A MODEL CATEGORY FOR LOCAL PO-SPACES

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ABSTRACT. Locally partial-ordered spaces (local po-spaces) have been used to model concurrent systems. We provide equivalences for these spaces by constructing a model category containing the category of local po-spaces. We show the category of simplicial presheaves on local po-spaces can be given Jardine’s model structure, in which we identify the weak equivalences between local po-spaces. In the process we give an equivalence between the category of sheaves on a local po-space and the category of étale bundles over a local po-space. Finally we describe a localization that should provide a good framework for studying concurrent systems.

1. Introduction

The motivation for this paper stems from the study of concurrent processes accessing shared resources. Such systems were originally described by discrete models based on graphs, possibly equipped with some additional information [Mil80]. The precision of these models suffers, however, from an inaccuracy in distinguishing between concurrent and non-deterministic executions. It turned out that a satisfactory way to organize this information can be based on cubical sets, giving rise to the notion of Higher-Dimensional Automata or HDA’s [Gou96, Gou02]. HDA’s live in slice categories of \( \text{cSet} \), the category of cubical sets and their morphisms.

A different view, which has its origins in Dijkstra’s notion of progress graphs [Dij68], takes the flow of time into account. The difficulty here is to adequately model the fact that time is irreversible as far as computation is concerned. On the other hand, one would like to identify execution paths corresponding to (at least) the same sequence of acquisitions of shared resources. However, in order not to lose precision, this notion of homotopy is also subject to the constraint above of the irreversibility of time. There are two distinct approaches, both based on topological spaces.

One approach, advocated by P. Gaucher, is to topologize the sets of paths between the states of an automaton, which technically amounts to an enrichment with no units [Gau03]. The intuition behind the setup is to distinguish between spatial and temporal deformations of computational paths. The related framework of Flows has clear technical advantages from a (model-)categorical point of view.
The other approach, advocated by Fajstrup, Goubault, Raussen and others, is to topologize partially ordered states of automata. Such objects are called partially-ordered spaces or po-spaces (also pospaces)\(^1\). The advantage of using po-spaces is that there is a very simple and intuitive way to express directed homotopy or dihomotopy \cite{Gou03, FGR99}.

However, the price paid is that po-spaces cannot model executions of (concurrent) programs with loops. The solution is to order the underlying topological space only \textit{locally}. Such objects are called \textit{local po-spaces} and the notion of dihomotopy becomes more intricate in this context. Nevertheless, practical reasons like tractability call for a good notion of equivalence in the category of local po-spaces. Put differently, it would be useful to be able to replace a given local po-space model with a simpler local po-space which nevertheless preserves the relevant computer-scientific properties.

In this paper, we study these questions in the framework of Quillen’s (closed) model categories \cite{Qui67, Hov99, Hir03}. Briefly, a model category is a category with all small limits and colimits and three distinguished classes of morphisms called \textit{weak equivalences}, \textit{cofibrations} and \textit{fibrations}. Weak equivalences that are also cofibrations or fibrations are called \textit{trivial cofibrations} and \textit{trivial fibrations}, respectively. These morphisms satisfy four axioms that allow one to apply the machinery of homotopy theory to the category. This machinery allows a rigorous study of equivalences. We remark that there are other frameworks for studying equivalence. However model categories have the most developed theory, and have succeeded in illuminating many diverse subjects.

Our aim is to construct a model category of locally partial-ordered spaces as a foundation for the study of concurrent systems. This is technically difficult because locally partial-ordered spaces are not closed under taking colimits. We will define a category \textbf{LPS} of local po-spaces, which embeds into the category \textbf{sPre}(\textbf{LPS}) of simplicial presheaves on local po-spaces. The objects of \textbf{sPre}(\textbf{LPS}) are contravariant functors from \textbf{LPS} to the category of simplicial sets and the morphisms are the natural transformations. This embedding is given by a Yoneda embedding (see Definition \ref{def:yoneda}),

$$\bar{y} : \textbf{LPS} \rightarrow \textbf{sPre}(\textbf{LPS}).$$

We now briefly describe some technical conditions on model categories which strengthen our theorems. For more details see Definitions \ref{def:proper} and \ref{def:cellular} and \cite{Hov99, Hir03}. A model category is \textit{proper} if the weak equivalences are closed under both pushouts with cofibrations and pullbacks with fibrations. It is \textit{left proper} if the first condition holds. A model category is \textit{cofibrantly generated} if the model category structure is induced by a set of generating cofibrations and a set of generating trivial cofibrations, both of which permit the small object argument. A \textit{cellular} model category is a cofibrantly generated model category in which the cell complexes are well behaved. A \textit{simplicial} model category \textbf{M} is a model category enriched over simplicial sets, which for any \(X \in \textbf{M}\) and any simplicial set \(K\) has objects \(X \otimes K\) and \(X^K\) which satisfy various compatibility conditions.

\textbf{Theorem 1.1.} The category \textbf{sPre}(\textbf{LPS}) has a proper, cellular, simplicial model structure in which

\(^1\)M. Grandis uses a related approach \cite{Gra03} in which the underlying topological space comes with a class of directed paths. However these spaces are not partially-ordered, even locally.
• the cofibrations are the monomorphisms,
• the weak equivalences are the stalkwise equivalences, and
• the fibrations are the morphisms which have the right lifting property with respect to all trivial cofibrations.

Furthermore among morphisms coming from \( \text{LPS} \) (using the Yoneda embedding \( \text{LPS} \hookrightarrow \text{sPre}(\text{LPS}) \)), the weak equivalences are precisely the isomorphisms. The model structure on \( \text{sPre}(\text{LPS}) \) is Jardine’s model structure \cite{Jar87, Jar96} on the category of simplicial presheaves on a small Grothendieck site. We show that \( \text{Shv}(\text{LPS}) \) is a Grothendieck topos which has enough points. Under this condition, Jardine showed that the weak equivalences are the stalkwise equivalences. This model category can be thought of as a localization of the universal injective model category of local po-spaces \cite{Joy84, Dug01, DHI04}. While in general the weak equivalences are interesting and nontrivial \cite{Jar87}, this is not true for those coming from \( \text{LPS} \). To obtain a more interesting category from the point of view of concurrency we would like to localize with respect to directed homotopy equivalences. In \cite{Dub04} it is argued that the relevant equivalences are the directed homotopy equivalences relative to some context. The context is a local po-space \( A \) and the directed homotopy equivalences rel \( A \) are a set of morphisms in \( A \downarrow \text{LPS} \).

We combine this approach with Theorem 1.1 as follows. First we remark that \( A \) embeds in \( \text{sPre}(\text{LPS}) \) as \( \tilde{y}(A) \). Next the model structure on \( \text{sPre}(\text{LPS}) \) induces a model structure on the coslice category \( \tilde{y}(A) \downarrow \text{sPre}(\text{LPS}) \). Finally one can take the left Bousfield localization of this model category with respect to the directed homotopy equivalences rel \( A \).

**Theorem 1.2.** Let \( I = \{ \tilde{y}(f) \mid f \text{ is a directed homotopy equivalence rel } A \} \). Then the category \( \tilde{y}(A) \downarrow \text{sPre}(\text{LPS}) \) has a left proper, cellular model structure in which

• the cofibrations are the monomorphisms,
• the weak equivalences are the \( I \)-local equivalences, and
• the fibrations are those morphisms which have the right lifting property with respect to monomorphisms which are \( I \)-local equivalences.

Recall that, given a topological space \( Z \), étale bundles over \( Z \) are maps \( W \to Z \) which are local homeomorphisms. Let \( O(Z) \) be \( Z \)’s locale of open subsets and recall that sheaves over \( Z \) are functors \( O(Z)^{\text{op}} \to \text{Set} \) that enjoy a good gluing property. There is a well-known correspondence between étale bundles and sheaves. We establish a directed version of this correspondence, which may be of independent interest.

**Theorem 1.3.** Let \( Z \in \text{LPS} \). Let \( \text{Etale}(Z) \) be the category of di-étale bundles over \( Z \), i.e. the category of bundles which are local dihomeomorphisms. Let \( O(Z) \) be the category of open subobjects of \( Z \). There is an equivalence of categories:

\[ \Gamma : \text{Etale}(Z) \cong \text{Shv}(O(Z)) : \Lambda. \]

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2. Background

This section contains some known definitions and facts we build on. We start by stating the definition of a model category in subsection 2.1. Next we review the basics on presheaves in subsection 2.2 and on sheaves in subsection 2.3. We then recall the notions of topoi and geometric morphisms in subsection 2.4 and of stalks in subsection 2.5. Our main reference for this material is [MLM92]. Subsection 2.6 is devoted to some important model structures on $\text{sSet}^{\text{op}}$, the category of simplicial presheaves over a category $\mathcal{C}$. The material is drawn from [Jar87, Jar96, DH104].

2.1. Model categories. Recall that a morphism $i : A \to B$ has the left lifting property with respect to a morphism $p : X \to Y$ if in every commutative diagram

\[
\begin{array}{ccc}
A & \to & X \\
i & \downarrow & \downarrow p \\
B & \to & Y \\
\end{array}
\]

there is a morphism $h : B \to X$ making the diagram commute. Also $f$ is a retract of $g$ if there is a commutative diagram:

\[
\begin{array}{ccc}
A & \to & A \\
f & \downarrow & \downarrow f \\
B & \to & B \\
\end{array} \quad \begin{array}{ccc}
X & \to & X \\
g & \downarrow & \downarrow f \\
B & \to & B \\
\end{array}
\]

Definition 2.1. A model category is a category with all small limits and colimits that has three distinguished classes of morphisms: $\mathcal{W}$, called the weak equivalences; $\mathcal{C}$, called the cofibrations; and $\mathcal{F}$, called the fibrations, which together satisfy the axioms below. We remark that morphisms in $\mathcal{W} \cap \mathcal{C}$, and $\mathcal{W} \cap \mathcal{F}$, are called trivial cofibrations and trivial fibrations, respectively.

1. Given composable morphisms $f$ and $g$ if any of the two morphisms $f$, $g$, and $g \circ f$ are in $\mathcal{W}$, then so is the third.
2. If $f$ is a retract of $g$ and $g$ is in $\mathcal{W}$, $\mathcal{C}$ or $\mathcal{F}$, then so is $f$.
3. Cofibrations have the left-lifting property with respect to trivial fibrations, and trivial cofibrations have the left-lifting property with respect to fibrations.
(4) Every morphism can be factored as a cofibration followed by a trivial fibration, and as a trivial cofibration followed by a fibration. These factorizations are functorial.

2.2. Presheaves. Recall that a presheaf $P$ on $C$ is just a functor $P \in \text{Set}^{\text{op}}$. In particular, “hom-ing” $C(\_\_,C)$ gives rise to a presheaf and further to the Yoneda embedding $y : C \hookrightarrow \text{Set}^{\text{op}}$, $X \mapsto C(\_\_, X)$. This embedding is dense, i.e.

$$P \cong \text{colim}(y \circ \pi)$$

canonically for any presheaf $P$, where $\pi : (y \downarrow P) \to C$ is the projection from the comma-category $y \downarrow P$. Recall that a presheaf in the image of the Yoneda-embedding (up to equivalence) is called representable.

