GROUPOIDS IN CATEGORIES WITH PRETOPOLOGY

RALF MEYER AND CHENCHANG ZHU

ABSTRACT. We survey the general theory of groupoids, groupoid actions, groupoid principal bundles, and various kinds of morphisms between groupoids in the framework of categories with pretopology. We study extra assumptions on pretopologies that are needed for this theory. We check these extra assumptions in several categories with pretopologies.

Functors between groupoids may be localised at equivalences in two ways. One uses spans of functors, the other bibundles (commuting actions) of groupoids. We show that both approaches give equivalent bicategories. Another type of groupoid morphisms, called actors, are closely related to functors between the categories of groupoid actions. We also generalise actors using bibundles, and show that this gives another bicategory of groupoids.

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1. Introduction

The notion of groupoid has many variants: topological groupoids, étale topological groupoids, Lie groupoids of finite and infinite dimension, algebraic groupoids, and so on. A subtle point is that the definition of a groupoid in a category depends on a notion of “cover” because the range and source maps are assumed to be covers. A pretopology gives a reasonable notion of cover in a category.

The need to assume range and source maps to be covers is plain for Lie groupoids: it ensures that the composable pairs of arrows form a smooth manifold. The covers also influence the notion of principal bundle because their bundle projections are assumed to be covers; this is equivalent to “local triviality” in the sense of the pretopology. If our category is that of topological spaces and the covers are the continuous surjections with local continuous sections, then we get exactly the usual notion of local triviality for principal bundles; this is why many geometers prefer this pretopology on topological spaces. Many operator algebraists prefer the pretopology of open continuous surjections instead.

Some authors (like Goehle [13]) make no assumptions on the range and source maps. Since any map with a continuous section is a biquotient map, this amounts to the same as choosing biquotient maps as covers; this is the largest subcanonical pretopology on the category of Hausdorff topological spaces (see Section 9.2.2). But how much of the usual theory remains true in this case?

We will see that some aspects of the theory of groupoid Morita equivalence require extra assumptions on pretopologies. In particular, we will show that for the pretopology of biquotient maps, equivalent groupoids may have non-equivalent categories of actions on spaces. We do not know whether Morita equivalence of groupoids is an equivalence relation when we choose the pretopology of biquotient maps. In addition to the theory of Morita equivalence with bibundles, we also develop a theory of “vague functors” that works without extra assumptions on the pretopology, but is less concrete.

Since we want to work in the abstract setting of groupoids in a category with pretopology, we develop all the general theory of groupoids and their actions from scratch. Most of our results are known for some types of groupoids, of course. Since we develop the theory from scratch, we also take the opportunity to suggest more systematic notation for various kinds of morphisms of groupoids. We study functors, vague functors, and bibundle functors, actors and bibundle actors; in addition, there are several kinds of equivalences: equivalence functors, vague isomorphisms,
vague equivalences, and bibundle equivalences; and there are the covering bibundle functors, which are the intersection of bibundle functors and bibundle actors. The categories of vague functors and bibundle functors are equivalent, and vague isomorphisms and bibundle equivalences are also equivalent notions; all the other types of morphisms are genuinely different and are useful in different situations.

Roughly speaking, functors and the related vague functors and bibundle functors are appropriate if we view groupoids as generalised spaces, whereas actors and bibundle actors are appropriate if we view them as generalised symmetries (groups).

Other new names we introduce are basic actions and basic groupoids. A groupoid action is basic if, together with some bundle projection, it is a principal action. A groupoid $G$ is basic if its action on $G^0$ is a basic action. (The name “principal groupoid” is already used for something else, so a new name is needed.)

Our initial goal was to generalise the bicategory of topological groupoids with Hilsum–Skandalis morphisms as arrows and isomorphisms of the latter as 2-arrows. It is well-known that this is a bicategory if, say, we use continuous maps with local continuous sections as covers (see [34]). Our bibundle functors are the analogue of Hilsum–Skandalis morphisms in a category with pretopology. To compose bibundle functors or bibundle actors, we need extra assumptions on the pretopology. We introduce these extra assumptions here and check them for some pretopologies.

We now explain the contents of the sections of the article.

Section 2 introduces pretopologies on categories with coproducts. Here a pretopology is a family of maps called covers, subject to some rather mild axioms. The more established notion of a topos is not useful for our purposes: it does not cover important examples like the category of smooth manifolds because all finite limits are required to exist in a topos.

All pretopologies are required subcanonical. We also introduce three extra assumptions that are only sometimes required. Assumption 2.8 concerns final objects and is needed to define groups and products of groupoids, as opposed to fibre products. Assumption 2.6 requires maps that are “locally covers” to be covers; the stronger Assumption 2.7 requires that if $f \circ p$ and $p$ are covers, then so must be $f$. We also prove that the property of being an isomorphism is local (this is also noticed by [42, Axiom 4]). Assumptions 2.6 and 2.7 are needed to compose bibundle functors and bibundle actors, respectively.

Section 3 introduces groupoids, functors and vague functors. We first define groupoids in a category with pretopology in two equivalent ways and compare these two definitions. One definition has the unit and inversion maps as data; the other one only has the multiplication, range and source maps as data and characterises groupoids by making sense of the elementwise condition that there should be unique solutions to equations of the form $g \cdot x = h$ or $x \cdot g = h$ for given arrows $g$ and $h$ with equal range or equal source, respectively. We explain in Section 3 how such elementwise formulas should be interpreted in a general category, following ideas from synthetic geometry [23,31]. We use elementwise formulas throughout because they clarify statements and proofs.

We define functors between groupoids and natural transformations between such functors in a category with pretopology. We observe that they form a strict 2-category. We define a “base-change” for groupoids: given a cover $p: X \to G^0$, we define a groupoid $p^*(G)$ with object space $X$ and a functor $p_*: p^*(G) \to G$; such functors are called hypercovers, and they are the prototypes of equivalences. A vague functor $G \to H$ is a triple $(X,p,F)$ with a functor $F: p^*(G) \to H$. A vague isomorphism is an isomorphism $p^*(G) \cong q^*(H)$ for two covers $p: X \to G^0$ and $q: X' \to H^0$. Vague functors form a bicategory. We characterise equivalences in this bicategory by two different but equivalent criteria: as those vague functors
that lift to a vague isomorphism, and functors that are almost fully faithful and
almost essentially surjective. These constructions all work in any category with a
subcanonical pretopology. If we assume that being a cover is a local condition, then
a functor is almost fully faithful and almost essentially surjective if and only if it is
fully faithful and essentially surjective.

