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Condensed homotopy theory

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Contents

Acronyms

Set the category of sets

Part I
Topological preliminaries

The general theory of condensed objects relies on some very precise results in general topology. Not all of these results would be included in a typical undergraduate course in topology, so we fill in some of these details.

Chapter 1
Aspects of set theory

Mathematicians' 'stock' set theory, ZFC (Zermelo–Fraenkel set theory ZF plus the Axiom of Choice AC) doesn't quite have the expressive power one needs for work with categories and higher categories. The issue ultimately comes down to Cantor's diagonal argument: there is no surjection of a set onto its powerset. This is ultimately why no one can contemplate a set of all sets, and it's also the key to Freyd's observation that if C is a category and κ is the cardinality of its set of arrows, then C has all κ-indexed products only if C is a poset. This, in turn, is what's behind the 'solution set condition' in representability theorems or the Adjoint Functor Theorem. Hence one really must distinguish between 'large' and 'small' objects.

One improves matters by passing to von Neumann–Bernays–Gödel set theory (NBG), which is a conservative extension of ZFC. In NBG, the formal language consists of the symbols $\in$ and $=$; a constant V; suitable variables; the usual connectives of first-order logic ($\neg, \wedge, \vee, \implies$, and $\iff$); and the quantifiers $\forall$ and $\exists$. The objects of the theory are called *classes*, and a class X is called a *set* if and only if $X \in V$; if $X \notin V$, then we call X a *proper class*. We summarize the axioms of NBG in informal language:

Extensionality Classes X and Y are equal if and only if, for any set Z, one has $Z \in X$ if and only if $Z \in Y$.

Regularity For every class X, there exists an element $Z \in X$ such that $Z \cap X = \varnothing$.

Infinity There is an infinite set.

Union If X is a set, then $\bigcup X = \bigcup_{Z \in X} Z$ is a set as well.

Pairing If X and Y are sets, then $\{X, Y\}$ is a set as well.

Powerset If X is a set, then the powerset $P(X)$ is a set as well.

Limitation of size A class X is a proper class if and only if there is a bijection between X and V.

Class comprehension For every first-order formula $\phi(X)$ with a free variable X in which the quantifiers are over sets, there exists a class $\{X \in V : \phi(X)\}$ whose elements are those sets X such that $\phi(X)$.

Definition 1.0.1 A *large category* C consists of a sequence $(C_n)_{n \in \mathbf{N}_0}$ of classes, along with a family of class maps $\phi^* : C_m \to C_n$ for each map $\phi \colon n \to m$, subject to the all the formulas that express the statement that C_n is a simplicial class that satisfies the inner Kan condition.

If the classes C_n are all sets, then we just say that C is a *category*.

A large category C is said to be *locally small* if and only if, for every subset $C'_0 \subseteq C_0$, the full subcategory $C' \subseteq C$ spanned by the elements of C'_0 is a category.

Example 1.0.2 We shall write $\mathbf{Set}_V$ for the large category of all sets. The objects of $\mathbf{Set}_V$ are thus precisely the elements of V.

We shall write $\boldsymbol{S}_V$ for the large category of all spaces. The objects of $\boldsymbol{S}_V$ are thus precisely the Kan complexes $\Delta^{op} \to \mathbf{Set}_V$.

We shall write $\mathbf{Cat}_V$ for the large category of all categories. The objects of $\mathbf{Cat}_V$ are thus precisely the weak Kan complexes $\Delta^{op} \to \mathbf{Set}_V$.

The Class Comprehension Axiom Schema implies the *Axiom of Global Choice*, which ensures the existence of a choice function $\tau : V \to V$ such that $\tau(X) \in X$. One needs this to make sense of a construction like 'the' functor $- \times X : C \to C$ for a large category C with all finite products and a fixed object $X \in C$.

Here, we will work with NBG as our base theory. Hence we may speak of proper classes and large categories whenever the occasion arises.

However, the whole project of category theory and higher category theory turns on the principle that we want to be able to deal with the collections of all objects of a given kind as a mathematical object in its own right, and that the passage up and down these category levels[1] is a fruitful way to understand even completely 'decategorified' objects. If we have a large category C, we cannot view C itself as an object of a still larger category of all categories, and that limits the kinds of operations we are permitted to do to C.

To give ourselves the space to perform these sorts of constructions, we need to have a hierarchy of 'scales' at which we can work. These scales will be identified by inaccessible cardinals or, equivalently, Grothendieck universes (Section 1.1). The existence of these cardinals is independent of NBG.

