

MODEL STRUCTURES

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CONTENTS

1. Preliminaries	1
2. Topological Spaces	6

This document follows Mark Hovey’s *Model Categories*, and its intention is to reproduce the proofs of several standard model categories in explicit detail.

1. PRELIMINARIES

We work with von Neumann ordinals, i.e., an ordinal is a transitive set of ordinals (this definition is not circular, the empty set is an ordinal which we call “0”). In the following discussion, let α and β be ordinals. We write $\alpha + 1$ to denote the successor ordinal $\alpha \cup \{\alpha\}$. We write $\alpha < \beta$ to mean $\alpha \in \beta$, and $\alpha \leq \beta$ denotes any of the equivalent conditions: (1) $\alpha < \beta$ or $\alpha = \beta$, (2) $\alpha \in \beta + 1$, (3) $\alpha \subseteq \beta$. Given a collection of ordinals B , we write $\sup B$ or $\sup_{\beta \in B} \beta$ to denote the ordinal $\bigcup_{\beta \in B} \beta$. We define the sum of ordinals α and β recursively: $\alpha + 0 := \alpha$, $\alpha + (\beta + 1) := (\alpha + \beta) + 1$, and $\alpha + \beta := \sup_{\delta < \beta} (\alpha + \delta)$ when β is a limit ordinal. Note that addition of ordinals is not commutative, but it is associative, and continuous in its right argument: given an ordinal α and a collection of ordinals B , $\alpha + \sup B = \sup_{\beta \in B} (\alpha + \beta)$. We say an ordinal λ is a *limit ordinal* if either of the following equivalent conditions hold: (1) $\lambda = \sup_{\beta < \lambda} \beta$ or (2) $\lambda \neq \beta + 1$ for all ordinals β . Note that 0 is a limit ordinal under our definition. We may regard an ordinal α as a poset category, in which case the colimit in α is given by the supremum. We let **Ord** denote the poset category of all (small) ordinals, so there exists a unique arrow $\alpha \rightarrow \beta$ if $\alpha \leq \beta$. Given a set X , we write $|X|$ to denote its *cardinality*, i.e., $|X|$ is the least ordinal α such that there exists a bijection between α and X . A cardinal number is an ordinal which is the cardinality of some set X .

Definition 1.1 (Hovey Definition 2.1.1). Suppose \mathcal{C} is a cocomplete category, and λ is an ordinal. A λ -sequence in \mathcal{C} is a colimit-preserving functor $X : \lambda \rightarrow \mathcal{C}$, commonly written as

$$X_0 \rightarrow X_1 \rightarrow \cdots \rightarrow X_\beta \rightarrow \cdots.$$

Since X preserves colimits, for all limit ordinals $\gamma < \lambda$, the arrows $X_\alpha \rightarrow X_\gamma$ for $\alpha < \gamma$ form a colimit cone under $\{X_\alpha\}_{\alpha < \gamma}$. We refer to the map $X_0 \rightarrow \operatorname{colim}_{\beta < \lambda} X_\beta$ as the *composition* of the λ -sequence. Given a collection \mathcal{D} of morphisms in \mathcal{C} such that every map $X_\beta \rightarrow X_{\beta+1}$ for $\beta + 1 < \lambda$ is in \mathcal{D} , we refer to the composition $X_0 \rightarrow \operatorname{colim}_{\beta < \lambda} X_\beta$ as a *transfinite composition* of arrows in \mathcal{D} .¹

Of particular importance to us will be collections of arrows which are *closed under transfinite composition*, i.e., collections \mathcal{D} for which given any ordinal λ and λ -sequence X of arrows in \mathcal{D} , for any choice of colimit $\operatorname{colim} X$, the canonical map $X_0 \rightarrow \operatorname{colim} X$ is also in \mathcal{D} . We prove the following useful result about when a class of morphisms is closed under transfinite composition:

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¹To be more precise, there may be different (isomorphic) choices of colimit $\operatorname{colim}_{\beta < \gamma} X_\beta$, which give rise to different choices of composition $X_0 \rightarrow \operatorname{colim}_{\beta < \gamma} X_\beta$. Thus, the composition of a λ -sequence is only unique up to composition by a unique isomorphism.

Lemma 1.2. *Let \mathcal{C} be a category, and \mathcal{D} a collection of arrows in \mathcal{C} satisfying the following properties: \mathcal{D} is closed under composition with isomorphisms, and given an ordinal λ and a λ -sequence $X : \lambda \rightarrow \mathcal{C}$ of arrows in \mathcal{D} (so $X_\beta \rightarrow X_{\beta+1}$ belongs to \mathcal{D} for all $\beta + 1 < \lambda$), if we then get for free that $X_\alpha \rightarrow X_\beta$ belongs to \mathcal{D} for all $\alpha \leq \beta < \lambda$, then \mathcal{D} is closed under transfinite composition.*

Proof. Let λ be an ordinal, and $X : \lambda \rightarrow \mathcal{C}$ a λ -sequence of arrows in \mathcal{D} . First, suppose $\lambda = \mu + 1$ is a successor ordinal. Since we know that any transfinite composition of X may be obtained from another by composing with an isomorphism and \mathcal{D} is closed under composition with isomorphisms, it suffices to show there exists *some* transfinite composition of X belonging to \mathcal{D} . We know $\sup_{\beta < \lambda} \beta = \sup_{\beta < \mu+1} \beta = \mu$, and X is colimit preserving, so that X_μ is a colimit of the diagram X via the arrows $X_\alpha \rightarrow X_\mu$ for $\alpha < \lambda = \mu + 1$. But we know in particular that $X_0 \rightarrow X_\mu$ belongs to \mathcal{D} , so we are done.

Conversely, suppose λ is a limit ordinal. Let $j : X \Rightarrow \underline{X}_\lambda$ be a colimit cone for X . We may use j to extend X to a $(\lambda + 1)$ -sequence in the obvious way (so for $\alpha < \lambda$, the structure map $X_\alpha \rightarrow X_\lambda$ is given by j and the arrow $X_\lambda \rightarrow X_\lambda$ is the identity, as is necessary). Further note that X is still a sequence of arrows in \mathcal{D} , as given $\beta + 1 < \lambda + 1$, so $\beta + 1 \leq \lambda$, it is not possible that $\beta + 1 = \lambda$ as λ is a limit ordinal, in which case we know the map $X_\beta \rightarrow X_{\beta+1}$ belongs to \mathcal{D} as $\beta + 1 < \lambda$. Hence, unravelling definitions and applying the asserted property of \mathcal{D} , we get for free that $j_0 : X_0 \rightarrow X_\lambda$ belongs to \mathcal{D} . \square

Lemma 1.3. *Given a cocomplete category \mathcal{C} and a collection \mathcal{D} of arrows in \mathcal{C} , if \mathcal{D} is closed under transfinite composition, then given any limit ordinal λ and λ -sequence $X : \lambda \rightarrow \mathcal{C}$, for all $\alpha < \lambda$ the canonical map $X_\alpha \rightarrow \text{colim } X$ belongs to \mathcal{D} .*

Proof Sketch. Let $\alpha < \lambda$, and fix a colimit cone $j : X \Rightarrow \text{colim } X$. Define $S := \{\beta : \alpha \leq \beta \leq \lambda\} \subseteq \lambda + 1$. Define a map $\phi : S \rightarrow \mathbf{Ord}$ via transfinite recursion. Let $\phi(\alpha) = 0$. Supposing $\phi(\beta)$ has been defined, let $\phi(\beta + 1) = \phi(\beta) + 1$. Finally, supposing $\alpha < \gamma \leq \lambda$ is a limit ordinal and $\phi(\beta)$ has been defined for $\alpha \leq \beta < \gamma$, define $\phi(\gamma) = \sup_{\alpha \leq \beta < \gamma} \phi(\beta)$. It is straightforward to verify that ϕ is order preserving, sends limit ordinals to limit ordinals, and satisfies $\alpha + \phi(\beta) = \beta$ for all $\alpha \leq \beta \leq \lambda$.

Now, construct a $\phi(\lambda)$ -sequence $Y : \phi(\lambda) \rightarrow \mathcal{C}$ by $Y_\beta := X_{\alpha+\beta}$, and given $\beta \leq \beta' < \phi(\lambda)$, define the map $Y_\beta \rightarrow Y_{\beta'}$ to be the arrow $X_{\alpha+\beta} \rightarrow X_{\alpha+\beta'}$ for X . Checking that Y is functorial and colimit-preserving follows directly from the fact that X is functorial and colimit-preserving. Then it can be seen that the $j_{\alpha+\beta}$'s for $\beta < \phi(\lambda)$ restrict to a colimit cone under Y . Since Y is a $\phi(\lambda)$ -sequence in \mathcal{D} and \mathcal{D} is closed under transfinite compositions, it follows that $j_\alpha \in \mathcal{D}$, as desired. \square

Definition 1.4 (Hovey Definition 2.1.2). Let γ be a cardinal. An ordinal α is γ -filtered if it is a limit ordinal and, if $A \subseteq \alpha$ and $|A| \leq \gamma$, then $\sup A < \alpha$.

Given a cardinal γ , a γ -filtered category \mathcal{C} is one such that any diagram $\mathcal{D} \rightarrow \mathcal{C}$ has a cocone when \mathcal{D} has $< \gamma$ arrows. A category is just “filtered” if it is ω -filtered, i.e., if every finite diagram in \mathcal{C} admits a cocone. Note that an ordinal α is γ -filtered precisely when it is γ -filtered as a category, and in particular every ordinal is ω -filtered.

Definition 1.5 (Hovey Definition 2.1.3). Suppose \mathcal{C} is a comcomplete category, $\mathcal{D} \subseteq \text{Mor } \mathcal{C}$ is some collection of morphisms of \mathcal{C} , A is an object of \mathcal{C} , and κ is a cardinal. We say that A is κ -small relative to \mathcal{D} if, for all κ -filtered ordinals λ and all λ -sequences

$$X_0 \rightarrow X_1 \rightarrow \cdots \rightarrow X_\beta \rightarrow \cdots$$

such that each map $X_\beta \rightarrow X_{\beta+1}$ is in \mathcal{D} for $\beta + 1 < \lambda$, the canonical map of sets

$$\text{colim}_{\beta < \lambda} \mathcal{C}(A, X_\beta) \rightarrow \mathcal{C}(A, \text{colim}_{\beta < \lambda} X_\beta)$$

is an isomorphism. We say that A is *small relative to \mathcal{D}* if it is κ -small relative to \mathcal{D} for some κ . We say that A is *small* if it is small relative to \mathcal{C} itself.

Definition 1.6 (Hovey Definition 2.1.4). Suppose \mathcal{C} is a cocomplete category, \mathcal{D} is a collection of morphisms of \mathcal{C} , and A is an object of \mathcal{C} . We say that A is *finite relative to \mathcal{D}* if A is κ -small relative to \mathcal{D} for some finite cardinal κ . We say A is *finite* if it is finite relative to \mathcal{C} itself. In particular, since *every* limit ordinal is κ -filtered for any finite cardinal κ , for an object A to be finite relative to \mathcal{D} , maps from A must commute with colimits of *arbitrary* λ -sequences for every limit ordinal λ .

Remark 1.7. Recall that given a small category \mathcal{D} and a functor $F : \mathcal{D} \rightarrow \mathbf{Set}$, we may explicitly construct the colimit of F as the set

$$\operatorname{colim} F := \left(\coprod_{d \in \mathcal{D}} F(d) \right) / \sim,$$

where the equivalence relation \sim is **generated** by

$$((x \in F(d)) \sim (x' \in F(d'))) \quad \text{if} \quad (\exists (f : d \rightarrow d') \text{ with } Ff(x) = x').$$

In particular, if \mathcal{D} is a filtered category then the resulting relation can be described as follows:

$$((x \in F(d)) \sim (x' \in F(d'))) \quad \text{iff} \quad (\exists d'', (f : d \rightarrow d'), (g : d' \rightarrow d'') \text{ with } Ff(x) = Fg(x')).$$

Then the colimit cone $\eta : F \Rightarrow \operatorname{colim} F$ is defined by $\eta_d(x) = [x]$ for $d \in \mathcal{D}$ and $x \in F(d)$, where $[x]$ denotes the equivalence class of x in $\operatorname{colim} F$. Given a cone $\varepsilon : F \Rightarrow \underline{Y}$ under F , the unique map $\operatorname{colim} F \rightarrow Y$ maps an equivalence class $[x]$ represented by an element $x \in F(d)$ to the element $\varepsilon_d(x)$.

