

USING THE INTERNAL LANGUAGE OF TOPOSES IN ALGEBRAIC GEOMETRY

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ABSTRACT. There are several important toposes associated to a scheme, for instance the petit and gros Zariski toposes. These support an internal mathematical language which closely resembles the usual formal language of mathematics, but is “local on the base scheme”: For example, from the internal perspective, the structure sheaf looks like an ordinary local ring (instead of a sheaf of rings with local stalks) and vector bundles look like ordinary free modules (instead of sheaves of modules satisfying a certain condition). The translation of internal statements and proofs is facilitated by an easy mechanical procedure.

These expository notes give an introduction to this topic and show how the internal point of view can be exploited to give simpler definitions and more conceptual proofs of the basic notions and observations in algebraic geometry. We also employ this framework to study the phenomenon that some properties spread from points to open neighbourhoods. We give a general sufficient condition for this spreading to occur, depending only on the logical form of the property in question.

No prior knowledge about topos theory or formal logic is assumed.

Rough draft in progress, missing explanations, references, proofs, and a proper copyediting. I am happy about comments of any kind; please direct them to
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1. INTRODUCTION

Internal language of toposes. A *topos* is a category which shares certain categorical properties with the category of sets; the archetypical example is the category of sets, and the most important example for the purposes of these notes is the category of set-valued sheaves on a topological space.

Any topos \mathcal{E} supports an *internal language*. This is a device which allows one to *pretend* that the objects of \mathcal{E} are plain sets and that the morphisms are plain maps between sets, even if in fact they are not. For instance, consider a morphism $\alpha : X \rightarrow Y$ in \mathcal{E} . From the *internal point of view*, this looks like a map between sets, and we can formulate the condition that this map is surjective; we write this as

$$\mathcal{E} \models \forall y : Y. \exists x : X. \alpha(x) = y.$$

The appearance of the colons instead of the usual element signs reminds us that this expression is not to be taken literally – X and Y are objects of \mathcal{E} and thus not necessarily sets. The definition of the internal language is made in such a way so that the meaning of this internal statement is that α is an epimorphism. Similarly, the translation of the internal statement that α is injective is that α is a monomorphism.

Furthermore, we can *reason* with the internal language. There is a metatheorem to the effect that if some statement φ holds from the internal point of view of a topos \mathcal{E} and if φ logically implies some further statement ψ , then ψ holds in \mathcal{E} as well. As a simple example, consider the elementary fact that the composition of surjective maps is surjective. Interpreting this statement in the internal language of \mathcal{E} , we obtain the more abstract result that the composition of epimorphisms in \mathcal{E} is epic.

There is, however, a slight caveat to this metatheorem. Namely, the internal language of a topos is in general only *intuitionistic*, not *classical*. This means that internally, one can not use the law of excluded middle ($\varphi \vee \neg\varphi$), the law of double negation elimination ($\neg\neg\varphi \Rightarrow \varphi$), or the axiom of choice. For instance, one rendition of the axiom of choice is that any vector space is free. But it need not be the case that a vector space internal to a topos is free as seen from the internal perspective: By the technique explained in these notes, this would imply the absurd statement that any sheaf of modules on a reduced scheme is locally free.

The restriction to intuitionistic reasoning is not as confining as it might first appear. We will discuss its practical consequences below (on page 12).

Algebraic geometry. We apply the internal language of toposes to algebraic geometry as follows. If X is a scheme, the structure sheaf \mathcal{O}_X is a sheaf of rings,

i. e. the sets of local sections carry ring structures and these ring structures are compatible with restriction. From the internal point of view of the topos of set-valued sheaves on X , denoted “ $\mathrm{Sh}(X)$ ” in the following, the structure sheaf \mathcal{O}_X looks much simpler: It looks just like a plain ring (and not a sheaf of rings). Similarly, a sheaf of \mathcal{O}_X -modules looks just like a plain module over that ring.

This allows to import notions and facts from basic linear and commutative algebra into the sheaf setting. For instance, it turns out that a sheaf of \mathcal{O}_X -modules is of finite type if and only if, from the internal perspective, it is finitely generated as an \mathcal{O}_X -module. Now consider the following fact of linear algebra: If in a short exact sequence of modules the two outer ones are finitely generated, then the middle one is too. The usual proof of this fact is intuitionistically acceptable and can thus be interpreted in the internal language. It then *automatically* yields the following more advanced proposition: If in a short exact sequence of sheaves of \mathcal{O}_X -modules the two outer ones are of finite type, then the middle one is too.

This example was not special: *Any (intuitionistically valid) theorem about modules yields a corresponding theorem about sheaves of modules.*

The internal language machinery thus allows us to understand the basic notions and statements of scheme theory as notions and statements of linear and commutative algebra, interpreted in a suitable sheaf topos. This brings conceptual clarity and reduces technical overhead.

In these notes, we explain how the internal language machinery works and then develop a *dictionary* between common notions of scheme theory and corresponding notions of algebra. Once built, this dictionary can be used arbitrarily often. We stress that no in-depth knowledge of topos theory or categorical logic is necessary to apply this apparatus.

Two highlights of our approach are the following. Let X be a reduced scheme and \mathcal{F} be a sheaf of \mathcal{O}_X -modules of finite type. Then it is well-known that \mathcal{F} is locally free on some dense open subset of X ; for instance, this is stated in Ravi Vakil’s lecture notes as an “important hard exercise” [43, Exercise 13.7.K]. In fact, this proposition is just the interpretation of the following statement of intuitionistic linear algebra in the sheaf topos: Any finitely generated vector space is *not not* free. The proof of this statement is entirely straightforward.¹

The second highlight is that we can shed light on the phenomenon that sometimes, truth of a property at a point x spreads to some open neighbourhood of x ; and in particular that sometimes, truth of a property at the generic point spreads to some dense open subset. For instance, if the stalk of a sheaf of finite type is zero at some point, the sheaf is even zero on some open neighbourhood; but this spreading does not occur for general sheaves which may fail to be of finite type.

We formalize this by introducing a *modal operator* \Box into the internal language, such that the internal statement $\Box\varphi$ means that φ holds on some open neighbourhood of x . Furthermore, we introduce a simple operation on formulas, the \Box -translation $\varphi \mapsto \varphi^\Box$, such that φ^\Box means that φ holds at the point x . This translation is defined on a purely syntactical level. The question whether truth at x spreads to

¹Intuitionistically, the statement that any finitely generated vector space is *free* is stronger than the doubly negated version and can not be shown. It would imply that any sheaf of finite type is not only locally free on some dense open subset, but locally free on the whole space. We discuss this example in more detail in Section 5 and in particular in Lemma 5.9.

truth on a neighbourhood can then be formulated in the following way: Does φ^{\Box} intuitionistically imply $\Box\varphi$?

This allows to deal with the question in a simpler, more logical way, with the technicalities of sheaves blinded out. We also give a metatheorem which covers a wide range of cases. Namely, spreading occurs for all those properties which can be formulated in the internal language without using “ \Rightarrow ”, “ \forall ”, and “ \neg ”.

To illustrate the example above, consider the property of a module \mathcal{F} being the zero module. In the internal language, it can be formulated as $(\forall x : \mathcal{F}. x = 0)$. Because of the appearance of “ \forall ”, the metatheorem is not applicable to this statement. But if \mathcal{F} is of finite type, there are generators $x_1, \dots, x_n : \mathcal{F}$ from the internal point of view, and the condition can be reformulated as $x_1 = 0 \wedge \dots \wedge x_n = 0$; the metatheorem is applicable to this statement.

Limitations. The internal language is *local*, in the sense that if $X = \bigcup_i U_i$ is an open covering and an internal statement holds in the sheaf toposes $\mathrm{Sh}(U_i)$, it holds in $\mathrm{Sh}(X)$ as well. On the one hand, this property is very useful. But on the other hand, it gives an inherent limitation of the internal language: Global properties of sheaves of modules like “being generated by global sections”, “being ample”, or “having vanishing sheaf cohomology” and global properties of schemes like “being quasicompact” can *not* be expressed in the internal language.

Thus for global considerations, the internal language of $\mathrm{Sh}(X)$ is only useful in that local subparts can be simplified. Also, some global features reflect themselves in certain metaproperties of the internal language. For instance, a scheme is quasicompact if and only if the internal language has a weak version of the so-called disjunction property of mathematical logic (Section 8).

Introductory literature. These notes are intended to be self-contained, requiring only basic knowledge of scheme theory. In particular, we assume no prior familiarity with topos theory or formal logic. But if the interested reader is so inclined, she will find a gentle introduction to topos theory in an article by Tom Leinster [30]. Standard references for the internal language of a topos include the book of Saunders Mac Lane and Ieke Moerdijk [32, Chapter VI], the book of Francis Borceux [9, Chapter 6], and part D of Peter Johnstone’s *Elephant* [25]. In the 1970s, there was a flurry of activity on applications of the internal language. An article by Christopher Mulvey [36] of this time gives a very accessible introduction to the topic, culminating in an internal proof of the Serre–Swan theorem (with just one external ingredient needed).

Related work. The internal language of toposes was applied to algebraic geometry before. For instance, Gavin Wraith used it to construct (and verify the universal property of) the big étale topos of a scheme by internally developing the theory of strict henselization [47]. However, to the best of my knowledge, systematically building a dictionary between external and internal notions has not been attempted before, and the use of modal operators to study the spreading of properties from points to neighbourhoods seems to be new as well.

Brandenburg put forward a related program of internalization in his PhD thesis [10]. However, he internalizes constructions of algebraic geometry not in toposes, but in tensor categories. There is some overlap in working out precise universal properties, particularly when dealing with the big Zariski topos (those results are not yet included in these notes).

In other branches of mathematics, the internal language of toposes is used as well. For instance, there is an ongoing effort in mathematical physics to understand quantum mechanical systems from an internal point of view: To any quantum mechanical system, one can associate a so-called Bohr topos containing an internal mirror image of the system. This mirror image looks like a system of classical mechanics from the internal perspective, and therefore tools like Gelfand duality can be used to construct an internal phase space for the system [11, 23].

In stochastics, the usefulness of an internal language was recently stressed by Tao [41]. Such a language makes the common notational practice of dropping the explicit dependence of the value $X(\omega)$ of a random variable on the sample ω completely rigorous and simplifies the basic theory. Tao also highlighted how a suitable language can be used to simplify “ ε/δ management” in analysis [40]. Furthermore, there is a topos-theoretic approach to measure theory, in which the sheaf of measurable real functions on a σ -algebra looks like the ordinary set of real numbers from an internal point of view [24]; this has applications in noncommutative geometry [22].

Intuitionistic methods have found many applications in computer science. Recently, the internal language of a topos of trees and a suitable modal operator was used to study guarded recursion, encompassing, for instance, an internal Banach fixed-point theorem [7].

In constructive mathematics, the internal language of toposes is routinely used to obtain models of intuitionistic theories fulfilling certain anti-classical axioms. For instance, there are toposes in which the axiom “any map $\mathbb{R} \rightarrow \mathbb{R}$ is continuous” (appropriately formulated) holds [29, 35] and toposes in which the Church–Turing thesis holds (realizability toposes). The internal language can also be used to extract computational content out of classical constructions. To cite just one recent example, Mannaa and Coquand used it to implement algorithms for working with the algebraic closure of an arbitrary field of characteristic zero [33].

More specifically, our contribution is related to the program of constructive mathematics in that intuitionistic mathematics gains new areas of application. For instance, the constructive account of the theory of Krull dimension was originally developed to remove Noetherian hypotheses, extract computational meaning, and simplify proofs [17, 16]. It can now also be used to reason about the dimension of schemes, since the topological dimension of a scheme X coincides with the Krull dimension of the structure sheaf \mathcal{O}_X (regarded as an ordinary ring from the internal perspective of $\mathrm{Sh}(X)$, Section 3.4).

Caramello uses topos theory to build bridges between different mathematical subjects, in a certain precise sense [13, 12]. She exploits that toposes can admit presentations by different sites. Since we focus only on a specific presentation of a specific topos associated to a scheme, our contribution is only indirectly related to her’s.

XXX: mention and explain: Mulvey/Burden, Vickers, Awodey, Coquand, ...

XXX: uses of the big Zariski topos, étale versions, further work, ...

Notational convention. Occasionally, when quantifying, we use colons instead of element signs not only in internal statements, but also in external ones; particularly if we want to stress that a discussion takes place in an intuitionistic context.

- dictionary; microscope/telescope into another universe; types instead of sets; (dependent types to encompass almost all mathematics)
- explain that with the internal language business, it becomes more transparent where scheme condition enters

2. THE INTERNAL LANGUAGE OF A SHEAF TOPOS

2.1. Internal statements. Let X be a topological space. Later, X will be the underlying space of a scheme. The meaning of internal statements is given by a set of rules, the *Kripke–Joyal semantics* of the topos of sheaves on X .

Definition 2.1. The meaning of

$$U \models \varphi \quad (\text{“}\varphi \text{ holds on } U\text{”})$$

for open subsets $U \subseteq X$ and formulas φ over U is given by the rules listed in Table 1, recursively in the structure of φ . In a *formula over* U there may appear sheaves defined on U as domains of quantifications, U -sections of sheaves as terms, and morphisms of sheaves on U as function symbols. The symbols “ \top ” and “ \perp ” denote truth and falsehood, respectively. The universal and existential quantifiers come in two flavors: for bounded and unbounded quantification. The translation of $U \models \neg\varphi$ does not have to be separately defined, since negation can be expressed using other symbols: $\neg\varphi \equiv (\varphi \Rightarrow \perp)$. If we want to emphasize the particular topos, we write

$$\mathrm{Sh}(X) \models \varphi \quad :\Longleftrightarrow \quad X \models \varphi.$$

Remark 2.2. The last two rules in Table 1, concerning *unbounded quantification*, and are not part of the classical Kripke–Joyal semantics. They are part of Mike Shulman’s stack semantics [38], a slight extension. They are needed so that we can formulate universal properties in the internal language.

Example 2.3. Let $\alpha : \mathcal{F} \rightarrow \mathcal{G}$ be a morphism of sheaves on X . Then α is a monomorphism of sheaves if and only if, from the internal perspective, α is simply an injective map:

$$\begin{aligned} X &\models \ulcorner \alpha \text{ is injective } \urcorner \\ \Longleftrightarrow X &\models \forall s : \mathcal{F}. \forall t : \mathcal{F}. \alpha(s) = \alpha(t) \Rightarrow s = t \\ \Longleftrightarrow &\text{for all open } U \subseteq X, \text{ sections } s \in \Gamma(U, \mathcal{F}): \\ &\text{for all open } V \subseteq U, \text{ sections } t \in \Gamma(V, \mathcal{F}): \\ &V \models \alpha(s) = \alpha(t) \Rightarrow s = t \\ \Longleftrightarrow &\text{for all open } U \subseteq X, \text{ sections } s \in \Gamma(U, \mathcal{F}): \\ &\text{for all open } V \subseteq U, \text{ sections } t \in \Gamma(V, \mathcal{F}): \\ &\text{for all open } W \subseteq V: \\ &\alpha_W(s|_W) = \alpha_W(t|_W) \text{ implies } s|_W = t|_W \\ \Longleftrightarrow &\text{for all open } U \subseteq X, \text{ sections } s, t \in \Gamma(U, \mathcal{F}): \\ &\alpha_U(s|_U) = \alpha_U(t|_U) \text{ implies } s|_U = t|_U \\ \Longleftrightarrow &\alpha \text{ is a monomorphism of sheaves} \end{aligned}$$

$U \models s = t : \mathcal{F}$	$:\iff$	$s _U = t _U \in \Gamma(U, \mathcal{F})$
$U \models s \in \mathcal{G}$	$:\iff$	$s _U \in \Gamma(U, \mathcal{G})$ (\mathcal{G} a subsheaf of \mathcal{F} , s a section of \mathcal{F})
$U \models \top$	$:\iff$	$U = U$ (always fulfilled)
$U \models \perp$	$:\iff$	$U = \emptyset$
$U \models \varphi \wedge \psi$	$:\iff$	$U \models \varphi$ and $U \models \psi$
$U \models \bigwedge_{j \in J} \varphi_j$	$:\iff$	for all $j \in J$: $U \models \varphi_j$ (J an index set)
$U \models \varphi \vee \psi$	$:\iff$	$U \models \varphi$ or $U \models \psi$ there exists a covering $U = \bigcup_i U_i$ such that for all i : $U_i \models \varphi$ or $U_i \models \psi$
$U \models \bigvee_{j \in J} \varphi_j$	$:\iff$	$U \models \varphi_j$ for some $j \in J$ (J an index set) there exists a covering $U = \bigcup_i U_i$ such that for all i : $U_i \models \varphi_j$ for some $j \in J$
$U \models \varphi \Rightarrow \psi$	$:\iff$	for all open $V \subseteq U$: $V \models \varphi$ implies $V \models \psi$
$U \models \forall s : \mathcal{F}. \varphi(s)$	$:\iff$	for all sections $s \in \Gamma(V, \mathcal{F})$, open $V \subseteq U$: $V \models \varphi(s)$
$U \models \exists s : \mathcal{F}. \varphi(s)$	$:\iff$	there exists a section $s \in \Gamma(U, \mathcal{F})$ such that $U \models \varphi(s)$ there exists an open covering $U = \bigcup_i U_i$ such that for all i : there exists $s_i \in \Gamma(U_i, \mathcal{F})$ such that $U_i \models \varphi(s_i)$
$U \models \forall \mathcal{F}. \varphi(\mathcal{F})$	$:\iff$	for all sheaves \mathcal{F} on V , open $V \subseteq U$: $V \models \varphi(\mathcal{F})$
$U \models \exists \mathcal{F}. \varphi(\mathcal{F})$	$:\iff$	there exists an open covering $U = \bigcup_i U_i$ such that for all i : there exists a sheaf \mathcal{F}_i on U_i such that $U_i \models \varphi(\mathcal{F}_i)$

TABLE 1. The Kripke–Joyal semantics of a sheaf topos.

The corner quotes “ $\ulcorner \dots \urcorner$ ” indicate that translation into formal language is left to the reader. Similarly, α is an epimorphism of sheaves if and only if, from the internal perspective, α is a surjective map. Notice that injectivity and surjectivity are notions of a simple element-based language. The Kripke–Joyal semantics takes care to properly handle *all* sections, not only global ones.

The rules are not all arbitrary. They are finely concerted to make the following propositions true, which are crucial for a proper appreciation of the internal language.

Proposition 2.4 (Locality of the internal language). *Let $U = \bigcup_i U_i$ be covered by open subsets. Let φ be a formula over U . Then*

$$U \models \varphi \quad \text{iff} \quad U_i \models \varphi \text{ for each } i.$$

Proof. Induction on the structure of φ . Note that the canceled rules would make this proposition false. \square

As a corollary, one may restrict the open coverings and universal quantifications in the the definition of the Kripke–Joyal semantics (Table 1) to open subsets of some basis of the topology. For instance, if X is a scheme, one may restrict to affine open subsets.

Furthermore, the proposition shows that the internal language is monotone in the following sense: If $U \models \varphi$, and V is an open subset of U , then $V \models \varphi$. (This follows by applying the proposition to the trivial covering $U = V \cup U$.)

Proposition 2.5 (Soundness of the internal language). *If a formula φ implies a further formula ψ in intuitionistic logic, then $U \models \varphi$ implies $U \models \psi$.*

Proof. Proof by induction on the structure of formal intuitionistic proofs; we are to show that any inference rule of intuitionistic logic is satisfied by the Kripke–Joyal semantics. For instance, there is the following rule governing disjunction:

If $\varphi \vee \psi$ holds, and both φ and ψ imply a further formula χ , then χ holds.

So we are to prove that if $U \models \varphi \vee \psi$, $U \models (\varphi \Rightarrow \chi)$, and $U \models (\psi \Rightarrow \chi)$, then $U \models \chi$. This is done as follows: By assumption, there exists a covering $U = \bigcup_i U_i$ such that on each U_i , $U_i \models \varphi$ or $U_i \models \psi$. Again by assumption, we may conclude that $U_i \models \chi$ for each i . The statement follows because of the locality of the internal language.

A complete list of which rules are to prove is in Appendix C. \square

In particular, if a formula ψ has an unconditional intuitionistic proof, then $U \models \psi$.

The restriction to intuitionistic logic is really necessary at this point. We will encounter many examples of classically equivalent internal statements whose translation using the Kripke–Joyal semantics are wildly different. In particular, our treatment of modal operators to understand spreading of properties from points to neighbourhoods depends on having the ability to make finer distinctions – distinctions which are not visible in classical logic. At the end of this section there are some notes on what the restriction to intuitionistic logic amounts to in practice.

XXX: Put rules into an appendix and give some explanation regarding contexts etc. Don’t forget the rules for \in , \wedge , \vee .

Because of the multitude of quantifiers, literal translations of internal statements can sometimes get slightly unwieldy. There are simplification rules for certain often-occurring special cases:

Proposition 2.6.

$$\begin{aligned}
 U \models \forall s : \mathcal{F}. \forall t : \mathcal{G}. \varphi(s, t) &\iff \text{for all open } V \subseteq U, \\
 &\quad \text{sections } s \in \Gamma(V, \mathcal{F}), t \in \Gamma(V, \mathcal{G}): V \models \varphi(s, t) \\
 U \models \forall s : \mathcal{F}. \varphi(s) \Rightarrow \psi(s) &\iff \text{for all open } V \subseteq U, \text{ sections } s \in \Gamma(V, \mathcal{F}): \\
 &\quad V \models \varphi(s) \text{ implies } V \models \psi(s) \\
 U \models \exists ! s : \mathcal{F}. \varphi(s) &\iff \text{for all open } V \subseteq U, \\
 &\quad \text{there is exactly one section } s \in \Gamma(V, \mathcal{F}) \text{ with:} \\
 &\quad V \models \varphi(s)
 \end{aligned}$$

Proof. Straightforward. By way of example, we prove the existence claim in the “only if” direction of the last rule. (Note that this rule formalizes the saying “unique existence implies global existence”.) By definition of $\exists !$, it holds that

$$U \models \exists s : \mathcal{F}. \varphi(s)$$

and

$$U \models \forall s, t : \mathcal{F}. \varphi(s) \wedge \varphi(t) \Rightarrow s = t.$$

Let $V \subseteq U$ be an arbitrary open subset. Then there exist local sections $s_i \in \Gamma(V_i, \mathcal{F})$ such that $V_i \models \varphi(s_i)$, where $V = \bigcup_i V_i$ is an open covering. By the locality of the internal language, on intersections it holds that $V_i \cap V_j \models \varphi(s_i)$, so by the uniqueness assumption, it follows that the local sections agree on intersections. They therefore glue to a section $s \in \Gamma(V, \mathcal{F})$. Since $V_i \models \varphi(s)$ for all i , the locality of the internal language allows us to conclude that $V \models \varphi(s)$. \square

Remark 2.7. Note that $\text{Sh}(X) \models \neg\varphi$ is in general a much stronger statement than merely supposing that $\text{Sh}(X) \models \varphi$ does not hold: The former always implies the latter (unless $X = \emptyset$, in which case *any* internal statement is true), but the converse does not hold: The former statement means that $U = \emptyset$ is the *only* open subset on which φ holds.

2.2. Internal constructions. The Kripke–Joyal semantics defines the interpretation of internal *statements*. The interpretation of internal *constructions* is given by the following definition.

Definition 2.8. The interpretation of an internal construction T is denoted by $\llbracket T \rrbracket \in \text{Sh}(X)$ and given by the following rules.

- If \mathcal{F} and \mathcal{G} are sheaves, $\llbracket \mathcal{F} \times \mathcal{G} \rrbracket$ is the categorical product of \mathcal{F} and \mathcal{G} (i. e. their product as presheaves).
- If \mathcal{F} and \mathcal{G} are sheaves, $\llbracket \mathcal{F} \amalg \mathcal{G} \rrbracket$ is the categorical coproduct of \mathcal{F} and \mathcal{G} , i. e. the sheafification of the presheaf $U \mapsto \Gamma(U, \mathcal{F}) \amalg \Gamma(U, \mathcal{G})$.
- If \mathcal{F} is a sheaf, the interpretation $\llbracket \mathcal{P}(\mathcal{F}) \rrbracket$ of the power set construction is the sheaf given by

$$U \subseteq X \text{ open} \longmapsto \{\mathcal{G} \hookrightarrow \mathcal{F}|_U\},$$

i. e. sections on an open set U are subsheaves of $\mathcal{F}|_U$ (either literally or isomorphism classes of arbitrary monomorphisms into $\mathcal{F}|_U$).

- If \mathcal{F} is a sheaf and $\varphi(s)$ is a formula containing a free variable $s : \mathcal{F}$, the interpretation $\llbracket \{s : \mathcal{F} \mid \varphi(s)\} \rrbracket$ is given by the subpresheaf of \mathcal{F} defined by

$$U \subseteq X \text{ open} \longmapsto \{s \in \Gamma(U, \mathcal{F}) \mid U \models \varphi(s)\}.$$

Note that by the locality of the internal language, this presheaf is in fact a sheaf.

The definition is made in such a way that, from the internal perspective, the constructions enjoy their expected properties. For instance, it holds that

$$\text{Sh}(X) \models (\forall x : \llbracket \{s : \mathcal{F} \mid \varphi(s)\} \rrbracket. \psi(x)) \iff (\forall x : \mathcal{F}. \varphi(x) \Rightarrow \psi(x)).$$

We gloss over several details here. See [25, section D4.1] for a proper treatment.

Morphisms can internally be constructed by appealing to the *principle of unique choice*: Let $\varphi(s, t)$ be a formula with free variables of type $s : \mathcal{F}, t : \mathcal{G}$. Assume

$$\text{Sh}(X) \models \forall s : \mathcal{F}. \exists ! t : \mathcal{G}. \varphi(s, t).$$

Then there is one and only one morphism $\alpha : \mathcal{F} \rightarrow \mathcal{G}$ of sheaves such that for any local section $s \in \Gamma(U, \mathcal{F})$, $\text{Sh}(X) \models \varphi(s, \alpha(s))$. This follows from the meaning of unique existence with the Kripke–Joyal semantics (Proposition 2.6).

An important application is showing that two sheaves \mathcal{F} and \mathcal{G} are isomorphic (usually as objects with more structure, for instance sheaves of modules). To this end, it suffices to give a formula $\varphi(s, t)$ satisfying, in addition to the condition above, the condition $\text{Sh}(X) \models \forall t : \mathcal{G}. \exists ! s : \mathcal{F}. \varphi(s, t)$, expressing that the induced

morphism α is a bijective map from the internal perspective. Note that this implies the statement

$$\mathrm{Sh}(X) \models \exists \alpha : \mathcal{H}\mathrm{om}(\mathcal{F}, \mathcal{G}). \ulcorner \alpha \text{ is bijective} \urcorner,$$

but this statement is strictly weaker: Its interpretation with the Kripke–Joyal semantics is that the sheaves \mathcal{F} and \mathcal{G} are *locally* isomorphic.

2.3. Geometric formulas and constructions. In formal and categorical logic so-called geometric formulas play a special role. They are named that way because, in a sense which can be made precise, their meaning is preserved under pullback with geometric morphisms.

Definition 2.9. A formula is *geometric* if and only if it consists only of

$$= \in \top \perp \wedge \vee \bigvee \exists,$$

but not “ \bigwedge ” nor “ \Rightarrow ” nor “ \forall ” (and thus not “ \neg ” either, since this is defined using “ \Rightarrow ”). A *geometric implication* is a formula of the form

$$\forall \dots \forall. (\dots) \Rightarrow (\dots)$$

with the bracketed subformulas being geometric.

The *parameters* of a formula φ are the sheaves being quantified over, sections of sheaves appearing as terms, and morphisms of sheaves appearing as function symbols in φ . We say that a formula φ holds *at a point* $x \in X$ if and only if the formula obtained by substituting all parameters in φ with their stalks at x holds in the usual mathematical sense.

Lemma 2.10. *Let $x \in X$ be a point. Let φ be a geometric formula (over some open neighbourhood V of x). Then φ holds at x if and only if there exists an open neighbourhood $U \subseteq X$ of x (contained in V) such that φ holds on U .*

Proof. This is a very general instance of the phenomenon that sometimes, truth at a point spreads to truth on a neighbourhood. It can be proven by induction on the structure of φ , but we will give a more conceptual proof later (Corollary 6.31). \square

This lemma is in fact a very useful metatheorem. We will properly discuss its significance in Section 6.7. For now, we just use it to prove a simple criterion for the internal truth of a geometric implication; we will apply this criterion many times.

Corollary 2.11. *A geometric implication holds on X if and only if it holds at every point of X .*

Proof. For notational simplicity, we consider a geometric implication of the form

$$\forall s : \mathcal{F}. \varphi(s) \Rightarrow \psi(s).$$

For the “only if” direction, assume that this formula holds on X and let $x \in X$ be an arbitrary point. Let $s_x \in \mathcal{F}_x$ be the germ of an arbitrary local section s of \mathcal{F} and assume that $\varphi(s)$ holds at x . Then by the lemma, it follows that $\varphi(s)$ holds on some open neighbourhood of x . By assumption, $\psi(s)$ holds on this neighbourhood as well. Again by the lemma, $\psi(s)$ holds at x .

For the “if” direction, assume that the geometric implication holds at every point. Let $U \subseteq X$ be an arbitrary open subset and let $s \in \Gamma(U, \mathcal{F})$ be a local section such that $\varphi(s)$ holds on U . By the lemma and the locality of the internal language, to show that $\psi(s)$ holds on U , it suffices to show that $\psi(s)$ holds at every point of U . This is clear, since again by the lemma, $\varphi(s)$ holds at every point of U . \square

Example 2.12. Injectivity and surjectivity are geometric implications (surjectivity can be spelled $\forall y : \mathcal{G}. (\top \Rightarrow \exists x : \mathcal{F}. \alpha(x) = y)$). Thus the corollary gives a deeper reason for the well-known fact that a morphism of sheaves is a monomorphism resp. an epimorphism if and only if it is stalkwise injective resp. surjective.

A construction is *geometric* if and only if it commutes with pullback under arbitrary geometric morphisms. We do not want to discuss the notion of geometric morphisms here; suffice it to say that calculating the stalk at a point $x \in X$ is an instance of such a pullback. Among others, the following constructions are geometric:

- finite product: $(\mathcal{F} \times \mathcal{G})_x \cong \mathcal{F}_x \times \mathcal{G}_x$
- finite coproduct: $(\mathcal{F} \amalg \mathcal{G})_x \cong \mathcal{F}_x \amalg \mathcal{G}_x$
- arbitrary coproduct: $(\coprod_i \mathcal{F}_i)_x \cong \coprod_i (\mathcal{F}_i)_x$
- set comprehension with respect to a *geometric* formula φ :

$$\llbracket \{s : \mathcal{F} \mid \varphi(s)\} \rrbracket_x \cong \{[s] \in \mathcal{F}_x \mid \varphi(s) \text{ holds at } x\}$$

- free module: $(\mathcal{R}\langle \mathcal{F} \rangle)_x \cong \mathcal{R}_x \langle \mathcal{F}_x \rangle$ (\mathcal{R} a sheaf of rings, \mathcal{F} a sheaf of sets)
- localization of a module: $\mathcal{F}[\mathcal{S}^{-1}]_x \cong \mathcal{F}_x[\mathcal{S}_x^{-1}]$

Note that compatibility with taking stalks is not sufficient for geometricity. It is just the most easily visualized requirement. The following constructions are not in general geometric:

- arbitrary product
- set comprehension with respect to a non-geometric formula
- powerset
- internal Hom: $\mathcal{H}om(\mathcal{F}, \mathcal{G})_x \not\cong \mathcal{H}om(\mathcal{F}_x, \mathcal{G}_x)$

2.4. Appreciating intuitionistic logic. The principal (and only) difference between classical and intuitionistic logic is that in classical logic, the axiom schemes of *excluded middle* and *double negation elimination* are added.

$$\varphi \vee \neg\varphi \qquad \neg\neg\varphi \Rightarrow \varphi$$

A classically trained mathematician might legitimately wonder why one should drop these axioms: Are they not obviously true? The pragmatic answer to this question is that the translations of these axioms with the Kripke–Joyal semantics are, except for uninteresting special cases of the base space X , plainly false – irrespective of one’s philosophical convictions. Therefore the internal language is in general only sound with respect to intuitionistic logic and not with respect to classical logic. Concretely, there is the following proposition.

Proposition 2.13. *The internal language of a T_1 -space X is Boolean, i. e. it verifies the classical axiom schemes displayed above, if and only if X is discrete. The internal language of an irreducible or locally Noetherian scheme X is Boolean if and only if X has dimension ≤ 0 .*

Proof. The internal language of $\text{Sh}(X)$ is Boolean if and only if for any open subset $U \subseteq X$ it holds that U is the only dense open subset of U . This can be checked manually, by using the definition of the Kripke–Joyal semantics, but we’ll be able to give a more conceptual proof later (Lemma 6.17). The first claim is then an exercise in point-set topology, while the second is more difficult (Corollary 3.15). \square

However, there is also a more satisfying answer, which furthermore illuminates how to intuitively picture intuitionistic mathematics. Namely, when doing intuitionistic mathematics, we use the same formal symbols as classically, but with a *different intended meaning*. For instance, the classical reading of an existential statement like $\exists x : A. \varphi(x)$ is that there exists some element $x : A$ with the property $\varphi(x)$. In contrast, its intuitionistic reading is that such an element can actually be *constructed*, i. e. explicitly given in some form. This is a much stronger statement. Classically, a proof that it is *not* the case that such an element does *not* exist – formally $\neg \neg \exists x : A. \varphi(x)$ (or, equivalently even in intuitionistic mathematics, $\neg \forall x : A. \neg \varphi(x)$) suffices to demonstrate the existential statement; this is not so in intuitionistic mathematics.

Similarly, the intuitionistic meaning of a disjunction $\varphi \vee \psi$ is not only that one of the disjuncts is true, but that one can explicitly state which case holds. It is in general not enough to show that it is impossible that both φ and ψ fail.

In this picture, it is obvious that one should not adopt the law of excluded middle or the principle of double negation elimination as axioms. Note that we do not *reject* those axioms in the sense of postulating their converses either, we simply don't use them. Therefore any intuitionistically true result is also true classically. In fact, for some special instances, these two classical axioms do hold intuitionistically. For example, any natural number is zero or is not zero – this is not a triviality, but can be proven by induction.²

A consequence of not adopting these axioms is that proofs by contradiction are not generally justified; they are intuitionistically acceptable only for those statements which can be proven to be true or false. Note that a proof of a *negated formula* is not the same as a proof by contradiction. For instance, the usual proof that $\sqrt{2}$ is not rational is intuitionistically perfectly fine: From the assumption that $\sqrt{2}$ is rational one deduces a contradiction (\perp). This is exactly the definition of $\neg(\ulcorner \sqrt{2} \text{ is rational } \urcorner)$.

A more positive consequence of not adopting the law of excluded middle and the principle of double negation elimination is that intuitionistically, we can make *finer distinctions*. For instance, for a formula φ , the doubly negated formula $\neg \neg \varphi$ (“*not not* φ ”) is a certain kind of weakening of φ : If φ holds, then $\neg \neg \varphi$ does as well, while the converse can not be shown in general.³ An example from everyday life runs as follows: If in the morning you can't find the key for your apartment, but you know that it must hide somewhere since you used it to open the door in the evening before, you intuitionistically know ($\neg \neg \exists x. \ulcorner \text{the key is at position } x \urcorner$), but you cannot claim the unnegated proposition. One cannot model this distinction with pure classical logic.

Double negation also has a concrete geometric meaning with the Kripke–Joyal semantics. Namely, $X \models \neg \neg \varphi$ holds if and only if there is a dense open subset U of X such that $U \models \varphi$. This is of course a weaker statement than $X \models \varphi$. In

²The analogous statement about real numbers cannot be shown. Intuitively, for a number given by a decimal expansion starting with $0.0000\dots$ one cannot decide whether the string of zeros will continue indefinitely or whether eventually a non-zero digit will occur. This argument can be made rigorous. The analogous statement about algebraic numbers *can* be proven; the information contained in a witness of algebraicity (a normed polynomial which the given number is a zero of) suffices to make the case distinction [34, Chapter VI.1, page 140].

³A detailed proof of the correct implication goes as follows: Assume φ . We are to show $\neg \neg \varphi$, i. e. ($\neg \varphi \Rightarrow \perp$). So assume $\neg \varphi$, we are to show \perp . Since φ and $\varphi \Rightarrow \perp$, \perp indeed follows.

Section 6, we will discuss this fact and other *modal operators* in more detail. For instance, there is a similarly defined modal operator \Box such that $X \models \Box\varphi$ if and only if there is an open neighbourhood U of a given point x such that $U \models \varphi$. Also there is a operator \Box such that $X \models \Box\varphi$ if and only if φ holds on a scheme-theoretically dense open subset.

For future reference, note that if $\varphi \Rightarrow \psi$, then also $\neg\neg\varphi \Rightarrow \neg\neg\psi$; and note that weakening twice has no further effect, i. e. $\neg\neg\neg\neg\varphi \Leftrightarrow \neg\neg\varphi$.⁴

A classical mathematician might then ask which classical results are valid intuitionistically. The answer is that in linear and commutative algebra, most of the basic theorems stay valid, provided one exercises some caution in formulating them (for instance, one should not arbitrarily weaken assumptions by introducing double negations). This is because the proofs of these statements are usually direct; if intuitionistically unacceptable case distinctions do occur, they can often be eliminated by streamlining the proof.

Consider as a simple example the proposition that the kernel of a linear map is a linear subspace. The case distinction “either the kernel consists just of the zero vector, in which case the claim is trivial, or otherwise ...” is not intuitionistically acceptable, but it can be entirely dispensed with: The proof for the general case works in the special case just as well.

Finally, we should clarify the status of the axiom of choice. This axiom, which is strictly speaking not part of classical logic, but of a classical set theory, is not accepted in an intuitionistic context: By *Diaconescu’s theorem*, it implies the law of excluded middle in presence of the other axioms of set theory.

The standard reference for intuitionistic algebra is a textbook by Ray Mines, Fred Richman and Wim Ruitenburg [34], the standard reference for intuitionistic analysis is a book by Erret Bishop and Douglas Bridges [8]. Further explanations and pointers to relevant literature can be found in an expository article and a recorded lecture by Andrej Bauer [5, 4].

Remark 2.14. For ease of exposition, we work in a classical metatheory. This means that we allow ourselves to occasionally use the law of excluded middle and the axiom of choice when reasoning *about* the internal language. In particular, we have the theory of schemes as commonly presented at our disposal. But we should note that this concession is really a cop out, and that it would be better to develop an intuitionistic theory of schemes. If this were done, one could extend our approach to understand morphisms of schemes from an internal point of view – a morphism $Y \rightarrow X$ would internally look like a morphism $Y \rightarrow \text{pt}$. See Section 12 for details.

3. SHEAVES OF RINGS

Recall that a *sheaf of rings* can be categorically described as a sheaf of sets \mathcal{R} together with maps of sheaves $+, \cdot : \mathcal{R} \times \mathcal{R} \rightarrow \mathcal{R}$ and global elements $0, 1$ such that certain axioms hold. For instance, the axiom on the commutativity of addition is

⁴In fact, negating thrice is the same as negating once: Assume $\neg\neg\neg\varphi$. We are to show $\neg\varphi$. So assume φ , we are to show \perp . Since $\varphi, \neg\varphi$. By $\neg\neg\varphi$, \perp follows.

rendered in diagrammatic form as follows:

$$\begin{array}{ccc}
 \mathcal{R} \times \mathcal{R} & \xrightarrow{\text{swap}} & \mathcal{R} \times \mathcal{R} \\
 & \searrow \quad \swarrow & \\
 & \mathcal{R} &
 \end{array}$$

$\quad \quad \quad + \quad \quad \quad +$

From the internal perspective, a sheaf of rings looks just like a plain ring. This is the content of the following proposition.