But now a rather different concern arises. We will also want to have reasonable assurance that the results we obtain at one scale remain valid at other scales. We would prefer to prove sentences about *all* sets, spaces, groups, etc., not just those within a universe. This sort of 'scale-invariance of truth' is expressed by a *reflection principle* (Section 1.2). The reflection principle we will use here states roughly that there is an inaccessible cardinal κ such that any statement of set theory that holds in the universe V_κ holds in V itself. This is the *Lévy scheme* LÉVY. In effect, it permits us to focus our attention on categories (as opposed to large categories). This axiom schema has a strictly stronger conistency strength than the existence of inaccessible cardinals; however, its consistency strength is strictly weaker than that of the existence of a single Mahlo cardinal.

Example 1.0.3 Keep the notations from Theorem 1.1.9 and **??**. If we have a formula in

[1] This is roughly a description of *microcosm principle* of Baez–Dolan.

1.1 Cardinals

We establish some notation and recall some basic results on cardinals in set and category theory.

Definition 1.1.1 If κ is a cardinal, then a set S is *κ-small* if and only if $|S| < \kappa$. We shall write $\mathbf{Set}_\kappa \subset \mathbf{Set}_V$ for the category of κ-small sets, Thus $\mathbf{Set}_V$ is the union of the categories $\mathbf{Set}_\kappa$ over the proper class of cardinals.

An infinite cardinal κ is *regular* if and only if, for every map $f: S \to T$ such that T is κ-small and every fiber $f^{-1}\{t\}$ is κ-small, the set S is κ-small as well. Equivalently, κ is regular if and only if $\mathbf{Set}_\kappa \subset \mathbf{Set}_V$ is stable under colimits indexed by κ-small posets.

Example 1.1.2 The countable cardinal $\aleph_0$ is regular. Every successor cardinal is regular; in particular, $\aleph_n$ for $n \in \boldsymbol{N}$ is regular as well. The cardinal $\aleph_\omega$ is the smallest cardinal that is not regular.

If κ is a regular cardinal, then $\mathbf{Set}_\kappa \subset \mathbf{Set}_V$ is in fact the smallest full subcategory that is stable under colimits indexed by κ-small posets and contains the singleton $\{0\}$.

Definition 1.1.3 If κ is a regular cardinal, then we shall write $\boldsymbol{S}_\kappa \subset \boldsymbol{S}_V$ for the smallest full subcategory that is stable under colimits indexed by κ-small posets and contains $\{0\}$.

Similarly, we shall write $\mathbf{Cat}_\kappa \subset \mathbf{Cat}_V$ for the smallest full subcategory that is stable under colimits indexed by κ-small posets and contains the categories $\{0\}$ and $\{0 < 1\}$.

Example 1.1.4 A set is $\aleph_0$-small if and only if it is finite.

A space is $\aleph_0$-small if and only if it is weak homotopy equivalent to a simplicial set with only finitely many nondegenerate simplices.

A category C is $\aleph_0$-small if and only if is is Joyal equivalent to a simplicial sets with only finitely many nondegenerate simplices.

Definition 1.1.5 Let κ be a regular cardinal. A category Λ is *κ-filtered* if and only if it satisfies the following equivalent conditions:

1. For every κ-small category I, every functor $f: I \to \Lambda$ can be extended to a functor $F: I^\triangleright \to \Lambda$.
2. For every κ-small category I, and every functer $H: \Lambda \times I \to \boldsymbol{S}_V$, the natural morphism
$$\operatorname*{colim}_{\lambda \in \Lambda} \lim_{i \in I} H(\lambda, i) \to \lim_{i \in I} \operatorname*{colim}_{\lambda \in \Lambda} H(\lambda, i)$$
is an equivalence.

A functor $f: C \to D$ between large categories will be said to be *κ-continuous* if and only if it preserves κ-filtered colimits. An object X of a large locally small category C is said to be *κ-compact* if and only if the functor よ$^X: C \to \boldsymbol{S}_V$ corepresented by X (i.e., the functor $Y \mapsto \mathrm{Map}_C(X, Y)$) is κ-continuous.

Example 1.1.6 Let κ be an uncountable regular cardinal. Then the following are equivalent for a category C.

1. The category C is κ-small.
2. The set of equivalence classes of objects of C is κ-small, and for every morphism $f : X \to Y$ of C and every $n \in \boldsymbol{N}_0$, the set $\pi_n(\mathrm{Map}_C(X, Y), f)$ is κ-small.
3. The category C is κ-compact as an object of $\mathbf{Cat}_V$.

In particular, a space X is κ-small if and only if all its homotopy sets are κ-small, if and only if it is κ-compact as an object of $\boldsymbol{S}_V$.

Definition 1.1.7 A cardinal κ is said to be a *strong limit cardinal* if and only if, for any $\alpha < \kappa$, one has $2^\alpha < \kappa$ as well. Equivalently, κ is a strong limit cardinal if and only if, for any κ-small sets X and Y, the set $\mathrm{Map}(X, Y)$ of maps $X \to Y$ is κ-small as well.