2.3. Sheaves.

Definition 2.2. A sieve on $M \in C$ is a subfunctor $S \subseteq C(\_\_, M)$. A Grothendieck topology $J$ on $C$ assigns to each $M \in C$ a collection $J(M)$ of sieves on $M$ such that

(i) (maximal sieve) $C(\_\_, M) \in J(M)$ for all $M \in C$;

(ii) (stability under pullback) if $g : M \to N$ and $S \in J(N)$, then $(g \circ \_\_)^*(S) \in J(M)$ as given by

$$(g \circ \_\_)^*(S) \to S \downarrow \downarrow \downarrow \downarrow \downarrow C(\_\_, M) \to C(\_\_, N)$$

(iii) (transitivity) if $S \in J(M)$ and $R$ is a sieve on $M$ such that $(f \circ \_\_)^*(R) \in J(U)$ for all $f : U \to M$ in the image of $S$, then $R \in J(M)$;

We say that a sieve $S$ on $M$ is a covering sieve or a cover of $M$ whenever $S \in J(M)$.

Remark 2.3. Unwinding definition pinpoints a sieve as a right ideal, i.e. a set of arrows $S$ with codomain $M$ such that $f \in S \implies f \circ h \in S$ whenever the codomain of $h$, $\text{cod}(h) = \text{dom}(f)$, the domain of $f$. From this point of view, pulling back a sieve $S$ on $M$ by an arrow $N \xrightarrow{f} M$ amounts to building the set

$$f^*(S) \overset{\text{def}}{=} \{ h \mid \text{cod}(h) = N, \ f \circ h \in S \}.$$ 

It is then immediate how to rephrase a Grothendieck topology in terms of right ideals.

Definition 2.4. Let $J$ be a Grothendieck topology on $C$. A presheaf $P \in \text{Set}^{\text{op}}$ is a sheaf with respect to $J$ provided any natural transformation $\theta : S \Rightarrow P$ uniquely extends through $y(M)$ as in
for all $S \in J(M)$ and all $M \in C$. $J$ is subcanonical if the representable presheaves are sheaves.

**Remark 2.5.** Let $\theta : S \to P$ be a natural transformation from a sieve $S$ to a presheaf $P$. If one sees $S$ as a right ideal $S = \{u_j : M_j \to M\}$, then $\theta$ amounts to a function that assigns to every $u_j : M_j \to M \in S$ an element $a_j \in P(M_j)$ such that

$$P(v)(a_j) = a_k$$

for all $v : M_k \to M_j$ and for all $u_k = u_j \circ v \in S$. Such a function is called a matching family for $S$ of elements of $P$. A matching family $a_j \in P(M_j)$ admits an amalgamation $a \in P(M)$ if

$$P(u_j)(a) = a_j$$

for all $u_j : M_j \to M \in S$. From this point of view, the Yoneda lemma characterizes a sheaf as a presheaf such that every matching family has a unique amalgamation for all $S \in J(M)$ and all $M \in C$.

A Grothendieck topology is a huge object. In practice, a generating device is used.

**Definition 2.6.** A basis $K$ for a Grothendieck topology assigns to each object $M$ a collection $K(M)$ of families of morphisms with codomain $M$ such that

(i) all isomorphisms $f : U \to M$ are contained in $K(M)$,

(ii) given a morphism $g : N \to M \in C$ and $\{f_i : U_i \to M\} \in K(M)$, then

- the family of pullbacks $\{\pi_2 : U_i \times_M N \to N\} \in K(N)$, and

(iii) given $\{f_i : U_i \to M\} \in K(M)$ and for each $i$, $\{h_{ij} : A_{ij} \to U_i\} \in K(U_j)$,

- then the family of composites $\{f_i \circ h_{ij} : A_{ij} \to M\} \in K(M)$.

**Remark 2.7.** Given a basis $K$ for a Grothendieck topology one generates the corresponding Grothendieck topology $J$ by defining

$$V \in J(M) \iff \text{there is } U \in K(M) \text{ such that } U \subset V.$$ 

As expected, the sheaf condition can be rephrased in terms of a basis.

As an example, consider the case $C = O(X)$ with $X$ a topological space and $O(X)$ its locale of opens. The basis of the open-cover (Grothendieck) topology is, as expected, given by open coverings of the opens.

**Theorem 2.8.** Let $\text{Shv}(C, J)$ be the full subcategory of $\text{Set}^{C^{op}}$ whose objects are sheaves for $J$. The inclusion functor $i : \text{Shv}(C, J) \to \text{Set}^{C^{op}}$ has a left adjoint $a$ called the associated sheaf functor or sheafification. This left adjoint preserves finite limits.

Theorem 2.8 is listed as Theorem III.5.1 in [MLM92]. There are several equivalent ways to construct the associated sheaf functor, the most classical one being the “plus-construction” applied twice.

**Remark 2.9.** A cover on $M$ amounts to a cocone in $C$ with vertex $M$. The associated sheaf functor maps these cocones onto colimiting ones. Moreover, it is universal with respect to this property.
2.4. Topoi.

**Definition 2.10.** A category $\mathcal{E}$ has exponentials provided that for all $X \in \mathcal{E}$, the functor $\_ \times X : \mathcal{E} \to \mathcal{E}$ has a right adjoint denoted $(\_)^X$, so that

$$\mathcal{E}(Y \times X, Z) \cong \mathcal{E}(Y, Z^X).$$

Suppose now $\mathcal{E}$ has a terminal object 1, and has finite limits. A subobject classifier is a monomorphism true : 1 $\rightarrowtail$ $\Omega$ such that for every monomorphism $s : S \rightarrowtail X$, there is a unique morphism $\phi_S$ such that pullback of true along $\phi_S$ yields $s$:

$$\begin{array}{ccc}
S & \rightarrow & 1 \\
\downarrow & & \downarrow \text{true} \\
X & \rightarrow & \Omega \end{array}$$

The category $\mathcal{E}$ is a topos if it has exponentials and a subobject classifier.

A subobject classifier is obviously unique (up to isomorphism). Furthermore, a topos has all finite colimits, though this is not easy to prove. It would take pages to enumerate all the remarkable features of a topos, see [Joh77] for an introduction to the lore of the material. Let us just say that topoi as introduced by Grothendieck and his collaborators had a very strong algebro-geometrical flavor [AGV72], yet the rich structure is relevant not only for algebraic geometers but for logicians as well [Law63, Law64, Law73].

**Definition 2.11.** A site $(\mathcal{C}, J)$ is a small category $\mathcal{C}$ equipped with a Grothendieck topology $J$. A Grothendieck topos is a category equivalent to the category $\text{Shv}(\mathcal{C}, J)$ of sheaves on $(\mathcal{C}, J)$.

The following are well known.

**Proposition 2.12.** (1) A Grothendieck topos is a topos; (2) $\text{Set}$ is a topos; (3) $\text{Set}^{\text{op}}$ is a topos for any $\mathcal{C}$.

**Definition 2.13.** Let $\mathcal{E}$ and $\mathcal{F}$ be topos. A geometric morphism $g : \mathcal{F} \to \mathcal{E}$ is a pair of adjoint functors

$$\begin{array}{ccc}
\mathcal{E} & \overset{g^*}{\longrightarrow} & \mathcal{F} \\
\downarrow & & \downarrow g_*
\end{array}$$

such that the left adjoint $g^*$ is left-exact (that is, it preserves finite limits). The right adjoint is called direct image and the left one inverse image.

As an example, $i : \text{Shv}(\mathcal{C}, J) \hookrightarrow \text{Set}^{\text{op}}$ is the direct image part of a geometric morphism. Notice that the convention for a geometric morphism is to have the direction of its direct image part.

**Definition 2.14.** A (geometric) point in a topos $\mathcal{E}$ is a geometric morphism

$$p : \text{Set} \to \mathcal{E}$$

(we write $p \in \mathcal{E}$ by abuse of notation). A topos $\mathcal{E}$ has enough points if given $f \neq g : P \to Q \in \mathcal{E}$ there is a point $p \in \mathcal{E}$ such that $p^*f \neq p^*g \in \text{Set}$.
2.5. Stalks and germs.

Definition 2.15. Let \((\mathbb{C}, J)\) be a site, \(a : \text{Set}^{\text{op}} \to \text{Shv}(\mathbb{C}, J)\) the associated sheaf functor and \(x \in \text{Shv}(\mathbb{C}, J)\) a point. The stalk functor at \(x\) is given by

\[
\text{stalk}_x \overset{\text{def}}{=} x^* \circ a : \text{Set}^{\text{op}} \to \text{Set}.
\]

Given a presheaf \(F\), we say that \(\text{stalk}_x(F)\) is the stalk of \(F\) at \(x\). As an example, consider again the case \(\mathbb{C} = \text{O}(X)\) with \(X\) a (this time) Hausdorff topological space and \(\text{O}(X)\) its locale of opens equipped with the open-cover topology. Let \(\text{Shv}(X)\) be the corresponding topos of sheaves. It can be shown that any geometric point \(x : \text{Set} \to \text{Shv}(X)\) corresponds to a “physical” point \(x' \in X\). The stalk of \(F \in \text{Set}^{\text{op}}\) at \(x\) is then given by

\[
\text{stalk}_x(F) := \text{colim}_{U \in \text{O}(X), x' \in U} F(U).
\]

Write \(\text{germ}_{x,U} : F(U) \to \text{stalk}_x(F)\) for the canonical map at \(U\) (\(\text{germ}_x\) when \(U\) is clear from the context). We call the equivalence class \(\text{germ}_{x,U}(s)\) of \(s\) in \(\text{stalk}_x(F)\) the germ of \(s\) at \(x\). Obviously,

\[
\text{stalk}_x(F) = \{\text{germ}_{x,U}(s) \mid U \in \text{O}(X), x' \in U, s \in F(U)\}.
\]

2.6. Simplicial Presheaves. For the rest of this section, let \(\mathbb{C}\) be a small category with a Grothendieck topology \(J\) such that \(\text{Shv}(\mathbb{C}, J)\) has enough points.

Let \(\Delta\) be the simplicial category which has objects \([n] = \{0, 1, \ldots, n\}\) for \(n \geq 0\), and whose morphisms are the maps such that \(x \leq y\) implies that \(f(x) \leq f(y)\). Then \(\text{sSet}\) is the category \(\text{Set}^{\Delta^{\text{op}}}\). This category has a well-known model structure (see [Hov99] for example) where \(\text{W}_{\text{sSet}}\) are the morphisms whose geometric realization is a weak homotopy equivalence and \(\text{C}_{\text{sSet}}\) are the monomorphisms.

Objects of \(\text{sSet}^{\text{op}}\) are called simplicial presheaves on \(\mathbb{C}\) since

\[
\text{sSet}^{\text{op}} = \left(\text{Set}^{\Delta^{\text{op}}}\right)^{\text{op}} \cong \text{Set}^{\Delta^{\text{op}} \times \text{Set}^{\text{op}}} \cong \left(\text{Set}^{\text{op}}\right)^{\Delta^{\text{op}}}.
\]

There is an embedding

\[
\kappa : \text{Set}^{\text{op}} \to \text{sSet}^{\text{op}}
\]

\[
F \mapsto \kappa_F
\]

where \(\kappa_F\) is constant levelwise i.e. \(\kappa_F(C)_n \overset{\text{def}}{=} F(C)\) for all \(n \in \mathbb{N}\), and all the face and degeneracy maps are the identity. There is a further embedding

\[
\gamma : \text{sSet} \to \text{sSet}^{\text{op}}
\]

\[
K \mapsto \gamma_K
\]

where \(\gamma_K\) is constant objectwise i.e. \(\gamma_K(C) \overset{\text{def}}{=} K\) for all \(C \in \mathbb{C}\).