Proposition 3.1. *Let X be a topological space. Let \mathcal{R} be a sheaf of sets on X . Let $+, \cdot : \mathcal{R} \times \mathcal{R} \rightarrow \mathcal{R}$ be maps of sheaves and let $0, 1$ be global elements of \mathcal{R} . Then these data define a sheaf of rings if and only if, from the internal perspective, these data fulfill the usual equational ring axioms.*

Proof. We only discuss the commutativity axiom. The internal statement

$$\text{Sh}(X) \models \forall x, y : \mathcal{R}. x + y = y + x$$

means that for any open subset $U \subseteq X$ and any local sections $x, y \in \Gamma(U, \mathcal{R})$, it holds that $x + y = y + x \in \Gamma(U, \mathcal{R})$. This is precisely the external commutativity condition. \square

Lemma 3.2. *Let X be a topological space. Let \mathcal{R} be a sheaf of rings on X . Let f be a global section of \mathcal{R} . Then the following statements are equivalent:*

- (1) *f is invertible from the internal point of view, i. e. $\text{Sh}(X) \models \exists g : \mathcal{R}. fg = 1$.*
- (2) *f is invertible in all stalks \mathcal{R}_x .*
- (3) *f is invertible in $\Gamma(X, \mathcal{R})$.*

Proof. Since invertibility is a geometric implication, the equivalence of the first two statements is clear. Also, it is obvious that the third statement implies the other two. For the remaining direction, note that the uniqueness of inverses in rings can be proven intuitionistically. Therefore, if f is invertible from the internal point of view, it actually holds that

$$\text{Sh}(X) \models \exists! g : \mathcal{R}. fg = 1.$$

Since unique internal existence implies global existence (Proposition 2.6), this shows that the first statement implies the third. \square

3.1. Reducedness. Recall that a scheme X is *reduced* if and only if all stalks $\mathcal{O}_{X,x}$ are reduced rings. Since the condition on a ring R to be reduced is a geometric implication,

$$\forall s : R. \left(\bigvee_{n \geq 0} s^n = 0 \right) \implies s = 0,$$

we immediately obtain the following characterization of reducedness in the internal language:

Proposition 3.3. *A scheme X is reduced iff, from the internal point of view, the ring \mathcal{O}_X is reduced.*

3.2. Locality. Recall the usual definition of a local ring: a ring possessing exactly one maximal ideal. This is a so-called *higher-order condition* since it involves quantification over subsets. It is also not of a geometric form. Therefore, for our purposes, it is better to adopt the following elementary definition of a local ring.

Definition 3.4. A *local ring* is a ring R such that $1 \neq 0$ in R and for all $x, y \in R$

$$x + y \text{ invertible} \implies x \text{ invertible} \vee y \text{ invertible}.$$

In classical logic, it is an easy exercise to show that this definition is equivalent to the usual one. In intuitionistic logic, we would need to be more precise in order to even state the question of equivalence, since intuitionistically, the notion of a maximal ideal bifurcates into several non-equivalent notions.⁵

Proposition 3.5. *In the internal language of a scheme X (or a locally ringed space), the ring \mathcal{O}_X is a local ring.*

Proof. The stated locality condition is a conjunction of two geometric implications (the first one being $1 = 0 \Rightarrow \perp$, the second being the displayed one) and holds on each stalk. \square

Remark 3.6. When first exposed to locally ringed spaces, one might ask why the requirement is that the *stalks* $\mathcal{O}_{X,x}$ are local rings, instead of the easier-to-define sets of sections $\mathcal{O}_X(U)$. This question has of course a good geometric answer. Using the internal language, it also has a purely formal answer: The requirement that the stalks are local rings is precisely the requirement that the ring \mathcal{O}_X is a local ring from the perspective of the internal language of X .

3.3. Field properties. From the internal point of view, the structure sheaf \mathcal{O}_X of a scheme X is *almost* a field, in the sense that any element which is not invertible is nilpotent. This is a genuine property of schemes, not shared with arbitrary locally ringed spaces. It is also a specific feature of the internal universe: Neither the local rings $\mathcal{O}_{X,x}$ nor the rings of local sections $\Gamma(U, \mathcal{O}_X)$ have this property in general.

Proposition 3.7. *Let X be a scheme. Then*

$$\mathrm{Sh}(X) \models \forall s : \mathcal{O}_X. \neg(\ulcorner s \text{ invertible} \urcorner) \Rightarrow \ulcorner s \text{ nilpotent} \urcorner.$$

Proof. By the locality of the internal language and since X can be covered by open affine subsets, it is enough to show that for any affine scheme $X = \mathrm{Spec} A$ and any global function $s \in \Gamma(X, \mathcal{O}_X) = A$ it holds that

$$X \models \neg(\ulcorner s \text{ invertible} \urcorner) \text{ implies } X \models \ulcorner s \text{ nilpotent} \urcorner.$$

The meaning of the antecedent is that any open subset on which s is invertible is empty. This implies in particular that the standard open subset $D(s)$ is empty. This means that s is an element of any prime ideal of A , thus nilpotent, and therefore implies the a priori weaker statement $X \models \ulcorner s \text{ nilpotent} \urcorner$ (which would allow s to have different indices of nilpotency on an open covering). \square

⁵For instance, should a maximal ideal \mathfrak{m} be such that if \mathfrak{n} is any ideal with $\mathfrak{m} \subseteq \mathfrak{n} \subseteq (1)$, then $\mathfrak{m} = \mathfrak{n}$? Or should the condition be that if \mathfrak{n} is any ideal with $\mathfrak{m} \subseteq \mathfrak{n}$, then $\mathfrak{m} = \mathfrak{n}$ or $\mathfrak{n} = (1)$? Intuitionistically, the latter condition is stronger than the former.

Remark 3.8. In classical logic, the statement “not invertible implies nilpotent” is equivalent to “any element is invertible or nilpotent”. However, in intuitionistic logic, the latter is strictly stronger than the former. We will see in the next section (Corollary 3.14) that the structure sheaf of a scheme fulfills the latter condition if and only if the scheme is zero-dimensional (or empty).

Corollary 3.9. *Let X be a scheme. If X is reduced, the ring \mathcal{O}_X is a field from the internal point of view, in the sense that*

$$\mathrm{Sh}(X) \models \forall s : \mathcal{O}_X. \neg(\ulcorner s \text{ invertible} \urcorner) \Rightarrow s = 0.$$

Conversely, if \mathcal{O}_X is a field in this internal sense, then X is reduced.

Proof. We can prove this purely in the internal language: It suffices to give an intuitionistic proof of the fact that a local ring which satisfies the condition of the previous proposition fulfills the stated field condition if and only if it is reduced. This is straightforward. \square

This field property is very useful. We will put it to good use when giving a simple proof of the fact that \mathcal{O}_X -modules of finite type on a reduced scheme are locally free on a dense open subset (Lemma 5.9). Note that the field property only holds precisely as stated in the corollary; the classically equivalent condition that any element is invertible or zero is intuitionistically stronger. This is a common phenomenon in intuitionistic mathematics: Classically equivalent notions may bifurcate into related but inequivalent notions intuitionistically.

The following proposition says that we can deduce a certain unconditional statement from the premise that, under the assumption that some element $f : \mathcal{O}_X$ is invertible, an element $s : \mathcal{O}_X$ is zero. This is interesting on its own, but will be of particular importance in understanding quasicohherence from the internal point of view (Section 9).

Proposition 3.10. *Let X be a scheme. Then*

$$\mathrm{Sh}(X) \models \forall f : \mathcal{O}_X. \forall s : \mathcal{O}_X. (\ulcorner f \text{ inv.} \urcorner \Rightarrow s = 0) \Rightarrow \bigvee_{n \geq 0} f^n s = 0.$$

Proof. It is enough to show that for any affine scheme $X = \mathrm{Spec} A$ and any global functions $f, s \in A$ such that

$$X \models (\ulcorner f \text{ inv.} \urcorner \Rightarrow s = 0),$$

it holds that $X \models \bigvee_{n \geq 0} f^n s = 0$. This indeed follows, since by assumption such a function s is zero on $D(f)$, i.e. s is zero as an element of $A[f^{-1}]$. \square

3.4. Krull dimension. Recall that the *Krull dimension* of a ring is usually defined as the supremum of the lengths of strictly ascending chains of prime ideals. As with the classical definition of a local ring, this definition does not lead to a well-behaved notion in an intuitionistic context. Furthermore, it is a higher-order condition, so interpreting it with the Kripke–Joyal semantics is a bit unwieldy.

Luckily, there is an elementary definition of the Krull dimension which works intuitionistically and which is classically equivalent to the usual notion. It was found by Thierry Coquand and Henri Lombardi, building upon work by André Joyal and Luis Español [17, 16], and can be used to give a short proof that $\dim k[X_1, \dots, X_n] = n$, where k is a field [15].

Definition 3.11. Let R be a ring. A *complementary sequence* for a sequence (a_0, \dots, a_n) of elements of R is a sequence (b_0, \dots, b_n) such that the following inclusions of radical ideals hold:

$$\left\{ \begin{array}{lcl} \sqrt{(1)} & \subseteq & \sqrt{(a_0, b_0)} \\ \sqrt{(a_0 b_0)} & \subseteq & \sqrt{(a_1, b_1)} \\ \sqrt{(a_1 b_1)} & \subseteq & \sqrt{(a_2, b_2)} \\ & \vdots & \\ \sqrt{(a_{n-1} b_{n-1})} & \subseteq & \sqrt{(a_n, b_n)} \\ \sqrt{(a_n b_n)} & \subseteq & \sqrt{(0)} \end{array} \right.$$

The ring R is of Krull dimension $\leq n$ if and only if for any sequence (a_0, \dots, a_n) there exists a complementary sequence. (The ring R is trivial if and only if it is of Krull dimension ≤ -1 .)

Note that unlike the usual definition, this definition posits only a condition on elements and not on ideals. It is thus of a simpler logical form. (The radical ideals appear only for convenience. We will dispose of them in the proof of Proposition 3.13.) Also note that we do not define the Krull dimension of a ring as some natural number (this is intuitionistically not possible for general rings). Instead, we only define what it means for the Krull dimension to be less than or equal to a given natural number.

For the following, no intuition about the definition is needed; however, we feel that some motivation might be of use. Recall that we can picture inclusions of radical ideals geometrically by considering standard open subsets $D(f) = \{\mathfrak{p} \in \text{Spec } R \mid f \notin \mathfrak{p}\}$: The inclusion $\sqrt{(f)} \subseteq \sqrt{(g, h)}$ holds if and only if $D(f) \subseteq D(g) \cup D(h)$, and intersections are calculated by products, i.e. $D(f) \cap D(g) = D(fg)$.

The condition that (b_0, \dots, b_n) is complementary to (a_0, \dots, a_n) thus means that $D(a_0)$ and $D(b_0)$ cover the whole of $\text{Spec } R$; that their intersection is covered by $D(a_1)$ and $D(b_1)$; that in turn their intersection is covered by $D(a_2)$ and $D(b_2)$; \dots ; and that finally, the intersection of $D(a_n)$ and $D(b_n)$ is empty.

For the special case $n = 0$, the condition that R is of Krull dimension ≤ 0 means that for any element a_0 there exists an element b_0 such that $D(a_0)$ and $D(b_0)$ cover $\text{Spec } R$ and are disjoint.

The definition of the Krull dimension can be written in such a way as to mimic the definition of the inductive Menger–Urysohn dimension of topological spaces [17, Section 1].

Theorem 3.12. *Let R be a ring.*

- (1) *In classical logic, the ring R is of Krull dimension $\leq n$ if and only if its Krull dimension as usually defined using chains of prime ideals is less than or equal to n .*
- (2) *If the ring R is of Krull dimension $\leq n$, the radical of any finitely generated ideal is equal to the radical of some ideal which can be generated by $n + 1$ elements. This holds intuitionistically, and there is an explicit algorithm for computing the reduced set of generators from the given ones. (Kronecker’s theorem)*

Proof. See [17, Theorem 1.2] for the first statement. The proof relies on the observation that $\dim R \leq n$ if and only if $\dim R[S_x^{-1}] \leq n - 1$ for all $x \in R$, where $S_x = x^{\mathbb{N}}(1 + xR) \subseteq R$. We put the second statement only to demonstrate

that the definition of the Krull dimension is constructively sensible. It follows from the identity $\sqrt{(x, a_0, \dots, a_n)} = \sqrt{(a_0 - xb_0, \dots, a_n - xb_n)}$, where (b_0, \dots, b_n) is a complementary sequence for (a_0, \dots, a_n) . \square

We can apply the constructive theory of Krull dimension to the structure sheaf \mathcal{O}_X of a scheme X as follows. Note that the condition that a scheme X has dimension exactly n (in the usual sense using ascending chains of closed irreducible subsets) is not local – the dimension may vary on an open cover; therefore it is not possible to characterize this condition in the internal language. However, the condition that the dimension of X is less than or equal to n is local, thus there is hope that it can be internalized. And indeed, this is the case.

Proposition 3.13. *Let X be a scheme. Then:*

$$\dim X \leq n \iff \text{Sh}(X) \models \ulcorner \mathcal{O}_X \text{ is of Krull dimension } \leq n \urcorner$$

Proof. A condition of the form “ $\sqrt{(f)} \subseteq \sqrt{(g, h)}$ ” like in the constructive definition of the Krull dimension is not a geometric formula when taken on face value. However, it is equivalent to a geometric condition, namely to

$$\begin{aligned} \exists a, b : \mathcal{O}_X. \bigvee_{m \geq 0} f^m = ag + bh \quad \wedge \\ \exists u : \mathcal{O}_X. \bigvee_{p \geq 0} g^p = uf \quad \wedge \quad \exists v : \mathcal{O}_X. \bigvee_{q \geq 0} h^q = vf. \end{aligned}$$

Therefore the condition $\ulcorner \mathcal{O}_X \text{ is of Krull dimension } \leq n \urcorner$ is (equivalent to) a geometric implication and thus holds internally if and only if it holds at every point $x \in X$. This in turn means that the Krull dimension of any stalk $\mathcal{O}_{X,x}$ is less than or equal to n . This is equivalent to the (Krull) dimension of X being less than or equal to n . \square

We will state and prove a generalization of this lemma about the dimension of closed subschemes later, as Lemma 10.9.

If X is a reduced scheme, we have seen in Corollary 3.9 that \mathcal{O}_X is a field from the internal perspective, in the sense that non-invertible elements are zero. But fields are well-known to be of Krull dimension zero. Why is this not a contradiction to the proposition just proven? Intuitionistically, one can only show that fields in the stronger sense that any element is zero or invertible have Krull dimension zero. Fields in the weaker sense can have higher Krull dimension, as exhibited by the structure sheaf of reduced schemes with positive dimension.

For the following corollary, note that if a scheme X is not empty, $\dim X \leq 0$ is equivalent to $\dim X = 0$.

Corollary 3.14. *Let X be a scheme. Then:*

$$\dim X \leq 0 \iff \text{Sh}(X) \models \forall s : \mathcal{O}_X. \ulcorner s \text{ inv.} \urcorner \vee \ulcorner s \text{ nilpotent} \urcorner.$$

If furthermore X is reduced, this is further equivalent to \mathcal{O}_X being a field in the strong sense that any element of \mathcal{O}_X is invertible or zero.

Proof. By the proposition and the fact that \mathcal{O}_X is a local ring from the internal perspective, this is an immediate consequence of interpreting the following standard fact of ring theory in the internal language of $\text{Sh}(X)$: A local ring R is of Krull dimension ≤ 0 if and only if any element of R is invertible or nilpotent.

It is well-known that this holds classically; to make sure that it holds intuitionistically as well (so that it can be used in the internal universe), we give a proof of the “only if” direction. Let $a : R$ be arbitrary. By assumption on the Krull dimension, there exists an element $b : R$ such that $\sqrt{(1)} \subseteq \sqrt{(a, b)}$ and $\sqrt{(ab)} = \sqrt{(0)}$. The latter means that ab is nilpotent. Since R is local, the former implies that a is invertible or that b is invertible. In the first case, we are done. In the second case, it follows that a is nilpotent, so we are done as well. \square

As a further corollary note the curious fact that the classicality of the internal language of $\text{Sh}(X)$, where X is a scheme, is tightly coupled with the properties of the ring \mathcal{O}_X : Internally, the law of excluded middle and the principle of double negation elimination are “almost equivalent” to the Krull dimension of \mathcal{O}_X being ≤ 0 .

Corollary 3.15. *Let X be a scheme. If the internal language of $\text{Sh}(X)$ is Boolean, then $\dim X \leq 0$. The converse holds if X is irreducible or locally Noetherian.*

Proof. We show that any element of \mathcal{O}_X is invertible or nilpotent, therefore verifying the hypothesis of the previous corollary. Let $s : \mathcal{O}_X$ be given. By assumption, either s is invertible or s is not invertible. In the latter case s is nilpotent by Proposition 3.7.

We defer the converse direction to Proposition 7.18 since we don’t want to interrupt the exposition here with a certain necessary technical condition. \square

3.5. Integrality. In intuitionistic logic, the notion of an integral domain bifurcates into several inequivalent notions. The following two are important for our purposes:

Definition 3.16. A ring R is an *integral domain in the weak sense* if and only if $1 \neq 0$ in R and

$$\forall x, y : R. xy = 0 \implies (x = 0) \vee (y = 0).$$

A ring R is an *integral domain in the strong sense* if and only if $1 \neq 0$ in R and

$$\forall x : R. x = 0 \vee \ulcorner x \text{ is regular} \urcorner,$$

where $\ulcorner x \text{ is regular} \urcorner$ means that $xy = 0$ implies $y = 0$ for any $y : R$.

For the following result, recall that a scheme X (or ringed space) is *integral at a point* $x \in X$ if and only if $\mathcal{O}_{X,x}$ is an integral domain (in either sense, since we have adopted a classical metatheory).

Proposition 3.17. *Let X be a ringed space. Then:*

- (1) *X is integral at all points if and only if, internally, \mathcal{O}_X is an integral domain in the weak sense.*
- (2) *If X is even a locally Noetherian scheme, then \mathcal{O}_X is an integral domain in the weak sense iff it is an integral domain in the strong sense from the internal point of view.*

Proof. The condition on a ring to be an integral domain in the weak sense is a conjunction of two geometric implications, “ $1 = 0 \implies \perp$ ” and the implication displayed in the definition. Therefore the first statement is obvious.

For the second statement, note that the condition on a function $f \in \Gamma(U, \mathcal{O}_X)$ to be regular from the internal perspective is open: It holds at a point $x \in U$ if and only if it holds on some open neighbourhood of x . We will give a proof of this specific feature of locally Noetherian schemes later on, when we have developed appropriate machinery to do so easily (Proposition 7.4). In any case, this openness property was the essential ingredient for the equivalence between “holding internally”

and “holding at every point” (Corollary 2.11). Therefore \mathcal{O}_X is an integral domain in the strong sense from the internal point of view if and only if all local rings $\mathcal{O}_{X,x}$ are integral domains. By the first statement, this is equivalent to \mathcal{O}_X being an integral domain in the weak sense from the internal point of view. \square

Lemma 3.18. *Let $X = \text{Spec } A$ be an affine scheme. Let $f \in A$. Then f is a regular element of A if and only if f is a regular element of \mathcal{O}_X from the internal perspective.*

Proof. The Kripke–Joyal translation of internal regularity is:

For any open subset $U \subseteq X$ and any function $g \in \Gamma(U, \mathcal{O}_X)$, $fg = 0$
in $\Gamma(U, \mathcal{O}_X)$ implies $g = 0$ in $\Gamma(U, \mathcal{O}_X)$.

So the “only if” direction is clear (use $U := X$). For the “if” direction, note that $\Gamma(U, \mathcal{O}_X)$ is a localization of A and that regular elements remain regular in localizations. \square

3.6. Bézout property. Recall that a *Bézout ring* is a ring in which any finitely generated ideal is a principal ideal. In intuitionistic mathematics, this is a better notion than that of a principal ideal ring: The requirement that *any* ideal is a principal ideal is far too strong. Intuitively, this is because without any given generators to begin with, one cannot hope to explicitly pinpoint a principal generator. One can (provably) not even verify this property for the ring \mathbb{Z} .⁶

Proposition 3.19. *Let X be a scheme (or ringed space).*

- (1) \mathcal{O}_X is a Bézout ring from the internal perspective if and only if all rings $\mathcal{O}_{X,x}$ are Bézout rings.
- (2) \mathcal{O}_X is such that, from the internal perspective, of any two elements, one divides the other, if and only if all rings $\mathcal{O}_{X,x}$ are such.

Proof. Both properties can be formulated as geometric implications:

- (1) $\forall f, g : \mathcal{O}_X. \top \Rightarrow \exists d : \mathcal{O}_X. (\exists a, b : \mathcal{O}_X. d = af + bg) \wedge$
 $(\exists u : \mathcal{O}_X. f = ud) \wedge (\exists v : \mathcal{O}_X. g = vd)$
- (2) $\forall f, g : \mathcal{O}_X. \top \Rightarrow (\exists u : \mathcal{O}_X. f = ug) \vee (\exists u : \mathcal{O}_X. g = uf)$ \square

Corollary 3.20. *Let X be a Dedekind scheme, i. e. a locally Noetherian normal scheme of dimension ≤ 1 . Then, from the internal perspective, any matrix over \mathcal{O}_X can be put into Smith canonical form, i. e. is equivalent to a (rectangular) diagonal matrix with diagonal entries $a_1 | a_2 | \cdots | a_n$ successively dividing each other.*

⁶Assume that any ideal of \mathbb{Z} is finitely generated. Let φ be an arbitrary proposition; we want to intuitionistically deduce $\varphi \vee \neg\varphi$. Consider the ideal $\mathfrak{a} := \{x \in \mathbb{Z} \mid (x = 0) \vee \varphi\} \subseteq \mathbb{Z}$. The definition is such that φ holds if and only if \mathfrak{a} contains an element other than zero; and that $\neg\varphi$ holds if and only if zero is the only element of \mathfrak{a} . By assumption, \mathfrak{a} is finitely generated. Since \mathbb{Z} is a Bézout ring, it is therefore even principal: $\mathfrak{a} = (x_0)$ for some $x_0 \in \mathbb{Z}$. Even intuitionistically we have $(x_0 = 0) \vee (x_0 \neq 0)$ (for the natural numbers, this can be proven by induction). In the first case, it follows that \mathfrak{a} contains only zero; in the second case, it follows that \mathfrak{a} contains an element other than zero. Thus $\neg\varphi \vee \varphi$.

This kind of reasoning is called *exhibiting a Brouwerian counterexample*. The definition of \mathfrak{a} may look slightly dubious, considering that φ does not depend on x ; but we will see that such definitions actually have a clear geometric meaning – they can be used to define extensions of sheaves by zero in the internal language (Lemma 10.2).

Proof. It is well-known that such a scheme has principal ideal domains as local rings $\mathcal{O}_{X,x}$. For local domains, the Bézout condition is equivalent to the property that of any two elements, one divides the other. Therefore all local rings have this property, and by the previous proposition, the internal ring \mathcal{O}_X has it as well. The statement thus follows from interpreting the following fact of linear algebra in the internal universe: Let R be a ring such that of any two elements, one divides the other. Then any matrix over R can be put into Smith canonical form.

The usual proof of this fact is indeed intuitionistically acceptable: Let a matrix over R be given. By induction, one can show that for any finite family of ring elements, one divides all the others. So some matrix entry is a factor of all the others. We can put this entry to the upper left by row and column transformations and then kill the other entries of the first row and the first column. After these operations, it is still the case that the entry in the first row and column is a factor of all other entries. Continuing in this fashion, we obtain a diagonal matrix. Its diagonal entries already fulfill the divisibility condition and thus do not have to be sorted. \square

Note that phrases such as “if by chance the entry in the upper left divides all the others, we can directly proceed with the next step; otherwise, some other entry must be a factor of all entries, so . . .” may not be included in a proof which is intended to be intuitionistically acceptable. Those phrases assume that one may make the case distinction that for any two ring elements x, y , either x divides y or not. Fortunately, those case distinctions are in fact superfluous.

A consequence of the corollary is that internally to the sheaf topos of a Dedekind scheme, the usual structure theorem on finitely presented \mathcal{O}_X -modules is available. We will exploit this in Lemma 4.20, where we give an internal proof of the fact that on Dedekind schemes, torsion-free \mathcal{O}_X -modules are locally free.

3.7. Normality. We will discuss the property of a ring to be *normal*, i. e. to be integrally closed in its total field of fractions, in Section 7.3, after giving an internal characterization of the sheaf of rational functions.

3.8. Special properties of constant sheaves of rings. Let R be an ordinary ring and \underline{R} the associated sheaf of locally constant R -valued functions on a topological space. If R is reduced, local, or a field, then \underline{R} is so as well, from the internal point of view.

We will prove this in greater generality: Appropriately formulated, a constant sheaf \underline{R} has some property φ from the internal point of view if and only if R has the property φ externally (Lemma 11.1).

4. SHEAVES OF MODULES

From the internal perspective, a sheaf of \mathcal{R} -modules, where \mathcal{R} is a sheaf of rings, looks just like a plain module over the plain ring \mathcal{R} . This is proven just as the correspondence between sheaf of rings and internal rings (Proposition 3.1).

4.1. Finite local freeness. Recall that an \mathcal{O}_X -module \mathcal{F} is *finite locally free* if and only if there exists a covering of X by open subsets U such that on each such U , the restricted module $\mathcal{F}|_U$ is isomorphic as an $\mathcal{O}_X|_U$ -module to $(\mathcal{O}_X|_U)^n$ for some natural number n (which may depend on U).

Proposition 4.1. *Let X be a scheme (or ringed space). Let \mathcal{F} be an \mathcal{O}_X -module. Then \mathcal{F} is finite locally free if and only if, from the internal perspective, \mathcal{F} is a finite free module, i. e.*

$$\mathrm{Sh}(X) \models \bigvee_{n \geq 0} \ulcorner \mathcal{F} \cong (\mathcal{O}_X)^n \urcorner,$$

or more elementarily

$$\mathrm{Sh}(X) \models \bigvee_{n \geq 0} \exists x_1, \dots, x_n : \mathcal{F}. \forall x : \mathcal{F}. \exists ! a_1, \dots, a_n : \mathcal{O}_X. x = \sum_i a_i x_i.$$

Proof. By the expression “ $(\mathcal{O}_X)^n$ ” in the internal language we mean the internally constructed object $\mathcal{O}_X \times \dots \times \mathcal{O}_X$ with its componentwise \mathcal{O}_X -module structure. This coincides with the sheaf $(\mathcal{O}_X)^n$ as usually understood.

It is clear that the two stated internal conditions are equivalent, since the corresponding proof in linear algebra is intuitionistically acceptable. The equivalence with the external notion of finite local freeness follows because the interpretation of the first condition with the Kripke–Joyal semantics is the following: There exists a covering of X by open subsets U such that for each such U , there exists a natural number n and a morphism of sheaves $\varphi : \mathcal{F}|_U \rightarrow (\mathcal{O}_X|_U)^n$ such that

$$U \models \ulcorner \varphi \text{ is } \mathcal{O}_X\text{-linear} \urcorner \quad \text{and} \quad U \models \ulcorner \varphi \text{ is bijective} \urcorner.$$

The first subcondition means that φ is a morphism of sheaves of $\mathcal{O}_X|_U$ -modules and the second one means that φ is an isomorphism of sheaves. \square

4.2. Finite type, finite presentation, coherence. Recall the conditions of an \mathcal{O}_X -module \mathcal{F} on a scheme X (or ringed space) to be of finite type, of finite presentation, and to be coherent:

- \mathcal{F} is of *finite type* if and only if there exists a covering of X by open subsets U such that for each such U , there exists an exact sequence

$$(\mathcal{O}_X|_U)^n \longrightarrow \mathcal{F}|_U \longrightarrow 0$$

of $\mathcal{O}_X|_U$ -modules.

- \mathcal{F} is of *finite presentation* if and only if there exists a covering of X by open subsets U such that for each such U , there exists an exact sequence

$$(\mathcal{O}_X|_U)^m \longrightarrow (\mathcal{O}_X|_U)^n \longrightarrow \mathcal{F}|_U \longrightarrow 0.$$

- \mathcal{F} is *coherent* if and only if \mathcal{F} is of finite type and the kernel of any $\mathcal{O}_X|_U$ -linear morphism $(\mathcal{O}_X|_U)^n \rightarrow \mathcal{F}|_U$, where $U \subseteq X$ is any open subset, is of finite type.

The following proposition gives translations of these definitions into the internal language.

Proposition 4.2. *Let X be a scheme (or ringed space). Let \mathcal{F} be an \mathcal{O}_X -module. Then:*

- \mathcal{F} is of *finite type* if and only if \mathcal{F} , considered as an ordinary module from the internal perspective, is finitely generated, i. e. if

$$\mathrm{Sh}(X) \models \bigvee_{n \geq 0} \exists x_1, \dots, x_n : \mathcal{F}. \forall x : \mathcal{F}. \exists a_1, \dots, a_n : \mathcal{F}. x = \sum_i a_i x_i.$$

- \mathcal{F} is of finite presentation if and only if \mathcal{F} is a finitely presented module from the internal perspective, i. e. if

$$\mathrm{Sh}(X) \models \bigvee_{n,m \geq 0} \ulcorner \text{there is a short exact sequence } \mathcal{O}_X^m \rightarrow \mathcal{O}_X^n \rightarrow \mathcal{F} \rightarrow 0 \urcorner.$$

- \mathcal{F} is coherent if and only if \mathcal{F} is a coherent module from the internal perspective, i. e. if

$$\begin{aligned} \mathrm{Sh}(X) \models \ulcorner \mathcal{F} \text{ is finitely generated} \urcorner \wedge \\ \bigwedge_{n \geq 0} \forall \varphi : \mathrm{Hom}_{\mathcal{O}_X}(\mathcal{O}_X^n, \mathcal{F}). \ulcorner \ker \varphi \text{ is finitely generated} \urcorner. \end{aligned}$$

Proof. Straightforward – the translations of the internal statements using the Kripke–Joyal semantics are precisely the corresponding external statements. \square

Recall that an \mathcal{O}_X -module \mathcal{F} is *generated by global sections* if and only if there exist global sections $s_i \in \Gamma(X, \mathcal{F})$ such that for any $x \in X$, the stalk \mathcal{F}_x is generated by the germs of the s_i . This condition is of course not local on the base. Therefore there cannot exist a formula φ such that for any space X and any \mathcal{O}_X -module \mathcal{F} it holds that \mathcal{F} is generated by global sections if and only if $\mathrm{Sh}(X) \models \varphi(\mathcal{F})$. But still, global generation can be characterized by a mixed internal/external statement:

Proposition 4.3. *Let X be a scheme (or ringed space). Let \mathcal{F} be an \mathcal{O}_X -module. Then \mathcal{F} is generated by global sections if and only if there exist global sections $s_i \in \Gamma(X, \mathcal{F})$, $i \in I$ such that*

$$\mathrm{Sh}(X) \models \forall x : \mathcal{F}. \bigvee_{J = \{i_1, \dots, i_n\} \subseteq I \text{ finite}} \exists a_1, \dots, a_n : \mathcal{O}_X. x = \sum_j a_j x_{i_j}.$$

Furthermore, \mathcal{F} is generated by finitely many global sections if and only if there exist global sections $s_1, \dots, s_n \in \Gamma(X, \mathcal{F})$ such that

$$\mathrm{Sh}(X) \models \forall x : \mathcal{F}. \exists a_1, \dots, a_n : \mathcal{O}_X. x = \sum_j a_j x_j.$$

Proof. The given internal statements are geometric implications, their validity can thus be checked stalkwise. \square

4.3. Tensor product and flatness. Recall that the tensor product of \mathcal{O}_X -modules \mathcal{F} and \mathcal{G} on a scheme X (or ringed space) is usually constructed as the sheafification of the presheaf

$$U \subseteq X \text{ open} \longmapsto \Gamma(U, \mathcal{F}) \otimes_{\Gamma(U, \mathcal{O}_X)} \Gamma(U, \mathcal{G}).$$

From the internal point of view, \mathcal{F} and \mathcal{G} look like ordinary modules, so that we can consider their tensor product as usually constructed in commutative algebra, as a certain quotient of the free module on the elements of $\mathcal{F} \times \mathcal{G}$:

$$\mathcal{O}_X \langle x \otimes y \mid x : \mathcal{F}, y : \mathcal{G} \rangle / R,$$

where R is the submodule generated by

$$\begin{aligned} (x + x') \otimes y - x \otimes y - x' \otimes y, \\ x \otimes (y + y') - x \otimes y - x \otimes y', \\ (sx) \otimes y - s(x \otimes y), \\ x \otimes (sy) - s(x \otimes y) \end{aligned}$$

with $x, x' : \mathcal{F}$, $y, y' : \mathcal{G}$, $s : \mathcal{O}_X$. This internal construction gives rise to the same sheaf of modules as the externally defined tensor product:

Proposition 4.4. *Let X be scheme (or a ringed space). Let \mathcal{F} and \mathcal{G} be \mathcal{O}_X -modules. Then the internally constructed tensor product $\mathcal{F} \otimes_{\mathcal{O}_X} \mathcal{G}$ coincides with the external one.*

Proof. Since the proof of the corresponding fact of commutative algebra is intuitionistically acceptable, the internally defined tensor product $\mathcal{F} \otimes_{\mathcal{O}_X} \mathcal{G}$ has the following universal property: For any \mathcal{O}_X -module H , any \mathcal{O}_X -bilinear map $\mathcal{F} \times \mathcal{G} \rightarrow H$ uniquely factors over the canonical map $\mathcal{F} \times \mathcal{G} \rightarrow \mathcal{F} \otimes_{\mathcal{O}_X} \mathcal{G}$.

Interpreting this property with the Kripke–Joyal semantics, we see that the internally constructed tensor product has the following external property: For any open subset $U \subseteq X$ and any $\mathcal{O}_X|_U$ -module \mathcal{H} on U , any $\mathcal{O}_X|_U$ -bilinear morphism $\mathcal{F}|_U \times \mathcal{G}|_U \rightarrow \mathcal{H}$ uniquely factors over the canonical morphism $\mathcal{F}|_U \times \mathcal{G}|_U \rightarrow (\mathcal{F} \otimes_{\mathcal{O}_X} \mathcal{G})|_U$.

In particular, for $U = X$, this property is well-known to be the universal property of the externally constructed tensor product. Therefore the claim follows. \square

A description of the stalks of the tensor product follows purely by considering the logical form of the construction:

Corollary 4.5. *Let X be scheme (or a ringed space). Let \mathcal{F} and \mathcal{G} be \mathcal{O}_X -modules. Then the stalks of the tensor product coincide with the tensor products of the stalks: $(\mathcal{F} \otimes_{\mathcal{O}_X} \mathcal{G})_x \cong \mathcal{F}_x \otimes_{\mathcal{O}_{X,x}} \mathcal{G}_x$.*

Proof. We constructed the tensor product using the following operations: product of two sets, free module on a set, quotient module with respect to a submodule; submodule generated by a set of elements given by a geometric formula. All of these operations are geometric, so the tensor product construction is geometric as well (see Section 2.3). Hence taking stalks commutes with performing the construction. \square

Recall that an \mathcal{O}_X -module \mathcal{F} is *flat* if and only if all stalks \mathcal{F}_x are flat $\mathcal{O}_{X,x}$ -modules. We can characterize flatness in the internal language.

Proposition 4.6. *Let X be a scheme (or ringed space). Let \mathcal{F} be an \mathcal{O}_X -module. Then \mathcal{F} is flat if and only if, from the internal perspective, \mathcal{F} is a flat \mathcal{O}_X -module.*

Proof. Recall that flatness of an A -module M can be characterized without reference to tensor products by the following condition (using suggestive vector notation): For any natural number p , any p -tuple $m : M^p$ of elements of M and any p -tuple $a : A^p$ of elements of A , it should hold that

$$a^T m = 0 \implies \bigvee_{q \geq 0} \exists n : M^q, B : A^{p \times q}. Bn = m \wedge a^T B = 0.$$

The equivalence of this condition with tensoring being exact holds intuitionistically as well [34, theorem III.5.3]. This formulation of flatness has the advantage that it is the conjunction of geometric implications (one for each $p \geq 0$); therefore it holds internally if and only if it holds at any point. \square

4.4. Support. Recall that the *support* of an \mathcal{O}_X -module \mathcal{F} is the subset $\text{supp } \mathcal{F} := \{x \in X \mid \mathcal{F}_x \neq 0\} \subseteq X$. If \mathcal{F} is of finite type, this set is closed, since its complement is then open by a standard lemma. (We will give an internal proof of this fact in Lemma 6.38.)

Proposition 4.7. *Let X be a scheme (or ringed space). Let \mathcal{F} be an \mathcal{O}_X -module. Then the interior of the complement of the support of \mathcal{F} can be characterized as the largest open subset of X on which the internal statement $\mathcal{F} = 0$ holds.*

Proof. For any open subset $U \subseteq X$, it holds that:

$$\begin{aligned} U &\subseteq \text{int}(X \setminus \text{supp } \mathcal{F}) \\ \iff U &\subseteq X \setminus \text{supp } \mathcal{F} \\ \iff U &\subseteq \{x \in X \mid \forall s \in \mathcal{F}_x. s = 0\} \\ \iff U &\models \forall s : \mathcal{F}. s = 0 \\ \iff U &\models \ulcorner \mathcal{F} = 0 \urcorner \end{aligned}$$

The second to last equivalence is because “ $\forall s : \mathcal{F}. s = 0$ ” is a geometric implication and can thus be checked stalkwise. \square

Remark 4.8. The support of a sheaf of *sets* \mathcal{F} is defined as the subset $\{x \in X \mid \mathcal{F}_x \text{ is not a singleton}\}$. A similar proof shows that the interior of its complement can be characterized as the largest open subset of X where the internal statement “ \mathcal{F} is a singleton” holds.

4.5. Torsion. Let R be a ring. Recall that the *torsion submodule* M_{tors} of an R -module M is defined as

$$M_{\text{tors}} := \{x : M \mid \exists a : R. \ulcorner a \text{ regular} \urcorner \wedge ax = 0\} \subseteq M.$$

This definition is meaningful even if R is not an integral domain. An R -module M is *torsion-free* if and only if M_{tors} is the zero submodule; an R -module M is a *torsion module* if and only if $M_{\text{tors}} = M$.

Recall also that if \mathcal{F} is a sheaf of \mathcal{O}_X -modules on an integral scheme X , there is a unique subsheaf $\mathcal{F}_{\text{tors}} \subseteq \mathcal{F}$ with the property that $\Gamma(U, \mathcal{F}_{\text{tors}}) = \Gamma(U, \mathcal{F})_{\text{tors}}$ for all affine open subsets $U \subseteq X$. The content of the following proposition is that internally constructing the torsion submodule of \mathcal{F} , regarded as a plain module from the internal perspective, gives exactly that subsheaf. There is therefore no harm in using the same notation “ $\mathcal{F}_{\text{tors}}$ ” for the result of the internal construction.

Proposition 4.9. *Let X be an integral scheme. Let \mathcal{F} be an \mathcal{O}_X -module. Let $U = \text{Spec } A \subseteq X$ be an affine open subset. Let $s \in \Gamma(U, \mathcal{F})$ be a local section. Then*

$$s \in \Gamma(U, \mathcal{F})_{\text{tors}} \quad \text{if and only if} \quad U \models s \in \mathcal{F}_{\text{tors}}.$$

Proof. The “only if” direction is trivial in light of Lemma 3.18: If s is a torsion element of $\Gamma(U, \mathcal{F})$, there exists a regular element $a \in \Gamma(U, \mathcal{O}_X)$ such that $as = 0$. By the lemma, this element is regular from the internal perspective as well, so $U \models \ulcorner a \text{ regular} \urcorner \wedge as = 0$.

For the “if” direction, we may assume that there exists an open covering $X = \bigcup_i U_i$ be standard open subsets $U_i = D(f_i)$ such that there are sections $a_i \in \Gamma(U_i, \mathcal{O}_X) = A[f_i^{-1}]$ with $U_i \models \ulcorner a_i \text{ regular} \urcorner \wedge a_i s = 0$. Without loss of generality, we may assume that the denominators of the a_i ’s are ones, that the f_i are finite in number, and that the f_i are regular (i. e. nonzero, since A is an integral domain). By Lemma 3.18, the a_i are regular in $A[f_i^{-1}]$ and by regularity of the f_i also regular in A . Therefore their product $\prod_i a_i \in A$ is regular in A as well and annihilates s . \square

Proposition 4.10. *Let X be a locally Noetherian scheme. Let \mathcal{F} be an \mathcal{O}_X -module. Let $x \in X$ be a point. Then $(\mathcal{F}_{\text{tors}})_x = (\mathcal{F}_x)_{\text{tors}}$.*

Proof. This would be obvious if the condition on an element $s : \mathcal{F}$ to belong to $\mathcal{F}_{\text{tors}}$ were a geometric formula. Because of the universal quantifier, it is not:

$$s \in \mathcal{F}_{\text{tors}} \iff \exists a : \mathcal{O}_X. (\forall b : \mathcal{O}_X. ab = 0 \Rightarrow b = 0) \wedge as = 0.$$

But since X is assumed to be locally Noetherian, regularity is an open property nonetheless (see Proposition 7.4 for an internal proof of this fact). Thus the claim still follows, just like in the proof of Proposition 3.17. \square

4.6. Internal proofs of common lemmas.

Lemma 4.11. *Let X be a scheme (or ringed space). Let*

$$0 \longrightarrow \mathcal{F} \longrightarrow \mathcal{G} \longrightarrow \mathcal{H} \longrightarrow 0$$

be a short exact sequence of \mathcal{O}_X -modules. If \mathcal{F} and \mathcal{H} are of finite type, so is \mathcal{G} ; similarly, if \mathcal{F} and \mathcal{H} are finite locally free, so is \mathcal{G} .