Section 4 introduces groupoid actions, their transformation groupoids, and ac-
tors. Our convention is that the anchor map of a groupoid action need not be a
cover; this is needed to associate bibundle functors to functors. We call an action
a sheaf if its anchor map is a cover. The transformation groupoid of a groupoid
action combines the action and the groupoid that is acting. An actor from $G$ to $H$
is a left action of $G$ on $H^1$ that commutes with the right translation action of $H$.
We show that such an actor allows to turn an $H$-action on $X$ into a $G$-action on $X$
in a natural way. Any such functor from $G$-actions to $H$-actions with some mild
extra conditions comes from an actor. This is the type of “morphism” that seems
most relevant when we think of a groupoid as a general form of symmetry, that is,
as something that acts on other objects.

Section 5 introduces principal bundles over groupoids and basic groupoid actions.
A principal $G$-bundle is a (right) $G$-action $m: X \times_{s,G^0,r} G^1 \to X$ with a cover $p: X \to Z$,
such that the map

\[(m, pr_1): X \times_{s,G^0,r} G^1 \to X \times_{r,p,p} X, \quad (x, g) \mapsto (x \cdot g, x),\]

is an isomorphism. Then $Z$ is the orbit space of the right $G$-action, so the bundle
projection is unique if it exists. A $G$-action is basic if it is a principal bundle when
taken together with its orbit space projection. We construct pull-backs of bundles
and relate maps on the base and total spaces of principal bundles; this is crucial for
the composition of bibundle functors. We show that the property of being principal
is local, that is, a pull-back of a “bundle” along a cover is principal if and only if
the original bundle is.

Principal bundles and basic actions allow us to define bibundle equivalences,
bibundle functors, and bibundle actors. These are all given by commuting actions
of $G$ and $H$ on some object $X$ of the category. For a bibundle functor, we require that
the right $H$-action together with the left anchor map $X \to G^0$ as bundle projection
is a principal bundle; for a bibundle equivalence, we require, in addition, that the
left $G$-action together with the right anchor map $X \to H^0$ is a principal bundle. For
a bibundle actor, we require the right action to be basic – with arbitrary orbit space
– and the right anchor map $X \to H^0$ to be a cover. If $X$ is both a bibundle actor and
a bibundle functor, so that both anchor maps are covers, then we call it a covering
bibundle functor.

We show that functors give rise to bibundle functors and that bibundle functors
give rise to vague functors. The bibundle functor associated to a functor is a
bibundle equivalence if and only if the functor is essentially surjective and fully
faithful.

The composition of bibundle functors, actors, and equivalences is only introduced
in Section 7 because it requires extra assumptions about certain actions being au-
tomatically basic. Section 7.1 discusses these extra assumptions. The stronger one,
Assumption 7.1, requires all actions of covering groupoids to be basic; the weaker one,
Assumption 7.2, only requires this for sheaves over covering groupoids, that is,
for actions of covering groupoids with a cover as anchor map. The weaker version of
the assumption together with Assumption 2.6 on covers being local suffices to com-
pose bibundle equivalences and bibundle functors; the stronger form together with
Assumption 2.7 (the two-out-of-three property for covers) is needed to compose cov-
ering bibundle functors and bibundle actors. Under the appropriate assumptions,
all these types of bibundles form bicategories.
We show in Section 7.8 that the equivalences in these bicategories are precisely the bibundle equivalences. Section 7.3 shows that the bicategory of bibundle functors is equivalent to the bicategory of vague functors. Section 7.4 describes the composite of two bibundle functors by an isomorphism similar to (1.1). Section 7.7 shows that the assumption needed for the composition of bibundle actors is equivalent to the assumption that the property of being basic is a local property of $G$-actions.

We show in Section 7.4 that every bibundle actor is a composite of an actor and a bibundle equivalence. Thus the bicategory of bibundle actors is the smallest one that contains bibundle equivalences and actors and is closed under the composition of bibundles. A similar decomposition of bibundle functors into bibundle equivalences and functors is constructed in Section 6.2 when passing from bibundle functors to vague functors.

Section 8 describes the quasi-categories of bibundle functors, covering bibundle functors, and bibundle equivalences very succinctly. The main point are similarities between the multiplication in a groupoid, a groupoid action, and the map relating the product of two bibundle functors to the composite.

Section 9 considers several examples of categories with classes of “covers” and checks whether these are pretopologies and satisfy our extra assumptions. Section 9.1 considers sets and surjective maps, a rather trivial case. Section 9.2 considers several classes of “covers” between topological spaces; quotient maps do not form a pretopology; biquotient maps form a subcanonical pretopology for which Assumption 7.1 fails; open surjections and several smaller classes of maps are shown to be subcanonical pretopologies satisfying all our assumptions.

Section 9.3 considers smooth manifolds, both of finite and infinite dimension, with submersions as covers. These form a subcanonical pretopology on locally convex manifolds and several subcategories, which satisfies the assumptions needed for the composition of bibundle functors and bibundle equivalences. For Banach manifolds, we also prove the stronger assumptions that are needed for the composition of bibundle actors and covering bibundle functors. It is unclear whether these stronger assumptions still hold for Fréchet or locally convex manifolds. Thus all the theory developed in this article applies to groupoids in the category of Banach manifolds and finite-dimensional manifolds, and most of it, but not all, applies also to Fréchet and locally convex manifolds.

For a category $C$, we write $X \in C$ for objects and $f \in C$ for morphisms of $C$.

2. Pretopologies

The notion of a Grothendieck (pre)topology from [14] formalises properties that “covers” in a category should have. Usually, a “cover” of an object $X$ is a family of maps $f_\alpha: U_\alpha \to X$, $\alpha \in A$. If our category has coproducts, we may replace such a family of maps by a single map

$$(f_\alpha)_{\alpha \in A}: \bigsqcup_{\alpha \in A} U_\alpha \to X.$$ 

This reduces notational overhead, and is ideal for our purposes because in the following definitions, we never meet covering families but only single maps that are covers.

**Definition 2.1.** Let $C$ be a category with coproducts. A pretopology on $C$ is a collection $\mathcal{T}$ of arrows, called covers, with the following properties:

1. isomorphisms are covers;
2. the composite of two covers is a cover;
(3) if \( f: Y \to X \) is an arrow in \( C \) and \( g: U \to X \) is a cover, then the fibre product \( Y \times_X U \) exists in \( C \) and the coordinate projection \( \text{pr}_1: Y \times_X U \to Y \) is a cover. Symbolically,

\[
\begin{array}{c}
Y \\
\downarrow f \\
U \\
\downarrow g \\
\end{array} \quad \Rightarrow \quad \begin{array}{c}
Y \times_{f,X,g} U \\
\downarrow \text{pr}_1 \\
Y \\
\downarrow f \\
U \\
\downarrow g \\
\end{array}
\]

We use double-headed arrows to denote covers.