One says that κ is *inaccessible*[2] if and only if it is a regular, uncountable, strong limit cardinal. Equivalently, an uncountable cardinal κ is inaccessible if and only if $\mathbf{Set}_\kappa$ has all κ-small colimits and is cartesian closed.

Example 1.1.8 The $\beth$ family of cardinals is defined by a function from the class of ordinal numbers to the class of cardinal numbers. It's defined by transfinite induction:

- By definition, $\beth_0 = \aleph_0$.
- For any ordinal α, one defines $\beth_{\alpha+1} \coloneqq 2^{\beth_\alpha}$.
- For any limit ordinal α, one defines $\beth_\alpha \coloneqq \sup\{\beth_\beta : \beta < \alpha\}$.

The cardinal $\beth_\alpha$ is the cardinality of $V_{\omega+\alpha}$.

A cardinal κ is a strong limit cardinal if and only if, for some limit ordinal α, one has $\kappa = \beth_\alpha$.

The cardinal $\beth_\omega$ is the smallest uncountable strong limit cardinal. It is not an inaccessible cardinal, however, because it is not regular.

An inaccessible cardinal is a $\beth$-*fixed point*: if κ is inaccessible, then $\beth_\kappa = \kappa$.

Example 1.1.9 Here's the sort of example that will give us grief. Let C be a large category, and suppose that we seek to make sense in NBG of the category $\boldsymbol{P}_0(C)$ of presheaves of sets $C^{op} \to \mathbf{Set}_V$.

Right away we encounter a problem: if the objects of C form a proper class C_0, then there is no class of class maps $\mathrm{Map}(C_0, V)$. Indeed, on one hand, in NBG, every element of a class is itself a set, and on the other hand, a class map $f : C_0 \to V$ cannot be a set.[3]

If C is locally small, then for any full subcategory $D \subset C$ spanned by a set of objects, we may contemplate the category $\boldsymbol{P}_0(D)$ of presheaves $D^{op} \to \mathbf{Set}_V$. The large category $\boldsymbol{P}_0(D)$ is locally small, and it enjoys many of the same good properties enjoyed by $\mathbf{Set}_V$ itself. In particular, it has all colimits,[4] and it is *cartesian closed*: for

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[2] Some authors say *strongly inaccessible* instead of *inaccessible*.

[3] Worse still, the very large category of classes is not cartesian closed, so there's no hope of defining $\mathrm{Map}(C_0, V)$ by some other artifice.

[4] by which we mean colimits of functors from categories, not large categories

every pair of presheaves $X, Y\colon D^{op} \to \mathbf{Set}_V$, the morphisms $X \to Y$ form a presheaf $\mathrm{Mor}(X, Y)\colon D^{op} \to \mathbf{Set}_V$.

If we have an inclusion of subcategories $D \subseteq D' \subset C$, then left Kan extension identifies $\boldsymbol{P}_0(D')$ with a full subcategory of $\boldsymbol{P}_0(D)$.

We might hope for the category $\boldsymbol{P}^0_\lambda(C_\kappa)$ to enjoy good properties. For example, we may want it to contain all λ-small colimits. We may want that for presheaves X, Y on C_κ valued in λ-small sets, the morphisms $X \to Y$ form a presheaf $\mathrm{Mor}(X, Y)$ on C_κ again valued in λ-small sets. These two conditions hold if and only if λ is inaccessible.

If the

Definition 1.1.10 ([?, Exposé I, §0 and Appendix]) An uncountable set $\boldsymbol{V}$ is a *Grothendieck universe* if it satisfies the following conditions.

1. The set $\boldsymbol{V}$ is *transitive*: $X \in Y \in \boldsymbol{V}$, then $X \in \boldsymbol{V}$ as well.
2. If $X, Y \in \boldsymbol{V}$, then $\{X, Y\} \in \boldsymbol{V}$ as well.
3. If $X \in \boldsymbol{V}$, then the powerset $P(X) \in \boldsymbol{V}$ as well.
4. If $A \in \boldsymbol{V}$ and $X\colon A \to \boldsymbol{V}$ is a map, then

$$\bigcup_{\alpha \in A} X(\alpha) \in \boldsymbol{V}$$

   as well.

Grothendieck universes are essentially the same thing as inaccessible cardinals, as demonstrated by Bourbaki.[**?**, Exposé I, Appendix]

Proposition 1.1.11 (Bourbaki) *If κ is an inaccessible cardinal, then the set V_κ of all sets of rank less than κ is a Grothendieck universe of rank and cardinality κ.*

If V is a Grothendieck universe, then there exists an inaccessible cardinal κ such that $V = V_\kappa$.