Proof. From the internal perspective, we are given a short exact sequence of modules with the outer ones being finitely generated (resp. finite free) and we have to show that the middle one is finitely generated (resp. finite free) as well. It is well-known that this follows; and since the usual proof of this fact is intuitionistically acceptable, we are done. \square

Note that the proof works very generally, in the context of arbitrary ringed spaces, and is still very simple. This is common to proofs using the internal language. Particular features of schemes enter only at clearly recognizable points, for instance when an internal property specific to the structure sheaf of schemes is used (such as in Proposition 3.7).

Lemma 4.12. *Let X be a scheme (or ringed space).*

- *Let $0 \rightarrow \mathcal{F} \rightarrow \mathcal{G} \rightarrow \mathcal{H} \rightarrow 0$ be an exact sequence of \mathcal{O}_X -modules. If two of the three modules are coherent, so is the third.*
- *Let $\mathcal{F} \rightarrow \mathcal{G}$ be a morphism of \mathcal{O}_X -modules such that \mathcal{F} is of finite type and \mathcal{G} is coherent. Then its kernel is of finite type as well.*
- *If \mathcal{F} is a finitely presented \mathcal{O}_X -module and \mathcal{G} is a coherent \mathcal{O}_X -module, the \mathcal{O}_X -modules $\text{Hom}(\mathcal{F}, \mathcal{G})$ and $\mathcal{F} \otimes \mathcal{G}$ are coherent as well.*

Proof. These statements follow directly from interpreting the corresponding standard proofs of commutative algebra in the internal language. For those standard proofs, see for instance the lecture notes of Ravi Vakil [43, Section 13.8], where they are given as a series of exercises. \square

Lemma 4.13. *Let X be a scheme (or locally ringed space). Let $\alpha : \mathcal{G} \rightarrow \mathcal{H}$ be an epimorphism of finite locally free \mathcal{O}_X -modules. Then the kernel of α is finite locally free as well.*

Proof. It suffices to give an intuitionistic proof of the following statement: The kernel of a matrix over a local ring, which as a linear map is surjective, is finite free.

Let $M : R^{n \times m}$ be such a matrix. Since by the surjectivity assumption some linear combination of the columns is e_1 (the first canonical basis vector), some linear combination of the entries of the first row of M is 1. By locality of R , at least

one entry of the first row is invertible. By applying appropriate column and row transformations, we may therefore assume that M is of the form

$$\left(\begin{array}{c|ccc} 1 & 0 & \cdots & 0 \\ \hline 0 & & & \\ \vdots & & \widetilde{M} & \\ 0 & & & \end{array} \right)$$

with the submatrix \widetilde{M} fulfilling the same condition as M . Continuing in this way, it follows that $m \geq n$ and that we may assume that M is of the form

$$\left(\begin{array}{ccc|c} 1 & & & \\ & \ddots & & \\ & & 1 & 0 \end{array} \right).$$

The kernel of such a matrix is obviously freely generated by the canonical basis vectors corresponding to the zero columns. In particular, the rank of the kernel is $m - n$. \square

Remark 4.14. The internal language machinery gives no reason to believe that the dual statement is true, i. e. that the cokernel of a monomorphism of finite locally free \mathcal{O}_X -modules is finite locally free. This would follow from an intuitionistic proof of the statement that the cokernel of an injective map between finite free modules over a local ring is finite free. But this statement is of course false (consider the exact sequence $0 \rightarrow \mathbb{Z}_{(2)} \xrightarrow{\cdot 2} \mathbb{Z}_{(2)} \rightarrow \mathbb{F}_2 \rightarrow 0$ of $\mathbb{Z}_{(2)}$ -modules).

Lemma 4.15. *Let X be a scheme (or locally ringed space). Let $\alpha : \mathcal{G} \rightarrow \mathcal{H}$ be an epimorphism of finite locally free \mathcal{O}_X -modules of the same rank. Then α is an isomorphism.*

Proof. It suffices to give an intuitionistic proof of the following statement: A square matrix over a local ring, which as a linear map is surjective, is invertible.

This follows from the proof of the previous lemma, since it shows that the kernel of such a matrix is finite free of rank zero. \square

Lemma 4.16. *Let X be a scheme (or ringed space). Let $0 \rightarrow \mathcal{F} \rightarrow \mathcal{G} \rightarrow \mathcal{H} \rightarrow 0$ be a short exact sequence of \mathcal{O}_X -modules. Then for the closures of the supports there holds the equation $\text{cl supp } \mathcal{G} = \text{cl supp } \mathcal{F} \cup \text{cl supp } \mathcal{H}$.*

Proof. Switching to complements, we have to prove that

$$\text{int}(X \setminus \text{supp } \mathcal{G}) = \text{int}(X \setminus \text{supp } \mathcal{F}) \cap \text{int}(X \setminus \text{supp } \mathcal{H}).$$

By Proposition 4.7, it suffices to prove

$$\text{Sh}(X) \models (\mathcal{G} = 0 \iff \mathcal{F} = 0 \wedge \mathcal{H} = 0);$$

this is a basic observation in linear algebra, valid intuitionistically. \square

Of course, a stronger version of this lemma – about the supports themselves instead of their closures – is easily proven without using the internal language. We included this example only for illustrative purposes.

Lemma 4.17. *Let X be a scheme (or locally ringed space). Let \mathcal{L} be a line bundle on X , i. e. an \mathcal{O}_X -module locally free of rank 1. Let $s_1, \dots, s_n \in \Gamma(X, \mathcal{L})$ be global sections. Then these sections globally generate \mathcal{F} if and only if*

$$\mathrm{Sh}(X) \models \bigvee_i \alpha(s_i) \text{ is invertible for some isomorphism } \alpha : \mathcal{L} \rightarrow \mathcal{O}_X.$$

Proof. It suffices to give an intuitionistic proof of the following fact: Let R be a local ring. Let L be a free R -module of rank 1. Let $s_1, \dots, s_n : L$ be given elements. Then L is generated as an R -module by these elements if and only if for some i , the image of s_i under some isomorphism $L \rightarrow R$ is invertible.

Note that the choice of such an isomorphism does not matter, since any two such isomorphisms $\alpha, \beta : L \rightarrow R$ differ by a unit of R : $\alpha(x) = \alpha(\beta^{-1}(1)) \cdot \beta(x)$ for any $x : L$, and $\alpha(\beta^{-1}(1)) \cdot \beta(\alpha^{-1}(1)) = 1$ in R .

For the “if” direction, we have that some $\alpha(s_i)$ is a generator of R . Since α is an isomorphism, it follows that s_i generates L , and thus that in particular, the family s_1, \dots, s_n generates L .

For the “only if” direction, we have that the unit of R can be expressed as a linear combination of the $\alpha(s_i)$, where $\alpha : L \rightarrow R$ is some isomorphism (whose existence is assured by the assumption on the rank of L). Since R is a local ring, it follows that one of the summands and thus one of the $\alpha(s_i)$ is invertible. \square

Remark 4.18. Note that the canonical ring homomorphism $\mathcal{O}_{X,x} \rightarrow k(x)$ is local. Therefore a germ in $\mathcal{O}_{X,x}$ is invertible if and only if its image in $k(x)$ is not zero. From this one can follow that global sections $s_1, \dots, s_n \in \Gamma(X, \mathcal{F})$ generate \mathcal{F} if and only if, for any point $x \in X$, the images $s_i \in \mathcal{F}|_x$ in the fibers do not vanish simultaneously.

Lemma 4.19. *Let X be a scheme (or ringed space). Let \mathcal{L} be a locally free \mathcal{O}_X -module of rank 1. Then $\mathcal{L}^\vee \otimes_{\mathcal{O}_X} \mathcal{L} \cong \mathcal{O}_X$.*

Proof. Recall that the dual is defined by $\mathcal{L}^\vee := \mathcal{H}om_{\mathcal{O}_X}(\mathcal{L}, \mathcal{O}_X)$. Since “Hom” looks like “Hom” from the internal point of view, the dual sheaf \mathcal{L}^\vee looks just like the ordinary dual module. However, to prove the claim, it does *not* suffice to give an intuitionistic proof of the following fact of linear algebra: “Let L be a free R -module of rank 1. Then there exists an isomorphism $L^\vee \otimes_R L \rightarrow R$.” Since the interpretation of “ \exists ” using the Kripke–Joyal semantics is local existence, this would only show that $\mathcal{L}^\vee \otimes_{\mathcal{O}_X} \mathcal{L}$ is *locally* isomorphic to \mathcal{O}_X .

Instead, we have to actually *write down* (i. e. explicitly give) a linear map in the internal language – not using the assumption that L is free of rank 1, as this would introduce an existential quantifier again (see Section 2.2). So we have to prove the following fact: Let L be an R -module. Then there explicitly exists a linear map $L^\vee \otimes_R L \rightarrow R$ such that this map is an isomorphism if L is free of rank 1.

This is done as usual: Define $\alpha : L^\vee \otimes_R L \rightarrow R$ by $\lambda \otimes x \mapsto \lambda(x)$. Since L is free of rank 1, there is an isomorphism $L \cong R$. Precomposing α with the induced isomorphism $R^\vee \otimes_R R \rightarrow L^\vee \otimes_R L$, we obtain the linear map $R^\vee \otimes_R R \rightarrow R$ given by the same term: $\lambda \otimes x \mapsto \lambda(x)$. One can check that an inverse is given by $x \mapsto \mathrm{id}_R \otimes x$. \square

Lemma 4.20. *Let X be a scheme (or ringed space). Let \mathcal{F} be an \mathcal{O}_X -module.*

- (1) *Assume X to be a locally Noetherian scheme. Then \mathcal{F} is torsion-free (meaning $\mathcal{F}_{\mathrm{tors}} = 0$) if and only if all stalks \mathcal{F}_x are torsion-free.*

- (2) *The quotient sheaf $\mathcal{F}/\mathcal{F}_{\text{tors}}$ is torsion-free and the torsion submodule $\mathcal{F}_{\text{tors}}$ is a torsion module.*
- (3) *The dual sheaf \mathcal{F}^\vee is torsion-free.*
- (4) *If \mathcal{F} is reflexive (meaning that the canonical morphism $\mathcal{F} \rightarrow \mathcal{F}^{\vee\vee}$ is an isomorphism), it is torsion-free.*
- (5) *If \mathcal{F} is locally finitely free, it is reflexive.*
- (6) *Assume X to be a Dedekind scheme and \mathcal{F} to be of finite presentation. If \mathcal{F} is torsion-free, then it is locally finitely free.*

Proof. The first statement follows from the observation that $(\mathcal{F}_{\text{tors}})_x = (\mathcal{F}_x)_{\text{tors}}$ (Proposition 4.10). All the others follow simply by interpreting the corresponding facts of linear algebra in the internal universe. For concreteness, we give intuitionistic proofs of the last three statements.

So let M be an reflexive R -module. We have to show that M is torsion-free. To this end, let an element $x : M$ and a regular element $a : R$ such that $ax = 0$ be given. For any $\vartheta : M^\vee$, it follows that $\vartheta(x) = 0$, since $a\vartheta(x) = \vartheta(ax) = \vartheta(0) = 0$ and a is regular. Thus the image of x under the canonical map $M \rightarrow M^{\vee\vee}$ is zero. By reflexivity, this implies that x is zero.

For statement (5), we have to prove that R -modules of the form R^n are reflexive. This is obvious, the required inverse map is $(R^n)^{\vee\vee} \rightarrow R^n$, $\lambda \mapsto \sum_i \lambda(\vartheta_i)$ where $\vartheta_i : R^n \rightarrow R$, $(x_j)_j \mapsto x_i$.

In light of Corollary 3.20 we can put matrices over \mathcal{O}_X into Smith canonical form if X is a Dedekind scheme. Therefore it suffices to give an intuitionistic proof of the following fact: Let R be an integral domain in the strong sense such that matrices over R can be put into Smith canonical form. Let M be a finitely presented torsion-free R -module. Then M is finite free.

This goes as follows: Since M is finitely presented, it is the cokernel of some matrix. Without loss of generality, we may assume that it is a diagonal matrix, so M is isomorphic to some (finite) direct sum $\bigoplus_i R/(a_i)$. Since M is torsion-free, all the summands $R/(a_i)$ are torsion-free as well. Since R is an integral domain in the strong sense, this holds if and only if the a_i are either zero or invertible. Thus $R/(a_i)$ is isomorphic to R or to the zero module. In any case, $R/(a_i)$ is finite free and therefore M is finite free as well. \square

5. UPPER SEMICONTINUOUS FUNCTIONS

5.1. Interlude on natural numbers. In classical logic, the natural numbers are complete in the sense that any inhabited set of natural numbers possesses a minimal element. This statement can not be proven intuitionistically – intuitively, this is because one cannot explicitly pinpoint the (classically existing) minimal element of an arbitrary inhabited set;⁷ see below for a sheaf-theoretic interpretation.

In intuitionistic logic, the completeness principle can be salvaged in two essentially different ways: either by strengthening the premise, or by weakening the conclusion.

Lemma 5.1. *Let $U \subseteq \mathbb{N}$ be an inhabited subset of the natural numbers.*

⁷Let φ be an arbitrary formula. Assuming that any inhabited subset of the natural numbers possesses a minimal element, we want to show that $\varphi \vee \neg\varphi$. Define the subset $U := \{n \in \mathbb{N} \mid (n = 1) \vee \varphi\} \subseteq \mathbb{N}$, which surely is inhabited by $1 \in U$. So by assumption, there exists a number $z \in \mathbb{N}$ which is the minimum of U . We have $z = 0$ or $z > 0$. If $z = 0$, we have $0 \in U$, so $(0 = 1) \vee \varphi$, so φ holds. If $z > 0$, then $\neg\varphi$ holds: If φ were true, zero would be an element of U , contradicting the minimality of z .

- (1) Assume U to be detachable, i. e. assume that for any natural number n , either $n \in U$ or $n \notin U$. Then U possesses a minimal element.
- (2) In any case, U does not not possess a minimal element.

Proof. The first statement can be proven by induction on the witness of inhabitation, i. e. the given number n such that $n \in U$. We omit further details, since we will not need this statement in our applications.

For the second statement, we give a careful proof since logical subtleties matter. To simplify the exposition, we assume that U is upward-closed, i. e. that any number larger than some element of U lies in U as well. Any subset can be closed in this way (by considering $\{n \in \mathbb{N} \mid \exists m \in U. n \geq m\}$) and a minimal element of the closure will be a minimal element for U as well.

We induct on the number $n \in U$ given by the assumption that U is inhabited. In the case $n = 0$ we are done since 0 is a minimal element of U . For the induction step $n \rightarrow n + 1$, the intuitionistically valid double negation of the law of excluded middle gives

$$\neg\neg(n \in U \vee n \notin U).$$

Because of the tautologies $(\varphi \Rightarrow \psi) \Rightarrow (\neg\neg\varphi \Rightarrow \neg\neg\psi)$ and $\neg\neg\neg\neg\varphi \Rightarrow \neg\neg\varphi$ (see Section 2.4), it suffices to show that $n \in U \vee n \notin U$ implies the conclusion. So assume $n \in U \vee n \notin U$. If $n \in U$, then U does *not not* possess a minimal element by the induction hypothesis. If $n \notin U$, then $n + 1$ is a minimal element (and so, in particular, U does *not not* possess a minimal element): If m is any element of U , we have $m \geq n + 1$ or $m \leq n$. In the first case, we're done. In the second case, it follows that $n \in U$ because U is upward-closed and so we obtain a contradiction. From this contradiction we can trivially deduce $m \geq n + 1$ as well. \square

If we want to work with a complete partially ordered set (poset) of natural numbers in intuitionistic logic, we have to construct a suitable completion. The idea of the following definition is to encode numbers as the (not necessarily existing) minimum of inhabited upward-closed subsets.

Definition 5.2. The *completed poset of natural numbers* the set $\widehat{\mathbb{N}}$ of all inhabited upward-closed subsets of \mathbb{N} , ordered by reverse inclusion. The elements of $\widehat{\mathbb{N}}$ are called *generalized natural numbers*.

Lemma 5.3. The *completed poset of natural numbers* is the least poset containing \mathbb{N} and possessing minima of arbitrary inhabited subsets.

Proof. The embedding $\mathbb{N} \hookrightarrow \widehat{\mathbb{N}}$ is given by

$$n \in \mathbb{N} \quad \longmapsto \quad \uparrow(n) := \{m \in \mathbb{N} \mid m \geq n\}.$$

If $M \subseteq \widehat{\mathbb{N}}$ is an inhabited subset, its minimum is

$$\min M = \bigcup M \in \widehat{\mathbb{N}}.$$

We omit the proof of the universal property. \square

Remark 5.4. In classical logic, the map $\widehat{\mathbb{N}} \rightarrow \mathbb{N}$, $U \mapsto \min U$ is a well-defined isomorphism of partially ordered sets. In fact, it is the inverse of the canonical embedding $\mathbb{N} \hookrightarrow \widehat{\mathbb{N}}$. In intuitionistic logic, this embedding is still injective, but it can not be shown to be surjective: It is only the case that any element of $\widehat{\mathbb{N}}$ does *not not* possess a preimage (by Lemma 5.1).

5.2. A geometric interpretation. We are interested in the completed natural numbers for the following reason: A generalized natural number in the topos of sheaves on a topological space X is the same as an upper semicontinuous function $X \rightarrow \mathbb{N}$.

Lemma 5.5. *Let X be a topological space. The sheaf $\widehat{\mathbb{N}}$ of generalized natural numbers on X is canonically isomorphic to the sheaf of upper semicontinuous \mathbb{N} -valued functions on X .*

Proof. When referring to the natural numbers in the internal language, we actually refer to the constant sheaf $\underline{\mathbb{N}}$ on X . (This is because the sheaf $\underline{\mathbb{N}}$ fulfills the axioms of a natural numbers object, cf. [32, section VI.1].) Recall that its sections on an open subset $U \subseteq X$ are continuous functions $U \rightarrow \mathbb{N}$, where \mathbb{N} is equipped with the discrete topology.

Therefore, a section of $\widehat{\mathbb{N}}$ on an open subset $U \subseteq X$ is given by a subsheaf $\mathcal{A} \hookrightarrow \underline{\mathbb{N}}|_U$ such that

$$U \models \exists n : \underline{\mathbb{N}}. n \in \mathcal{A} \quad \text{and} \quad U \models \forall n, m : \underline{\mathbb{N}}. n \geq m \wedge n \in \mathcal{A} \Rightarrow m \in \mathcal{A}.$$

Since these conditions are geometric implications, they are satisfied if and only if any stalk \mathcal{A}_x is an inhabited upward-closed subset of $\underline{\mathbb{N}}_x \cong \mathbb{N}$. The association

$$x \in X \quad \longmapsto \quad \min\{n \in \mathbb{N} \mid n \in \mathcal{A}_x\}$$

thus defines a map $X \rightarrow \mathbb{N}$. This map is indeed upper semicontinuous, since if $n \in \mathcal{A}_x$, there exists an open neighbourhood V of x such that the constant function with value n is an element of $\Gamma(V, \mathcal{A})$ and therefore $n \in \mathcal{A}_y$ for all $y \in V$.

Conversely, let $\alpha : U \rightarrow \mathbb{N}$ be a upper semi-continuous function. Then

$$V \subseteq U \text{ open} \quad \longmapsto \quad \{f : V \rightarrow \mathbb{N} \mid f \text{ continuous, } f \geq \alpha \text{ on } V\}$$

is a subobject of $\underline{\mathbb{N}}|_U$ which internally is inhabited and upward-closed. Further details are left to the reader. \square

Under the correspondence given by the lemma, locally *constant* functions map exactly to the (image of the) *ordinary* internal natural numbers (in the completed natural numbers). In a similar vein, the sheaf given by the internal construction of the set of *all* upward-closed subsets of the natural numbers (not only the inhabited ones) is canonically isomorphic to the sheaf of upper semicontinuous functions with values in $\mathbb{N} \cup \{+\infty\}$.

Note that the correspondence can be used to understand classical facts about upper semicontinuous functions as features of intuitionistic number theory. For instance, it is well-known that any upper semicontinuous \mathbb{N} -valued function on an arbitrary topological space is locally constant on a dense open subset. This can be explained as follows: The generalized natural number associated to such a function is *not not* an ordinary natural number from the internal point of view. Since “not not” translates to “holding on a dense open subset” (Proposition 6.4), it follows that there is a dense open subset on which the function corresponds to an ordinary internal natural number, i. e. is locally constant.

5.3. The upper semicontinuous rank function. Recall that the rank of an \mathcal{O}_X -module \mathcal{F} on a scheme X (or locally ringed space) at a point $x \in X$ is defined as the $k(x)$ -dimension of the vector space $\mathcal{F}_x \otimes_{\mathcal{O}_{X,x}} k(x)$. If we assume that \mathcal{F} is of

finite type around x , this dimension is finite and equals the minimal number of elements needed to generate \mathcal{F}_x as an $\mathcal{O}_{X,x}$ -module (by Nakayama's lemma).

In the internal language, we can define an element of $\widehat{\mathbb{N}}$ by

$$\text{rank } \mathcal{F} := \min\{n \in \mathbb{N} \mid \ulcorner \text{there is a gen. family for } \mathcal{F} \text{ consisting of } n \text{ elements} \urcorner\} \in \widehat{\mathbb{N}}.$$

If the module \mathcal{F} is finite locally free, it will be a finite free module from the internal point of view and the rank defined in this way will be an actual natural number (see below); but in general, the rank is really an element of the completion.

Proposition 5.6. *Let \mathcal{F} be an \mathcal{O}_X -module of finite type on a scheme X (or locally ringed space). Under the correspondence given by the previous lemma, the internally defined rank maps to the rank function of \mathcal{F} .*

Proof. We have to show that for any point $x \in X$ and natural number n , there exists a generating family for \mathcal{F}_x consisting of n elements if and only if there exists an open neighbourhood U of x such that

$$U \models \ulcorner \text{there exists a generating family for } \mathcal{F} \text{ consisting of } n \text{ elements} \urcorner.$$

The “if” direction is obvious. For the “only if” direction, consider (liftings to local sections of a) generating family s_1, \dots, s_n of \mathcal{F}_x . Since \mathcal{F} is of finite type, there also exist sections t_1, \dots, t_m on some neighbourhood V of x which generate any stalk \mathcal{F}_y , $y \in V$. Since the t_i can be expressed as a linear combination of the s_j in \mathcal{F}_x , the same is true on some open neighbourhood $U \subseteq V$ of x . On this neighbourhood, the s_j generate any stalk \mathcal{F}_y , $y \in U$, so by geometricity we have

$$U \models \ulcorner s_1, \dots, s_n \text{ generate } \mathcal{F} \urcorner. \quad \square$$

Remark 5.7. Once we understand when properties holding at a point spread to neighbourhoods, we will be able to give a simpler proof of the proposition (see Lemma 6.40).

Lemma 5.8. *Let X be a scheme (or a locally ringed space). Let \mathcal{F} be an \mathcal{O}_X -module of finite type. If \mathcal{F} is finite locally free, its rank function is locally constant. The converse holds if X is a reduced scheme.*

Proof. The rank function is locally constant if and only if internally, the rank of \mathcal{F} is an actual natural number. Also recall that the structure sheaf fulfills a certain field condition if X is a reduced scheme (Corollary 3.9). Therefore it suffices to give a proof of the following fact of intuitionistic linear algebra: Let R be a local ring. Let M be a finitely generated R -module. If M is finite free, its rank is an actual natural number. The converse holds if R fulfills the field condition that any element which is not invertible is zero.

So assume that such a module M is finite free. Then it is isomorphic to R^n for some actual natural number n ; by the internal proof in Lemma 4.13, the rank of M is therefore this number n (for any surjection $R^m \twoheadrightarrow R^n$ it holds that $m \geq n$).

Conversely, assume that the rank of M is an actual natural number. Then there exists a minimal generating family $x_1, \dots, x_n : M$. We can verify that this family is indeed linearly independent (and thus a basis, demonstrating that M is finite free): Let $\sum_i a_i x_i = 0$ with $a_i : R$. If any a_i were invertible, the family $x_1, \dots, x_{i-1}, x_{i+1}, \dots, x_n$ would too generate M , contradicting the minimality. So each a_i is not invertible. By the field property of R , each a_i is zero. \square

Lemma 5.9. *Let X be a reduced scheme. Let \mathcal{F} be an \mathcal{O}_X -module of finite type. Then \mathcal{F} is finite locally free on a dense open subset.*

Proof. Since “dense open” translates to “not not” in the internal language (Proposition 6.4), it suffices to give an intuitionistic proof of the following fact: Let R be a local ring which fulfills an appropriate field condition. Let M be a finitely generated R -module. Then R is *not not* finite free.

By Remark 5.4, the rank of such a module M is *not not* an actual natural number. By the last part of the previous proof, it thus follows that M is *not not* finite free. \square

Remark 5.10. Note that besides basics on natural numbers in an intuitionistic setting and some dictionary terms (“reduced”, “finite locally free”, “finite type“, “dense open”), this proof does not depend on any further tools. In particular, Nakayama’s lemma and facts about semicontinuous functions do not enter. For the (more complex) standard proof of this fact, see for instance [43], where the claim is dubbed an “important hard exercise” (Exercise 13.7.K).

5.4. The upper semicontinuous dimension function. Recall that the dimension of a topological space X at a point $x \in X$ is defined as the infimum

$$\dim_x X := \inf\{\dim U \mid U \text{ open neighbourhood of } x\}.$$

One may restrict to open *connected* neighbourhoods of X , since an arbitrary open neighbourhood of x contains such a one and the dimension decreases (weakly) on subsets.

The map $X \rightarrow \mathbb{N} \cup \{+\infty\}$, $x \mapsto \dim_x X$ is upper semicontinuous and thus corresponds to an internal generalized (possibly unbounded) natural number. The following proposition shows that this number has an explicit description.

Proposition 5.11. *Let X be a scheme. Then the upper semicontinuous function associated to the internal number “Krull dimension of \mathcal{O}_X ” is the dimension function $x \mapsto \dim_x X$.*

Proof. Internally, we define the Krull dimension of \mathcal{O}_X as the infimum over all natural numbers n such that \mathcal{O}_X is of Krull dimension $\leq n$. This infimum need not exist in the natural numbers, of course; so we really mean the upward-closed set \mathcal{A} of all those numbers. (It is inhabited if and only if, from the external perspective, the dimension of X is locally finite. In this case, it defines a generalized natural number.)

We thus have to show for any point $x \in X$:

$$\inf\{n \in \mathbb{N} \cup \{+\infty\} \mid n \in \mathcal{A}_x\} = \dim_x X.$$

The condition on n can be expressed as follows, where we write “ \underline{n} ” to denote the constant function with value n :

$$\begin{aligned}
 & n \in \mathcal{A}_x \\
 \iff & \text{for some open neighbourhood } U \text{ of } x, \underline{n} \in \Gamma(U, \mathcal{A}) \\
 \iff & \text{for some open connected neighbourhood } U \text{ of } x, \underline{n} \in \Gamma(U, \mathcal{A}) \\
 \iff & \text{for some open connected neighbourhood } U \text{ of } x, \\
 & U \models \ulcorner \mathcal{O}_X \text{ is of Krull dimension } \leq n \urcorner \\
 \iff & \text{for some open connected neighbourhood } U \text{ of } x, \\
 & \dim U \leq n
 \end{aligned}$$

We thus have:

$$\begin{aligned}
 \inf\{n \mid n \in \mathcal{A}_x\} &= \inf\{\dim U \mid U \text{ open connected neighbourhood of } x\} \\
 &= \dim_x X. \quad \square
 \end{aligned}$$

6. MODALITIES

Philosophers and logicians do not only study what is *true*, but also what is *known*, what is *believed*, what is *possible*, and so on. Such *modalities* are absent from the usual mathematical practice. However, it turns out that a specific kind of such modalities plays a role in understanding when properties spread from points to neighbourhoods.

Briefly, this is because for any point x of a topological space X , there exists a modal operator \Box such that for any formula φ of the internal language of the sheaf topos $\text{Sh}(X)$, the internal statement $\Box\varphi$ means that φ holds on some open neighbourhood of the given point x . In this way, we can reduce sheaf-theoretic questions to questions of modal intuitionistic (non-sheafy) mathematics.

The techniques developed in this section also enable us to use the internal language of $\text{Sh}(X)$ to talk about sheaves on *subspaces* of X (and more general *sublocales* of X).

Topological interpretations of modal logic were studied before, for instance by Awodey and Kishida [3]. However, they study a different kind of modal operators, not corresponding to the Lawvere–Tierney topologies of topos theory, and pursue different goals.

6.1. Basics on truth values and modal operators.

Definition 6.1. The *set of truth values* Ω is the powerset of the singleton set $1 := \{\star\}$, where \star is a formal symbol.

In classical logic, any subset of $\{\star\}$ is either empty or inhabited, so that Ω contains exactly two elements, the empty set (“false”) and $\{\star\}$ (“true”). But in intuitionistic logic, this can not be shown; indeed, if we interpret the definition in the topos of sheaves on a space X , we obtain a (large) sheaf Ω with

$$U \subseteq X \text{ open} \longmapsto \Gamma(U, \Omega) = \{V \subseteq U \mid V \text{ open}\}.$$

(This is because by definition of Ω as the power object of the terminal sheaf 1 , sections of Ω on an open subset U correspond to subsheaves $\mathcal{F} \hookrightarrow 1|_U$, and those are given by the greatest open subset $V \subseteq U$ such that $\Gamma(V, \mathcal{F})$ is inhabited.)

Obviously, in general, this sheaf has many sections, in particular more than the binary coproduct $1 \amalg 1$ (unless any open subset of X is also closed).

The *truth value* of a formula φ is by definition the subset $\{x \in 1 \mid \varphi\} \in \Omega$, where “ x ” is a fresh variable not appearing in φ . This subset is inhabited if and only if φ holds and is empty if and only if $\neg\varphi$ holds. Conversely, we can associate to a subset $F \subseteq 1$ the proposition “ F is inhabited”.

By the above description of Ω in a sheaf topos $\text{Sh}(X)$, the interpretation of the truth value of a formula φ in the internal language of $\text{Sh}(X)$ is a certain open subset of X . Tracing the definitions, we see that this open subset is precisely the largest open subset on which φ holds, i. e. the union of all open subsets $U \subseteq X$ such that $U \models \varphi$.

Under the correspondence of formulas with truth values, logical operations like \wedge and \vee map to set-theoretic operations like \cap and \cup – for instance, we have

$$\{x \in 1 \mid \varphi\} \cap \{x \in 1 \mid \psi\} = \{x \in 1 \mid \varphi \wedge \psi\}.$$

This justifies a certain abuse of notation: We will sometimes treat elements of Ω as propositions and use logical instead of set-theoretic connectives. In particular, if φ and ψ are elements of Ω , we will write “ $\varphi \Rightarrow \psi$ ” to mean $\varphi \subseteq \psi$; “ \perp ” to mean \emptyset ; and “ \top ” to mean 1 .

Definition 6.2. A *modal operator* (or *Lawvere–Tierney topology*) is a map $\Box : \Omega \rightarrow \Omega$ such that for all $\varphi, \psi \in \Omega$,

- (1) $\varphi \Rightarrow \Box\varphi$,
- (2) $\Box\Box\varphi \Rightarrow \Box\varphi$,
- (3) $\Box(\varphi \wedge \psi) \iff \Box\varphi \wedge \Box\psi$.

The intuition is that $\Box\varphi$ is a certain weakening of φ , where the precise meaning of “weaker” depends on the modal operator. By the second axiom, weakening twice is the same as weakening once.

In classical logic, where $\Omega = \{\perp, \top\}$, there are only two modal operators: the identity map and the constant map with value \top . Both of these are not very interesting: The identity operator does not weaken propositions at all, while the constant operator weakens every proposition to the trivial statement \top .

In intuitionistic logic, there can potentially exist further modal operators. For applications to algebraic geometry, the following four operators will have a clear geometric meaning and be of particular importance:

- (1) $\Box\varphi \equiv (\alpha \Rightarrow \varphi)$, where α is a fixed proposition.
- (2) $\Box\varphi \equiv (\varphi \vee \alpha)$, where α is a fixed proposition.
- (3) $\Box\varphi \equiv \neg\neg\varphi$ (the *double negation modality*).
- (4) $\Box\varphi \equiv ((\varphi \Rightarrow \alpha) \Rightarrow \alpha)$, where α is a fixed proposition.

Lemma 6.3. Any modal operator \Box is monotonic, i. e. if $\varphi \Rightarrow \psi$, then $\Box\varphi \Rightarrow \Box\psi$. Furthermore, there holds a modus ponens rule: If $\Box\varphi$ holds, and φ implies $\Box\psi$, then $\Box\psi$ holds as well.

Proof. Assume $\varphi \Rightarrow \psi$. This is equivalent to supposing $\varphi \wedge \psi \Leftrightarrow \varphi$. We are to show that $\Box\varphi \Rightarrow \Box\psi$, i. e. that $\Box\varphi \wedge \Box\psi \Leftrightarrow \Box\varphi$. This follows since by the third axiom on a modal operator, we have $\Box\varphi \wedge \Box\psi \Leftrightarrow \Box(\varphi \wedge \psi)$, and \Box respects equivalence of propositions.

For the second statement, consider that if $\varphi \Rightarrow \Box\psi$, by monotonicity and the second axiom on a modal operator it follows that $\Box\varphi \Rightarrow \Box\Box\psi \Rightarrow \Box\psi$. \square

The modus ponens rule justifies the following proof scheme: When trying to show, given that some boxed statement $\Box\varphi$ holds, that some further boxed statement $\Box\psi$ holds, we may give a proof of $\Box\psi$ under the stronger assumption φ . Symbolically:

$$(\Box\varphi \Rightarrow \Box\psi) \iff (\varphi \Rightarrow \Box\psi).$$

6.2. Geometric meaning. Let X be a topological space. As discussed above, an open subset $U \subseteq X$ defines an internal truth value (a global section of the sheaf Ω). We also denote it by “ U ”, such that

$$V \models U \iff V \subseteq U$$

for any open subset $V \subseteq X$. (Shortcutting the various intermediate steps, this can also be taken as a definition of “ $V \models U$ ”.) If $A \subseteq X$ is a closed subset, there is thus an internal truth value A^c corresponding to the open subset $A^c = X \setminus A$. If $x \in X$ is a point, we define “ $!x$ ” to denote the truth value corresponding to $\text{int}(X \setminus \{x\})$, such that

$$V \models !x \iff V \subseteq \text{int}(X \setminus \{x\}) \iff x \notin V.$$

Proposition 6.4. *Let $U \subseteq X$ be a fixed open and $A \subseteq X$ be a fixed closed subset. Let $x \in X$. Then, for any open subset $V \subseteq X$, it holds that:*

$$\begin{aligned} V \models (U \Rightarrow \varphi) &\iff V \cap U \models \varphi. \\ V \models (\varphi \vee A^c) &\iff \text{there is an open subset } W \subseteq V \\ &\quad \text{containing } A \cap V \text{ such that } W \models \varphi. \\ V \models \neg\neg\varphi &\iff \text{there is a dense open subset } W \subseteq V \text{ s.t. } W \models \varphi. \\ V \models ((\varphi \Rightarrow !x) \Rightarrow !x) &\iff x \notin V \text{ or there is an open neighbourhood } W \subseteq V \\ &\quad \text{of } x \text{ such that } W \models \varphi. \end{aligned}$$

Proof. (1) Omitted.

- (2) Let $V \models \varphi \vee A^c$. Then there exists an open covering $V = \bigcup_i V_i$ such that for each i , $V_i \models \varphi$ or $V_i \subseteq A^c$. Let $W \subseteq V$ be the union of those V_i such that $V_i \models \varphi$. Then $W \models \varphi$ by the locality of the internal language and $A \cap V \subseteq W$.

Conversely, let $W \subseteq V$ be an open subset containing $A \cap V$ such that $W \models \varphi$. Then $V = W \cup (V \cap A^c)$ is an open covering attesting $V \models \varphi \vee A^c$.

- (3) For the “only if” direction, let $W \subseteq V$ be the largest open subset on which φ holds, i.e. the union of all open subsets of V on which φ holds. For the “if” direction, we may assume that the given set W is also the largest open subset on which φ holds (by enlarging W if necessary). The claim then follows by the following chain of equivalences:

$$\begin{aligned} V \models \neg\neg\varphi &\iff \forall Y \subseteq V \text{ open. } (\forall Z \subseteq Y \text{ open. } (Z \models \varphi) \Rightarrow Z = \emptyset) \implies Y = \emptyset \\ &\iff \forall Y \subseteq V \text{ open. } (\forall Z \subseteq Y \text{ open. } Z \subseteq W \Rightarrow Z = \emptyset) \implies Y = \emptyset \\ &\iff \forall Y \subseteq V \text{ open. } Y \cap W = \emptyset \implies Y = \emptyset \\ &\iff W \text{ is dense in } V. \end{aligned}$$

Modal operator	associated nucleus	$j(V) = X$ iff ...	subspace
$\Box\varphi := (U \Rightarrow \varphi)$	$j(V) = \text{int}(U^c \cup V)$	$U \subseteq V$	U
$\Box\varphi := (\varphi \vee A^c)$	$j(V) = V \cup A^c$	$A \subseteq V$	A
$\Box\varphi := \neg\neg\varphi$	$j(V) = \text{int}(\text{cl}(V))$	V is dense in X	smallest dense sublocale of X
$\Box\varphi := ((\varphi \Rightarrow !x) \Rightarrow !x)$	$j(V) = X \setminus \text{cl}\{x\},$ if $x \notin V$ $j(V) = X,$ if $x \in V$	$x \in V$	$\{x\}$

TABLE 2. List of important modal operators and their associated nuclei (notation as in Proposition 6.4).

- (4) Straightforward, since the interpretation of the internal statement with the Kripke–Joyal semantics is

$$\forall Y \subseteq V \text{ open. } \left(\forall Z \subseteq Y \text{ open. } Z \models \varphi \Rightarrow x \notin Z \right) \implies x \notin Y. \quad \square$$

6.3. The subspace associated to a modal operator. Any modal operator $\Box : \Omega \rightarrow \Omega$ in the sheaf topos of X induces on global sections a map

$$j : \text{Op}(X) \rightarrow \text{Op}(X),$$

where $\text{Op}(X) = \Gamma(X, \Omega)$ is the set of open subsets of X . Explicitly, it is given by

$$\begin{aligned} j(U) &= \text{largest open subset of } X \text{ on which } \Box U \text{ holds} \\ &= \bigcup \{V \subseteq X \mid V \text{ open, } V \models \Box U\}. \end{aligned}$$

By the axioms on a modal operator, the map j fulfills similar such axioms: For any open subsets $U, V \subseteq X$,

- (1) $U \subseteq j(U)$,
- (2) $j(j(U)) \subseteq j(U)$,
- (3) $j(U \cap V) = j(U) \cap j(V)$.

Such a map is called a *nucleus* on $\text{Op}(X)$. table 2 lists the nuclei associated to the four modal operators of Proposition 6.4.

Any nucleus j defines a subspace X_j of X , to be described below, with a small caveat: In general, the subspace X_j can not be realized as a topological subspace, but only as a so-called *sublocale*; the notion of a locale is a slight generalization of the notion of a topological space, in which an underlying set of points is not part of the definition. Instead, a locale is simply given by a lattice of arbitrary *opens* satisfying some axioms – these opens may, but do not necessarily have to, be sets of points. Sheaf theory carries over to locales essentially unchanged, since the notions of presheaves and sheaves only refer to open sets and coverings, but not points. Accessible introductions to the theory of locales include two notes by Johnstone [26, 27].

Definition 6.5. Let j be a nucleus on $\text{Op}(X)$. Then the sublocale X_j of X is given by the lattice of opens $\text{Op}(X_j) := \{U \in \text{Op}(X) \mid j(U) = U\}$.

If j is induced by a modal operator \Box , we also write “ X_\Box ” for X_j . In three of the four cases listed in Table 2, the sublocale X_\Box can indeed be realized as a topological subspace. The only exception is the sublocale $X_{\neg\neg}$ associated to the double negation modality. It can be also be described as the *smallest dense sublocale* of X ; this is obviously a genuine locale-theoretic notion, since there is (in general) no smallest dense topological subspace (consider \mathbb{R} and its dense subsets \mathbb{Q} and $\mathbb{R} \setminus \mathbb{Q}$).