Recall that for \(C \in \mathbb{C}\) and \(F \in \text{Set}^{\text{op}}\), the Yoneda lemma gives the isomorphism \(\text{Set}^{\text{op}}(y(C), F) \cong F(C)\), where \(y\) is the Yoneda embedding (see Section 2.2). In the simplicial case we have the following variation, which can be proved using the same idea used in the proof of the Yoneda lemma.

Proposition 2.16. (Bi-Yoneda) Let \(C \in \mathbb{C}\) and \(F \in \text{sSet}^{\text{op}}\). There is an isomorphism

\[
\text{sSet}^{\text{op}}(\kappa_y(C) \times \gamma_{\Delta[n]}, F) \cong F(C)_n
\]

natural in all variables.
Definition 2.17. Using the Yoneda embedding $y : \mathcal{C} \to \text{Set}^{\mathcal{C}^{op}}$ for presheaves one can define an embedding

$$\bar{y} : \mathcal{C} \to \text{Set}^{\mathcal{C}^{op}} \to \text{sSet}^{\mathcal{C}^{op}}$$

for simplicial presheaves. The functor $\bar{y}$ is also called a Yoneda embedding.

There are two Quillen equivalent model structures on $\text{sSet}^{\mathcal{C}^{op}}$ which are in a certain sense objectwise:

- the **projective** model structure $\text{sSet}^{\mathcal{C}^{op}}_{\text{prj}}$ where $W_{\text{prj}}$ and $F_{\text{prj}}$ are objectwise (that is, $f : P \to Q \in W_{\text{prj}}(F_{\text{prj}})$ if and only if for all $C \in \mathcal{C}$, $f(C) : P(C) \to Q(C) \in W_{\text{sSet}}(F_{\text{sSet}})$), and

- the **injective** model structure $\text{sSet}^{\mathcal{C}^{op}}_{\text{inj}}$ where $W_{\text{inj}}$ and $C_{\text{inj}}$ are objectwise.

These were studied by Bousfield and Kan [BK72] and Joyal [Joy84], respectively.

Proposition 2.18. Both $\text{sSet}^{\mathcal{C}^{op}}_{\text{prj}}$ and $\text{sSet}^{\mathcal{C}^{op}}_{\text{inj}}$ are proper, simplicial, cellular model categories. All objects are cofibrant in the latter. The identity functor is a left Quillen equivalence from the projective model structure to the injective model structure.

The injective one is more handy when it comes down to calculating homotopical localizations, yet the fibrant objects are easier to grasp in the projective one\(^2\).

Using the stalk functor for presheaves, one can define a simplicial stalk functor for simplicial presheaves.

Definition 2.19. The simplicial stalk functor at a point $p$ in $\text{Shv}(\mathcal{C})$ is given by

$$(_p) : \text{sSet}^{\mathcal{C}^{op}} \to \text{sSet} \quad P \mapsto \{\text{stalk}_p(P_n)\}_{n \geq 0}.$$ 

A morphism $f : P \to Q \in \text{sSet}^{\mathcal{C}^{op}}$ is a stalkwise equivalence if $f_p : P_p \to Q_p \in \text{sSet}$ is a weak equivalence for all points $p$ in $\text{Shv}(\mathcal{C})$.

Jardine [Jar87] proved the existence of a local version of Joyal’s injective model structure. Since we will only be interested in the special case where $\text{Shv}(\mathcal{C})$ has enough points, we will not recall the definition of local weak equivalences.

Theorem 2.20 ([Jar87, Jar98]). Let $\mathcal{C}$ be a small category with a Grothendieck topology. Then $\text{sSet}^{\mathcal{C}^{op}}$ the category of simplicial presheaves on $\mathcal{C}$ has a proper, simplicial, cellular model structure in which

- the cofibrations are the monomorphisms, i.e. the levelwise monomorphisms of presheaves,

- the weak equivalences are the local weak equivalences, and

- the fibrations are the morphisms which have the right lifting property with respect to all trivial cofibrations.

Furthermore, if the Grothendieck topos $\text{Shv}(\mathcal{C})$ has enough points, then the local weak equivalences are the stalkwise equivalences.

Jardine’s model structure can be seen to be cellular since it can also be constructed as a left Bousfield localization of the injective model structure [DHI04].

\(^2\)They are objectwise Kan.
3. Local po-spaces

The focus of this section is to provide the reader with the main definitions and constructions. We define a small category of local po-spaces \( \text{LPS} \) and state some of the properties, most of which are proved in the later sections. We show that Theorem 1.1 follows from these properties and a theorem of Jardine.

To simplify the analysis, we will only work with topological spaces which are subspaces of \( \mathbb{R}^n \) for some \( n \), since this provides more than enough generality for studying concurrent systems. The main technical advantage of this setting is that we obtain small categories.

**Definition 3.1.**
(i) Let \( \text{Spaces} \) be the category whose objects are subspaces of \( \mathbb{R}^n \) for some \( n \), and whose morphisms are continuous maps.

(ii) Let \( \text{PoSpaces} \) be the category whose objects are po-spaces: that is \( U \in \text{Spaces} \) together with a partial order (a reflexive, transitive, anti-symmetric relation) \( \leq \) such that \( \leq \) is a closed subset of \( U \times U \) in the product topology.

(iii) For any \( M \in \text{Spaces} \) define an order-atlas on \( M \) to be an open cover \(^3\)

\[
U = \{U_i\} \text{ of } M \text{ indexed by a set } I, \text{ where } U_i \in \text{PoSpaces}. \text{ These partial orders are compatible: } \leq_i \text{ agrees with } \leq_j \text{ on } U_i \cap U_j \text{ for all } i, j \in I. \text{ We will usually omit the index set from the notation.}
\]

(iv) Let \( U \) and \( U' \) be two order atlases on \( M \). Say that \( U' \) is a refinement of \( U \) if for all \( U_i \in U \), there exists a \( U'_j \in U' \) such that \( x \in U'_j \subseteq U_i \) and for all \( a, b \in U'_j \), \( a \leq_j b \) if and only if \( a \leq_i b \).

(v) Say that two order atlases are equivalent if they have a common refinement. This is an equivalence relation: reflexivity and symmetry follow from the definition. For transitivity, if \( U \) and \( U' \) have a refinement \( V = \{V_i\} \) and \( U' \) and \( U'' \) have a refinement \( W = \{W_j\} \), let \( T = \{V_i \cap W_j\} \). One can check that \( T \) is an order atlas of \( M \) and that is a refinement of \( U' \) and \( U'' \).

Any po-space \((U, \leq)\) is a local po-space with the equivalence class of order atlases generated by the order atlas \( \{U\} \). As a further example, we remark that any discrete space has a unique equivalence class of order-atlases.

**Definition 3.2.** Let \( \text{LPS} \) be the category of local po-spaces described as follows. The objects, called local po-spaces, are all pairs \((M, \mathcal{U})\) where \( M \) is an object in \( \text{Spaces} \) and \( \mathcal{U} \) is an equivalence class of order-atlases of \( M \). The morphisms, called dimaps are described as follows. \( f \in \text{LPS}((M, \mathcal{U}), (N, \mathcal{V})) \) if and only if \( f \in \text{Spaces}(M, N) \) and for all \( V = \{V_j\}_{j \in J} \in \mathcal{V} \) there is a \( U = \{U_i\}_{i \in I} \in \mathcal{U} \) such that for all \( i \in I, j \in J \), for all \( x, y \in U_i \cap f^{-1}(V_j) \),

\[
x \leq U_i, y \implies f(x) \leq V_j f(y).
\]

**Remark 3.3.** This condition is not necessarily true for arbitrary \( U \in \mathcal{U} \). For example, take \( M = \{-1, 1\} \) with \( \mathcal{U} \) the unique equivalence class of order atlases generated by the order atlas \( U = \{-1\}, \{1\} \). Let \( f = \text{Id}_M : (M, \mathcal{U}) \to (M, \mathcal{U}) \).

Now let \( M_+ \) be the po-space on \( M \) with the ordering \(-1 \leq 1 \) and let \( M_- \) be the po-space on \( M \) with the ordering \( 1 \leq -1 \). Then \( \{M_+\} \in \mathcal{U} \) and \( \{M_-\} \in \mathcal{U} \) (both have \( U \) as a common refinement). However, even though \(-1, 1 \in M_+ \cap f^{-1}(M_-)\),

\[
-1 \leq M_+ 1 \text{ but } f(-1) \nleq M_- f(1).
\]

\(^3\)That is, for all \( i \), \( U_i \) is open as a subspace of \( M \) and \( M = \cup_i U_i \).
Remark 3.4. It is easy to check that a dimap of po-spaces is also a dimap of local po-spaces. Thus \textbf{PoSpaces} the category of po-spaces is a subcategory of \textbf{LPS}.

Remark 3.5. Subobjects in \textbf{LPS}.

If \((M, \mathcal{U}) \in \text{LPS}\), then a subspace \(L \subseteq M \in \text{Spaces}\) inherits local po-space structure as follows. Let \(U = \{U_i\} \in \mathcal{U}\) and let \(W = \{W_i\}\) where \(W_i = L \cap U_i\) and \(W_i\) has the partial order inherited from \(U_i\). Then \(W\) is an open cover of \(L\) and the partial orders are compatible. That is \(W\) is an order atlas. Let \(\mathcal{W}\) be the equivalence class of \(W\).

We claim that \(W\) does not depend on the choice of \(U\). Let \(\tilde{U} = \{\tilde{U}_i\} \in \mathcal{U}\), let \(\tilde{W}_i = L \cap \tilde{U}_i\), and let \(\tilde{W} = \{\tilde{W}_i\}\). Let \(\tilde{W}_i = L \cap \tilde{U}_i\) and let \(\tilde{W} = \{\tilde{W}_i\}\). Then one can check that \(\tilde{W}\) is a common refinement of \(W\) and \(\tilde{W}\). So the equivalence class of \(\tilde{W}\) is also \(W\).

Next we claim that there is a dimap \(\iota : (L, \mathcal{W}) \to (M, \mathcal{U})\) given by the inclusion \(\iota : L \to M\). Let \(U = \{U_k\} \in \mathcal{U}\), let \(W_k = L \cap U_k\), and let \(W = \{W_k\}\). Then \(W \in \mathcal{W}\). Let \(x, y \in W_j \cap \iota^{-1}(U_k) = W_j \cap L \cap U_k = W_j \cap W_k\). Note that \(\iota(x) = x\) and \(\iota(y) = y\). Then

\[
x \leq_{W_j} y \iff x \leq_{W_k} y \iff x \leq_{U_k} y.
\]

Therefore when \(L \subseteq M \in \text{Spaces}\), then there is an induced inclusion \((L, \mathcal{W}) \subseteq (M, \mathcal{U}) \in \text{LPS}\).