We always require pretopologies to be subcanonical:

**Definition and Lemma 2.2.** A pretopology \( T \) is subcanonical if it satisfies the following equivalent conditions:

1. each cover \( f: U \to X \) in \( T \) is a coequaliser, that is, it is the coequaliser of some pair of parallel maps \( g_1, g_2: Z \rightrightarrows U \);
2. each cover \( f: U \to X \) in \( T \) is the coequaliser of \( \text{pr}_1, \text{pr}_2: U \times_{f,X,f} U \rightrightarrows U \);
3. for any object \( W \) and any cover \( f: U \to X \), we have a bijection

\[
\mathcal{C}(X,W) \rightrightarrows \{ h \in \mathcal{C}(U,W) \mid h \circ \text{pr}_1 = h \circ \text{pr}_2 \text{ in } \mathcal{C}(U \times_{f,X,f} U,W) \}, \quad g \mapsto g \circ f;
\]

4. all the representable functors \( \mathcal{C}(\_ , W) \) on \( C \) are sheaves.

**Proof.** Condition (3) makes explicit what it means for \( \mathcal{C}(\_ , W) \) to be a sheaf and for \( f \) to be the coequaliser of \( \text{pr}_1, \text{pr}_2 \), so (2) \iff (3) \iff (4). (2) implies (1) by taking \( Z = U \times_{f,X,f} U \) and \( g_i = \text{pr}_i \) for \( i = 1, 2 \). It remains to prove (1) \Rightarrow (3).

Let \( g_1, g_2: Z \rightrightarrows U \) be as in (1). Then \( fg_1 = fg_2 \), so that \( (g_1, g_2) \) is a map \( Z \to U \times_{f,X,f} U \). Let \( \text{pr}_i: U \times_{f,X,f} U \to U \) for \( i = 1, 2 \) be the coordinate projections. Since \( \text{pr}_i \circ (g_1, g_2) = g_i \) for \( i = 1, 2 \), a map \( h \in \mathcal{C}(U,W) \) with \( h \circ \text{pr}_1 = h \circ \text{pr}_2 \) also satisfies \( h \circ g_1 = h \circ g_2 \). Since we assume \( f \) to be a coequaliser of \( g_1 \) and \( g_2 \), such a map \( h \) is of the form \( \tilde{h} \circ f \) for a unique \( \tilde{h} \in \mathcal{C}(X,W) \). Conversely, any map of the form \( \tilde{h} \circ f \) satisfies \( (\tilde{h} \circ f) \circ \text{pr}_1 = (\tilde{h} \circ f) \circ \text{pr}_2 \). Thus (1) implies (3). \( \square \)

**Definition 2.3.** Let \( T \) be a pretopology on \( C \) and let \( P \) be a property that arrows in \( C \) may or may not have. An arrow \( f: Y \to X \) has \( P \) locally if there is a cover \( g: U \to Y \) such that \( \text{pr}_2: Y \times_{f,X,g} U \to U \) has \( P \).

The property \( P \) is local if an arrow has \( P \) if and only if it has \( P \) locally, that is, in the situation of (2.1), \( f: Y \to X \) has \( P \) if and only if \( \text{pr}_2: Y \times_{f,X,g} U \to U \) has \( P \).

**2.1. Isomorphisms are local.**

**Proposition 2.4.** If the pretopology is subcanonical, then the property of being an isomorphism is local.

**Proof.** It is clear that \( \text{pr}_2: Y \times_{f,X,g} U \to U \) is an isomorphism if \( f: Y \to X \) is one. Conversely, let \( g \) be a cover and \( \text{pr}_2 \) an isomorphism. We are going to show that for any \( \hat{y} \in \mathcal{C} \) and any map \( x: ? \to \hat{X} \) there is a unique \( y: ? \to Y \) with \( f \circ y = x \). This implies that \( f: Y \to X \) is an isomorphism by the Yoneda Lemma. The following
diagram shows the auxiliary objects and maps needed in the proof:

\[
\begin{array}{ccc}
\text{??} \times_{q_2,\tau_2} \text{??} & \xrightarrow{\tilde{y}} & \text{Y} \\
\downarrow q_1 & & \downarrow \tilde{y} & \Rightarrow & \downarrow y \\
\text{??} & \xrightarrow{q_2} & U & \xrightarrow{Q} & \text{X} \\
\downarrow x & & \downarrow g & \Rightarrow & \downarrow f \\
x & \xrightarrow{f} & \text{X} & \rightarrow & \text{Y}
\end{array}
\]

Let ?? := U ×_{g,X} x and let q_1: ?? → U and q_2: ?? → ? denote the coordinate projections; since g is a cover, so is q_2 and ?? exists. Since pr_2: Y ×_{f,X,\sigma} U → U is an isomorphism, the map q_1: ?? → U has a unique lifting (pr_2)^{-1} q_1: ?? → Y ×_{f,X,\sigma} U; this means that there is a unique map \( \tilde{y}: ?? → Y \) with \( f \circ \tilde{y} = g \circ q_1 = x \circ q_2 \).

We claim that \( \tilde{y} \) factors as \( \tilde{y} = y \circ q_2 \) for a unique map \( y: ?? → Y \). Since q_2 is a cover and the pretopology is subcanonical (Definition and Lemma 2.2), such a factorisation exists if and only if \( \tilde{y} \circ Q_1 = \tilde{y} \circ Q_2 \) for the two coordinate projections \( Q_1, Q_2: ?? ×_{q_2,\tau_2} ?? → ?? \). As above, we show that there is a unique map \( \tilde{y}: ?? ×_{q_2,\tau_2} ?? → Y \) with \( f \circ \tilde{y} = x \circ q_2 \circ Q_1 = x \circ q_2 \circ Q_2 \). Since \( f \circ \tilde{y} \circ Q_1 = x \circ q_2 \circ Q_1 \), for \( i = 1, 2 \) and \( \tilde{y} \) is uniquely determined by this, we get \( \tilde{y} = y \circ Q_1 \) and \( \tilde{y} = y \circ Q_2 \).

Thus \( y \circ Q_1 = y \circ Q_2 \), so that \( \tilde{y} \) factors uniquely through a map \( y: ?? → Y \) by subcanonicity.

Since q_2 is a coequaliser, \( f \circ y \circ q_2 = x \circ q_2 \) implies \( f \circ y = x \). If \( y_1, y_2: ?? → Y \) are maps with \( f \circ y_1 = x \circ y_2 \), then \( y_1 \circ q_2, y_2 \circ q_2: ?? → Y \) are maps with \( f \circ (y_1 \circ q_2) = x \circ q_2 = f \circ (y_2 \circ q_2) \). Since \( \tilde{y} \) is unique, this implies \( y_1 \circ q_2 = y_2 \circ q_2 \), and hence \( y_1 = y_2 \) because q_2 is a coequaliser. Thus the map \( y \) with \( f \circ y = x \) is unique.