The inclusion $i : X_j \hookrightarrow X$ can not in general be described on the level of points, since X_j might not be realizable as a topological subspace. But for sheaf-theoretic purposes, it suffices to describe i on the level of opens. This is done as follows:

$$i^{-1} : \text{Op}(X) \longrightarrow \text{Op}(X_j), \quad U \longmapsto j(U).$$

Thus we can relate the toposes of sheaves on X_j and X by the usual pullback and pushforward functors.

$$\begin{aligned} i^{-1}\mathcal{F} &= \text{sheafification of } (U \mapsto \text{colim}_{V \leq i^{-1}U} \Gamma(V, \mathcal{F})) \\ i_*\mathcal{G} &= (U \mapsto \Gamma(i^{-1}U, \mathcal{G})) = (U \mapsto \Gamma(j(U), \mathcal{G})) \end{aligned}$$

As familiar from honest topological subspace inclusions, the pushforward functor $i_* : \text{Sh}(X_j) \rightarrow \text{Sh}(X)$ is fully faithful and the composition $i^{-1} \circ i_* : \text{Sh}(X_j) \rightarrow \text{Sh}(X_j)$ is (canonically isomorphic to) the identity.

6.4. Internal sheaves and sheafification. It turns out that the image of the pushforward functor $i_* : \text{Sh}(X_\Box) \rightarrow \text{Sh}(X)$, where \Box is a modal operator in $\text{Sh}(X)$, can be explicitly described. Namely, it consists exactly of those sheaves which from the internal point of view are so-called \Box -*sheaves*, a notion explained below.

Furthermore, if we identify $\text{Sh}(X_\Box)$ with its image in $\text{Sh}(X)$, the pullback functor is given by an internal sheafification process with respect to the modality \Box . Thus the external situation of pushforward/pullback translates to forget/sheafify. This broadens the scope of the internal language of $\text{Sh}(X)$: It can not only be used to talk about sheaves on X in a simple, element-based language, but also to talk about sheaves on arbitrary subspaces of X .

To describe the notion of \Box -sheaves and related ones, we switch to the internal perspective and thus forget X ; we are simply given a modal operator $\Box : \Omega \rightarrow \Omega$ and have to take care that our proofs are intuitionistically acceptable. A reference for the material in this subsection is a preprint by Fer-Jan de Vries [46].⁸

Recall that a set S is a *subsingleton* if and only if $\forall x, y : S. x = y$, and that a set S is a *singleton* if and only if it is a subsingleton and inhabited (i. e. $\exists x : S$); this amounts to $\exists! x : S$.

Definition 6.6. A set F is \Box -*separated* if and only if

$$\forall x, y : F. \Box(x = y) \implies x = y.$$

A set F is a \Box -*sheaf* if and only if it is \Box -separated and

$$\forall S \subseteq F. \Box(\ulcorner S \text{ is a singleton} \urcorner) \implies \exists x : F. \Box(x \in S).$$

⁸Note that on page 5 of that preprint there is a slight typing error: Fact 2.1(i) gives the characterization of j -closedness, not j -denseness. The correct characterization of j -denseness in that context is $\forall b \in B. j(b \in A)$.

The two conditions can be combined: A set F is a \Box -sheaf if and only if

$$\forall S \subseteq F. \Box(\ulcorner S \text{ is a singleton} \urcorner) \implies \exists! x : F. \Box(x \in S).$$

XXX: explain how to read these definitions

Definition 6.7. The *plus construction* of a set F with respect to \Box is the set

$$F^+ := \{S \subseteq F \mid \Box(\ulcorner S \text{ is a singleton} \urcorner)\} / \sim,$$

where the equivalence relation is defined by $S \sim T :\Leftrightarrow \Box(S = T)$. There is a canonical map $F \rightarrow F^+$ given by $x \mapsto [\{x\}]$. The \Box -sheafification of a set F is the set F^{++} .

If F is \Box -separated, then for any subset $S \subseteq F$ it holds that

$$\Box(\ulcorner S \text{ is a singleton} \urcorner) \iff \ulcorner S \text{ is a subsingleton} \urcorner \wedge \Box(\ulcorner S \text{ is inhabited} \urcorner).$$

Remark 6.8. The topos of presheaves on a topological space X admits an internal language as well [32, Section VI.7, discussion after Theorem 1]. In it, there exists a modal operator \Box reflecting the topology of X . A presheaf on X is separated in the usual sense if, from the internal perspective of $\mathbf{PSh}(X)$, it is \Box -separated; and it is a sheaf if, from the internal perspective, it is a \Box -sheaf. Furthermore, the \Box -sheafification of a presheaf (considered as a set from the internal perspective) coincides with the usual sheafification.

Example 6.9. Any singleton set is a \Box -sheaf. The empty set is always \Box -separated (trivially) and is a \Box -sheaf if and only if $\Box \perp \Rightarrow \perp$.

We will see geometric examples of \Box -sheaves in further sections. For instance, on an integral scheme X , the structure sheaf \mathcal{O}_X is $\neg\neg$ -separated and its $\neg\neg$ -sheafification is the sheaf \mathcal{K}_X of rational functions (Proposition 7.9).

Lemma 6.10. *For any set F , it holds that:*

- (1) F^+ is \Box -separated.
- (2) The canonical map $F \rightarrow F^+$ is injective if and only if F is \Box -separated.
- (3) If F is \Box -separated, then F^+ is a \Box -sheaf.
- (4) If F is a \Box -sheaf, then the canonical map $F \rightarrow F^+$ is bijective.

Let “ $\mathbf{Sh}_\Box(\mathbf{Set})$ ” denote the full subcategory of \mathbf{Set} consisting of the \Box -sheaves. Then it holds that:

- (5) The functor $(_)^+ : \mathbf{Set} \rightarrow \mathbf{Set}$ is left exact.
- (6) The functor $(_)^{++} : \mathbf{Set} \rightarrow \mathbf{Sh}_\Box(\mathbf{Set})$ is left exact and left adjoint to the forgetful functor $\mathbf{Sh}_\Box(\mathbf{Set}) \rightarrow \mathbf{Set}$, $F \mapsto F$.

Proof. These are all straightforward, and in fact simpler than their classical counterparts, since there are no colimit constructions which would have to be dealt with. \square

Remark 6.11. As is to be expected from the familiar inclusion of sheaves in presheaves on topological spaces, the forgetful functor $\mathbf{Sh}_\Box(\mathbf{Set}) \rightarrow \mathbf{Set}$ does not in general preserve colimits. It is instructive to see why epimorphisms in $\mathbf{Sh}_\Box(\mathbf{Set})$ need not be epimorphisms in \mathbf{Set} : A map $f : A \rightarrow B$ between \Box -sheaves is an epimorphism in $\mathbf{Sh}_\Box(\mathbf{Set})$ if and only if

$$\forall y : B. \Box(\exists x : X. f(x) = y),$$

i. e. preimages do not need to exist, it suffices for them to “ \Box -exist”. (Using results about the \Box -translation, to be introduced below, this characterization will be obvious.) This condition is intuitionistically weaker than the condition that f is an epimorphism in \mathbf{Set} , i. e. that f is surjective. Compare this to the failure of the forgetful functor $\mathbf{Sh}(X) \rightarrow \mathbf{PSh}(X)$ to preserve epimorphisms: A morphism of sheaves does not need to have preimages for any local section in order to be an epimorphism. Instead, it suffices for any local section to *locally* have preimages.

Proposition 6.12. *Let X be a topological space. Let \Box be a modal operator in $\mathbf{Sh}(X)$. Let $i : X_\Box \hookrightarrow X$ be the inclusion of the associated sublocale. Corestricting the pushforward functor $i_* : \mathbf{Sh}(X_\Box) \rightarrow \mathbf{Sh}(X)$ to its essential image, it induces an equivalence $\mathbf{Sh}(X_\Box) \simeq \mathbf{Sh}_\Box(\mathbf{Sh}(X))$ between the category of sheaves on X_\Box and the category of \Box -sheaves in $\mathbf{Sh}(X)$.*

Proof. For the further development of the theory, we need the statement of this proposition, but not the proof, which really is routine in dealing with subtoposes and modal operators. Nevertheless, a proof goes like follows: Combine Example A4.6.2(a) and Theorem C1.4.7 of [25] and note that for a topos of sheaves on a locale Y , it holds that $\mathbf{Op}(Y) = \Gamma(Y, \Omega_{\mathbf{Sh}(Y)})$, and that the subobject classifier of $\mathbf{Sh}_\Box(\mathbf{Sh}(X))$ is $\{\varphi : \Omega_{\mathbf{Sh}(X)} \mid \Box\varphi \Leftrightarrow \varphi\}$. \square

6.5. Sheaves for the double negation modality. Recall that if \Box is the modal operator associated to a subspace Y of a topological space X , then the sheaves on X which are \Box -sheaves are easy to describe: These are precisely the sheaves in the essential image of the pushforward functor $\mathbf{Sh}(Y) \rightarrow \mathbf{Sh}(X)$. For the double negation modality, the same is true, only that Y is then the perhaps unfamiliar *smallest dense sublocale* of X .

The following proposition gives a characterization of $\neg\neg$ -separated presheaves and $\neg\neg$ -sheaves in explicit terms.

Proposition 6.13. *Let X be a topological space. Let \mathcal{F} be a sheaf on X . Then:*

- (1) *\mathcal{F} is $\neg\neg$ -separated if and only if any two local sections of \mathcal{F} , which are defined on a common domain and which agree on a dense open subset of their domain, are already equal.*
- (2) *\mathcal{F} is a $\neg\neg$ -sheaf if and only if it is $\neg\neg$ -separated and for any open subset $U \subseteq X$ and any open subset $V \subseteq U$ dense in U , any V -section of \mathcal{F} extends to a U -section of \mathcal{F} .*
- (3) *If \mathcal{F} is $\neg\neg$ -separated, the sections of \mathcal{F}^+ on an open subset $U \subseteq X$ can be described by pairs (V, s) , where V is a dense open subset of U and s is a section of \mathcal{F} on V . Two such pairs $(V, s), (V', s')$ determine the same element in $\Gamma(U, \mathcal{F}^+)$ if and only if s and s' agree on $V \cap V'$.*

Proof. The first statement is obvious from the definition of $\neg\neg$ -separatedness (Definition 6.6 for $\Box = \neg\neg$) and the geometric interpretation of double negation (Proposition 6.4).

For the second statement, we need to show that if \mathcal{F} is $\neg\neg$ -separated, \mathcal{F} has the extension property if and only if

$$\begin{aligned} \mathbf{Sh}(X) \models \forall \mathcal{S} : \mathcal{P}(\mathcal{F}). \ulcorner \mathcal{S} \text{ is a subsingleton} \urcorner \wedge \neg(\ulcorner \mathcal{S} \text{ is inhabited} \urcorner) \implies \\ \exists x : \mathcal{F}. \neg\neg(x \in \mathcal{S}). \end{aligned}$$

Note that a section $\mathcal{S} \in \Gamma(U, \mathcal{P}(\mathcal{F}))$ which internally is a subsingleton and *not* inhabited is precisely a subsheaf $\mathcal{S} \hookrightarrow \mathcal{F}|_U$ such that all stalks \mathcal{S}_x , $x \in U$ are subsingletons and such that for some dense open subset $V \subseteq U$, the stalks \mathcal{S}_x , $x \in V$ are inhabited. This is precisely the datum of a section of \mathcal{F} defined on some dense open subset of U : Consider the gluing of the unique germs in \mathcal{S}_x for those points x such that \mathcal{S}_x is inhabited. (Conversely, a section $s \in \Gamma(V, \mathcal{F})$ defines a subsheaf \mathcal{S} by setting $\Gamma(W, \mathcal{S}) := \{s|_W \mid W \subseteq V\}$.)

In view of this explicit description and the observation that the asserted existence (“ $\exists x : \mathcal{F}. \neg(x \in \mathcal{S})$ ”) is actually a question of unique existence, the second statement follows.

For the third statement, one can check that the presheaf on X defined by

$$U \subseteq X \text{ open} \quad \longmapsto \quad \{(V, s) \mid V \subseteq U \text{ dense open, } s \in \Gamma(V, \mathcal{F})\} / \sim$$

is in fact a sheaf (with respect to the topology of X), internally a $\neg\neg$ -sheaf, and that it has the universal property of the $\neg\neg$ -sheafification of \mathcal{F} . \square

The conditions (1) and (2) of the previous proposition can be summarized as follows: A sheaf \mathcal{F} on a topological space is a $\neg\neg$ -sheaf if and only if, for any open subset $U \subseteq X$, the restriction map $\Gamma(\text{int cl } U, \mathcal{F}) \rightarrow \Gamma(U, \mathcal{F})$ is bijective [24, Lemma 36].

In the case that X contains a *generic point*, that is a point $\xi \in X$ such that $\text{cl}\{\xi\} = X$, we can describe the sublocale $X_{\neg\neg}$ in very explicit terms: In this case, it coincides with the subspace $\{\xi\}$. Such a point exists and is unique if X is an irreducible scheme and need not exist otherwise.

Lemma 6.14. *Let X be a topological space and $\xi \in X$ a point such that $\text{cl}\{\xi\} = X$. Then the modal operator $\Box := ((_ \Rightarrow !\xi) \Rightarrow !\xi)$ coincides with the double negation modality and $X_{\neg\neg} = \{\xi\}$ as sublocales of X .*

Proof. The semantics of the formula $!\xi$ was defined by the equivalence

$$U \models !\xi \quad \Longleftrightarrow \quad \xi \notin U.$$

By the assumption on ξ , this is equivalent to requiring $U = \emptyset$. Thus for any open subset U the formulas $!\xi$ and \perp have the same meaning; they are therefore logically equivalent from the internal point of view. The given modal operator thus simplifies to

$$\Box\varphi \quad \equiv \quad ((\varphi \Rightarrow !\xi) \Rightarrow !\xi) \quad \Leftrightarrow \quad ((\varphi \Rightarrow \perp) \Rightarrow \perp) \quad \Leftrightarrow \quad \neg\neg\varphi.$$

The second claim follows Table 2. \square

Corollary 6.15. *Let X be a topological space and $\xi \in X$ a point such that $\text{cl}\{\xi\} = X$. Since $X_{\neg\neg} = \{\xi\}$, the category of $\neg\neg$ -sheaves in $\text{Sh}(X)$ coincides with the category of sheaves on $\{\xi\}$ and can therefore be identified with the category of sets. Under this identification,*

- (1) *sheafifying an object $\mathcal{F} \in \text{Sh}(X)$ with respect to the double negation modality (i. e. pulling back to $X_{\neg\neg}$) is the same as calculating its generic stalk \mathcal{F}_ξ and*
- (2) *pushing forward a set M along $X_{\neg\neg} \hookrightarrow X$ is the same as calculating the constant sheaf associated to M .*

Proof. The first statement follows because pulling back to $X_{\neg\neg}$ is the same as pulling back to $\{\xi\}$. The pushforward of a set M , considered as a sheaf on $X_{\neg\neg}$,

to M is explicitly given by

$$U \mapsto \begin{cases} M, & \text{if } U \neq \emptyset, \\ \{\star\}, & \text{else.} \end{cases}$$

We omit the routine verification that this sheaf coincides with the constant sheaf \underline{M} associated to M . \square

The following technical lemma will occasionally be handy. It is an internal reflection of the fact that an open subset of an affine scheme can always be written as the union of standard open subsets. We will generalize it to schemes which are not necessarily irreducible in Section 7 (see Lemma 7.17).

Lemma 6.16. *Let X be an irreducible scheme. Let φ be any formula over X . Then*

$$\mathrm{Sh}(X) \models \neg\neg\varphi \implies \exists f : \mathcal{O}_X. \neg\neg(\ulcorner f \text{ inv. } \urcorner) \wedge (\ulcorner f \text{ inv. } \urcorner \Rightarrow \varphi).$$

Proof. We may assume that X is the spectrum of an integral domain A and that there is a dense open subset $U \subseteq X$ on which φ holds. The open set U may be covered by standard open subsets $D(f_i)$; by the irreducibility hypothesis, at least one of these is itself dense. We may take this f_i as the sought f . \square

We can now also follow up on a promise made earlier and prove the following somewhat tangential lemma.

Lemma 6.17. *Let X be a topological space. The internal language of $\mathrm{Sh}(X)$ is Boolean if and only if for any open subset $U \subseteq X$ it holds that U is the only dense open subset of U .*

Proof. That the internal language of $\mathrm{Sh}(X)$ is Boolean amounts to

$$\mathrm{Sh}(X) \models \forall \varphi : \Omega. \neg\neg\varphi \Rightarrow \varphi.$$

This is equivalent to the external statement that for any open subset $U \subseteq X$ and for any open subset $V \subseteq U$ it holds that: If V is dense in U , then V is equal to U . \square

6.6. The \Box -translation. There is certain well-known transformation $\varphi \mapsto \varphi^{\neg\neg}$ on formulas, the *double negation translation*, with the following curious property: A formula φ is derivable in classical logic if and only if its translation $\varphi^{\neg\neg}$ is derivable in intuitionistic logic. The translation $\varphi^{\neg\neg}$ is obtained from φ by putting “ $\neg\neg$ ” before any subformula, i.e. before any “ \exists ” and “ \forall ”, around any logical connective, and around any atomic statement (“ $x = y$ ”, “ $x \in A$ ”).

We will describe a slight generalization of the double negation translation, the \Box -translation for any modal operator \Box . It will be pivotal for using the internal language of a space X to express internal statements about sheaves defined on subspaces of X . The \Box -translation has been studied in other contexts before [1, 19]. To the best of my knowledge, this application – expressing the internal language of subtoposes in the internal language of the ambient topos – is new.

Definition 6.18. The \Box -translation is recursively defined as follows.

$$\begin{aligned}
(f = g)^\Box &::= \Box(f = g) \\
(x \in A)^\Box &::= \Box(x \in A) \\
\top^\Box &::= \Box\top \quad (\Leftrightarrow \top) \\
\perp^\Box &::= \Box\perp \\
(\varphi \wedge \psi)^\Box &::= \Box(\varphi^\Box \wedge \psi^\Box) & (\bigwedge_i \varphi_i)^\Box &::= \Box(\bigwedge_i \varphi_i^\Box) \\
(\varphi \vee \psi)^\Box &::= \Box(\varphi^\Box \vee \psi^\Box) & (\bigvee_i \varphi_i)^\Box &::= \Box(\bigvee_i \varphi_i^\Box) \\
(\varphi \Rightarrow \psi)^\Box &::= \Box(\varphi^\Box \Rightarrow \psi^\Box) \\
(\forall x : X. \varphi)^\Box &::= \Box(\forall x : X. \varphi^\Box) & (\forall X. \varphi)^\Box &::= \Box(\forall X. \varphi^\Box) \\
(\exists x : X. \varphi)^\Box &::= \Box(\exists x : X. \varphi^\Box) & (\exists X. \varphi)^\Box &::= \Box(\exists X. \varphi^\Box)
\end{aligned}$$

Definition 6.19. A formula φ is \Box -stable if and only if $\Box\varphi$ implies φ .

Lemma 6.20. (1) *Formulas in the image of the \Box -translation are \Box -stable, i. e. for any formula φ it holds that $\Box(\varphi^\Box) \Rightarrow \varphi^\Box$.*
(2) *In the definition of the \Box -translation, one may omit the boxes printed in gray.*

Proof. The first statement is obvious, since one of the axioms on a modal operator demands that $\Box\Box\varphi \Rightarrow \Box\varphi$ for any formula φ . The second statement follows by an induction on the formula structure. By way of example, we prove the case for “ \Rightarrow ”:

$$\begin{aligned}
&(\varphi \Rightarrow \psi)^\Box \text{ with the gray parts} \\
&\Leftrightarrow \Box(\varphi^\Box \text{ with the gray parts} \Rightarrow \psi^\Box \text{ with the gray parts}) \\
&\Leftrightarrow (\varphi^\Box \text{ with the gray parts} \Rightarrow \psi^\Box \text{ with the gray parts}) \\
&\Leftrightarrow (\varphi^\Box \text{ without the gray parts} \Rightarrow \psi^\Box \text{ without the gray parts}) \\
&\Leftrightarrow (\varphi \Rightarrow \psi)^\Box \text{ without the gray parts}
\end{aligned}$$

The first step is by definition; the second by \Box -stability of ψ^\Box with the gray parts and the intuitionistic tautology $\Box(\alpha \Rightarrow \beta) \Leftrightarrow (\alpha \Rightarrow \beta)$ for \Box -stable formulas β ; the third by induction hypothesis; the fourth by definition. \square

Lemma 6.21. *The \Box -translation is sound with respect to intuitionistic logic: Assume that there exists an intuitionistic proof of an implication $\varphi \Rightarrow \psi$. Then there is also an intuitionistic proof of the translated implication $\varphi^\Box \Rightarrow \psi^\Box$.*

Proof. This follows by an induction on the structure of intuitionistic proofs. We have to verify that we can mirror any inference rule of intuitionistic logic in the translation. For instance, one of the disjunction rules justifies the following proof scheme: In order to prove $\varphi \vee \psi \Rightarrow \chi$, it suffices to give proofs of $\varphi \Rightarrow \chi$ and $\psi \Rightarrow \chi$. We have to justify the translated proof scheme: In order to prove $(\varphi \vee \psi)^\Box \Rightarrow \chi^\Box$, it suffices to give proofs of $\varphi^\Box \Rightarrow \chi^\Box$ and $\psi^\Box \Rightarrow \chi^\Box$.

So assume that proofs of the two implications are given. Further assume $(\varphi \vee \psi)^\Box$, i. e. $\Box(\varphi^\Box \vee \psi^\Box)$. We want to show χ^\Box . Since this is a \Box -stable statement, we may assume that in fact $\varphi^\Box \vee \psi^\Box$ holds. Then the claim is obvious by the two given proofs.

The cases for the other rules (see Appendix C for a list) are similar and left to the reader. \square

Remark 6.22. The reader well-versed in formal logic will have noticed that we are mixing syntax and semantics here. The proper way to state the lemma would be to formally adjoin a box operator to the language of intuitionistic logic, governed by three inference rules which are modeled on the three axioms on a modal operator. This formal box operator could then be instantiated by any concrete modal operator $\Box : \Omega \rightarrow \Omega$.

Soundness of the \Box -translation is important for the following reason (among others). If φ and φ' are equivalent formulas, we are accustomed to be able to freely substitute φ by φ' anywhere we want. Since a modal operator \Box is semantically defined as a map $\Omega \rightarrow \Omega$, it is trivially justified that $\Box\varphi$ and $\Box\varphi'$ are equivalent: The formulas φ and φ' give rise to the *same* element $\{x \in 1 \mid \varphi\} = \{x \in 1 \mid \varphi'\}$ of Ω , and therefore their images under \Box are equal as well.

However, it is *not* clear and in fact wrong in general that the translated formulas φ^\Box and $(\varphi')^\Box$ are equivalent. This follows only if the soundness lemma can be applied (two times, once for each direction). We should stress that to apply this lemma, it is not enough to merely *know* that φ and φ' are equivalent; instead, there has to be an intuitionistic proof of this equivalence. This is really a stronger requirement, since an equivalence $\varphi \Leftrightarrow \varphi'$ might hold in a particular model, i.e. in the internal language of some particular topos, without possessing an intuitionistic proof, i.e. holding in any topos. We give an explicit example of this situation below (Example 6.37).

Lemma 6.23. *Let φ be a formula such that for any subformulas ψ appearing as antecedents of implications, it holds that $\psi^\Box \Rightarrow \Box\psi$. (In particular, this condition is satisfied if there are no “ \Rightarrow ” signs in φ or if φ is a geometric formula.) Then $\Box\varphi \Rightarrow \varphi^\Box$.*

Proof. We prove this by an induction on the formula structure. All cases except for “ \Rightarrow ” are obvious. For this case, assume $\Box(\psi \Rightarrow \chi)$; we are to show that $(\psi^\Box \Rightarrow \chi^\Box)$. Since this is a \Box -stable statement, we can in fact assume that $(\psi \Rightarrow \chi)$. We then have

$$\psi^\Box \Rightarrow \Box\psi \Rightarrow \Box\chi \Rightarrow \chi^\Box,$$

with the first step being by the requirement on antecedents, the second by the monotonicity of \Box , and the third by the induction hypothesis. \square

Lemma 6.24. *Let φ be a geometric formula. Then $\varphi^\Box \Rightarrow \Box\varphi$.*

Proof. By induction on the formula structure. By way of example, we verify the case about “ \bigvee ”. So assume $\Box(\bigvee_i \varphi_i^\Box)$; we are to show that $\Box(\bigvee_i \varphi_i)$. Since this is a boxed statement, we may in fact assume $\bigvee_i \varphi_i^\Box$, so for some index j , it holds that φ_j^\Box . By the induction hypothesis, it follows that $\Box\varphi_j$. By $\varphi_j \Rightarrow \bigvee_i \varphi_i$ and the monotonicity of \Box , it follows that that $\Box(\bigvee_i \varphi_i)$. \square

Note that an analogous argument for infinite conjunctions is not valid: Assume $(\bigwedge_i \varphi_i)^\Box$. So for all j , φ_j^\Box holds. By the induction hypothesis, $\Box\varphi_j$ holds for any j . But from this we may not deduce $\Box\bigwedge_i \varphi_i$, since the axioms on a modal operator only require commutativity with finite conjunctions. This failure also has a geometric interpretation, for instance in the special case $\Box = \neg\neg$: Given dense

open subsets U_i on which formulas φ_i hold, we may not conclude that there exists a single dense open subset U on which all the formulas φ_i hold.

Remark 6.25. In the special case that \Box is the double negation modality, the lemma holds with slightly weaker hypotheses: Namely, implications may occur in φ , provided that for their antecedents ψ it holds that $\psi \Rightarrow \psi^\Box$. This is because for the double negation modality, the formula $\Box(\psi \Rightarrow \chi)$ is equivalent to $\psi \Rightarrow \Box\chi$. (In general, for an arbitrary modality, only the former implies the latter, but not vice versa.) The case for “ \Rightarrow ” in the inductive proof then goes as follows: Assume $(\psi \Rightarrow \chi)^\Box$. Then $\psi \Rightarrow \psi^\Box \Rightarrow \chi^\Box \Rightarrow \Box\chi$, so $\Box(\psi \Rightarrow \chi)$.

Lemma 6.26. *Let φ, φ', ψ be formulas. Assume that:*

- *The formula φ' is geometric. (More generally, it suffices for $(\varphi')^\Box$ to imply $\Box\varphi'$.)*
- *There is an intuitionistic proof that φ and φ' are equivalent under the (only) hypothesis ψ .*
- *Both $\Box\psi$ and ψ^\Box hold.*

Then $\varphi^\Box \Rightarrow \Box\varphi$.

Proof. Assume φ^\Box . Since ψ^\Box , $(\varphi \wedge \psi)^\Box$. Because the \Box -translation is sound with respect to intuitionistic logic (Lemma 6.21) it follows that $(\varphi')^\Box$. As φ' is geometric, it follows that $\Box\varphi'$. Since $\Box\psi$ holds, it follows that $\Box\varphi$. \square

Example 6.27. Let M be an R -module. Then the statement that M is zero is not geometric: $\varphi := (\forall x : M. x = 0)$. But if M is generated by some finite family $x_1, \dots, x_n : M$, then φ is equivalent to the statement $\varphi' := (x_1 = 0 \wedge \dots \wedge x_n = 0)$ which is geometric; and there is an intuitionistic proof of this equivalence. Since no implication signs occur in $\psi := \ulcorner M \text{ is generated by } x_1, \dots, x_n \urcorner$, the lemma is applicable and shows that φ^\Box implies $\Box\varphi$. This example will gain geometric meaning in Lemma 6.38.

Lemma 6.28. *For the modality \Box defined by $\Box\varphi := ((\varphi \Rightarrow \alpha) \Rightarrow \alpha)$, where α is a fixed proposition, the \Box -translation of the law of excluded middle holds. In particular, this applies to the double negation modality $\Box = \neg\neg$, where $\alpha = \perp$.*

Proof. We are to show that $(\varphi \vee \neg\varphi)^\Box$, i. e. that

$$(((\varphi^\Box \vee (\varphi^\Box \Rightarrow \alpha)) \Rightarrow \alpha) \Rightarrow \alpha).$$

So assume that the antecedent holds. If φ^\Box would hold, then in particular $\varphi^\Box \vee (\varphi^\Box \Rightarrow \alpha)$ and thus α would hold. Therefore it follows that $(\varphi^\Box \Rightarrow \alpha)$. This implies $\varphi^\Box \vee (\varphi^\Box \Rightarrow \alpha)$ and thus α . \square

6.7. Truth at stalks vs. truth on neighbourhoods. We now state the crucial property of the \Box -translation. Recall that “ X_\Box ” denotes the sublocale of X induced by \Box (Definition 6.5).

Theorem 6.29. *Let X be a topological space. Let \Box be a modal operator in $\text{Sh}(X)$. Let φ be a formula over X . Then*

$$\text{Sh}(X) \models \varphi^\Box \quad \text{iff} \quad \text{Sh}(X_\Box) \models \varphi,$$

where on the right hand side, all parameters occuring in φ were pulled back to X_\Box along the inclusion $X_\Box \hookrightarrow X$.

XXX: think about powersets appearing as domains of quantification

We have not yet explicitly stated the Kripke–Joyal semantics for a sheaf topos over a locale, which X_\square is in general. The definition is exactly the same as in the case for sheaf toposes over a topological space, only that any mention of “open sets” has to be substituted by the more general “opens” and any mention of the union operator “ \bigcup ” has to be interpreted by the supremum operator in the lattice of opens of the locale. For X_\square , this is $\sup U_i = j(\bigcup_i U_i)$. Before giving a proof of the theorem, we want to discuss some of its consequences.

Corollary 6.30. *Let X be a topological space.*

- (1) *Let $U \subseteq X$ be an open subset and let $\Box\varphi := (U \Rightarrow \varphi)$. Then*

$$\text{Sh}(X) \models \varphi^\Box \quad \text{iff} \quad \text{Sh}(U) \models \varphi.$$

- (2) *Let $A \subseteq X$ be a closed subset and let $\Box\varphi := (\varphi \vee A^c)$. Then*

$$\text{Sh}(X) \models \varphi^\Box \quad \text{iff} \quad \text{Sh}(A) \models \varphi.$$

- (3) *Let $\Box\varphi := \neg\neg\varphi$. Then*

$$\text{Sh}(X) \models \varphi^\Box \quad \text{iff} \quad \text{Sh}(X_{\neg\neg}) \models \varphi.$$

- (4) *Let $x \in X$ be a point and let $\Box\varphi := ((\varphi \Rightarrow !x) \Rightarrow !x)$. Then*

$$\text{Sh}(X) \models \varphi^\Box \quad \text{iff} \quad \varphi \text{ holds at } x.$$

Proof. Combine Theorem 6.29 and Table 2. □

We want to discuss the last case of the corollary in more detail. Let x be a point of a topological space X and let φ be a formula. Let \Box be the modal operator given in the corollary. Then φ holds at x if and only if, from the internal perspective of $\text{Sh}(X)$, the translated formula φ^\Box holds; and φ holds on some open neighbourhood of x if and only if, from the internal perspective, the formula $\Box\varphi$ holds.

Thus the question whether the truth of φ at the point x spreads to some open neighbourhood can be formulated in the following way:

Does φ^\Box imply $\Box\varphi$ in the internal language of $\text{Sh}(X)$?

Phrased this way, technicalities like appropriately shrinking open neighbourhoods are blinded out. A purposefully trivial example to illustrate this is the following. Let X be a scheme (or ringed space). Let $f, g \in \Gamma(X, \mathcal{O}_X)$ be global functions. Suppose that the germs of f and g are zero in some stalk $\mathcal{O}_{X,x}$; we want to show that they are zero on a common open neighbourhood of x .

Usual proof. Since the germ of f vanishes in $\mathcal{O}_{X,x}$, there is an open neighbourhood U_1 of x such that $f|_{U_1} = 0$ in $\Gamma(U_1, \mathcal{O}_X)$. Since furthermore the germ of g vanishes in the same stalk, there exists an open neighbourhood U_2 of x such that $g|_{U_2} = 0$. The intersection of both neighbourhoods is still an open neighbourhood of x ; on this it holds that f and g both vanish. □

Proof in the internal language. We may suppose that $(f = 0 \wedge g = 0)^\Box$, i. e. $\Box(f = 0) \wedge \Box(g = 0)$, and have to prove that $\Box(f = 0 \wedge g = 0)$. (To this end, we could simply invoke the third axiom on a modal operator, but we want to stay close to the given external proof.) So by assumption, both $\Box(f = 0)$ and $\Box(g = 0)$ hold. Since our goal is to prove a boxed statement, we may in fact assume that $f = 0$ and $g = 0$. Thus $f = 0 \wedge g = 0$. □

By using the internal language with its modal operators, we can thus reduce basic facts of scheme theory which deal with stalks and neighbourhoods to facts of algebra in a *modal intuitionistic context*. As with using the internal language in its basic form without modalities, this brings conceptual clarity and reduced technical overhead. There are however two more distinctive advantages. Firstly, many internal proofs do not require specific properties of the modal operator and thus work with any modal operator. By interpreting such a proof using different operators, one obtains a whole family of external statements without any additional work (see Lemma 6.38 for an example).

Secondly, the following corollary gives a general metatheorem which is applicable to a wide range of cases. It allows to decide whether spreading will occur (or is likely not to occur) simply by looking at the *logical form* of the statement in question.

Corollary 6.31. *Let X be a topological space. Let φ be a formula. If φ is geometric, truth of φ at a point $x \in X$ implies truth of φ on some open neighbourhood of x , and vice versa.*

Proof. By the purely logical lemmas of the previous section, it holds that $\varphi^\Box \Leftrightarrow \Box\varphi$. □

Corollary 6.32. *Let X be a topological space. Let φ be a formula. If φ is geometric, the property “ φ holds at a point $x \in X$ ” is open.*

Proof. This is just a reformulation of the previous corollary: If φ holds at a point $x \in X$, it holds on some open neighbourhood U of x as well. Going back to stalks, it follows that φ holds at every point of U . □

Example 6.33. Let X be a scheme (or a ringed space). Since the condition for a function $f: \mathcal{O}_X$ to be nilpotent is geometric (it is $\bigvee_{n \geq 0} f^n = 0$), nilpotency of f at a point is equivalent to nilpotency on some open neighbourhood.

Combined with Lemma 6.26, this metatheorem is quite useful. We will illustrate it with many examples in the next subsection.

An important special case of spreading from stalks to neighbourhoods is the case of spreading from the generic point (should it exist) to a dense open subset. Whether this occurs can be phrased by Lemma 6.14 as follows:

Does $\varphi^{\neg\neg}$ imply $\neg\neg\varphi$ in the internal language of $\mathrm{Sh}(X)$?

This question is a question of ordinary (non-modal) intuitionistic algebra.

Example 6.34. We have seen in Remark 6.11 that a morphism $f: A \rightarrow B$ in $\mathrm{Sh}(X_\Box) \simeq \mathrm{Sh}_\Box(\mathrm{Sh}(X))$ is an epimorphism if and only if $\mathrm{Sh}(X) \models \forall y: B. \Box(\exists x: X. f(x) = y)$. We can now understand a simple proof of this fact:

$$\begin{aligned} & f \text{ is an epimorphism in } \mathrm{Sh}_\Box(\mathrm{Sh}(X)) \\ \iff & \mathrm{Sh}_\Box(\mathrm{Sh}(X)) \models \ulcorner f \text{ is surjective} \urcorner \\ \iff & \mathrm{Sh}(X) \models (\ulcorner f \text{ is surjective} \urcorner)^\Box \\ \iff & \mathrm{Sh}(X) \models \forall y: B. \Box(\exists x: X. f(x) = y). \end{aligned}$$

Remark 6.35. Theorem 6.29 can also be motivated by purely logical considerations. Namely, one can check that interpreting a formula φ by $\mathrm{Sh}(X) \models \varphi^\Box$ gives rise to a model of intuitionistic logic – if φ intuitionistically implies ψ , then $\mathrm{Sh}(X) \models \varphi^\Box$ implies $\mathrm{Sh}(X) \models \psi^\Box$. In categorical logic, it is therefore a natural question whether

there exists a topos \mathcal{E} such that $\mathcal{E} \models \varphi$ if and only if $\text{Sh}(X) \models \varphi^\square$. Theorem 6.29 gives an affirmative answer to this question, explicitly stating that $\mathcal{E} := \text{Sh}(X_\square)$ is such a topos.

Proof of Theorem 6.29. A fancy proof goes as follows. First, one shows intuitionistically that for a modal operator \square in Set , it holds that

$$\text{Set} \models \varphi^\square \iff \text{Sh}_\square(\text{Set}) \models \varphi.$$

This can be done by an easy and nontechnical induction on the structure of formulas φ . Then one interprets this result in the sheaf topos $\text{Sh}(X)$:

$$\begin{aligned} & \text{Sh}(X) \models \varphi^\square \\ \iff & \text{Sh}(X) \models \ulcorner \text{Set} \models \varphi^\square \urcorner && \text{by idempotency} \\ \iff & \text{Sh}(X) \models \ulcorner \text{Sh}_\square(\text{Set}) \models \varphi \urcorner && \text{by the first step} \\ \iff & \text{Sh}_\square(\text{Sh}(X)) \models \varphi && \text{by idempotency} \\ \iff & \text{Sh}(X_\square) \models \varphi && \text{since } \text{Sh}_\square(\text{Sh}(X)) \simeq \text{Sh}(X_\square) \end{aligned}$$

By *idempotency*, we mean that internally employing the Kripke–Joyal semantics to interpret doubly-internal statements is the same as using the Kripke–Joyal semantics once. However, we do not want to discuss this here any further; some details can be found in the original article on the stack semantics [38, Lemma 7.20], but the lemma given there is not general enough to justify the second use of idempotency above. For this, one would have to extend the stack semantics to support internal statements about locally internal categories like $\text{Sh}(X_\square) \hookrightarrow \text{Sh}(X)$ (which then look like locally small categories from the internal point of view). This is worthwhile for other reasons too, but shall not be pursued in these notes.

Therefore, we give a more explicit proof. By induction, we are going to prove that for any open subset $U \subseteq X$ and any formula φ over U , it holds that

$$U \models_X \varphi^\square \iff j(U) \models_{X_\square} \varphi,$$

where the internal statements are to be interpreted by the Kripke–Joyal semantics of X and X_\square respectively and j is the nucleus associated to \square . We may assume that any sheaves occurring in φ as domains of quantifications are in fact \square -sheaves; we justify this with a separate lemma below.

The cases $\varphi \equiv \top$, $\varphi \equiv (\psi \wedge \chi)$, and $\varphi \equiv \bigwedge_i \psi_i$ are trivial. For $\varphi \equiv \perp$, the claim is that $U \models_X \square \perp$ if and only if $j(U) \models_{X_\square} \perp$. The former means $U \subseteq j(\emptyset)$ and the latter means $j(U) \leq \sup \emptyset = j(\emptyset)$, so the claim follows from the first two axioms on a nucleus. \square

Lemma 6.36. *Let \square be a modal operator. Let φ be a formula. Let $\psi := \varphi^\square$ be the \square -translation of φ . Let ψ' be the formula obtained from ψ by substituting any occurring domain of quantification by its \square -sheafification, as syntactically defined in Definition 6.7. Then ψ and ψ' are intuitionistically equivalent.*

Proof. For any formula φ , we denote by “ φ^\boxplus ” the result of first applying the \square -translation to φ and then substituting any set F occurring in φ as a domain of quantification by the plus construction F^+ . Recall that for any such F there is a canonical map $F \rightarrow F^+$, $x \mapsto [\{x\}]$. We are going to show by induction that for any formula $\varphi(x_1, \dots, x_n)$ in which elements $x_i : F_i$ may occur as terms, it holds

that $\varphi^\square(x_1, \dots, x_n)$ is equivalent to $\varphi^\boxplus([\{x_1\}], \dots, [\{x_n\}])$. This suffices to prove the lemma.

The cases for

$$\top \quad \perp \quad \wedge \quad \bigwedge \quad \vee \quad \bigvee \quad \implies$$

are trivial. The cases for unbounded “ \forall ” and “ \exists ” are trivial as well. The case for “ $=$ ” is slightly more interesting; let $\varphi(x, y) \equiv (x = y)$. Then we are to show that $\varphi^\square(x, y) \equiv \square(x = y)$ (equality in some set F) is equivalent to $\varphi^\boxplus([\{x\}], [\{y\}]) \equiv \square([\{x\}] = [\{y\}])$ (equality in F^+). This follows by the definition of the plus construction. The case for “ \in ” is similar.