The remark above will be used implicitly and without reference in Section 6.

Definition 3.6. A collection of dimaps \(\{\phi_j : (M_j, \mathcal{U}^j) \to (M, \mathcal{U})\}\) \textbf{LPS} is an open discover if

(i) \(\{\phi_j : M_j \to M\}\) is an open cover, and

(ii) for each \(j\), \(\mathcal{U}^j\) is the local po-space structure inherited from \((M, \mathcal{U})\).

Remark 3.7. The local po-space structures inherited by the subspaces of \((M, \mathcal{U})\) are compatible. So if \(\{\phi_j : (M_j, \mathcal{U}^j) \to (M, \mathcal{U})\}\) is a open cover, then for each \(j\), there is a \(U_j = \{U_k\} \subseteq \mathcal{U}^j\) such that \(U_j = \{U_{k,j}\}_{j,k}\) is an order atlas for \(M\) and \(U_j \in \mathcal{U}\).

The following is easy to check.

Lemma 3.8. \textbf{Spaces} and \textbf{LPS} are small categories.

Define \(U : \text{LPS} \to \text{Spaces}\) to be the forgetful functor defined on objects and morphisms as follows \((M, \mathcal{U}) \mapsto M\) and \(\varphi \mapsto \varphi\).

Define \(F : \text{Spaces} \to \text{LPS}\) as follows. If \(M\) is an object in \textbf{Spaces}, then let \(F(M) = (M, \bar{M}_\varphi)\), where \(\bar{M}_\varphi\) is the equivalence class of \(M_\varphi = \{M\}\) with \(x \leq_M y \iff x = y\). If \(f : M \to N \in \text{Spaces}\), then \(F(f) = f : (M, \bar{M}_\varphi) \to (N, \bar{N}_\varphi)\). This is a dimap since for any \(V = \{V_j\} \in \bar{N}_\varphi\) with \(x, y \in f^{-1}V_j\), \(x \leq_M y \implies x = y \implies f(x) = f(y) \implies f(x) \leq_{V_j} f(y)\).

Remark 3.9. Note that \(U\) is faithful and \(F\) includes \textbf{Spaces} as a full subcategory of \textbf{LPS}.

Proposition 3.10. \(F : \text{Spaces} \rightleftharpoons \text{LPS} : U\) is an adjunction.

Proof. Let \(M\) be an object in \textbf{Spaces} and \((N, \bar{V}) \in \text{LPS}\). We claim that there is a natural bijection

\[
\text{LPS}(F(M), (N, \bar{V})) \cong \text{Spaces}(M, U(N, \bar{V})�).
\]
We need to show that there is a natural bijection

$$\theta : \text{Spaces}(M, N) \xrightarrow{\sim} \text{LPS}((M, M_\varphi), (N, \bar{V})).$$

If $f \in \text{LPS}((M, M_\varphi), (N, \bar{V}))$, then $f \in \text{Spaces}(M, N)$ such that for any $V = \{V_j\} \in \bar{V}$, for all $j$, $f|_{f^{-1}(V_j)}$ satisfies $x \leq_M y \implies f(x) \leq_{V_j} f(y)$. Since $x \leq_M y$ if and only if $x = y$ this last condition is vacuous. Thus the bijection is simply $\theta : f \mapsto f$.

To show naturality let $\alpha : (N, \bar{V}) \to (N', \bar{V}') \in \text{LPS}$ and $\xi : M' \to M \in \text{Spaces}$. Then

$$\theta(U(\alpha) \circ f \circ \xi) = \alpha \circ f \circ \xi = \alpha \circ \theta(f) \circ \xi.$$ 

\[\blacksquare\]

Remark 3.11. \textit{LPS} does not have colimits.

Consider the product of the directed circle and an interval. Now collapse the top circle of this cylinder. The vertex of the resulting cone does not have a local partial order.

4. The open-dicover topology

We define the open cover Grothendieck topology for \text{Spaces} and the open dicover Grothendieck topology for \text{LPS} in the following lemma. The proof of the lemma follows directly from the definition of a basis for a Grothendieck topology.

Lemma 4.1. (1) \text{Spaces} has a Grothendieck topology whose basis is given by the open covers. For $M \in \text{Spaces}$ let $K(M) = \{\text{open covers of } M\}$. Let $J$ be the Grothendieck topology generated by $K$. Call $J$ the open cover topology.

(2) Analogously, \text{LPS} has a Grothendieck topology whose basis is given by the open dicovers in \text{LPS}. Let $K((M, U)) = \{\text{open dicovers of } (M, U)\}$. Call the Grothendieck topology generated by $K$ the open-dicover topology.

In Section 3, we defined a Grothendieck topology to be subcanonical if every representable presheaf a sheaf. In this section, we will prove that the open-dicover topology is subcanonical.

The following proposition shows that if a Grothendieck topology is generated by a basis $K$, then to see if a presheaf is a sheaf it suffices to check the basis. For the definition of matching families and amalgamations see Remark 2.5.

Proposition 4.2 (\cite[Proposition III.4.1]{MLM92}). Let $C$ be a small category with a Grothendieck topology $J$ generated by a basis $K$. Then a presheaf $P \in \text{Set}^{C^{\text{op}}}$ is a sheaf for $J$ if and only if for every $M \in C$ and every cover $\{\phi_j : M_j \to M\} \in K(M)$, every matching family for $\{\phi_j\}$ of elements of $P$ has a unique amalgamation.

Example 4.3. Let $N \in \text{Spaces}$ and $y(N) = \text{Spaces}(-, N) \in \text{Set}^{\text{Spaces}^{op}}$. Let $\phi_j : M_j \to M$ be an open cover, and let $\alpha_j : M_j \to N$ be a matching family. Then $\phi_j$ has a unique amalgamation $\phi : M \to N$. Therefore $y(N)$ is a sheaf for the open cover topology, and hence the open cover topology is subcanonical.

Proposition 4.4. In the open-dicover topology $J$ for local po-spaces every representable presheaf is a sheaf. That is $J$ is subcanonical.
Proof. Consider the representable presheaf

\[ y((N, \tilde{V})) = \text{LPS}(\cdot, (N, \tilde{V})) \in \text{Set}_{\text{LPS}^{op}}. \]

By Proposition \ref{prop:representable}, \( y((N, \tilde{V})) \) is a sheaf if and only if for all open dicovers \( \{\phi_j\} \in K((M, \bar{U})) \), any matching family

\[ \{\alpha_j : (M_j, \bar{U}_j) \to (N, \tilde{V})\} \]

has a unique amalgamation \( \alpha : (M, \bar{U}) \to (N, \tilde{V}) \). That is, there is a map \( \alpha \) such that the diagrams

\[ \begin{array}{ccc}
(M_j, \bar{U}_j) & \xrightarrow{\phi_j} & (M, \bar{U}) \\
\downarrow \alpha_j & & \downarrow \alpha \\
(N, \tilde{V}) & & 
\end{array} \]

commute in \( \text{LPS} \) for all \( j \).

Let \( \{\alpha_j\} \) be such a matching family for an open dicover \( \{\phi_j\} \). Since \( \{\phi_j\} \) is an open dicover, then by Remark 3.7 for each \( j \) there is a \( U^j = \{U^j_k\} \in \bar{U}_j \) such that \( U' = \{U^j_k\}_{j,k} \) is an order atlas and \( U' \in \bar{U} \).

By definition \( \{\phi_j : M_j \to M\} \) is a cover in \( \text{Spaces} \) and \( \{\alpha_j : M_j \to N\} \) is a matching family. Therefore there is a unique amalgamation \( \alpha : M \to N \in \text{Spaces} \).

That is, there is a map \( \alpha \) such that

\[ \begin{array}{ccc}
M_j & \xrightarrow{\phi_j} & M \\
\downarrow \alpha_j & & \downarrow \alpha \\
N & & 
\end{array} \]

commutes in \( \text{Spaces} \) for all \( j \). It remains to show that \( \alpha \) is a dimap. Let \( V = \{V_l\} \in \bar{V} \). Since \( \alpha_j : (M_j, \bar{U}_j) \to (N, \tilde{V}) \in \text{LPS} \), there is a \( \tilde{U}^j = \{\tilde{U}^j_k\} \in \tilde{U}_j \) such that for all \( k, l, \)

\[
\text{for all } x, y \in \tilde{U}^j_k \cap \alpha^{-1}_j(V_l), \quad x \leq_{\tilde{U}^j_k} y \implies \alpha_j(x) \leq_{V_l} \alpha_j(y). \]

Now for each \( j \), let \( \tilde{U}^j = \{\tilde{U}^j_k\} \in \bar{U}_j \) be a common refinement of \( \tilde{U}^j \) and \( U^j \). Then since \( \tilde{U}^j \) is a refinement of \( \bar{U}^j \),

\[
(1) \quad \text{for all } x, y \in \tilde{U}^j_k \cap \alpha^{-1}_j(V_l), \quad x \leq_{\tilde{U}^j_k} y \implies \alpha_j(x) \leq_{V_l} \alpha_j(y), \]

and since \( \tilde{U}^j \) is a refinement of \( U^j \), if we define \( U = \{U^j_k\}_{j,k} \), then \( U \in \bar{U} \).

Since \( \alpha \) is an amalgamation of \( \{\alpha_j\} \) in \( \text{Spaces} \) if \( x \in \tilde{U}^j_k \subset M \), then \( \alpha(x) = \alpha_j(x) \) and for all \( l, \tilde{U}^j_k \cap \alpha^{-1}_j(V_l) = \tilde{U}^j_k \cap \alpha^{-1}(V_l) \). Therefore using (1) for all \( k, l, \)

\[
\text{for all } x, y \in \tilde{U}^j_k \cap \alpha^{-1}(V_l), \quad x \leq_{\tilde{U}^j_k} y \implies \alpha(x) \leq_{V_l} \alpha(y). \]

That is \( \alpha \) is a dimap. Therefore \( \alpha : (M, \bar{U}) \to (N, \tilde{V}) \) is a unique amalgamation of \( \{\alpha_j\} \). \qed
5. Equivalence of sheaves and di-
étale bundles

In this section \( C \) is either \( \text{Spaces} \) or \( \text{LPS} \) with the Grothendieck topology generated by open (di)covers.

**Notation 5.1.** We will use \( A \subset B \) to denote that \( A \) is an open subset of \( B \).

**Notation 5.2.** Let \( Z \in C \) and let \( F \in \text{Set}^{\text{op}} \). Choose \( x \in U \subset Z \) and \( s \in F(U) \). Then for open subobjects of \( U \), \( L \hookrightarrow U \), we have \( F(i) : F(U) \to F(L) \) and we will use the notation \( s|_L := F(i)(s) \).

Recall that \( \text{stalk}_x(F) = \text{colim}_{x \in L \subset U} F(L) \) and germ\(_x(s) \) is the equivalence class represented by \( s \) in \( \text{stalk}_x(F) \).

**Definition 5.3.** Given \( Z \in C \), a bundle over \( Z \) is just a morphism \( p : W \to Z \in C \).

An (di)étale bundle is a bundle which is a local (di)homeomorphism. That is, given \( y \in W \) there is some open set \( V \subset W \) such that \( p(V) \) is open in \( Z \) and \( p|_V \) is an isomorphism in \( C \).