Now we unravel what the “canonical map” of [Definition 1.5](#) is. Suppose we are given a cocomplete category \mathcal{C} , an element $A \in \mathcal{C}$, an ordinal λ , and a λ -sequence $X : \lambda \rightarrow \mathcal{C}$. For $\alpha \leq \beta < \lambda$, let $\iota_{\alpha, \beta}$ be the map $X_\alpha \rightarrow X_\beta$. Let $\eta : X \Rightarrow \operatorname{colim} X$ be the colimit cone. By whiskering the colimit cone along the functor $\mathcal{C}(A, -)$, we get a cone $\mathcal{C}(A, \eta) : \{\mathcal{C}(A, X_\beta)\}_{\beta < \lambda} \Rightarrow \mathcal{C}(A, \operatorname{colim} X)$. Then if we let $\varepsilon : \{\mathcal{C}(A, X_\beta)\}_{\beta < \lambda} \Rightarrow \operatorname{colim}_{\beta < \lambda} \mathcal{C}(A, X_\beta)$ be the colimit cone, the universal property of the colimit gives us the canonical map $\ell : \operatorname{colim}_{\beta < \lambda} \mathcal{C}(A, X_\beta) \rightarrow \mathcal{C}(A, \operatorname{colim} X)$, so that the following diagram commutes:

$$\begin{array}{ccccccc} \mathcal{C}(A, X_0) & \xrightarrow{(\iota_{0,1})_*} & \mathcal{C}(A, X_1) & \xrightarrow{(\iota_{1,2})_*} & \dots & \xrightarrow{\quad} & \mathcal{C}(A, X_\beta) \xrightarrow{(\iota_{\beta, \beta+1})_*} \dots \\ & \searrow \varepsilon_0 & \searrow \varepsilon_1 & & & & \searrow \varepsilon_\beta \\ & & & \searrow & & & \\ & & & \operatorname{colim}_{\beta < \lambda} \mathcal{C}(A, X_\beta) & & & \\ & \searrow (\eta_0)_* & \searrow (\eta_1)_* & \downarrow \ell & \swarrow (\eta_\beta)_* & & \\ & & & \mathcal{C}(A, \operatorname{colim} X) & & & \end{array}$$

In particular, by [Remark 1.7](#), we know elements of $\operatorname{colim}_{\beta < \lambda} \mathcal{C}(A, X_\beta)$ are equivalence classes of arrows $f : A \rightarrow X_\beta$ for $\beta < \lambda$ under the relation $[f : A \rightarrow X_\beta] = [g : A \rightarrow X_{\beta'}]$ iff there exists $\beta'' \geq \beta, \beta'$ with $\iota_{\beta, \beta''} \circ f = \iota_{\beta', \beta''} \circ g$, and the map ε_β sends an arrow $f \in \mathcal{C}(A, X_\beta)$ to the element $[f]$. Then it follows that $\ell([f : A \rightarrow X_\beta]) = \eta_\beta \circ f$. Thus, this gives us the following result:

Proposition 1.8. *Given a cocomplete category \mathcal{C} , a collection \mathcal{D} of arrows in \mathcal{C} , an object A in \mathcal{C} , and a cardinal κ , A is κ -small relative to \mathcal{D} , if, for all κ -filtered ordinals λ and all λ -sequences $X : \lambda \rightarrow \mathcal{C}$ such that the map $X_\beta \rightarrow X_{\beta+1}$ belongs to \mathcal{D} for all $\beta + 1 < \lambda$, given any colimit $\operatorname{colim} X$ for X , the following holds:*

- (i) *Given arrows $f : A \rightarrow X_\alpha$ and $g : A \rightarrow X_\beta$ in \mathcal{C} , if f and g agree in the colimit (i.e., if the compositions $A \xrightarrow{f} X_\alpha \rightarrow \operatorname{colim} X$ and $A \xrightarrow{g} X_\beta \rightarrow \operatorname{colim} X$ are equal), then f and g are equal in some stage of the colimit (i.e., there exists $\gamma < \lambda$ with $\alpha, \beta \leq \gamma$ such that the compositions $A \xrightarrow{f} X_\alpha \rightarrow X_\gamma$ and $A \xrightarrow{g} X_\beta \rightarrow X_\gamma$ are equal).*
- (ii) *Any arrow $f : A \rightarrow \operatorname{colim} X$ factors through some stage of the colimit (i.e., there exists $\beta < \lambda$ and an arrow $\tilde{f} : A \rightarrow X_\beta$ such that the composition $A \xrightarrow{\tilde{f}} X_\beta \rightarrow \operatorname{colim} X$ equals f).*

In terms of the canonical map $\operatorname{colim}_{\beta < \lambda} \mathcal{C}(A, X_\beta) \rightarrow \mathcal{C}(A, \operatorname{colim} X)$, the first condition shows injectivity, while the second shows surjectivity.

We will use the characterization of smallness given by this remark whenever proving smallness arguments, as in the following example.

Example 1.9 (Hovey 2.1.5). Every set is small. Indeed, if A is a set we claim that A is $|A|$ -small. To see this, suppose λ is an $|A|$ -filtered ordinal, and X is a λ -sequence of sets. First of all, by [Remark 1.7](#), the elements of $\operatorname{colim} X$ are equivalence classes of elements $a \in X_\alpha$ where $a \in X_\alpha$ and $b \in X_\beta$ represent the same element of $\operatorname{colim} X$ iff there exists $\alpha, \beta \leq \gamma < \lambda$ so that a and b are sent to the same elements by the maps $X_\alpha \rightarrow X_\gamma$ and $X_\beta \rightarrow X_\gamma$, respectively. Now, we show the conditions of [Proposition 1.8](#).

First, we need to show that given $\alpha, \beta < \lambda$, if $f : A \rightarrow X_\alpha$ and $g : A \rightarrow X_\beta$ such that the compositions $\bar{f} : A \xrightarrow{f} X_\alpha \rightarrow \operatorname{colim} X$ and $\bar{g} : A \xrightarrow{g} X_\beta \rightarrow \operatorname{colim} X$ are equal, then f and g are equal in some stage of the colimit. For each $a \in A$, since $\bar{f}(a) = \bar{g}(a)$ in $\operatorname{colim} X$, by the above characterization of $\operatorname{colim} X$, there exists $\gamma_a < \lambda$ with $\alpha, \beta \leq \gamma_a$ such that $f(a)$ and $g(a)$ are sent to the same element in X_{γ_a} by the maps $X_\alpha \rightarrow X_{\gamma_a}$ and $X_\beta \rightarrow X_{\gamma_a}$, respectively. Then let $\gamma := \sup_{a \in A} \gamma_a$. Since $|\{\gamma_a\}_{a \in A}| \leq |A|$ and λ is $|A|$ -filtered, necessarily $\gamma < \lambda$. Then clearly the compositions $A \xrightarrow{f} X_\alpha \rightarrow X_\gamma$ and $A \xrightarrow{g} X_\beta \rightarrow X_\gamma$ agree for all $a \in A$.

Secondly, we wish to show that given a map $f : A \rightarrow \operatorname{colim} X$, that f factors through $X_\beta \rightarrow \operatorname{colim} X$ for some $\beta < \lambda$. For each $a \in A$, by the explicit description of $\operatorname{colim} X$, there exists some $\beta_a < \lambda$ and some $x_a \in X_{\beta_a}$ such that $f(a) = [x_a]$. Then let $\beta := \sup_{a \in A} \beta_a$, so $\beta < \lambda$ as X is $|A|$ -filtered. Now define $\tilde{f} : A \rightarrow X_\beta$ like so: for $a \in A$, define $\tilde{f}(a) \in X_\beta$ to be the image of x_a along the map $X_{\beta_a} \rightarrow X_\beta$. Then clearly the composition $f' : A \xrightarrow{\tilde{f}} X_\beta \rightarrow \operatorname{colim} X$ is equal to f , by unravelling definitions.

Definition 1.10 (Hovey Definition 2.1.7). Let I be a class of maps in a category \mathcal{C} .

- (1) A map is *I -injective* if it has the right lifting property w.r.t. every map in I . The class of I -injective maps is denoted $I\text{-inj}$ (or I_\perp).
- (2) A map is *I -projective* if it has the left lifting property w.r.t. every map in I . The class of I -projective maps is denoted $I\text{-proj}$ (or ${}_\perp I$).
- (3) A map is an *I -cofibration* if it has the left lifting property w.r.t. every I -injective map. The class of I -cofibrations is the class $(I\text{-inj})\text{-proj}$ and is denoted $I\text{-cof}$ (or ${}_\perp(I_\perp)$).
- (4) A map is an *I -fibration* if it has the right lifting property w.r.t. every I -projective map. The class of I -fibrations is the class $(I\text{-proj})\text{-inj}$ and is denoted $I\text{-fib}$ (or $({}_\perp I)_\perp$).

The following is asserted in Hovey on pg. 30 following Definition 2.1.7, but not proven. We provide a proof.

Lemma 1.11. *Given classes A and B of maps in a category \mathcal{C} with $A \subseteq B$, we have $A \subseteq {}_\perp(A_\perp)$, $A \subseteq ({}_\perp A)_\perp$, $({}_\perp(A_\perp))_\perp = A_\perp$, ${}_\perp({}_\perp A)_\perp = {}_\perp A$, $A_\perp \supseteq B_\perp$, ${}_\perp A \supseteq {}_\perp B$, ${}_\perp(A_\perp) \subseteq {}_\perp(B_\perp)$, and $({}_\perp A)_\perp \subseteq ({}_\perp B)_\perp$.*

Proof. Each of these amount to unravelling definitions and are entirely straightforward. \square

Definition 1.12 (Hovey Definition 2.1.9). Let I be a set of maps in a cocomplete category \mathcal{C} . A *relative I -cell complex* is a transfinite composition of pushouts of elements of I . That is, if $f : A \rightarrow B$ is a relative I -cell complex, then there is an ordinal λ and a λ -sequence $X : \lambda \rightarrow \mathcal{C}$ such that f is the composition of X and such that, for each β such that $\beta + 1 < \lambda$, there is a pushout square

$$\begin{array}{ccc} C_\beta & \longrightarrow & X_\beta \\ g_\beta \downarrow & \lrcorner & \downarrow \\ D_\beta & \longrightarrow & X_{\beta+1} \end{array}$$

with $g_\beta \in I$. We denote the collection of relative I -cell complexes by $I\text{-cell}$. We say that $A \in \mathcal{C}$ is an *I -cell complex* if the map $0 \rightarrow A$ is a relative I -cell complex.

Lemma 1.13. *Let \mathcal{C} be a category and I a class of morphisms in \mathcal{C} . Then $I\text{-cell}$ is closed under composition with isomorphisms.*

Proof. Suppose that $f : B \rightarrow C$ is an element of $I\text{-cell}$, and $h : A \rightarrow B$ and $g : C \rightarrow D$ are isomorphisms in \mathcal{C} . We wish to show $f \circ h$ and $g \circ f$ are also elements of $I\text{-cell}$. Since $f \in I\text{-cell}$, there exists an ordinal λ , a λ -sequence X with $X_0 = B$, and a colimit cone $\eta : X \Rightarrow \underline{C}$, such that $\eta_0 = f$.

First of all, construct a new cone $\eta' : X \Rightarrow \underline{D}$ under X where $\eta'_\beta := g \circ \eta_\beta$. It is straightforward to verify that η' is a colimit cone for X since η is a colimit cone and g is an isomorphism. Thus, $g \circ f = g \circ \eta_0 = \eta'_0 \in I\text{-cell}$, as η'_0 is the composition of a sequence of pushouts of elements of I .