Let $\varphi \equiv (\exists x : F. \psi(x))$, where we have dropped further variables occurring in ψ for simplicity. Then we are to show that $\varphi^\square \equiv \square(\exists x : F. \psi^\square(x))$ is equivalent to $\varphi^\boxplus \equiv \square(\exists \bar{x} : F^+. \psi^\boxplus(\bar{x}))$. The “only if” direction is trivial (set $\bar{x} := [\{x\}]$). For the “if” direction, we may assume that there exists $\bar{x} : F^+$ such that $\psi^\boxplus(\bar{x})$, since we want to prove a boxed statement. By definition of the plus construction, it holds that $\square(\ulcorner \bar{x} \text{ is a singleton } \urcorner)$. So, again since we want to prove a boxed statement, we may assume that \bar{x} is actually a singleton. Therefore there exists $x : F$ such that $\bar{x} = [\{x\}]$ and that $\psi^\boxplus([\{x\}])$ holds. By the induction hypothesis, it follows that $\psi^\square(x)$. From this the claim follows.

The case for “ \forall ” is similar. \square

Example 6.37. Let X be a scheme. Let f be a global function on X . Let $\varphi := \neg(\ulcorner f \text{ inv. } \urcorner)$ and $\varphi' := \ulcorner f \text{ nilpotent } \urcorner$. Then, by Proposition 3.10, we have $\text{Sh}(X) \models (\varphi \Leftrightarrow \varphi')$. But in general, this does not imply that $\text{Sh}(X) \models (\varphi^\square \Leftrightarrow (\varphi')^\square)$. Consider for instance the modal operator given by $\square\alpha := ((\alpha \Rightarrow !x) \Rightarrow !x)$ associated to a point $x \in X$. Then $\text{Sh}(X) \models (\varphi^\square \Leftrightarrow (\varphi')^\square)$ means that the equivalence $\varphi \Leftrightarrow \varphi'$ holds at the point x . This is false for $X = \text{Spec } \mathbb{Z}$, $f = 2$, and $x = (2)$, since in the local ring $\mathcal{O}_{X,x} = \mathbb{Z}_{(2)}$, the element f is not invertible while also not being nilpotent.

6.8. Internal proofs of common lemmas.

Lemma 6.38. *Let X be a scheme (or ringed space). Let \mathcal{F} be an \mathcal{O}_X -module of finite type.*

- *Let $x \in X$ be a point. Then the stalk \mathcal{F}_x is zero if and only if \mathcal{F} is zero on some open neighbourhood of x .*
- *Let $A \subseteq X$ be a closed subset. Then the restriction $\mathcal{F}|_A$ (i. e. the pullback of \mathcal{F} to A) is zero if and only if \mathcal{F} is zero on some open subset of X containing A .*

Proof. Both statements are simply internalizations of Example 6.27, using the modal operators $\square = (_\vee A^c)$ and $\square = ((_\Rightarrow !x) \Rightarrow !x)$. \square

Remark 6.39. Note that the proposition fails if one drops the hypothesis that \mathcal{F} is of finite type. Indeed, in this case one cannot reformulate the condition that \mathcal{F} is zero in a geometric way.

In a remark after the proof of Proposition 5.6, we promised to present a simpler proof of it once we would have developed the theory for doing so. We can now follow up on this promise.

Lemma 6.40. *Let X be a scheme (or ringed space). Let \mathcal{F} be an \mathcal{O}_X -module of finite type. Let $x \in X$ be a point. Let n be a natural number. Then the following statements are equivalent:*

- (1) *There exists a generating family for \mathcal{F}_x consisting of n elements.*
- (2) *There exists an open neighbourhood U of x such that*

$U \models \ulcorner \text{there exists a generating family for } \mathcal{F} \text{ consisting of } n \text{ elements} \urcorner$.

Proof. Using the modal operator \Box defined by $\Box\varphi \equiv ((\varphi \Rightarrow !x) \Rightarrow !x)$, we have to show that the following statements in the internal language are equivalent:

- (1) $\ulcorner \text{there exists a generating family for } \mathcal{F} \text{ consisting of } n \text{ elements} \urcorner^{\Box}$.
- (2) $\Box(\ulcorner \text{there exists a generating family for } \mathcal{F} \text{ consisting of } n \text{ elements} \urcorner)$.

By Lemma 6.23, the second statement implies the first – note that in a formal spelling of the statement in quotes,

$$(1) \quad \exists x_1, \dots, x_n : \mathcal{F}. \forall x : \mathcal{F}. \exists a_1, \dots, a_n : \mathcal{O}_X. x = \sum_i a_i x_i,$$

no implication signs occur. To show the converse direction, we may assume that there is a generating family $y_1, \dots, y_m : \mathcal{F}$ for \mathcal{F} (since \mathcal{F} is, externally speaking, of finite type). Then the \Box -translation of the statement that the y_i generate \mathcal{F} holds as well (again by Lemma 6.23). Since there is an intuitionistic proof of

$$\begin{aligned} \ulcorner y_1, \dots, y_m \text{ generate } \mathcal{F} \urcorner &\implies \\ &(\ulcorner \text{there exist } x_1, \dots, x_n : \mathcal{F} \text{ which generate } \mathcal{F} \urcorner \iff \\ &\quad \exists x_1, \dots, x_n : \mathcal{F}. \exists A : \mathcal{O}^{m \times n}. \ulcorner \vec{y} = A\vec{x} \urcorner), \end{aligned}$$

we can substitute the non-geometric formula (1) by the geometric formula

$$\exists x_1, \dots, x_n : \mathcal{F}. \exists A : \mathcal{O}^{m \times n}. \ulcorner \vec{y} = A\vec{x} \urcorner$$

(Lemma 6.26). Thus the claim follows. \square

Lemma 6.41. *Let X be a scheme (or ringed space). Let $\alpha : \mathcal{F} \rightarrow \mathcal{G}$ be a morphism of \mathcal{O}_X -modules. Let \mathcal{G} be of finite type and assume that $\alpha_x : \mathcal{F}_x \rightarrow \mathcal{G}_x$ is surjective for some point $x \in X$. Then α is an epimorphism on some open neighbourhood of x .*

Proof. In the presence of generators $y_1, \dots, y_n : \mathcal{G}$, the non-geometric surjectivity condition $(\forall y : \mathcal{G}. \exists x : \mathcal{F}. \alpha(x) = y)$ can be reformulated in a geometric way: $\bigwedge_{i=1}^n \exists x : \mathcal{F}. \alpha(x) = y_i$. Thus the claim follows by Lemma 6.26. \square

Lemma 6.42. *Let $i : A \hookrightarrow X$ be a closed immersion of schemes (or ringed spaces). Let \mathcal{F} be an \mathcal{O}_A -module. Then $i_*\mathcal{F}$ is of finite type if and only if \mathcal{F} is of finite type.*

Proof. Let \Box be the modal operator defined by $\Box\varphi \equiv (\varphi \vee A^c)$. From the internal perspective, we have a surjective ring homomorphism $i^\# : \mathcal{O}_X \rightarrow \mathcal{O}_A$, where we omit the forgetful functor i_* from \Box -sheaves to arbitrary sets in the notation, and an \mathcal{O}_A -module \mathcal{F} . Furthermore, we may assume that \mathcal{F} is a \Box -sheaf. We can regard \mathcal{F} as an \mathcal{O}_X -module by $i^\#$.

Note that $A^c \Rightarrow (\mathcal{F} = 0)$, by \Box -separatedness of \mathcal{F} .

We are to show that \mathcal{F} is a finitely generated \mathcal{O}_X -module if and only if the \Box -translation of “ \mathcal{F} is a finitely generated \mathcal{O}_A -module” holds. In explicit terms, we have to show the equivalence of the following statements:

- (1) $\bigvee_{n \geq 0} \exists x_1, \dots, x_n : \mathcal{F}. \forall x : \mathcal{F}. \exists a_1, \dots, a_n : \mathcal{O}_X. x = \sum_i i^\#(a_i)x_i.$
- (2) $\Box(\bigvee_{n \geq 0} \Box(\exists x_1, \dots, x_n : \mathcal{F}. \forall x : \mathcal{F}. \Box(\exists b_1, \dots, b_n : \mathcal{O}_A. \Box(x = \sum_i b_i x_i))))).$

It is clear that the first statement implies the second. For the converse direction, we just have to repeatedly use the observation that $\Box\varphi$ implies $\varphi \vee (\mathcal{F} = 0)$ (once for each occurrence of \Box). So in each step, we either obtain the statement we want or may assume that \mathcal{F} is the trivial module, in which case any subclaim trivially follows. By surjectivity of i^\sharp , we may write any $b : \mathcal{O}_A$ as $b = i^\sharp(a)$ for some $a : \mathcal{O}_X$. \square

Lemma 6.43. *Let X be a scheme (or a ringed space). Let \mathcal{F} and \mathcal{G} be \mathcal{O}_X -modules. Let $x \in X$. Then $\mathrm{Hom}_{\mathcal{O}_X}(\mathcal{F}, \mathcal{G})_x \cong \mathrm{Hom}_{\mathcal{O}_{X,x}}(\mathcal{F}_x, \mathcal{G}_x)$ if \mathcal{F} is of finite presentation around x .*

Proof. It suffices to give an intuitionistic proof of the following fact: The construction $\mathrm{Hom}_R(M, _)$ is geometric if M is a finitely presented R -module. So assume that M is the cokernel of a presentation matrix $(a_{ij}) : R^{n \times m}$. Then we can calculate the Hom with any R -module N as

$$\mathrm{Hom}_R(M, N) \cong \left\{ x : N^n \mid \bigwedge_{j=1}^m \sum_{i=1}^n a_{ij} x_i = 0 : N \right\},$$

and this construction is patently geometric, as a set comprehension with respect to a geometric formula. \square

Lemma 6.44. *Let X be a scheme (or a ringed space). Let \mathcal{F} be an \mathcal{O}_X -module of finite presentation. Let $x \in X$. Then the stalk \mathcal{F}_x is a finite free $\mathcal{O}_{X,x}$ -module if and only if \mathcal{F} is finite locally free on some open neighbourhood of x .*

Proof. The internal statement that \mathcal{F} is a finite free module is not geometric:

$$\bigvee_{n \geq 0} \exists x_1, \dots, x_n : \mathcal{F}. \forall x : \mathcal{F}. \exists! a_1, \dots, a_n : \mathcal{O}_X. x = \sum_i a_i x_i.$$

But it can equivalently be reformulated as

$$\bigvee_{n \geq 0} \exists \alpha : \mathrm{Hom}_{\mathcal{O}_X}(\mathcal{F}, \mathcal{O}_X^n). \exists \beta : \mathrm{Hom}_{\mathcal{O}_X}(\mathcal{O}_X^n, \mathcal{F}). \alpha \circ \beta = \mathrm{id} \wedge \beta \circ \alpha = \mathrm{id}.$$

This reformulation is geometric, therefore it holds at x if and only if it holds on some open neighbourhood of x . The claim follows since, by the previous proposition, taking stalks commutes with calculating $\mathrm{Hom}_{\mathcal{O}_X}(\mathcal{F}, _)$ resp. $\mathrm{Hom}_{\mathcal{O}_X}(\mathcal{O}_X^n, _)$; thus the pulled back formula indeed expresses that \mathcal{F}_x is finite free as an $\mathcal{O}_{X,x}$ -module. \square

Lemma 6.45. *Let X be an integral scheme with generic point ξ . Let \mathcal{F} be a quasicoherent \mathcal{O}_X -module. Then \mathcal{F} is a torsion module if and only if its generic stalk \mathcal{F}_ξ vanishes.*

Proof. The generic stalk vanishes if and only if the internal statement “ $(\mathcal{F} = 0)^{\neg\neg}$ ” holds. Therefore it suffices to give an intuitionistic proof of the following internal statement: The module \mathcal{F} is torsion if and only if any element of \mathcal{F} is *not not* zero.

For the “only if” direction, let $x : \mathcal{F}$ be an arbitrary element. Since \mathcal{F} is a torsion module, there exists a regular element $a : \mathcal{O}_X$ such that $ax = 0$. Since X is reduced, regularity is equivalent to not-not-invertibility. Since we want to verify the $\neg\neg$ -stable statement “ $\neg\neg(x = 0)$ ”, we may in fact assume that a is invertible. Then $x = 0$ obviously follows.

For the “if” direction, let $x : \mathcal{F}$ be an arbitrary element; by assumption, x is *not not* zero. Since X is integral, Lemma 6.16 is applicable. Therefore there exists an element $a : \mathcal{O}_X$ such that a is *not not* invertible and such that invertibility of a

implies $x = 0$. Since \mathcal{F} is quasicohherent, for some natural number n it holds that $a^n x = 0$ (Theorem 9.3 below). Since a is *not not* invertible, it is regular (see Lemma 7.7 below for a short and self-contained proof), and therefore a^n is regular. So $x \in \mathcal{F}_{\text{tors}}$. \square

By simply using a different modal operator than “*not not*”, we will – without any additional work – obtain a more general form of this lemma, applicable to non-integral schemes (see Lemma 7.19).

- general explanation of modalities (as for instance in philosophy)
- explain that for some modal operators, the \Box -translation of the law of excluded middle is valid; explain consequences
- spreading of properties from stalk to neighbourhood: give many examples
- give proof of the expressions for the nuclei listed in the table

7. RATIONAL FUNCTIONS AND CARTIER DIVISORS

7.1. The sheaf of rational functions. Recall that the sheaf \mathcal{K}_X of rational functions on a scheme X (or ringed space) can be defined as the sheaf associated to the presheaf

$$U \subseteq X \text{ open} \quad \mapsto \quad \Gamma(U, \mathcal{O}_X)[\Gamma(U, \mathcal{S})^{-1}],$$

where $\Gamma(U, \mathcal{S})$ is the multiplicative set of those sections of \mathcal{O}_X on U , which are regular in each stalk $\mathcal{O}_{X,x}$, $x \in U$. Recall also that there are some wrong definitions in the literature [28].

Using the internal language, we can give a simpler definition of \mathcal{K}_X . Recall that we can associate to any ring R its total quotient ring, i.e. its localization at the multiplicative subset of regular elements. Since from the internal perspective \mathcal{O}_X is an ordinary ring, we can associate to it its total quotient ring $\mathcal{O}_X[\mathcal{S}^{-1}]$, where \mathcal{S} is internally defined by the formula

$$\mathcal{S} := \{s : \mathcal{O}_X \mid \ulcorner s \text{ is regular} \urcorner\} \subseteq \mathcal{O}_X.$$

Externally, this ring is the sheaf \mathcal{K}_X .

Proposition 7.1. *Let X be a scheme (or a ringed space). The sheaf of rings defined in the internal language by localizing \mathcal{O}_X at its set of regular elements is (canonically isomorphic to) the sheaf \mathcal{K}_X of rational functions.*

Proof. Internally, the ring $\mathcal{O}_X[\mathcal{S}^{-1}]$ has the following universal property: For any ring R and any homomorphism $\mathcal{O}_X \rightarrow R$ which maps the elements of \mathcal{S} to units, there exists exactly one homomorphism $\mathcal{O}_X[\mathcal{S}^{-1}] \rightarrow R$ which renders the evident diagram commutative.

$$\begin{array}{ccc} \mathcal{O}_X & \xrightarrow{\quad} & R \\ & \searrow & \nearrow \\ & \mathcal{O}_X[\mathcal{S}^{-1}] & \end{array}$$

The translation using the Kripke–Joyal semantics gives the following universal property: For any open subset $U \subseteq X$, any sheaf of rings \mathcal{R} on U and any homomorphism $\mathcal{O}_X|_U \rightarrow \mathcal{R}$ which maps all elements of $\Gamma(V, \mathcal{S})$, $V \subseteq U$ to units, there exists exactly one homomorphism $\mathcal{O}_X[\mathcal{S}^{-1}]|_U \rightarrow \mathcal{R}$ which renders the evident diagram commutative. It is well-known that the sheaf \mathcal{K}_X as usually defined has this universal property as well. \square

Proposition 7.2. *Let X be a scheme (or ringed space). Then the stalks of \mathcal{K}_X are given by*

$$\mathcal{K}_{X,x} = \mathcal{O}_{X,x}[\mathcal{S}_x^{-1}].$$

The elements of \mathcal{S}_x are exactly the germs of those local sections which are regular not only in $\mathcal{O}_{X,x}$, but in all rings $\mathcal{O}_{X,y}$ where y ranges over some open neighbourhood of x (depending on the section).

Proof. Since localization is a geometric construction, the first statement is made entirely trivial by our framework. The second statement follows since

$$\Gamma(U, \mathcal{S}) = \{s \in \Gamma(U, \mathcal{O}_X) \mid U \models \ulcorner s \text{ is regular} \urcorner\}$$

and regularity is a geometric implication, so that $U \models \ulcorner s \text{ is regular} \urcorner$ if and only if the germ s_y is regular in $\mathcal{O}_{X,y}$ for all $y \in U$. \square

Remark 7.3. Speaking internally, the multiplicative set \mathcal{S} is saturated. Therefore an element $s/t : \mathcal{K}_X$ is invertible in \mathcal{K}_X if and only if the numerator s belongs to \mathcal{S} , i. e. is an regular element of \mathcal{O}_X .

7.2. Regularity of local functions. It is well known that on a locally Noetherian scheme, regularity spreads from stalks to neighbourhoods, i. e. a section of \mathcal{O}_X is regular in $\mathcal{O}_{X,x}$ if and only if it is regular on some open neighbourhood of x . This fact has a simple proof in the internal language.

Proposition 7.4. *Let X be a locally Noetherian scheme. Let $s \in \Gamma(U, \mathcal{O}_X)$ be a local function on X . Let $x \in U$. Then the following statements are equivalent:*

- (1) *The section s is regular in $\mathcal{O}_{X,x}$.*
- (2) *The section s is regular in all local rings $\mathcal{O}_{X,y}$ where y ranges over some open neighbourhood of x .*

Proof. Let \Box be the modal operator defined by $\Box\varphi \equiv ((\varphi \Rightarrow !x) \Rightarrow !x)$. By Corollary 6.30, we are to show that the following statements of the internal language are equivalent:

- (1) $(\ulcorner s \text{ is regular} \urcorner)^\Box$, i. e. $\forall t : \mathcal{O}_X. st = 0 \Rightarrow \Box(t = 0)$.
- (2) $\Box(\ulcorner s \text{ is regular} \urcorner)$, i. e. $\Box(\forall t : \mathcal{O}_X. st = 0 \Rightarrow t = 0)$.

It is clear that the second statement implies the first – in fact, this is true without any assumptions on X : Let $t : \mathcal{O}_X$ be such that $st = 0$. Since we want to prove the boxed statement $\Box(t = 0)$, we may assume that s is regular and prove $t = 0$. This is immediate. (This direction also follows simply by examining the logical form and applying Lemma 6.23.)

For the converse direction, consider the annihilator of s , i. e. the ideal

$$I := \text{Ann}_{\mathcal{O}_X}(s) = \{t : \mathcal{O}_X \mid st = 0\} \subseteq \mathcal{O}_X.$$

This ideal satisfies the quasicohherence condition (Example 9.6), thus I is a quasi-coherent submodule of a finitely generated module. Since X is locally Noetherian, it follows that I is finitely generated as well, say by $x_1, \dots, x_n : I$. By assumption, each generator $x_i : I$ fulfills $\Box(x_i = 0)$. Since we want to prove a boxed statement, we may in fact assume $x_i = 0$. Thus $I = (0)$ and the assertion that s is regular follows. \square

Note that the proof critically depends on the ideal I being finitely generated, since a modal operator need only commute with finite conjunctions. Intuitively, each

time we use the modus ponens rule $\Box\varphi \wedge (\varphi \Rightarrow \psi) \Rightarrow \Box\psi$, we restrict to a smaller open neighbourhood of x . Since infinite intersections of open sets need not be open, we cannot expect an infinitary modus ponens rule to hold.

Corollary 7.5. *Let X be a locally Noetherian scheme. Then the stalks $\mathcal{K}_{X,x}$ of the sheaf of rational functions are given by the total quotient rings of the local rings $\mathcal{O}_{X,x}$.*

Proof. Combine Proposition 7.2 and Proposition 7.4. \square

7.3. Normality. Recall that a ring R is *normal* if and only if it is integrally closed in its total quotient ring. Recall also that a scheme X (or ringed space) is *normal* if and only if all rings $\mathcal{O}_{X,x}$ are normal.

Proposition 7.6. *A locally Noetherian scheme is normal if and only if the ring \mathcal{O}_X is normal from the internal perspective.*

Proof. The condition of normality can be put into a form which is almost a geometric implication:

$$\forall s, t : \mathcal{O}_X. \left(\ulcorner t \text{ regular} \urcorner \wedge (\exists a_0, \dots, a_{n-1} : \mathcal{O}_X. s^n + a_{n-1}ts^{n-1} + \dots + a_1t^{n-1}s + a_0t^n = 0) \implies \exists u : \mathcal{O}_X. s = ut \right).$$

The only non-geometric subpart is the condition on t to be regular. However, by Proposition 7.4, for the purposes of comparing its truth at points vs. on neighbourhoods, it behaves just like a geometric formula. Therefore the claim follows. \square

7.4. Geometric interpretation of rational functions. Recall that on integral schemes, rational functions (i.e. sections of \mathcal{K}_X) are the same thing as regular functions defined on dense open subsets. This amounts to saying that \mathcal{K}_X is the $\neg\neg$ -sheafification of \mathcal{O}_X (see Proposition 6.13). We want to rederive this result, as far as possible in the internal language, and generalize it to arbitrary (not necessarily locally Noetherian) schemes.

Lemma 7.7. *Let X be a reduced scheme. Then:*

- (1) \mathcal{O}_X is $\neg\neg$ -separated.
- (2) Internally, an element $s : \mathcal{O}_X$ is regular if and only if it is not not invertible.

Proof. Recall from Corollary 3.9 that

$$(2) \quad \text{Sh}(X) \models \forall s : \mathcal{O}_X. \neg(\ulcorner s \text{ invertible} \urcorner) \Leftrightarrow s = 0.$$

From this we can deduce that \mathcal{O}_X is $\neg\neg$ -separated: Assume $\neg\neg(s = 0)$ for $s : \mathcal{O}_X$. If s were invertible, we would have $\neg\neg(1 = 0)$ and thus \perp . Therefore s is not invertible and thus zero.

For the “only if” direction of the second statement, note that a regular element is not zero (if it were, then the true statement $0 \cdot 0 = 0 \cdot 1$ would imply the false statement $0 = 1$) and thus *not not* invertible (by the contrapositive of equivalence (2)). For the “if” direction, let $st = 0$ in \mathcal{O}_X . Since s is *not not* invertible, it follows that t is *not not* zero. Since \mathcal{O}_X is $\neg\neg$ -separated, this implies that t really is zero. \square

For the following, we need two technical conditions. Say that an affine scheme $\text{Spec } A$ has property (\star) if and only if:

Every open dense subset $U \subseteq \operatorname{Spec} A$ contains a *standard open* dense subset.

Say that $\operatorname{Spec} A$ has property $(\star\star)$ if and only if:

Every open scheme-theoretically dense subset $U \subseteq \operatorname{Spec} A$ contains a *standard open* scheme-theoretically dense subset.

The first condition is satisfied if A is an irreducible ring (i. e. if $\operatorname{Spec} A$ is irreducible). Both conditions are satisfied if A is integral or if A is Noetherian; for the convenience of the reader, we give a proof in the latter case.

Proposition 7.8. *Let A be a Noetherian ring. Then $\operatorname{Spec} A$ has property (\star) and $(\star\star)$.*

Proof. Recall that an open subset of $\operatorname{Spec} A$ is dense if and only if it contains all minimal prime ideals and, under the Noetherian hypothesis, that it is scheme-theoretically dense if and only if it contains all associated prime ideals. There are only a finite number of these prime ideals. Therefore the claim is reduced to the following statement: Let $\mathfrak{p}_1, \dots, \mathfrak{p}_n$ be a finite number of points of an open subset $U \subseteq \operatorname{Spec} A$. Then there exists a standard open subset $D(f) \subseteq U$ which also contains these points. The proof of this statement is an easy application of the prime avoidance lemma. \square

Proposition 7.9. *Let X be a reduced scheme. Assume that X can be covered by open affine subsets which have property (\star) . For instance, this condition is satisfied if X is integral or locally Noetherian. Then \mathcal{K}_X is the $\neg\neg$ -sheafification of \mathcal{O}_X .*

Proof. We first show that \mathcal{K}_X is $\neg\neg$ -separated, so assume $\neg\neg(a/s = 0)$ for $a/s : \mathcal{K}_X$. Since \mathcal{K}_X is obtained from \mathcal{O}_X by localizing at regular elements, the fraction a/s vanishes in \mathcal{K}_X if and only if $a = 0$ in \mathcal{O}_X . Thus it follows that $\neg\neg(a = 0)$ in \mathcal{O}_X and therefore $a = 0$ in \mathcal{O}_X ; in particular, $a/s = 0$ in \mathcal{K}_X .

We defer the proof that \mathcal{K}_X is a $\neg\neg$ -sheaf to the end and first verify the universal property of $\neg\neg$ -sheafification. So let G be a $\neg\neg$ -sheaf and let $\alpha : \mathcal{O}_X \rightarrow G$ be a map. We can define an extension $\bar{\alpha} : \mathcal{K}_X \rightarrow G$ in the following way: Let $f : \mathcal{K}_X$. Define the subsingleton $S := \{x : G \mid \exists b : \mathcal{O}_X. f = b/1 \wedge x = \alpha(b)\} \subseteq G$. Since f can be written in the form a/s with s *not not* invertible, it follows that S is *not not* inhabited. Since G is a $\neg\neg$ -sheaf, there exists a unique $x : G$ such that $\neg\neg(x \in S)$. We declare $\bar{\alpha}(f)$ to be this x . It is straightforward to check that the composition $\mathcal{O}_X \rightarrow \mathcal{K}_X \rightarrow G$ equals α and that $\bar{\alpha}$ is unique with this property.

Up to this point, the proof did not need that X is a scheme – it was enough for X to be a ringed space such that equivalence (2) holds and such that $\neg(0 = 1)$ in \mathcal{O}_X . Only now, in showing that \mathcal{K}_X is a $\neg\neg$ -sheaf, the scheme condition enters. To this end, we first reformulate the sheaf condition in a way such that it only refers to \mathcal{O}_X , not \mathcal{K}_X : The quotient ring \mathcal{K}_X is a $\neg\neg$ -sheaf if and only if

$$\begin{aligned} \operatorname{Sh}(X) \models \forall T \subseteq \mathcal{O}_X. \ulcorner T \text{ subsingleton} \urcorner \wedge \neg\neg(\ulcorner T \text{ inhabited} \urcorner) \implies \\ \exists a, b : \mathcal{O}_X. \ulcorner b \text{ regular} \urcorner \wedge \neg\neg(b^{-1}a \in T). \end{aligned}$$

This is done just as in the proof of Theorem 9.3. Note that “ b^{-1} ” refers to the inverse of b which indeed exists in a doubly negated context, since b is assumed regular. More explicitly, we should write

$$\neg\neg(\exists c : \mathcal{O}_X. bc = 1 \wedge ca \in T) \quad \text{instead of} \quad \neg\neg(b^{-1}a \in T).$$

To verify the Kripke–Joyal interpretation of the rewritten sheaf condition, let an affine open subset $U = \operatorname{Spec} A \subseteq X$ (having property (\star)) and a subsheaf $T \hookrightarrow \mathcal{O}_X|_U$ be given such that T is internally a subsingleton and *not not* inhabited. We may glue the unique germs in the inhabited stalks of T to obtain a section $s \in \Gamma(V, \mathcal{O}_X)$ where $V \subseteq U$ is a dense open subset. Since U has property (\star) , we may assume that $V = D(f)$ is a standard open subset. Because V is dense and A is reduced, the function f is a regular element of A . Since $\Gamma(V, \mathcal{O}_X) = A[f^{-1}]$, we can write $s = a/f^n$ with $a \in A$ and $n \geq 0$.

By Lemma 3.18, the function $b := f^n$ is also regular as an element of \mathcal{O}_U from the internal point of view. Note that b is invertible on V , since $V = D(f) \subseteq D(b)$. It follows that on the dense open subset $V \subseteq U$, the sections s and $b^{-1}a$ agree. This observation concludes the proof. \square

Corollary 7.10. *Let X be a reduced scheme admitting a cover by affine open subschemes with property (\star) . Then \mathcal{K}_X is the result of pulling back \mathcal{O}_X to the sublocale $X_{\neg\neg}$ and then pushing forward again. If X is irreducible with generic point ξ , then \mathcal{K}_X is the constant sheaf associated to the set $\mathcal{O}_{X,\xi}$.*

Proof. Recall from Section 6.4 that pulling back to $X_{\neg\neg}$ is equivalent to sheafifying with respect to the double negation modality; and that pushing forward is equivalent to forgetting the sheaf property. Therefore the first statement holds.

For the second statement, recall from Lemma 6.14 that the sublocale $X_{\neg\neg}$ is given by the subspace $\{\xi\}$; that the sheafification functor $\operatorname{Sh}(X) \rightarrow \operatorname{Sh}(\{\xi\}) \simeq \operatorname{Set}$ is given by calculating the stalk at ξ ; and that the inclusion functor $\operatorname{Set} \simeq \operatorname{Sh}(\{\xi\}) \hookrightarrow \operatorname{Sh}(X)$ is given by the constant sheaf construction. \square

If X is a general scheme (not necessarily reduced), we can describe \mathcal{K}_X in a similar way as a sheafification of \mathcal{O}_X ; specifically, it is the sheafification with respect to the modal operator defined by

$$\widehat{\Box}\varphi := \ulcorner \mathcal{O}_X \text{ is } (\varphi \Rightarrow _) \text{-separated} \urcorner$$

in the internal language of $\operatorname{Sh}(X)$, i. e.

$$\widehat{\Box}\varphi := \forall s : \mathcal{O}_X. (\varphi \Rightarrow s = 0) \Rightarrow s = 0.$$

This modal operator has a simple scheme-theoretical description.

Proposition 7.11. *Let U be an open subset of a scheme X . Then $\operatorname{Sh}(X) \models \widehat{\Box}U$ if and only if U is scheme-theoretically dense in X .*

Proof. We have the following chain of equivalences.

$$\begin{aligned} X &\models \widehat{\Box}U \\ \iff \ulcorner \mathcal{O}_X \text{ is } (U \Rightarrow _) \text{-separated} \urcorner \\ \iff X &\models \ulcorner \mathcal{O}_X \rightarrow \mathcal{O}_X^+ \text{ is injective} \urcorner \\ &\quad (\text{where the plus construction is wrt. the modality } (U \Rightarrow _)) \\ \iff X &\models \ulcorner \mathcal{O}_X \rightarrow \mathcal{O}_X^{++} \text{ is injective} \urcorner \\ &\quad (\text{by the factorization } \mathcal{O}_X \rightarrow \mathcal{O}_X^+ \rightarrow \mathcal{O}_X^{++}) \\ \iff &\text{the canonical morphism } \mathcal{O}_X \rightarrow j_*\mathcal{O}_U \text{ (with } j : U \hookrightarrow X) \text{ is injective} \\ \iff &U \text{ is scheme-theoretically dense in } X. \end{aligned} \quad \square$$

Using the internal language of a scheme, talking about scheme-theoretically dense open subsets is therefore just as easy as talking about ordinary topologically dense open subsets; the difference simply amounts to using the modal operator “ $\hat{\square}$ ” instead of “*not not*”.

Proposition 7.12. *Let X be a ringed space. Then:*

- (1) *The operator $\hat{\square}$ fulfills the axioms on a modal operator.*
- (2) *\mathcal{O}_X is $\hat{\square}$ -separated.*
- (3) *\mathcal{K}_X is $\hat{\square}$ -separated.*
- (4) *Internally, it holds that $\hat{\square}(\ulcorner f \text{ inv. } \urcorner)$ implies that f is regular for any $f : \mathcal{O}_X$.*

Suppose furthermore that X is a scheme. Then:

- (5) *The converse in (4) holds.*
- (6) *If X can be covered by open affine subschemes with property $(\star\star)$, then \mathcal{K}_X is the $\hat{\square}$ -sheafification of \mathcal{O}_X .*

Proof. The first four properties are entirely formal; we thus skip over some details. For the first property, we verify the second axiom on a modal operator. So we assume $\hat{\square}\hat{\square}\varphi$ and have to show $\hat{\square}\varphi$. To this end, let $s : \mathcal{O}_X$ be arbitrary such that $\varphi \Rightarrow (s = 0)$; we have to prove that $s = 0$. If \mathcal{O}_X were separated with respect to the modal operator ($\varphi \Rightarrow _$), it would follow that $s = 0$. So unconditionally it holds that $\hat{\square}\varphi \Rightarrow (s = 0)$. Since by assumption \mathcal{O}_X is $\hat{\square}\varphi$ -separated, the claim follows.

For the second property, let $s : \mathcal{O}_X$ be arbitrary such that $\hat{\square}(s = 0)$. Obviously it holds that $(s = 0) \Rightarrow (s = 0)$. Thus, since \mathcal{O}_X is separated with respect to $((s = 0) \Rightarrow _)$, it follows that $s = 0$. The proof of the third property is similar.

For the fourth property, assume $\hat{\square}(\ulcorner f \text{ inv. } \urcorner)$ and let $h : \mathcal{O}_X$ be arbitrary such that $fh = 0$. Then, trivially, it holds that $\ulcorner f \text{ inv. } \urcorner \Rightarrow h = 0$. Since \mathcal{O}_X is separated with respect to $(\ulcorner f \text{ inv. } \urcorner \Rightarrow _)$, it follows that $h = 0$.

We may now suppose that X is a scheme. To verify the fifth property, let a regular element $f : \mathcal{O}_X$ be given. We have to show that \mathcal{O}_X is separated with respect to the modality $(\ulcorner f \text{ inv. } \urcorner \Rightarrow _)$. So assume that $\ulcorner f \text{ inv. } \urcorner \Rightarrow (s = 0)$ for some $s : \mathcal{O}_X$. By Proposition 3.10 it follows that $f^n s = 0$ for some natural number n . Since f is regular, we may conclude that $s = 0$.

The verification of the universal property of \mathcal{K}_X is done analogously as in the case that X is reduced: For the proof of Proposition 7.9, it was critical that regular elements of \mathcal{O}_X are *not not* invertible. We now need (and have) that regular elements of \mathcal{O}_X are $\hat{\square}(\ulcorner \text{invertible} \urcorner)$.

Thus it only remains to verify that \mathcal{K}_X is a $\hat{\square}$ -sheaf. We may again imitate the proof of Proposition 7.9; using the same notation, we may now suppose that V is a standard open subset such that $U \models \hat{\square}V$ (previously, we supposed that $U \models \neg\neg V$). The proof that the denominator b is regular (as seen from the internal perspective, as an element of \mathcal{O}_U) now goes as follows: We have $V \subseteq D(b)$. Therefore $U \models \hat{\square}V$ implies $U \models \hat{\square}(\ulcorner b \text{ inv. } \urcorner)$. By the fourth property, it follows that $U \models \ulcorner b \text{ is regular} \urcorner$. \square

Remark 7.13. The modal operator $\hat{\square}$ is the largest (weakest) operator such that \mathcal{O}_X is $\hat{\square}$ -separated, i.e. if \square is any modal operator such that \mathcal{O}_X is \square -separated, then $\square\varphi \Rightarrow \hat{\square}\varphi$ for any proposition φ .

In the special case that X is a reduced scheme, Proposition 7.12 recovers the result of Proposition 7.9:

Proposition 7.14. *Let X be a scheme. Then $\widehat{\Box}\varphi \Rightarrow \neg\neg\varphi$ for any formula φ . The converse holds if X is reduced, such that in this case the modal operator $\widehat{\Box}$ coincides with the double negation modality.*

Proof. Let φ be an arbitrary formula and assume $\widehat{\Box}\varphi$. Note that $\neg\varphi$ is equivalent to $\varphi \Rightarrow (1 = 0)$. Since by assumption \mathcal{O}_X is separated with respect to the $(\varphi \Rightarrow _)$ -modality, this in turn is equivalent to $1 = 0 : \mathcal{O}_X$, i. e. to \perp . Thus $\neg\neg\varphi$.

For the converse direction, let $\varphi \Rightarrow (s = 0)$ for some $s : \mathcal{O}_X$; we have to show that in fact $s = 0$. Since by assumption $\neg\neg\varphi$, it follows that s is *not not* zero. Since X is reduced, \mathcal{O}_X is $\neg\neg$ -separated, so this implies that s is really zero. \square

As a corollary, we can reprove the following basic lemma about scheme-theoretical density.

Lemma 7.15. *Let U be an open subset of a scheme X . If U is scheme-theoretically dense, then U is also dense in the plain topological sense. The converse holds if X is reduced.*

Proof. The set U is scheme-theoretically dense if and only if $\mathrm{Sh}(X) \models \widehat{\Box}U$ and is dense if and only if $\mathrm{Sh}(X) \models \neg\neg U$. Therefore the claim follows from the previous proposition. \square

Proposition 7.16. *Let X be a scheme admitting a cover of open affine subsets with property $(\star\star)$. Then \mathcal{K}_X is the result of pulling back \mathcal{O}_X to the sublocale $X_{\widehat{\Box}}$ associated to the modal operator $\widehat{\Box}$ and then pushing forward again. If X is locally Noetherian, this sublocale is the subspace of associated points in X .*

In formulas, the proposition says that the canonical map

$$\mathcal{K}_X \longrightarrow i_* i^{-1} \mathcal{O}_X$$

is an isomorphism, where $i : X_{\widehat{\Box}} \hookrightarrow X$ is the inclusion of the sublocale $X_{\widehat{\Box}}$. This result holds needs a cover with property $(\star\star)$, but no Noetherian hypothesis.

Proof. The first statement follows trivially by the results of Section 6.4 and the fact that \mathcal{K}_X is the $\widehat{\Box}$ -sheafification of \mathcal{O}_X .

For the second statement, we need to verify that the nucleus $j_{\mathrm{Ass}(\mathcal{O}_X)}$ associated to the subspace of associated points coincides with the nucleus $j_{\widehat{\Box}}$ associated to the modal operator $\widehat{\Box}$. Recall from Subsection 6.3 that the latter is given by

$$\begin{aligned} j_{\widehat{\Box}}(U) &= \text{largest open subset of } X \text{ on which } \widehat{\Box}U \text{ holds} \\ &= \bigcup \{V \subseteq X \mid V \text{ open, } V \models \widehat{\Box}U\} \end{aligned}$$

and note that the former is given by

$$j_{\mathrm{Ass}(\mathcal{O}_X)}(U) = \bigcup \{V \subseteq X \mid V \text{ open, } V \cap \mathrm{Ass}(\mathcal{O}_X) \subseteq U\}.$$

This is a general fact of locale theory, not depending on particular properties of $\mathrm{Ass}(\mathcal{O}_X)$. To verify this, check that $j_{\mathrm{Ass}(\mathcal{O}_X)}$ is indeed a nucleus and that $\{U \in \mathrm{Op}(X) \mid j_{\mathrm{Ass}(\mathcal{O}_X)}(U) = U\} \rightarrow \mathrm{Op}(\mathrm{Ass}(\mathcal{O}_X))$, $U \mapsto \mathrm{Ass}(\mathcal{O}_X) \cap U$ is an isomorphism of frames with inverse given by $\mathrm{Ass}(\mathcal{O}_X) \cap U \mapsto j_{\mathrm{Ass}(\mathcal{O}_X)}(U)$.