Remark 2.5. Example 9.10 provides Hausdorff topological spaces \((X, \tau_1), (X, \tau_2)\) and \( Y \) such that the identity map \((X, \tau_1) → (X, \tau_2)\) is a continuous bijection but not a homeomorphism, and a quotient map \( f: (X, \tau_2) → Y \) such that the map \( f: (X, \tau_1) → Y \) is a quotient map as well, and such that the identical map

\[
(X, \tau_1) ×_{f,Y,f} (X, \tau_1) → (X, \tau_1) ×_{f,Y,f} (X, \tau_2)
\]

is a homeomorphism. Thus the pull-back of a non-homeomorphism along a quotient map may become a homeomorphism. Quotient maps on topological spaces do not form a pretopology, so this does not contradict Proposition 2.4.

2.2. **Simple extra assumptions on pretopologies.** Consider the fibre-product situation of 2.1. Then \( g \) is a cover by assumption and \( pr_1 \) is one by the definition of a pretopology. If \( f \) is a cover as well, then so is \( pr_2 \) by the definition of a pretopology. That the converse holds is an extra assumption on the pretopology, which means that the property of being a cover is local.

**Assumption 2.6.** The property of being a cover is local, that is, in the fibre-product situation of 2.1, if \( g \) and \( pr_2 \) in 2.1 are covers, then so is \( f \).

If \( g \) and \( pr_2 \) are covers, then so is \( g \circ pr_2 = f \circ pr_1 \) as a composite of covers, and \( pr_1 \) is a cover by definition of a pretopology. Hence Assumption 2.6 is weaker than the following two-out-of-three property:

**Assumption 2.7.** Let \( f ∈ C(Y, Z) \) and \( p ∈ C(X, Y) \) be composable. If \( f \circ p \) and \( p \) are covers, then so is \( f \).
A pretopology is called saturated if \( f \) is a cover whenever \( f \circ p \) is one, without requiring \( p \) to be a cover as well (see [23, Definition 3.11]). This stronger assumption fails in many cases where Assumption 2.7 holds (see Example 9.31, and Assumption 2.7 suffices for all our applications. For the categories of locally convex and Fréchet manifolds with surjective submersions as covers, Assumption 2.6 holds, but we cannot prove Assumption 2.7. The other examples we consider in Section 9 all verify the stronger Assumption 2.7).

**Assumption 2.8.** There is a final object \( \ast \) in \( C \), and all maps to it are covers.

**Lemma 2.9.** Under Assumption 2.8 \( C \) has finite products. If \( f_1: U_1 \to X_1 \) and \( f_2: U_2 \to X_2 \) are covers, then so is \( f_1 \times f_2: U_1 \times U_2 \to X_1 \times X_2 \).

**Proof.** The first statement is clear because products are fibre products over the final object \( \ast \). The second one is [19, Lemma 2.7].

Assumption 2.8 has problems with initial objects. For instance, the unique map from the empty set to the one-point set is not surjective, so Assumption 2.8 fails for any subcanonical pretopology on the category of sets. We must exclude the empty set for Assumption 2.8 to hold. We will not use Assumption 2.8 much.

### 3. Groupoids in a category with pretopology

Let \( C \) be a category with coproducts and let \( T \) be a subcanonical pretopology on \( C \). We define groupoids in \((C,T)\) in two equivalent ways, with more or less data.

#### 3.1. First definition.** A groupoid in \((C,T)\) consists of

- objects \( G^0 \subseteq C \) (objects) and \( G^1 \subseteq C \) (arrows),
- arrows \( r \in C(G^1,G^0) \) (range), \( s \in C(G^1,G^0) \) (source), \( m \in C(G^1 \times_{s \times G^0} G^1,G^1) \) (multiplication), \( u \in C(G^0,G^1) \) (unit), and \( i \in C(G^1,G^1) \) (inversion),

such that

1. \( r \) and \( s \) are covers;
2. \( m \) is associative, that is, \( r \circ m = r \circ pr_1 \) and \( s \circ m = s \circ pr_2 \) for the coordinate projections \( pr_1, pr_2: G^1 \times_{s \times G^0} G^1 \to G^1 \), and the following diagram commutes:

\[
\begin{array}{ccc}
G^1 \times_{s \times G^0} G^1 \times_{s \times G^0} G^1 & m \\
\downarrow \downarrow & \\
G^1 \times_{s \times G^0} G^1 & m \\
\end{array}
\]

3. the following equations hold:

\[
\begin{align*}
\text{r o u} &= \text{id}_{G^0}, & \text{r(1)} &= \text{x,} & \forall x \in G^0, \\
\text{s o u} &= \text{id}_{G^0}, & \text{s(1)} &= \text{x,} & \forall x \in G^0, \\
\text{m o (u o r, id}_{G^1} &= \text{id}_{G^1}, & \text{l}_{r(g)} \cdot g &= \text{g,} & \forall g \in G^1, \\
\text{m o (id}_{G^1}, u o s) &= \text{id}_{G^1}, & g \cdot \text{l}_{s(g)} &= \text{g,} & \forall g \in G^1, \\
\text{s o i} &= r, & s(g^{-1}) &= r(g), & \forall g \in G^1, \\
\text{r o i} &= s, & r(g^{-1}) &= s(g), & \forall g \in G^1, \\
\text{m o (i, id}_{G^1}) &= u o s, & g^{-1} \cdot g &= \text{l}_{s(g)}, & \forall g \in G^1, \\
\text{m o (id}_{G^1}, i) &= u o r, & g \cdot g^{-1} &= 1_{r(g)}, & \forall g \in G^1.
\end{align*}
\]
The right two columns interpret the equalities of maps in the left column in terms of elements. The conditions above imply

\[
m \circ (u,u) = u, \quad 1_x \circ 1_x = 1_x, \quad \forall x \in \mathcal{G}^0, \quad i^2 = \text{id}_{\mathcal{G}^1}, \quad (g^{-1})^{-1} = g, \quad \forall g \in \mathcal{G}^1,
\]

\[
m \circ (i \times r, g, s, i) = i \circ m \circ \sigma, \quad g^{-1} \cdot h^{-1} = (h \cdot g)^{-1}, \quad \forall g, h \in \mathcal{G}^1, r(g) = s(h);
\]

here \( \sigma : G^1 \times_{s,r} G^1 \rightarrow G^1 \times_{s,r} G^1 \) denotes the flip of the two factors.

Most statements and proofs are much clearer in terms of elements. It is worthwhile, therefore, to introduce the algorithm that interprets equations in terms of elements as in the middle and right columns above as equations of maps as in the left column.