On the other hand, we may construct a new λ -sequence X' by defining $X'_0 = A$, $X'_\beta = X_\beta$ for all $0 < \beta < \lambda$, the map $X'_0 \rightarrow X'_\beta$ for $0 < \beta < \lambda$ to be the composition

$$A \xrightarrow{h} B = X_0 \longrightarrow X_\beta,$$

and the composition $X'_\alpha \rightarrow X'_\beta$ to simply be the same map $X_\alpha \rightarrow X_\beta$ for $0 < \alpha \leq \beta < \lambda$. It is straightforward to verify that defines a λ -sequence, and that we may define a colimit cone $\eta' : X' \Rightarrow \underline{C}$ by $\eta'_0 = \eta_0 \circ h = f \circ h$, and $\eta'_\beta = \eta_\beta$ for $0 < \beta < \lambda$. Furthermore, clearly for all $1 < \beta + 1 < \lambda$, we have the arrow $X'_\beta \rightarrow X'_{\beta+1}$ is a pushout of a map in I . Thus, in order to show $f \circ h \in I\text{-cell}$, it remains to show that the arrow $A = X'_0 \rightarrow X'_1 = X_1$ is a pushout of a map in I . Indeed, we know since $B = X_0 \rightarrow X_1$ is a pushout of a map $k : P \rightarrow Q$ in I , and it can be easily verified the diagram on the right is a pushout diagram:

$$\begin{array}{ccc} P & \longrightarrow & X_0 \\ \downarrow k & & \downarrow \\ Q & \longrightarrow & X_1 \end{array} \quad \rightsquigarrow \quad \begin{array}{ccc} P & \longrightarrow & X_0 \xrightarrow{h^{-1}} X'_0 \\ \downarrow & & \downarrow h \\ & & X_0 \\ & & \downarrow \\ Q & \longrightarrow & X'_1 \end{array}$$

□

Lemma 1.14 (Hovey 2.1.10). *Suppose I is a class of maps in a cocomplete category \mathcal{C} . Then $I\text{-cell} \subseteq {}_\perp(I_\perp)$.*

Proof. **TODO.**

□

Theorem 1.15 (Small Object Argument, Hovey 2.1.14). *Suppose \mathcal{C} is a cocomplete category, and I is a set of maps in \mathcal{C} . Suppose the domains of the maps of I are small relative to $I\text{-cell}$. Then there is a functorial factorization (γ, δ) on \mathcal{C} such that for all morphisms $f \in \mathcal{C}$, the map $\gamma(f)$ is in $I\text{-cell}$ and the map $\delta(f)$ is in $I\text{-inj}$.*

Proof. **TODO.**

□

Corollary 1.16 (Hovey 2.1.15). *Suppose that I is a set of maps in a cocomplete category \mathcal{C} . Suppose as well that the domains of I are small relative to $I\text{-cell}$. Then given $f : A \rightarrow B$ in ${}_\perp(I_\perp)$, there is a $g : A \rightarrow C$ in $I\text{-cell}$ such that f is a retract of g by a map which fixes A .*

Proof. **TODO**

□

Definition 1.17 (Hovey Definition 2.1.17). Suppose \mathcal{C} is a model category. We say that \mathcal{C} is *cofibrantly generated* if there are sets I and J of maps such that:

1. The domains of the maps of I are small relative to $I\text{-cell}$;
2. The domains of the maps of J are small relative to $J\text{-cell}$;
3. The class of fibrations is J_\perp ; and
4. The class of trivial fibrations is I_\perp .

We refer to I as the set of *generating cofibrations* and to J as the set of *generating trivial cofibrations*. A cofibrantly generated model category is *finitely generated* if we can choose the sets I and J above so that the domains and codomains of I and J are finite relative to $I\text{-cell}$.

Proposition 1.18 (Hovey Proposition 2.1.18). *Suppose \mathcal{C} is a cofibrantly generated model category, with generating cofibrations I and generating trivial fibrations J .*

- (a) *The cofibrations form the class ${}_\perp(I_\perp)$.*
- (b) *Every cofibration is a retract of a relative $I\text{-cell}$ complex.*
- (c) *The domains of I are small relative to the cofibrations.*
- (d) *The trivial cofibrations form the class ${}_\perp(J_\perp)$.*
- (e) *Every trivial cofibration is a retract of a relative $J\text{-cell}$ complex.*
- (f) *The domains of J are small relative to the trivial cofibrations.*

If \mathcal{C} is fibrantly generated, then the domains and codomains of I and J are finite relative to the cofibrations.

Proof. **TODO.**

□

Theorem 1.19 (Hovey Theorem 2.1.19). *Suppose \mathcal{C} is a complete \mathcal{E} cocomplete category. Suppose \mathcal{W} is a subcategory of \mathcal{C} , and I and J are sets of maps of \mathcal{C} . Then there is a cofibrantly generated model structure on \mathcal{C} with I as the set of generating cofibrations, J as the set of generating trivial fibrations, and \mathcal{W} as the subcategory of weak equivalences if and only if the following conditions are satisfied.*

1. *The subcategory \mathcal{W} has the 2-of-3 property and is closed under retracts.*
2. *The domains of I are small relative to I -cell.*
3. *The domains of J are small relative to J -cell.*
4. *$J\text{-cell} \subseteq \mathcal{W} \cap {}_{\perp}(I_{\perp})$.*
5. *$I_{\perp} \subseteq \mathcal{W} \cap J_{\perp}$.*
6. *Either $\mathcal{W} \cap {}_{\perp}(I_{\perp}) \subseteq {}_{\perp}(J_{\perp})$ or $\mathcal{W} \cap J_{\perp} \subseteq I_{\perp}$.*

Proof. **TODO.** □

Definition 1.20. Let \mathcal{C} be a category and I a collection of morphisms in \mathcal{C} . Then if I is closed under transfinite composition, pushouts, and retracts then we say I is *saturated*.

2. TOPOLOGICAL SPACES

A map $f : X \rightarrow Y$ in **Top** is an *inclusion* if it is continuous, injective, and for all $U \subseteq X$ open, there is some $V \subseteq Y$ open such that $f^{-1}(V) = U$. If f is a closed inclusion and every point in $Y \setminus f(X)$ is closed, then we call f a *closed T_1 inclusion*. We will let \mathcal{T} denote the class of closed T_1 inclusions in **Top**.

The symbol D^n will denote the unit disk in \mathbb{R}^n , and the symbol S^{n-1} will denote the unit sphere in \mathbb{R}^n , so that we have the boundary inclusions $S^{n-1} \hookrightarrow D^n$. In particular, for $n = 0$ we let $D^0 = \{0\}$ and $S^{-1} = \emptyset$.

Recall: If $F : \mathcal{J} \rightarrow \mathbf{Top}$ is a functor, where \mathcal{J} is a small category, the limit of F is obtained by taking the limit in the category of sets, and then topologizing it with the *initial topology*, where if $\eta : \varinjlim F \Rightarrow F$ is the limit cone, then the topology on $\varinjlim F$ is that with subbasis given by sets of the form $\eta_j^{-1}(U)$ where $j \in \mathcal{J}$ and $U \subseteq F_j$ is open. Similarly, the colimit of F is obtained by taking the colimit $\varinjlim F$ in the category of sets and endowing it with the *final topology*, where a set $U \subseteq \varinjlim F$ is open if and only if $\varepsilon_j^{-1}(U)$ is open in F_j for all $j \in \mathcal{J}$, where $\varepsilon : F \Rightarrow \varinjlim F$ is the colimit cone (equivalently, a set $C \subseteq \varinjlim F$ is closed if and only if $\varepsilon_j^{-1}(C)$ is closed in F_j for all $j \in \mathcal{J}$).

Given a space X , we construct a functor $(-)^X : \mathbf{Top} \rightarrow \mathbf{Top}$ as follows: Given a space Y , define Y^X to be the space whose underlying set is the set $\mathbf{Top}(X, Y)$ of continuous maps $X \rightarrow Y$, and the topology on Y^X is the *compact-open topology*, i.e., the topology with subbasis given by the sets of the form

$$S(K, U) := \{f \in \mathbf{Top}(X, Y) : f(K) \subseteq U\}$$

for $K \subseteq X$ compact and $U \subseteq Z$ open. Given a continuous map $f : Y \rightarrow Z$, define the induced map $f_* : Y^X \rightarrow Z^X$ by $f_*(g) := f \circ g$. Unravelling definitions, we have that given $f : Y \rightarrow Z$ continuous, $f_*^{-1}(S(K, U)) = S(K, f^{-1}(U))$ for all $K \subseteq X$ compact and $U \subseteq Z$ open, so that f_* is continuous. Furthermore, $(-)^X$ is clearly functorial, by associativity and unitality of function composition.

Given a topological space X , we say that X is *locally compact* if for all points $x \in X$ and open neighborhoods U of x , there exists an open set $V \subseteq X$ with $x \in V$, $\overline{V} \subseteq U$, and \overline{V} compact. We claim that $(-)^X$ is right adjoint to $- \times X$ when X is locally compact and Hausdorff.

Proposition 2.1. *If X is a locally compact Hausdorff space, then functor $- \times X$ is left adjoint to $(-)^X$ (so that in particular $- \times X$ preserves colimits).*

Proof. We start by constructing the counit and unit of the adjunction. Given a space Z , define the counit $\varepsilon_Z : X \times Z^X \rightarrow Z$ to be the evaluation function, taking a pair $(x, f) \mapsto f(x)$. First, we claim ε_Z is continuous. Suppose we are given an open set $V \subseteq Z$ and a point $(x, f) \in \varepsilon_Z^{-1}(V)$ (so $f(x) \in V$). Since f is continuous and X is locally compact, there exists an open set $U \subseteq X$ containing x such that $x \in U \subseteq \overline{U} \subseteq f^{-1}(V)$ with \overline{U} compact. Then consider the open set $U \times S(\overline{U}, V)$ in $X \times Z^X$. First of all, $(x, f) \in U \times S(\overline{U}, V)$, as $x \in U$ and $\overline{U} \subseteq f^{-1}(V)$, so that $f(\overline{U}) \subseteq V$ meaning $f \in S(\overline{U}, V)$. Furthermore, given $(y, g) \in U \times S(\overline{U}, V)$, we have $\varepsilon_Z(y, g) = g(y) \in g(U) \subseteq g(\overline{U}) \subseteq V$, so $U \times S(\overline{U}, V)$ is an open neighborhood of x contained in $\varepsilon_Z^{-1}(V)$, as desired. Hence, ε_Z is continuous. It remains to show naturality. Given a map $f : Z \rightarrow W$, we

wish to show the following diagram commutes:

$$\begin{array}{ccc} X \times Z^X & \xrightarrow{\varepsilon_Z} & Z \\ \text{id}_X \times f_* \downarrow & & \downarrow f \\ X \times W^X & \xrightarrow{\varepsilon_W} & W \end{array}$$

Indeed, chasing an element (x, g) around the diagram yields:

$$\begin{array}{ccc} (x, g) & \longmapsto & g(x) \\ \downarrow & & \downarrow \\ (x, f \circ g) & \longmapsto & f(g(x)) \end{array}$$

so it does indeed commute.

Now we wish to define the unit $\eta_Y : Y \rightarrow (Y \times X)^X$. Given $y \in Y$, define $\eta_Y(y) \in (Y \times X)^X$ by $\eta_Y(y)(x) := (y, x)$. First of all, for it to be true that $\eta_Y(y) \in (X \times Y)^X$, it must be true that $\eta_Y(y)$ is continuous. Indeed, this is clear as η_Y is obtained as the product map $y \times \text{id}_X : X \rightarrow Y \times X$, where y represents the constant function on y (which is obviously continuous). Furthermore, η_Y itself is continuous: given $K \subseteq X$ compact and $U \subseteq Y \times X$ open, we wish to show that $\eta_Y^{-1}(S(K, U))$ is open in Y . It suffices to show that given $y \in \eta_Y^{-1}(S(K, U))$, there exists an open neighborhood W of y that is mapped by η_Y into $S(K, U)$. Since $y \in \eta_Y^{-1}(S(K, U))$, $\eta_Y(y)(K) = \{y\} \times K \subseteq U$. Then $U \cap (Y \times K)$ is an open set in the subspace $Y \times K$ containing the slice $\{y\} \times K$. By definition of the product topology, for each $k \in K$, there exist open sets $W_k \subseteq Y$ and $V_k \subseteq K$ such that $(y, k) \in W_k \times V_k \subseteq U \cap (Y \times K)$. Then the V_k 's form an open cover of K , which is compact, so that there exist $k_1, \dots, k_n \in K$ with $V_{k_1} \cup \dots \cup V_{k_n} = K$. Hence if we define $W := W_{k_1} \cap \dots \cap W_{k_n}$, then $\{y\} \times K \subseteq W \times K \subseteq U \cap (Y \times K)$, and W is open in Y as it is a finite intersection of open sets. Then for all $w \in W$, $\eta_Y(w)(K) = \{w\} \times K \subseteq W \times K \subseteq U$. Hence, indeed η_Y is continuous. It remains to show naturality. Given a map $f : Y \rightarrow W$, we wish to show the following diagram commutes:

$$\begin{array}{ccc} Y & \xrightarrow{\eta_Y} & (Y \times X)^X \\ f \downarrow & & \downarrow (f \times \text{id}_X)_* \\ W & \xrightarrow{\eta_W} & (W \times X)^X \end{array}$$

Indeed, chasing an element y around the top of the diagram yields the function obtained as the composition $x \mapsto (y, x) \mapsto f \times \text{id}_X(y, x) = (f(y), x)$, while chasing around the bottom of the diagram more directly yields the function $x \mapsto (f(y), x)$.