The equivalence thus follows from a standard result on the set of associated points on locally Noetherian schemes:

$$\begin{aligned}
& V \cap \text{Ass}(\mathcal{O}_X) \subseteq U \\
& \iff \text{Ass}(\mathcal{O}_V) \subseteq U \\
& \iff U \cap V \text{ is scheme-theoretically dense in } U \\
& \quad \text{(this step requires the Noetherian assumption)} \\
& \iff V \models \widehat{\Box}U. \quad \square
\end{aligned}$$

Lemma 7.17. *Let X be a scheme admitting a cover by affine open subschemes with property (\star) respectively $(\star\star)$. Let φ be any formula over X . Then*

$$\text{Sh}(X) \models \neg\neg\varphi \implies \exists f : \mathcal{O}_X. \neg\neg(\ulcorner f \text{ inv. } \urcorner) \wedge (\ulcorner f \text{ inv. } \urcorner \Rightarrow \varphi)$$

respectively

$$\text{Sh}(X) \models \widehat{\Box}\varphi \implies \exists f : \mathcal{O}_X. \widehat{\Box}(\ulcorner f \text{ inv. } \urcorner) \wedge (\ulcorner f \text{ inv. } \urcorner \Rightarrow \varphi).$$

Proof. The proof of Lemma 6.16 carries over, *mutatis mutandis*. \square

Proposition 7.18. *Let X be an irreducible or locally Noetherian scheme of dimension ≤ 0 . Then the internal language of $\text{Sh}(X)$ is Boolean. (The converse holds as well and was already stated as Corollary 3.15.)*

Proof. It suffices to verify the principle of double negation elimination, since the law of excluded middle is equivalent to it.⁹ So let φ be an arbitrary formula and assume $\neg\neg\varphi$. By the previous lemma there exists an element $f : \mathcal{O}_X$ such that f is *not not* invertible and such that $(\ulcorner f \text{ inv. } \urcorner \Rightarrow \varphi)$. Since $\dim X \leq 0$, this element is invertible or nilpotent (Corollary 3.14). In the first case, we are done. In the second case, some power f^n is zero and therefore in particular *not not* zero. Since f is *not not* invertible, this implies that *not not* $1 = 0$. On the other hand $1 \neq 0$, so we obtain a contradiction; from this contradiction φ trivially follows. \square

Lemma 7.19. *Let X be a locally Noetherian scheme. Let \mathcal{F} be a quasicoherent \mathcal{O}_X -module. Then \mathcal{F} is a torsion module if and only if the restriction of \mathcal{F} to $\text{Ass}(\mathcal{O}_X)$ vanishes.*

Proof. By Proposition 7.16 and Lemma 7.17 it suffices to repeat the proof of Lemma 6.45 with “*not not*” substituted by “ $\widehat{\Box}$ ”. \square

7.5. Cartier divisors. Let X be a scheme (or ringed space). Recall that a *Cartier divisor* on x is a global section of the sheaf of groups $\mathcal{K}_X^*/\mathcal{O}_X^*$. This sheaf can be constructed internally, with the same notation: It is the quotient of the group of invertible elements of the ring \mathcal{K}_X by the subgroup of invertible elements of the ring \mathcal{O}_X . So an arbitrary section of $\mathcal{K}_X^*/\mathcal{O}_X^*$ is internally of the form $[s/t]$ with $s, t : \mathcal{O}_X$ being regular elements; this is a simpler description than the usual external one (as a family $(f_i)_i$ of functions $f_i \in \Gamma(U_i, \mathcal{K}_X^*)$ such that $f_i^{-1}|_{U_i \cap U_j} \cdot f_j|_{U_i \cap U_j} \in \Gamma(U_i \cap U_j, \mathcal{O}_X^*)$ for all i, j).

⁹This is a standard fact of intuitionistic logic. Assume that the principle of double negation elimination holds. We want to verify the law of excluded middle, so let an arbitrary formula φ be given. Even intuitionistically it holds that $\neg\neg(\varphi \vee \neg\varphi)$. By double negation elimination it follows that $\varphi \vee \neg\varphi$.

We can sketch the basic theory of Cartier divisors completely from the internal perspective. In accordance with common practice, we write the group operation of $\mathcal{K}_X^*/\mathcal{O}_X^*$ (which is induced by multiplication of elements in \mathcal{K}_X^*) additively.

Definition 7.20. A Cartier divisor is *effective* if and only if, from the internal perspective, it can be written in the form $[s/1]$ with $s : \mathcal{O}_X$ being a regular element.

Thus a Cartier divisor $[s/t]$ is effective if and only if s is an \mathcal{O}_X -multiple of t .

Definition 7.21. A Cartier divisor D is *principal* if and only if there exists a global section $f \in \Gamma(X, \mathcal{K}_X^*)$ such that internally, $D = [f]$. Two Cartier divisors are *linearly equivalent* if and only if their difference is a principal divisor.

Note that decidedly, principality is a global notion: For *any* divisor D it is true that locally there exists sections f of \mathcal{K}_X^* such that $D = [f]$.

Definition 7.22. The *line bundle associated to a Cartier divisor* D is the \mathcal{O}_X -submodule

$$\mathcal{O}_X(D) := \{g \in \mathcal{K}_X \mid gD \in \mathcal{O}_X\} = D^{-1}\mathcal{O}_X \subseteq \mathcal{K}_X$$

of \mathcal{K}_X . Here we are abusing language for “ $gD \in \mathcal{O}_X$ ” to mean that $gf \in \mathcal{O}_X$ if $D = [f]$ with $f : \mathcal{K}_X$; and for “ $D^{-1}\mathcal{O}_X$ ” to mean $f^{-1}\mathcal{O}_X$. This condition respectively submodule does not depend on the representative f , since f is well-defined up to multiplication by an element of \mathcal{O}_X^* .

The submodule $\mathcal{O}_X(D)$ is indeed locally free of rank 1, since internally f^{-1} gives an one-element basis. Note that D is effective if and only if $\mathcal{O}_X(-D)$ is a subset of \mathcal{O}_X from the internal perspective (this comparison makes sense, since $\mathcal{O}_X(-D)$ and \mathcal{O}_X are both canonically embedded in \mathcal{K}_X). In this case, we can define the *support* of D to be the closed subscheme of X associated to the sheaf of ideals $\mathcal{O}_X(-D) \subseteq \mathcal{O}_X$.

Definition 7.23. The *Cartier divisor associated to a free \mathcal{O}_X -submodule $\mathcal{L} \subseteq \mathcal{K}_X$ of rank 1* is $D := [f^{-1}]$, where $f : \mathcal{K}_X$ is the unique element of some one-element basis of \mathcal{L} .

The basis element $f : \mathcal{K}_X$ does indeed lie in \mathcal{K}_X^* : Write $f = s/t$ with $s, t : \mathcal{O}_X$. It suffices to show that s is a regular element of \mathcal{O}_X . So let $h : \mathcal{O}_X$ such that $sh = 0$ in \mathcal{O}_X . Then in particular $hf = 0$ in \mathcal{K}_X . By linear independence, it follows that $h = 0$ in \mathcal{K}_X and thus $h = 0$ in \mathcal{O}_X .

Furthermore, the associated divisor does not depend on the choice of f , since f is well-defined up to multiplication by an element of \mathcal{O}_X^* : If $f\mathcal{O}_X = g\mathcal{O}_X \subseteq \mathcal{K}_X$, then there exist $u, v : \mathcal{O}_X$ such that $fu = g$ and $gv = f$ in \mathcal{K}_X . It follows that $uv = fuvf^{-1} = gvf^{-1} = ff^{-1} = 1$ in \mathcal{K}_X and thus in \mathcal{O}_X , by injectivity of the canonical map $\mathcal{O}_X \rightarrow \mathcal{K}_X$. Therefore u and v are elements of \mathcal{O}_X^* .

Lemma 7.24. Let D and D' be divisors on X . Then $\mathcal{O}_X(D) \otimes_{\mathcal{O}_X} \mathcal{O}_X(D') \cong \mathcal{O}_X(D + D')$.

Proof. The wanted morphism of sheaves $\mathcal{O}_X(D) \otimes_{\mathcal{O}_X} \mathcal{O}_X(D') \rightarrow \mathcal{O}_X(D + D')$ is given by multiplication. That this is well-defined and an isomorphism can be checked from the internal point of view, where the claims are obvious. \square

Proposition 7.25. The association $D \mapsto \mathcal{O}_X(D)$ defines an one-to-one correspondence between Cartier divisors on X and rank-one submodules of \mathcal{K}_X . This correspondence descends to an one-to-one correspondence between Cartier divisors

up to linear equivalence and rank-one submodules of \mathcal{K}_X up to isomorphism (as abstract \mathcal{O}_X -modules, ignoring their embedding into \mathcal{K}_X).

Proof. The first statement is obvious from the definitions. For the second statement, it suffices to show that $\mathcal{O}_X(D)$ is isomorphic to \mathcal{O}_X if and only if D is principal. A given isomorphism $\mathcal{O}_X \rightarrow \mathcal{O}_X(D)$ gives a global section $f \in \mathcal{K}_X^*$ (by considering the image of the unit element) such that internally, $D = [f^{-1}]$; this shows that D is principal. The converse is similar. \square

For the following definition, recall that we can localize an \mathcal{O}_X -module \mathcal{L} away from the set $\mathcal{S} \subseteq \mathcal{O}_X$ of regular elements to obtain a \mathcal{K}_X -module $\mathcal{L}[\mathcal{S}^{-1}]$.

Definition 7.26. Let $f : \mathcal{L}[\mathcal{S}^{-1}]$ be a rational section of a line bundle \mathcal{L} on X . Assume that “ f is nontrivial”, that is multiplication by f is an injective map $\mathcal{O}_X \rightarrow \mathcal{L}[\mathcal{S}^{-1}]$. Then the *associated divisor* of f is $\text{div}(f) := [\psi(s)/t]$, where $f = s/t$ with $s : \mathcal{L}$ and $t : \mathcal{O}_X$ and $\psi : \mathcal{L} \rightarrow \mathcal{O}_X$ is an isomorphism.

One can check that $\psi(s)$ is a regular element of \mathcal{O}_X ; this statement is in fact equivalent to the multiplication map $\mathcal{O}_X \rightarrow \mathcal{L}[\mathcal{S}^{-1}]$ being injective. Furthermore one can check that $[\psi(s)/t]$ does not depend on the choice of s , t , and ψ .

Proposition 7.27. Let $f : \mathcal{L}[\mathcal{S}^{-1}]$ be a nontrivial rational section of a line bundle \mathcal{L} on X . Then multiplication by f induces an isomorphism $\mathcal{O}_X(\text{div}(f)) \rightarrow \mathcal{L}$.

Proof. The isomorphism should map a rational function g to $g \cdot f$. This is a priori an element of $\mathcal{L}[\mathcal{S}^{-1}]$; we have to check that it can be regarded as an element of \mathcal{L} . Just as in the definition of $\text{div}(f)$, write $f = s/t$ and fix an isomorphism $\psi : \mathcal{L} \rightarrow \mathcal{O}_X$. Write $g = (t/\psi(s)) \cdot h$ for some function $h : \mathcal{O}_X$. Then $g \cdot f = sh/\psi(s) = h\psi^{-1}(1)$, since $s = \psi^{-1}(\psi(s)) = \psi(s) \cdot \psi^{-1}(1)$. The element $h\psi^{-1}(1)$ can indeed be considered as an element of \mathcal{L} .

Injectivity of the map $\mathcal{O}_X(\text{div}(f)) \rightarrow \mathcal{L}$ is by the nontriviality of f . For surjectivity, note that $(t/\psi(s)) \cdot \psi(v)$ is a preimage to $v : \mathcal{L}$, since $(t/\psi(s)) \cdot \psi(v) \cdot f = \psi(v)\psi(s)\psi^{-1}(1)/\psi(s) = v$. \square

Proposition 7.28. Let \mathcal{L} be a line bundle on X . Assume that \mathcal{L} can be embedded into \mathcal{K}_X . Then \mathcal{L} possesses a nontrivial rational section.

Proof. Let $i : \mathcal{L} \rightarrow \mathcal{K}_X$ denote the given injection. Let (v) be an one-element basis for \mathcal{L} . Write $i(v) = s/t$. Then s is regular, since $hs = 0$ implies $i(hv) = 0$ and thus $h = 0$, for any $h : \mathcal{O}_X$. Therefore $f := tv/s$ is a well-defined element of $\mathcal{L}[\mathcal{S}^{-1}]$. Furthermore it is nontrivial in the desired sense: If $h \cdot (tv/s) = 0$, then $htv = 0$, thus $ht = 0$ and $h = 0$.

It remains to check that f is independent of the choice of v and of the representation $i(v) = s/t$; else we defined only local sections which might not glue to a single nontrivial rational section (externally speaking). This is obvious. \square

Proposition 7.29. Let D be an effective divisor on X . Then the complement of its support is scheme-theoretically dense.

Proof. The complement of the support of D , that is $D(\mathcal{O}_X(-D))$, is the truth value associated to the statement “ $1 \in \mathcal{O}_X(-D)$ ”. By Lemma 7.11, we therefore have to verify that \mathcal{O}_X is separated with respect to the modal operator $(1 \in \mathcal{O}_X(-D) \Rightarrow _)$.

Let $s : \mathcal{O}_X$ be given such that $1 \in \mathcal{O}_X(-D) \Rightarrow s = 0$; we have to show that $s = 0$. Writing $D = [f/1]$ where $f : \mathcal{O}_X$ is a regular element, this condition is equivalent

to $\ulcorner f \text{ inv. } \urcorner \Rightarrow s = 0$. By Proposition 3.10 it follows that $f^n s = 0$ for some $n \geq 0$. Since f is regular, we may cancel f^n in this equation. \square

Proposition 7.30. *Assume that X is an integral scheme. Then any line bundle on X is (uncanonically) a submodule of \mathcal{K}_X .*

Proof. Let ξ be the generic point of X and let $\Box := \neg\neg$ denote the modal operator such that internal sheafification with respect to \Box is the same as pulling back to $\{\xi\}$ and then pushing forward to X again (see Section 6.5). Let \mathcal{L} be a line bundle on X . Since $\mathcal{L}_\xi \cong \mathcal{O}_{X,\xi}$ (uncanonically), there is some injection $\mathcal{L}_\xi \rightarrow \mathcal{K}_{X,\xi}$; this corresponds internally to an injection $\mathcal{L}^{++} \rightarrow \mathcal{K}_X^{++}$. Since \mathcal{K}_X is already a \Box -sheaf (see Proposition 7.9) and \mathcal{L} is \Box -separated (being isomorphic to \mathcal{O}_X), we have the global injection

$$\mathcal{L} \hookrightarrow \mathcal{L}^{++} \hookrightarrow \mathcal{K}_X^{++} \xrightarrow{(\cong)^{-1}} \mathcal{K}_X. \quad \square$$

- show $\mathcal{K}_X = j_*(\mathcal{O}_X)$?
- “ $\text{div}(g) + D \geq 0$ ”

8. COMPACTNESS AND METAPROPERTIES

8.1. Quasicompactness. As stated in the introduction, quasicompactness of a space can not be detected by the internal language: There cannot exist a formula φ such that a topological space is quasicompact if and only if $\text{Sh}(X) \models \varphi$, since the latter is always a local property on X while quasicompactness is not. However, quasicompactness can be characterized by a *metaproperty* of the internal language.

This result is best stated in a way which does not explicitly refer to a notion of finiteness. So recall that quasicompactness of a topological space X can be phrased in the following way: For any directed set I and any monotone family $(U_i)_{i \in I}$ of open subsets, if $X = \bigcup_i U_i$ then $X = U_i$ for some $i \in I$. As usual, a *directed set* is an inhabited partially ordered set such that for any two elements there exists a common upper bound. A family $(U_i)_{i \in I}$ is *monotone* if and only if $i \preceq j$ implies $U_i \subseteq U_j$.

Proposition 8.1. *Let X be a topological space. Then X is quasicompact if and only if the internal language of $\text{Sh}(X)$ has the following metaproperty: For any directed set I and any monotone family $(\varphi_i)_{i \in I}$ of formulas over X ,*

$$\text{Sh}(X) \models \bigvee_{i \in I} \varphi_i \quad \text{implies} \quad \text{for some } i \in I, \text{Sh}(X) \models \varphi_i.$$

The monotonicity condition means that $\text{Sh}(X) \models (\varphi_i \Rightarrow \varphi_j)$ for any $i \preceq j$ in I .

Stated more succinctly, a topological space X is quasicompact if and only if “ $\text{Sh}(X) \models$ ” commutes with directed “ $\bigvee_{i \in I}$ ”’s.

Proof. For the “only if” direction, let such a family of formulas be given. Declare U_i to be the largest open subset of X where φ_i holds. Then by assumption, the U_i form a monotone family and cover X . By quasicompactness of X , some single U_i covers X as well, such that the corresponding formula φ_i holds on X .

For the “if” direction, note that a monotone family (U_i) of open subsets induces a monotone family of formulas by defining $\varphi_i := U_i$. This correspondence is such that $\text{Sh}(X) \models \bigvee_i \varphi_i$ holds if and only if $X = \bigcup_i U_i$ and such that $\text{Sh}(X) \models \varphi_i$ if and only if $X = U_i$. With these observations the claim is obvious. \square

XXX: formulate for locally constant index sheaves \mathbf{I} as well.

Example 8.2. Let X be a quasicompact scheme (or quasicompact ringed space). Let $f \in \Gamma(X, \mathcal{O}_X)$ be a global function. Endow the set of natural numbers with the usual ordering. Then the family of formulas given by $(f^n = 0)_{n \in \mathbb{N}}$ is monotone. Thus, if it internally holds that f is nilpotent, then f is nilpotent as an element of $\Gamma(X, \mathcal{O}_X)$ as well.

Proposition 8.3. *Let X be a topological space. Let $K \subseteq X$ be an open subset which is locally quasicompact in the sense that there exists an open covering $X = \bigcup_j U_j$ such that each $K \cap U_j$ is quasicompact. Then the internal language of $\text{Sh}(X)$ has the following metaproperty: For any directed set I and monotone family $(\varphi_i)_{i \in I}$ of formulas over X it holds that*

$$\text{Sh}(X) \models (K \Rightarrow \bigvee_i \varphi_i) \quad \text{implies} \quad \text{Sh}(X) \models \bigvee_i (K \Rightarrow \varphi_i).$$

If additionally for any open subset $V \subseteq X$ the set $K \cap V$ is locally quasicompact in V , the following stronger and purely internal statement holds:

$$\text{Sh}(X) \models (K \Rightarrow \bigvee_i \varphi_i) \implies \bigvee_i (K \Rightarrow \varphi_i).$$

Proof. Assume that $\text{Sh}(X) \models (K \Rightarrow \bigvee_i \varphi_i)$. This is equivalent to $K \models \bigvee_i \varphi_i$. By the locality of the internal language, it follows that $K \cap U_j \models \bigvee_i \varphi_i$ for each j . Since $K \cap U_j$ is quasicompact, it follows by the previous proposition that there exists an index $i_j \in I$ such that $K \cap U_j \models \varphi_{i_j}$. This is equivalent to $U_j \models (K \Rightarrow \varphi_{i_j})$. In particular, it holds that $U_j \models \bigvee_i (K \Rightarrow \varphi_i)$. Since this is true for any j , it follows that $X \models \bigvee_i (K \Rightarrow \varphi_i)$, again by the locality of the internal language.

The second statement is a corollary of the first one. \square

Example 8.4. Any retrocompact subset of a scheme is locally quasicompact in the sense of the proposition.

Example 8.5. Let X be a scheme and $f \in \Gamma(X, \mathcal{O}_X)$ be a global function. Then the open set $D(f) = \{x \in X \mid f_x \text{ is invertible in } \mathcal{O}_{X,x}\}$ is locally quasicompact in the sense of the proposition, even in the stronger sense: Let $V \subseteq X$ be any open set. Consider a covering $V = \bigcup_i U_i$ by open affine subsets $U_i = \text{Spec } A_i$. Then $D(f) \cap U_i \cong \text{Spec } A_i[f^{-1}]$ is quasicompact.

From this example, it will trivially follow that the nilradical $\sqrt{(0)} \subseteq \mathcal{O}_X$ of a scheme and indeed the radical of any quasicoherent ideal sheaf is quasicoherent (Example 9.7).

Remark 8.6. In applications, the open set K of the proposition is often given as the largest open subset on which some formula ψ holds. (For instance, in the previous example, K was given by the formula $\ulcorner f \text{ is invertible in } \mathcal{O}_X \urcorner$.) Then the conclusion of the proposition is that *assuming that ψ holds commutes with directed disjunctions*.

8.2. Locality. A stronger condition on a topological space X than quasicompactness is locality: A topological space is *local* if and only if for any open covering $X = \bigcup_i U_i$ (not necessarily directed) a certain single subset U_i covers X as well. For instance, the spectrum of a ring A is local if and only if A is a local ring. Locality has the following characterization as a metaproperty of $\text{Sh}(X)$.

Proposition 8.7. *Let X be a topological space. Then X is local if and only if the internal language of $\text{Sh}(X)$ has the following metaproperty: For any set I and any family $(\varphi_i)_{i \in I}$ of formulas over X , it holds that*

$$\text{Sh}(X) \models \bigvee_{i \in I} \varphi_i \quad \text{implies} \quad \text{for some } i \in I, \text{Sh}(X) \models \varphi_i.$$

In this case, the internal language has additionally the following (weaker) metaproperty: For any sheaf \mathcal{F} on X and any formula $\varphi(s)$ containing a variable $s : \mathcal{F}$, it holds that

$$\text{Sh}(X) \models \exists s : \mathcal{F}. \varphi(s) \quad \text{implies} \quad \text{for some } s \in \Gamma(X, \mathcal{F}), \text{Sh}(X) \models \varphi(s).$$

Proof. The proof of the first part is very similar to the proof of the previous proposition. For the “only if” direction of the second part, note that the antecedent implies that there exist local section $s_i \in \Gamma(U_i, \mathcal{F})$ such that $U_i \models \varphi(s_i)$ for some open covering $X = \bigcup_i U_i$. By locality of X , one such U_i suffices to cover X ; so the corresponding section s_i is actually a global section and verifies $X \models \varphi(s_i)$. \square

Remark 8.8. The second metaproperty stated in the proposition is indeed weaker than the condition that X is local. For instance, let X be a space consisting of two discrete points. Then $\text{Sh}(X)$ has the second metaproperty, but X is not local.

8.3. Irreducibility. In intuitionistic logic, De Morgan’s law $\neg(\alpha \wedge \beta) \Rightarrow \neg\alpha \vee \neg\beta$ is not generally justified; therefore we can’t use it when working internally to the topos of sheaves on a general scheme X . The following proposition demonstrates that if X is irreducible, the law does hold.

Proposition 8.9. *A topological space X is irreducible if and only if the internal language of $\text{Sh}(X)$ has the following metaproperty: For any formulas φ and ψ*

$$\text{Sh}(X) \models \neg(\varphi \wedge \psi) \quad \text{implies} \quad \text{Sh}(X) \models \neg\varphi \text{ or } \text{Sh}(X) \models \neg\psi.$$

Furthermore, in this case the following internal logical principle holds:

$$\text{Sh}(X) \models \forall \alpha, \beta \in \Omega. \neg(\alpha \wedge \beta) \Rightarrow (\neg\alpha \vee \neg\beta).$$

Proof. The statement “ $\text{Sh}(X) \models \neg(\varphi \wedge \psi)$ ” means that $U \cap V = \emptyset$, where U and V are the largest open subsets on which φ respectively ψ hold. The disjunction “ $\text{Sh}(X) \models \neg\varphi$ or $\text{Sh}(X) \models \neg\psi$ ” means that $U = \emptyset$ or $V = \emptyset$.

Therefore, if X is irreducible, then the internal language has the claimed metaproperty. The converse can be seen by instantiating φ and ψ with the formulas associated to given open subsets having empty intersection. It then follows that one of these formulas is false in the internal language; thus the associated subset is empty.

The stated internal logical principle holds since nonempty open subsets of irreducible spaces are irreducible. \square

8.4. Internal proofs of common lemmas.

Lemma 8.10. *Let X be an irreducible reduced scheme. Then all local rings $\mathcal{O}_{X,x}$ are integral domains.*

Proof. It suffices to give a proof of the following statement: Let R be a local ring such that elements which are not invertible are nilpotent. Further assume that R is reduced. Then R is an integral domain in the weak sense.

This proof may, additionally to the rules of intuitionistic logic, use the classical axiom given by Proposition 8.9.

So let arbitrary elements $x, y : R$ with $xy = 0$ be given. Then it is not the case that x and y are both invertible: If they were, their product xy would be invertible as well, contradicting $1 \neq 0$. By the classicality principle, it follows that x is not invertible or that y is not invertible. Thus x or y is nilpotent and therefore zero. \square

- basic lemmas: filtered colimits, flatness, ...

9. QUASICOHERENT SHEAVES OF MODULES

Recall that an \mathcal{O}_X -module \mathcal{F} on a ringed space X is *quasicoherent* if and only if there exists a covering of X by open subsets U such that on each such U , there exists an exact sequence

$$(\mathcal{O}_X|_U)^J \longrightarrow (\mathcal{O}_X|_U)^I \longrightarrow \mathcal{F}|_U \longrightarrow 0$$

of $\mathcal{O}_X|_U$ -modules, where I and J are arbitrary sets (which may depend on U).

If X is indeed a scheme, quasicoherence can also be characterized in terms of inclusions of distinguished open subsets of affines: An \mathcal{O}_X -module \mathcal{F} is quasicoherent if and only if for any open affine subscheme $U = \text{Spec } A$ of X and any function $f \in A$, the canonical map

$$\Gamma(U, \mathcal{F})[f^{-1}] \longrightarrow \Gamma(D(f), \mathcal{F}), \quad \frac{s}{f^n} \longmapsto f^{-n}s|_{D(f)}$$

is an isomorphism of $A[f^{-1}]$ -modules. Here $D(f) \subseteq U$ denotes the standard open subset $\{\mathfrak{p} \in \text{Spec } A \mid f \notin \mathfrak{p}\}$. Both conditions can be internalized.

Proposition 9.1. *Let X be a ringed space. Let \mathcal{F} be an \mathcal{O}_X -module. Then \mathcal{F} is quasicoherent if and only if*

$$\text{Sh}(X) \models \exists I, J \text{ lc. } \ulcorner \text{there exists an exact sequence } \mathcal{O}_X^J \rightarrow \mathcal{O}_X^I \rightarrow \mathcal{F} \rightarrow 0 \urcorner.$$

The “lc” indicates that when interpreting this internal statement with the Kripke–Joyal semantics, I and J should only be instantiated with locally constant sheaves.

Proof. We only sketch the proof. The translation of the internal statement is that there exists a covering of X by open subsets U such that for each such U , there exist sets I, J and an exact sequence

$$(\mathcal{O}_X|_U)^{\underline{J}} \longrightarrow (\mathcal{O}_X|_U)^{\underline{I}} \longrightarrow \mathcal{F}|_U \longrightarrow 0$$

where \underline{I} and \underline{J} are the constant sheaves associated to I respectively J . The term “ $(\mathcal{O}_X|_U)^{\underline{I}}$ ” refers to the internally defined free \mathcal{O}_X -module with basis the elements of \underline{I} . By exploiting that \underline{I} is a discrete set from the internal point of view (i.e. any two elements are either equal or not), one can show that this is the same as $(\mathcal{O}_X|_U)^I$; similarly for J . With this observation, the statement follows. \square

Remark 9.2. The restriction to locally constant sheaves is really necessary: The internal statement $\text{Sh}(X) \models \exists I, J. \ulcorner \text{there exists an exact sequence } \mathcal{O}_X^J \rightarrow \mathcal{O}_X^I \rightarrow \mathcal{F} \rightarrow 0 \urcorner$ is true for *any* \mathcal{O}_X -module \mathcal{F} . This is because the usual proof of the fact that any module admits a resolution by (not necessarily finite) free modules is intuitionistically acceptable and thus also valid in the internal universe.

At the moment, we do not know of any useful internal characterization of locally constant sheaves. The internal condition given by the following theorem does not need such a characterization.

Theorem 9.3. *Let X be scheme. Let \mathcal{F} be an \mathcal{O}_X -module. Then \mathcal{F} is quasicoherent if and only if, from the internal perspective, for any $f : \mathcal{O}_X$, the localized module $\mathcal{F}[f^{-1}]$ is a sheaf for the modal operator $(\ulcorner f \text{ inv. } \urcorner \Rightarrow _)$.*

In detail, the internal condition is that for any $f : \mathcal{O}_X$, it holds that

$$\forall s : \mathcal{F}[f^{-1}]. (\ulcorner f \text{ inv. } \urcorner \Rightarrow s = 0) \implies s = 0$$

and for any subsingleton $\mathcal{S} \subseteq \mathcal{F}[f^{-1}]$ it holds that

$$(\ulcorner f \text{ inv. } \urcorner \Rightarrow \ulcorner \mathcal{S} \text{ inhabited } \urcorner) \implies \exists s : \mathcal{F}[f^{-1}]. (\ulcorner f \text{ inv. } \urcorner \Rightarrow s \in \mathcal{S}).$$

Unlike with the internalizations of finite type, finite presentation and coherence, this condition is *not* a standard condition of commutative algebra. In fact, in classical logic, this condition is always satisfied – for trivial logical reasons if f is invertible, and because $\mathcal{F}[f^{-1}]$ is the zero module if f is not invertible (since f is nilpotent then, by Proposition 3.7).

That this condition is not known in commutative algebra is to be expected: Quasicoherence is a condition on sheaves of modules, ensuring that they are locally isomorphic to sheaves of the form M^\sim , where M is a plain module. But in commutative algebra, one *only* studies plain modules (and not sheaves of modules). The quasicoherence condition is imported into the realm of commutative algebra only by the internal language.

We give the proof of the theorem below, after first discussing some examples and consequences. The proof will explain the origin of this condition.

Example 9.4. The zero \mathcal{O}_X -module is quasicoherent, since (it and) all localizations of it are singleton sets from the internal perspective and thus \square -sheaves for any modal operator \square (Example 6.9).

Corollary 9.5. *Let X be a scheme. Let \mathcal{F} be a quasicoherent \mathcal{O}_X -module. Let $\mathcal{G} \subseteq \mathcal{F}$ be a submodule. Then \mathcal{G} is quasicoherent if and only if*

$$\text{Sh}(X) \models \forall f : \mathcal{O}_X. \forall s : \mathcal{F}. (\ulcorner f \text{ inv. } \urcorner \Rightarrow s \in \mathcal{G}) \implies \bigvee_{n \geq 0} f^n s \in \mathcal{G}.$$

Proof. We can give a purely internal proof. Let $f : \mathcal{O}_X$. Since subpresheaves of separated sheaves are separated, the module $\mathcal{G}[f^{-1}]$ is in any case separated with respect to the modal operator $(\ulcorner f \text{ inv. } \urcorner \Rightarrow _)$.

Now suppose that \mathcal{G} is quasicoherent. Let $f : \mathcal{O}_X$. Let $s : \mathcal{F}$ and assume that if f were invertible, s would be an element of \mathcal{G} . Define the subsingleton $S := \{t : \mathcal{G}[f^{-1}] \mid \ulcorner f \text{ inv. } \urcorner \wedge t = s/1\}$. Then S would be inhabited by $s/1$ if f were invertible. Since $\mathcal{G}[f^{-1}]$ is a sheaf, it follows that there exists an element u/f^n of $\mathcal{G}[f^{-1}]$ such that, if f were invertible, it would be the case that $u/f^n = s/1 \in \mathcal{G}[f^{-1}] \subseteq \mathcal{F}[f^{-1}]$. Since $\mathcal{F}[f^{-1}]$ is separated, it follows that it actually holds that $u/f^n = s/1 \in \mathcal{F}[f^{-1}]$. Therefore there exists $m : \mathbb{N}$ such that $f^m f^n s = f^m u \in \mathcal{F}$. Thus $f^{m+n} s$ is an element of \mathcal{G} .

For the converse direction, assume that \mathcal{G} fulfills the stated condition. Let $f : \mathcal{O}_X$. Let $S \subseteq \mathcal{G}[f^{-1}]$ be a subsingleton which would be inhabited if f were invertible. By regarding S as a subset of $\mathcal{F}[f^{-1}]$, it follows that there exists an element $u/f^n \in \mathcal{F}[f^{-1}]$ such that, if f were invertible, u/f^n would be an element of S . In particular, u would be an element of \mathcal{G} . By assumption it follows that there exists $m : \mathbb{N}$ such that $f^m u \in \mathcal{G}$. Thus $(f^m u)/(f^m f^n)$ is an element of $\mathcal{G}[f^{-1}]$ such that, if f were invertible, it would be an element of S . \square

Example 9.6. Let X be a scheme and s be a global section of \mathcal{O}_X . Then the annihilator of s , i.e. the sheaf of ideals internally defined by the formula

$$I := \text{Ann}_{\mathcal{O}_X}(s) = \{t : \mathcal{O}_X \mid st = 0\} \subseteq \mathcal{O}_X$$

is quasicoherent. To prove this in the internal language it suffices to verify the condition of the proposition. So let $f : \mathcal{O}_X$ and $t : \mathcal{O}_X$ be arbitrary and assume $\ulcorner f \text{ inv.} \urcorner \Rightarrow t \in I$, i.e. assume that if f were invertible, then st would be zero. By Proposition 3.10 it follows that $f^n st = 0$ for some $n : \mathbb{N}$, i.e. that $f^n t \in I$.

Example 9.7. Let X be a scheme and $\mathcal{I} \subseteq \mathcal{O}_X$ be a quasicoherent ideal sheaf. Then the radical of \mathcal{I} , internally definable as

$$\sqrt{\mathcal{I}} := \left\{ s : \mathcal{O}_X \mid \bigvee_{n \geq 0} s^n \in \mathcal{I} \right\},$$

is quasicoherent as well: Let $f : \mathcal{O}_X$ and $s : \mathcal{O}_X$ be arbitrary and assume $\ulcorner f \text{ inv.} \urcorner \Rightarrow s \in \sqrt{\mathcal{I}}$, i.e. assume that if f were invertible, some power s^n would be an element of \mathcal{I} . Since *assuming that f is invertible commutes with directed disjunctions* (Example 8.5), it follows that for some natural number n , it holds that $\ulcorner f \text{ inv.} \urcorner \Rightarrow s^n \in \mathcal{I}$. By quasicoherence of \mathcal{I} , we may deduce that for some natural number m , it holds that $f^m s^n \in \mathcal{I}$. Thus $fs \in \sqrt{\mathcal{I}}$.

Proposition 9.8. *Let X be a scheme of dimension ≤ 0 . Then any \mathcal{O}_X -module is quasicoherent.*

Proof. By Corollary 3.14, any element $f : \mathcal{O}_X$ is invertible or nilpotent. Therefore the quasicoherence condition of Theorem 9.3 is for any \mathcal{O}_X -module trivially satisfied. \square

Remark 9.9. In general intuitionistic mathematics – not inside the internal universe of a scheme – the notion of quasicoherence as given by the internal condition of Theorem 9.3 does not seem to be very interesting: For many important rings, there are few quasicoherent modules in this sense. For instance, let M be a module over a ring R in which every element is invertible or not invertible. (The ring \mathbb{Z} is such a ring.) Then M is quasicoherent if and only if for any $f : R$ which is not invertible, the localized module $M[f^{-1}]$ is the zero module, i.e. any element of M is annihilated by some power f^n . As a concrete example, any \mathbb{Z} -submodule of \mathbb{Z} which contains a nonzero element fails to be quasicoherent.

Proof of Theorem 9.3. By the well-known characterization of quasicoherence in terms of inclusions of distinguished open subsets, an \mathcal{O}_X -module \mathcal{F} is quasicoherent if and only if for any affine open subset $U \subseteq X$ and any function $f \in \Gamma(U, \mathcal{O}_U)$, the canonical map

$$(3) \quad \Gamma(U, \mathcal{F})[f^{-1}] \longrightarrow \Gamma(D(f), \mathcal{F}), \quad s/f^n \longmapsto f^{-n}s|_{D(f)}$$

is bijective. We will see that this map is injective for all such U and f if and only if from the internal perspective, for any $f : \mathcal{O}_X$, the set $\mathcal{F}[f^{-1}]$ is a separated presheaf with respect to the modal operator $(\ulcorner f \text{ inv.} \urcorner \Rightarrow _)$; and we will see that in this case, the map is additionally surjective for all such U and f if the full sheaf condition is fulfilled.

Since the sheaf $\mathcal{F}[f^{-1}]$ does not appear in the stated characterization, we will first reformulate the separatedness and the sheaf condition in terms of \mathcal{F} instead

of $\mathcal{F}[f^{-1}]$. To this end, note that the separatedness condition is equivalent to

$$(4) \quad \forall f : \mathcal{O}_X. \forall s : \mathcal{F}. (\ulcorner f \text{ inv.} \urcorner \Rightarrow s = 0 : \mathcal{F}) \Longrightarrow \bigvee_{n \geq 0} f^n s = 0 : \mathcal{F}.$$

The equivalence can easily be proven in the internal language. The sheaf condition is equivalent to the conjunction of the separatedness condition and

$$(5) \quad \forall f : \mathcal{O}_X. \forall \mathcal{K} \subseteq \mathcal{F}. (\ulcorner f \text{ inv.} \urcorner \Rightarrow \ulcorner \mathcal{K} \text{ is a singleton} \urcorner) \Longrightarrow \bigvee_{n \geq 0} \exists s : \mathcal{F}. \ulcorner f \text{ inv.} \urcorner \Rightarrow f^{-n} s \in \mathcal{K}.$$

In one direction, a set $\mathcal{S} \subseteq \mathcal{F}[f^{-1}]$ is given; construct $K := \{s : \mathcal{F} \mid s/1 \in \mathcal{S}\} \subseteq \mathcal{F}$. In the other direction, a set $\mathcal{K} \subseteq \mathcal{F}$ is given; construct $S := \{s : \mathcal{F}[f^{-1}] \mid \exists s' : \mathcal{F}. s' \in \mathcal{K} \wedge s = s'/1\} \subseteq \mathcal{F}[f^{-1}]$. The remaining details can easily be filled in.

We now interpret the internal statement (4) with the Kripke–Joyal semantics. Using the simplification rules, the external meaning is that for any affine open subset $U \subseteq X$ and any function $f \in \Gamma(U, \mathcal{O}_U)$ the following condition is satisfied: For any section $s \in \Gamma(U, \mathcal{F})$ it should hold that

$$U \models (\ulcorner f \text{ inv.} \urcorner \Rightarrow s = 0) \quad \text{implies} \quad U \models \bigvee_{n \geq 0} f^n s = 0.$$

The antecedent is equivalent to saying that s is zero in $\Gamma(D(f), \mathcal{F})$. The consequent is (by quasicompactness of U , see Example 8.2) equivalent to saying that for some $n \geq 0$, the section $f^n s$ is zero in $\Gamma(U, \mathcal{F})$, i. e. that s is zero in $\Gamma(U, \mathcal{F})[f^{-1}]$. So this condition is precisely the injectivity of the canonical map (3).

The external meaning of statement (5) is that for any affine open subset $U \subseteq X$ and any function $f \in \Gamma(U, \mathcal{O}_U)$ the following condition is satisfied: For any subsheaf $\mathcal{K} \subseteq \mathcal{F}|_U$ it should hold that

$$U \models (\ulcorner f \text{ inv.} \urcorner \Rightarrow \ulcorner \mathcal{K} \text{ is a singleton} \urcorner) \quad \text{implies} \quad U \models \bigvee_{n \geq 0} \exists s : \mathcal{F}. \ulcorner f \text{ inv.} \urcorner \Rightarrow f^{-n} s \in \mathcal{K}.$$

Given the injectivity of the canonical map (3) (for any affine open subset, not only U), this condition is equivalent to its surjectivity: To see that surjectivity is sufficient, let a subsheaf $\mathcal{K} \subseteq \mathcal{F}|_U$ verifying the antecedent be given. Since $\mathcal{K}|_{D(f)}$ is a singleton sheaf, we can consider its unique section $u \in \Gamma(D(f), \mathcal{K}) \subseteq \Gamma(D(f), \mathcal{F})$. By surjectivity, there exists a preimage, i. e. a fraction $s/f^n \in \Gamma(U, \mathcal{F})[f^{-1}]$ such that $u = f^{-n} s|_{D(f)}$ in $\Gamma(D(f), \mathcal{F})$. Thus $U \models f^{-n} s \in \mathcal{K}$ holds and the consequent is verified.

To see that surjectivity is necessary, let a section $u \in \Gamma(D(f), \mathcal{F})$ be given. Define a subsheaf $\mathcal{K} \subseteq \mathcal{F}|_U$ by setting $\Gamma(V, \mathcal{K}) := \{u|_V \mid V \subseteq D(f)\}$. Then \mathcal{K} verifies the antecedent. Thus the consequent holds: There exists an open covering $U = \bigcup_i U_i$ such that for each i , there exists a natural number n_i and a section $s_i \in \Gamma(U_i, \mathcal{F})$ such that $f^{-n_i} s_i = u$ on $U_i \cap D(f)$. Without loss of generality, we may assume that the U_i are distinguished open subsets $D(g_i) \subseteq U$; that they are finite in number; and that the natural numbers n_i agree with each other and thus equal some number n . Since $s_i = s_j$ in $\Gamma(U_i \cap U_j \cap D(f), \mathcal{F})$, injectivity of the canonical map (3) (on the affine set $U_i \cap U_j = D(g_i g_j)$) implies that $s_i = s_j$ in $\Gamma(U_i \cap U_j, \mathcal{F})[f^{-1}]$. Thus for any i, j there exists a natural number m_{ij} such that $f^{m_{ij}} s_i = f^{m_{ij}} s_j$ in $\Gamma(U_i \cap U_j, \mathcal{F})$.

