrm{Var}_k)$ will take care of item (1) on our checklist! After we define what homotopy means there, homotopic maps in this category will give isomorphic torsors.

This doesn't take care of point (2), and we shouldn't really expect it to. The equivalence between a variety and the Čech nerve of the cover should depend on *what covers are permissible*. In other words, it should bake in the Grothendieck topology somehow. We'll see that we can get point (2) (while retaining a notion of homotopy compatible with that of presheaves) by passing to the category of *sheaves* in our site. We'll make all this precise soon.

3. TORSORS III: SITES, SHEAVES, AND HILBERT 90

We have seen that $H^1(X, G)$ classifies G -torsors for X , but we've been a little vague about Grothendieck topologies (i.e. what kinds of covers are we considering for our varieties). Today we'll make things more precise.

Definition 3.1. Let \mathcal{C} be a category with pullbacks. Then a *Grothendieck topology* τ consists of collections of morphisms $\{U_i \rightarrow X\}_{i \in I}$ in \mathcal{C} called *covers* or *coverings*, satisfying the following properties:

- (1) *Closure under pullbacks:* If $\{U_i \rightarrow X\}_{i \in I}$ is a covering and $f: Y \rightarrow X$ is any morphism, then the collection of base change morphisms $\{U_i \times_X Y \rightarrow Y\}_{i \in I}$ is a covering.
- (2) *Closure under refinement:* If $\{U_i \in X\}$ is a covering and $\{V_{ij} \rightarrow U_i\}_j$ is a covering for each i , then the composite $\{V_{ij} \rightarrow U_i \rightarrow X\}_{i,j}$ is a covering
- (3) *Isomorphisms:* Any isomorphism $f: Y \xrightarrow{\sim} X$ gives a one-element cover $\{Y \rightarrow X\}$.

A pair of a category and a topology (\mathcal{C}, τ) is called a *site*.

Example 3.2. A *Zariski cover* is a collection of open immersions $\{U_i \rightarrow U\}$ which are jointly surjective. This generates the *Zariski site* on Sch_S .

Example 3.3. An *étale cover* is a collection of étale morphisms, jointly surjective.

Example 3.4. A *Nisnevich cover* is a collection of étale morphisms $\{U_i \rightarrow U\}$ so that for each $x \in X$ there exists an i and a $y \in U_i$ so that $y \mapsto x$ induces an isomorphism on residue fields.

Note 3.5. If $R \rightarrow S$ is an étale ring extension, then $\mathrm{Spec}(S) \rightarrow \mathrm{Spec}(R)$ is an étale cover but not necessarily a Nisnevich cover. For example $\mathrm{Spec}(L) \rightarrow \mathrm{Spec}(k)$ is étale if L/k is a finite separable extension, but not Nisnevich unless $k = L$.

Example 3.6. [Stacks, 021M] An *fppf cover* is a jointly surjective collection of morphisms $\{U_i \xrightarrow{f_i} U\}$ so that each f_i is flat and locally of finite presentation.

Example 3.7. [Stacks, 03NW] An *fpqc cover* is a jointly surjective collection of morphisms $\{U_i \xrightarrow{f_i} U\}$ so that $\coprod_i U_i \rightarrow U$ is faithfully flat and quasi-compact.

Example 3.8. A map $\mathrm{Spec}(S) \rightarrow \mathrm{Spec}(R)$ is an fpqc cover if and only if the ring map $R \rightarrow S$ is faithfully flat.

Terminology 3.9. If t and τ are two Grothendieck topologies, we write $t \leq \tau$ if every t -cover is a τ -cover. We say t is *coarser* than τ or that τ *refines* t in this case.

Proposition 3.10. We have that

$$\mathrm{Zar} \leq \mathrm{Nis} \leq \mathrm{et} \leq \mathrm{fppf} \leq \mathrm{fpqc}.$$

For more topologies see [Belmans: topologies comparison](#).

Question 3.11. If $t \leq \tau$ then what is the difference between t -torsors and τ -torsors?

Let's break this into two parts

3.1. Torsors in finer topologies.

Proposition 3.12. Let \mathcal{C} be some fixed category of schemes, with topologies t and τ . Let \mathcal{G} be a sheaf of groups in the τ -topology. Let \mathcal{F} be a \mathcal{G} -torsor in the t -topology. Then \mathcal{F} is also a τ -torsor if \mathcal{F} is a τ -sheaf.

Proof. The only thing that could fail is the sheaf condition in the definition. If \mathcal{F} is a t -torsor, then there exists a t -cover $\{U_i \rightarrow U\}$ trivializing \mathcal{F} , and this is also a τ -cover since τ refines t . \square

We want to make some guarantee that \mathcal{G} will still be a sheaf in a finer topology. In our cases, we care about the case where \mathcal{G} is representable, and a classical result guarantees this for us.

Theorem 3.13. (Grothendieck, [Stacks, 023Q]) Every representable presheaf is a sheaf in the fpqc topology (and hence in any coarser topology, e.g. Zariski, Nisnevich, étale, syntomic, fppf).

Corollary 3.14. Let G be an affine group scheme, and let $t \leq \tau \leq \mathrm{fppf}$. Then every t -torsor is a τ -torsor.

Proof. Let \mathcal{F} be a G -torsor. By [Proposition 1.30](#) it is representable, hence it is a sheaf in the τ topology as well by [Theorem 3.13](#). Therefore by [Proposition 3.12](#) it is also a τ -torsor. \square

3.2. Torsors in coarser topologies. Now we're interested in the reverse question — when $t \leq \tau$, when is a τ -torsor a t -torsor? The only thing that could fail is condition (2) of [Definition 1.6](#), so we get the following answer/definition.

Definition 3.15. Let $t \leq \tau$ be topologies on a fixed category of schemes \mathcal{C} , let \mathcal{G} be a τ -sheaf of groups and let \mathcal{F} be a \mathcal{G} -torsor. Then \mathcal{F} is a t -torsor if and only if there exists a t -cover over which \mathcal{F} is trivialized. We say \mathcal{F} is *locally trivial in the t -topology*.

We can now leverage some tools from algebraic geometry to prove this.

Proposition 3.16. Every smooth morphism of schemes admits a section étale-locally.

Corollary 3.17. If G is a smooth group scheme, then there is an equivalence of categories between étale G -torsors and fppf-torsors.

Proof. See [Hal, Proposition 4] for a proof. \square

We can summarize what we've learned in the following cheatsheet:

Cheatsheet: topologies

Let $t \leq \tau$ be two covers, we say that τ *refines* t , or that t is *coarser* than τ . What this means is that

- (1) Every t -cover is a τ -cover
- (2) Every τ -sheaf is a t -sheaf
- (3) If \mathcal{F} is a t -torsor then it is a τ -torsor if it is a τ -sheaf
- (4) If \mathcal{F} is a τ -torsor it is a t -torsor if and only if it is t -locally trivial.

3.3. Special algebraic groups.

Definition 3.18. We say an algebraic group (a group object in varieties) over a field k is *linear* if it admits a faithful finite-dimensional representation (c.f. [Mil15, p. 72]).

Note 3.19. If an algebraic group is linear, it is automatically affine ([Mil15, 1.29]) and finite type. Also, all linear algebraic groups are closed subgroups of GL_n .

Proposition 3.20. Every affine group scheme of finite type over a field k is linear ([Mil15, 4.8]).

Definition 3.21. [Gro, p. 5-11] A group scheme is called *special* if it is a linear algebraic group G with the property that every G -torsor²⁰ is locally trivial in the Zariski topology.

Theorem 3.22. [Gro, Théorème 3] The group GL_n is special.

Corollary 3.23. [Mil13, 11.4] There is a natural bijection

$$H_{\mathrm{Zar}}^1(X, \mathrm{GL}_n) \leftrightarrow H_{\mathrm{Nis}}^1(X, \mathrm{GL}_n) \leftrightarrow H_{\mathrm{et}}^1(X, \mathrm{GL}_n) \leftrightarrow H_{\mathrm{fpqc}}^1(X, \mathrm{GL}_n).$$

Hence any of the groups above can be thought of as parametrizing isomorphism classes of *algebraic vector bundles* on X .

4. INFINITY CATEGORIES

Example 4.1. If \mathcal{C} is a small 1-category, it gives rise to a simplicial set $N_{\bullet}\mathcal{C}$, called the *nerve* of \mathcal{C} , with the following data:

- ▷ 0-simplices = objects of \mathcal{C}
- ▷ 1-simplices = morphisms in \mathcal{C}
- ▷ 2-simplices = pairs of composable morphisms $x \xrightarrow{f} y \xrightarrow{g} z$ in \mathcal{C}
- ▷ \vdots
- ▷ n -simplices = strings of n -composable morphisms

Here the degeneracy maps $(N\mathcal{C})_n \rightarrow (N\mathcal{C})_{n+1}$ insert an identity, while the face maps $(N\mathcal{C})_n \rightarrow (N\mathcal{C})_{n-1}$ compose maps. Observe that in \mathcal{C} , composition happens *strictly*, by which we mean there is no notion of homotopy between maps — if $x \xrightarrow{f} y \xrightarrow{g} z$ is a composite of maps, and $h: x \rightarrow z$, then either $h = g \circ f$, or it is not equal, and this is encoded by the data of a *unique* 2-cell:

$$\begin{array}{ccc} & y & \\ f \nearrow & & \searrow g \\ x & \xrightarrow{h} & z. \end{array}$$

We think about this 2-cell as a *witness* for the composition. Note that if no 2-cell exists filling the diagram above, this means that h is not equal to $g \circ f$. It is just some other map from x to z .

Example 4.2. If \mathcal{C} is a one-object groupoid (e.g. a group G), then $N_{\bullet}\mathcal{C}$ is the bar construction of G , and its realization $B\mathcal{C} := |N_{\bullet}\mathcal{C}|$ is called the *classifying space* of the category. Some examples:

²⁰Since G is affine, every G -torsor in $\tau \leq \mathrm{fppf}$ is automatically a principal G -bundle.

- (1) $BC_2 = \mathbb{RP}^\infty$
- (2) $B\mathbb{N} = S^1$
- (3) $B\mathbb{Z} = S^1$
- (4) $B(\bullet \rightarrow \bullet) = \Delta_{\text{top}}^1$
- (5) $B(\bullet \xrightarrow{\sim} \bullet) = S^\infty$
- (6) $BPBr_n = \text{Conf}_n(\mathbb{R}^2)$

Q: Given a simplicial set, when can you tell whether it arose as the nerve of a 1-category?

A: Given any diagram of the form $\bullet \rightarrow \bullet \rightarrow \bullet$, it has to fill in uniquely to a 2-cell. But we also need to fill in composites of three morphisms uniquely (to get a tetrahedron), and composites of four morphisms, and so on. To that end, let Λ_n^k be the simplicial set obtained from Δ^n by deleting the k th face. This is called a *horn*.

This isn't a definition of a horn — we might instead characterize the horns by their representable functors, i.e. $\text{Hom}_{\text{sSet}}(\Lambda_2^1, -)$ represents the set of “composable” edges $x \xrightarrow{f} y \xrightarrow{g} z$ in any simplicial set.

Proposition 4.3. A simplicial set X_\bullet is the nerve of a 1-category if and only if it admits *unique inner horn filling*, meaning for every n and every $0 < k < n$, given any map $\Lambda_n^k \rightarrow X_\bullet$ it admits a unique lift:

$$\begin{array}{ccc} \Lambda_n^k & \longrightarrow & X_\bullet \\ \downarrow & \nearrow & \\ \Delta^n & & \end{array}$$

Example 4.4. Let X be a topological space. Then it gives rise to a simplicial set called its *fundamental ∞ -groupoid* $\Pi_\infty X$, with the data

- ▷ 0-simplices = points $x \in X$
- ▷ 1-simplices = paths x to y in X
- ▷ 2-simplices = homotopies between paths
- ▷ 3-simplices = homotopies between homotopies between paths
- ⋮

Note that a 2-cell is no longer unique! There can be many homotopies between paths. In particular composition of paths isn't well-defined, in the sense that many paths can function naturally as a composite. We might define $g \circ f$ to be any path together with a 2-cell making the diagram commute:

$$\begin{array}{ccc} & y & \\ f \nearrow & & \searrow g \\ x & \xrightarrow{\quad\quad\quad} & z. \end{array}$$

In order to specify a composite now, we need to give the data not only of the 1-cell but also of the 2-cell! This is the vibe of higher-categorical composition. Note that horns don't fill uniquely here.

Exercise 4.5. If you're familiar with the singular chains construction

$$|-|: \text{sSet} \rightleftarrows \text{Top} : \text{Sing}(-),$$

convince yourself that $\text{Sing}(-)$ is the same as $\Pi_\infty(-)$.

Definition 4.6. A *quasicategory* is any simplicial set with (not necessarily unique) inner horn filling. We denote by $\text{qCat} \subseteq \text{sSet}$ the full subcategory on the quasi-categories.

A natural question to ask is to what extent there is ambiguity in composition — how many choices do we have for horn filling? Do different choices *mean* different things? The following proposition answers this to some extent.

Proposition 4.7. (Joyal) If \mathcal{C} is a quasi-category, then the map of simplicial sets

$$\mathrm{Fun}(\Delta^2, \mathcal{C}) \rightarrow \mathrm{Fun}(\Lambda_2^1, \mathcal{C})$$

has contractible fibers (i.e., the geometric realization of the fibers under this map are contractible spaces).²¹

Definition 4.8. A *Kan complex* is a quasi-category which also has *outer horn filling*, meaning we have a lift

$$\begin{array}{ccc} \Lambda_n^k & \longrightarrow & X_\bullet \\ \downarrow & \nearrow & \\ \Delta^n & & \end{array}$$

not only for $0 < k < n$, but also for $k = 0, n$. For $n = 2$, this means we are also allowed to fill the horns:



Exercise 4.9. Show a Kan complex is the nerve of a 1-groupoid if and only if its inner horn filling is unique.

The homotopy hypothesis: The functor

$$\begin{aligned} (\mathrm{Top}, \text{weak equiv}) &\rightarrow (\mathrm{Kan}, \text{weak equiv}) \\ X &\mapsto \Pi_\infty(X) \end{aligned}$$

yields an equivalence of ∞ -categories.²² Hence we can think about spaces as Kan complexes without much loss of generality. We use \mathcal{S} to denote the ∞ -category of spaces.