Now that we have constructed the unit and counit, it remains to verify the counit-unit equations, i.e., that for each $Y \in \mathbf{Top}$ that $\varepsilon_{Y \times X} \circ (\eta_Y \times \text{id}_X) = \text{id}_{Y \times X}$ and $(\varepsilon_Y)_* \circ \eta_{Y \times X} = \text{id}_{Y \times X}$. First of all, given $(y, x) \in Y \times X$, we have

$$(\varepsilon_{Y \times X} \circ (\eta_Y \times \text{id}_X))(y, x) = \varepsilon_{Y \times X}(\eta_Y(y), x) = \eta_Y(y)(x) = (y, x).$$

On the other hand, given $f \in Y^X$, we have

$$(\varepsilon_Y)_*(\eta_{Y \times X}(f)) = (\varepsilon_Y)_*([x \mapsto (f, x)]) = [x \mapsto (f, x) \mapsto \varepsilon_Y(f, x) = f(x)] = f.$$

Hence, indeed ε and η form the counit and unit for the adjoint pair $(- \times X, (-)^X)$. \square

Now that we have gotten some topological preliminaries out of the way, we are ready to define the model structure.

Definition 2.2. A map $f : X \rightarrow Y$ in \mathbf{Top} is called a *weak equivalence* if

$$\pi_n(f, x) : \pi_n(X, x) \rightarrow \pi_n(Y, f(x))$$

is an isomorphism for all $n \geq 0$ and for all $x \in X$. We will write \mathcal{W} to refer to the class of all weak equivalences in \mathbf{Top} .

Define the set of maps I' to consist of all the boundary inclusion $S^{n-1} \hookrightarrow D^n$ for all $n \geq 0$, and define the set J to consist of all the inclusions $D^n \hookrightarrow D^n \times I$ mapping $x \mapsto (x, 0)$ for $n \geq 0$. Then a map f will be called a *cofibration* if it is in I' -cof $= {}_\perp(I'_\perp)$, and a *fibration* if it is in J -inj $= J_\perp$.

A map in I' -cell is usually called a *relative cell complex*; a relative CW-complex is a special case of a relative cell complex, where, in particular, the cells can be attached in order of their dimension. Note that in particular maps of J are relative CW complexes, hence are relative I' -cell complexes. A fibration is often known as a *Serre fibration* in the literature.

Theorem 2.3 (Hovey Theorem 2.4.19). *There is a finitely generated model structure on \mathbf{Top} with I' as the set of generating cofibrations, J as the set of generating trivial cofibrations, and the cofibrations, fibrations, and weak equivalences as above. Every object of \mathbf{Top} is fibrant, and the cofibrant objects are retracts of relative cell complexes.*

Proof. We will apply [Theorem 1.19](#) to get that there is a cofibrantly generated model structure on \mathbf{Top} with I' as the set of generating cofibrations, J as the set of generating trivial fibrations, and \mathcal{W} as the subcategory of weak equivalences. The six requirements outlined in the theorem will be verified like so:

1. \mathcal{W} is a subcategory of \mathcal{C} which has the 2-of-3 property and is closed under retracts: [Lemma 2.12](#).
2. The domains of I' are small relative to I' -cell: [Proposition 2.11](#).
3. The domains of J are small relative to J -cell: [Proposition 2.11](#).
4. $J\text{-cell} \subseteq \mathcal{W} \cap {}_{\perp}(I'_{\perp})$: In [Proposition 2.13](#), we will show ${}_{\perp}(J_{\perp}) \subseteq \mathcal{W} \cap {}_{\perp}(I'_{\perp})$, and by [Lemma 1.14](#) $J\text{-cell} \subseteq {}_{\perp}(J_{\perp})$.
5. $I'_{\perp} \subseteq \mathcal{W} \cap J_{\perp}$: [Proposition 2.14](#)
6. $\mathcal{W} \cap J_{\perp} \subseteq I'_{\perp}$: [Proposition 2.15](#)

It will follow by the definition of a cofibrantly generated model structure ([Definition 1.17](#)) that the fibrations in this model structure are given by J_{\perp} , which is precisely how we defined it. By [Proposition 1.18](#), the class of cofibrations will be given by ${}_{\perp}(I'_{\perp})$, which is likewise exactly how we defined them.

In [Proposition 2.8](#), we will show that compact spaces are finite relative to the class \mathcal{T} of closed T_1 inclusions. Hence, this model structure will be finitely generated, as the domains and codomains of I' and J are all compact, and by the reasoning given above we will have shown $I'\text{-cell} \subseteq \mathcal{T}$.

We will show that every object of \mathbf{Top} is fibrant in [Corollary 2.16](#). □

Lemma 2.4. *Let λ be an ordinal, and X a λ -sequence in \mathbf{Top} . Then:*

- (i) *If X is a λ -sequence of injections, then $X_{\alpha} \rightarrow X_{\beta}$ is an injective for all $\alpha \leq \beta < \lambda$.*
- (ii) *If X is a λ -sequence of inclusions, then the map $X_{\alpha} \rightarrow X_{\beta}$ is an inclusion for all $\alpha \leq \beta < \lambda$.*
- (iii) *If X is a λ -sequence of closed T_1 inclusions, then the map $X_{\alpha} \rightarrow X_{\beta}$ is a closed T_1 inclusion for all $\alpha \leq \beta < \lambda$.*

Proof. In what follows, given $\alpha \leq \beta < \lambda$, let $\iota_{\alpha,\beta}$ denote the map $X_{\alpha} \rightarrow X_{\beta}$.

- (i) Let $\alpha < \lambda$. We perform a proof by transfinite induction on β for $\alpha \leq \beta < \lambda$ that $\iota_{\alpha,\beta} : X_{\alpha} \rightarrow X_{\beta}$ is injective. For the zero case, clearly $\iota_{\alpha,\alpha} = \text{id}_{X_{\alpha}}$ is injective. Supposing $\iota_{\alpha,\beta}$ is injective for some $\alpha < \beta + 1 < \lambda$, we have $\iota_{\alpha,\beta+1} = \iota_{\beta,\beta+1} \circ \iota_{\alpha,\beta}$ is a composition of injections, and is therefore clearly injective itself. Finally, suppose γ is a limit ordinal with $\alpha \leq \gamma < \lambda$ such that $\iota_{\alpha,\beta}$ is injective for all $\alpha \leq \beta < \gamma$. We claim $\iota_{\alpha,\gamma}$ is injective. Since X_{γ} is colimit preserving and γ is a limit ordinal, X_{γ} is the colimit of the diagram $\{X_{\beta}\}_{\beta < \gamma}$ via the maps $\iota_{\beta,\gamma}$, so that in particular by [Remark 1.7](#) and the fact that the forgetful functor $\mathbf{Top} \rightarrow \mathbf{Set}$ preserves colimits, given $a, b \in X_{\alpha}$ with $\iota_{\alpha,\gamma}(a) = \iota_{\alpha,\gamma}(b)$, there exists some $\beta < \gamma$ with $\iota_{\alpha,\beta}(a) = \iota_{\alpha,\beta}(b)$, and $\iota_{\alpha,\beta}$ is injective for all $\beta < \gamma$, so it must have been true $a = b$ in X_{α} .
- (ii) By part(i), we know that $\iota_{\alpha,\beta}$ is injective for $\alpha \leq \beta < \lambda$. Thus it suffices to prove the following statement: For all $\alpha < \lambda$ and $U \subseteq X_{\alpha}$, for all $\alpha \leq \beta < \lambda$, there exists $U_{\beta} \subseteq X_{\beta}$ with $U_{\alpha} = U$ such that for all $\alpha \leq \beta' \leq \beta < \lambda$, $\iota_{\beta',\beta}^{-1}(U_{\beta}) = U_{\beta'}$. We prove this by transfinite recursion on $\alpha \leq \beta < \lambda$.

The zero case has been taken care of: $U_{\alpha} = U$. For the successor case, given $\alpha < \beta + 1 < \lambda$, supposing U_{β} has been defined with the desired properties, since $\iota_{\beta,\beta+1}$ is an inclusion, there exists $U_{\beta+1} \subseteq X_{\beta+1}$ with $\iota_{\beta,\beta+1}^{-1}(U_{\beta+1}) = U_{\beta}$. Then given $\alpha \leq \beta' \leq \beta + 1$, we have

$$\iota_{\beta',\beta+1}^{-1}(U_{\beta+1}) = (\iota_{\beta,\beta+1} \circ \iota_{\beta',\beta})^{-1}(U_{\beta+1}) = \iota_{\beta',\beta}^{-1}(\iota_{\beta,\beta+1}^{-1}(U_{\beta+1})) = \iota_{\beta',\beta}^{-1}(U_{\beta}) = U_{\beta'}.$$

Finally, the limit case. Suppose γ is a limit ordinal with $\alpha < \gamma \leq \lambda$, and suppose U_{β} has been constructed with the desired properties for $\alpha \leq \beta < \gamma$. We wish to define U_{γ} . Since X is colimit preserving and $\gamma = \sup_{\alpha \leq \beta < \gamma} \beta$, the maps $\iota_{\beta,\gamma}$ for $\alpha \leq \beta < \gamma$ form a colimit cone for the diagram $\{X_{\beta}\}_{\alpha \leq \beta < \gamma}$. Let $S = \{0, 1\}$ be the Sierpinski space whose open sets are $\{\emptyset, \{1\}, \{0, 1\}\}$. For

$\alpha \leq \beta < \gamma$, define a map $s_\beta : X_\beta \rightarrow S$ mapping everything in U_β to 1 and every other point to 0. Each s_β is clearly continuous, as $s_\beta^{-1}(1) = U_\beta$. Furthermore, we claim the s_β 's form a cone under the diagram $\{X_\beta\}_{\alpha \leq \beta < \gamma}$, i.e., that given $\alpha \leq \beta' \leq \beta < \gamma$, the following diagram commutes

$$\begin{array}{ccc} X_{\beta'} & \xrightarrow{\iota_{\beta',\beta}} & X_\beta \\ & \searrow s_{\beta'} \quad \swarrow s_\beta & \\ & S & \end{array}$$

To see this, let $x \in X_{\beta'}$. If $x \in U_{\beta'} = \iota_{\beta',\beta}^{-1}(U_\beta)$, then $\iota_{\beta',\beta}(x) \in U_\beta$, so $s_\beta(\iota_{\beta',\beta}(x)) = 1 = s_{\beta'}(x)$. Conversely, if $x \in X_{\beta'} \setminus U_{\beta'} = X_{\beta'} \setminus \iota_{\beta',\beta}^{-1}(U_\beta)$, then $x \notin \iota_{\beta',\beta}^{-1}(U_\beta)$, so $\iota_{\beta',\beta}(x) \notin U_\beta$, meaning $s_\beta(\iota_{\beta',\beta}(x)) = 0 = s_{\beta'}(x)$. Hence, the s_β 's do indeed form a cone under $\{X_\beta\}_{\alpha \leq \beta < \gamma}$, so by universal property of the colimit there exists a unique map $\ell : X_\gamma \rightarrow S$ such that $s_\beta = \ell \circ \iota_{\beta,\gamma}$ for all $\alpha \leq \beta < \gamma$. Define $U_\gamma := \ell^{-1}(1)$, which is open as $\{1\}$ is open in S . It remains to show that for all $\alpha \leq \beta \leq \gamma$ that $\iota_{\beta,\gamma}^{-1}(U_\gamma) = U_\beta$. Indeed, we have

$$\iota_{\beta,\gamma}^{-1}(U_\gamma) = \iota_{\beta,\gamma}^{-1}(\ell^{-1}(1)) = (\ell \circ \iota_{\beta,\gamma})^{-1}(1) = s_\beta^{-1}(1) = U_\beta.$$