We may assume that the numbers m_{ij} equal some common number m ; thus the local sections $f^m s_i$ glue to a section $s \in \Gamma(U, \mathcal{F})$. The sought preimage of u is the fraction s/f^{n+m} , since $f^{-(n+m)}s|_{D(f)}$ equals u in $\Gamma(D(f), \mathcal{F})$ (as this is true on the covering $D(f) = \bigcup_i (D(f) \cap U_i)$). \square

- is the condition good enough to show that modules of finite type are quasicoherent? To show that cokernels are quasicoherent?
- discussion meaning of the sheaf condition in external language
- give more examples: $(h), \dots$
- Noetherian hypotheses: for example, that any quasicoherent submodule of a module of finite type is of finite type as well

10. SUBSCHEMES

10.1. Sheaves on open and closed subspaces. It is well-known that sheaves defined on open or closed subspaces of a topological space X can be related with certain sheaves on X , by using appropriate extension functors. We can define these functors and show their basic properties in the internal language. Recall from Section 6.2 that we have defined a formula “ U ” for any open subset $U \subseteq X$ such that $V \models U$ if and only if $V \subseteq U$.

Lemma 10.1. *Let X be a topological space. Let $j : U \hookrightarrow X$ be the inclusion of an open subspace. Then there is a canonical functor $j_! : \text{Sh}(U) \rightarrow \text{Sh}(X)$ called extension by the empty set with the following properties:*

- (1) *The functor $j_!$ is left adjoint to the restriction functor $j^{-1} : \text{Sh}(X) \rightarrow \text{Sh}(U)$.*
- (2) *The composition $j^{-1} \circ j_! : \text{Sh}(U) \rightarrow \text{Sh}(U)$ is (canonically isomorphic to) the identity.*
- (3) *The essential image of $j_!$ consists of exactly those sheaves on X whose stalks are empty at all points of U^c . For those sheaves \mathcal{F} , it holds that $j_! j^{-1} \mathcal{F} \cong \mathcal{F}$ (canonically).*

Proof. Internally, for a set \mathcal{F} , we can define $j_!(\mathcal{F})$ simply be the set comprehension

$$j_!(\mathcal{F}) := \{x : \mathcal{F} \mid U\}.$$

Externally, the sections of the thusly defined sheaf on an open subset $V \subseteq X$ are given by $\{x \in \Gamma(V, \mathcal{F}) \mid V \subseteq U\}$, i. e. the whole of $\Gamma(V, \mathcal{F})$ if $V \subseteq U$ and the empty set otherwise. With this short internal description, all of the stated properties can be easily verified in the internal language.

For instance, recall that internally the functor j^{-1} is given by sheafifying with respect to the modal operator $\Box : \equiv (U \Rightarrow _)$. Thus, to show the second statement, we have to give a bijection $(j_!(\mathcal{F}))^{++} \rightarrow \mathcal{F}$ for any \Box -sheaf \mathcal{F} . (This map has to be given explicitly, to not only show a weaker statement about a local isomorphism – see Section 2.2). To this end, we can use the composition

$$(j_!(\mathcal{F}))^{++} \hookrightarrow \mathcal{F}^{++} \xrightarrow{(\cong)^{-1}} \mathcal{F},$$

where the first map is injective since sheafifying is exact. It is also surjective, since the \Box -translation of the statement $\ulcorner j_!(\mathcal{F}) \rightarrow \mathcal{F} \text{ is surjective} \urcorner$ holds: For any element $x : \mathcal{F}$, it holds that $\Box(\ulcorner x \text{ possesses a preimage} \urcorner)$.

For the third property, note that a sheaf \mathcal{F} on X fulfills the stated condition on stalks if and only if, from the internal perspective, it holds that $U \Rightarrow \ulcorner \mathcal{F} \text{ is inhabited} \urcorner$. We omit further details. \square

Lemma 10.2. *Let X be a ringed space. Let $j : U \hookrightarrow X$ be the inclusion of an open subspace. Then there is a canonical functor $j_! : \text{Mod}_U(\mathcal{O}_U) \rightarrow \text{Mod}_X(\mathcal{O}_X)$ called extension by zero with the following properties:*

- (1) *The functor $j_!$ is left adjoint to the restriction functor $j^{-1} : \text{Mod}_X(\mathcal{O}_X) \rightarrow \text{Mod}_U(\mathcal{O}_U)$.*
- (2) *The composition $j^{-1} \circ j_! : \text{Mod}_U(\mathcal{O}_U) \rightarrow \text{Mod}_U(\mathcal{O}_U)$ is (canonically isomorphic to) the identity.*
- (3) *The essential image of $j_!$ consists of exactly those \mathcal{O}_X -modules whose stalks are zero at all points of U^c . For those sheaves \mathcal{F} , it holds that $j_! j^{-1} \mathcal{F} \cong \mathcal{F}$ (canonically).*

Proof. Internally, a sheaf of modules on \mathcal{O}_U is simply a module on \mathcal{O}_X^{++} which is a \Box -sheaf, where $\Box := (U \Rightarrow _)$. The suitable internal definition for the extension by zero of such a module \mathcal{F} is

$$j_!(\mathcal{F}) := \{x : \mathcal{F} \mid (x = 0) \vee U\}.$$

With this description, all necessary verifications are easy. Note that an \mathcal{O}_X -module \mathcal{F} fulfills the stated condition on stalks if and only if internally, it holds that $\forall x : \mathcal{F}. ((x = 0) \vee U)$. \square

Lemma 10.3. *Let X be a topological space. Let $i : A \hookrightarrow X$ be the inclusion of a closed subspace. The essential image of the inclusion $i_* : \text{Sh}(A) \rightarrow \text{Sh}(X)$ consists of exactly those sheaves whose support is a subset of A . For those sheaves \mathcal{F} , it holds that $i_* i^{-1} \mathcal{F} \cong \mathcal{F}$ (canonically).*

Proof. Recall that the modal operator associated to A is $\Box\varphi := (\varphi \vee A^c)$, and that by Section 6.4 the essential image of i_* consists of exactly those sheaves which are \Box -sheaves from the internal perspective. Let \mathcal{F} be a sheaf on X . Then it holds that

$$\text{supp } \mathcal{F} \subseteq A \iff A^c \subseteq X \setminus \text{supp } \mathcal{F} \iff A^c \subseteq \text{int}(X \setminus \text{supp } \mathcal{F}).$$

Since the interior of the complement of $\text{supp } \mathcal{F}$ can be characterized as the largest open subset of X on which the internal statement “ \mathcal{F} is a singleton” holds (Remark 4.8), the condition on the support is fulfilled if and only if

$$\text{Sh}(X) \models (A^c \Rightarrow \ulcorner \mathcal{F} \text{ is a singleton } \urcorner).$$

We thus have to show that this internal condition is equivalent to \mathcal{F} being a \Box -sheaf. For the “if” direction, assume A^c . Then the empty subset $S \subseteq \mathcal{F}$ trivially verifies the condition that $\Box(\ulcorner S \text{ is a singleton } \urcorner)$. There thus exists an element $x : \mathcal{F}$ (such that $\Box(x \in S)$). If we’re given a further element $y : \mathcal{F}$, it trivially holds that $\Box(x = y)$. By \Box -separatedness, it thus follows that $x = y$. Thus \mathcal{F} is the singleton $\{x\}$. The proof of the “only if” direction is similar.

The second statement says that internally, sheafifying a \Box -sheaf with respect to the modal operator \Box and then forgetting that the result is a \Box -sheaf amounts to doing nothing. This is obvious. \square

10.2. Closed subschemes. Let X be a ringed space. Recall that an ideal sheaf $\mathcal{I} \subseteq \mathcal{O}_X$ defines a closed subset $V(\mathcal{I}) = \{x \in X \mid \mathcal{I}_x \neq (1) \subseteq \mathcal{O}_{X,x}\}$, a sheaf of rings $\mathcal{O}_X/\mathcal{I}$, and a ringed space $(V(\mathcal{I}), \mathcal{O}_{V(\mathcal{I})})$ where $\mathcal{O}_{V(\mathcal{I})}$ is the pullback of $\mathcal{O}_X/\mathcal{I}$ to $V(\mathcal{I})$. In the internal universe, we can reify $V(\mathcal{I})$ by giving a modal operator \Box such that externally, the subspace X_\Box coincides with $V(\mathcal{I})$.

Proposition 10.4. *Let X be a ringed space. Let $\mathcal{I} \subseteq \mathcal{O}_X$ be an ideal sheaf. Then:*

- (1) *The subspace of X associated to the modal operator \Box defined by $\Box\varphi := (\varphi \vee (1 \in \mathcal{I}))$ is $V(\mathcal{I})$.*
- (2) *The support of $\mathcal{O}_X/\mathcal{I}$ is exactly $V(\mathcal{I})$.*
- (3) *The canonical morphism $i : V(\mathcal{I}) \rightarrow X$ is a closed immersion of ringed spaces.*

Proof. For any open subset $U \subseteq X$, it holds that $U \models 1 \in \mathcal{I}$ if and only if $U \subseteq D(\mathcal{I}) = X \setminus V(\mathcal{I})$. Thus $D(\mathcal{I})$ can be characterized as the largest open subset on which “ $1 \in \mathcal{I}$ ” holds. According to Table 2 on page 38, the stated modal operator thus defines the subspace $D(\mathcal{I})^c$, i. e. $V(\mathcal{I})$.

For the second statement, note that since $\mathcal{O}_X/\mathcal{I}$ is a sheaf of rings, its support is closed. Therefore the largest open subset of X where the internal statement “ $\mathcal{O}_X/\mathcal{I} = 0$ ” holds is the complement of the support (Proposition 4.7). Since $D(\mathcal{I})$ is the largest open subset where the internal statement “ $\mathcal{I} = (1)$ ” holds, it suffices to show that internally, $\mathcal{O}_X/\mathcal{I} = 0$ if and only if $\mathcal{I} = (1)$. This is obvious.

The topological part of the third statement is clear. For the ring-theoretic part, we have to show that the canonical ring homomorphism $\mathcal{O}_X \rightarrow i_*\mathcal{O}_{V(\mathcal{I})}$, that is the canonical projection $\mathcal{O}_X \rightarrow \mathcal{O}_X/(\mathcal{I})$, is an epimorphism of sheaves. This is obvious. \square

By Lemma 10.3, the sheaf $\mathcal{O}_X/\mathcal{I}$ is thus a \Box -sheaf from the internal perspective.

Proposition 10.5. *Let X be a locally ringed space. Let $\mathcal{I} \subseteq \mathcal{O}_X$ be an ideal sheaf. Then the ringed space $(V(\mathcal{I}), \mathcal{O}_{V(\mathcal{I})})$ is too locally ringed.*

Proof. We have to show that

$$\text{Sh}(V(\mathcal{I})) \models \ulcorner \mathcal{O}_{V(\mathcal{I})} \text{ is a local ring } \urcorner.$$

By Theorem 6.29, this is equivalent to

$$\text{Sh}(X) \models (\ulcorner \mathcal{O}_X/\mathcal{I} \text{ is a local ring } \urcorner)^\Box,$$

where \Box is the modal operator given by $\Box\varphi := (\varphi \vee (1 \in \mathcal{I}))$. We therefore have to give an intuitionistic proof of the fact

$$\forall x, y : \mathcal{O}_X/\mathcal{I}. \ulcorner x + y \text{ inv.} \urcorner \implies \Box(\ulcorner x \text{ inv.} \urcorner \vee \ulcorner y \text{ inv.} \urcorner).$$

So let $x = [s], y = [t] : \mathcal{O}_X/\mathcal{I}$ such that $x + y$ is invertible in $\mathcal{O}_X/\mathcal{I}$. This means that there exists $u : \mathcal{O}_X$ and $v : \mathcal{I}$ such that $us + ut + v = 1$ in \mathcal{O}_X . Since \mathcal{O}_X is a local ring, it follows that us , ut , or v is invertible. In the first two cases, it follows that x respectively y are invertible in $\mathcal{O}_X/\mathcal{I}$. In the third case, it follows that $1 \in \mathcal{I}$ and thus any boxed statement is trivially true. \square

If X is a scheme and $\mathcal{I} \subseteq \mathcal{O}_X$ is an ideal sheaf, it is well-known that the locally ringed space $V(\mathcal{I})$ is a scheme if and only if \mathcal{I} is quasicohherent. We cannot give an internal proof of this fact since we lack an internal characterization of being a scheme.

Lemma 10.6. *Let X be a scheme (or ringed space). Let $\mathcal{I} \subseteq \mathcal{O}_X$ be an ideal sheaf. The ringed space $V(\mathcal{I})$ is reduced if and only if, from the internal perspective of $\text{Sh}(X)$, the ideal \mathcal{I} is a radical ideal.*

Proof. The following chain of equivalences holds:

$$\begin{aligned}
 & \text{Sh}(V(\mathcal{I})) \models \ulcorner \mathcal{O}_{V(\mathcal{I})} \text{ is a reduced ring} \urcorner \\
 \iff & \text{Sh}(V(\mathcal{I})) \models \bigwedge_{n \geq 0} \forall s : \mathcal{O}_{V(\mathcal{I})}. s^n = 0 \implies s = 0 \\
 \iff & \text{Sh}(X) \models \left(\bigwedge_{n \geq 0} \forall s : \mathcal{O}_X / \mathcal{I}. s^n = 0 \implies s = 0 \right)^\square \\
 \iff & \text{Sh}(X) \models \bigwedge_{n \geq 0} \forall s : \mathcal{O}_X / \mathcal{I}. s^n = 0 \implies \Box(s = 0) \\
 \iff & \text{Sh}(X) \models \bigwedge_{n \geq 0} \forall s : \mathcal{O}_X. s^n \in \mathcal{I} \implies \Box(s \in \mathcal{I}) \\
 \iff & \text{Sh}(X) \models \bigwedge_{n \geq 0} \forall s : \mathcal{O}_X. s^n \in \mathcal{I} \implies s \in \mathcal{I} \\
 \iff & \text{Sh}(X) \models \ulcorner \mathcal{I} \text{ is a radical ideal} \urcorner
 \end{aligned}$$

In the second-to-last step, we used that $\Box(s \in \mathcal{I}) \equiv ((s \in \mathcal{I}) \vee (1 \in \mathcal{I}))$ implies $s \in \mathcal{I}$. This is trivial in both cases of the disjunction. \square

Lemma 10.7. *Let X be a scheme (or ringed space).*

- (1) *There exists a reduced closed sub-ringed space $X_{\text{red}} \hookrightarrow X$ having the same underlying topological space as X with the following universal property: Any morphism $Y \rightarrow X$ of (ringed or locally ringed) spaces such that Y is reduced factors uniquely over the closed immersion $X_{\text{red}} \hookrightarrow X$.*
- (2) *Let $A \subseteq X$ be a closed subset. Then there exists a structure of a reduced closed ringed subspace on A with a similar universal property.*

Proof. For the first statement, let $\mathcal{N} \subseteq \mathcal{O}_X$ be the nilradical of \mathcal{O}_X . This can internally be simply defined by $\mathcal{N} := \sqrt{(0)} = \{s : \mathcal{O}_X \mid \bigvee_{n \geq 0} s^n = 0\}$. Define X_{red} as the closed subspace associated to this ideal sheaf. This ringed space is reduced by the previous lemma. If X is a scheme, then quasicohherence of \mathcal{N} (which is necessary and sufficient for X_{red} to be a scheme) can be shown internally (Example 9.7). The proof of the universal property can also be done in the internal language, by using that the well-known fact of locale theory that the category of locales over X is equivalent to internal locales in $\text{Sh}(X)$; but we do not want to discuss this further.

For the second statement, internally define the ideal $\mathcal{I} := \sqrt{\{s : \mathcal{O}_X \mid s = 0 \vee A^c\}} \subseteq \mathcal{O}_X$. Then $1 \in \mathcal{I}$ if and only if A^c , thus by Proposition 10.4 the closed ringed subspace defined by \mathcal{I} has A as underlying topological space. It is reduced since \mathcal{I} is a radical ideal. **XXX: is \mathcal{I} quasicohherent, if X is a scheme?** \square

Lemma 10.8. *Let X be a scheme of dimension $\leq n$. Let $V(\mathcal{I}) \hookrightarrow X$ be a closed subscheme which is locally cut out by a regular equation. Then $\dim V(\mathcal{I}) \leq n - 1$.*

Proof. By Proposition 3.13, it suffices to give an intuitionistic proof of the following fact of dimension theory: Let A be an arbitrary ring of dimension $\leq n$. Let $I = (s) \subseteq A$ be an ideal which is generated by a regular element $s : A$. Then the \Box -translation of “ A/I is of dimension $\leq n - 1$ ” holds. In fact, we can show that A/I really is of dimension $\leq n - 1$; since no implication signs occur in a formal rendering of “being of dimension $\leq n - 1$ ”, Lemma 6.23 is applicable and implies that this a stronger statement.

For this, let a sequence $([a_0], \dots, [a_{n-1}])$ of elements in A/I be given. We can lift and extend this sequence to the sequence (a_0, \dots, a_{n-1}, s) of elements of A . Since $\dim A \leq n$, there exists a complementary sequence $(b_0, \dots, b_{n-1}, b_n)$. Since s is regular, the inclusion $\sqrt{(sb_n)} \subseteq \sqrt{(0)}$ given by the definition of complementarity implies that b_n is nilpotent. Thus we have that $\sqrt{(a_{n-1}b_{n-1})} \subseteq \sqrt{(s, b_n)} = \sqrt{(s)}$ in A , which translates to $\sqrt{([a_{n-1}][b_{n-1}])} \subseteq \sqrt{(0)}$ in A/I . Therefore $([b_0], \dots, [b_{n-1}])$ is a complementary sequence to $([a_0], \dots, [a_{n-1}])$ in A/I . \square

Lemma 10.9. *Let X be a scheme. Let \mathcal{I} be a sheaf of \mathcal{O}_X -modules. Then:*

$$\dim V(\mathcal{I}) \leq n \iff \text{Sh}(X) \models \ulcorner \mathcal{O}_X/\mathcal{I} \text{ is of Krull dimension} \leq n \urcorner.$$

Proof. By Proposition 3.13, the condition $\dim V(\mathcal{I}) \leq n$ is equivalent to

$$\text{Sh}(V(\mathcal{I})) \models \ulcorner \mathcal{O}_{V(\mathcal{I})} \text{ is of Krull dimension} \leq n \urcorner.$$

By Theorem 6.29 this is equivalent to

$$\text{Sh}(X) \models (\ulcorner \mathcal{O}_X/\mathcal{I} \text{ is of Krull dimension} \leq n \urcorner)^\square,$$

where \square is the modal operator given by $\square\varphi := (\varphi \vee (1 \in \mathcal{I}))$. The claimed equivalence then follows by Lemma 6.23 (for “ \Leftarrow ”) and by direct inspection similar to the proof of Lemma 6.42 (for “ \Rightarrow ”). \square

- open subschemes
- Koszul resolution

11. TRANSFER PRINCIPLES

Let M be an A -module. A natural question is how properties of M relate to properties of the induced quasicohherent sheaf M^\sim of modules on $\text{Spec } A$. For instance it is well-known that

- M is finitely generated iff M^\sim is of finite type,
- M is flat over A iff M^\sim is flat over $\mathcal{O}_{\text{Spec } A}$, and
- M is torsion iff M^\sim is a torsion sheaf.

Using the internal language of the little Zariski topos of $\text{Spec } A$, we can give a simple, conceptual, and uniform explanation of these equivalences. Namely, from the internal point of view, the module M^\sim is obtained from the constant sheaf \underline{M} by localizing at the *generic filter*, a particular multiplicative subset to be introduced below, and the set M and the sheaf \underline{M} share the same properties (by Lemma 11.1 below).

This makes it obvious that, for instance, properties which are stable under localization pass from M to M^\sim .

11.1. Internal properties of constant sheaves.

Lemma 11.1. *Let φ be a formula in which arbitrary sets and elements may occur as parameters. Let X be a topological space and let $U \subseteq X$ be an open subset. Then*

$$U \models \varphi \iff (U \text{ inhabited} \Rightarrow \varphi).$$

Note that we are abusing notation on the left hand side: The parameters of φ , which are sets and elements, must be read as the induced constant sheaves and constant functions (sections of that sheaves). Possible unbounded quantifiers have to be read as ranging only over locally constant sheaves, not all sheaves.

Proof. By induction on the structure of φ . By way of example, we give the argument in the case that $\varphi \equiv (a = b)$, where a and b are elements of some set M . Then $U \models \varphi$ means by definition that the constant functions $U \rightarrow M$ with value a respectively b coincide. This is equivalent to saying that a and b coincide if U is inhabited. \square

This lemma in particular implies that constant sheaves enjoy several classical properties from the internal point of view, even though the internal language only supports intuitionistic reasoning in general. For instance, for a constant sheaf \underline{M} it holds that

$$\mathrm{Sh}(X) \models \forall x, y : \underline{M}. x = y \vee x \neq y \quad \text{and} \quad \mathrm{Sh}(X) \models \forall x, y : \underline{M}. \neg\neg(x = y) \Rightarrow x = y.$$

11.2. The generic filter. Let A be a ring.

Definition 11.2. A *filter* in A is a subset $F \subseteq A$ such that

- $0 \notin F$,
- $1 \in F$,
- $x + y \in F \implies (x \in F) \vee (y \in F)$, and
- $xy \in F \iff (x \in F) \wedge (y \in F)$

for all $x, y : A$.

In classical logic, the complement of a prime ideal is a filter and furthermore every filter is of such a form. In constructive mathematics however, it is useful to axiomatize complements of prime ideals directly, avoiding negations.

A filter is in particular a multiplicative subset. Inverting the elements of a filter results in a local ring, while intuitionistically the localization of a ring at a prime ideal might not be local.

Definition 11.3. The *generic filter* \mathcal{F} is the subsheaf of \underline{A} on $\mathrm{Spec} A$ given by

$$\Gamma(U, \mathcal{F}) := \{f : U \rightarrow A \mid f(\mathfrak{p}) \notin \mathfrak{p} \text{ for all } \mathfrak{p} \in U\}.$$

Proposition 11.4.

- (1) Let $f \in A$ and $x \in A$. Then $D(f) \models x \in \mathcal{F}$ if and only if $f \in \sqrt{(x)}$.
- (2) The stalk $\mathcal{F}_{\mathfrak{p}}$ at a point $\mathfrak{p} \in \mathrm{Spec} A$ is in canonical bijection with $A \setminus \mathfrak{p}$.
- (3) From the internal point of view of $\mathrm{Sh}(\mathrm{Spec} A)$, the generic filter is indeed a filter in \underline{A} .

Proof. By definition $D(f) \models x \in \mathcal{F}$ means that $x \notin \mathfrak{p}$ for all prime ideals \mathfrak{p} with $f \in \mathfrak{p}$. This is well-known to be equivalent to $f \in \sqrt{(x)}$.

For the claim about stalks, note that the canonical map $\mathcal{F}_{\mathfrak{p}} \rightarrow A \setminus \mathfrak{p}$ sending a germ $[f]$ to $f(\mathfrak{p})$ is invertible with inverse being the map which sends an element $x \notin \mathfrak{p}$ to the germ of the constant function with value x (defined on $D(x)$).

Regarding the third statement we only verify the axiom regarding sums, the other axioms being easier. Interpreting this axiom with the Kripke–Joyal semantics and restricting without loss of generality to open subsets where given locally constant functions are constant, let elements $x, y \in A$ be given such that $D(f) \models x + y \in \mathcal{F}$. By the first statement $f \in \sqrt{(x + y)}$. Therefore $D(f) \subseteq D(x) \cup D(y)$, and on $D(x)$ it holds that $x \in \mathcal{F}$ and on $D(y)$ it holds that $y \in \mathcal{F}$. \square

The significance of the generic filter is given by the following proposition.

Proposition 11.5. From the internal point of view of $\mathrm{Sh}(\mathrm{Spec} A)$, ...

- (1) the structure sheaf $\mathcal{O}_{\mathrm{Spec} A}$ is the localization of the constant sheaf \underline{A} away from the generic filter: $\mathcal{O}_{\mathrm{Spec} A} = \underline{A}[\mathcal{F}^{-1}]$, and
- (2) the quasicoherent sheaf of modules M^\sim associated to an A -module M is the localization of the constant sheaf \underline{M} away from the generic filter.

Proof. Ignoring the ring respectively module structure, the second statement is more general; therefore we prove this one. We didn't discuss the case of quotients in Section 2.2. However it should be perspicuous that the interpretation of $\underline{M}[\mathcal{F}^{-1}]$ is defined as the colimit of $\mathcal{E} \rightarrow \underline{M} \times \mathcal{F}$, taken in the category of sheaves on $\mathrm{Spec} A$, where \mathcal{E} is the subsheaf of $\mathcal{F} \times (\underline{M} \times \mathcal{F}) \times (\underline{M} \times \mathcal{F})$ given by $\mathcal{E}(U) := \{(s, (x, t), (y, u)) \mid sux = sty\}$.

This colimit can be obtained as the sheafification of the similarly defined presheaf colimit $\mathcal{E}' \rightarrow \underline{M}_{\mathrm{pre}} \times \mathcal{F}$, where $\underline{M}_{\mathrm{pre}}$ is the constant *presheaf* associated to M . On an open subset U this presheaf colimit is simply the localization $\Gamma(U, \underline{M}_{\mathrm{pre}})[\Gamma(U, \mathcal{F})^{-1}] = M[\Gamma(U, \mathcal{F})^{-1}]$. In the special case that $U = D(f)$ is a standard open subset, Proposition 11.4(a) shows that this module is canonically isomorphic to $M[f^{-1}]$. The quasicoherent sheaf M^\sim of modules admits the same description. \square

Recognizing $\mathcal{O}_{\mathrm{Spec} A}$ as a localization of \underline{A} fits nicely into the following abstract algebraic motivation for schemes: Does the ring A admit a *universal localization*, i.e. a homomorphism $A \rightarrow A'$ into a local ring such that every homomorphism $A \rightarrow B$ into a local ring factors via a local map over $A \rightarrow A'$? Intuitively speaking, can we localize a ring at all prime ideals at once, or equivalently away from all filters? The answer is *no* in general,¹⁰ but always *yes* if we are willing to change the topos in which we look for a solution: The universal localization of A is given by the ring $\mathcal{O}_{\mathrm{Spec} A}$ in the topos $\mathrm{Sh}(\mathrm{Spec} A)$; this ring is constructed by localizing \underline{A} away from the generic filter, a filter which exists in $\mathrm{Sh}(\mathrm{Spec} A)$ but not in Set .

For transferring properties of M^\sim to M , the following metatheorem is crucial.

Proposition 11.6. *Let \mathcal{I} be an ideal in \underline{A} such that, for all inhabited open subsets $U \subseteq \mathrm{Spec} A$ and elements $x \in A$, the set $\Gamma(U, \mathcal{I})$ contains the constant function with value x if $\Gamma(U, \mathcal{I})$ does. Then*

$$D(f) \models \ulcorner \mathcal{I} \cap \mathcal{F} \text{ is inhabited} \urcorner \quad \text{implies} \quad \text{for some } n \geq 0, D(f) \models f^n \in \mathcal{I}.$$

Lemma 11.1 gives a simple and purely syntactical criterion for the hypothesis on \mathcal{I} : It suffices for \mathcal{I} to be internally defined by an expression of the form $\{a : \underline{A} \mid \varphi(a)\}$, where φ is a formula which refers only to constant sheaves.

The metatheorem reflects the following well-known fact of classical ring theory: If an ideal meets every filter (that is, the complement of every prime ideal), it is the unit ideal. In this formulation the statement can't be proven intuitionistically; the occurrence of *every filter* has to be replaced by the *generic filter*. Intuitively, the generic filter is a reification of the abstract idea of an "arbitrary filter", a filter about which nothing is known except that it satisfies the filter axioms.

Proof. Let $D(f) \models \ulcorner \mathcal{I} \cap \mathcal{F} \text{ is inhabited} \urcorner$. Then there exists an open cover $D(f) = \bigcup_i D(f_i)$ and elements $x_i \in A$ such that $D(f_i) \models x_i \in \mathcal{F}$ and $D(f_i) \models x_i \in \mathcal{I}$.

¹⁰Assume that the universal localization exists. Then any two prime ideals \mathfrak{p} and \mathfrak{q} of A are equal: Let $s \notin \mathfrak{p}$. Since s is invertible in the local ring $A_{\mathfrak{p}}$ and the map $A' \rightarrow A_{\mathfrak{p}}$ is local, it is also invertible in A' . Therefore the image of s in $A_{\mathfrak{q}}$ is invertible as well. Thus $s \notin \mathfrak{q}$.

By Proposition 11.4 we have that $f_i \in \sqrt{(x_i)}$ and therefore $D(f_i) \models f_i^{m_i} \in \mathcal{I}$ for some $m_i \geq 0$. We may assume that all the $D(f_i)$ are inhabited and that the exponents m_i are all equal to some number m . The assumption on \mathcal{I} implies $D(f) \models f_i^m \in \mathcal{I}$ for all i . By a standard argument we can write $f^n = \sum_i a_i f_i^m$ for some coefficients a_i ; thus $D(f) \models f^n \in \mathcal{I}$. \square

Remark 11.7. The stronger statement

$$D(f) \models (\ulcorner \mathcal{I} \cap \mathcal{F} \text{ is inhabited} \urcorner \Rightarrow \bigvee_{n \geq 0} (f^n \in \mathcal{I}))$$

does not hold in general. Indeed, consider the example $f := 1$ and $\mathcal{I} := \llbracket (g) \rrbracket := \llbracket \{a : \underline{A} \mid \exists b : \underline{A}, a = bg\} \rrbracket$, where g is a fixed element of A which is not nilpotent and not invertible. Since $D(g) \models g \in \mathcal{I} \cap \mathcal{F}$, the stronger statement would imply $D(g) \models 1 \in \mathcal{I}$. By Lemma 11.1, this is equivalent to g being invertible in A .

11.3. Internal proofs of common lemmas.

Lemma 11.8. *Let A be a ring. Then A is reduced if and only if the scheme $\text{Spec } A$ is reduced.*

Proof. By Proposition 3.3 the scheme $\text{Spec } A$ is reduced if and only if $\mathcal{O}_{\text{Spec } A}$ is a reduced ring from the internal point of view of $\text{Sh}(\text{Spec } A)$.

For the “only if” direction assume that A is reduced. Then \underline{A} is reduced as well, by Lemma 11.1. Since localizations of reduced rings are reduced (and this fact has an intuitionistic proof), in particular $\mathcal{O}_{\text{Spec } A} = \underline{A}[\mathcal{F}^{-1}]$ is reduced.

For the “if” direction let $x \in A$ be an element such that $x^n = 0$. Since $\mathcal{O}_{\text{Spec } A} = \underline{A}[\mathcal{F}^{-1}]$ is reduced from the internal point of view, the element x is zero in that ring, that is

$$\text{Sh}(\text{Spec } A) \models \exists s : \mathcal{F}. sx = 0.$$

Therefore the ideal internally defined by

$$\mathcal{I} := \{a : \underline{A} \mid ax = 0\}$$

meets the generic filter. By Proposition 11.6 it follows that $\text{Sh}(\text{Spec } A) \models 1 \in \mathcal{I}$. By Lemma 11.1 this is equivalent to $1 \cdot x = 0$ as elements of A . \square

Note that the “if” direction also admits a shorter proof, by simply considering the Kripke–Joyal interpretation of $\text{Sh}(\text{Spec } A) \models \ulcorner \mathcal{O}_{\text{Spec } A} \text{ is reduced} \urcorner$ and using $\Gamma(\text{Spec } A, \mathcal{O}_{\text{Spec } A}) \cong A$. We included the given proof to give a simple example of the mixed internal/external reasoning with the generic filter.

Lemma 11.9. *Let M be an A -module. Then M^\sim is of finite type if and only if M is finitely generated.*

Proof. First assume that M is finitely generated over A . Then \underline{M} is finitely generated over \underline{A} , by Lemma 11.1. Since localizations of finitely generated modules are finitely generated (over the localized ring), the module $M^\sim = \underline{M}[\mathcal{F}^{-1}]$ is finitely generated from the internal point of view. By Proposition 4.2 this means that M^\sim is of finite type from the external point of view.

For the “only if” direction, we assume that M^\sim is finitely generated over $\mathcal{O}_{\text{Spec } A}$ from the internal point of view and have to verify that M is finitely generated over A . So it holds that

$$\text{Sh}(\text{Spec } A) \models \bigvee_{n \geq 0} \exists x_1, \dots, x_n : \underline{M}[\mathcal{F}^{-1}]. \ulcorner \text{the } x_i \text{ span } \underline{M}[\mathcal{F}^{-1}] \text{ over } \underline{A}[\mathcal{F}^{-1}] \urcorner.$$

Since multiplying a generating family by an unit results again in a generating family, we have in fact that

$$\text{Sh}(\text{Spec } A) \models \bigvee_{n \geq 0} \exists x_1, \dots, x_n : \underline{M}. \ulcorner \text{the } x_i/1 \text{ span } \underline{M}[\mathcal{F}^{-1}] \text{ over } \underline{A}[\mathcal{F}^{-1}] \urcorner$$

or equivalently

$$\text{Sh}(\text{Spec } A) \models \bigvee_{n \geq 0, x_1, \dots, x_n \in M} \ulcorner \text{the } x_i/1 \text{ span } \underline{M}[\mathcal{F}^{-1}] \text{ over } \underline{A}[\mathcal{F}^{-1}] \urcorner.$$

Since this is a directed disjunction and $\text{Spec } A$ is quasicompact, Proposition 8.1 is applicable and shows that there exists a natural number $n \geq 0$ and elements $x_1, \dots, x_n \in M$ such that

$$\text{Sh}(\text{Spec } A) \models \ulcorner \text{the } x_i/1 \text{ span } \underline{M}[\mathcal{F}^{-1}] \text{ over } \underline{A}[\mathcal{F}^{-1}] \urcorner.$$

We claim that these x_i also span M as an A -module. So let $x \in M$ be arbitrary. By elementary linear algebra we can deduce that

$$\text{Sh}(\text{Spec } A) \models \exists s : \mathcal{F}. \exists a_1, \dots, a_n : \underline{A}. sx = \sum_i a_i x_i.$$

Therefore the ideal internally defined by

$$\mathcal{I} := \{s : \underline{A} \mid \exists a_1, \dots, a_n : \underline{A}. sx = \sum_i a_i x_i\}$$

meets the generic filter. Proposition 11.6 shows that $\text{Sh}(\text{Spec } A) \models 1 \in \mathcal{I}$, that is x is an element of the A -span of the x_i . \square

Remark 11.10. If M^\sim can be generated by $\leq n$ elements over $\mathcal{O}_{\text{Spec } A}$ from the internal point of view, it needn't be the case that M can be generated by $\leq n$ elements over A . It is instructive to see where the appropriately modified version of the above proof fails: In this case we still have

$$\text{Sh}(\text{Spec } A) \models \bigvee_{x_1, \dots, x_n \in M} \ulcorner \text{the } x_i/1 \text{ span } \underline{M}[\mathcal{F}^{-1}] \text{ over } \underline{A}[\mathcal{F}^{-1}] \urcorner,$$

but this disjunction is no longer directed.

11.4. An application to constructive mathematics. The generic filter has a practical application in constructive mathematics. Recall that intuitionistically prime and maximal ideals don't work very well, since one often needs the axiom of choice or related set-theoretical principles in dealing with them. This is unfortunate, since prime and maximal ideals are very useful in some situations. For example:

- To verify that a ring element is nilpotent, it suffices to verify that it is an element of every prime ideal. This might be computationally simpler.
- To verify that there is an relation of the form $1 = p_1 f_1 + \dots + p_m f_m$ among polynomials $f_1, \dots, f_m \in K[X_1, \dots, X_n]$ where K is an algebraically closed field, it suffices to show that the f_i don't have a common zero.

One could of course simply switch to classical logic in this case. However this might not be desirable, as a constructive proof would contain more information: For instance, if we have classically proven that an element x is an element of every prime ideal, then we know that some power x^n is zero. But from such a proof we can't extract any upper bound on n .

There is a way to combine some of the powerful tools of classical ring theory with the advantages that constructive reasoning provides. Namely we can devise a

Statement	constructive substitution	meaning
The stalks $A_{\mathfrak{p}}$ are reduced.	$\mathcal{A}[\mathcal{F}^{-1}]$ is reduced.	A is reduced.
$x \in \mathfrak{p}$ for all \mathfrak{p} .	$x \notin \mathcal{F}$.	x is nilpotent.
$x \in \mathfrak{p}$ for all \mathfrak{p} such that $y \in \mathfrak{p}$.	$x \in \mathcal{F} \Rightarrow y \in \mathcal{F}$.	$x \in \sqrt{(y)}$.
The stalks $M_{\mathfrak{p}}$ vanish.	$\underline{M}[\mathcal{F}^{-1}] = 0$.	$M = 0$.
The stalks $M_{\mathfrak{p}}$ are fin. gen. over $A_{\mathfrak{p}}$.	$\underline{M}[\mathcal{F}^{-1}]$ is fin. gen. over $\underline{A}[\mathcal{F}^{-1}]$.	M is fin. gen. over A .
The stalks $M_{\mathfrak{p}}$ are flat over $A_{\mathfrak{p}}$.	$\underline{M}[\mathcal{F}^{-1}]$ is flat over $\underline{A}[\mathcal{F}^{-1}]$.	M is flat over A .
The maps $M_{\mathfrak{p}} \rightarrow N_{\mathfrak{p}}$ are injective.	$\underline{M}[\mathcal{F}^{-1}] \rightarrow \underline{N}[\mathcal{F}^{-1}]$ is injective.	$M \rightarrow N$ is injective.
The maps $M_{\mathfrak{p}} \rightarrow N_{\mathfrak{p}}$ are surjective.	$\underline{M}[\mathcal{F}^{-1}] \rightarrow \underline{N}[\mathcal{F}^{-1}]$ is surjective.	$M \rightarrow N$ is surjective.

TABLE 3. Substituting the use of prime ideals by the generic filter.

language in which we can usefully talk about prime ideals, but which substitutes all non-constructive arguments by constructive arguments “behind the scenes”. The key idea is to substitute the phrase “for all prime ideals” (or equivalently “for all filters”) by “for the generic filter”.

This was already explored by Coquand, Coste, Lombardi, Roy, and others under the theme of *dynamical methods in algebra* [18, 14]. Here we show how one can use the generic filter, as reified by a sheaf in the little Zariski topos, to achieve similar effects.

Proposition 11.11. *Let M and N be A -modules. Let $\alpha : M \rightarrow N$ be a ring homomorphism. The interpretations of the statements in the second column of Table 3 in the internal language of $\text{Sh}(\text{Spec } A)$ are intuitionistically equivalent to the statements given in the third column.*

Proof. To demonstrate the technique we verify the second and last claim. To make the following proofs constructive we would have to define $\text{Spec } A$ and its sheaf topos in a constructive fashion, not using prime ideals. This can be done, using the frame of radical ideals in A , but we won’t discuss details here.

The interpretation of $\text{Sh}(\text{Spec } A) \models x \notin \mathcal{F}$ by the Kripke–Joyal semantics is that $D(f) \models x \in \mathcal{F}$ implies $D(f) = \emptyset$ for all $f \in A$. By Proposition 11.4(a) this is equivalent to

$$\forall f \in A. f \in \sqrt{(x)} \Rightarrow f \in \sqrt{(0)},$$

that is the statement that x is nilpotent in A .

Assume that $\alpha : M \rightarrow N$ is surjective. By Lemma 11.1 the induced map $\underline{M} \rightarrow \underline{N}$ is surjective from the internal point of view. Since localization preserves surjectivity, also the map $\underline{M}[\mathcal{F}^{-1}] \rightarrow \underline{N}[\mathcal{F}^{-1}]$ is surjective.

Conversely, assume that $\underline{M}[\mathcal{F}^{-1}] \rightarrow \underline{N}[\mathcal{F}^{-1}]$ is surjective from the internal point of view. To verify that $\alpha : M \rightarrow N$ is surjective, let $y \in N$. The assumption implies that the ideal internally defined by

$$\mathcal{I} := \{s : \underline{A} \mid \exists x : \underline{A}. sy = \underline{\alpha}(x)\}$$

meets the generic filter. By Proposition 11.6 this implies that $\text{Sh}(\text{Spec } A) \models 1 \in \mathcal{I}$, that is there exists an element $x \in A$ such that $\alpha(x) = y$. \square

The sheaf-theoretical approach using the generic filter is different from the dynamical methods in the following aspect. We have to reword classical arguments using (the generic) filter instead of (the generic) prime ideal. Depending on the situation this might be a nuisance. One might be tempted to employ the complement of the generic filter, but this is only an ideal, not a prime ideal from the internal point of view.¹¹

12. RELATIVE SPECTRUM

Recall that if \mathcal{A} is a quasicoherent \mathcal{O}_X -algebra on a scheme X , one can construct the *relative spectrum* $\text{RelSpec}_X \mathcal{A}$ by appropriately gluing the spectra $\text{Spec } \Gamma(U, \mathcal{A})$ where U ranges over the affine opens of X . This relative spectrum comes equipped with a canonical morphism $\text{RelSpec}_X \mathcal{A} \rightarrow X$. We can give a simple construction of the relative spectrum in the internal language of $\text{Sh}(X)$, imitating the usual construction of the spectrum of a ring (as opposed to a sheaf of rings).