Remark 4.10. (On other models of ∞ -categories) There are a ton of different models of ∞ -categories, we stick with quasi-categories since they have become the standard to some extent. The main advantage is that functors are much easier to describe – they are just maps of the underlying simplicial sets. Functor ∞ -categories $\mathrm{Fun}(\mathcal{C}, \mathcal{D})$ between two quasi-categories are simply given by the internal hom in simplicial sets.

Proposition 4.11. If \mathcal{C} is a quasi-category and S is any simplicial set, then the internal hom $\mathrm{Fun}(S, \mathcal{C})$ is also a quasi-category. We think about this as “ S -shaped diagrams in \mathcal{C} .”

4.1. Homotopy in an ∞ -category.

Definition 4.12. Let \mathcal{C} be a quasi-category. We define its *homotopy category*, denoted $h\mathcal{C}$ to be the category freely generated by the 1-truncation $\tau_{\leq 1}\mathcal{C}$ (i.e. objects and edges), modulo the relations coming from 2-simplices.

Definition 4.13. We say that a morphism $f: x \rightarrow y$ in a quasi-category \mathcal{C} is an *isomorphism/equivalence* if there exists some $g: y \rightarrow x$ so that $[gf] = \mathrm{id}_x$ and $[fg] = \mathrm{id}_y$ in $h\mathcal{C}$. Note that g is *not uniquely defined*, unlike in ordinary 1-category theory.

Remark 4.14. We should think about this less like isomorphisms in 1-categories, and more like homotopy equivalences in topology.

²¹In fact \mathcal{C} is a quasi-category if and only if this holds.

²²We haven’t defined what we mean by Top or Kan as an ∞ -category, and it’s a bit subtle. We want to incorporate the weak equivalences, so really we should take the hammock localization of Kan at the simplicial weak equivalences, then take its homotopy coherent nerve, but fibrantly replace $L^W \mathrm{Kan}$ first before taking N_Δ so that the resulting simplicial set is an honest quasi-category. An analogous procedure should be carried out with topological spaces, assuming we work with all spaces and not just CW complexes.

Example 4.15. A morphism $f: X \rightarrow Y$ between CW complexes is a (weak) homotopy equivalence if and only if $[f]$ is an isomorphism in $h\text{Top}$. Hence the “isomorphisms” in the ∞ -category of spaces are not homeomorphisms but rather homotopy equivalences.

Proposition 4.16. There is an adjunction²³

$$h: \mathbf{qCat} \rightleftarrows \mathbf{Cat} : N.$$

Remark 4.17. We recall that the nerve is fully faithful. This is equivalent to the counit of the adjunction being a natural isomorphism:

$$hN\mathcal{C} \xrightarrow{\sim} \mathcal{C},$$

in other words any 1-category can be recovered as the homotopy category of its nerve.

Example 4.18. Let R be any ring. Then its category of chain complexes $\text{Ch}(R)$ is naturally an ∞ -category, and the notion of homotopy recovers the idea of chain homotopy equivalence. We have to be careful constructing this explicitly, refer to §13 of DAG for more info.

4.2. Mapping spaces. We want to make precise the model of quasi-categories as $(\infty, 1)$ -categories. The vibe of higher categories is that homs in 1-categories are 0-categories (sets). Homs in 2-categories are 1-categories, homs in 3-categories are 2-categories, etc. Hence homs in $(\infty, 1)$ -categories should be $(\infty, 0)$ -categories. From the models we’re working in:

$$\begin{aligned} (\infty, 1)\text{-categories} &= \text{quasi-categories} \\ (\infty, 0)\text{-categories} &= \text{Kan complexes,} \end{aligned}$$

hence we want to argue that, for any quasicategory \mathcal{C} , and any pair of objects (0-simplices) $x, y \in \mathcal{C}$, there is a mapping space $\text{Map}_{\mathcal{C}}(x, y)$ which is a Kan complex.

Definition 4.19. For $x, y \in \mathcal{C}$, where \mathcal{C} is a quasicategory, we denote by $\text{Map}_{\mathcal{C}}(x, y)$ the pullback in simplicial sets:

$$\begin{array}{ccc} \text{Map}_{\mathcal{C}}(x, y) & \longrightarrow & \text{Fun}(\Delta^1, \mathcal{C}) \\ \downarrow & \lrcorner & \downarrow (\text{ev}_0, \text{ev}_1) \\ \{x, y\} & \longrightarrow & \mathcal{C} \times \mathcal{C}. \end{array}$$

Here $\text{Fun}(\Delta^1, \mathcal{C})$ denotes an internal hom from the interval Δ^1 to \mathcal{C} . The rightmost vertical map is what’s called a *bifibration* (the proof that this map is a bifibration is [Lur09, 2.4.7.11]), which in particular means that $\text{Map}_{\mathcal{C}}(x, y)$ is a Kan complex.

Intuition 4.20. The mapping space is intended to generalize the idea of the homotopy category, in the sense that

$$\pi_0 \text{Map}_{\mathcal{C}}(x, y) = \text{Hom}_{h\mathcal{C}}(x, y).$$

In particular its connected components correspond to homotopy classes of maps between x and y , but it remembers more information about *how* the homotopies were witnessed, encoded in the higher homotopy type of $\text{Map}_{\mathcal{C}}(x, y)$.

Remark 4.21. Alternatively we may define $\text{Map}_{\mathcal{C}}(x, y)$ as the simplicial set whose n -simplices are given by the set of all

$$z: \Delta^{n+1} \rightarrow \mathcal{C},$$

²³If we consider the codomain of the nerve construction to be all simplicial sets, it still admits a left adjoint called the homotopy category, however it is not given by the formula in Definition 4.12. Technically there is a more general construction $h: \mathbf{sSet} \rightarrow \mathbf{Cat}$, which is left adjoint to N , and which agrees with Definition 4.12, which we should call $\tau_{\leq 1}$, when the simplicial set is a quasi-category. We’ll only apply the homotopy category construction to quasi-categories here so this distinction won’t matter.

with the $\{n+1\}$ -vertex mapping to y , and the vertices $\{0, \dots, n\}$ mapping to x . Technically speaking this is the space of *right morphisms* but when \mathcal{C} is an ∞ -category this models the mapping space (it is canonically isomorphic in the homotopy category). As an exercise, verify that $\mathrm{Map}_{\mathcal{C}}(x, y)$ is indeed a Kan complex from the definition.

What is $\mathrm{Map}_{\mathcal{C}}(x, y)$ intended to capture? Its 0-simplices are maps from x to y in the homotopy category $h\mathcal{C}$. In other words, they are equivalence classes of zig-zags of morphisms in \mathcal{C} from x to y , where maps going the wrong way are all invertible.

Notation 4.22. If \mathcal{C} is an ∞ -category and $x, y \in \mathcal{C}$, we denote by

$$[x, y] := \pi_0 \mathrm{Map}_{\mathcal{C}}(x, y).$$

We call this *homotopy classes of maps* from x to y .

Warning 4.23. It is not true that $[x, y]_{\mathcal{C}}$ is simply the edges from x to y in the quasi-category \mathcal{C} modulo an equivalence relation, it is more subtle. In the presence of a model structure, we can replace x and y by equivalent objects Qx and Ry respectively, so that $[x, y] \cong [Qx, Ry]$, and this latter set can be literally identified with the 1-cells $Qx \rightarrow Ry$ in \mathcal{C} modulo an explicit equivalence relation. We'll come back to this when we talk about sheaves.

Example 4.24. If \mathcal{C} is a 1-category, we can view it trivially as an ∞ -category via the nerve construction. In this case $\mathrm{Map}_{\mathcal{C}}(x, y) = \mathrm{Hom}_{\mathcal{C}}(x, y)$ is just a set (a discrete simplicial set). The homotopy category of \mathcal{C} is just \mathcal{C} , because there are no equivalences which aren't isomorphisms.

4.3. Presentable ∞ -categories. Modulo some set-theoretic technicalities, we can now be content with the existence of a model for infinity-categories. All notions of functors, colimits, adjunctions, etc. should now be understood in the higher categorical sense, i.e. up to higher coherence.

Definition 4.25. [Lur09, 5.4.2.1] An ∞ -category is *accessible* if it is generated under κ -filtered colimits by a small category.

Example 4.26. The category \mathcal{S} of spaces is accessible, since it admits all colimits and every space is built out of finite CW complexes.

Remark 4.27. By [Lur09, 5.4.3.6], a small ∞ -cat is accessible if and only if it is idempotent complete.²⁴ Observe that the category of finitely generated free R -modules fail to contain retracts (projectives) so they're not idempotent complete and hence not accessible.

Definition 4.28. Given any ∞ -category \mathcal{C} , we denote by $\mathrm{PSh}(\mathcal{C}) := \mathrm{Fun}(\mathcal{C}^{\mathrm{op}}, \mathcal{S})$ the category of (∞) -presheaves.

Example 4.29. We can think about presheaves of simplicial sets $\mathrm{Fun}(\mathrm{Sch}_S^{\mathrm{op}}, \mathrm{sSet})$ as the presheaf category $\mathrm{PSh}(\mathrm{Sch}_S)$. Note what lives in here:

- (1) Schemes all live in here via the Yoneda embedding $\mathrm{Sch}_S \hookrightarrow \mathrm{Fun}(\mathrm{Sch}_S^{\mathrm{op}}, \mathrm{Set}) \subseteq \mathrm{Fun}(\mathrm{Sch}_S^{\mathrm{op}}, \mathrm{sSet})$, by viewing $\mathrm{Set} \subseteq \mathrm{sSet}$ as discrete simplicial sets (no non-degenerate n -simplices for $n \geq 1$).
- (2) *Simplicial schemes* also live in here, by moving some adjoint stuff around:

$$\mathrm{Fun}(\Delta^{\mathrm{op}}, \mathrm{Sch}_S) \xrightarrow{y} \mathrm{Fun}(\Delta^{\mathrm{op}}, \mathrm{Fun}(\mathrm{Sch}_S^{\mathrm{op}}, \mathrm{Set})) \cong \mathrm{Fun}(\mathrm{Sch}_S^{\mathrm{op}}, \mathrm{Fun}(\Delta^{\mathrm{op}}, \mathrm{Set})) = \mathrm{PSh}(\mathrm{Sch}_S).$$
- (3) Spaces (viewed as simplicial sets by Π_{∞}) live in here as constant presheaves $\mathrm{sSet} \hookrightarrow \mathrm{Fun}(\mathrm{Sch}_S^{\mathrm{op}}, \mathrm{sSet})$.

Thus we have a natural home for schemes and spaces, as well as these simplicial scheme data types we've been looking at.

²⁴Idempotent complete has a number of definitions, in particular it implies that idempotent endomorphisms $f: X \rightarrow X$ (i.e. $f \circ f = f$) correspond bijectively to retracts of X , i.e. composites $Y \hookrightarrow X \rightarrow Y$. If \mathcal{C} is idempotent complete then it is closed under retracts.

Definition 4.30. We say an ∞ -category \mathcal{C} is *presentable* if it is accessible and admits all colimits (cocomplete).

Example 4.31. By the previous two examples, $\mathrm{PSh}(\mathcal{C})$ is presentable for any \mathcal{C} . This is the coYoneda lemma — that any presheaf is a colimit of representable ones.

Theorem 4.32. (*Adjoint functor theorem*) Let $F: \mathcal{C} \rightarrow \mathcal{D}$ be a functor between presentable categories. Then

- ▷ F admits a right adjoint if and only if F preserves all colimits
- ▷ F admits a left adjoint if and only if it preserves all limits and κ -filtered colimits

Really hard to write down functors explicitly in quasi-categories, since we are writing down a map of simplicial sets, which is a lot of data. AFT is nice because it lets us get functors without writing them explicitly, but they are still characterized by being adjoints.

Notation 4.33. We denote by Pr^L the category of presentable ∞ -categories and colimit-preserving functors between them. Note every functor in Pr^L is a left adjoint.

Theorem 4.34. Every presentable category is complete (admits all limits).

4.4. Localization.

Definition 4.35. [Lur09, 5.2.7.2] A functor $f: \mathcal{C} \rightarrow \mathcal{D}$ is a *localization* if it admits a fully faithful right adjoint.

In many cases a localization is given by inverting a class of morphisms in \mathcal{C} . In particular let $S \subseteq \mathrm{mor}\mathcal{C}$ be a class of morphisms in \mathcal{C} , then we can try to *invert* S by cooking up a new category $\mathcal{C}[S^{-1}]$.

Example 4.36.

- (1) The *homotopy category* of spaces is obtained from the category of compactly generated weakly Hausdorff spaces by inverting all homotopy equivalences.
- (2) The *derived category* of a ring is obtained from the category of chain complexes by inverting the chain homotopy equivalences.
- (3) A group (as a one-object groupoid) is obtained from a monoid by freely inverting each morphism.

Definition 4.37. [Lur09, 5.5.4.1] Let $S \subseteq \mathrm{mor}\mathcal{C}$. We say $z \in \mathcal{C}$ is *S -local* if for every $s: x \rightarrow y$ in S , the induced map

$$\mathrm{Map}_{\mathcal{C}}(y, z) \rightarrow \mathrm{Map}_{\mathcal{C}}(x, z)$$

is an equivalence.

Remark 4.38. Let $\mathcal{C}_0 \subseteq \mathcal{C}$ be the full subcategory of S -local objects. If this admits a left adjoint, it makes sense to call that adjoint L_S , that is, S -localization, since it inverts every morphism in S . *This is where presentable categories give us an advantage.* In general arguing for the existence of a left adjoint isn't easy, however if \mathcal{C} is presentable, then the adjoint functor theorem tells us that we just have to check the inclusion $\mathcal{C}_0 \subseteq \mathcal{C}$ preserves limits and filtered colimits.

Let $\mathcal{C}_0 \subseteq \mathcal{C}$ be the full subcategory of S -local objects. If this admits a left adjoint, it makes sense to call that adjoint L_S , that is, S -localization, since it inverts every morphism in S .

Proposition 4.39. [Lur09, 5.5.4.15] If \mathcal{C} is presentable and $S \subseteq \mathrm{mor}\mathcal{C}$ is small, then the inclusion of the full subcategory of S -local objects admits a left adjoint.²⁵

²⁵The terminology for this is that $\mathcal{C}_0 \subseteq \mathcal{C}$ is a *reflective subcategory*.