The variables \( x \in \mathcal{G}^0, g, h \in \mathcal{G}^1 \) are interpreted as maps in \( \mathcal{C} \) from some object \( ? \in \mathcal{C} \) to \( \mathcal{G}^0 \) and \( \mathcal{G}^1 \), respectively. Thus an element \( x \in X \in \mathcal{C} \) is interpreted as a map \( x : ? \rightarrow X \), and denoted by \( x \in X \). The elements of \( X \) form a category, which determines \( X \) by the Yoneda Lemma.

If an elementwise expression \( A \) is already interpreted as a map \( A : ? \rightarrow \mathcal{G}^1 \), then \( r(A) \) means \( r \circ A : ? \rightarrow \mathcal{G}^0 \), \( s(A) \) means \( s \circ A : ? \rightarrow \mathcal{G}^0 \), and \( A^{-1} \) means the composite map \( i \circ A : ? \rightarrow \mathcal{G}^1 \), if an elementwise expression \( A \) is interpreted as \( A : ? \rightarrow \mathcal{G}^0 \), then \( 1_A \) means \( u \circ A : ? \rightarrow \mathcal{G}^1 \). If \( A \) and \( B \) are elementwise expressions that translate to maps \( A, B : ? \rightarrow \mathcal{G}^1 \) with \( s(A) = s(B) \), that is, \( s \circ A = r \circ B : ? \rightarrow \mathcal{G}^0 \), then \( A \cdot B \) means the composite map

\[
m \circ (A, B) : ? \overset{(A,B)}{\rightarrow} \mathcal{G}^1 \times_{s,r} \mathcal{G}^1 \xrightarrow{m} \mathcal{G}^1.
\]

This algorithm turns the conditions in the middle and right column above into the conditions in the left column if we let \( ? \) vary through all objects of \( \mathcal{C} \). More precisely, the equation in the left column implies the interpretation of the condition in the other two columns for any choice of \( ? \), and the converse holds for a suitable choice of \( ? \).

For instance, in the last condition \( g^{-1} \cdot h^{-1} = (h \cdot g)^{-1} \), we may choose \( ? = \mathcal{G}^1 \times_{s,r} \mathcal{G}^1, g = \text{pr}_1 : ? \rightarrow \mathcal{G}^1 \), and \( h = \text{pr}_2 : ? \rightarrow \mathcal{G}^1 \). The interpretation of the formula \( g^{-1} \cdot h^{-1} = (h \cdot g)^{-1} \) for these choices is \( m \circ (i \times r, g, s, i) = i \circ m \circ \sigma \).

As another example, the associativity diagram \( \text{[3.1]} \) is equivalent to the elementwise statement

\[
(3.2) \quad (g_1 \cdot g_2) \cdot g_3 = g_1 \cdot (g_2 \cdot g_3) \quad \forall g_1, g_2, g_3 \in \mathcal{G}^1, \quad s(g_1) = r(g_2), \quad s(g_2) = r(g_3).
\]

To go from the elementwise statement to \( \text{[3.1]} \), choose \( ? = \mathcal{G}^1 \times_{s,r} \mathcal{G}^1 \times_{s,r} \mathcal{G}^1, \quad g_1 = \text{pr}_1, \quad g_2 = \text{pr}_2, \quad g_3 = \text{pr}_3 \) (we take one factor for each of the free variables \( g_1, g_2, g_3 \), and implement the assumptions \( s(g_1) = r(g_2), \quad s(g_2) = r(g_3) \) by fibre-product conditions). Then \( A := g_1 \cdot g_2 \) is interpreted as \( m \circ (\text{pr}_1, \text{pr}_2) : \mathcal{G}^1 \times_{s,r} \mathcal{G}^1 \rightarrow \mathcal{G}^1 \), so \( (g_1 \cdot g_2) \cdot g_3 = A \cdot g_3 \) becomes the map

\[
m \circ (m \circ (\text{pr}_1, \text{pr}_2, \text{pr}_3)) = m \circ (m \times \text{id}_{\mathcal{G}^1}) \circ (\text{pr}_1, \text{pr}_2, \text{pr}_3) = m \circ (m \times \text{id}_{\mathcal{G}^1}) \circ (\text{id}_{\mathcal{G}^1}, \text{id}_{\mathcal{G}^1}, \text{id}_{\mathcal{G}^1})
\]

from \( \mathcal{G}^1 \times_{s,r} \mathcal{G}^1 \times_{s,r} \mathcal{G}^1 \) to \( \mathcal{G}^1 \). Similarly, \( g_1 \cdot (g_2 \cdot g_3) \) is interpreted as \( m \circ (\text{id}_{\mathcal{G}^1}, \text{id}_{\mathcal{G}^1}, m) \). Thus \( (g_1 \cdot g_2) \cdot g_3 = g_1 \cdot (g_2 \cdot g_3) \) implies that \( \text{[3.1]} \) commutes. Conversely, if \( \text{[3.1]} \) commutes, then \( (g_1 \cdot g_2) \cdot g_3 = g_1 \cdot (g_2 \cdot g_3) \) for any choice of \( ? \in \mathcal{C} \) and \( g_1, g_2, g_3 \) in \( \mathcal{G}^1 \) with \( s(g_1) = r \circ g_2 \) and \( s \circ g_2 = r \circ g_3 \). Thus \( \text{[3.1]} \) is equivalent to the elementwise statement above.

We may also use elementwise formulas to define maps. For instance, suppose that we have already defined maps \( f : X \rightarrow \mathcal{G}^1 \) and \( g : Y \rightarrow \mathcal{G}^1 \). Then there is a unique map \( F : X \times_{s,r} \mathcal{G}^0 \otimes Y \rightarrow \mathcal{G}^1 \) given elementwise by \( F(x, y) := f(x) \cdot g(y) \) for all \( x \in X, y \in Y \) with \( s(f(x)) = r \circ g(y) \). If a map \( f \in \mathcal{C}(X, Z) \) is given in terms of elements, then it is an isomorphism if and only if every element \( z \) of \( Z \) may be
written as \( f(x) \) for a unique \( x \in X \); this interpretation of this statement in terms of maps is exactly the Yoneda Lemma.

**Remark 3.1.** Why do we need the range and source maps to be covers? Of course, we need some assumption for the fibre product \( G^1 \times_{s,G^0,s} G^1 \) to exist, but there are deeper reasons. Many results in the theory of principal bundles depend on the locality of isomorphisms (Proposition 2.4), which holds only for pull-backs along covers. Thus the composition of bibundle equivalences cannot work unless we require their anchor maps to be covers. The range and source maps of a groupoid must be covers because they are the anchor maps for the unit bibundle equivalence \( G^1 \) on \( G \).