12.1. Internal locales. Let X be a topological space (or a locale). A fundamental fact in the theory of locales is that there is a canonical equivalence between the category of *locales over X* – that is locales Y equipped with a morphism $Y \rightarrow X$ – and *internal locales in $\text{Sh}(X)$* [27, page 49]. An internal locale in a topos \mathcal{E} is given by an object L of \mathcal{E} (the internal lattice of opens of the locale) together with a binary relation $(\preceq) \hookrightarrow L \times L$ such that the axioms on a locale hold from the internal point of view. (In these notes, we do not need a precise wording of these axioms.)

The equivalence is described as follows: A locale $f : Y \rightarrow X$ over X induces an internal locale $I(Y)$ with object of opens given by $\text{Op}(I(Y)) := f_* \Omega_{\text{Sh}(Y)} \in \text{Sh}(X)$, where f_* is the pushforward functor and $\Omega_{\text{Sh}(Y)}$ is the object of truth values in the topos of sheaves on Y . Conversely, an internal locale $\mathcal{L} \in \text{Sh}(X)$ induces an (external) locale $E(\mathcal{L})$ with lattice of opens given by $\text{Op}(E(\mathcal{L})) := \Gamma(X, \mathcal{L})$. This comes equipped with a canonical morphism $Y \rightarrow X$ of locales which we do not need to describe explicitly [25, section C1.6].

As a special case, the internalization of the trivial locale $\text{id} : X \rightarrow X$ over X has as lattice of opens the object $\text{id}_* \Omega_{\text{Sh}(X)} = \Omega_{\text{Sh}(X)} = \mathcal{P}(1)$. This is precisely the lattice of opens of the one-point space. Thus $I(X) \cong \text{pt}$. This illustrates the intuition behind working internally in $\text{Sh}(X)$ very well: From the perspective of $\text{Sh}(X)$, the space X looks like the one-point space (even if in fact it is not).

One can associate to an internal locale L in a topos \mathcal{E} a topos of internal sheaves on it: $\text{Sh}_{\mathcal{E}}(L)$. The correspondence is made in such a way that the topos of sheaves on a locale Y over X is equivalent to the topos of sheaves on the internal locale $I(Y)$: $\text{Sh}(Y) \simeq \text{Sh}_{\text{Sh}(X)}(I(Y))$.

There is no similarly nice correspondence between topological spaces over X and internal topological spaces in $\text{Sh}(X)$ [25, corollary C1.6.7]. This is one of the reasons why locales are better suited for working internally and for switching between internal and external perspectives.

12.2. The spectrum of a ring as a locale. Recall that the spectrum of a ring A is usually constructed as the set

$$\text{Spec } A := \{\mathfrak{p} \subseteq A \mid \mathfrak{p} \text{ is a prime ideal}\}$$

¹¹One can check that the complement of \mathcal{F} in \underline{A} is the subsheaf \mathcal{P} defined by $\Gamma(U, \mathcal{P}) := \{f : U \rightarrow A \mid f(\mathfrak{p}) \in \mathfrak{p} \text{ for all } \mathfrak{p} \in U\}$ and that $D(f) \models x \in \mathcal{P}$ if and only if fx is nilpotent. This can be used to show that the statement $\text{Sh}(\text{Spec } A) \models \forall x, y : \underline{A}. xy \in \mathcal{P} \Rightarrow x \in \mathcal{P} \vee y \in \mathcal{P}$ is false in general.

endowed with a certain topology and a sheaf of rings $\mathcal{O}_{\text{Spec } A}$. From an intuitionistic (and thus internal) point of view, this construction does not work well: Prime ideals are intuitionistically much more elusive than classically, where one can appeal to Zorn's lemma to obtain maximal (and thus prime) ideals. More to the point, one can not show that this construction of the spectrum as a topological space verifies the expected universal property.

On the other hand, the lattice of opens of $\text{Spec } A$ admits a simple description not needing the notion of prime ideals:

$$\text{Op}(\text{Spec } A) \cong \{\mathfrak{a} \subseteq A \mid \mathfrak{a} \text{ is a radical ideal}\}.$$

An open subset $U \subseteq \text{Spec } A$ corresponds to the radical ideal $\{h \in A \mid D(h) \subseteq U\}$ (so in particular, the open subset $D(f)$ corresponds to the radical ideal $\sqrt{(f)}$); conversely, a radical ideal \mathfrak{a} corresponds to the open subset $\bigcup_{h \in \mathfrak{a}} D(h)$.

Thus, in an intuitionistic context, we will construct the spectrum of a ring A only as a locale, not as a topological space; we will use the lattice of radical ideals as the lattice opens. This construction has the expected universal property, namely that it is adjoint to the global sections functor:

$$\text{Hom}_{\text{LRL}}(X, \text{Spec } A) \cong \text{Hom}_{\text{Ring}}(A, \Gamma(X, \mathcal{O}_X)).$$

Here, “LRL” refers to the category of *locally ringed locales*, i. e. locales X equipped with a sheaf of rings \mathcal{O}_X such that from the internal point of view of $\text{Sh}(X)$, the ring \mathcal{O}_X is a local ring. A morphism $Y \rightarrow X$ of locally ringed locales consists of a locale morphism $f : Y \rightarrow X$ and a morphism $f^\# : f^{-1}\mathcal{O}_X \rightarrow \mathcal{O}_Y$ of sheaves of rings on Y such that, from the internal point of view of $\text{Sh}(Y)$, the ring homomorphism $f^\#$ is a local homomorphism. The notion of a locally ringed locale is thus a straightforward generalization of that of a locally ringed space.

The importance of a locale-theoretic approach to spectra of rings, especially in relative situations, has also been stressed by Lurie [31, page 37].

For later use, we study the question when the spectrum is the one-point space. The answer is well-known classically, but since we want to use this result in an internal context, we have to give an intuitionistic proof.

Lemma 12.1. *Let A be a ring with $0 \neq 1$. Its spectrum is a one-point space (as a locale) if and only if any element of A is nilpotent or invertible.*

Proof. The locale $\text{Spec } A$ is a one-point space if and only if the canonical map

$$\begin{aligned} \Omega = \mathcal{P}(1) &\longrightarrow \text{Op}(\text{Spec } A) \\ \varphi &\longmapsto \mathfrak{a}_\varphi := \sup\{\sqrt{(1)} \mid \varphi\} = \{x : A \mid \ulcorner x \text{ nilpotent} \urcorner \vee \varphi\} \end{aligned}$$

is bijective. It is always injective: If $\mathfrak{a}_\varphi = \mathfrak{a}_\psi$, then $(1 \in \mathfrak{a}_\varphi) \Leftrightarrow (1 \in \mathfrak{a}_\psi)$. Since the unit of A is not nilpotent, this amounts to $\varphi \Leftrightarrow \psi$.

The map is surjective if and only if for any radical ideal $\mathfrak{a} \subseteq A$, it holds that $\mathfrak{a} = \{x : A \mid \ulcorner x \text{ nilpotent} \urcorner \vee \varphi\}$ for some proposition φ . By considering the condition “ $1 \in \mathfrak{a}$ ”, it follows that this proposition φ must be equivalent to the proposition “ $1 \in \mathfrak{a}$ ” (if it is at all possible to write \mathfrak{a} in such a way).

So the map is surjective if and only if for any radical ideal $\mathfrak{a} \subseteq A$ and any element x of A it holds that

$$x \in \mathfrak{a} \iff \ulcorner x \text{ nilpotent} \urcorner \vee (1 \in \mathfrak{a}).$$

The “if” direction always holds. If any element of A is nilpotent or invertible, the “only if” direction holds as well (for any \mathfrak{a} and any x). Considering the radical ideal $\sqrt{(f)}$ for an element $f : A$, one verifies that the converse holds as well. \square

12.3. The relative spectrum as an ordinary spectrum from the internal point of view. Let X be a scheme and \mathcal{A} be a quasicoherent \mathcal{O}_X -algebra. Since \mathcal{A} looks like a plain algebra from the internal perspective of $\mathrm{Sh}(X)$, we can consider its internally defined spectrum. This is a locale internal to $\mathrm{Sh}(X)$; we might hope that its externalization is precisely the relative spectrum of \mathcal{A} (considered as a locale):

$$E(\mathrm{Spec} \mathcal{A}) \stackrel{?}{\cong} \mathrm{RelSpec}_X \mathcal{A}.$$

However, this turns out to be too naive. The externalization of the internally defined spectrum has the universal property

$$\begin{aligned} \mathrm{Hom}_{\mathrm{LRL}/E(\mathrm{Spec} \mathcal{O}_X)}(Y, E(\mathrm{Spec} \mathcal{A})) &\cong \mathrm{Hom}_{\mathrm{LRL}_{\mathrm{Sh}(X)}/\mathrm{Spec} \mathcal{O}_X}(I(Y), \mathrm{Spec} \mathcal{A}) \\ &\cong \mathrm{Hom}_{\mathcal{O}_X}(\mathcal{A}, \mu_* \mathcal{O}_Y) \end{aligned}$$

for all locally ringed locales Y over $E(\mathrm{Spec} \mathcal{O}_X)$. Here, μ is the structure morphism $Y \rightarrow \mathrm{Spec} \mathcal{O}_X$, $E(\mathrm{Spec} \mathcal{O}_X)$ is the locally ringed locale associated to the internally defined spectrum of \mathcal{O}_X , and $\mathrm{LRL}_{\mathrm{Sh}(X)}$ is the category of locally ringed locales internal to $\mathrm{Sh}(X)$. However, the relative spectrum has the different universal property

$$\begin{aligned} \mathrm{Hom}_{\mathrm{LRL}/X}(Y, \mathrm{RelSpec}_X \mathcal{A}) &\cong \mathrm{Hom}_{\mathrm{LRL}_{\mathrm{Sh}(X)}/(\mathrm{pt}, \mathcal{O}_X)}(I(Y), I(\mathrm{RelSpec}_X \mathcal{A})) \\ &\cong \mathrm{Hom}_{\mathcal{O}_X}(\mathcal{A}, \mu_* \mathcal{O}_Y) \end{aligned}$$

for all locally ringed locales Y over X . The crucial difference is that in general, the internally defined locally ringed locale $\mathrm{Spec} \mathcal{O}_X$ does *not* coincide with the internal locally ringed locale $(\mathrm{pt}, \mathcal{O}_X)$ (which is simply (X, \mathcal{O}_X) from the external point of view). More succinctly, the functor $E \circ \mathrm{Spec}$ is an adjoint to the global sections functor $\mathrm{LRL}/E(\mathrm{Spec} \mathcal{O}_X) \rightarrow \mathrm{Alg}(\mathcal{O}_X)^{\mathrm{op}}$, while the relative spectrum functor is an adjoint to the global sections functor $\mathrm{LRL}/X \rightarrow \mathrm{Alg}(\mathcal{O}_X)^{\mathrm{op}}$. **XXX: check details?**

The internal construction which correctly reflects the relative spectrum is the following.

Definition 12.2. Let A be an R -algebra which is quasicoherent in the sense that the condition given in Theorem 9.3 is fulfilled. The lattice of opens of its *quasicoherent spectrum* is given by

$$\mathrm{Op}(\mathrm{Spec}_R^{\mathrm{qcoh}} A) := \{\mathfrak{a} \subseteq A \mid \mathfrak{a} \text{ is a quasicoherent radical ideal}\},$$

where again “quasicoherent” is meant as in Theorem 9.3. If this lattice fulfills the axioms on a locale, we further define a structure sheaf on a base by $\Gamma(\sqrt{(f)}, \mathcal{O}_{\mathrm{Spec}_R^{\mathrm{qcoh}} A}) := A[f^{-1}]$.

Proposition 12.3. *Let X be a scheme and \mathcal{A} a quasicoherent \mathcal{O}_X -algebra. Then:*

- (1) *The internal lattice $\mathrm{Op}(\mathrm{Spec}_{\mathcal{O}_X}^{\mathrm{qcoh}} \mathcal{A})$ fulfills the axioms on an internal locale.*
- (2) *The externalization $E(\mathrm{Spec}_{\mathcal{O}_X}^{\mathrm{qcoh}} \mathcal{A})$ coincides with the relative spectrum $\mathrm{RelSpec}_{\mathcal{O}_X} \mathcal{A}$.*

Proof. We first show that the internalization $I(\mathrm{RelSpec}_{\mathcal{O}_X} \mathcal{A})$ coincides with the internal lattice $\mathrm{Op}(\mathrm{Spec}_{\mathcal{O}_X}^{\mathrm{qcoh}} \mathcal{A})$. Both of these objects are sheaves on X ; so to show that they are canonically isomorphic, it suffices to give compatible canonical

isomorphisms on the base of X consisting of all affine opens. On such an open $U = \text{Spec } R$ the quasicoherent algebra \mathcal{A} is given by a tilde construction: $\mathcal{A}|_U = S^\sim$ for some R -algebra S . Thus it holds that

$$\begin{aligned} \Gamma(U, I(\text{RelSpec}_{\mathcal{O}_X} \mathcal{A})) &\cong \text{Op}(\text{RelSpec}_{\mathcal{O}_X}(\mathcal{A}) \times_X U) \\ &\cong \text{Op}(\text{RelSpec}_{\mathcal{O}_X|_U} \mathcal{A}|_U) \\ &\cong \text{Op}(\text{Spec } S) \\ &\cong \{\mathfrak{a} \subseteq S \mid \mathfrak{a} \text{ is a radical ideal}\}, \end{aligned}$$

$$\Gamma(U, \text{Op}(\text{Spec}_{\mathcal{O}_X}^{\text{qcoh}} \mathcal{A})) \cong \{\mathcal{I} \hookrightarrow \mathcal{A}|_U \mid \mathcal{I} \text{ is a quasicoherent radical ideal sheaf}\}.$$

Clearly, these lattices are isomorphic, by $\mathfrak{a} \mapsto \mathfrak{a}^\sim$ and $\mathcal{I} \mapsto \Gamma(U, \mathcal{I})$.

This is already enough to prove the claims: By a general lemma of locale theory [25, discussion before proposition C1.6.1], the internal lattice $\text{Op}(\text{Spec}_{\mathcal{O}_X}^{\text{qcoh}} \mathcal{A})$ defines an internal locale (as the pushforward under $\text{RelSpec}_{\mathcal{O}_X} \mathcal{A} \rightarrow X$ of a locale), and its externalization coincides with $\text{RelSpec}_{\mathcal{O}_X} \mathcal{A}$. \square

There is also a general spectrum functor by Gillam [20] which works for arbitrary \mathcal{O}_X -algebras (instead of only quasicoherent ones). It coincides with the relative spectrum construction (and thus the externalization of the internal quasicoherent spectrum) on quasicoherent \mathcal{O}_X -algebras. Furthermore, there is a general spectrum construction by Hakim [21], sending ringed toposes to locally ringed toposes. We hope to study its relationship with the internal spectrum construction in the future; it may turn out that they coincide.

Proposition 12.4. *Let X be a scheme. Then $E(\text{Spec } \mathcal{O}_X) \cong X$ as locales over X if and only if X is the empty scheme or X has dimension zero.*

Proof. The externalization of $\text{Spec } \mathcal{O}_X$ coincides with X if and only if from the internal point of view, the locale $\text{Spec } \mathcal{O}_X$ coincides with the one-point locale. By interpreting Lemma 12.1 in the internal language of $\text{Sh}(X)$, it follows that this is the case if and only if

$$\text{Sh}(X) \models \forall f : \mathcal{O}_X. \ulcorner f \text{ nilpotent} \urcorner \vee \ulcorner f \text{ invertible} \urcorner.$$

(Internally, it always holds that $\neg(1 = 0)$ in \mathcal{O}_X , even if X happens to be the empty scheme. Therefore the lemma is indeed applicable.) By Corollary 3.14, this condition is equivalent to the dimension of X being less than or equal to zero, i.e. to X being empty or having dimension exactly zero. \square

Corollary 12.5. *Let X be a scheme. Then the relative spectrum of quasicoherent \mathcal{O}_X -algebras can be calculated by the internal spectrum (instead of the internal quasicoherent spectrum) if and only if X is empty or zero-dimensional.*

Proof. The externalization of the internal spectrum of arbitrary quasicoherent \mathcal{O}_X -algebras \mathcal{A} coincides with the relative spectrum if and only if it coincides in the special case $\mathcal{A} = \mathcal{O}_X$. This is apparent by the universal properties of both constructions. Thus the claim follows by the previous proposition. \square

13. BIG ZARISKI TOPOS, UNSORTED

- synthetic scheme theory
- basics: \mathbb{A}^1 is a local ring and even a field, never reduced
- $[\mathbb{A}^1, \mathbb{A}^1] \cong \mathbb{A}^1[T]$

- definition of the functor of points of important schemes in the internal language: affine space, projective space (acknowledge Zhen Lin Low), open and closed subschemes
- Let X be an S -scheme. Define the tangent “bundle” $TX := \operatorname{Spec} \operatorname{Sym} \Omega_{X/S}^1$. Then $TX = [\Delta, X]$ internally in the big Zariski topos over S , where $\Delta = \{a : \mathbb{A}^1 \mid a^2 = 0\}$. Perhaps use Martin Brandenburg’s Lemma 5.12.1.
- synthetic topology?
- internal spectrum
- affine morphisms
- Kähler differentials
- (co-)tangent space

14. UNSORTED

- “functoriality”
- Kähler differentials
- closed and open subschemes
- $j_! \mathcal{O}_U$ flat over \mathcal{O}_X , ...
- Koszul resolution; Beilinson resolution?
- meta properties: some lemmas about limits of modules
- locally small categories
- open/closed immersions
- morphisms of schemes...
- proper maps...
- limits and colimits...
- Kähler differentials; clear myth that the definition via free modules “does not glue very well” (<http://www.mathematik.uni-kl.de/~gathmann/class/algeom-2002/chapter-7.pdf>)

APPENDIX A. NOETHERIANITY

Recall the usual notion of a Noetherian ring: Any sequence $\mathfrak{a}_0 \subseteq \mathfrak{a}_1 \subseteq \dots$ of ideals should stabilize, i. e. there should exist a natural number n such that $\mathfrak{a}_n = \mathfrak{a}_{n+1} = \dots$.

Intuitionistically, this definition has two problems. Firstly, without the axiom of dependent choice, it is often not possible to construct a *sequence* of ideals: Often, it is only possible to show that there *exists* a suitable ideal \mathfrak{a}_{n+1} depending on \mathfrak{a}_n . But since in general there is no canonical choice for this successor ideal, the axiom of dependent choice would be required to collect those into a sequence, i. e. a function from \mathbb{N} to the set of ideals.

Secondly, the conclusion that the sequence stabilizes is too strong: Intuitionistically, one cannot even show that a weakly descending sequence of natural numbers stabilizes in this sense; the statement that one could is equivalent to the *limited principle of omniscience* for \mathbb{N} . Intuitionistically, it is only true that a weakly descending sequence $a_0 \geq a_1 \geq \dots$ of natural numbers eventually *halts* in the sense that there exists an index n such that $a_n = a_{n+1}$ (but $a_{n+1} > a_{n+2}$ is allowed).

We therefore adopt the following definitions.

Definition A.1. Let M be a partially ordered set. An *ascending process with values in M* is a function $f : \mathbb{N} \rightarrow \mathcal{P}(M)$ such that the subset $f(0)$ is inhabited and

such that for any $x \in f(n)$, $n \in \mathbb{N}$, there exists an element $y \in f(n+1)$ with $x \preceq y$. (In particular, all subsets $f(n)$ are inhabited.) Such a process *halts* if and only if there exists a step n such that there is an element $x \in f(n) \cap f(n+1)$. The set M satisfies the *ascending process condition* if and only if any ascending process with values in M halts.

Definition A.2. A ring R is *processly Noetherian* if and only if the set of finitely generated ideals in R satisfies the ascending process condition.

Any ascending chain of elements $a_0 \preceq a_1 \preceq \dots$ in a partially ordered set gives rise to an ascending process by setting $f(n) := \{a_n\}$. Conversely, the axiom of dependent choice would allow to construct an ascending chain from an ascending process. In classical logic, a ring is processly Noetherian if and only if it is Noetherian in the usual sense.

The notion of a processly Noetherian ring works well in an intuitionistic context: Important rings such as \mathbb{Z} and more generally \mathcal{O}_K for any algebraic number field K are processly Noetherian, and matrices over Bézout rings which are integral domains in the weak sense and processly Noetherian can be put into Smith canonical form.

Proposition A.3. *A scheme X is locally Noetherian if and only if the ring \mathcal{O}_X is processly Noetherian from the internal point of view.*

Proof. We only prove the “only if” direction. We may assume that $X = \text{Spec } A$ is affine with A a Noetherian ring and that internally, we are given an ascending process on the set of finitely generated ideals of \mathcal{O}_X . Externally, this is a morphism $\underline{\mathbb{N}} \rightarrow \mathcal{P}(\mathcal{M})$ where \mathbb{N} is the constant sheaf with value \mathbb{N} and U -sections of \mathcal{M} are finite type ideal sheaves of $\mathcal{O}_X|_U$.

Since $X \models \ulcorner f(0) \text{ is inhabited} \urcorner$, there exists an open covering $X = \bigcup_i U_i$ and finite type ideal sheaves $\mathcal{I}_i \hookrightarrow \mathcal{O}_X|_{U_i}$ such that $U_i \models \mathcal{I}_i \in f(0)$. Without loss of generality, we may assume that the open sets U_i are standard open sets $D(f_i)$ and that the covering is finite. Since the sheaves \mathcal{I}_i are quasicoherent (being of finite type), they correspond to ideals $J_i \subseteq A[f_i^{-1}]$. Note for future reference that $\mathcal{I}_i|_{D(g)}$ corresponds to the extension of J_i in the further localized ring $A[g^{-1}]$, if $D(g) \subseteq D(f_i)$.

For each i , $D(f_i) \models \exists \mathfrak{a} \in f(1)$. $\mathcal{I}_i \subseteq \mathfrak{a}$. Thus there exists an open covering $D(f_i) = \bigcup_j D(g_{ij})$ and finite type ideal sheaves $\mathcal{I}_{ij} \hookrightarrow \mathcal{O}_X|_{D(g_{ij})}$; these correspond to ideals $J_{ij} \subseteq A[g_{ij}^{-1}]$ such that $J_i \subseteq J_{ij}$ (where we have suppressed the localization morphism $A[f_i^{-1}] \rightarrow A[g_{ij}^{-1}]$ in the notation). Equivalently, writing $J'_i := A \cap J_i$ and $J'_{ij} := A \cap J_{ij}$ for the contractions, we have the inclusions $J'_i \subseteq J'_{ij}$ of ideals of A .

Continuing in this fashion, we obtain a tree of ideals $J'_{i_1 \dots i_n}$. Each path in this tree is a chain of ascending ideals and thus stabilizes since A is Noetherian. Since only finitely many subtrees branch off at each node, there appear only finitely many distinct ideals in this tree (this is an application of the graph-theoretical *König's lemma*).

There thus exists a natural number n such that $J'_{i_1 \dots i_n} = J'_{i_1 \dots i_n i_{n+1}}$ for all appropriate indices i_1, \dots, i_n, i_{n+1} . For this number n , the internal statement $X \models \exists \mathfrak{a} \in f(n) \cap f(n+1)$ holds; we leave further details to the reader. \square

Remark A.4. Let X be a locally Noetherian scheme. The proof shows that even the set of all quasicoherent ideals (instead of merely the finitely generated ones) fulfills

the ascending process condition. We have not taken this property as the definition of a processly Noetherian ring since it is a notion not usually studied in constructive mathematics (compare Remark 9.9).

XXX: Find appropriate place for the material in this appendix

XXX: Give examples made possible by the internal Noetherianity

APPENDIX B. DICTIONARY BETWEEN INTERNAL AND EXTERNAL NOTIONS

external	internal	
sheaves of sets		
sheaf of sets	set	
$\alpha : \mathcal{F} \rightarrow \mathcal{G}$ epimorphism	α surjective	Example 2.3
$\alpha : \mathcal{F} \rightarrow \mathcal{G}$ monomorphism	α injective	Example 2.3
$\text{int}(X \setminus \text{supp } \mathcal{F})$	truth value of “ \mathcal{F} is a singleton”	Remark 4.8
$f : X \rightarrow \mathbb{N}$ upper semicontinuous	element of $\widehat{\mathbb{N}}$	Lemma 5.5
$f : X \rightarrow \mathbb{N}$ locally constant	element of \mathbb{N}	discussion after Lemma 5.5
sheaves of rings		
sheaf of rings	ring	Proposition 3.1
local sheaf of rings	local ring	Proposition 3.5
\mathcal{O}_X is reduced	\mathcal{O}_X is reduced	Proposition 3.3; a field property holds: $\neg\text{invertible} \Rightarrow \text{zero}$
sheaves of modules		
sheaf of modules	module	
\mathcal{F} is finite locally free	\mathcal{F} is finite free	Proposition 4.1
\mathcal{F} is of finite type	\mathcal{F} is finitely generated	Proposition 4.2
\mathcal{F} is of finite presentation	\mathcal{F} is finitely presented	Proposition 4.2
\mathcal{F} is coherent	\mathcal{F} is coherent	Proposition 4.2
\mathcal{F} is quasicohherent	$\mathcal{F}[f^{-1}]$ is a sheaf wrt. $(\ulcorner f \text{ inv. } \urcorner \Rightarrow _)$ for any $f : \mathcal{O}_X$	Theorem 9.3
\mathcal{F} is flat	\mathcal{F} is flat	Proposition 4.6
tensor product $\mathcal{F} \otimes \mathcal{G}$	tensor product $\mathcal{F} \otimes \mathcal{G}$	Proposition 4.4
dual $\mathcal{F}^\vee = \mathcal{H}\text{om}_{\mathcal{O}_X}(\mathcal{F}, \mathcal{O}_X)$	dual $\mathcal{F}^\vee = \mathcal{H}\text{om}_{\mathcal{O}_X}(\mathcal{F}, \mathcal{O}_X)$	
$\text{int}(X \setminus \text{supp } \mathcal{F})$	truth value of “ $\mathcal{F} = 0$ ”	Proposition 4.7
rank function of \mathcal{F}	minimal number of generators for \mathcal{F}	Proposition 5.6
subspaces		
sheaf supported on closed subset A	\square -sheaf, where $\square = (_ \vee A^c)$	Lemma 10.3

sheaf of the form $j_*(\mathcal{F})$	\Box -sheaf, where $\Box = (U \Rightarrow _)$	$j : U \hookrightarrow X$ open inclusion
extension of \mathcal{F} by the empty set	$j_!(\mathcal{F}) = \{x : \mathcal{F} \mid U\}$	Lemma 10.1
extension of \mathcal{F} by zero	$j_!(\mathcal{F}) = \{x : \mathcal{F} \mid (x = 0) \vee U\}$	Lemma 10.2
sheaf with empty/zero stalks on U^c	sheaf of the form $j_!(\mathcal{F})$	$j : U \hookrightarrow X$
sections of \mathcal{F} are equal if they agree on dense open	\mathcal{F} is $\neg\neg$ -separated	Proposition 6.13
sheaf of sections of \mathcal{F} defined on dense open subsets	\mathcal{F}^{++} with respect to $\Box = \neg\neg$	Proposition 6.13, assuming \mathcal{F} is $\neg\neg$ -separated
$V(\mathcal{I})$ is a reduced scheme	\mathcal{I} is a radical ideal	Lemma 10.6
$\mathcal{O}_{X_{\text{red}}}$	$\mathcal{O}_X / \sqrt{(0)}$	Lemma 10.7

rational functions and Cartier divisors

\mathcal{K}_X	total quotient ring of \mathcal{O}_X	Proposition 7.1
Cartier divisor	element of $\mathcal{K}_X^* / \mathcal{O}_X^*$	
effective Cartier divisor	$[s/1]$ with $s : \mathcal{O}_X$ regular	Definition 7.20
line bundle $\mathcal{O}_X(D)$	$D^{-1}\mathcal{O}_X \subseteq \mathcal{K}_X$	Definition 7.22

XXX: update table to contain all concepts discussed in these notes

APPENDIX C. THE INFERENCE RULES OF INTUITIONISTIC LOGIC

XXX: cite [25, section D1.3.1], talk about \in , and explain contexts

Structural rules

$$\frac{}{\varphi \vdash_{\vec{x}} \varphi} \quad \frac{\varphi \vdash_{\vec{x}} \psi}{\varphi[\vec{s}/\vec{x}] \vdash_{\vec{y}} \psi[\vec{s}/\vec{x}]} \quad \frac{\varphi \vdash_{\vec{x}} \psi \quad \psi \vdash_{\vec{x}} \chi}{\varphi \vdash_{\vec{x}} \chi}$$

Rules for nullary and binary conjunction

$$\frac{}{\varphi \vdash_{\vec{x}} \top} \quad \frac{}{\varphi \wedge \psi \vdash_{\vec{x}} \varphi} \quad \frac{}{\varphi \wedge \psi \vdash_{\vec{x}} \psi} \quad \frac{\varphi \vdash_{\vec{x}} \psi \quad \varphi \vdash_{\vec{x}} \chi}{\varphi \vdash_{\vec{x}} \psi \wedge \chi}$$

Rules for nullary and binary disjunction

$$\frac{}{\perp \vdash_{\vec{x}} \varphi} \quad \frac{}{\varphi \vdash_{\vec{x}} \varphi \vee \psi} \quad \frac{}{\psi \vdash_{\vec{x}} \varphi \vee \psi} \quad \frac{\varphi \vdash_{\vec{x}} \chi \quad \psi \vdash_{\vec{x}} \chi}{\varphi \vee \psi \vdash_{\vec{x}} \chi}$$

Rules for arbitrary set-indexed conjunction and disjunction

$$\frac{}{\bigwedge_{i \in I} \varphi_i \vdash_{\vec{x}} \varphi_j \text{ for all } j \in I} \quad \frac{\varphi \vdash_{\vec{x}} \psi_j \text{ for all } j \in I}{\varphi \vdash_{\vec{x}} \bigwedge_{i \in I} \psi_i}$$

$$\frac{}{\varphi_j \vdash_{\vec{x}} \bigvee_{i \in I} \varphi_i \text{ for all } j \in I} \quad \frac{\varphi_j \vdash_{\vec{x}} \psi \text{ for all } j \in I}{\bigvee_{i \in I} \varphi_i \vdash_{\vec{x}} \psi}$$

Double rule for implication

$$\frac{\varphi \wedge \psi \vdash_{\vec{x}} \chi}{\varphi \vdash_{\vec{x}} \psi \Rightarrow \chi}$$

Double rules for bounded and unbounded quantification

$$\frac{\varphi \vdash_{\vec{x}, y} \psi}{\exists y : Y. \varphi \vdash_{\vec{x}} \psi} \quad (y \text{ not occurring in } \psi) \qquad \frac{\varphi \vdash_{\vec{x}, y} \psi}{\varphi \vdash_{\vec{x}} \forall y : Y. \psi} \quad (y \text{ not occurring in } \varphi)$$

$$\frac{\varphi \vdash_{\vec{x}, Y} \psi}{\exists Y. \varphi \vdash_{\vec{x}} \psi} \quad (Y \text{ not occurring in } \psi) \qquad \frac{\varphi \vdash_{\vec{x}, Y} \psi}{\varphi \vdash_{\vec{x}} \forall Y. \psi} \quad (Y \text{ not occurring in } \varphi)$$

Rules for equality

$$\frac{}{\top \vdash_{\vec{x}} x = x} \qquad \frac{}{(\vec{x} = \vec{y}) \wedge \varphi \vdash_{\vec{z}} \varphi[\vec{y}/\vec{x}]}$$

(“ $\vec{x} = \vec{y}$ ” is short for “ $x_1 = y_1 \wedge \dots \wedge x_n = y_n$ ”.)

REFERENCES

- [1] P. Aczel. “The Russell–Prawitz modality”. In: *Math. Structures Comput. Sci.* 11.4 (2001), pp. 541–554.
- [2] S. Awodey and A. Bauer. “Propositions as [Types]”. In: *J. Logic Comput.* 14.4 (2004), pp. 447–471.
- [3] S. Awodey and K. Kishida. “Topology and modality: The topological interpretation of first-order modal logic”. In: *The Review of Symbolic Logic* (2008).
- [4] A. Bauer. *Five Stages of Accepting Constructive Mathematics*. Lecture at the Institute for Advanced Study. 2013. URL: <http://video.ias.edu/members/1213/0318-AndrejBauer>.
- [5] A. Bauer. “Intuitionistic Mathematics and Realizability in the Physical World”. In: *A Computable Universe*. Ed. by H. Zenil. World Scientific Pub Co, 2012.
- [6] J. Bell. “The development of categorical logic”. In: *Handbook of Philosophical Logic*. Ed. by D. Gabbay and F. Guenther. 2nd ed. Vol. 12. Springer, 2005, pp. 279–361.
- [7] L. Birkedal et al. “First steps in synthetic guarded domain theory: step-indexing in the topos of trees”. In: *Proc. of the 2011 IEEE 26th Annual Symposium on Logic in Computer Science*. 2012. URL: <http://www.cs.au.dk/~birke/papers/sgdt-journal.pdf>.
- [8] E. Bishop and D. Bridges. *Constructive Analysis*. Springer, 1985.
- [9] F. Borceux. *Handbook of Categorical Algebra: Volume 3, Sheaf Theory*. Encyclopedia Math. Appl. Cambridge University Press, 1994.
- [10] M. Brandenburg. “Tensor categorical foundations of algebraic geometry”. PhD thesis. Universität Münster, 2014. URL: <http://arxiv.org/abs/1410.1716>.
- [11] J. Butterfield, J. Hamilton, and C. Isham. “A topos perspective on the Kochen–Specker theorem, I. quantum states as generalized valuations”. In: *Internat. J. Theoret. Phys.* 37.11 (1998), pp. 2669–2733.

- [12] O. Caramello. “A topos-theoretic approach to Stone-type dualities”. 2011. URL: <http://arxiv.org/abs/1103.3493>.
- [13] O. Caramello. “The unification of mathematics via topos theory”. 2010. URL: <http://arxiv.org/abs/1006.3930>.
- [14] T. Coquand and H. Lombardi. “A logical approach to abstract algebra”. In: *Math. Structures Comput. Sci.* 16.5 (2006), pp. 885–900. URL: <http://www.cse.chalmers.se/~coquand/FISCHBACHAU/AlgebraLogicCoqLom.pdf>.
- [15] T. Coquand and H. Lombardi. “A short proof for the Krull dimension of a polynomial ring”. In: *Amer. Math. Monthly* 112.9 (2005), pp. 826–829.
- [16] T. Coquand, H. Lombardi, and M.-F. Roy. “An elementary characterisation of Krull dimension”. In: *From Sets and Types to Analysis and Topology: Towards Practicable Foundations for Constructive Mathematics*. Oxford Univ. Press, 2005, pp. 239–244.
- [17] T. Coquand et al. “Constructive Krull dimension I: integral extensions”. In: *J. Algebra Appl.* 8.1 (2009), pp. 129–138.
- [18] M. Coste, H. Lombardi, and M.-F. Roy. “Dynamical method in algebra: effective Nullstellensätze”. In: *Ann. Pure Appl. Logic* 111.3 (2001), pp. 203–256. URL: <http://perso.univ-rennes1.fr/michel.coste/publis/clr.pdf>.
- [19] M. Escardó and P. Oliva. “The Peirce translation and the double negation shift”. In: *Programs, Proofs, Processes*. Ed. by F. Ferreira et al. Vol. 6158. Lecture Notes in Comput. Sci. Springer, 2010, pp. 151–161.
- [20] W. D. Gillam. “Localization of ringed spaces”. In: *Adv. Pure Math.* 1.5 (2011), pp. 250–263.
- [21] M. Hakim. *Topos annelés et schémas relatifs*. Vol. 64. Ergeb. Math. Grenzgeb. Springer, 1972.
- [22] S. Henry. *Measure theory over boolean toposes*. 2014. URL: <http://arxiv.org/abs/1411.1605>.
- [23] C. Heunen, N. Landsman, and B. Spitters. “A topos for algebraic quantum theory”. In: *Comm. Math. Phys.* 291.1 (2009), pp. 63–110.
- [24] M. Jackson. “A sheaf theoretic approach to measure theory”. PhD thesis. University of Pittsburgh, 2006.
- [25] P. T. Johnstone. *Sketches of an Elephant: A Topos Theory Compendium*. Oxford University Press, 2002.
- [26] P. T. Johnstone. “The art of pointless thinking: a student’s guide to the category of locales”. In: *Category theory at work (Bremen, 1990)*. Res. Exp. Math. 18. Heldermann, 1991, pp. 85–107.
- [27] P. T. Johnstone. “The point of pointless topology”. In: *Bull. Amer. Math. Soc.* 8.1 (1983), pp. 41–53.
- [28] S. Kleiman. “Misconceptions about K_X ”. In: *Enseign. Math.* 25 (1979), pp. 203–206.
- [29] A. Kock. *Synthetic Differential Geometry*. 2nd ed. London Math Soc. Lecture Note Ser. 333. Cambridge University Press, 2006. URL: <http://home.math.au.dk/kock/sdg99.pdf>.
- [30] T. Leinster. “An informal introduction to topos theory”. In: *Publications of the nLab* 1.1 (2011).
- [31] J. Lurie. “Derived Algebraic Geometry V: Structured Spaces”. 2009. URL: <http://arxiv.org/abs/0905.0459>.

- [32] S. Mac Lane and I. Moerdijk. *Sheaves in Geometry and Logic: a First Introduction to Topos Theory*. Universitext. Springer, 1992.
- [33] B. Manna and T. Coquand. “A sheaf model of the algebraic closure”. In: *Proc. of the Fifth International Workshop on Classical Logic and Computation*. 2014. URL: <http://arxiv.org/abs/1404.4549>.
- [34] R. Mines, F. Richman, and W. Ruitenburg. *A Course in Constructive Algebra*. Universitext. Springer, 1988.
- [35] I. Moerdijk and G. Reyes. *Models for Smooth Infinitesimal Analysis*. Springer, 1991.
- [36] C. Mulvey. “Intuitionistic algebra and representations of rings”. In: *Recent Advances in the Representation Theory of Rings and C^* -algebras by Continuous Sections*. Ed. by K. H. Hofmann and J. R. Liukkonen. Vol. 148. Mem. Amer. Math. Soc. American Mathematical Society, 1974, pp. 3–57.
- [37] F. Pasquali. *A sheafification theorem for doctrines*. 2014. URL: <http://arxiv.org/abs/1311.1424>.
- [38] M. Shulman. “Stack semantics and the comparison of material and structural set theories”. 2010. URL: <http://arxiv.org/abs/1004.3802>.
- [39] The Stacks Project Authors. *Stacks Project*. URL: <http://stacks.math.columbia.edu/>.
- [40] T. Tao. *A cheap version of nonstandard analysis*. 2012. URL: <http://terrytao.wordpress.com/2012/04/02/a-cheap-version-of-nonstandard-analysis/>.
- [41] T. Tao. *Real analysis relative to a finite measure space*. 2014. URL: <http://terrytao.wordpress.com/2014/07/15/real-analysis-relative-to-a-finite-measure-space/>.
- [42] A. S. Troelstra and D. van Dalen. *Constructivism in Mathematics: An Introduction*. North-Holland Publishing, 1988.
- [43] Ravi Vakil. *Foundations of Algebraic Geometry*. 2013. URL: <http://math.stanford.edu/~vakil/216blog/>.
- [44] S. Vickers. “Continuity and geometric logic”. In: *J. Appl. Log.* 12.1 (2014), pp. 14–27.
- [45] S. Vickers. “Locales and Toposes as Spaces”. In: *Handbook of Spatial Logics*. Ed. by M. Aiello, I. Pratt-Hartmann, and J. van Benthem. Springer, 2007, pp. 429–496.
- [46] F.-J. de Vries. “Applications of constructive logic to sheaf constructions in toposes”. In: *Logic Group preprint series, Rijksuniversiteit Utrecht* 25 (1987).
- [47] G. Wraith. “Generic Galois theory of local rings”. In: *Applications of sheaves*. Ed. by M. Fourman, C. Mulvey, and D. Scott. Vol. 753. Lecture Notes in Math. Springer, 1979, pp. 739–767.

XXX: remark on possible pitfalls

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