Example 4.40. In the next talk, our primary application of this machinery will be looking at the presheaf category $\mathrm{PSh}(\mathcal{C})$, which is presentable by [Example 4.31](#). We can look at full subcategories of presheaves which satisfy a certain sheaf condition and argue this is a reflective subcategory hence we will have an adjoint we call *sheafification*.

Remark 4.41. Given a class of arrows $S \subseteq \mathrm{mor}\mathcal{C}$, we can always form $\mathcal{C}[S^{-1}]$ by adjoining formal inverses to S and considering all composites of morphisms in \mathcal{C} and formal inverses (zig-zags). This is called *Dwyer–Kan localization* or *hammock localization*. This satisfies the correct universal property of localization, but we might encounter size issues. Bousfield localization is a particular example of Dwyer–Kan localization, but where we are able to guarantee that we don’t encounter any size issues since the localization is a subcategory of the original category.

Example 4.42. We define \mathcal{S} to be the Dwyer–Kan localization of the category Top of compactly generated weakly Hausdorff spaces at the weak homotopy equivalences. This has the property that $h\mathcal{S} = \mathrm{Ho}(\mathrm{Top})$. See [\[Lur09, §1.2.16\]](#) for more information. As a model category we are invited to think about \mathcal{S} as

- (1) simplicial sets with the classical model structure
- (2) Kan complexes with the classical model structure
- (3) topological spaces with the classical model structure

Hence we think about $\mathrm{PSh}(\mathcal{C}) = \mathrm{Fun}(\mathcal{C}^{\mathrm{op}}, \mathcal{S})$ as simplicial presheaves, equipped with a *levelwise* notion of weak equivalence, coming from weak homotopy equivalence of simplicial sets.

5. DESCENT

Goal 5.1. Define the ∞ -topos of Nisnevich sheaves $\mathrm{Sh}_{\mathrm{Nis}}(\mathrm{Sm}_k)$.

Assumption 5.2. We will work over a base scheme S which is qcqs and Noetherian.

5.1. Descent, higher categorically. Very roughly speaking, a *sheaf* is a presheaf that glues along covers. We’re going to give a general definition, then show how it recovers what we know and remember.

Notation 5.3. Suppose $\mathcal{U} = \{U_i \rightarrow X\}_i$ is a cover in Sch_S , giving rise to a Čech nerve $\Delta^{\mathrm{op}} \rightarrow \mathrm{Sch}_S$. Then if \mathcal{C} is any ∞ -category and $F: \mathrm{Sch}_S^{\mathrm{op}} \rightarrow \mathcal{C}$ a presheaf, then we denote by $F(\mathcal{U}) \in \mathrm{Fun}(\Delta, \mathcal{C})$ the cosimplicial object given by applying F everywhere in the Čech nerve.²⁶

Definition 5.4. Let \mathcal{C} be an ∞ -category with all limits, let (Sch_S, τ) be a site, and let $F: \mathrm{Sch}_S^{\mathrm{op}} \rightarrow \mathcal{C}$ be a presheaf valued in \mathcal{C} . Then we say F is a τ -*sheaf* if for every τ -cover $\mathcal{U} = \{U_i \rightarrow X\}$, we have that the induced map

$$F(X) \rightarrow \lim_{\Delta} F(\mathcal{U})$$

is an equivalence.

Example 5.5. If \mathcal{C} is a 1-category, e.g. sets, then a higher categorical limit just recovers the notion of an ordinary limit, since there is no higher structure. In particular, the limit reduces to seeing that the pair of parallel morphisms $[0] \rightrightarrows [1]$, viewed as a subcategory of Δ , is *final* (see [Example A.6](#)). In this case the sheaf condition reduces to asking whether the map

$$F(X) \rightarrow \lim \left(\prod_i F(U_i) \rightrightarrows \prod_{i,j} F(U_{ij}) \right)$$

is an equivalence, i.e. it witnesses $F(X)$ as a 1-categorical limit (in particular, an equalizer).

²⁶If F is product-preserving this is immediate, if not we have to apply F at each level and then take products.

Example 5.6. If \mathcal{C} is an abelian category, then the equalizer of two maps is just the kernel of their difference, so we get the familiar sheaf condition that

$$0 \rightarrow F(X) \rightarrow \prod F(U_i) \rightarrow \prod_{i,j} F(U_{ij})$$

is left exact.

Example 5.7. If \mathcal{C} is a 2-category, then $\Delta_{\leq 2}^{\text{inj}} \subseteq \Delta$ is 2-final (reference needed), so we get that the sheaf condition becomes

$$F(X) \rightarrow \lim \left(\prod_i F(U_i) \rightrightarrows \prod_{i,j} F(U_{ij}) \rightrightarrows \prod_{i,j,k} F(U_{ijk}) \right)$$

If $\mathcal{C} = \text{Grpd}$ is the category of groupoids, viewed as an ∞ -subcategory of qCat via the nerve construction, then this is precisely the stack condition! So this is what we meant when we said “sheaf of categories” earlier.

Remark 5.8. These limits are not 1-categorical limits, they are taking place in a higher categorical sense. The following example is worth thinking about as it makes this more concrete.

Example 5.9. Let R be a ring, and $\langle f, g \rangle = R$ two objects generating the unit ideal, giving rise to a two-object cover $\{\text{Spec}(R_f) \rightarrow \text{Spec}(R), \text{Spec}(R_g) \rightarrow \text{Spec}(R)\}$.

- (1) Argue that the stack condition for this particular cover truncates at the double overlaps, since there are no interesting triple overlaps.
- (2) See that $\mathcal{F}: \text{Sch}^{\text{op}} \rightarrow \text{Grpd}$ satisfies descent for this cover if and only if

$$\begin{array}{ccc} \mathcal{F}(\text{Spec}(R)) & \longrightarrow & \mathcal{F}(\text{Spec}(R_f)) \\ \downarrow & \lrcorner & \downarrow \\ \mathcal{F}(\text{Spec}(R_g)) & \longrightarrow & \mathcal{F}(\text{Spec}(R_{fg})) \end{array}$$

is a *pullback of groupoids*.

- (3) As a particular example, show that $\text{Mod}(-)$ satisfies descent for two-object Zariski covers. That is, $\text{Mod}(R)$ is equivalent to the 2-categorical pullback, often called the *category of descent data* attached to the cover.

5.2. cd-structures. We saw in the previous example how a sheaf condition can simplify on covers with fewer objects. A natural question to ask would be whether descent along a small collection of covers implies descent along all covers. A formalism that often lets us deal with this is the idea of a *cd-structure*. We’re also going to zoom in on presheaves of spaces.

Definition 5.10. A *cd-structure* is a collection of commutative squares in \mathcal{C} closed under isomorphism:

$$\begin{array}{ccc} A & \longrightarrow & B \\ \downarrow & & \downarrow \\ C & \longrightarrow & D. \end{array}$$

Terminology 5.11. Given a cd-structure on Sch_S , we define its associated topology τ to be the coarsest topology for which $\{B \rightarrow D, C \rightarrow D\}$ is a τ -cover for every distinguished square.

Example 5.12. The *Zariski cd-structure* is defined by commutative squares of the form

$$\begin{array}{ccc} U \cap V & \longrightarrow & U \\ \downarrow & & \downarrow \\ V & \longrightarrow & U \cup V. \end{array}$$

We will call these squares *distinguished Zariski squares*.

Theorem 5.13. Let $\mathcal{F} \in \text{PSh}(\text{Sch}_S^{\text{op}})$ be a presheaf. Then \mathcal{F} is a Zariski sheaf if and only if $\mathcal{F}(\emptyset) = *$ and \mathcal{F} sends every distinguished Zariski square to a (homotopy) pullback square.

Example 5.14. The Nisnevich topology is generated by a cd-structure given by *distinguished Nisnevich squares*, of the form

$$\begin{array}{ccc} U \times_X V & \longrightarrow & V \\ \downarrow & & \downarrow p \\ U & \xrightarrow{i} & X, \end{array}$$

where i is an open immersion, p is étale, and p restricts to an isomorphism $p^{-1}(X - U) \rightarrow X - U$.

Example 5.15. (*Affine distinguished Nisnevich square*). Suppose $f : R \rightarrow S$ is a finite étale ring homomorphism, and $h \in R$ is some element for which $R/h \cong S/f(x)$ is a ring isomorphism. Then we have a distinguished Nisnevich square:

$$\begin{array}{ccc} \text{Spec}(S_{f(x)}) & \longrightarrow & \text{Spec}(S) \\ \downarrow & \lrcorner & \downarrow \\ \text{Spec}(R_f) & \longrightarrow & \text{Spec}(R). \end{array}$$

Proof. The right map is étale, the bottom is an open immersion, and the restriction of $\text{Spec}(S) \rightarrow \text{Spec}(R)$ to the complement of the open distinguished affine $D(f) \subseteq \text{Spec}(R)$ is the hypothesis that $R/h \cong S/f(x)$. \square

Definition 5.16. We say $\mathcal{F} \in \text{PSh}(\text{Sm}_S)$ is a *Nisnevich sheaf* if $\mathcal{F}(\emptyset) = *$ and \mathcal{F} sends every distinguished Nisnevich square to a pullback square.

Exercise 5.17. Show that $\text{Mod}(-)$ is a Nisnevich sheaf on the site of affine schemes.

5.3. Sheafification and accessible localizations.

Definition 5.18. If $\mathcal{C} \subseteq \mathcal{D}$, then we say a localization $L : \mathcal{D} \rightarrow \mathcal{C}$ is *accessible* if and only if the composite $\mathcal{D} \xrightarrow{L} \mathcal{C} \hookrightarrow \mathcal{D}$ is accessible. If \mathcal{D} is an accessible category, this is equivalent to the statement that $\mathcal{C} \subseteq \mathcal{D}$ is an accessible subcategory [Lur09, 5.5.4.2].

Definition 5.19. [Lur09, 6.1.0.4] If \mathcal{X} is an ∞ -category, we say it is an ∞ -topos if there exists a small category \mathcal{C} and an accessible left exact localization functor $\text{PSh}(\mathcal{C}) \rightarrow \mathcal{X}$.

This is some higher categorical analogue of the fact from topos theory that every (Grothendieck) topos is the category of sheaves of sets on a site.

Proposition 5.20. [Lur09, 6.2.2.7] If \mathcal{C} is a (small) ∞ -category with a Grothendieck topology, then $\text{Shv}_\tau(\mathcal{C})$ is an accessible left exact localization of $P(\mathcal{C})$, in particular it is an ∞ -topos.

Proof. The precise statement of [Lur09, 6.2.2.7] is that $\text{Shv}_\tau(\mathcal{C}) \subseteq \text{PSh}(\mathcal{C})$ is a so-called *topological* localization (defined in [Lur09, 6.2.1.4]). In [Lur09, 6.2.1.6] it is proved that every topological localization of a presentable ∞ -category is accessible and left exact. \square

Terminology 5.21. We refer to the localization functor

$$L_\tau : \text{PSh}(\mathcal{C}) \hookrightarrow \text{Shv}_\tau : i$$

as *sheafification*.

Proposition 5.22. [Lur09, 6.2.2.17] If \mathcal{C} is a small ∞ -category there is a bijection between Grothendieck topologies on \mathcal{C} and (equivalence classes of) topological localizations of $\text{PSh}(\mathcal{C})$.

5.4. About the sheaf topos.

Corollary 5.23. Some consequences:

- (1) The *sheafification* functor $L_\tau: \text{PSh}(\mathcal{C}) \rightarrow \text{Shv}_\tau(\mathcal{C})$ preserves all colimits (being a left adjoint) and all small limits (being left exact).
- (2) The inclusion functor $i: \text{Shv}_\tau(\mathcal{C}) \hookrightarrow \text{PSh}(\mathcal{C})$ preserves all limits and all filtered colimits, by the adjoint functor theorem.

Explicitly, by this second point, we have that *limits and filtered colimits of sheaves can be computed in the presheaf category*. This is a crucial fact.

Example 5.24. (Examples of τ -sheaves):

- (1) Any τ -sheaf of *sets* is a τ -sheaf of discrete spaces. So we have

$$\text{Sh}_\tau(\mathcal{C}; \text{Set}) \subseteq \text{Sh}_\tau(\mathcal{C}).$$

- (2) If τ is subcanonical, then the representable presheaf

$$h_X := \text{Hom}_{\mathcal{C}}(-, X): \mathcal{C}^{\text{op}} \rightarrow \text{Set}$$

is a sheaf of sets, and hence a sheaf of spaces.

- (3) Consider any presheaf of groupoids

$$\mathcal{F}: \mathcal{C}^{\text{op}} \rightarrow \text{Grpd}.$$

We denote by $B\mathcal{F}$ the composite $\mathcal{C}^{\text{op}} \xrightarrow{\mathcal{F}} \text{Grpd} \xrightarrow{N} \text{sSet}$. Then \mathcal{F} is a τ -stack if and only if $B\mathcal{F}$ is a τ -sheaf [Hol08, 3.9].

- (4) If $Y \in \mathcal{S}$ is any space, we may sheafify the constant presheaf valued at Y in order to obtain a sheaf \underline{Y} .

Terminology 5.25. From the canonical equivalence

$$\text{Fun}(\Delta^{\text{op}}, \text{Fun}(\mathcal{C}^{\text{op}}, \text{Set})) \cong \text{Fun}(\mathcal{C}^{\text{op}}, \text{sSet}),$$

simplicial objects in set-valued presheaves naturally give rise to ∞ -categorical presheaves. Consider an object on the left, of the form $X_\bullet: \Delta^{\text{op}} \rightarrow \text{PSh}(\mathcal{C}; \text{Set})$. If this functor factors through $\text{Sh}_\tau(\mathcal{C}; \text{Set}) \subseteq \text{PSh}(\mathcal{C}; \text{Set})$, that is if X_n is a sheaf of sets for each n , we call this a *simplicial object in sheaves*.

Warning 5.26. (c.f. [Lur09, 7.1.3.1]) In the literature, we can find objects X_\bullet of the form in **Terminology 5.25** referred to as “simplicial sheaves.” This is overloaded terminology, and suggests that ∞ -categorical sheaves are just those presheaves of simplicial sets which are levelwise sheaves of sets, an erroneous claim that can be found throughout the literature.