- (iii) By part (ii), we know that $\iota_{\alpha,\beta}$ is an inclusion for $\alpha \leq \beta < \lambda$. Fix $\alpha < \lambda$. We perform transfinite induction on $\alpha \leq \beta < \lambda$ to show that $\iota_{\alpha,\beta}$ is a closed T_1 inclusion, assuming it is already an inclusion. For the zero case, clearly $\iota_{\alpha,\alpha} = \text{id}_{X_\alpha}$ is closed, and vacuously every point in $X_\alpha \setminus \iota_{\alpha,\alpha}(X_\alpha) = \emptyset$ is a closed point. For the successor case, supposing $\iota_{\alpha,\beta} : X_\alpha \rightarrow X_\beta$ is a closed T_1 inclusion, we wish to show that $\iota_{\alpha,\beta+1} : X_\alpha \rightarrow X_{\beta+1}$ is a closed T_1 inclusion. Since $\iota_{\alpha,\beta+1} = \iota_{\beta,\beta+1} \circ \iota_{\alpha,\beta}$ is a composition of closed T_1 inclusions, it is clearly closed. It remains to show that every point in $X_{\beta+1} \setminus \iota_{\alpha,\beta+1}(X_\alpha)$ is closed in $X_{\beta+1}$. Indeed, let $x \in X_{\beta+1} \setminus \iota_{\alpha,\beta+1}(X_\alpha)$. First, if $x \in X_{\beta+1} \setminus \iota_{\beta,\beta+1}(X_\beta)$, we are done, as $\iota_{\beta,\beta+1}$ is a closed T_1 inclusion. Hence, we may assume that $x \in \iota_{\beta,\beta+1}(X_\beta)$, so there exists some $y \in X_\beta$ such that $\iota_{\beta,\beta+1}(y) = x$. Since $\iota_{\beta,\beta+1}$ is closed, in order to show x is a closed point in $X_{\beta+1}$, it suffices to show that y is a closed point in X_β . Since $\iota_{\alpha,\beta}$ is a closed T_1 inclusion, it further suffices to show that y is not in the image of $\iota_{\alpha,\beta}$. Suppose for the sake of a contradiction that there existed $z \in X_\alpha$ with $\iota_{\alpha,\beta}(z) = y$. Then we would have

$$\iota_{\alpha,\beta+1}(z) = \iota_{\beta,\beta+1}(\iota_{\alpha,\beta}(z)) = \iota_{\beta,\beta+1}(y) = x,$$

a contradiction of the fact that $x \in X_{\beta+1} \setminus \iota_{\alpha,\beta+1}(X_\alpha)$. Hence, it must have been true that y is not in the image of $\iota_{\alpha,\beta}$ in the first place, the desired result. Finally, the limit case. Suppose γ is a limit ordinal with $\alpha < \gamma \leq \lambda$ such that $\iota_{\alpha,\beta}$ is a closed T_1 inclusion for all $\alpha \leq \beta < \gamma$. Then we wish to show $\iota_{\alpha,\gamma}$ is a closed T_1 inclusion.

First, we show $\iota_{\alpha,\gamma}$ is closed. Let $C \subseteq X_\alpha$ be closed. Since $\gamma = \sup_{\alpha \leq \beta < \gamma} \beta$ and X is colimit-preserving, X_γ is the colimit of the X_β 's for $\alpha \leq \beta < \gamma$ via the maps $\iota_{\beta,\gamma}$, and the topology on X_γ is the final topology induced by these maps. Hence, in order to show $\iota_{\alpha,\gamma}(C)$ is closed in X_γ , it suffices to show that $\iota_{\beta,\gamma}^{-1}(\iota_{\alpha,\gamma}(C))$ is closed in X_β for all $\alpha \leq \beta < \gamma$. It further suffices to show that $\iota_{\beta,\gamma}^{-1}(\iota_{\alpha,\gamma}(C)) = \iota_{\alpha,\beta}(C)$, as $\iota_{\alpha,\beta}$ is closed. First, suppose $x \in \iota_{\beta,\gamma}^{-1}(\iota_{\alpha,\gamma}(C))$, so $\iota_{\beta,\gamma}(x) = \iota_{\alpha,\gamma}(c)$ for some $c \in C$. Then since the forgetful functor $\mathbf{Top} \rightarrow \mathbf{Set}$ preserves colimits, by the explicit description of the colimit in **Set** (Remark 1.7), there exists μ with $\alpha, \beta \leq \mu < \gamma$ such that $\iota_{\beta,\mu}(x) = \iota_{\alpha,\mu}(c)$. But $\iota_{\alpha,\mu} = \iota_{\beta,\mu} \circ \iota_{\alpha,\beta}$, and $\iota_{\beta,\mu}$ is injective (by (i)) so $x = \iota_{\alpha,\beta}(c)$, meaning $x \in \iota_{\alpha,\beta}(C)$, as desired. Conversely, suppose we are given $c \in C$, then we wish to show $\iota_{\alpha,\beta}(c) \in \iota_{\beta,\gamma}^{-1}(\iota_{\alpha,\gamma}(C))$, i.e., that $\iota_{\beta,\gamma}(\iota_{\alpha,\beta}(c)) \in \iota_{\alpha,\gamma}(C)$. This follows immediately as $\iota_{\beta,\gamma} \circ \iota_{\alpha,\beta} = \iota_{\alpha,\gamma}$.

Lastly, we show that for all $x \in X_\gamma \setminus \iota_{\alpha,\gamma}(X_\alpha)$ that x is a closed point in X_γ . Again by the description of the colimit in **Set** (Remark 1.7), the fact that the forgetful functor $\mathbf{Top} \rightarrow \mathbf{Set}$ preserves colimits, and that X preserves colimits, we know that every point in X_γ is in the image of some $\iota_{\beta,\gamma}$ for some $\alpha \leq \beta < \gamma$. Hence, there exists some $\alpha < \beta < \gamma$ and a point $y \in X_\beta$ with $\iota_{\beta,\gamma}(y) = x$. By the preceding paragraph, $\iota_{\beta,\gamma}$ is closed, so in order to show x is a closed point in X_γ it suffices to show that y is a closed point in X_β . It further suffices to show that $y \in X_\beta \setminus \iota_{\alpha,\beta}(X_\alpha)$, as $\iota_{\alpha,\beta}$ is a closed T_1 inclusion. Suppose for the sake of a contradiction that there existed some $z \in X_\alpha$ such that $\iota_{\alpha,\beta}(z) = y$. Then we would have

$$\iota_{\alpha,\gamma}(z) = \iota_{\beta,\gamma}(\iota_{\alpha,\beta}(z)) = \iota_{\beta,\gamma}(y) = x,$$

a contradiction of the fact that $x \in X_\gamma \setminus \iota_{\alpha,\gamma}(X_\alpha)$. Hence, y must not have been in the image of $\iota_{\alpha,\beta}$ in the first place, as desired. \square

This result, by [Lemma 1.2](#) and [Lemma 1.3](#), gives the following corollaries:

Corollary 2.5. *The class of injective maps (resp. inclusions, closed T_1 inclusions) in **Top** is closed under transfinite composition.*

Corollary 2.6. *Let λ be an ordinal, and X be a λ -sequence in **Top**. Then:*

- (i) *If X is a λ -sequence of injections, then the canonical map $X_\alpha \rightarrow \text{colim } X$ is an injection for all $\alpha < \lambda$.*
- (ii) *If X is a λ -sequence of inclusions, then the canonical map $X_\alpha \rightarrow \text{colim } X$ is an inclusion for all $\alpha < \lambda$.*
- (iii) *If X is a λ -sequence of closed T_1 inclusions, then the canonical map $X_\alpha \rightarrow \text{colim } X$ is a closed T_1 inclusion for all $\alpha < \lambda$.*

Lemma 2.7 (Hovey 2.4.1). *Every topological space is small relative to the inclusions.*

Proof. We claim that every topological space A is $|A|$ -small relative to the inclusions. We use the characterization of smallness afforded by [Proposition 1.8](#). Let λ be an $|A|$ -filtered ordinal, and let $X : \lambda \rightarrow \mathbf{Top}$ be a λ -sequence so that $X_\beta \rightarrow X_{\beta+1}$ is an inclusion for all $\beta + 1 < \lambda$. Recall that the forgetful functor $\mathbf{Top} \rightarrow \mathbf{Set}$ is forgetful, so elements of $\text{colim } X$ are equivalence classes of elements $a \in X_\alpha$ for $\alpha < \lambda$, where $a \in X_\alpha$ and $b \in X_\beta$ represent the same equivalence class iff there exists $\alpha, \beta \leq \gamma < \lambda$ so that a and b are sent to the same element by the maps $X_\alpha \rightarrow X_\gamma$ and $X_\beta \rightarrow X_\gamma$, respectively.

First, suppose $f : A \rightarrow X_\alpha$ and $g : A \rightarrow X_\beta$ are continuous maps such that the compositions $A \xrightarrow{f} X_\alpha \rightarrow \text{colim } X$ and $A \xrightarrow{g} X_\beta \rightarrow \text{colim } X$ are equal. Then the same proof given in [Example 1.9](#) works to show that f and g are equal in some stage of the colimit, as desired.

Conversely, suppose we are given a (continuous) map $f : A \rightarrow \text{colim } X$. As in the proof of [Example 1.9](#), we may find some $\beta < \lambda$ and a map of sets $\tilde{f} : A \rightarrow X_\beta$ such that the composition $A \xrightarrow{\tilde{f}} X_\beta \xrightarrow{j} \text{colim } X$ is equal to f (note we have given the canonical map $X_\beta \rightarrow \text{colim } X$ the name j). It remains to show that \tilde{f} is continuous. Let $U \subseteq X_\beta$ be open. Since j is an inclusion ([Corollary 2.6](#)), there exists $V \subseteq \text{colim } X_\beta$ open such that $j^{-1}(V) = U$. Then $\tilde{f}^{-1}(U) = \tilde{f}^{-1}(j^{-1}(V)) = (j \circ \tilde{f})^{-1}(V) = f^{-1}(V)$, and f is continuous, so $\tilde{f}^{-1}(U) = f^{-1}(V)$ is open. Thus \tilde{f} is continuous, as desired. \square

Proposition 2.8 (Hovey 2.4.2). *Compact topological spaces are finite relative to the class \mathcal{T} of closed T_1 inclusions.*

Proof. We use the characterization of smallness afforded by [Proposition 1.8](#). Let λ be a limit ordinal, and let $X : \lambda \rightarrow \mathbf{Top}$ be a λ -sequence so that $X_\beta \rightarrow X_{\beta+1}$ is a closed T_1 inclusion for all $\beta + 1 < \lambda$. Let $j : X \Rightarrow \text{colim } X$ be a colimit cone for X . Recall that the forgetful functor $\mathbf{Top} \rightarrow \mathbf{Set}$ is forgetful, so by [Remark 1.7](#) elements of $\text{colim } X$ are equivalence classes of elements $a \in X_\alpha$ for $\alpha < \lambda$, where $a \in X_\alpha$ and $b \in X_\beta$ represent the same equivalence class iff there exists $\alpha, \beta \leq \gamma < \lambda$ so that a and b are sent to the same element by the maps $X_\alpha \rightarrow X_\gamma$ and $X_\beta \rightarrow X_\gamma$, respectively.

First, we show condition (i) of [Proposition 1.8](#). Let $j : X \Rightarrow \text{colim } X$ be a colimit cone for X , and suppose we are given maps $f : A \rightarrow X_\alpha$ and $g : A \rightarrow X_\beta$ such that $j_\alpha \circ f = j_\beta \circ g$. WLOG, suppose $\alpha \leq \beta$. Then

$$j_\beta \circ \iota_{\alpha,\beta} \circ f = j_\alpha \circ f = j_\beta \circ g,$$

and j_β is injective ([Corollary 2.6](#)) and therefore a monomorphism in **Top**, so $\iota_{\alpha,\beta} \circ f = g$, meaning f and g do indeed agree in some stage of the colimit, as desired.

Now we show condition (ii) of [Proposition 1.8](#). Let $f : A \rightarrow \text{colim } X$ be a continuous map. In order to show f factors through some X_α , we first claim it is sufficient for there to be some $\alpha < \lambda$ with $f(A) \subseteq j_\alpha(X_\alpha)$. Given an ordinal $\alpha < \lambda$, for each $a \in A$, there exists $\tilde{f}(a) \in X_\alpha$ such that $j_\alpha(\tilde{f}(a)) = f(a)$. Thus we have defined a function $\tilde{f} : A \rightarrow X_\alpha$ such that $j_\alpha \circ \tilde{f} = f$. It remains to show that \tilde{f} is continuous. Indeed, we know j_α is an inclusion ([Corollary 2.6](#)), so given $U \subseteq X_\alpha$ open, there exists $V \subseteq \text{colim } X$ open with $j_\alpha^{-1}(V) = U$, in which case

$$\tilde{f}^{-1}(U) = \tilde{f}^{-1}(j_\alpha^{-1}(V)) = (j_\alpha \circ \tilde{f})^{-1}(V) = f^{-1}(V),$$

which is open as f is continuous. Hence, \tilde{f} is continuous, as desired.