A morphism of (étale) bundles \( p : W \to Z \) and \( p' : W' \to Z \) is a morphism \( \theta : W \to W' \in C \) such that the following diagram commutes:

\[
\begin{array}{ccc}
W & \xrightarrow{\theta} & W' \\
\downarrow{p} & & \downarrow{p'} \\
Z & \xrightarrow{\theta^*} & Z
\end{array}
\]

Let \( \text{Etale}(Z) \) denote the category of (di)étale bundles over \( Z \). In addition let \( \mathcal{O}(Z) \) denote the category of open subobjects of \( Z \), where the objects are open subobjects of \( Z \) and the morphisms are the inclusions.

**Theorem 5.4** (Theorem [13]). Let \( Z \in C \). Then there is an equivalence of categories

\[
\Gamma : \text{Etale}(Z) \rightleftarrows \text{Shv}(\mathcal{O}(Z)) : \Lambda.
\]

**Proof.** It is well known that the statement of Theorem [13] is true when \( C = \text{Spaces} \) (see for example [MLM92, Corollary II.6.3]). We will show that this equivalence between étale bundles on topological spaces and sheaves on topological spaces extends to local po-spaces.

First we describe the functors \( \Gamma \) and \( \Lambda \) in the case where \( C = \text{Spaces} \). The functor \( \Gamma \) assigns to each bundle \( W \xrightarrow{p} Z \) the presheaf of cross-sections:

\[
P : (\mathcal{O}(Z))^{\text{op}} \to \text{Set}
\]

\[
U \quad \mapsto \quad \{ s : U \to W \in C \mid p \circ s = \text{Id}_U \}
\]

\[
U \xleftarrow{\theta^*} V \quad \mapsto \quad \theta^*(t) = t \circ \theta.
\]

One can check that if \( p \) is étale, then \( P \) is in fact a sheaf [MLM92, p.79]. Thus \( \Gamma \) restricts to a functor \( \Gamma : \text{Etale}(Z) \to \text{Shv}(\mathcal{O}(Z)) \).

Given a presheaf \( P : (\mathcal{O}(Z))^{\text{op}} \to \text{Set} \), let \( \Lambda(P) \) be the bundle \( W \xrightarrow{p} Z \) where

\[
W = \{ \text{germ}_x s \mid x \in U \subset Z, s \in P(U) \}
\]

and \( p : \text{germ}_x s \mapsto x \).
A basis for the topology on \( W \) is given by the sets \( \tilde{s}(U) \), where \( U \) is an open set in \( Z \), \( s \in P(U) \) and

\[
\tilde{s} : U \rightarrow \Lambda(P) \\
x \mapsto \text{germ}_x s.
\]

Using this topology, \( p : W \rightarrow Z \) is a continuous map. Again, one can check that if \( P \) is a sheaf, then \( W \xrightarrow{p} Z \) is in fact an \( \acute{e}tale \) bundle [MLM92, p.85]. So \( \Lambda \) restricts to a functor \( \Lambda : \text{Shv}(\mathcal{O}(Z)) \rightarrow \text{Etale}(Z) \).

Now we will show that \( \Gamma \) and \( \Lambda \) can be similarly defined in the case where \( \mathbb{C} = \text{LPS} \). Let \( p : (W, \bar{T}) \rightarrow (Z, \bar{U}) \) be an \( \acute{e}tale \) bundle of local po-spaces. The definition of \( \Gamma \) is exactly the same: \( \Gamma((W, \bar{T}) \xrightarrow{p} (Z, \bar{U})) \) is the sheaf of cross-sections.

Given a sheaf \( P \) on a local po-space \( (Z, \bar{U}) \), \( \Lambda(P) = (W \xrightarrow{p} Z) \) is an \( \acute{e}tale \) bundle of topological spaces. To extend \( \Lambda \) to local po-spaces it remains to define a local order on \( W \) and show that this makes \( p \) a dimap.

**Lemma 5.5.** \( W \) has a canonical local po-space structure such that \( p \) is a dimap.

**Proof.** Recall that the sets \( \tilde{s}(U) \) defined above form a basis for the topology of \( W \). Choose an order atlas \( \{(U_i, \leq_i)\} \in \bar{U} \) for \( Z \). For each open sub-po-space \( V \subset U_i \) and each \( s \in P(V) \), \( \tilde{s}(V) \subset W \) is a po-space under the relation

\[
\text{germ}_x s \leq \tilde{s}(V) \text{ germ}_y s \text{ if and only if } x \leq_i y.
\]

This is well-defined since \( \{U_i\} \) is an order-atlas, and it makes \( \tilde{s}(V) \) a po-space since \( \tilde{s} : U_i \rightarrow \tilde{s}(U_i) \) is a homeomorphism.

We claim that

\[
T := \{ \tilde{s}(V) \mid V \subset_{\text{open}} U_i, s \in P(V) \}
\]

is an order atlas on \( W \). First we need to show that it is an open cover. Each of the sets is open by construction. If \( U \in \mathcal{O}(Z) \) and \( s \in P(U) \), consider \( \text{germ}_x s \). Since \( \{U_i\} \) is an open cover of \( Z \), for some \( i, x \in U_i \). Let \( V = U \cap U_i \). Then \( \text{germ}_x s = \text{germ}_x s|_V \in (\tilde{s}|_V)(V) \). Therefore \( T \) is an open cover of \( W \).

Finally we need to show that the orders are compatible. For \( k = 1, 2 \) let \( V_k \subset_{\text{open}} U_{k_1} \), and \( s_k \in P(V_k) \). Assume \( g_1, g_2 \in \tilde{s}_1(V_1) \cap \tilde{s}(V_2) \). That is, \( g_1 = \text{germ}_x s_1 \) and \( g_2 = \text{germ}_x s_2 \). For \( k = 1, 2 \),

\[
g_1 \leq \tilde{s}(V_1) g_2 \iff x_1 \leq_{i_k} x_2.
\]

Since \( \{U_i\} \) is an order-atlas, the order \( \leq_{i_1} \), and \( \leq_{i_2} \) are compatible. Therefore the orders \( \leq_{\tilde{s}(V_1)} \) and \( \leq_{\tilde{s}(V_2)} \) are compatible, and \( T \) is an order-atlas on \( W \).

Let \( \bar{T} \) be the equivalence class of order atlases of \( T \). We claim that \( \bar{T} \) does not depend on the choice of \( U \in \bar{U} \).

Let \( U, U' \in \bar{U} \), then \( U \) and \( U' \) have a common refinement \( U'' \). Let \( T, T', T'' \) be the corresponding order-atlas for \( W \) constructed as above. We will show that \( T'' \) is a refinement of \( T \).

Let \( A \subset_{\text{open}} U_j \in U \), \( s \in P(A) \) and \( \text{germ}_x s \in \tilde{s}(A) \). Then there is some \( U''_k \in U'' \) such that \( x \in U''_k \) and \( U''_k \) is a sub-po-space of \( U_j \). Let \( A'' = A \cap U''_k \). It follows that \( \tilde{s}(A'') \subset \tilde{s}(A) \), and \( \text{germ}_x s = \text{germ}_x s|_{A''} \in (\tilde{s}|_{A''})(A'') \subset T'' \). Since \( U''_k \) is a sub-po-space of \( U_j \) it follows that \( (\tilde{s}|_{A''})(A'') \) is a sub-po-space of \( \tilde{s}(A) \). Thus \( T'' \) is a refinement of \( T \).

Similarly \( T'' \) is a refinement of \( T' \) and is hence a common refinement of \( T \) and \( T' \). Therefore \( \bar{T} \) does not depend on the choice of \( U \in \bar{U} \).
Finally we will show that the projection \( p : W \to Z \) given by germ\(_x\) \( s \mapsto x \) is a dimap. Let \( U \in \tilde{U} \) be an order-atlas on \( Z \). Let \( T \) be the order-atlas on \( W \) constructed above from \( U \). Observe that \( T \in \tilde{T} \), since \( \tilde{T} \) does not depend on the choice of \( U \in \tilde{U} \). Let \( U_j \in U \), let \( A_{\bar{\phi}} U_i \in U \), and let \( s \in P(A) \). Assume that

\[
g\text{erm}_x\; s, \text{germ}_x\; s \in \mathring{s}(A) \cap p^{-1}(U_j).
\]

Then \( x_1, x_2 \in U_i \cap U_j \). By the construction of \( T \) and since \( U \) is an order atlas,

\[
\text{germ}_x\; s \leq \mathring{s}(A) \text{ germ}_x\; s \iff x_1 \leq U_i, x_2 \iff x_1 \leq U_j, x_2.
\]

Therefore \( \Lambda \) can be extended to local po-spaces. \( \square \)

Thus we have maps

\[
\Gamma : \text{Etale}(Z) \cong \text{Shv}(O(Z)) : \Lambda.
\]

To show that they give an equivalence of categories we will show that for a sheaf \( P \) and an étale space \( W \xrightarrow{p} Z \) there are natural isomorphisms

\[
\epsilon_W : \Lambda \Gamma W \to W \quad \text{and} \quad \eta_P : P \to \Gamma \Lambda P.
\]

Recall that elements of \( \Lambda \Gamma W \) are of the form \( \mathring{s}(x) = \text{germ}_x\; s \), where \( s : U \to W \) satisfies \( p \circ s = \text{Id}_U \) and \( x \in U \). Define \( \epsilon_W \) to be the map \( \mathring{s}x \mapsto sx \). We will show this is an isomorphism by constructing an inverse \( \theta_W \). Let \( y \in W \) and let \( x = py \). Since \( W \) is étale there exists \( y \in V \in \phi_W W \) such that \( \phi_W : V \xrightarrow{\cong} p(V) \). Let \( q = (\phi_W)^{-1} \). Then define \( \theta_W(y) = \text{germ}_x\; q = \mathring{q}x \). Then we claim \( \theta_W \) is an inverse for \( \epsilon_W \). Indeed

\[
\epsilon_W \theta_W y = \epsilon_W \mathring{q}x = qx = y.
\]

Also for all \( \mathring{s}x \in \Lambda \Gamma W, \theta_W \epsilon_W \mathring{s}x = \theta_W sx = \text{germ}_x\; t \), where \( t \) is a restriction of \( s \). So \( \text{germ}_x\; t = \text{germ}_x\; s = \mathring{s}x \).

Finally we claim that \( \epsilon_W \) and \( \theta_W \) are dimaps. First choose \( T = \{ T_k \} \in \tilde{T} \) and \( U = \{ U_i \} \in \tilde{U} \) such that \( p \) satisfies the dimap condition. From \( T \) construct the canonical order atlas of the form \( \{ \bar{s}V \} \) for \( \Lambda \Gamma W \) as in the proof of Lemma 5.5. Now let \( \mathring{s}x_1, \mathring{s}x_2 \in \bar{s}V \cap \epsilon_{\Lambda \Gamma}^{-1}(T_k) \). Then by construction,

\[
\mathring{s}x_1 \leq \bar{s}V \mathring{s}x_2 \iff x_1 \leq U_i, x_2.
\]

Since \( s \) satisfies the dimap condition this implies \( sx_1 \leq T_k, sx_2 \) which is the same as \( \epsilon_W \mathring{s}x_1 \leq T_k, \epsilon_W \mathring{s}x_2 \). Thus \( \epsilon_W \) is a dimap. Next let \( y_1, y_2 \in T_k \cap \epsilon_{\Lambda \Gamma}^{-1}(\bar{s}V) = T_k \cap \epsilon_{W}(\bar{s}V) = T_k \cap sV \). Then there are \( x_1, x_2 \in V \) such that \( y_1 = sx_1 \) and \( y_2 = sx_2 \).