5.5. Slice categories. Recall if \mathcal{C} is any (∞) -category and $x \in \mathcal{C}$, we have the under and over categories $\mathcal{C}_{x/}$ and $\mathcal{C}_{/x}$, respectively. If $* \in \mathcal{C}$ is a terminal object, then it becomes both initial and terminal in $\mathcal{C}_{*/}$, that is, it is a zero object. We call a category with a zero object *pointed*.

Proposition 5.27. We have that $\Delta^0 \in \mathcal{S}$, viewed as a constant sheaf, is terminal in the sheaf topos $\text{Shv}_\tau(\mathcal{C})$ for any site.

Proof. The inclusion $\text{Sh}_\tau(\mathcal{C}) \subseteq \text{PSh}(\mathcal{C})$ will preserve terminal objects, being a limit over an empty diagram, so it suffices to observe that the constant presheaf Δ^0 is already a sheaf. \square

Proposition 5.28. Let $h_S \in \text{PSh}(\text{Sm}_S)$ denote the representable sheaf attached to the base. Then the map $h_S \xrightarrow{!} \Delta^0$ of presheaves is a local equivalence.

Proof. It suffices to observe that the presheaves are identical, which is true because for any $U \in \text{Sm}_S$, we have that $h_S(U) = \text{Hom}_S(U, S)$, which is a one-object set consisting of the structure map (since S is terminal in Sm_S). \square

Notation 5.29. We denote by $\mathrm{Shv}_\tau(\mathcal{C})_* := \mathrm{Shv}_\tau(\mathcal{C})_{\Delta^0/}$ the pointed slice category. An object here is a map of sheaves $\Delta^0 \rightarrow F$, which we observe is equivalent to picking a basepoint in $F(U)$ for every $U \in \mathcal{C}$. Hence we can think of these as sheaves of *pointed* spaces.

5.6. Connectivity.

Definition 5.30. Let $(X, x) \in \mathrm{Shv}_\tau(\mathcal{C})_*$ and $n \geq 0$. Then we denote by $\pi_n(X, x)$ the n th *homotopy sheaf*, defined to be the τ -sheafification of the presheaf of sets

$$\begin{aligned} \mathcal{C}^{\mathrm{op}} &\rightarrow \mathrm{Set} \\ U &\mapsto \pi_n(X(U), x). \end{aligned}$$

Remark 5.31. There is a more intrinsic definition of π_n , leveraging that an ∞ -topos is cotensored over spaces,²⁷ and considering the map $X^{S^n} \rightarrow X$ in the slice topos $\mathrm{Shv}/_X$, and defining π_n to be its 0-truncation.

Proposition 5.32. We have that

- (1) π_0 is a sheaf of sets
- (2) π_1 is a sheaf of groups
- (3) π_n is a sheaf of abelian groups for $n \geq 2$.

Notation 5.33. If \mathcal{C} is any pointed ∞ -category admitting limits, and $X \in \mathcal{C}$, we denote by ΩX its *loop space*, defined as the pullback

$$\begin{array}{ccc} \Omega X & \longrightarrow & * \\ \downarrow & \lrcorner & \downarrow \\ * & \longrightarrow & X. \end{array}$$

The loop space interacts with the homotopy groups in a topos in the way we might expect from topology:

Proposition 5.34. If \mathcal{C} is an ∞ -topos and $(X, x) \in \mathcal{C}_*$, then

$$\pi_n(X, x) = \pi_0(\Omega^n(X, x)).$$

Proof. (reference needed) □

Example 5.35. Let $\mathcal{F}: \mathrm{Sm}_S^{\mathrm{op}} \rightarrow \mathrm{Set}$ be any sheaf of sets, groups, abelian groups, etc. Then

$$\pi_n(\mathcal{F}) = \begin{cases} \mathcal{F} & n = 0 \\ * & n > 0. \end{cases}$$

Proof. It suffices to observe that the presheaf $\pi_n \mathcal{F}$ is identical to the constant presheaf sheaf Δ^0 since $\mathcal{F}(U)$ has no higher homotopy for each $U \in \mathrm{Sm}_S$. □

Definition 5.36. [Lur09, 6.5.1.10] Let \mathcal{C} be an ∞ -topos, and take $X \in \mathcal{C}$.

- (1) We say X is *n-connective* if $\pi_k(X, x) = *$ for every $k < n$ and for every basepoint x .
- (2) We say that X is *connected* if it is 1-connective, meaning $\tau_{\leq 0} X = *$.
- (3) We say X is *n-truncated* if $\pi_k(X, x) = *$ for all $k > n$ and for every basepoint x .

Proposition 5.37. [Lur09, 5.5.6.18] If \mathcal{C} is a presentable category, and $\tau_{\leq k} \mathcal{C} \subseteq \mathcal{C}$ the full subcategory consisting of the k -truncated objects, then the inclusion admits an accessible left adjoint, in other words there is a truncation functor $\tau_{\leq k}$ which is a localization.

²⁷This means that for any $F \in \mathrm{Shv}_\tau(\mathrm{Sch}_S)$ and any $X \in \mathrm{sSet}$, we have a natural object $F^X \in \mathrm{Shv}_\tau(\mathrm{Sch}_S)$ with natural equivalences of mapping spaces

$$\mathrm{Map}_{\mathrm{Shv}}(G, F^X) \cong \mathrm{Map}_{\mathrm{sSet}}(X, \mathrm{Map}_{\mathrm{Shv}}(G, F)).$$

In particular the collection of n -truncated spaces is closed under limits.

Definition 5.38. If (\mathcal{C}, τ) is any site, then the category $\tau_{\leq 0}\mathrm{Sh}_{\tau}(\mathcal{C}) =: \mathrm{Sh}_{\tau}(\mathcal{C})_{\leq 0}$ is the category of sheaves of sets $\mathrm{Sh}_{\tau}(\mathcal{C}; \mathrm{Set})$.

Notation 5.39. We write $\mathrm{Ab}(\mathrm{Sh}_{\tau}(\mathcal{C})_{\leq 0})$ for the sheaves of abelian groups.

5.7. Whitehead's theorem.

Theorem 5.40. (Whitehead's theorem) Let $f: X \rightarrow Y$ be a map of CW complexes. Then f is a homotopy equivalence if and only if $f: \pi_i(X) \rightarrow \pi_i(Y)$ is an isomorphism for each $i \geq 0$.

A way to say this is that “ ∞ -connective morphisms are homotopy equivalences.” The ∞ -categorical analogue of this is the notion of *hypercompleteness*.

Definition 5.41. An ∞ -topos is *hypercomplete* if and only if every object is ∞ -connective.

Definition 5.42. [Lur09, 7.2.11] An ∞ -topos has *homotopy dimension* $\leq n$ if every $(n-1)$ -connected object X receives a map from the terminal object $* \rightarrow X$.

Theorem 5.43. If an ∞ -topos has finite homotopy dimension then it is hypercomplete.

Warning 5.44. The étale topos $\mathrm{Shv}_{\mathrm{et}}(\mathrm{Sm}_S)$ need not be hypercomplete, even for nice S (reference needed).

Theorem 5.45. (Voevodsky) If S is qcqs and Noetherian, then the homotopy dimension of $\mathrm{Shv}_{\mathrm{Nis}}(\mathrm{Sm}_S)$ is bounded above by $\dim(S)$. In particular this implies it is hypercomplete.

Truncation and connectivity fit into fiber sequences

$$\tau_{>n} \rightarrow \mathrm{id} \rightarrow \tau_{\leq n},$$

which allow us to form Postnikov towers out of objects of ∞ -topoi:

$$\begin{array}{ccc} & \tau_{\leq n} X & \\ & \downarrow & \\ & \vdots & \\ & \downarrow & \\ X & \longrightarrow & \tau_{\leq 0} X \end{array}$$

Hypercompleteness implies *Postnikov completeness* (reference needed) meaning that the induced map

$$X \rightarrow \lim_n \tau_{\leq n} X$$

is an equivalence. That is, the Postnikov towers converge and we can make sense of obstruction theory.

We'll see soon that this is a valuable perspective, e.g. for classifying torsors via homotopy theory. However the obstruction theory won't be very useful in the sheaf topos setting. This is one of the advantages we gain by passing to motivic spaces.

Upshot 5.46. In a hypercomplete topos, equivalences can be checked on homotopy sheaves.

Corollary 5.47. Let $F \rightarrow G$ be a map in the sheaf topos $\mathrm{Shv}_{\mathrm{Nis}}(\mathrm{Sch}_S)$ (or any hypercomplete topos) where S is qcqs and Noetherian. Then the following are equivalent:

- (1) The map $F \rightarrow G$ is an equivalence in $\mathrm{Shv}_{\mathrm{Nis}}(\mathrm{Sm}_S)$
- (2) The induced maps $\pi_n(F) \rightarrow \pi_n(G)$ are isomorphisms for every $n \geq 0$.

So this gives us a way to check equivalence on homotopy groups.

Notation 5.48. For $F, G \in \mathrm{Shv}_\tau(\mathrm{Sch}_S)$, we denote by

$$[F, G]_\tau := \pi_0 \mathrm{Map}_{\mathrm{Shv}_\tau(\mathrm{Sch}_S)}(F, G).$$

Remark 5.49. If F, G are presheaves, then their mapping space in presheaves and the mapping space of their associated sheafifications are quite different. We notice that if G is already a sheaf, then the unit $G \rightarrow iL_{\mathrm{Nis}}G$ is an equivalence, inducing an equivalence of mapping spaces

$$\mathrm{Map}_{\mathrm{PSh}(\mathrm{Sch}_S)}(F, G) \cong \mathrm{Map}_{\mathrm{PSh}(\mathrm{Sch}_S)}(F, iL_{\mathrm{Nis}}G) \cong \mathrm{Map}_{\mathrm{Shv}_\tau(\mathrm{Sch}_S)}(L_{\mathrm{Nis}}F, L_{\mathrm{Nis}}G).$$

We think of this as a higher categorical analogue of the universal property of sheafification: that a map from a presheaf to a sheaf factors uniquely through its sheafification.

5.8. Equivalences of sheaves and presheaves. Recall that if $f: F \rightarrow G$ is a map in $\mathrm{PSh}(\mathrm{Sch}_S)$, then it is an equivalence if and only if $F(U) \rightarrow G(U)$ is an equivalence of spaces for each $U \in \mathrm{Sch}_S$, also called a *sectionwise equivalence*. If $f: F \rightarrow G$ is an equivalence, then so is the associated map after sheafification. The converse doesn't hold though, since different presheaves can admit the same sheafification. To that end, we introduce a new notion.

Definition 5.50. Let $F, G \in \mathrm{PSh}(\mathrm{Sch}_S)$ be presheaves, and let $f: F \rightarrow G$ be a map of presheaves. We say that f is a *local equivalence* if

$$L_{\mathrm{Nis}}(f): L_{\mathrm{Nis}}F \rightarrow L_{\mathrm{Nis}}G$$

is an equivalence of sheaves.

Example 5.51. The unit of the sheafification adjunction $L_{\mathrm{Nis}} \dashv i$ has components

$$F \rightarrow iL_{\mathrm{Nis}}F,$$

which are all local equivalences.

Proof. Since i is fully faithful, we have that the counit $L_{\mathrm{Nis}}i \rightarrow \mathrm{id}$ is a natural equivalence. We'd like to argue that

$$L_{\mathrm{Nis}}F \rightarrow L_{\mathrm{Nis}}iL_{\mathrm{Nis}}F$$

is an equivalence. Since i is fully faithful, it reflects equivalences, so it suffices to check that

$$iL_{\mathrm{Nis}}F \rightarrow iL_{\mathrm{Nis}}iL_{\mathrm{Nis}}F$$

is a natural equivalence, which follows from the counit being a natural equivalence. \square

Notation 5.52. Let X be a scheme and $x \in X$. We denote by $\mathrm{Hen}_{X,x}$ the category of maps $f: (Y, y) \rightarrow (X, x)$ where $f: Y \rightarrow X$ is étale, $f(y) = x$, and f induces an isomorphism $k(x) \xrightarrow{\sim} k(y)$.

Definition 5.53. Let X be a scheme and $x \in X$. We denote by

$$X_x^h := \lim_{(Y,y) \in \mathrm{Hen}_{X,x}} Y = \lim_{(Y,y) \in \mathrm{Hen}_{X,x}} Y_y$$

See [Stacks, 04GV], or [Bac, 2.22].

Notation 5.54. Denote by $\mathrm{Sm}_S \subseteq \mathrm{Sch}_S$ the full subcategory of smooth S -schemes. Here S is still qcqs and Noetherian as assumed. We will restrict our attention here as it will be needed for upcoming results.

Definition 5.55. Let $f: F \rightarrow G$ be a map of presheaves in $\mathrm{PSh}(\mathrm{Sm}_S)$. Then we say f is a *stalkwise (Nisnevich) weak equivalence* if for every $X \in \mathrm{Sm}_S$ and every $x \in X$, the induced map

$$\mathrm{colim}_{\mathrm{Hen}_{X,x}} F(Y) \rightarrow \mathrm{colim}_{\mathrm{Hen}_{X,x}} G(Y)$$

is an equivalence of spaces.

Warning 5.56. This is *not* the same as saying that $F(X_x^h) \rightarrow G(X_x^h)$ is an equivalence.

Theorem 5.57. (Voevodsky) Let S be qcqs and Noetherian, and let $f: F \rightarrow G$ in $\mathrm{PSh}(\mathrm{Sm}_S)$. Then f is a local equivalence if and only if it is a stalkwise equivalence.

Proof. (todo — hard) □

As a particular case of [Theorem 5.57](#) applied to [Example 5.51](#), we recover the following familiar result.

Corollary 5.58. A presheaf and its Nisnevich sheafification admit the same stalks in the Nisnevich site.

5.9. Torsors revisited.

Proposition 5.59. Let S be qcqs and Noetherian, and let τ be a topology on Sch_S . Then given any τ -cover $\mathcal{U} := \{U_i \rightarrow X\}$, we can look at the induced map from the Čech nerve (viewed as a simplicial object of representable presheaves) to X viewed as a discrete representable simplicial presheaf. This map

$$N_\bullet(\mathcal{U}) \rightarrow X$$

is a local equivalence of presheaves.