### 3.2. Second definition.

For groupoids in sets, the existence of units and inverses is equivalent to the existence of unique solutions \( x \in G^1 \) to equations of the form \( x \cdot g = h \) for \( g, h \in G^1 \) with \( s(g) = s(h) \) and \( g \cdot x = h \) for \( g, h \in G^1 \) with \( t(g) = t(h) \). This leads us to the following equivalent definition of a groupoid in \( (C, T) \):

**Definition 3.2.** A groupoid in \( (C, T) \) consists of \( G^0 \in C \) (objects), \( G^1 \in C \) (arrows) of \( C \), \( r \in C(G^1, G^0) \) (range), \( s \in C(G^1, G^0) \) (source), and \( m \in C(G^1 \times_{s,G^0,r} G^1, G^1) \) (multiplication), such that

1. the maps \( r \) and \( s \) are covers;
2. the maps

\[
\begin{align*}
\text{(3.3)} & \quad (pr_2, m): G^1 \times_{s,G^0,r} G^1 \to G^1 \times_{s,G^0,s} G^1, \quad (x, g) \mapsto (g, x \cdot g), \\
\text{(3.4)} & \quad (pr_1, m): G^1 \times_{s,G^0,r} G^1 \to G^1 \times_{r,G^0,r} G^1, \quad (g, x) \mapsto (g, g \cdot x),
\end{align*}
\]

are well-defined isomorphisms;
3. \( m \) is associative in the sense of (5.1) or, equivalently, (3.2).

The first condition implies that the fibre products \( G^1 \times_{s,G^0,r} G^1, G^1 \times_{s,G^0,s} G^1 \) and \( G^1 \times_{r,G^0,r} G^1 \) used above exist in \( C \). The maps in (3.3) and (3.4) are well-defined if and only if \( s \circ m = s \circ pr_2 \) and \( r \circ m = r \circ pr_1 \), so these two equations are assumed implicitly.

If \((G^1, G^0, r, s, m, u, i)\) is a groupoid in the first sense above, then it is one in the sense of Definition 3.2: the map \((g, h) \mapsto (h \cdot g^{-1}, g)\) is inverse to (3.3), and the map \((g, h) \mapsto (g, g^{-1} \cdot h)\) is inverse to (3.4). The converse is proved in Proposition 3.6.

**Lemma 3.3.** The invertibility of the map in (3.3) is equivalent to the elementwise statement that for all \( g, h \in G^1 \) with \( s(g) = s(h) \) there is a unique \( x \in G^1 \) with \( s(x) = r(g) \) and \( x \cdot g = h \). The invertibility of the map in (3.4) is equivalent to the elementwise statement that for all \( g, h \in G^1 \) with \( t(g) = t(h) \) there is a unique \( x \in G^1 \) with \( s(g) = r(x) \) and \( g \cdot x = h \).

**Proof.** We only prove the first statement, the second one is similar.

We interpret \( g, h, x \) as maps \( g, h, x: ? \to G^1 \in C \). The elementwise statement says that for \( g, h, x \): \( x \in G^1 \) with \( s(x) = r(g) \) and \( x \cdot g = h \). The maps \( g \) and \( h \) with \( s \circ g = s \circ h \) are equivalent to a single map \((g, h): ? \to G^1 \times_{s,G^0,s} G^1 \), and the conditions \( s \circ x = r \circ g \) and \( m \circ (x, g) = h \) together are equivalent to \((x, g) \) being a map \( ? \to G^1 \times_{r,G^0,r} G^1 \) with \((pr_2, m) \circ \) \( (x, g) = (g, h) \). Hence the elementwise statement is equivalent to the statement that for each object ? of \( C \) and each map \((g, h): ? \to G^1 \times_{s,G^0,s} G^1 \) there is a unique map \( A: ? \to G^1 \times_{s,G^0,r} G^1 \) with \((pr_2, m) \circ A = (g, h) \). This statement means that \((pr_2, m) \) is invertible by the Yoneda Lemma.

To better understand (3.3) and (3.4), we view \( m \) as a ternary relation on \( G^1 \).

**Definition 3.4.** An \( n \)-ary relation between \( X_1, \ldots, X_n \in C \) is \( R \in C \) with maps \( p_j: R \to X_j \) for \( j = 1, \ldots, n \) such that given \( x_j \in X_j \) for \( j = 1, \ldots, n \), there is at most one \( r \in R \) with \( p_j(r) = x_j \) for \( j = 1, \ldots, n \).
The multiplication relation defined by \( \mathbf{m} \) has

\[
R := G^1 \times_{s, G^0} r, G^1,
\]

\[p_1 := \text{pr}_1, \quad p_2 := \text{pr}_2, \quad p_3 := \mathbf{m}.
\]

**Lemma 3.5.** The maps in (3.3) and (3.4) are well-defined isomorphisms if and only if the following three maps are well-defined isomorphisms:

\[
(p_1, p_2) : R \rightarrow G^1 \times_{s, G^0} r, G^1,
\]

\[
(p_2, p_3) : R \rightarrow G^1 \times_{s, G^0, r} G^1,
\]

\[
(p_1, p_3) : R \rightarrow G^1 \times_{r, G^0, r} G^1.
\]

**Proof.** The first isomorphism is the definition of \( R \), the second one is (3.3), the third one is (3.4).

When we view the multiplication as a relation, then the isomorphisms (3.3) and (3.4) become similar to the statement that the multiplication is a partially defined map.

### 3.3. Equivalence of both definitions of a groupoid.

**Proposition 3.6.** Let \((C, T)\) be a category with a subcanonical pretopology. Let \((G^0, G^1, r, s, \mathbf{m})\) be a groupoid in \((C, T)\) as in Definition 3.2. Then there are unique maps \(u: G^0 \rightarrow G^1\) and \(i: G^1 \rightarrow G^1\) with the properties of unit map and inversion listed above. Moreover, the multiplication \( \mathbf{m} \) is a cover.

**Proof.** We write down the proof in terms of elements. Interpreting this as explained above gives a proof in a general category with pretopology.

First we construct the unit map. For any \(g \in G^1\), the elementwise interpretation of (3.3) in Lemma 3.3 gives a unique map \( \bar{u}: G^1 \rightarrow G^1\) with \( s(\bar{u}(g)) = r(g) \) and \( \bar{u}(g) \cdot g = g \). Hence \( r(\bar{u}(g)) = r(\bar{u}(g) \cdot g) = r(g) \). Associativity implies

\[
\bar{u}(g) \cdot (g \cdot h) = (\bar{u}(g) \cdot g) \cdot h = g \cdot h = \bar{u}(g \cdot h) \cdot (g \cdot h)
\]

for all \(g, h \in G^1\) with \( s(g) = r(h) \). Since \( \bar{u}(g \cdot h) \) is unique, this gives \( \bar{u}(g \cdot h) = \bar{u}(g) \) for all \(g, h \in G^1\) with \( s(g) = r(h) \), that is, \( \bar{u} \circ \mathbf{m} = \bar{u} \circ \text{pr}_1 \). The map \((\text{pr}_1, \mathbf{m})\) is the isomorphism in (3.4), so we get \( \bar{u} \circ \text{pr}_1 = \bar{u} \circ \text{pr}_2 \) on \( G^1 \times_{r, G^0, r} G^1 \). Since the pretopology \( T \) is subcanonical, the cover \( r \) is the coequaliser of \( \text{pr}_1, \text{pr}_2 : G^1 \times_{r, G^0, r} G^1 \rightarrow G^1 \). Hence there is a unique map \( u: G^0 \rightarrow G^1\) with \( \bar{u} = u \circ r \). Since \( r \) is an epimorphism, the equations \( s \circ \bar{u} = s \) and \( r \circ u = r \) imply \( s \circ u = \text{id}_{G^0} \) and \( r \circ u = \text{id}_{G^0} \). Interpreting \( 1_x = u(x) \) for \( x \in G^0 \), this becomes \( s(1_x) = x = r(1_x) \) for all \( x \in G^0 \).