Since \( p \) satisfies the dimap condition

\[
y_1 \leq T_k, y_2 \implies py_1 \leq U_i, py_2.
\]

But this is the same as \( x_1 \leq U_i, x_2 \) which implies that \( \mathring{s}x_1 \leq \bar{s}V \mathring{s}x_2 \). Therefore \( \theta_W \) is a dimap.

The proof that the morphism \( \eta_P \) is a bijection is the same as the proof in the case of topological spaces [MLM92 Theorem II.5.1]. \( \square \)
6. Points

In this section $\mathcal{C}$ is either $\text{Spaces}$ or $\text{LPS}$ with the Grothendieck topology generated by open (di)covers.

Let $\text{Set}^{\text{C}^{\text{op}}}$ and $\text{Shv}(\mathcal{C})$ be the topoi of presheaves and sheaves on $\mathcal{C}$. Recall that the inclusion functor $i : \text{Shv}(\mathcal{C}) \to \text{Set}^{\text{C}^{\text{op}}}$ has a right adjoint $a$ called the associated sheaf functor. Recall from Definition 2.15 that if $p$ is a point in $\text{Shv}(\mathcal{C})$ and $\alpha \in \text{Set}^{\mathcal{C}^{\text{op}}}$, then $\text{stalk}_p(F) = p^* \circ a(\alpha)$.

Let $Z \in \mathcal{C}$. Then $Z$ is a topological space or a local po-space and we can choose any point (in the usual sense) $x \in Z$. Define

$$p_x^* : \text{Set}^{\mathcal{C}^{\text{op}}} \to \text{Set}$$

$$F \mapsto \colim_{x \in L \subseteq Z} F(L)$$

where the colimit is taken over all open subsets of $Z$ containing $x$. See Remark 3.5 for a discussion of subobjects in $\text{LPS}$.

Given a functor $p^* : \text{Set}^{\mathcal{C}^{\text{op}}} \to \text{Set}$ there is an induced functor

$$A : \mathcal{C} \to \text{Set}^{\mathcal{C}^{\text{op}}} \xrightarrow{\text{y}} \text{Set},$$

where $y$ is the Yoneda embedding defined on objects and morphisms by $Z \mapsto \mathcal{C}(-, Z)$ and $\varphi \mapsto \mathcal{C}(-, \varphi)$.

Given a functor $A : \mathcal{C} \to \text{Set}$ one can define induced adjoint functors $p^* : \text{Set}^{\mathcal{C}^{\text{op}}} \to \text{Set}$ and $p_* : \text{Set} \to \text{Set}^{\mathcal{C}^{\text{op}}}$ ($p^* = - \otimes_{\mathcal{C}} A$ and $p_* = \mathcal{C}(A, -)$, see [MLM92, Section VII.2]).

Definition 6.1. (i) The functor $A : \mathcal{C} \to \text{Set}$ is flat if the corresponding $p^*$ is left exact.

(ii) $A$ is continuous if $A$ sends each covering sieve to an epimorphic family of functions. That is, if $S$ is a covering sieve, then the family of functions $\{A(\varphi) | \varphi \in S\}$ is jointly surjective.

Proposition 6.2 ([MLM92, Corollary VII.5.4]). Using the correspondence above, $p$ is a point in $\text{Set}^{\mathcal{C}^{\text{op}}}$ if and only if $A$ is flat. Furthermore $p$ descends to a point in $\text{Shv}(\mathcal{C})$ if and only if $A$ is flat and continuous.

Proposition 6.3. $p_x$ defined above descends to a point in $\text{Shv}(\mathcal{C})$.

Proof. Let $A_x = p_x^* \circ y$, where $y$ is the Yoneda embedding.

First we show that $p_x^*$ is left exact, that is it preserves finite limits. Let $F \times G H$ be a pullback in $\text{Set}^{\mathcal{C}^{\text{op}}}$.

$$p_x^*(F \times_G H) = \colim_{x \in L \subseteq Z} (F \times_G H)(L)$$

$$= \colim_{x \in L \subseteq Z} F(L) \times_G H(L)$$

$$= \colim F(L) \times \colim_G H(L)$$

$$= p_x^* F \times_G p_x^* H$$
Lemma 7.1. Let $y$ be the definition of stalkwise equivalence in Definition 2.19 which uses the simplex $\mathcal{V}$. With this abuse of notation, the stalk of $\text{Shv}(\mathcal{V})$ is represented by

$$p^*_x \circ g(Y_i : Y_i \to N) = p^*_x(C(-, Y_i) \xrightarrow{(\varphi_i)_*} C(-, N)) = \colim_{x \in L \subseteq Z} (C(L, Y_i) \xrightarrow{(\varphi_i)_*} C(L, N)) = (y(Y_i))_x \xrightarrow{(\varphi_i)_*} y(N)_x.$$

We claim that this is an epimorphic family of functions in $\text{Set}$. Let $f \in y(N)_x$. Then there is an open subspace $L$ such that $x \in L \subseteq Z$ and $f$ is represented by a morphism $f' \in C(L, N)$. Since $\{Y_i\}$ covers $N$, $f'(x) \in Y_k$ for some $k$. Let $K = (f')^{-1}(Y_k)$. Then $K$ is open and $x \in K \subseteq L \subseteq Z$. Furthermore $f'|_K \in C(K, Y_k)$ which represents an element $f'' \in y(Y_k)_x$, and $(\varphi_k)_*f'' = f$. Hence we have an epimorphic family as claimed. Thus $A$ is continuous and $p_x$ descends to a point in $\text{Shv}(\mathcal{C})$.

Abusing notation we will also denote the induced functor in diagram (2) by $p^*_x$. With this abuse of notation, the stalk of $F \in \text{Set}^{\mathcal{C}^{op}}$ at $x$ is given by $\text{stalk}_x(F) = p^*_x a(F) = p^*_x (F)$. Note that $\text{stalk}_x(F) = \{\text{germ}_x(s) \mid x \in U \in \mathcal{C}^{op} Z, s \in F(U)\}$.

Theorem 6.4. The points $p_x$ defined above provide enough points for $\text{Shv}(\mathcal{C})$. That is, given $f \neq g : P \to Q \in \text{Shv}(\mathcal{C})$, there is an $Z \in \mathcal{C}$ and a $x \in Z$ such that $p^*_x f \neq p^*_x g : p^*_x P \to p^*_x Q \in \text{Set}$.

Proof. Given $Z \in \mathcal{C}$ and either $P \in \text{Shv}(\mathcal{C})$ or $f \in \text{Mor} \text{Shv}(\mathcal{C})$, let $P_Z$ or $f_Z$ denote the restriction to $\text{Shv}(\text{O}(Z))$.

Assume that $f \neq g : P \to Q \in \text{Shv}(\mathcal{C})$. Thus there is some $Z \in \mathcal{C}$ such that $f_Z \neq g_Z : P_Z \to Q_Z \in \text{Shv}(\text{O}(Z))$.

By Theorem 1.3, this is equivalent to saying that the corresponding maps between étale spaces are not equal. That is,

$$\Lambda f_Z \neq \Lambda g_Z : \Lambda P_Z \to \Lambda Q_Z \in \text{Etale}(Z).$$

Thus there is some point $y \in \Lambda P_Z$ such that $\Lambda f_Z(y) \neq \Lambda g_Z(y)$.

By the definition of $\Lambda$, $y = \text{germ}_x s$ for some $x \in U \in \mathcal{C}^{op} Z$ and $s \in P_Z(U)$. That is $y \in \text{stalk}_x(P) = p^*_x P$. Therefore $p^*_x f \neq g^*_x g : p^*_x P \to p^*_x Q$. □

7. Stalkwise equivalences

Let $(\mathcal{C}, \tau)$ be a site with a subcanonical Grothendieck topology such that $\text{Shv}(\mathcal{C})$ has enough points and let $\mathcal{V} : \mathcal{C} \to \text{sSet}^{\mathcal{C}^{op}}$ be the Yoneda embedding. Recall the definition of stalkwise equivalence in Definition 2.19 which uses the simplicial stalk functor $(\cdot)_P$. Also recall the Yoneda embedding $\mathcal{V} : \mathcal{C} \to \text{sSet}^{\mathcal{C}^{op}}$ given in Definition 2.19. Let $\varphi : X \to Y \in \mathcal{C}$.

Lemma 7.1. $\mathcal{V}(\varphi) \text{ is a stalkwise equivalence if and only if for all points } p \text{ in } \text{Shv}(\mathcal{C}), p^* \mathcal{V}(\varphi) \text{ is an isomorphism.}$
Proof. Let $p$ be a point in $\text{Shv}(\mathbb{C})$. Recall that the simplicial stalk of $\bar{y}(\varphi)$ at $p$ is given by

$$(\bar{y}(\varphi)_p = \{\text{stalk}_p(\bar{y}(\varphi)_n)\}_{n \geq 0} = \{p^* ay(\varphi)\}_{n \geq 0},$$

which is simplicially constant. Thus $\bar{y}(\varphi)_p \in \text{sSet}$ is an isomorphism if and only if $p^* ay(\varphi) \in \text{Set}$ is an isomorphism. □

Lemma 7.2. If the Grothendieck topology $\tau$ is subcanonical, then the composite functor $\mathbb{C} \xrightarrow{y} \text{Set}^{\text{op}} \xrightarrow{\phi} \text{Shv}(\mathbb{C})$ is faithful.

Proof. By the Yoneda lemma, $y$ is full and faithful. Since $\tau$ is subcanonical $\text{im}(y) \subset \text{Shv}(\mathbb{C})$. Furthermore $a \circ i : \text{Shv}(\mathbb{C}) \rightarrow \text{Shv}(\mathbb{C})$ is naturally isomorphic to the identity functor [MLM92, Corollary III.5.6]. Thus $ay$ is naturally isomorphic to $y$ which is faithful. □

Theorem 7.3. Let $\varphi : X \rightarrow Y \in \mathbb{C}$ and assume that $\bar{y}(\varphi)$ is a stalkwise equivalence. Then $\varphi$ is bijective.

The proof of this theorem is split into the following two propositions.

Proposition 7.4. Let $\varphi : X \rightarrow Y \in \mathbb{C}$ and assume that $\bar{y}(\varphi)$ is a stalkwise equivalence. Then $\varphi$ is epi.