Remark 5.60. (How to prove this)

- (1) One way to prove this is by identifying the sheaf topos, as a simplicial model category, with the Bousfield localization of the category of simplicial presheaves, endowed with the projective model structure, at the class of hypercovers in the topology. We insist on S being qcqs and Noetherian so we don't have to stress about the difference between covers and hypercovers here, although there is a more general statement over any base. This follows a body of work by Jardine, Bousfield and Kan, Dugger, Hollander and Isaksen.
- (2) Another direction is by formal nonsense of ∞ -topos theory. For instance if $X \in \text{Sm}_S$, we can apply [\[Lur, A.5.3.1\]](#) to the Čech nerve of a cover after pulling it back to the slice topos $\text{Shv}_\tau(\text{Sm}_S)_{/X}$.

What about classifying spaces $B_\bullet \mathcal{G} \in \text{PSh}(\text{Sch}_S)$? We would like to understand them in the sheaf topos.

Notation 5.61. If τ is a topology, we denote by $B_\tau \mathcal{G} := L_\tau B_\bullet \mathcal{G}$ the sheafification of the bar construction in the τ topology.

Example 5.62. For any \mathcal{G} , we have a stack of \mathcal{G} -torsors, which we denote by

$$\text{Tors}_\tau(\mathcal{G}): \mathcal{C}^{\text{op}} \rightarrow \text{Grpd}.$$

This gives rise to a sheaf $B\text{Tors}_\tau(\mathcal{G})$ by post-composing with the nerve ([Example 5.24](#)).

Theorem 5.63. [\[AHW18, 2.3.2\]](#) There is a morphism of simplicial presheaves $B_\bullet \mathcal{G} \rightarrow B\text{Tors}_\tau(\mathcal{G})$, defined on sections by sending the unique vertex of $B_\bullet \mathcal{G}(U)$ to the trivial \mathcal{G} -torsor over U . This map is a local equivalence.

Corollary 5.64. For any τ -sheaf of groups \mathcal{G} , there is a natural isomorphism of sheaves of sets

$$[-, B_\tau \mathcal{G}]_\tau = \pi_0 \text{Map}_{\text{Shv}_\tau(\text{Sch}_S)}(-, B_\tau \mathcal{G}) \cong H_\tau^1(-, \mathcal{G}).$$

This is the result we've been hoping for. It tells us we can classify torsors in the sheaf topos $\text{Sh}_\tau(\text{Sch}_S)$, and it is a completely topos-theoretic fact. In particular we gain access to all the homotopically flavored tools available to us in an ∞ -topos. For instance, we could attempt to leverage Postnikov towers to deal with obstruction theory for the classifying sheaf $B_\tau \mathcal{G}$. The following result indicates that this tower won't contain any interesting information.

Example 5.65. If \mathcal{G} is a sheaf of discrete groups, we have that

$$\pi_n B_\tau \mathcal{G} = \begin{cases} \mathcal{G} & i = 1 \\ 0 & \text{otherwise} \end{cases}$$

Proof. By [Theorem 5.63](#) we have that $B_\tau \mathcal{G} \simeq B\mathrm{Tors}_\tau \mathcal{G}$, and the latter is a sheaf whose sections are exactly the nerves of discrete groupoids, and hence $K(\pi, 1)$'s. \square

6. MOTIVIC SPACES

We are interested in studying \mathbb{A}^1 -invariance of presheaves. There are a few ways we might impose this, the first being the most naive — we can study presheaves F for which

- (1) any projection $X \times \mathbb{A}^1 \rightarrow X$ induces an equivalence $F(X) \xrightarrow{\sim} F(X \times \mathbb{A}^1)$
- (2) any vector bundle torsor $E \rightarrow X$ induces an equivalence $F(X) \xrightarrow{\sim} F(E)$
- (3) any algebraic vector bundle *torsor* $Y \rightarrow X$ induces an equivalence $F(X) \xrightarrow{\sim} F(Y)$.

We have a strengthening of conditions here, but we notice that in the context of sheaves they all become equivalent, so the definition is only really important for presheaves. We will work with the first one as it is classically what people work with, and the last one since it will simplify some proofs. Let's first define vector bundle torsors explicitly.

Definition 6.1. [[Wei89](#), 4.2] A *vector bundle torsor* is an affine map $Y \rightarrow X$ which is a torsor for an algebraic vector bundle $E \rightarrow X$. Explicitly, $Y \rightarrow X$ is a Zariski locally trivial affine morphism with fibers isomorphic to affine space.

Example 6.2. If $X = \mathrm{Spec}(A)$ is an affine scheme, then algebraic vector bundle torsors over X are the same as vector bundles over X .

todo - find an example of a non-affine X for which vector bundle torsors and vector bundles don't agree

Notation 6.3. Let Sm_S denote the category of smooth S -schemes of finite type over S . The finite type assumption is needed in order to guarantee that Sm_S is essentially small (see [Theorem B.1](#)).

Definition 6.4. Let $F \in \mathrm{PSh}(\mathrm{Sm}_S)$ be a presheaf.

- (1) We say F is \mathbb{A}^1 -invariant if for every $X \in \mathrm{Sm}_S$, the projection map $X \times \mathbb{A}^1 \rightarrow X$ induces an equivalence

$$F(X) \xrightarrow{\sim} F(X \times \mathbb{A}^1).$$

- (2) We say F is *strongly homotopy invariant* if for every vector bundle torsor $Y \rightarrow X$, the restriction map

$$F(X) \xrightarrow{\sim} F(Y)$$

is an equivalence.

We denote by $\mathrm{PSh}_{\mathbb{A}^1}(\mathrm{Sm}_S)$ and $\mathrm{PSh}_{\mathrm{htp}}(\mathrm{Sm}_S)$ the full subcategories of $\mathrm{PSh}(\mathrm{Sm}_S)$ spanned by the \mathbb{A}^1 -invariant and strongly homotopy invariant presheaves, respectively.

Remark 6.5. It is clear that we have containments

$$\mathrm{PSh}_{\mathrm{htp}}(\mathrm{Sm}_S) \subseteq \mathrm{PSh}_{\mathbb{A}^1}(\mathrm{Sm}_S) \subseteq \mathrm{PSh}(\mathrm{Sm}_S),$$

but neither of the reverse inclusions hold.

Proposition 6.6. Both of $\mathrm{PSh}_{\mathbb{A}^1}(\mathrm{Sm}_S)$ and $\mathrm{PSh}_{\mathrm{htp}}(\mathrm{Sm}_S)$ are accessible subcategories of $\mathrm{PSh}(\mathrm{Sm}_S)$, and therefore their inclusions admit left adjoints.

Proof. By [Proposition 4.39](#) it suffices to check they are defined by being local with respect to a *set* of maps. In the first case note that a presheaf F is \mathbb{A}^1 -invariant if and only if it is S -local, meaning that

$$\mathrm{Map}_{\mathrm{PSh}(\mathrm{Sm}_S)}(h_X, F) \xrightarrow{\sim} \mathrm{Map}_{\mathrm{PSh}(\mathrm{Sm}_S)}(h_{X \times \mathbb{A}^1}, F)$$

is an equivalence. Here we are using the Yoneda lemma together with the fact that the Yoneda embedding preserves products. Since Sm_S has a small skeleton, we may pick a set of maps

$\{X \times \mathbb{A}^1 \rightarrow X\}$ for each isomorphism class of smooth scheme X . An analogous argument works for $\mathrm{PSh}_{\mathrm{htp}}(\mathrm{Sm}_S)$. \square

Terminology 6.7. In light of the previous remark, we might also call presheaves or sheaves \mathbb{A}^1 -local instead of \mathbb{A}^1 -invariant. This is the terminology used in [MV99].

Example 6.8. (*Not every representable is \mathbb{A}^1 -invariant*) Representable presheaves need not be \mathbb{A}^1 -invariant. For example:

- ▷ \mathbb{G}_m is \mathbb{A}^1 invariant assuming the base is reduced. This is because it represents units, which are \mathbb{A}^1 -invariant.
- ▷ \mathbb{A}^1 is not \mathbb{A}^1 -invariant, since it represents global sections.

Notation 6.9. We denote by

$$\begin{aligned} L_{\mathbb{A}^1}: \mathrm{PSh}(\mathrm{Sm}_S) &\rightarrow \mathrm{PSh}_{\mathbb{A}^1}(\mathrm{Sm}_S), \\ L_{\mathrm{htp}}: \mathrm{PSh}(\mathrm{Sm}_S) &\rightarrow \mathrm{PSh}_{\mathrm{htp}}(\mathrm{Sm}_S) \end{aligned}$$

the associated localizations which are left adjoint to the inclusions.

6.1. Singular chains. Here we develop an explicit formula for $L_{\mathbb{A}^1}$ which will help us do computations.

Notation 6.10. We denote by Δ^n the *algebraic n -simplex*

$$\Delta^n := \mathrm{Spec}(\mathbb{Z}[t_0, \dots, t_n] / (\sum t_i - 1)).$$

These give a cosimplicial scheme $\Delta^\bullet \in \mathrm{Fun}(\Delta, \mathrm{Sch})$.

Definition 6.11. We define the *singular chains* construction

$$\mathrm{Sing}: \mathrm{PSh}(\mathrm{Sm}_S) \rightarrow \mathrm{PSh}(\mathrm{Sm}_S)$$

by the formula

$$\mathrm{Sing}(F)(X) = \mathrm{colim}_{\Delta^{\mathrm{op}}} F(X \times \Delta^n)$$

Proposition 6.12. We have that $\mathrm{Sing}(F)$ is \mathbb{A}^1 -invariant for any F .

Proof sketch. We want to prove for any $X \in \mathrm{Sch}_S$ that the projection map $\pi: X \times \mathbb{A}^1 \rightarrow X$ induces an equivalence

$$\pi^*: (\mathrm{Sing} F)(X \times \mathbb{A}^1) \rightarrow (\mathrm{Sing} F)(X).$$

Let $z: X \rightarrow X \times \mathbb{A}^1$ denote the zero section. Then we claim z^* exhibits a simplicial homotopy equivalence with π^* . Since $\pi z = \mathrm{id}$, it is clear that $z^* \pi^* = \mathrm{id}$, so it suffices to exhibit a simplicial homotopy $\pi^* z^* \simeq \mathrm{id}$. Since any functor will preserve simplicial homotopies, and geometric realizations will send simplicial homotopies to honest homotopies, it suffices to exhibit a homotopy of cosimplicial simplicial varieties

$$\mathrm{id}, z \circ \pi: X \times \mathbb{A}^1 \times \Delta^\bullet \rightarrow X \times \mathbb{A}^1 \times \Delta^\bullet,$$

meaning maps whose opposites satisfy the simplicial homotopy identities. (todo: add explicit simplicial homotopy) \square

Proposition 6.13. If F is already \mathbb{A}^1 -invariant, then the natural map

$$F \rightarrow \mathrm{Sing}(F)$$

is an equivalence of presheaves.

Proof. Immediate since F is \mathbb{A}^1 -invariant, so we can turn $F(X \times \Delta^\bullet)$ into a constant diagram. \square

Proposition 6.14. There is a natural equivalence of functors $L_{\mathbb{A}^1} \simeq \mathrm{Sing}$.

Proof. We note that the essential image of Sing is precisely $\text{PSh}_{\mathbb{A}^1}(\text{Sm}_k)$ by [Proposition 6.13](#). By that same result, the natural transformation

$$\eta: \text{id} \rightarrow \text{Sing}$$

induces an equivalence between the maps $\text{Sing}(\eta(-))$ and $\eta_{\text{Sing}(-)}$ on its components. By [\[Lur09, 5.2.7.4\]](#), this implies that $\text{Sing}(-)$ is a left adjoint, with right adjoint given by the fully faithful inclusion of its essential image $\text{PSh}_{\mathbb{A}^1}(\text{Sm}_k) \subseteq \text{PSh}(\text{Sm}_k)$. By uniqueness of adjoints, this implies $\text{Sing} \simeq L_{\mathbb{A}^1}$. \square

Corollary 6.15. $L_{\mathbb{A}^1}$ preserves finite products.

Proof. This is not immediate from the definition, but it follows after identifying $L_{\mathbb{A}^1}$ with $\text{Sing}(-)$. Since Δ^{op} is sifted (c.f. [\[Lur09, 5.5.4.8\]](#)), colimits indexed over Δ^{op} commute with products, hence the result follows. \square

Proposition 6.16. For any $X \in \text{Sm}_S$, we have that $X \times \mathbb{A}_S^n \rightarrow X$ is an equivalence after \mathbb{A}^n -localization.

Proof. For $n = 1$ this is by definition of the localization, and for higher n this follows from $L_{\mathbb{A}^1}$ preserving finite products. \square

Remark 6.17. An analogous formula holds for L_{htp} — if we let $\text{VBT}_{/X}$ denote the category of vector bundle torsors over X , then $\text{VBT}_{/X}$ is cosifted, and we obtain an identification

$$(18) \quad (L_{\text{htp}}F)(X) = \text{colim}_{Y \in \text{VBT}_{/X}} F(Y),$$

with the same properties that it preserves finite products and is locally cartesian [\[Hoy17, 3.5\]](#)

6.2. The category of motivic spaces.

Definition 6.19. We define the category of *motivic spaces* $\text{Spc}(k)$ as

$$\text{Spc}(k) = \text{Shv}_{\text{Nis}}(\text{Sm}_k) \cap \text{PSh}_{\mathbb{A}^1}(\text{Sm}_k) \subseteq \text{PSh}(\text{Sm}_k),$$

that is, the full subcategory of presheaves which are both Nisnevich sheaves and are \mathbb{A}^1 -invariant.

Remark 6.20. Since every affine bundle torsor is locally trivialized, once we impose the sheaf condition, the properties of being \mathbb{A}^1 -invariant and strongly homotopy invariant can be checked locally, and hence agree:

$$\text{Shv}_{\text{Nis}}(\text{Sm}_S) \cap \text{PSh}_{\mathbb{A}^1}(\text{Sm}_S) = \text{Shv}_{\text{Nis}}(\text{Sm}_S) \cap \text{PSh}_{\text{htp}}(\text{Sm}_S).$$

In other words we could equivalently define motivic spaces via $\text{PSh}_{\mathbb{A}^1}$, or via PSh_{htp} . The former is more common, although the latter has some nice advantages (see [\[Hoy17, p. 204\]](#) for a discussion, and [\[Hoy17, 3.13\]](#) for the equality above).