The defining condition \( u(g) \cdot g = g \) for \( g \in G^1 \) becomes \( 1_{r(g)} \cdot g = g \) for all \( g \in G^1 \).

If \( g, h \in G^1\) satisfy \( s(g) = r(h) \), then

\[
(g \cdot 1_{s(g)}) \cdot h = g \cdot (1_{s(g)} \cdot h) = g \cdot (1_{r(h)} \cdot h) = g \cdot h.
\]

Since \( g \) is the unique map \( x: G^1 \rightarrow G^1\) with \( x \cdot h = g \cdot h \) by (3.3), we also get \( g \cdot 1_{s(g)} = g \) for all \( g \in G^1\). Hence the unit map has all required properties.

The inverse map \( i: G^1 \rightarrow G^1\) is defined as the unique map with \( s(i(g)) = r(g) \) and \( i(g) \cdot g = 1_{s(g)} \) for all \( g \in G^1\). Since \( s(g) = s(1_{s(g)}) \), (3.3) provides a unique map with this property. We write \( g^{-1} \) instead of \( i(g) \) in the following. Then \( s(g^{-1}) = r(g) \), \( g^{-1} \cdot g = 1_{s(g)} \) by definition, and \( r(g^{-1}) = r(g^{-1} \cdot g) = r(1_{s(g)}) = s(g) \). Associativity gives

\[
(g \cdot g^{-1}) \cdot g = g \cdot (g^{-1} \cdot g) = g \cdot 1_{s(g)} = g = 1_{r(g)} \cdot g.
\]

Since the map \( x: G^1 \rightarrow G^1\) with \( x \cdot g = 1_{r(g)} \cdot g \) is unique by (3.3), this implies \( g \cdot g^{-1} = 1_{r(g)} \). Similarly, associativity gives

\[
(g \cdot h)^{-1} \cdot (g \cdot h) = 1_{s(g \cdot h)} = 1_{s(h)} = (h^{-1} \cdot g^{-1}) \cdot (g \cdot h)
\]
for all $g, h \in G^1$ with $s(g) = r(h)$. Hence the uniqueness of the solution of $x \cdot (g \cdot h) = 1_{s(h)}$ implies $(g \cdot h)^{-1} = h^{-1} \cdot g^{-1}$ for all $g, h \in G^1$ with $s(g) = r(h)$. Similarly,

$$(g^{-1})^{-1} = 1_{s(g^{-1})} = 1_{r(g)} = g \cdot g^{-1},$$

and the uniqueness of the solution to $x \cdot g^{-1} = 1_{r(g)}$ gives $(g^{-1})^{-1} = g$ for all $g \in G^1$. Thus the inversion has all expected properties.

Since $s$ is a cover, so is the coordinate projection $pr_2: G^1 \times_x G^0, G^1 \to G^1$. Composing $pr_2$ with the invertible map in $\mathcal{C}$ gives that $m: G^1 \times_x G^0, G^1 \to G^1$ is a cover. \hfill $\square$

### 3.4. Examples

The following examples play an important role for the general theory.

**Example 3.7.** An object $X$ of $\mathcal{C}$ is viewed as a groupoid by taking $G^1 = G^0 = X$, $r = s = id_X$, and letting $m$ be the canonical isomorphism $X \times_X X \to X$. A groupoid is isomorphic to one of this form if and only if its range or source map is an isomorphism. Such groupoids are called 0-groupoids.

**Example 3.8.** Let $f: X \to Y$ be a cover. Its **covering groupoid** is the groupoid defined by $G^0 = X$, $G^1 = X \times_{f, Y, f} X$, $r(x_1, x_2) = x_1$, $s(x_1, x_2) = x_2$ for all $x_1, x_2 \in X$ with $f(x_1) = f(x_2)$, and $(x_1, x_2) \cdot (x_2, x_3) := (x_1, x_3)$ for all $x_1, x_2, x_3 \in X$ with $f(x_1) = f(x_2) = f(x_3)$. The range and source maps are covers by construction. The multiplication is clearly associative. The canonical isomorphisms

$$G^1 \times_{s,G^0, r} G^1 \xrightarrow{\sim} X \times_{f, Y, f} X \times_{f, Y, f} X, \quad (x_1, x_2, x_3) \mapsto (x_1, x_2, x_3),$$

$$G^1 \times_{r,G^0, s} G^1 \xrightarrow{\sim} X \times_{f, Y, f} X \times_{f, Y, f} X, \quad (x_1, x_2, x_3) \mapsto (x_1, x_2, x_3),$$

show that (3.3) and (3.4) are isomorphisms. Thus we have a groupoid in $(\mathcal{C}, T)$. Its unit and inversion maps are given by $1_x = (x, x)$ and $(x_1, x_2)^{-1} = (x_2, x_1)$.

**Example 3.9.** Let $G$ be a groupoid and let $p: X \to G^0$ be a cover. We define a groupoid $p^*G = G(X)$ with objects $X$ and arrows $X \times_{p, G^0, r} G^1 \times_{s, G^0, p} X$, range and source maps $pr_1$ and $pr_3$, and with the multiplication map defined elementwise by

$$(x_1, g_1, x_2) \cdot (x_2, g_2, x_3) := (x_1, g_1 \cdot g_2, x_3)$$

for all $x_1, x_2, x_3 \in X$, $g_1, g_2 \in G^1$ with $p(x_1) = r(g_1)$, $p(x_2) = s(g_1) = r(g_2)$, $p(x_3) = s(g_2)$; this multiplication is associative. Since the maps $s$, $r$, and $p$ are covers, the fibre product $X \times_{p, G^0, r} G^1 \times_{s, G^0, p} X$ exists and the source and range maps of $G(X)$ are covers. Routine computations show that (3.3) and (3.4) are isomorphisms. Units and inverses are given by $1_x = (x, 1_{p(x)}, x)$ and $(x_1, g, x_2)^{-1} = (x_2, g^{-1}, x_1)$ for all $x, x_1, x_2 \in X$, $g \in G^1$ with $p(x_1) = r(g)$, $p(x_2) = s(g)$.