Now, suppose for the sake of a contradiction that for all $\alpha < \lambda$, $f(A) \not\subseteq j_\alpha(X_\alpha)$. Thus we may construct a **strictly increasing** sequence $\{\alpha_n\}_{n=0}^\infty \subseteq \lambda$ such that for $n > 0$, there exists $x_n \in j_{\alpha_n}(X_{\alpha_n}) \setminus j_{\alpha_{n-1}}(X_{\alpha_{n-1}})$ with $x_n \in f(A)$. Thus for each $n > 0$, there exists $y_n \in X_{\alpha_n}$ such that $j_{\alpha_n}(y_n) = x_n$. Note in particular that given $0 \leq m < n$, y_n is not in the image of $\iota_{\alpha_m, \alpha_n}$. Suppose for the sake of a contradiction that $y_n = \iota_{\alpha_m, \alpha_n}(z)$ for some $z \in X_{\alpha_m}$ and $0 \leq m < n$. Then we know $j_{\alpha_m}(z) = j_{\alpha_n}(\iota_{\alpha_m, \alpha_n}(z)) = j_{\alpha_n}(y_n) = x_n$, and

$$x_n \in j_{\alpha_n}(X_{\alpha_n}) \setminus j_{\alpha_{n-1}}(X_{\alpha_{n-1}}) \supseteq j_{\alpha_n}(X_{\alpha_n}) \setminus j_{\alpha_{n-1}}(\iota_{\alpha_m, \alpha_{n-1}}(X_{\alpha_m})) = j_{\alpha_n}(X_{\alpha_n}) \setminus j_{\alpha_m}(X_{\alpha_m}).$$

Hence we reach a contradiction, as $j_{\alpha_m}(z) = x_m$ but x_n is not in the image of j_{α_m} . Let $\mu := \sup_{n=1}^\infty \alpha_n$. Clearly $\mu \leq \lambda$; if $\mu = \lambda$, define $X_\mu := \text{colim } X$, $j_\mu := \text{id}_{X_\mu}$, and for $\alpha < \lambda$ define $\iota_{\alpha, \mu} := j_\alpha$. Let $K := \{\iota_{\alpha_n, \mu}(y_n)\}_{n=1}^\infty \subseteq X_\mu$. We claim every subset of K is closed in X_μ . Since X is colimit preserving and $\mu = \sup_{n=1}^\infty \alpha_n$, the topology on X_μ is the final topology induced by the maps $\iota_{\alpha_n, \mu} : X_{\alpha_n} \rightarrow X_\mu$ for $n = 1, 2, \dots$. Thus, given a subset $C \subseteq K$, in order to show that C is closed in X_μ , it is sufficient (and necessary) for $\iota_{\alpha_n, \mu}^{-1}(C)$ to be closed in X_{α_n} for $n = 1, 2, \dots$. Let $n > 0$. Given $y \in \iota_{\alpha_n, \mu}^{-1}(C)$, then $\iota_{\alpha_n, \mu}(y) \in C \subseteq K$, so that in particular $\iota_{\alpha_n, \mu}(y) = \iota_{\alpha_m, \mu}(y_m)$ for some $m = 1, 2, \dots$. We claim $m \leq n$. Suppose for the sake of a contradiction that $m > n$, then we would have

$$\iota_{\alpha_m, \mu}(y_m) = \iota_{\alpha_n, \mu}(y) = \iota_{\alpha_m, \mu}(\iota_{\alpha_n, \alpha_m}(y)),$$

and $\iota_{\alpha_m, \mu}$ is injective (by either [Lemma 2.4](#) if $\mu < \lambda$ or by [Corollary 2.6](#) if $\mu = \lambda$, in which case recall we defined $\iota_{\alpha_m, \mu} = j_{\alpha_m}$), thus $y_m = \iota_{\alpha_n, \alpha_m}(y)$, meaning y_m is in the image of $\iota_{\alpha_n, \alpha_m}$ for $m > n$, a contradiction, as we showed earlier this is impossible. Thus it must have been true that $m \leq n$ in the first place, so

$$\iota_{\alpha_n, \mu}(y) \in \{\iota_{\alpha_m, \mu}(y_m)\}_{m=1}^n \implies y \in \iota_{\alpha_n, \mu}^{-1}(\{\iota_{\alpha_m, \mu}(y_m)\}_{m=1}^n).$$

We further claim $\iota_{\alpha_n, \mu}^{-1}(\{\iota_{\alpha_m, \mu}(y_m)\}_{m=1}^n) = \{\iota_{\alpha_m, \alpha_n}(y_m)\}_{m=1}^n$. To see the inclusion \subseteq , suppose $z \in X_{\alpha_n}$ with $\iota_{\alpha_n, \mu}(z) = \iota_{\alpha_m, \mu}(y_m)$ for some $m \leq n$. Then $\iota_{\alpha_n, \mu}(z) = \iota_{\alpha_n, \mu}(\iota_{\alpha_m, \alpha_n}(y_m))$ and $\iota_{\alpha_n, \mu}$ is injective ([Lemma 2.4](#) if $\mu < \lambda$ and [Corollary 2.6](#) if $\mu = \lambda$), so $z = \iota_{\alpha_m, \alpha_n}(y_m)$, as desired. To see the opposite inclusion, given $m \leq n$, we have $\iota_{\alpha_n, \mu}(\iota_{\alpha_m, \alpha_n}(y_m)) = \iota_{\alpha_m, \mu}(y_m)$, so $\iota_{\alpha_m, \alpha_n}(y_m) \in \iota_{\alpha_n, \mu}^{-1}(\{\iota_{\alpha_m, \mu}(y_m)\}_{m=1}^n)$, as desired. Thus, we have shown $y \in \{\iota_{\alpha_m, \alpha_n}(y_m)\}_{m=1}^n$. Recall our choice of $y \in \iota_{\alpha_n, \mu}^{-1}(C)$ was arbitrary, so $\iota_{\alpha_n, \mu}^{-1}(C)$ is contained in $\{\iota_{\alpha_m, \alpha_n}(y_m)\}_{m=1}^n$. Thus, because $\{\iota_{\alpha_m, \alpha_n}(y_m)\}_{m=1}^n$ is finite, in order to show $\iota_{\alpha_n, \mu}^{-1}(C)$ is closed in X_{α_n} , it suffices to show that $\iota_{\alpha_m, \alpha_n}(y_m)$ is a closed point in X_{α_n} for $m = 1, \dots, n$. As we have shown above, y_m is not in the image of $\iota_{\alpha_0, \alpha_m}$ for any $m \geq 1$, and $\iota_{\alpha_0, \alpha_m}$ is a closed T_1 inclusion ([Lemma 2.4](#)), so y_m is a closed point of X_{α_m} for $m = 1, \dots, n$. Then since $\iota_{\alpha_m, \alpha_n}$ is closed (again by [Lemma 2.4](#)), $\iota_{\alpha_m, \alpha_n}(y_m)$ is closed in X_{α_n} for $m = 1, \dots, n$, precisely the desired result.

Now, we have shown that every subset of K is closed in X_μ . Then $j_\mu : X_\mu \rightarrow \text{colim } X$ is a closed and injective (this follows by [Corollary 2.6](#) if $\mu < \lambda$, and if $\mu = \lambda$, $X_\mu = \text{colim } X$, in which case j_μ is the identity), so every subset of $S := j_\mu(K)$ is closed in $\text{colim } X$. Note that

$$S = \{j_\mu(\iota_{\alpha_n, \mu}(y_n))\}_{n=1}^\infty = \{j_{\alpha_n}(y_n)\}_{n=1}^\infty = \{x_n\}_{n=1}^\infty \subseteq f(A),$$

Then for $n = 1, 2, \dots$, define $U_n := f(A) \setminus (S \setminus \{x_n\})$. Each U_n is open in $f(A)$ (as $S \setminus \{x_n\}$ is a subset of S and is therefore closed in $\text{colim } X$, thus in $f(A)$), and the collection $\{U_n\}_{n=1}^\infty$ forms an infinite open cover of $f(A)$. Finally, this open cover has no finite subcover, as U_n is the only element of the cover containing x_n for $n = 1, 2, \dots$. Hence we reach a contradiction, as f is continuous and A is compact, so $f(A)$ is compact, but we have found an infinite open cover of $f(A)$ which has no finite subcover. Thus, there must have existed some $\alpha < \lambda$ with $f(A) \subseteq j_\alpha(X_\alpha)$ in the first place, in which case, as we have shown, this implies f factors through X_α via a continuous map, as desired. \square

Proposition 2.9 (Hovey 2.4.5 & 2.4.6). *The class of injective maps (resp. inclusions, closed T_1 inclusions) in **Top** is saturated.*

Proof. We know these three classes are closed under transfinite compositions ([Corollary 2.5](#)), so it suffices to show these classes are closed under pushouts and retracts. In what follows, fix a pushout diagram and a

retract diagram of the following form:

$$\begin{array}{ccc}
 A & \xrightarrow{f} & C \\
 i \downarrow & & \downarrow j \\
 B & \xrightarrow{g} & D
 \end{array}
 \qquad
 \begin{array}{ccccc}
 A & \xrightarrow{f} & B & \xrightarrow{g} & A \\
 j \downarrow & & \downarrow i & & \downarrow j \\
 C & \xrightarrow{h} & D & \xrightarrow{k} & C
 \end{array}$$

- (i) First, consider the pushout diagram, and suppose i is injective. We wish to show j is injective. Suppose for the sake of a contradiction there existed distinct points $c_1, c_2 \in C$ such that $j(c_1) = j(c_2)$. Define $h : C \rightarrow \{1, 2, 3\}$ mapping $c_1 \mapsto 1$, $c_2 \mapsto 2$, and every other point in C maps to 3. Define $k : B \rightarrow \{1, 2, 3\}$ to map every point in $i(f^{-1}(c_1))$ to 1, every point in $i(f^{-1}(c_2))$ to 2, and every other point to 3. We may give $\{1, 2, 3\}$ the indiscrete topology so that h and k are continuous. Then clearly $h \circ f = k \circ i$, so there exists a map $\ell : D \rightarrow \{1, 2, 3\}$ such that $\ell \circ j = h$ and $\ell \circ g = k$. But we reach a contradiction, as $\ell(j(c_1)) = \ell(j(c_2))$, but $h(c_1) \neq h(c_2)$.

Now, consider the retract diagram, and suppose i is injective. We wish to show j is injective. Suppose $a_1, a_2 \in A$ such that $j(a_1) = j(a_2)$. Then $h(j(a_1)) = h(j(a_2))$, and $h \circ j = i \circ f$, so $i(f(a_1)) = i(f(a_2))$. Note that since $g \circ f = \text{id}_A$, necessarily f is injective, and we are assuming i is injective, so $i(f(a_1)) = i(f(a_2)) \implies a_1 = a_2$.

- (ii) First, consider the pushout diagram, and suppose i is an inclusion. We wish to show j is an inclusion. We know j is injective by (i). It remains to show that given $U \subseteq C$ open, there exists $V \subseteq D$ open with $j^{-1}(V) = U$. Given $U \subseteq C$ open, $f^{-1}(U)$ is open in A as f is continuous, and i is an inclusion, so there exists $W \subseteq B$ open with $i^{-1}(W) = f^{-1}(U)$. Now let $S = \{0, 1\}$ be the Sierpinski space with open sets $\{\emptyset, \{1\}, \{0, 1\}\}$. Define $h : C \rightarrow S$ to map every point of U to 1, and every other point to 0. Define $k : B \rightarrow S$ to map every point of W to 1, and every other point to 0. Clearly h and k are continuous. We claim $h \circ f = k \circ i$. Indeed, let $a \in A$. If $a \in f^{-1}(U)$, then $h(f(a)) = 1$, as $f(a) \in U$, while $k(i(a)) = 1$, as $a \in U = i^{-1}(W)$, so $i(a) \in W$. Conversely, if $a \notin f^{-1}(U)$, then $h(f(a)) = 0$ as $f(a) \notin U$, while $k(i(a)) = 0$, as $a \notin i^{-1}(W)$ meaning $i(a) \notin W$. Hence, there exists a (unique) continuous map $\ell : D \rightarrow S$ with $\ell \circ j = h$ and $\ell \circ g = k$. Define $V := \ell^{-1}(1)$, which is open in D as $\{1\}$ is open in S . Then finally, we claim $j^{-1}(V) = U$. Indeed,

$$j^{-1}(V) = j^{-1}(\ell^{-1}(1)) = (\ell \circ j)^{-1}(1) = h^{-1}(1) = U.$$

Thus j is an inclusion, as desired.