Problem: Nisnevich sheafifying an \mathbb{A}^1 -invariant presheaf needs not preserve \mathbb{A}^1 -invariance, and \mathbb{A}^1 -localizing a sheaf may break the sheaf condition.

Example 6.21. [\[MV99, 3.2.7\]](#) Let $U_0 = \mathbb{A}^1 - 0$ and $U_1 = \mathbb{A}^1 - 1$, and let $U_{01} = U_0 \cap U_1 \subseteq \mathbb{A}^1$. Since both U_0 and U_1 are \mathbb{A}^1 -invariant, we claim that U_{01} is as well. Pick a closed embedding of U_{01} in \mathbb{A}^n for some n , and consider the non-smooth scheme

$$Y := (U_0 \times \mathbb{A}^n) \amalg_{U_{01}} (U_1 \times \mathbb{A}^n) \in \text{Sch}_S.$$

Then for any connected $X \in \text{Sm}_S$, we have that

$$\text{Hom}_{\text{Sch}_S}(X, Y) = \text{Hom}_{\text{Sm}_S}(X, U_0 \times \mathbb{A}^n) \coprod_{\text{Hom}_{\text{Sm}_S}(X, U_{01})} \text{Hom}_{\text{Sm}_S}(X, U_1 \times \mathbb{A}^n).$$

Since $L_{\mathbb{A}^1}$ preserves pushouts, we have that

$$L_{\mathbb{A}^1} h_Y = L_{\mathbb{A}^1}(U_0 \times \mathbb{A}^n) \amalg_{L_{\mathbb{A}^1}(U_{01})} L_{\mathbb{A}^1}(U_1 \times \mathbb{A}^n).$$

By [Proposition 6.16](#) we can contract away the \mathbb{A}^n 's, and we invoke that U_0 , U_1 , and U_{01} were already \mathbb{A}^1 -local to get that the above is equivalent to

$$\simeq L_{\mathbb{A}^1}(U_0) \coprod_{L_{\mathbb{A}^1}(U_{01})} L_{\mathbb{A}^1}(U_1) = U_0 \coprod_{U_{01}} A_1.$$

If this were a sheaf, it would agree with its sheafification, and since sheafification preserves pushouts, we would have that it is equal to the *pushout of sheaves*

$$U_0 \amalg_{U_{01}} U_1 = \mathbb{A}^1,$$

which is the representable sheaf given by \mathbb{A}^1 by Zariski descent. But note that \mathbb{A}^1 is not \mathbb{A}^1 -invariant, so we get that $L_{\mathbb{A}^1}h_Y$ cannot be a sheaf.

Proposition 6.22. The category $\mathrm{Spc}(S) \subseteq \mathrm{PSh}(\mathrm{Sm}_S)$ is an accessible localization, hence the inclusion admits a left adjoint.

We call this adjoint *motivic localization*, and we can describe it explicitly as the infinite composition of both functors.

Definition 6.23. We define $L_{\mathrm{mot}}: \mathrm{PSh}(\mathrm{Sm}_S) \rightarrow \mathrm{Spc}(S)$ by the formula

$$L_{\mathrm{mot}} := \mathrm{colim}_{n \rightarrow \infty} (L_{\mathbb{A}^1} \circ L_{\mathrm{Nis}})^{\circ n},$$

where this colimit is computed in the presheaf category.

6.3. Properties of motivic localization. We know that L_{mot} preserves colimits, being a left adjoint. What other properties does it admit?

Proposition 6.24. [[Hoy14](#), C.6] We have that L_{mot} preserves finite products.

Proof. This follows by both L_{Nis} and $L_{\mathbb{A}^1}$ preserving finite products, together with transfinite composition preserving products. \square

Proposition 6.25. [[Hoy17](#), 3.15] L_{mot} is locally cartesian, meaning that for a cospan $X \rightarrow Y \leftarrow Z$ in $\mathrm{PSh}(\mathrm{Sm}_S)$, if both X and Y are motivic spaces, then the natural map

$$L_{\mathrm{mot}}(X \times_Y Z) \rightarrow X \times_Y L_{\mathrm{mot}}(Z)$$

is an equivalence. Note the pullback on the domain is in the category of presheaves, while the pullback on the right is in the category of motivic spaces.

Corollary 6.26. Colimits in $\mathrm{Spc}(S)$ are universal (pullback-stable).

Proof. Let X and Y be some motivic spaces, and let $j: I \rightarrow \mathrm{Spc}(S)$ be a diagram, whose colimit maps to Y . We claim that

$$\mathrm{colim}_{i \in I} (X \times_Y j(i)) \rightarrow X \times_Y \mathrm{colim}_{i \in I} j(i)$$

is an equivalence in L_{mot} . This is true in the ambient presheaf category since it is a topos, but this doesn't immediately imply the result for motivic spaces, since pullbacks of presheaves do not in general yield pullbacks of motivic spaces. However by applying L_{mot} to both sides, and using the fact that it is locally cartesian, the result follows. \square

Proposition 6.27. We have that L_{mot} is *not left exact*. In particular $\mathrm{Spc}(k)$ is not an ∞ -topos.

We will come back to prove [Proposition 6.27](#) later when we have a little more machinery.

6.4. Motivic equivalences.

Definition 6.28. We say that $f: F \rightarrow G$ in $\mathrm{PSh}(\mathrm{Sm}_S)$ is a *motivic equivalence* if $L_{\mathrm{mot}}f$ is an equivalence in $\mathrm{Spc}(S)$.

Proposition 6.29. We have that $\Delta^0 \cong S$ in $\mathrm{Spc}(S)$, and moreover these are terminal, hence we will often denote them by $*$.

Proof. This follows from $\mathrm{Spc}(S) \subseteq \mathrm{Shv}_{\mathrm{Nis}}(\mathrm{Sm}_S)$ being an accessible subcategory (hence preserving terminal objects) together with [Proposition 5.28](#). \square

Proposition 6.30. The map to the terminal object in schemes $\mathbb{A}_S^n \rightarrow S$ is a motivic equivalence.

Proof. It is clear that $\mathbb{A}_S^1 \rightarrow S$ is a motivic equivalence essentially by definition. The more general statement follows from both the Yoneda embedding and motivic localization preserving finite products. \square

The following proposition is also essentially by definition.

Proposition 6.31. For any $X \in \mathrm{Sm}_S$, the projection map $X \times \mathbb{A}_S^n \rightarrow X$ is a motivic equivalence.

Proposition 6.32. For any $F \in \mathrm{PSh}(\mathrm{Sm}_S)$, the projection map $F \times \mathbb{A}^n \rightarrow F$ is a motivic equivalence.

Proof. By the co-Yoneda lemma, any presheaf is a colimit of representable presheaves. Since L_{mot} is locally cartesian, colimits are pullback stable, and hence product-stable, meaning that

$$F \times \mathbb{A}^n \cong (\mathrm{colim}_U h_U) \times \mathbb{A}^n.$$

Since colimits are universal in any ∞ -topos (in particular in the presheaf category), we have that we can distribute the colimit over the product. Then the result follows by [Proposition 6.31](#). \square

7. JOUANOLOU DEVICES AND MOTIVIC EQUIVALENCES

Theorem 7.1. (Jouanolou–Thomason trick) Suppose that S is qcqs and further suppose either S is affine or it is noetherian, regular, and separated. Then for any quasi-projective $X \in \mathrm{Sch}_S$, there exists an affine bundle $Y \rightarrow X$, where Y is affine.

Remark 7.2. The above result probably holds under weaker assumptions – we’re citing [\[Hoy17, 2.20\]](#), pulling our assumptions on S from [\[Hoy17, 2.8\]](#) and letting G be trivial. In most cases we apply this, S will be a field, and X will be smooth, and we can apply this trick by e.g. [\[AF14, 3.3.3\]](#).

Example 7.3. The easiest example is \mathbb{P}_k^1 over a field k . There is a map

$$\mathrm{Spec} \left(\frac{k[x, y, z, w]}{x + w - 1, xw - yz} \right) \rightarrow \mathbb{P}^1$$

$$(x, y, z, w) \mapsto \begin{cases} [x : y] & (x, y) \neq (0, 0) \\ [z : w] & (z, w) \neq (0, 0). \end{cases}$$

We claim this is well-defined, exhibiting an affine torsor over \mathbb{P}^1 .

Example 7.4. In a similar vein, the map

$$\mathrm{SL}_2 \rightarrow \mathbb{A}^2 \setminus 0$$

$$\begin{pmatrix} a & b \\ c & d \end{pmatrix} \mapsto (b, d)$$

is an affine vector bundle torsor over $\mathbb{A}^2 \setminus 0$. More generally

$$\mathrm{SL}_n \rightarrow \mathbb{A}^n \setminus \{0\}$$

is an affine vector bundle torsor, by sending an invertible determinant one matrix to its last column.

Proposition 7.5. Any affine vector bundle torsor $E \rightarrow B$ is a motivic equivalence.

Proof. It suffices to verify on a local cover where the bundle is trivialized, at which point it follows by [Proposition 6.31](#). \square

7.1. Checking motivic equivalences on affines.

Proposition 7.6. The category $\mathrm{Spc}(S)$ is generated under sifted colimits by (the motivic localization of the representable presheaves attached to) affine S -schemes in Sm_S [Hoy17, 3.16].

Proof. We do this in two steps:

- (1) First we argue that $\mathrm{Spc}(S)$ is generated under filtered colimits by Sm_S . Let $F \in \mathrm{Spc}(S)$ be any motivic space, then, considered as a presheaf, it is a colimit of representable presheaves. What is furthermore true is that it is a filtered colimit of coproducts of representable presheaves. While it is not true that $h_U \amalg h_V$ is $h_{U \amalg V}$ in the category of presheaves, it *is true* in the category of sheaves (and hence in the category of motivic spaces), by descent. Hence any motivic localization is in fact a filtered colimit of the motivic localization of representable sheaves.
- (2) Second we argue that $\mathrm{Sm}_S \subseteq \mathrm{Spc}(S)$ is generated under sifted colimits by affine S -schemes in Sm_S . Given any $X \in \mathrm{Sm}_S$, we can write it as an Δ^{op} -indexed colimit in the category $\mathrm{Spc}(S)$ over the Čech nerve of a Nisnevich cover. Each fiber product appearing in the cover is equivalent to a smooth affine scheme by Jouanolou's trick, and we can get rid of finite coproducts by the same trick. Hence X can be written as a Δ^{op} -indexed colimit over smooth affine S -schemes.

As sifted colimits are combinations of filtered colimits and geometric realizations (Proposition A.17), the result follows. \square

This gives us a powerful way to check motivic equivalences between presheaves.

Proposition 7.7. [Hoy17, 3.16] Let $f: F \rightarrow G$ be a morphism in $\mathrm{PSh}(\mathrm{Sm}_S)$. If

$$F(U) \rightarrow G(U)$$

is an equivalence for every affine $U \in \mathrm{Sm}_S$, then f is a motivic equivalence.

Proof. By Yoneda it suffices to argue that

$$\mathrm{Map}_{\mathrm{Spc}(S)}(-, L_{\mathrm{mot}}F) \rightarrow \mathrm{Map}_{\mathrm{Spc}(S)}(-, L_{\mathrm{mot}}G)$$

is a natural equivalence. Since $\mathrm{Map}(-, -)$ sends colimits to limits in the first variable, by Proposition 7.6 it suffices to argue that

$$\mathrm{Map}_{\mathrm{Spc}(S)}(L_{\mathrm{mot}}h_U, L_{\mathrm{mot}}F) \rightarrow \mathrm{Map}_{\mathrm{Spc}(S)}(L_{\mathrm{mot}}h_U, L_{\mathrm{mot}}G)$$

is an equivalence for each affine $U \in \mathrm{Sm}_S$. By adjunction, this is equivalent to asking that $L_{\mathrm{mot}}F \rightarrow L_{\mathrm{mot}}G$ is a sectionwise equivalence of presheaves when restricted to affines.

We first argue $L_{\mathrm{htp}}F \rightarrow L_{\mathrm{htp}}G$ is a sectionwise equivalence. Since every $X \in \mathrm{Sm}_S$ admits an affine bundle torsor $U \rightarrow X$ which is itself affine by the Jouanolou trick, we have that $(L_{\mathrm{htp}}F)(X) \xrightarrow{\sim} (L_{\mathrm{htp}}F)(U)$ is an equivalence, so it suffices to check that $L_{\mathrm{htp}}F \rightarrow L_{\mathrm{htp}}G$ is a sectionwise equivalence on affines. Since every vector bundle torsor over an affine is affine²⁸, we can leverage the formula for L_{htp} (Equation 18) in order to write

$$(L_{\mathrm{htp}}F)(U) = \mathrm{colim}_{V \in \mathrm{VBT}/U} F(V).$$

Since $F(V) \rightarrow G(V)$ is an equivalence for each V above, it is clear that $(L_{\mathrm{htp}}F)(U) \rightarrow (L_{\mathrm{htp}}G)(U)$ is an equivalence for each affine U , hence $L_{\mathrm{htp}}F \rightarrow L_{\mathrm{htp}}G$ is a sectionwise equivalence.

Finally, since a sectionwise equivalence of presheaves is a local equivalence, we have that

$$L_{\mathrm{Nis}}L_{\mathrm{htp}}F \rightarrow L_{\mathrm{Nis}}L_{\mathrm{htp}}G$$

is an equivalence of presheaves. Passing to the colimit it is now clear that $F \rightarrow G$ is a motivic equivalence. \square

²⁸Over an affine scheme, vector bundle torsors are just vector bundles. If \mathcal{F} is a vector bundle (considered as a sheaf of modules) over $X = \mathrm{Spec}(A)$, then the underlying scheme is $\mathrm{Spec}_X(\mathrm{Sym}(\mathcal{F}^*))$ which is affine over X , and hence is itself affine over the base.

8. POINTED MOTIVIC SPACES

Notation 8.1. By abuse of notation, if $X \in \mathrm{Sm}_S$, then we also denote by $X \in \mathrm{Spc}(S)$ the motivic space $L_{\mathrm{mot}}h_S$.

Notation 8.2. We denote by $\mathrm{Spc}(S)_*$ the category of pointed motivic spaces. This has a zero object, which we denote by $*$. This comes with an adjunction

$$(-)_+ : \mathrm{Spc}(S) \rightleftarrows \mathrm{Spc}(S)_* : U,$$

where X_+ is the coproduct $X \amalg S$, pointed at that copy of S , and the right adjoint forgets the basepoint.