Proof. For $i = 1, 2$, let $\psi_i : Y \rightarrow Z \in \mathbb{C}$ be a morphism such that $\psi_1 \circ \varphi = \psi_2 \circ \varphi : X \rightarrow Z$. Then for all points $p$ in $\text{Shv}(\mathbb{C})$, $p^* ay(\psi_1 \circ \varphi) = p^* ay(\psi_2 \circ \varphi)$. From this it follows that

$$\text{p}^* \text{ay}(\psi_1) \circ \text{p}^* \text{ay}(\varphi) = \text{p}^* \text{ay}(\psi_2) \circ \text{p}^* \text{ay}(\varphi).$$

But by Lemma 7.1 $p^* ay(\varphi)$ is a set isomorphism, so in particular it is epi. Therefore $p^* ay\psi_1 = p^* ay\psi_2$ for all points $p$ in $\text{Shv}(\mathbb{C})$. Since $\mathbb{C}$ has enough points, $ay\psi_1 = ay\psi_2$. By Lemma 7.2 $a \circ y$ is faithful, thus $\psi_1 = \psi_2$. Therefore $\varphi$ is epi. □

Proposition 7.5. Let $\varphi : X \rightarrow Y \in \mathbb{C}$ and assume that $\bar{y}(\varphi)$ is a stalkwise equivalence. Then $\varphi$ is mono.

Proof. For $i = 1, 2$, let $\psi_i : W \rightarrow X \in \mathbb{C}$ be a morphism such that $\varphi \circ \psi_1 = \varphi \circ \psi_2 : W \rightarrow Y$. As in the proof of the previous proposition, for all points $p$ in $\text{Shv}(\mathbb{C})$,

$$\text{p}^* \text{ay}(\varphi) \circ \text{p}^* \text{ay}(\psi_1) = \text{p}^* \text{ay}(\varphi) \circ \text{p}^* \text{ay}(\psi_2).$$

Again by Lemma 7.1 $p^* ay(\varphi)$ is mono. Therefore $p^* ay\psi_1 = p^* ay\psi_2$ for all points $p$ in $\text{Shv}(\mathbb{C})$. Since $\mathbb{C}$ has enough points, $ay\psi_1 = ay\psi_2$. By Lemma 7.2 $a \circ y$ is faithful, thus $\psi_1 = \psi_2$. Therefore $\varphi$ is mono. □

Let $\mathbb{C} = \text{Spaces}$ or $\text{LPS}$ with the open cover topology. By Example 13 and Proposition 14 this topology is subcanonical.

Recall from Section 6 that if $Z \in \mathbb{C}$ and $x \in Z$, then

$$p_x^* : \text{Set}^{\text{op}} \rightarrow \text{Set}$$

(3) $$F \mapsto \text{colim}_{x \in \text{L}_{\text{op}} \in Z} F(L)$$

descends to a point in $\text{Shv}(\mathbb{C})$ (where the colimit is taken over open subspaces of $Z$ which contain $x$).

Theorem 7.6. Let $\varphi : X \rightarrow Y \in \mathbb{C}$. Then $\bar{y}(\varphi)$ is a stalkwise equivalence if and only if $\varphi$ is an isomorphism in $\mathbb{C}$. 

Proof. (⇐) If \( \varphi \) is an isomorphism, then for all points \( p \) in \( \mathbf{Shv}(\mathbb{C}) \) \( \psi^* \Phi^*(\varphi) \) is an isomorphism. Hence by Lemma \ref{L1} \( \bar{y}(\varphi) \) is a stalkwise equivalence.

(⇒) Assume that \( \bar{y}(\varphi) \) is a stalkwise equivalence. Then by Theorem \ref{L5} \( \varphi \) is a bijection.

Let \( x \in Y \). Let \( p_x \) be the corresponding point defined in (3). Then
\[
\psi_x : S_x \to X \quad \text{such that} \quad \psi_x |_{S_x} = \varphi |_{S_x}.
\]
Since \( \psi \) is a bijection, all local inverses must agree. That is, \( \{ \psi_x : S_x \to X \} \) is a matching family on the open cover \( \{ S_x \} \) of \( Y \). Since the topology is subcanonical, there is a unique amalgamation \( \psi : Y \to X \). It remains to show that \( \psi \) is an inverse for \( \varphi \).

For all \( S_x \), \( \varphi \circ \psi |_{S_x} = \varphi \circ \psi_x = \text{Id}_{S_x}. \)

Therefore \( \varphi \) is an isomorphism in \( \mathbb{C} \).

\( \blacksquare \)

8. Model categories for local po-spaces

8.1. A model category for local po-spaces. Using our results on \( \mathbf{LPS} \), Theorem \ref{T6} will now follow directly from Jardine’s model structure (Theorem \ref{T220}).

Proof of Theorem \ref{T6}. The open dicovers induce a Grothendieck topology on the small category \( \mathbf{LPS} \). Applying Theorem \ref{T6} the Grothendieck topos \( \mathbf{Shv}(\mathbf{LPS}) \) has enough points. So by Jardine’s Theorem (Theorem \ref{T220}), \( \mathbf{sPre}(\mathbf{LPS}) \) has a proper, simplicial, cellular model structure in which

- the cofibrations are the monomorphisms, i.e. the levelwise monomorphisms of presheaves,
- the weak equivalences are the stalkwise equivalences, and
- the fibrations are the morphisms which have the right lifting property with respect to all trivial cofibrations.

Finally by Theorem \ref{T7} the weak equivalences coming from \( \mathbf{LPS} \) (via the Yoneda embedding) are precisely the isomorphisms.

\( \blacksquare \)

8.2. Localization. Our main motivation for constructing a model category for local po-spaces was to model concurrent systems. In particular we would like to be able to define and understand equivalences of concurrent systems using such a model category. However our model structure on \( \mathbf{sPre}(\mathbf{LPS}) \) does not have any non-trivial equivalences among the morphisms coming from \( \mathbf{LPS} \). To obtain a model category more directly useful for studying concurrency, we need to localize with respect to a set of morphisms. In particular we want morphisms which preserve certain computer-scientific information.
How to best choose such morphisms is an important question and has been studied in [Bub04]. For the sake of simplicity that paper studied only the category \textbf{PoSpaces} of po-spaces (a subcategory of \textbf{LPS}). There it was shown that the set of morphisms which should be equivalences depends on the context. That is, instead of choosing equivalences for \textbf{PoSpaces} one should be choosing equivalences for the coslice category or undercategory \(A \downarrow \text{PoSpaces}\) of po-spaces under a po-space \(A\), where \(A\) is called the context.

This result can be easily extended to our setting. First we remark that if we choose a local po-space \(A\) then the undercategory \(A \downarrow \text{LPS}\) is the category whose objects are dimaps \(\iota_M : A \to (M, U)\) and whose morphisms are dimaps \(f : (M, U) \to (N, V)\) such that the following diagram commutes:

\[
\begin{array}{c}
\downarrow \iota_M \\
(M, U) \xrightarrow{f} (N, V) \\
\downarrow \iota_N
\end{array}
\]

Next, \(\bar{y}(A) \in \text{sPre(LPS)}\) and the undercategory \(\bar{y}(A) \downarrow \text{sPre(LPS)}\) is the category whose objects are morphisms of simplicial presheaves \(\iota_\alpha : \bar{y}(A) \to \alpha\) and whose morphisms are morphisms of simplicial presheaves \(f : \alpha \to \beta\) such that the following diagram commutes:

\[
\begin{array}{c}
\downarrow \iota_\alpha \\
\bar{y}(A) \xrightarrow{f} \beta \\
\downarrow \iota_\beta
\end{array}
\]

Since \(\bar{y} : \text{LPS} \rightarrow \text{sPre(LPS)}\) is a functor

\[
\bar{y}(\iota_M) : \bar{y}(A) \to \bar{y}(M, U) \quad \text{and} \quad \bar{y}(\iota_N) = \bar{y}(f \circ \iota_M) = \bar{y}(f) \circ \bar{y}(\iota_M).
\]

Hence \(A \downarrow \text{LPS}\) embeds as a subcategory of \(\bar{y}(A) \downarrow \text{sPre(LPS)}\).

Define morphisms in \(\bar{y}(A) \downarrow \text{sPre(LPS)}\) to be weak equivalences, cofibrations and fibrations if and only if they are weak equivalence, cofibrations and fibrations in \(\text{sPre(LPS)}\). Then this makes \(\bar{y}(A) \downarrow \text{sPre(LPS)}\) into a model category (see [Hir03, Theorem 7.6.5]).

We will show that this model category is again proper and cellular. We will need the following definitions and a theorem of Kan.

\textbf{Definition 8.1.} \quad • Let \(\mathcal{C}\) be a category and \(I\) be a set of maps in \(\mathcal{C}\). A \textit{relative I-cell complex} is a map that can be constructed by a transfinite composition of pushouts of elements of \(I\).

• An object \(A \in \mathcal{C}\) is \textit{small relative to a collection of morphisms} \(\mathcal{D}\) in \(\mathcal{C}\) if there exists a cardinal \(\kappa\) such that for all regular cardinals \(\lambda \geq \kappa\) and for all \(\lambda\)-sequences

\[
X_0 \to X_1 \to X_2 \to \ldots \to X_\beta \to \ldots
\]

with \(X_\beta \to X_{\beta+1}\) in \(\mathcal{D}\) for \(\beta + 1 < \lambda\), the set map

\[
\colim_{\beta < \lambda} \mathcal{C}(A, X_\beta) \to \mathcal{C}(A, \colim_{\beta < \lambda} X_\beta)
\]

is an isomorphism.
Definition 8.2. A model category $\mathcal{M}$ is cofibrantly generated if there are sets $I$ and $J$ such that

- the domains of $I$ are small relative to the relative $I$-cell complexes,
- the domains of $J$ are small relative to the relative $J$-cell complexes,
- the fibrations have the right lifting property with respect to $J$, and
- the trivial fibrations have the right lifting property with respect to $I$.

We say that $\mathcal{M}$ is cofibrantly generated by $I$ and $J$.

Definition 8.3. Let $\mathcal{M}$ be a model category cofibrantly generated by $I$ and $J$. An object $A \in \mathcal{M}$ is compact if there is a cardinal $\gamma$ such that for all relative $I$-cell complexes $f : X \to Y$ with a particular presentation, every map $A \to Y$ factors through a subcomplex of size at most $\gamma$.

$f : A \to B$ is an effective monomorphism if $f$ is the equalizer of the inclusions $B \rightrightarrows B \amalg A B$.

Definition 8.4. A cellular model category is a model category cofibrantly generated by $I$ and $J$ such that

- the domains and codomains of elements of $I$ and $J$ are compact,
- the domains of elements of $J$ are small relative to relative $I$-cell complexes, and
- the cofibrations are effective monomorphisms.

Theorem 8.5 ([Hir03, Theorem 11.3.2]). Let $\mathcal{M}$ be a model category cofibrantly generated by the sets $I$ and $J$, and let $\mathcal{N}$ be a bicomplete category such that there exists a pair of adjoint functors $F : \mathcal{M} \rightleftarrows \mathcal{N} : U$. Define $FI = \{ Fu \mid u \in I \}$ and $FJ = \{ Fv \mid v \in J \}$. If

1. the domains of $FI$ and $FJ$ are small relative to $FI$-cell and $FJ$-cell, respectively, and
2. $U$ maps relative $FJ$-cell complexes to weak equivalences,

then $\mathcal{N}$ has a model category structure cofibrantly generated by $FI$ and $FJ$ such that $f$ is a weak equivalence in $\mathcal{N}$ if and only if $UF$ is a weak equivalence in $\mathcal{M}$, and $(F,U)$ is a Quillen pair.