Theorem 1.1.12 *If κ is an inaccessible cardinal, then V_κ models ZFC, and $V_{\kappa+1}$ models NBG.*

Assuming that ZFC (respectively, NBG) is consistent, then the existence of inaccessible cardinals is not provable by methods formalizable in ZFC (resp., NBG).

Axiom 1.1.13 *Axiom of Universes* (AU) is the assertion that every cardinal is dominated by an inaccessible cardinal, or, equivalently, every set is an element of some Grothendieck universe. *Tarski–Grothendieck set theory* is the schema TG = NBG + AU.

1. On one hand, one can choose to consider presheaves on a small model of the category C, which is given by the full subcategory $C^\kappa \subset C$ spanned by the κ-compact objects for some regular cardinal κ, and one can demand that This can be done either by restricting the category to C to some subcategory of sufficiently small objects, or by enlarging the sizes of the sets. This has the advantage that we have easy representability theorems to ensure the existence of various objects defined by universal properties. It has the disadvantage that a careful formulation requires either a certain degree of extra care with the choice of the size of C, or else additional axioms of set theory that are not equiconsistent with ZFC.

2. On the other hand, one can contemplate only those presheaves that are themselves small in the sense that they are determined by their values on some small subcategory. This has the advantage of remaining within the confines of ZFC. It has the disadvantage of not having recourse to easy representability theorems.

These two approaches lead, respectively, to the pyknotic or condensed formalism.

In practice, the distinction between pyknotic and condensed objects is quite mild, so the typical end-user of the theory will in many cases be able to ignore the distinction. We will want to highlight those few places where the distinction is relevant, and we will want to dispatch hastily those places where it is not. The set-theoretic framework we here is chosen for exactly that purpose.

1.2 Refection principles

The *Lévy scheme*, LÉVY was originally proposed by Lévy,[**?**]. Since then essentially the same set theory arrived under different names:

Its suitability for the tasks of category theory was recently emphasized by Mike Shulman [**?**]. It addresses the following informal points.

1. We must avoid any of the usual known paradoxes of set theory, particularly, the Russell paradox, the Cantor paradox, and the Burali–Forti paradox. This is the point that *large objects are genuinely different from small objects*. This can be formalised by means of a (relatively modest) large cardinal axiom. This is precisely the motivation for the Axiom of the Universe as formulated by Grothendieck et al.[**?**, Exposé I, §0 and Appendix]
2. At the same time, constructions of objects that involve representability theorems — for example — may not be stable under passage to higher universes.[5] The axioms of our set theory should formalise the idea that *large objects are different from small objects, but they still behave in the same manner*. This is the core of the *Reflection Principle*, which is also the primary insight in Feferman's construction of ZFC/$\boldsymbol{S}$.
3. Though there are genuine (and genuinely relevant) mathematical ideas at work in the Reflection Principle, those mathematicians who do not wish to contemplate large cardinal axioms should be able to make use of the assertions made here naively without consequential errors. This is achieved by working with an extension of the more familiar ZFCcombined with a few rules as to what sort of manoeuvres are permitted with large objects.

We now set about describing the axioms beyond the usual axioms of ZFCwe shall employ. For more details, we refer the reader to Jech's comprehensive text.[**?**]

[5] There are examples of this. Waterhouse constructs a presheaf whose fpqc sheafification actually depends upon the universe one is in. One may take this as a sign that fpqc sheafification is to be avoided.

Notation 1.2.1 We denote by $\mathscr{L}$ the language formal set theory, which consists of the symbols $\in$ and $=$; suitable variables; connectives $\neg$, $\wedge$, $\vee$, $\implies$, and $\iff$; and quantifiers $\forall$ and $\exists$.

We denote by ZFCthe theory given by the following axioms and axiom schemata in the language $\mathscr{L}$.

1. Axiom of Extensionality.[**?**, p. 4]
2. Axiom of Pairing.[**?**, p. 6]
3. Axiom Schema of Separation.[**?**, p. 7]
4. Axiom of Union.[**?**, p. 9]
5. Axiom of Powerset.[**?**, p. 9]
6. Axiom of Infinity.[**?**, p. 12]
7. Axiom Schema of Replacement.[**?**, p. 13]
8. Axiom of Regularity.[**?**, p. 63]
9. Axiom of Choice.[**?**, p. 47]

Axiom 1.2.2 We add to the language $\mathscr{L}$ an additional constant κ, and we add the following axioms to ZFC to form *the Lévy scheme* LÉVY.

1. κ is an inaccessible cardinal.
2. *Axiom of Reflection.* For any formula ϕ, and for any element $x \in V_\kappa$, one has

$$\phi(x) \iff \boldsymbol{V}_\kappa \vDash \phi[x].$$

The Lévy scheme implies ZFC + OM, where OM is the scheme[6] asserting that any closed unbounded subclass of ORD that is definable from parameters contains an inaccessible cardinal. On the other hand, if ZFC + OM is consistent, then so is LÉVY.