Notation 8.3. If $Y \rightarrow X$ is a map of (pointed) motivic spaces, we denote by X/Y the cofiber, computed as the pushout

$$\begin{array}{ccc} Y & \longrightarrow & X \\ \downarrow & & \downarrow \\ * & \longrightarrow & X/Y. \end{array}$$

We denote by $X \vee Y$ the coproduct in the category $\mathrm{Spc}(S)_*$ of pointed motivic spaces, and by

$$X \wedge Y = \frac{X \times Y}{X \vee Y}$$

the *smash product*.

Notation 8.4. Since $\mathrm{Spc}(S)_*$ has a zero object, we can denote by ΣX the pushout

$$\begin{array}{ccc} X & \longrightarrow & * \\ \downarrow & \lrcorner & \downarrow \\ * & \longrightarrow & \Sigma X, \end{array}$$

for any motivic space X .

Proposition 8.5. If X is a pointed motivic space, then there is a canonical equivalence

$$\Sigma X \simeq S^1 \wedge X.$$

Proof. Since L_{mot} preserves coproducts and $\mathrm{PSh}(\mathrm{Sm}_S)$ is cocomplete, it suffices to compute the pushout at the level of simplicial presheaves. In this setting, the coproduct is computed levelwise, in which case it is clear that $\Sigma X(U) = S^1 \wedge X(U)$ for any $U \in \mathrm{Sm}_S$. Hence as pointed presheaves, we have that $\Sigma X \simeq S^1 \wedge X$. Finally, L_{mot} preserves the smash product construction since it preserves finite products, as well as coproducts and cofibers. \square

By descent, Nisnevich covers of schemes give rise to colimits of motivic spaces. One of the most immediate examples is the following:

Example 8.6. The following diagram of (pointed) motivic spaces is a pushout:

$$\begin{array}{ccc} \mathbb{G}_m & \xrightarrow{z} & \mathbb{A}^1 \\ z^{-1} \downarrow & & \downarrow \\ \mathbb{A}^1 & \longrightarrow & \mathbb{P}^1. \end{array}$$

Since $\mathbb{A}^1 \xrightarrow{\sim} *$ is trivial, and since all our colimits are ∞ -colimits, we can replace the above diagram with the weakly equivalent span $* \leftarrow \mathbb{G}_m \rightarrow \mathbb{G}_m$ and compute the same colimit. This implies that the natural map

$$(7) \quad \Sigma \mathbb{G}_m \xrightarrow{\sim} \mathbb{P}^1$$

is a motivic equivalence.

8.1. Motivic spheres.

Terminology 8.8. We have *two kinds of spheres* in motivic homotopy theory: ones coming from algebraic geometry (the multiplicative group scheme \mathbb{G}_m or the projective line \mathbb{P}^1) and ones coming from algebraic topology (the constant presheaf at S^1 or at S^n for any n). So we get bigradings on the spheres. There are competing conventions in the literature for motivic grading, but the increasingly standardized convention is to write

$$\begin{aligned} S^{1,1} &:= \mathbb{G}_m \\ S^{1,0} &= S^1 \\ S^{2,1} &= \mathbb{P}^1. \end{aligned}$$

Example 8.9. We have that $S^1 \simeq \mathbb{A}^1 / \{0, 1\}$.

Proof. We can consider the cofiber diagram

$$\begin{array}{ccc} S^0 & \xrightarrow{(0,1)} & \mathbb{A}^1 \\ \downarrow & \lrcorner & \downarrow \\ * & \longrightarrow & S^1. \end{array}$$

□

Exercise 8.10. The diagram

$$\begin{array}{ccc} X \times Y & \longrightarrow & X \\ \downarrow & \lrcorner & \downarrow \\ Y & \longrightarrow & \Sigma(X \wedge Y) \end{array}$$

is a pushout.

Proposition 8.11. There is a motivic equivalence

$$\mathbb{A}^n \setminus \{0\} \simeq (S^1)^{\wedge(n-1)} \wedge (\mathbb{G}_m)^{\wedge n} = S^{2n-1,n}.$$

Corollary 8.12. We have that

$$\frac{\mathbb{A}^n}{\mathbb{A}^n \setminus \{0\}} \simeq S^{2n,n}.$$

Proposition 8.13. We have that

$$\frac{\mathbb{P}^n}{\mathbb{P}^n - 0} \simeq S^{n,n}.$$

Proof. By covering \mathbb{P}^n with \mathbb{A}^n and $\mathbb{P}^n \setminus \{0\}$, we get a pushout diagram

$$\begin{array}{ccc} \mathbb{A}^n \setminus \{0\} & \longrightarrow & \mathbb{P}^n \setminus \{0\} \\ \downarrow & \lrcorner & \downarrow \\ \mathbb{A}^n & \longrightarrow & \mathbb{P}^n. \end{array}$$

The cofibers of the vertical maps are equivalent, yielding

$$S^{2n,n} \xrightarrow{\sim} \frac{\mathbb{P}^n}{\mathbb{P}^n - 0}.$$

□

9. \mathbb{A}^1 -HOMOTOPY CLASSES OF MAPS

Given two simplicial presheaves $F, G \in \text{PSh}(\text{Sm}_S)$, by abuse of notation we denote by $[F, G]_{\mathbb{A}^1}$ homotopy classes of maps of their associated motivic localizations

$$[F, G]_{\mathbb{A}^1} := \pi_0 \text{Map}_{\text{Spc}(S)}(L_{\text{mot}} F, L_{\text{mot}} G).$$

A goal is to understand how to compute this. There are some easy cases first:

Example 9.1. Let X be a representable sheaf and \mathcal{Y} be a motivic space. Then via the Yoneda lemma, we have

$$\text{Map}_{\text{Spc}(S)}(L_{\text{mot}} h_X, \mathcal{Y}) \cong \text{Map}_{\text{PSh}(\text{Sm}_S)}(h_X, \mathcal{Y}) \cong \mathcal{Y}(X).$$

Hence $[X, \mathcal{Y}]_{\mathbb{A}^1} = \pi_0 \mathcal{Y}(X)$.

Example 9.2. We have a bijection

$$[X, \mathbb{G}_m]_{\mathbb{A}^1} = \mathbb{G}_m(X)$$

for any $X \in \text{Sm}_S$.

Example 9.3. If X and Y are both varieties, then

$$[X, Y]_{\mathbb{A}^1} = \pi_0(L_{\text{mot}} h_Y)(X).$$

This is much harder to access in general.

9.1. Connected components. Given a motivic space X , we can consider the presheaf of sets

$$\begin{aligned} \text{Sm}_S^{\text{op}} &\rightarrow \text{Set} \\ U &\mapsto [U, X]_{\mathbb{A}^1}. \end{aligned}$$

Its sheafification is called the *sheaf of connected components*, and we denote it by

$$\pi_0^{\mathbb{A}^1}(X) \in \text{Shv}_{\text{Nis}}(\text{Sm}_k).$$

Note 9.4. We have that $\pi_0^{\mathbb{A}^1}(X) = \pi_0(X)$ is the same as the homotopy sheaf in the sheaf topos, provided X is a motivic space. We have to be a bit careful what we mean here — if F is an arbitrary presheaf, then $\pi_0(F)$ will mean $\pi_0(L_{\text{Nis}} F)$ by convention, while $\pi_0^{\mathbb{A}^1} F$ will mean $\pi_0(L_{\text{mot}} F)$.

Proposition 9.5. For $n \geq 3$, we have that $\pi_0^{\mathbb{A}^1}(\text{SL}_n) \simeq *$.

Proof. First suppose M is an elementary matrix. Then there is a map

$$\mathbb{A}^1 \rightarrow \text{SL}_n,$$

sending 0 to the identity and 1 to M . Since SL_n is generated by elementary matrices for $n \geq 3$, the result follows. \square

Definition 9.6. If (X, x) is a pointed motivic space, we have that $\pi_n^{\mathbb{A}^1}(X, x)$ is defined to be the Nisnevich presheaf of

$$U \mapsto [\Sigma^n U_+, X]_{\text{Spc}(S)_*}.$$

Proposition 9.7. If (X, x) is a motivic space, then $\pi_n^{\mathbb{A}^1}(X, x) = \pi_n(X, x)$.

Proof. We show the presheaves are identical before sheafifying. By adjunction we have that

$$[\Sigma^n U_+, X]_{\text{Spc}(S)_*} \cong [U_+, \Omega^n X]_{\text{Spc}(S)_*} = [U, \Omega^n X]_{\text{Spc}(S)}.$$

The latter is the presheaf attached to $\pi_n(X, x)$ by **Proposition 5.34**. \square

Proposition 9.8. Let $f: F \rightarrow G$ be a map of simplicial presheaves. Then it is a motivic equivalence if and only if

$$\pi_n^{\mathbb{A}^1}(f): \pi_n^{\mathbb{A}^1}(F, x) \rightarrow \pi_n^{\mathbb{A}^1}(G, f(x))$$

is an equivalence for all $n \geq 0$ and all basepoints $x \in F$.

Proof. The forward direction is clear, since f being a motivic equivalence would induce a natural isomorphism $[-, X]_{\mathbb{A}^1} \cong [-, Y]_{\mathbb{A}^1}$, hence the associated homotopy (pre)sheaves would be identical. For the backwards direction, this condition on homotopy groups unwinds to tell us that $L_{\text{mot}} F \rightarrow L_{\text{mot}} G$ is an equivalence of sheaves by ??, which in particular implies it is an equivalence of motivic spaces. \square

Terminology 9.9. We say that a motivic space X is \mathbb{A}^1 - n -connected if $\pi_i^{\mathbb{A}^1}(X, x)$ is trivial for all $i \leq n$ and all basepoints. Some special cases:

$$\begin{aligned} \mathbb{A}^1\text{-connected} &= \mathbb{A}^1\text{-0-connected} \\ \mathbb{A}^1\text{-simply connected} &= \mathbb{A}^1\text{-1-connected} \\ \mathbb{A}^1\text{-contractible} &= \mathbb{A}^1\text{-}\infty\text{-connected.} \end{aligned}$$

Example 9.10. We have that $S^{i,j}$ is \mathbb{A}^1 -($i-1$)-connected (see [AO19, 2.4.5]).

10. STRONG AND STRICT \mathbb{A}^1 -INVARIANCE

Goal 10.1. We have seen that in order to check a map is a motivic equivalence, it suffices to look at homotopy sheaves. We'd therefore like to better understand when homotopy sheaves are equivalent. It turns out homotopy sheaves (for $n \geq 2$) are a prototypical example of a particularly nice class of sheaves of abelian groups called *strictly invariant* sheaves. These have nice properties that make them easier to work with.

Note that $\pi_n^{\mathbb{A}^1}(X)$ is a Nisnevich sheaf of sets, but it is not necessarily a motivic space. We can ask to what extent it is \mathbb{A}^1 -invariant.

It was conjectured by Morel that $\pi_0^{\mathbb{A}^1}(X)$ was always \mathbb{A}^1 -invariant, but a counterexample was found by Ayoub (todo). Nevertheless we can ask for $\pi_i^{\mathbb{A}^1}(X)$ for $i \geq 1$. A more general question is to understand conditions that tell us a sheaf of groups is invariant.

Let \mathcal{G} denote a Nisnevich sheaf of groups. Since $\mathcal{G}(X) = H_{\text{Nis}}^0(X, \mathcal{G})$, the condition that \mathcal{G} is \mathbb{A}^1 -invariant is equivalent to asking whether

$$H^0(X; \mathcal{G}) \rightarrow H^0(X \times \mathbb{A}^1; \mathcal{G})$$

is \mathbb{A}^1 -invariant.

Definition 10.2. Let \mathcal{G} be a Nisnevich sheaf of groups over S . Then we say

- (1) \mathcal{G} is \mathbb{A}^1 -invariant if $H^0(X; \mathcal{G}) \rightarrow H^0(X \times \mathbb{A}^1; \mathcal{G})$ is an equivalence for every $X \in \text{Sm}_S$
- (2) \mathcal{G} is *strongly* \mathbb{A}^1 -invariant if

$$H^i(X; \mathcal{G}) \rightarrow H^i(X \times \mathbb{A}^1; \mathcal{G})$$

is an equivalence for $i = 0, 1$ and for all X

- (3) if \mathcal{G} is a sheaf of abelian groups, we say it is *strictly* \mathbb{A}^1 -invariant if

$$H^i(X; \mathcal{G}) \rightarrow H^i(X \times \mathbb{A}^1; \mathcal{G})$$

is an equivalence for all i and for all X .

Example 10.3. We have that \mathbb{G}_m is strongly invariant, since both units and the Picard group are \mathbb{A}^1 -invariant over a base field.

Example 10.4. The additive group $\mathbb{G}_a = (\mathbb{A}^1, +)$ is not \mathbb{A}^1 -invariant.

Theorem 10.5. Let $f: F \rightarrow G$ be a morphism of strictly invariant sheaves on Sm_k , where k is a perfect field. Then f is an isomorphism if and only if

$$f(L): F(L) \rightarrow G(L)$$

is an equivalence for every finitely generated (separable) field extension L/k .

Proof. See [Hoy15, 2.7] for this statement, and [Mor12, 2.3, 2.8] for the proof. \square

Corollary 10.6. Let $f: X \rightarrow Y$ be a map of motivic spaces in $\mathrm{Spc}(k)$, for k perfect. Then it is an equivalence if and only if it induces an isomorphism on π_0 , and for $n \geq 1$ and every finitely generated field extension L/k we have that

$$\pi_n(X, x)(L) \rightarrow \pi_n(Y, y)(L)$$

is an equivalence.

Theorem 10.7. (Morel) If X is a motivic space over a field k , then $\pi_1^{\mathbb{A}^1}(X)$ is strongly \mathbb{A}^1 -invariant.

Theorem 10.8. (Morel) If k is a perfect field, and \mathcal{A} is a sheaf of abelian groups on Sm_k , then it is strong if and only if it is strict.

The proof of these theorems is hard — to see them worked out in detail we refer the reader to an amazing recent survey paper of Bachmann [Bac24].

Assumption 10.9. From here on out, we'll assume k is a perfect field, so that we can access these results.