Theorem 8.6. Let $\mathcal{M}$ be a model category and let $A \in \mathcal{M}$. Then $A \downarrow \mathcal{M}$ has a model structure where a morphism $A \to C$ is a weak equivalence, cofibration or fibration if and only if $f$ is a weak equivalence, cofibration or fibration, respectively, in $\mathcal{M}$. If $\mathcal{M}$ is proper, cofibrantly generated or cellular, then so is $A \downarrow \mathcal{M}$.

Remark 8.7. For a more detailed proof we invite the reader to regard Hirschhorn’s note [Hir03].

Proof. That $A \downarrow \mathcal{M}$ has the stated model structure follows from the definitions (see [Hir03, Theorem 7.6.5]).

Pushouts and pullbacks in $A \downarrow \mathcal{M}$ can be formed by taking pushouts and pullbacks of the underlying morphisms in $\mathcal{M}$, and then taking the induced maps from $A$. It thus follows that if $\mathcal{M}$ is proper so is $A \downarrow \mathcal{M}$.

Assume $\mathcal{M}$ is cofibrantly generated by $I$ and $J$. The method for showing that $A \downarrow \mathcal{M}$ is cofibrantly generated will be to apply Theorem 8.5 to the following adjoint
functors:

\[ F : \mathcal{M} \xrightarrow{\cong} (A \downarrow \mathcal{M}) : U \]

where for \( B \in \mathcal{M} \) and \( f : B \to C \in \mathcal{M} \),

\[ F(B) = \begin{array}{ccc}
  A & \xrightarrow{\iota_B} & A \uplus B \\
  i_1 & & \downarrow \text{Id}_{i_1} \\
  \end{array}, \quad F(f) = \begin{array}{ccc}
  A & \xrightarrow{i_1} & A \uplus B \\
  & & \downarrow \text{Id}_f \\
  \end{array} \quad \begin{array}{ccc}
  A \uplus B & \xrightarrow{i_1} & A \uplus C \\
  & & \downarrow \text{Id}_{i_1} \\
  \end{array} \]

and \( U \) is the forgetful functor

\[ U \left( \begin{array}{ccc}
  A & \xrightarrow{i_B} & B \\
  \end{array} \right) = B, \quad U \left( \begin{array}{ccc}
  A & \xrightarrow{i_B} & B \\
  C & \xrightarrow{\delta} & C \\
  \end{array} \right) = B \xrightarrow{\delta} C. \]

Define \( FI = \{ Fu \mid u \in I \} \) and \( FJ = \{ Fv \mid v \in J \} \).

The main observation for the proof is that for a morphism \( u \in \mathcal{M} \), the pushout of \( Fu \) is obtained from the pushout of \( u \) in \( \mathcal{M} \). That is,

\[
\begin{array}{ccc}
  A & \xrightarrow{\alpha} & B \\
  \downarrow \text{Id}_A & & \downarrow \text{Id}_B \\
  A \uplus B & \xrightarrow{i_1} & A \uplus C \\
  \downarrow \text{id} & & \downarrow \text{Id}_C \\
  X & \xrightarrow{\delta} & P \\
\end{array}
\]

where \( P \) is defined by \( B \xrightarrow{\delta} C \).

From this it follows that for a set of morphisms \( S \) in \( \mathcal{M} \), the underlying morphisms of a relative \( FS \)-complex are a relative \( S \)-complex.

Hence the conditions on \( A \downarrow \mathcal{M} \) in Theorem 8.5 and the definition of a cellular model category (Definition 8.4) are all inherited from the corresponding conditions in \( \mathcal{M} \).

Finally one can check that the model category structure given by Theorem 8.5 coincides with the one in the statement of the theorem. \( \square \)

Let \( \mathcal{M} \) denote the model structure above on \( \widetilde{\mathcal{Y}}(A) \downarrow \text{sPre}(LPS) \). Since \( \mathcal{M} \) is cellular we can apply left Bousfield localization \([\text{Hir03}]\) to this model structure \( \mathcal{M} \) with respect to a set of morphisms which will preserve the computer-scientific properties we are interested in. In \([\text{Bub04}]\), one inverted the set of dihomotopy equivalences in \( A \downarrow \text{PoSpaces} \). So in our setting we will let \( I \) be the set of dihomotopy equivalences in \( A \downarrow \text{LPS} \) defined below. We will invert the set \( \mathcal{I} = \{ \bar{y}(f) \mid f \in I \} \subset \widetilde{\mathcal{Y}}(A) \downarrow \text{sPre}(LPS) \).

**Definition 8.8.**

- Let \( \bar{I} \) be the po-space \(([0,1], \leq) \) where \( \leq \) is the usual total order on \([0,1] \). Given dimaps \( f, g : (M, \bar{U}) \to (N, \bar{V}) \in A \downarrow \text{LPS} \), \( \phi \) is a dihomotopy from \( f \) to \( g \) if \( \phi : (M, \bar{U}) \times \bar{I} \to (N, \bar{V}) \), \( \phi|_{(M, \bar{U}) \times \{0\}} = f, \phi|_{(M, \bar{U}) \times \{1\}} = g \), and for all \( a \in A \), \( \phi(\iota_M(a), t) = \iota_N(a) \). In this case write \( \phi : f \to g \).

- The symmetric, transitive closure of dihomotopy is an equivalence relation. Write \( f \simeq g \) if there is a chain of dihomotopies \( f \to f_1 \leftarrow f_2 \to \ldots \leftarrow f_n \to g \).

- A dimap \( f : (M, \bar{U}) \to (N, \bar{V}) \) is a dihomotopy equivalence if there is a dimap \( g : (N, \bar{V}) \to (M, \bar{U}) \) such that \( g \circ f \simeq \text{Id}_M \) and \( f \circ g \simeq \text{Id}_N \).
The left Bousfield localization of $\mathcal{M}$ with respect to $\mathcal{I}$ provides a model structure on $\mathcal{Y}(\mathcal{A}) \downarrow \text{sPre(LPS)}$ in which the weak equivalences are the $\mathcal{I}$-local equivalences (see [Hir03]), the cofibrations are the cofibrations in $\mathcal{M}$ and the fibrations are morphisms which have the right lifting property with respect to morphisms which are both cofibrations and $\mathcal{I}$-local equivalences.

**Theorem 8.9** (Theorem 1.2). Let $\mathcal{I} = \{ \mathcal{Y}(f) \mid f$ is a directed homotopy equivalence rel $\mathcal{A} \}$. The category $\mathcal{Y}(\mathcal{A}) \downarrow \text{sPre(LPS)}$ has a left proper, cellular model structure in which

- the cofibrations are the monomorphisms,
- the weak equivalences are the $\mathcal{I}$-local equivalences, and
- the fibrations are those morphisms which have the right lifting property with respect to monomorphisms which are $\mathcal{I}$-local equivalences.

We claim that this model category provides a good model for studying concurrency. An analysis of this model category will be the subject of future research.

**Appendix A. Hypercovers**

Suppose now $\mathcal{C}$ is small and equipped with a Grothendieck topology, i.e. we have a site $(\mathcal{C}, \tau)$. The Čech structure $\text{sSet}_{(\tau)}^\text{op}$ is obtained from the projective structure by homotopically localizing the comparison morphisms given by the Čech covers with respect to $\tau$ or, up-to homotopy, from the injective structure by localizing at the same set of morphisms.

**Definition A.1.** Let $U = \left\{ U_i \overset{u_i}{\to} X \right\}_{i \in I}$ be a cover. Let $i_p \in I$ for each $0 \leq p \leq n$ and $U_{i_0...i_n}$ be the wide pullback of the $u_{i_p}$’s, i.e. the limiting object of the diagram

\[
\begin{array}{ccc}
U_{i_0} & \rightarrow & \cdots & \rightarrow & U_{i_p} & \rightarrow & \cdots & \rightarrow & U_{i_n} \\
\downarrow_{u_{i_0}} & & & & \downarrow_{u_{i_p}} & & & & \downarrow_{u_{i_n}} \\
X & \rightarrow & \cdots & \rightarrow & \cdots & \rightarrow & \cdots & \rightarrow & X
\end{array}
\]

The Čech nerve $\check{U}$ of $U$ is the simplicial presheaf given by

\[
\check{U}_n \overset{\text{def}}{=} \prod_{i_0,...,i_n \in I} y(U_{i_0...i_n})
\]

**Remark A.2.** For any $n \in \mathbb{N}$, $X \in \mathcal{C}$ and $U \in J(X)$ there is a morphism $u_{i_0...i_n} : U_{i_0...i_n} \to X$ and a diagram of presheaves

\[
\begin{array}{ccc}
\check{U}_n & \overset{E_{U,X,n}}{\rightarrow} & y(X) \\
\downarrow_{y(U_{i_0,...,i_n})} & & \downarrow_{y(u_{i_0,...,i_n})} \\
y(U_{i_0,...,i_n}) & \rightarrow & y(X)
\end{array}
\]

where $E_{U,X,n}$ is given by universal property. The $E_{U,X,n}$ assemble to a morphism of simplicial presheaves $E_{U,X} : \check{U} \to \kappa y(X)$.
Remark A.3. Given $U \in J(X)$ seen as a subcategory of the slice $C/X$, there is the evident functor

$$\delta_U : U \to \text{sSet}^{C_{\text{op}}}$$

where $\delta_U : U_i \mapsto \kappa_{y(U_i)}$.

**Proposition A.4.**

Localizing $\text{sSet}^{C_{\text{op}}}_{\text{proj}}$ at the sets

(i) $\{E_{U,X} \mid X \in C, U \in J(X)\}$;
(ii) $\{\text{hocolim} (\delta_U) \to \kappa_{y(X)} \mid X \in C, U \in J(X)\}$;
(iii) $\{\kappa(U) \mid X \in C, U \in J(X)\}$ where, given $X \in C$ and $R$ a sieve on $X$, $i_R : R \to y(X)$ is the corresponding inclusion of presheaves;
(iv) $\{\eta_F : F \to j(F) \mid F \in \text{sSet}^{C_{\text{op}}}_{\text{proj}}\}$ where $j : \text{sSet}^{C_{\text{op}}} \to \text{sSet}^{C_{\text{op}}}$ is the objectwise sheafification functor;

yields the same model structure $\text{sSet}^{C_{\text{op}}}_{\text{proj}}$. The same holds for the projective version.

Finally, there is a model structure $\text{sSet}^{C_{\text{op}}}_{\text{hyp}}$ obtained from the projective structure by homotopically localizing at the set of the comparison morphisms given by hypercovers with respect to $\tau$. This model structure is Quillen equivalent to Jar- dine’s model structure (Theorem 2.20) on $\text{sSet}^{C_{\text{op}}}_{\text{proj}}$. As with the Čech structure, there is also an injective version. Since Čech covers are particular hypercovers, there is the series of inclusions

$$W_{\text{proj}} \subseteq W_{(\tau)} \subseteq W_{\text{hyp}}$$

and a similar series for the injective version. It is in general the case that $W_{(\tau)} \subseteq W_{\text{hyp}}$, yet equality holds in some important particular cases like the smooth Nisnevitch site (c.f. [DH04, Example A10]). It is an interesting question whether or not $W_{(\tau)} = W_{\text{hyp}}$ for local po-spaces.

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