Now, consider the retract diagram, and suppose i is an inclusion. We wish to show j is an inclusion. We know j is injective by (i). It remains to show that given $U \subseteq A$ open, there exists $V \subseteq C$ open with $j^{-1}(V) = U$. Then since g is continuous, $g^{-1}(U)$ is open in B , and i is an inclusion, so there exists $W \subseteq D$ open with $i^{-1}(W) = g^{-1}(U)$. Then

$$j^{-1}(h^{-1}(W)) = (h \circ j)^{-1}(W) = (i \circ f)^{-1}(W) = f^{-1}(i^{-1}(W)) = f^{-1}(g^{-1}(U)) = (g \circ f)^{-1}(U) = U,$$

and $h^{-1}(W)$ is open as h is continuous and W is open, so we are done, as if we set $V := h^{-1}(W)$, then we have shown V is open in C and $j^{-1}(V) = U$, as desired.

- (iii) First, consider the pushout diagram, and suppose i is a closed T_1 inclusion. We wish to show j is a closed T_1 inclusion. We know j is an inclusion by (ii). It remains to show j is closed, and every point of $D \setminus j(C)$ is closed in D . First, we show closedness. Let $V \subseteq C$ be a closed set, we want to show $j(V)$ is closed in D . By definition of the colimit topology on D (which is the final topology on D induced by j and g by the discussion at the beginning of this chapter), in order to show $j(V)$ is closed in D it suffices to show that $j^{-1}(j(V))$ is closed in C and $g^{-1}(j(V))$ is closed in B . Since j is injective by (i), $j^{-1}(j(V)) = V$, which we have defined to be closed in A . Now, to show $g^{-1}(j(V))$ is closed, since i is a closed map and f is continuous, it suffices to show $i(f^{-1}(V)) = g^{-1}(j(V))$. First of all, let $b \in i(f^{-1}(V))$, then $b = i(a)$ for some $a \in A$ with $f(a) \in V$. Then $g(b) = g(i(a)) = j(f(a)) \in j(V)$, so $b \in g^{-1}(j(V))$. Conversely, let $b \in g^{-1}(j(V))$, so $g(b) = j(c)$ for some $c \in V$. Then by the explicit description of the colimit in **Set** and the fact that the forgetful functor **Top** \rightarrow **Set** preserves colimits, there exists $a \in A$ such that $f(a) = c$ and $i(a) = b$. Then in particular, $f(a) = c \in V$, so $a \in f^{-1}(V)$, so $b \in i(f^{-1}(V))$ as desired. Hence, j is indeed a closed map. It remains to show that for all $d \in D \setminus j(C)$, d is a closed point in D . Given

$d \in D \setminus j(C)$, by the explicit characterization of the colimit topology, it suffices to show that $j^{-1}(d)$ and $g^{-1}(d)$ are closed in C and B , respectively. First of all, $j^{-1}(d) = \emptyset$, which is closed. Now, since d is not in the image of j , d is not in the image of $g \circ i = j \circ f$, so $g^{-1}(d) \subseteq B \setminus i(A)$. Thus since i is a closed T_1 inclusion, in order to show $g^{-1}(d)$ is closed, it suffices to show that $g^{-1}(d)$ is a singleton. Suppose for the sake of a contradiction there existed distinct points $x, y \in B$ with $g(x) = g(y) = d$. Define $h : C \rightarrow \{1, 2, 3\}$ to map every point to 3. Define $k : B \rightarrow \{1, 2, 3\}$ to map $x \mapsto 1$, $y \mapsto 2$, and every other point in B maps to 3. Endue $\{1, 2, 3\}$ with the indiscrete topology so that h and k are continuous. Note $h \circ f = k \circ i$: given $a \in A$, since $x, y \in g^{-1}(d) \subseteq B \setminus i(A)$, $i(a)$ does not equal x or y , thus $k(i(a)) = 3 = h(f(a))$. Hence by the definition of the colimit, there exists a map $\ell : D \rightarrow X$ such that $\ell \circ g = k$ and $\ell \circ j = h$. Then we reach a contradiction, as $k(x) \neq k(y)$ but $\ell(g(x)) = \ell(g(y)) = \ell(d)$. Hence, $g^{-1}(d) \notin i(A)$ must have been a singleton in the first place, meaning $g^{-1}(d)$ is closed in B as desired.

Now, consider the retract diagram, and suppose i is a closed T_1 inclusion. We wish to show j is a closed T_1 inclusion. We know j is an inclusion by (ii). It remains to show j is closed, and every point of $C \setminus j(A)$ is closed in C . First, we show closedness. Let $V \subseteq A$ be closed. First, we claim $j(V) = h^{-1}(i(g^{-1}(V)))$. Given $c \in j(V)$, $c = j(a)$ for some $a \in V$, in which we have $h(c) = h(j(a)) = i(f(a))$, and $g(f(a)) = a \in V$, so $f(a) \in g^{-1}(V)$, meaning $h(c) \in i(g^{-1}(V))$, so $c \in h^{-1}(i(g^{-1}(V)))$. Conversely, given $c \in h^{-1}(i(g^{-1}(V)))$, so $h(c) = i(b)$ for some $b \in B$ with $g(b) \in V$. Then

$$c = k(h(c)) = k(i(b)) = j(g(b)) \in j(V),$$

as desired. Thus, we have shown $j(V) = h^{-1}(i(g^{-1}(V)))$. Note that since $V \subseteq A$ is closed and g is continuous, $g^{-1}(V)$ is closed in B . Since i is a closed map, $i(g^{-1}(V))$ is closed in D . Finally, since h is continuous, $h^{-1}(i(g^{-1}(V))) = j(V)$ is closed in C , as desired. It remains to show that for all $c \in C \setminus j(A)$ that c is a closed point in C . Given $c \in C \setminus j(A)$, note that $h(c) \notin i(B)$, as if $h(c) = i(b)$ for some $b \in B$, then we would have $c = k(h(c)) = k(i(b)) = j(g(b))$, yet we chose c not in the image of j . Hence, since i is a closed T_1 inclusion, and $h(c)$ is not in the image of i , $h(c)$ is a closed point in D . Then note that since $k \circ h = \text{id}_C$, h is injective, so $c = h^{-1}(h(c))$ is a closed point, as it is the preimage of the closed set $\{h(c)\}$ along the continuous map h . \square

Lemma 2.10 (Hovey 2.4.8). $\mathcal{W} \cap \mathcal{T}$ is closed under transfinite compositions.

Proof. **TODO.** \square

Proposition 2.11. *The domains of I' (resp. J) are small relative to I' -cell.*

Proof. By **Lemma 2.7**, every space is small relative to the inclusions, and in particular every space is small relative to the class \mathcal{T} of closed T_1 inclusions. Hence, it suffices to show that $J\text{-cell}, I'\text{-cell} \subseteq \mathcal{T}$. We showed above in **Proposition 2.9** that \mathcal{T} is closed under transfinite composition and pushouts, and clearly every map in I' and J is a closed T_1 inclusion, so the desired result follows. \square

Lemma 2.12 (Hovey Lemma 2.4.4). *The weak equivalences in **Top** are closed under retracts and satisfy 2-of-3 axiom (so that in particular the weak equivalences form a subcategory, as clearly identities are weak equivalences).*

Proof. First we show that weak equivalences satisfy 2-of-3. Let $f : X \rightarrow Y$ and $g : Y \rightarrow Z$ be continuous functions of topological spaces.

First of all, suppose f and g are both weak equivalences. Then by functoriality of π_n , since $\pi_n(f, x)$ and $\pi_n(g, f(x))$ are isomorphisms for all $x \in X$, $\pi_n(g \circ f, x) = \pi_n(g, f(x)) \circ \pi_n(f, x)$ is likewise an isomorphism for all $x \in X$, so that $g \circ f$ is a weak equivalence.

Now, suppose that $g \circ f$ and g are weak equivalences. Pick a point $x \in X$. We wish to show that $\pi_n(f, x) : \pi_n(X, x) \rightarrow \pi_n(Y, f(x))$ is an isomorphism for all $n \geq 0$. We know that $\pi_n(g \circ f, x)$ is an isomorphism, and $\pi_n(g, f(x))$ is an isomorphism, say with inverse, φ , so that

$$\varphi \circ \pi_n(g \circ f, x) = \varphi \circ \pi_n(g, f(x)) \circ \pi_n(f, x) = \pi_n(f, x)$$

is an isomorphism, as it is a composition of isomorphisms.

Now, suppose that $g \circ f$ and f are weak equivalences. Pick a point $y \in Y$. Since $\pi_0(f)$ is an isomorphism, there exists a point $x \in X$ such that $f(x)$ belongs to the path component containing y , so that there exists some $\alpha : I \rightarrow Y$ with $\alpha(0) = f(x)$ and $\alpha(1) = f(y)$. Then consider the following diagram

$$\begin{array}{ccc} \pi_n(Y, y) & \xrightarrow{\pi_n(g, y)} & \pi_n(Z, g(y)) \\ \downarrow & & \downarrow \\ \pi_n(Y, f(x)) & \xrightarrow{\pi_n(g, f(x))} & \pi_n(Z, g(f(x))) \end{array}$$

where the left arrow is the isomorphism given by conjugation by the path α , and the right arrow is the isomorphism given by conjugation by the path $g \circ \alpha$. It is tedious yet straightforward to verify that the diagram commutes. Furthermore, we know that $\pi_n(f, x)$ and $\pi_n(g \circ f, x) = \pi_n(g, f(x)) \circ \pi_n(f, x)$ are isomorphisms for all n , so that if we denote the inverse of $\pi_n(f, x)$ by φ , then

$$\pi_n(g \circ f, x) \circ \varphi = \pi_n(g, f(x)) \circ \pi_n(f, x) \circ \varphi = \pi_n(g, f(x))$$

is an isomorphism, as it is given as a composition of isomorphisms. Hence, the top arrow must likewise be an isomorphism, precisely the desired result.

The fact that weak equivalences in **Top** are closed under retracts is entirely straightforward and follows from the fact that the functors π_n preserve retract diagrams and that the class of isomorphisms in any category is closed under retracts. \square

Proposition 2.13 (Hovey 2.4.9). $\perp(J_\perp) \subseteq \mathcal{W} \cap \perp(I'_\perp)$.

Proof. First, in order to show $\perp(J_\perp) \subseteq \perp(I'_\perp)$, It suffices to show that $J \subseteq I'$ -cell, as by [Lemma 1.14](#) we would have $J \subseteq \perp(I'_\perp)$, and

$$J \subseteq \perp(I'_\perp) \implies \perp(J_\perp) \subseteq \perp((\perp(I'_\perp))_\perp) = \perp(I'_\perp),$$

where the implication and equality both follow from [Lemma 1.11](#) which gives that

$$A \subseteq B \implies \perp(A_\perp) \subseteq \perp(B_\perp) \quad \text{and} \quad (\perp(A_\perp))_\perp = A_\perp.$$

Now, to show $J \subseteq I'$ -cell, first consider the composition $j_n : D^n \hookrightarrow S^n \hookrightarrow D^{n+1}$, where the first map is the pushout

$$\begin{array}{ccc} S^{n-1} & \hookrightarrow & D^n \\ \downarrow & & \downarrow \\ D^n & \longrightarrow & S^n \end{array}$$

obtained by gluing two copies of D^n along their boundary, and the second map is simply the inclusion $S^n \hookrightarrow D^{n+1}$, which can be written as the pushout

$$\begin{array}{ccc} S^n & \xlongequal{\quad} & S^n \\ \downarrow & & \downarrow \\ D^{n+1} & \xlongequal{\quad} & D^{n+1} \end{array}$$

It can be seen that j_n includes D^n as a hemisphere of $S^n = \partial D^{n+1} \subseteq D^{n+1}$. Note that $D^n \times I$ is homeomorphic to D^{n+1} (“smooth out” the sharp edges of the cylinder) via some homeomorphism $h_n : D^{n+1} \rightarrow D^n \times I$, and in particular, we may define h_n so that $h_n(j_n(D^n)) = D^n \times \{0\} \subseteq D^n \times I$ by squashing the hemisphere $j_n(D^n)$ to be one of the faces of the cylinder $D^n \times I$, in which case $h_n \circ j_n : D^n \rightarrow D^n \times I$ is precisely the inclusion $D^n \hookrightarrow D^n \times I$ sending $x \mapsto (x, 0)$, and since $j_n \in I'$ -cell, $h_n \circ j_n \in I'$ -cell by [Lemma 1.13](#).