The Lévy scheme is stronger than the Axiom of Universes (AU), which asserts that every cadinal is dominated by an inaccessible cardinal; on the other hand, if δ is a *Mahlo* cardinal, then $\boldsymbol{V}_\delta \vDash$ LÉVY, so the Lévy scheme is of strictly lower conistency strength than the existence of a single Mahlo cardinal. Among large cardinal axioms, therefore, it appears that LÉVY is quite weak.

Finally, it turns out that by adding the axioms for the Lévy scheme, we may do so at the same time we *remove* the Axiom Schema of Replacement and Axiom of Infinity and get an equivalent theory.

1.3 Limits, colimits, and cardinals

1.4 Ultrafilters

Notation 1.4.1 Write **Set** for the category of finite sets. Write **Fin** $\subset$ **Set** for the full subcategory of finite sets, and write i for the inclusion **Fin** $\hookrightarrow$ **Set**.

[6] The notation OM is meant to stand for 'ORD is Mahlo.'

Definition 1.4.2 For any tiny set S, write h^S for the functor **Fin** → **Set** given by $I \mapsto \mathrm{Map}(S, I)$. An *ultrafilter* μ on S is a natural transformation

$$\int_S (\cdot)\, d\mu \colon h^S \to i\,,$$

which for any finite set I gives a map

$$\begin{aligned} \mathrm{Map}(S, I) &\longrightarrow I \\ f &\longmapsto \int_S f\, d\mu \end{aligned}$$

Write $\beta(S)$ for the set of ultrafilters on S. For any set S, the set $\beta(S)$ is the set

$$\beta(S) = \lim_{I \in \mathbf{Fin}_{S/}} I\,.$$

The functor

$$\beta \colon \mathbf{Set} \to \mathbf{Set}$$

is thus the right Kan extension of the inclusion **Fin** ↪ **Set** along itself.

Example 1.4.3 Let S be a set, and let $s \in S$ be an element. The *principal ultrafilter* δ_s is then defined so that

$$\int_S f\, d\delta_s = f(s)\,.$$

Every ultrafilter on a finite set is principal, but infinite sets have ultrafilters that are not principal. To prove the existence of these, let us look at a more traditional way of defining an ultrafilter on a set.

Definition 1.4.4 Let S be a set, $T \subseteq S$, and μ an ultrafilter on S. There is a unique *characteristic map* $\chi_T \colon S \to \{0, 1\}$ such that $\chi_T(s) = 1$ if and only if $s \in T$. Let us write

$$\mu(T) \coloneqq \int_S \chi_T\, d\mu\,.$$

We say that T *is μ-thick* if and only if $\mu(T) = 1$. Otherwise (that is, if $\mu(T) = 0$), then we say that T is *μ-thin*.

For any $s \in S$, the principal ultrafilter δ_s is the unique ultrafilter relative to which $\{s\}$ is thick.

Scholium 1.4.5 *If S is a set and μ is an ultrafilter on S, then we can observe the following facts about the collection of thick and thin subsets (relative to μ):*

1. *The empty set is thin.*
2. *Complements of thick sets are thin.*
3. *Every subset is either thick or thin.*
4. *Subsets of thin sets are thin.*
5. *The intersection of two thick sets is thick.*

In other words, if S is a set, then an ultrafilter on S is tantamount to a Boolean algebra homomorphism $\boldsymbol{P}(S) \to \{0,1\}$.

It is possible to define ultrafilters on more general posets, and if P is a Boolean algebra, then an ultrafilter is precisely a Boolean algebra homomorphism $P \to \{0,1\}$.

Scholium 1.4.6 *Ultrafilters are functorial in maps of sets. Let $\phi\colon S \to T$ be a map, and let μ be an ultrafilter on S. The ultrafilter $\phi_*\mu$ on T given by*

$$\int_T f\, d(\phi_*\mu) = \int_S (f \circ \phi)\, d\mu\,.$$

For any $U \subseteq T$, one has in particular

$$(\phi_*\mu)(U) = \mu(\phi^{-1}(U))\,.$$

Thus U is $\phi_*\mu$-thick if and only if $\phi^{-1}U$ is μ-thick.

Definition 1.4.7 A *system of thick subsets* of S is a collection $F \subseteq \boldsymbol{P}(S)$ such that for any finite set I and any partition

$$S = \coprod_{i \in I} S_i\,,$$

there is a unique $i \in I$ such that $S_i \in F$.

Construction 1.4.8 We have seen that an ultrafilter μ specifies the system F_μ of μ-thick subsets. In the other direction, attached to any system F of thick subsets is an ultrafilter μ_F: for any finite set I and any map $f\colon S \to I$, the element $i = \int_S f\, d\mu \in I$ is the unique one such that $S_i \in F$.