Corollary 10.10. If $X \in \mathrm{Spc}(k)_*$, then $\pi_n^{\mathbb{A}^1}(X)$ is strictly invariant for $n \geq 2$ and strongly invariant for $n = 1$.

Proof. We apply **Theorem 10.7** to $\Omega^{n-1}X$ and get that

$$\pi_n(X) = \pi_1(\Omega X)$$

is strongly invariant, which is strictly invariant for $n > 1$ by **Theorem 10.8**. \square

Theorem 10.11. [MV99, §3.22] (c.f. [AD09, 2.7]) For any $F \in \mathrm{Shv}_{\mathrm{Nis}}(\mathrm{Sm}_k)$, the map to its singularization $F \rightarrow \mathrm{Sing}(F)$ induces a surjection on π_0 .

Corollary 10.12. (c.f. [Bac24, 1.2]) If $F \in \mathrm{Shv}_{\mathrm{Nis}}(\mathrm{Sm}_k)$ is connected, then so is $L_{\mathrm{mot}}F$.

Proof. Homotopy sheaves commute with filtered colimits, so we have that

$$\pi_0 L_{\mathrm{mot}}X = \mathrm{colim}(\pi_0 L_{\mathrm{Nis}}X \rightarrow \pi_0 L_{\mathrm{Nis}}L_{\mathbb{A}^1}L_{\mathrm{Nis}}X \rightarrow \cdots).$$

Since the colimit will be a quotient of the sheaf $\pi_0 X$, which is trivial, the result follows \square

This is the $n = 0$ of the *unstable connectivity theorem*, which says that if F is n -connected then so is $L_{\mathrm{mot}}F$. We will come back to prove this.

APPENDIX A. MORE CATEGORY THEORY

A.1. Cofinality.

Definition A.1. We say a subcategory $I \subseteq J$ is *cofinal* if for any functor $F: J \rightarrow \mathcal{C}$, the induced map on colimits

$$(2) \quad \operatorname{colim}_I F \rightarrow \operatorname{colim}_J F$$

is an isomorphism.²⁹ In other words, in order to compute a J -shaped colimit, it suffices to restrict to the subdiagram $I \subseteq J$.

Remark A.3. This definition makes sense in 1-category theory as well as it does in ∞ -category theory, however we remark that the two notions are different, so let's differentiate between the two, continuing the story of [Definition A.1](#):

- ▷ $I \subseteq J$ is *1-cofinal* if for any 1-category \mathcal{C} and 1-functor $F: J \rightarrow \mathcal{C}$, the induced map [Equation 2](#) is an isomorphism.
- ▷ $I \subseteq J$ is *cofinal* (∞ -cofinal if we want to be really pedantic) if for any ∞ -category and ∞ -functor $F: J \rightarrow \mathcal{C}$, the induced map [Equation 2](#) is an equivalence.

Note this latter definition extends to the case where I and J are themselves ∞ -categories, or even just simplicial sets.

It is straightforward to check when a subdiagram is 1-cofinal:

Proposition A.4. [[Stacks](#), 04E6] $I \subseteq J$ is 1-cofinal if

- ▷ every $j \in J$ has some $i \in I$ with a morphism $j \rightarrow i$
- ▷ for every $j \in J$ and pair of objects $i, i' \in I$, there is a zig-zag of morphisms between $i, i' \in I$ and maps from j into the zig-zag making the diagram commute:

$$\begin{array}{ccccccc} & & j & & & & \\ & \swarrow & \downarrow & \searrow & & & \\ \cdots & \longrightarrow & i_n & \longleftarrow & i_{n+1} & \longrightarrow & i_{n+2} \longleftarrow \cdots \end{array}$$

Notation A.5. Let $\Delta^{\operatorname{inj}} \subseteq \Delta$ be the subcategory of injective maps, and let $\Delta_{\leq n} \subseteq \Delta$ denote the full subcategory of objects $[k]$ for $k \leq n$. For example $\Delta_{\leq 1}^{\operatorname{inj}}$ is just a the category with two parallel arrows, i.e. the “(co)equalizer” category:

$$\Delta_{\leq 1}^{\operatorname{inj}} := \bullet \rightrightarrows \bullet$$

Example A.6. We have that $\Delta_{\leq 1}^{\operatorname{inj}, \operatorname{op}} \subseteq \Delta^{\operatorname{op}}$ is 1-cofinal (c.f. [[Rie14](#), 8.3.8]).

Proposition A.7. The inclusion $\Delta_{\leq n}^{\operatorname{inj}, \operatorname{op}} \subseteq \Delta^{\operatorname{op}}$ is n -cofinal for any $1 \leq n \leq \infty$.

It turns out by a souped-up extension of Quillen Theorem A, originally due to Joyal, we have a necessary condition for cofinality in the ∞ -categorical setting.

Theorem A.8. (Joyal, Quillen) Let $f: I \rightarrow J$ be a functor of 1-categories which is (∞) -cofinal. Then the induced map on classifying spaces

$$BI \rightarrow BJ$$

is a weak homotopy equivalence [[Lur09](#), 4.1.3.1, 4.1.3.3].

Example A.9. The same subcategory $\Delta_{\leq 1}^{\operatorname{inj}, \operatorname{op}} \subseteq \Delta^{\operatorname{op}}$ is *not* ∞ -cofinal.

²⁹We dually say $I \subseteq J$ is *final* if the natural map $\lim_I F \rightarrow \lim_J F$ is an isomorphism for any F .

Proof. The classifying space of the coequalizer diagram is S^1 , however since $[0] \in \Delta$ is terminal, it is initial in Δ^{op} , hence $B\Delta^{\text{op}} \simeq *$ is contractible. \square

Remark A.10. Removing this injectivity hypothesis is also interesting, since we include the opposite of the map $[1] \rightarrow [0]$ — the category $\Delta_{\leq 1}^{\text{op}}$ is the *split coequalizer* category:

$$\bullet \begin{array}{c} \xrightarrow{\quad} \\ \xleftarrow{\quad} \end{array} \bullet$$

Proposition A.11. Each of the composites

$$\Delta_{\leq 1}^{\text{inj, op}} \subseteq \Delta_{\leq 1}^{\text{op}} \subseteq \Delta^{\text{op}}$$

is 1-cofinal, however none of these inclusions are ∞ -cofinal.

Proof. The universal property of the 1-categorical colimit for both $\Delta_{\leq 1}^{\text{inj, op}}$ and $\Delta_{\leq 1}^{\text{op}}$ agree, so this is direct. The other inclusion now follows by [Example A.6](#). \square

In general we cannot truncate in order to obtain an ∞ -cofinal diagram. We can, however, restrict only to face maps and throw out degeneracies:

Lemma A.12. [[Lur09](#), 6.5.3.7] The inclusion $\Delta^{\text{inj, op}} \subseteq \Delta$ is cofinal.

Definition A.13. An ∞ -category \mathcal{C} is *sifted* if the diagonal map $\mathcal{C} \rightarrow \mathcal{C} \times \mathcal{C}$ is cofinal [[Lur09](#), 5.5.8.1].

Proposition A.14. Sifted colimits valued in Set commute with finite limits.

Remark A.15. In the 1-categorical setting, the converse of [Proposition A.14](#) holds, meaning we can take this to be the definition of sifted colimits.

Example A.16.

- (1) The category Δ^{op} is sifted
- (2) Any filtered category is sifted

The examples above are the only interesting examples, in the following more precise sense.

Proposition A.17. A category \mathcal{C} admits all sifted colimits if and only if it admits all filtered colimits and it admits geometric realizations (meaning Δ^{op} -indexed colimits).

Corollary A.18. A 1-category admits all sifted colimits if and only if it admits all filtered colimits and it has coequalizers.

Proof. Δ^{op} -indexed colimits are just coequalizers in 1-categories by [Example A.6](#). \square

APPENDIX B. ESSENTIAL SMALLNESS

Being small is not a property of categories that is invariant under equivalence, so it is more meaningful to ask whether a category is *essentially small* (whether it is equivalent to a small category). This is equivalent to a category admitting a small skeleton, although the axiom of choice is required in order to pick representatives for each isomorphism class of object.

Theorem B.1. The category of finite type S -schemes is essentially small.

Proof sketch. (see [MO251044](#) for details) If $S = \text{Spec}(A)$ is affine, then the category $\text{Alg}_A^{\text{f.t.}}$ of finite type A -algebras is essentially small, since all the objects are isomorphic to algebras of the form $A[x_1, \dots, x_n]/(f_1, \dots, f_r)$, of which there are a set. We can glue finite type S -schemes over affines, and then bootstrap to the more general case of the base S not being affine by gluing finite type schemes over all affine subschemes of S . \square

Remark B.2. The category of all S -schemes is not essentially small.

REFERENCES

- [AD09] Aravind Asok and Brent Doran. *A^1 -homotopy groups, excision, and solvable quotients*. 2009. arXiv: [0902.1564 \[math.AG\]](#).
- [AF14] Aravind Asok and Jean Fasel. “Algebraic vector bundles on spheres”. In: *Journal of Topology* 7.3 (Feb. 2014), pp. 894–926.
- [AHW18] Aravind Asok, Marc Hoyois, and Matthias Wendt. “Affine representability results in A^1 -homotopy theory, II: Principal bundles and homogeneous spaces”. In: *Geom. Topol.* 22.2 (2018), pp. 1181–1225.
- [AHW20] Aravind Asok, Marc Hoyois, and Matthias Wendt. “Affine representability results in A^1 -homotopy theory III: finite fields and complements”. In: *Algebr. Geom.* 7.5 (2020), pp. 634–644.
- [AO19] Aravind Asok and Paul Arne Østvær. *A^1 -homotopy theory and contractible varieties: a survey*. 2019. arXiv: [1903.07851 \[math.AG\]](#).
- [Aso21] Aravind Asok. *Algebraic geometry from an A^1 -homotopic viewpoint*. 2021.
- [Bac] Tom Bachmann. *Algebraic K-theory from the viewpoint of motivic homotopy theory*.
- [Bac24] Tom Bachmann. *Strongly A^1 – invariantsheaves(after F. Morel)*. 2024. arXiv: [2406.11526 \[math.AG\]](#).
- [Del74] Pierre Deligne. “Théorie de Hodge. III”. In: *Inst. Hautes Études Sci. Publ. Math.* 44 (1974), pp. 5–77.
- [Dug01] Daniel Dugger. “Universal homotopy theories”. In: *Adv. Math.* 164.1 (2001), pp. 144–176.
- [Fri82] Eric M. Friedlander. *Étale homotopy of simplicial schemes*. Vol. No. 104. Annals of Mathematics Studies. Princeton University Press, Princeton, NJ; University of Tokyo Press, Tokyo, 1982, pp. vii+190.
- [Ful98] William Fulton. *Intersection theory*. Second. Vol. 2. Ergebnisse der Mathematik und ihrer Grenzgebiete. 3. Folge. A Series of Modern Surveys in Mathematics [Results in Mathematics and Related Areas. 3rd Series. A Series of Modern Surveys in Mathematics]. Springer-Verlag, Berlin, 1998, pp. xiv+470.
- [GJ99] Paul G. Goerss and John F. Jardine. *Simplicial homotopy theory*. Vol. 174. Progress in Mathematics. Birkhäuser Verlag, Basel, 1999, pp. xvi+510.
- [Gro] Alexandre Grothendieck. “Torsion homologique et sections rationnelles”. fr. In: ().
- [Hal] Connor Halleck-Dubé. *Some remarks on Galois cohomology and linear algebraic groups*.
- [Har77] Robin Hartshorne. *Algebraic geometry*. Vol. No. 52. Graduate Texts in Mathematics. Springer-Verlag, New York-Heidelberg, 1977, pp. xvi+496.
- [Hol08] Sharon Hollander. “A homotopy theory for stacks”. In: *Israel J. Math.* 163 (2008), pp. 93–124.
- [Hoy14] Marc Hoyois. “A quadratic refinement of the Grothendieck-Lefschetz-Verdier trace formula”. In: *Algebr. Geom. Topol.* 14.6 (2014), pp. 3603–3658.
- [Hoy15] Marc Hoyois. “From algebraic cobordism to motivic cohomology”. In: *J. Reine Angew. Math.* 702 (2015), pp. 173–226.
- [Hoy17] Marc Hoyois. “The six operations in equivariant motivic homotopy theory”. In: *Adv. Math.* 305 (2017), pp. 197–279.
- [Lur] Jacob Lurie. *Spectral algebraic geometry*.
- [Lur09] Jacob Lurie. *Higher topos theory*. Vol. 170. Annals of Mathematics Studies. Princeton University Press, Princeton, NJ, 2009, pp. xviii+925.
- [Mil13] James S. Milne. *Lectures on Étale Cohomology (v2.21)*. Available at www.jmilne.org/math/. 2013.
- [Mil15] James S. Milne. *Algebraic Groups (v2.00)*. Available at www.jmilne.org/math/. 2015.
- [Mor12] Fabien Morel. *A^1 -Algebraic Topology over a Field*. en. Vol. 2052. Lecture Notes in Mathematics. Berlin, Heidelberg: Springer Berlin Heidelberg, 2012.

- [MV99] Fabien Morel and Vladimir Voevodsky. “ \mathbf{A}^1 -homotopy theory of schemes”. In: *Inst. Hautes Études Sci. Publ. Math.* 90 (1999), pp. 45–143.
- [Rie14] Emily Riehl. *Categorical homotopy theory*. Vol. 24. New Mathematical Monographs. Cambridge University Press, Cambridge, 2014, pp. xviii+352.
- [Stacks] The Stacks Project Authors. *Stacks Project*. <https://stacks.math.columbia.edu>. 2018.
- [Tra70] Carlo Traverso. “Seminormality and Picard group”. In: *Ann. Scuola Norm. Sup. Pisa Cl. Sci. (3)* 24 (1970), pp. 585–595.
- [Wei89] Charles A. Weibel. “Homotopy algebraic K -theory”. In: *Algebraic K-theory and algebraic number theory (Honolulu, HI, 1987)*. Vol. 83. Contemp. Math. Amer. Math. Soc., Providence, RI, 1989, pp. 461–488.
- [Wei94] Charles A. Weibel. *An introduction to homological algebra*. Vol. 38. Cambridge Studies in Advanced Mathematics. Cambridge University Press, Cambridge, 1994, pp. xiv+450.
- [You] Alex Youcis. “A brief discussion of torsors”.