Now, we claim that $\perp(J_\perp) \subseteq \mathcal{W}$. First note that by [Corollary 1.16](#) and [Proposition 2.11](#), every map in $\perp(J_\perp)$ is a retract of an element of J -cell. Furthermore, we know that \mathcal{W} is closed under retracts ([Lemma 2.12](#)), so that it suffices to show that J -cell $\subseteq \mathcal{W}$. We claim it suffices to show that pushouts of maps in J are weak equivalences. Supposing we had shown this, we would have that pushouts of maps in J are weak equivalences and T_1 inclusions, as $J \subseteq \mathcal{T}$ and \mathcal{T} is saturated by [Proposition 2.9](#). Then by [Lemma 2.10](#), we would have that J -cell $\subseteq \mathcal{W} \cap \mathcal{T}$, precisely the desired result.

Now, let \mathcal{S} be the class of *inclusions of a deformation retract*, i.e., those **injective** maps $i : A \rightarrow B$ such that there exists a homotopy $H : B \times I \rightarrow B$ with $H(i(a), t) = i(a)$ for all $a \in A$, $H(b, 0) = b$ for all $b \in B$, and $H(b, 1) = i(r(b))$ for all $b \in B$ for some map $r : B \rightarrow A$ ². We will show the following:

- (1) $\mathcal{S} \subseteq \mathcal{W}$.

It suffices to show that if $i : A \rightarrow B$ belongs to \mathcal{S} , then i is a homotopy equivalence. Indeed, given $i : A \rightarrow B$, let $H : B \times I \rightarrow B$ and $r : B \rightarrow A$ be a homotopy and retract satisfying the conditions above. Then in particular, H is a homotopy between id_B (at time $t = 0$) and $i \circ r$ (at time $t = 1$). It remains to show that $r \circ i = \text{id}_A$. First of all, note that since $H(b, 1) = i(r(b))$ for all $b \in B$, we have $H(i(a), 1) = i(r(i(a)))$. Yet, we also know that $H(i(a), t) = i(a)$ for all $t \in I$, so $i(r(i(a))) = i(a)$, and i is injective so $r(i(a)) = a$.

- (2) $J \subseteq \mathcal{S}$.

For $n \geq 0$, let $j_n : D^n \hookrightarrow D^n \times I$ denote the inclusion of D^n as the subset $D^n \times \{0\}$. Define a deformation retract $H : D^n \times I \times I \rightarrow D^n \times I$ by $(x, s, t) \mapsto (x, s(1-t))$. Then indeed we have $H(j_n(x), t) = H(x, 0, t) = (x, 0) = j_n(x)$ for all $x \in D^n$, $H(x, t, 0) = (x, t(1-0)) = (x, t)$ for all $(x, t) \in D^n \times I$, and $H(x, t, 1) = (x, t(1-1)) = (x, 0) = j_n(r(x))$ for all $(x, t) \in D^n \times I$, where $r : D^n \times I \rightarrow D^n$ is the projection onto time zero sending $(x, t) \mapsto (x, 0)$. Finally, j_n is clearly injective. Thus, indeed $J \subseteq \mathcal{S}$.

- (3) \mathcal{S} is closed under pushouts.

Suppose we are given a pushout diagram

$$\begin{array}{ccc} A & \xrightarrow{f} & C \\ i \downarrow & \lrcorner & \downarrow j \\ B & \xrightarrow{g} & D \end{array}$$

where $i \in \mathcal{S}$. Then we wish to show $j \in \mathcal{S}$. First, we know j is injective by [Proposition 2.9](#). Now, we look to construct H and r . Let $K : B \times I \rightarrow B$ and $r' : B \rightarrow A$ be maps satisfying the conditions for i to be an inclusion of a deformation retract.

We wish to define a homotopy $H : D \times I \rightarrow D$. Then I is a locally compact Hausdorff space (in particular, it is compact and Hausdorff), so that the functor $- \times I : \mathbf{Top} \rightarrow \mathbf{Top}$ preserves colimits ([Proposition 2.1](#)), meaning the following is a pushout diagram:

$$\begin{array}{ccc} A \times I & \xrightarrow{f \times \text{id}_I} & C \times I \\ i \times \text{id}_I \downarrow & \lrcorner & \downarrow j \times \text{id}_I \\ B \times I & \xrightarrow{g \times \text{id}_I} & D \times I \end{array}$$

Then by the universal property of the pushout, there is a map $H : D \times I \rightarrow D$ (the dashed line) such that the following diagram commutes

$$\begin{array}{ccccc} A \times I & \xrightarrow{f \times \text{id}_I} & C \times I & \xrightarrow{\pi_1} & C \\ i \times \text{id}_I \downarrow & \lrcorner & \downarrow j \times \text{id}_I & \searrow & \downarrow j \\ B \times I & \xrightarrow{g \times \text{id}_I} & D \times I & \xrightarrow{H} & D \\ & \searrow K & \xrightarrow{g} & & \\ & & B & \xrightarrow{g} & D \end{array}$$

Now, note $r' \circ i = \text{id}_A$. Indeed, given $a \in A$, we have $i(r'(i(a))) = K(i(a), t) = i(a)$ and i is injective, so that $r'(i(a)) = a$, as desired. Hence, there exists a unique map $r : D \rightarrow C$ (the dashed line) such

²Hovey has a typo here, namely, he does not specify that i must be injective. Without this specification, his assertion fails. For example, take $A = \mathbb{R}^2$, $B = \mathbb{R}$, $i(x, y) = x$, $H(b, t) = b$, and $r(b) = (b, 0)$. Then i is an inclusion of a deformation retract according to Hovey's "definition," but i is not injective and r is not a retract.

that the following diagram commutes:

$$\begin{array}{ccc}
 A & \xrightarrow{f} & C \\
 \downarrow i & & \downarrow j \\
 B & \xrightarrow{g} & D \\
 & \searrow r' & \nearrow r \\
 & A & \xrightarrow{f} C
 \end{array}$$

(Note: The diagram shows a square with \$A \to C\$ on top, \$B \to D\$ on bottom, \$A \to B\$ on left (\$i\$), and \$C \to D\$ on right (\$j\$). A curved arrow \$r'\$ goes from \$B\$ to \$A\$, and a curved arrow \$r\$ goes from \$D\$ to \$C\$. A dashed arrow \$r\$ also points from \$D\$ to \$A\$.)

Now we claim that our constructions H and r endue j with the structure of an inclusion of a deformation retract, as desired. First $c \in C$, we wish to show $H(j(c), t) = j(c)$ for all t . Indeed, we have

$$H(j(c), t) = H(j \times \text{id}_I(c, t)) = j(\pi_1(c, t)) = j(c).$$

Given $d \in D$, we want to show $H(d, 0) = d$. By the explicit description of the colimit in **Top**, we know that every element of D is in the image of either j or g . If $d = j(c)$ for some c , then we have just shown $H(d, 0) = H(j(c), 0) = j(c) = d$, as desired. On the other hand, if $d = g(b)$ for some $b \in B$ we have

$$H(d, 0) = H(g \times \text{id}_I(b, 0)) = g(K(b, 0)) = g(b) = d.$$

Finally, we claim that $H(d, 1) = j(r(d))$ for all $d \in D$. If $d = j(c)$ for some $c \in C$, then we have

$$H(d, 1) = H(j(c), 1) = j(c) = j(r(j(c))) = j(r(d)),$$

as desired. On the other hand, if $d = g(b)$ for some $b \in B$, then

$$H(d, 1) = H(g \times \text{id}_I(b, 1)) = g(K(b, 1)) = g(i(r'(b))) = j(f(r'(b))) = j(r(g(b))) = j(r(d)). \quad \square$$

Proposition 2.14 (Hovey 2.4.10). $I'_\perp \subseteq \mathcal{W} \cap J_\perp$

Proof. First, by [Proposition 2.13](#) we know ${}_\perp(J_\perp) \subseteq {}_\perp(I'_\perp)$, and this implies $I'_\perp \subseteq J_\perp$, as by [Lemma 1.11](#) we have

$${}_\perp(J_\perp) \subseteq {}_\perp(I'_\perp) \implies J_\perp = ({}_\perp(J_\perp))_\perp \supseteq ({}_\perp(I'_\perp))_\perp = I'_\perp.$$

Thus, it suffices to show that $I'_\perp \subseteq \mathcal{W}$. Now, suppose $p : (X, x_0) \rightarrow (Y, p(x_0))$ is in I'_\perp . We wish to show that the map $\pi_n(p, x_0) : \pi_n(X, x_0) \rightarrow \pi_n(Y, p(x_0))$ is an isomorphism for all n .

First we show that $\pi_n(p, x_0)$ is surjective. Let $g : (S^n, *) \rightarrow (Y, p(x_0))$ be a map. Then we have the following commutative diagram

$$\begin{array}{ccc}
 * & \longrightarrow & X \\
 \downarrow & & \downarrow p \\
 S^n & \xrightarrow{g} & Y
 \end{array}$$

where the top arrow picks out x_0 . Note that the map $* \rightarrow S^n$ may be realized as a pushout of the diagram $D^n \leftarrow S^{n-1} \rightarrow *$, so that $* \rightarrow S^n$ belongs to I' -cell, and therefore ${}_\perp(I'_\perp)$ by [Lemma 1.14](#), and $p \in I'_\perp$, so $* \rightarrow S^n$ has the left lifting property against p . Thus, the above diagram has a lift $f : (S^n, *) \rightarrow (X, x_0)$ such that $p \circ f = g$, so that $\pi_n(p, x_0)([f]) = [p \circ f] = [g]$, as desired.

Finally, we show that $\pi_n(p, x_0)$ is injective. Suppose we have two maps $f, g : (S^n, *) \rightarrow (X, x_0)$ such that $p \circ f$ and $p \circ g$ represent the same element of $\pi_n(Y, p(x_0))$. Then there is a homotopy $H : S^n \times I \rightarrow Y$ such that for all $s \in S^n$ and $t \in I$, $H(s, 0) = p(f(s))$, $H(s, 1) = p(g(s))$, and $H(*, t) = p(x_0)$. By the universal property of the quotient, H induces a map $\overline{H} : S^n \wedge I_+ := (S^n \times I)/(* \times I)$ sending the equivalence class $[s, t] \mapsto H(s, t)$. Hence, the following diagram commutes:

$$\begin{array}{ccc}
 S^n \vee S^n & \xrightarrow{f \vee g} & X \\
 \downarrow & & \downarrow p \\
 S^n \wedge I_+ & \xrightarrow{\overline{H}} & Y
 \end{array}$$

where the left arrow is an element of I' -cell, as it may be obtained by attaching an $n+1$ cell to $S^n \vee S^n$ (when $n = 0$, the attaching map is obvious; when $n > 0$, the attaching map is the quotient map $S^n \twoheadrightarrow S^n \vee S^n$ obtained by collapsing the equator). Thus, by similar reasoning to above there exists a lift $\overline{K} : S^n \wedge I_+ \rightarrow X$.

Then if we define K to be the composition $S^n \times I \rightarrow S^n \wedge I_+ \xrightarrow{\overline{K}} X$, this gives us the desired homotopy between f and g : given $s \in S^n$ and $t \in I$, we have $K(s, 0) = \overline{K}([s, 0]) = f(s)$, $K(s, 1) = \overline{K}([s, 1]) = g(s)$, and $K(*, t) = \overline{K}([*, t])$ \square

Proposition 2.15 (Hovey 2.4.12). $\mathcal{W} \cap J_\perp \subseteq I'_\perp$

Proof. **TODO.** □

Corollary 2.16 (Hovey 2.4.14). *Every topological space is fibrant, i.e., given a space X , the unique map $X \rightarrow *$ is an element of J_\perp .*

Proof. **TODO.** □

Questions/Comments:

- (1) I am getting down and dirty fiddling with the details, but I feel I don't have much big-picture understanding. In particular,