The assignments $\mu \mapsto F_\mu$ and $F \mapsto \mu_F$ together define a bijection between ultrafilters on S and systems of thick subsets.

Definition 1.4.9 If S is a set, and if $G \subseteq \boldsymbol{P}(S)$, then an ultrafilter μ is said to be *supported on G* if and only if every element of G is μ-thick, that is, $G \subseteq F_\mu$.

Lemma 1.4.10 *Let S be a set, and let $G \subseteq \boldsymbol{P}(S)$. Assume that no finite intersection of elements of G is empty. Then there exists an ultrafilter μ on S supported on G.*

Proof Consider all the families $A \subseteq \boldsymbol{P}(S)$ with the following properties:

1. A contains G;
2. no finite intersection of elements of A is empty.

By Zorn's lemma there is a maximal such family, F.

We claim that F is a system of thick subsets. For this, let $S = \coprod_{i \in I} S_i$ be a finite partition of S. Condition 2 ensures that at most one of the summands S_i can lie in F. Now suppose that none of the summands S_i lies in F. Consider, for each $i \in I$, the family $F \cup \{S_i\} \subseteq \boldsymbol{P}(S)$; the maximality of F implies that none of these families can satisfy Condition 2. Thus for each $i \in I$, there is an empty finite intersection

$S_i \cap \bigcap_{j=1}^{n_i} T_{ij} = \varnothing$. But this implies that the intersection $\bigcap_{i\in I}\bigcap_{j=1}^{n_i} T_{ij}$ is empty, contradicting Condition 2 for F itself. Hence at least one – and thus exactly one – of the summands S_i lies in F. Thus F is a system of thick subsets of S. □

1.4.11 It is not quite accurate to say that the Axiom of Choice is *necessary* to produce nonprincipal ultrafilters, but it is true that their existence is independent of Zermelo–Fraenkel set theory.

1.4.12 If ϕ is a functor **Set** → **Set**, then a natural transformation $\phi \to \beta$ is the same thing as a natural transformation $\phi \circ i \to i$. Please observe that we have a canonical identification $\beta \circ i = i$.

It follows readily that the functor β is a monad: the unit $\delta\colon \mathrm{id} \to \beta$ corresponds to the identification $\mathrm{id} \circ i = i$, and the multiplication $\mu\colon \beta^2 \to \beta$ corresponds to the identification $\beta^2 \circ i = i$.

The unit for the monad β structure is the assignment $s \mapsto \delta_s$ that picks out the principal ultrafilter at a point.

To describe the multiplication $\tau \mapsto \mu_\tau$, let us write $T^\dagger$ for the set of ultrafilters supported on $\{T\}$. Now if τ is an ultrafilter on $\beta(S)$, then μ_τ is the ultrafilter on S such that

$$\mu_\tau(T) = \tau(T^\dagger)\,.$$

Construction 1.4.13 Let **Top** denote the category of tiny topological spaces. If S is a set, we can introduce a topology on $\beta(S)$ simply by forming the inverse limit $\lim_{I\in \mathbf{Fin}_{S/}} I$ in **Top**. That is, we endow $\beta(S)$ with the coarsest topology such that all the projections $\beta(S) \to I$ are continuous. We call this the *Stone topology* on $\beta(S)$. By Tychonoff, this limit is a compact Hausdorff topological space. This lifts β to a functor **Set** → **Top**.

1.4.14 Let's be more explicit about the topology on $\beta(S)$. The topology on $\beta(S)$ is generated by the sets $T^\dagger$ (for $T \subseteq S$). In fact, since the sets $T^\dagger$ are stable under finite intersections, they form a base for the Stone topology on $\beta(S)$. Additionally, since the sets $T^\dagger$ are stable under the formation of complements, they even form a base of clopens of $\beta(S)$.

Definition 1.4.15 A *compactum* is an algebra for the monad β. Hence a compactum consists of a set K and a map $\lambda_K\colon \beta(K) \to K$, which is required to satisfy the usual identities:

$$\lambda_K(\lambda_{K,*}\tau) = \lambda_K(\mu_\tau) \qquad \text{and} \qquad \lambda_K(\delta_s) = s\,,$$

for any ultrafilter τ on $\beta(S)$ and any point $s \in S$. The image $\lambda_K(\mu)$ will be called the *limit* of the ultrafilter μ. We write **Comp** for the category of compacta, and write **Free** ⊂ **Comp** for the full subcategory spanned by the *free compacta* – *i.e.*, free algebras for β.

Construction 1.4.16 If K is a compactum, then we use the limit map $\lambda_K\colon \beta(K) \to K$ to topologise K as follows. For any subset $T \subseteq K$, we define the closure of T as the image $\lambda_K(T^\dagger)$.

A subset $Z \subseteq K$ is thus closed if and only if the limit of any ultrafilter relative to which Z is thick lies in Z. Dually, a subset $U \subseteq K$ is open if and only if it is thick with respect to any ultrafilter whose limit lies in U.

We denote the resulting topological space K^{top}. The assignment $K \mapsto K^{top}$ defines a lift $\mathbf{Alg}(\beta) \to \mathbf{Top}$ of the forgetful functor $\mathbf{Alg}(\beta) \to \mathbf{Set}$.

Proposition 1.4.17 *The functor $K \mapsto K^{top}$ identifies the category of compacta with the category of compact Hausdorff topological spaces.*

We will spend the remainder of this section proving this claim. Please observe first that $K \mapsto K^{top}$ is faithful. What we will do now is prove:

1. that for any compactum K, the topological space K^{top} is compact Hausdorff;
2. that for any compact Hausdorff topological space X, there is a β-algebra structure K on the underlying set of X such that $X \cong K^{top}$; and
3. that for any compacta K and L, any continuous map $K^{top} \to L^{top}$ lifts to a β-algebra homomorphism $K \to L$.

To do this, it is convenient to describe a related idea: that of *convergence* of ultrafilters on topological spaces.

Definition 1.4.18 Let X be a topological space, and let $x \in X$. We say that x is a *limit point* of an ultrafilter μ on (the underlying set of) X if and only if every open neighbourhood of x is μ-thick. In other words, x is a limit point of μ if and only if, for every open neighbourhood U of x, one has $\mu \in U^{\dagger}$.

Lemma 1.4.19 *Let X be a topological space, and let $U \subseteq X$ be a subset. Then U is open if and only if it is thick with respect to any ultrafilter with limit point in U.*

Proof If U is open, then U is by definition thick with respect to any ultrafilter with limit point in U.

Conversely, assume that U is thick with respect to any ultrafilter with limit point in U. Let $u \in U$. Consider the set $G \coloneqq N(u) \cup \{X \smallsetminus U\}$, where $N(u)$ is the collection of open neighbourhoods of u. If U does not contain any open neighbourhood of u, then no finite intersection of elements of G is empty. By Theorem 1.4.10 there is an ultrafilter μ supported on the $N(u) \cup \{X \smallsetminus U\}$, whence u is a limit point of μ, but U is not μ-thick. This contradicts our assumption, and so we deduce that U contains an open neighbourhood of u. ☐

Lemma 1.4.20 *Let X and Y be topological spaces, and let $\phi\colon X \to Y$ be a map. Then ϕ is continuous if and only if, for any ultrafilter μ on X with limit point $x \in X$, the point $\phi(x)$ is a limit point of $\phi_*\mu$.*

Proof Assume that ϕ is continuous, and let μ be an ultrafilter on X, and assume that $x \in X$ is a limit point of μ. Now assume that V is an open neighbourhood of $\phi(x)$. Since $\phi^{-1}V$ is an open neighbourhood of x, so it is μ-thick, whence V is $\phi_*\mu$-thick. Thus $\phi(x)$ is a limit point of $\phi_*\mu$.

Assume now that if $x \in X$ is a limit point of an ultrafilter μ, then $\phi(x)$ is a limit point of $\phi_*\mu$. Let $V \subseteq Y$ be an open set. Let $x \in \phi^{-1}(V)$, and let μ be an ultrafilter on X with limit point x. Then $\phi(x)$ is a limit point of $\phi_*\mu$, so V is $\phi_*\mu$-thick, whence $\phi^{-1}(V)$ is μ-thick. It follows from Theorem 1.4.19 that $\phi^{-1}(V)$ is open. □

Lemma 1.4.21 *Let X be a topological space. Then X is quasicompact if and only if every ultrafilter on X has at least one limit point.*

Proof Assume first that X is quasicompact. Let μ be an ultrafilter on X, and assume that μ has no limit point. Select, for every point $x \in X$, an open neighbourhood U_x thereof that is not μ-thick. Quasicompactness implies that there is a finite collection $x_1, \dots, x_n \in X$ such that $\left\{U_{x_1}, \dots, U_{x_n}\right\}$ covers X. But at least one of $U_{x_1}, \dots, U_{x_n}$ must be μ-thick. This is a contradiction.

Now assume that X is not quasicompact. Then there exists a collection $G \subseteq \boldsymbol{P}(X)$ of closed subsets of X such that the intersection all the elements of G is empty, but no finite intersection of elements of G is empty. In light of Theorem 1.4.10, there is an ultrafilter μ with the property that every element of G is thick. For any $x \in X$, there is an element $Z \in G$ such that $x \in X \smallsetminus Z$. Since Z is μ-thick, $X \smallsetminus Z$ is not. Thus μ has no limit points. □

Lemma 1.4.22 *Let X be a topological space. Then X is Hausdorff if and only if every ultrafilter on X has at most one limit point.*

Proof Assume that μ is an ultrafilter with two distinct limit points x_1 and x_2. Choose open neighbourhoods U_1 of x_1 and U_2 of x_2. Since they are both μ-thick, they cannot be disjoint; hence X is not Hausdorff.

Conversely, assume that X is not Hausdorff. Select two points x_1 and x_2 such that every open neighbourhoods U_1 of x_1 and U_2 of x_2 intersect. Now the set G consisting of open neighbourhoods of either x_1 *or* x_2 has the property that no finite intersection of elements of G is empty. In light of Theorem 1.4.10, there is an ultrafilter μ with the property that every element of G is thick. Thus x_1 and x_2 are limit points of μ. □

Let us now return to our functor $K \mapsto K^{top}$.

Lemma 1.4.23 *Let K be a compactum, and let μ be an ultrafilter on K. Then a point of K^{top} is a limit point of μ in the sense of Theorem 1.4.18 if and only if it is the limit of μ in the sense of Theorem 1.4.15.*

Proof Let $x \coloneqq \lambda_K(\mu)$. The open neighbourhoods U of x are by definition thick (relative to μ), so certainly x is a limit point of μ.

Now assume that $y \in K^{top}$ is a limit point of μ. To prove that the limit of μ is y, we shall build an ultrafilter τ on $\beta(K)$ with the following properties:

1. under the multiplication $\beta^2 \to \beta$, the ultrafilter τ is sent to μ; and
2. under the map $\lambda_* : \beta^2 \to \beta$, the ultrafilter τ is sent to δ_y.

Once we have succeeded, it will follow that

$$\lambda_K(\mu) = \lambda_K(\mu_\tau) = \lambda_K(\lambda_{K,*}\tau) = \lambda_K(\delta_y) = y\,,$$

and the proof will be complete.

Consider the family G' of subsets of $\beta(K)$ of the form $T^{\dagger}$ for a μ-thick subset $T \subseteq S$; since these are all nonempty and they are stable under finite intersections, it follows that no finite intersection of elements of G' is empty.

Now consider the set $G \coloneqq G' \cup \{\lambda_K^{-1}\{y\}\}$. If T is μ-thick, then we claim that there is an ultrafilter $\nu \in \lambda_K^{-1}\{y\} \cap T^{\dagger}$. Indeed, consider the set $N(y) \cup \{T\}$, where $N(y)$ is the collection of open neighbourhoods of y. Since every open neighbourhood of y is μ-thick, no intersection of an open neighbourhood of y with T is empty. By Theorem 1.4.10 there is an ultrafilter supported on $N(y) \cup \{T\}$, which implies that no finite intersection of elements of G is empty.

Applying Theorem 1.4.10 again, we see that G supports an ultrafilter τ on $\beta(K)$. For any $T \subseteq K$,

$$\mu_{\tau}(T) = \tau(T^{\dagger}) ,$$

so since τ is supported on G', it follows that $\mu_{\tau} = \mu$. At the same time, since τ is supported on $\{\lambda_K^{-1}\{y\}\}$, it follows that $\{y\}$ is thick relative to $\lambda_{K,*}\tau$, whence $\lambda_{K,*}\tau = \delta_y$. □

Proof (Proof of Theorem 1.4.17) Let K be a compactum. Combine Theorems 1.4.21 to 1.4.23 to conclude that K^{top} is a compact Hausdorff topological space.

Let X be a compact Hausdorff topological space with underlying set K. Define a map $\lambda_K : \beta(K) \to K$ by carrying an ultrafilter μ to its unique limit point in X. This is a β-algebra structure on X, and it follows from Theorem 1.4.23 and the definition of the topology together imply that $X \cong K^{top}$.

Finally, let K and L be compacta, and let $\phi \colon K^{top} \to L^{top}$ be a continuous map. To prove that ϕ is a β-algebra homomorphism, it suffices to confirm that if μ is an ultrafilter on K, then

$$\lambda_L(\phi_*\mu) = \phi(\lambda_K(\mu)) ,$$

but this follows exactly from Theorem 1.4.20. □

1.4.24 We opted in Theorem 1.4.16 to define the topology on a compactum K in very explicit terms, but note that the map $\lambda_K : \beta(K) \to K^{top}$ is a continuous surjection between compact Hausdorff topological spaces. Thus K^{top} is endowed with the quotient topology relative to λ_K.

Part II
Condensed sets

Part III
Condensed groups

Part IV
Condensed abelian groups

Part V
Condensed spaces

Part VI
Condensed spectra

Glossary

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