If $G$ is just a space $Y$ viewed as a groupoid (Example 3.7), then $G(X)$ is the covering groupoid defined in Example 3.8.

Let $p_1: X_1 \to X_2$ and $p_2: X_2 \to G^0$ be covers. Then $p_2 \circ p_1$ is a cover and there is a natural groupoid isomorphism $p_1^*(p_2^*G) \cong (p_2 \circ p_1)^*G$.

**Example 3.10.** Assume Assumption 2.8 about a final object $\ast$. Then a group in $(\mathcal{C}, T)$ is a groupoid $G$ with $G^0 = \ast$. The range and source maps $G^1 \to G^0 = \ast$ are automatically covers by Assumption 2.8. The multiplication is now defined on the full product $G^1 \times X \to G^1 \times G^1$, and the isomorphisms (3.3) and (3.4) also take place on the product $G^1 \times G^1$. The unit in a groupoid is a map $u: \ast \to G^1$. For any object $? \in \mathcal{C}$, let $1?: ? \to G^1$ be the composite of $u$ with the unique map $? \to \ast$. These maps give the unit element in $G^1$. It satisfies $1 \cdot g = g = g \cdot 1$ for any map $g: ? \to G^1$. 
3.5. Functors and natural transformations.

**Definition 3.11.** Let $G$ and $H$ be groupoids in $(\mathcal{C}, \mathcal{T})$. A functor from $G$ to $H$ is given by arrows $F^i \in \mathcal{C}(G^i, H^i)$ in $\mathcal{C}$ for $i = 0, 1$ with $\pi_i(F^1(g)) = F^0(\pi_i(g))$ and $s_i(F^1(g)) = F^0(s_i(g))$ for all $g \in G^i$ and $F^1(g_1 \cdot g_2) = F^1(g_1) \cdot F^1(g_2)$ for all $g_1, g_2 \in G^i$ with $s_i(g_1) = r_i(g_2)$.

The identity functor $id_G : G \to G$ on a groupoid $G$ has $F^i = id_{G^i}$ for $i = 0, 1$.

The product of two functors $F_1 : G \to H$ and $F_2 : H \to K$ is the functor $F_2 \circ F_1 : G \to K$ given by the composite maps $F_2 \circ F_1 : G^i \to K^i$ for $i = 1, 2$.

Let $F_1, F_2 : \mathcal{C} \rightrightarrows \mathcal{C}$ be two parallel functors. A natural transformation $F_1 \Rightarrow F_2$ is $\Phi \in \mathcal{C}(G^0, H^1)$ with $s(\Phi(x)) = F^0_1(x)$, $r(\Phi(x)) = F^0_2(x)$ for all $x \in G^0$ and $\Phi((g) \cdot F^1_1(g)) = F^1_2(g) \cdot \Phi(s(g))$ for all $g \in G^1$:

$$
\begin{array}{ccc}
F^0_1(s(g)) & F^1_1(g) & F^0_1(r(g)) \\
\Phi(s(g)) & \Phi(r(g)) & F^0_2(s(g)) \\
F^1_2(g) & F^0_2(r(g))
\end{array}
$$

The identity transformation $1_{F} : F \Rightarrow F$ on a functor $F : G \to H$ is given by $\Phi(x) = 1_{F(x)}$ for all $x \in G^0$. If $\Phi : F_1 \Rightarrow F_2$ is a natural transformation, then its inverse $\Phi^{-1}$ is the natural transformation $F_2 \Rightarrow F_1$ given by $i \circ \Phi : g \mapsto \Phi(g)^{-1}$.

The vertical product of natural transformations $\Phi : F_1 \Rightarrow F_2$ and $\Psi : F_2 \Rightarrow F_3$ for three functors $F_1, F_2, F_3 : \mathcal{C} \rightrightarrows \mathcal{C}$ is the natural transformation $\Psi \circ \Phi : F_1 \Rightarrow F_3$ defined by $(\Psi \circ \Phi)(x) := \Psi(x) \cdot \Phi(x)$ for all $x \in G^0$.

Let $F_1, F_2 : \mathcal{C} \rightrightarrows \mathcal{C}$ and $F_2, F'_2 : \mathcal{C} \rightrightarrows \mathcal{C}$ be composable pairs of parallel functors and let $\Phi : F_1 \Rightarrow F'_1$ and $\Psi : F_2 \Rightarrow F'_2$ be natural transformations. Their horizontal product is the natural transformation $\Phi \circ \Psi : F_2 \circ F_1 \Rightarrow F'_2 \circ F'_1$ defined for all $x \in G^0$ by

$$
\begin{array}{cccc}
\Psi(F^0_1(x)) & F^1_1(\Phi(x)) & F^0_2(F^0_1(x)) \\
\Phi((F^0_1(x)) & (F^1_2 \circ F^0_1)(x)) & (F^1_2 \circ F^0_1)(x)
\end{array}
$$

This diagram commutes because of the naturality of $\Psi$ applied to $\Phi(x)$.

If $\Phi : F_1 \Rightarrow F_2$ is a natural transformation, then $\Phi^{-1} \cdot \Phi = 1_{F_1} : F_1 \Rightarrow F_1$, $\Phi \cdot \Phi^{-1} = 1_{F_2} : F_2 \Rightarrow F_2$, justifying the name inverse. Thus all natural transformations between groupoids are natural isomorphisms.

**Proposition 3.12.** Groupoids, functors, and natural transformations in $(\mathcal{C}, \mathcal{T})$ with the products defined above form a strict 2-category in which all 2-arrows are invertible.

**Proof.** See [1][25][35] for the definition of a strict 2-category. The proof is routine. \hfill $\square$

**Example 3.13.** Let $G$ be a groupoid and let $p : X \to G^0$ be a cover. Then $p$ and the map $p_2 : X \times_{p, G^0} G^1 \times_{G^1, p} X \to G^1$ form a functor $p_* : G(X) \to G$. Functors of this form are called hypocoovers.
Example 3.14. Let $G$ and $H$ be groupoids, $F: G \to H$ a functor, and $p: X \to H^0$ a cover. Let $\tilde{X} := G^0 \times_{p^0 \circ p} X$; this exists and $\text{pr}_1: \tilde{X} \to G^0$ is a cover because $p$ is a cover. We define a functor $p^*(F) = F(\tilde{X}): G(\tilde{X}) \to H(X)$ by $\text{pr}_2: \tilde{X} \to X$ on objects and by $(x_1, g, x_2) \mapsto (\text{pr}_2(x_1), F^1(g), \text{pr}_2(x_2))$ for all $x_1, x_2 \in \tilde{X}, g \in G^1$ with $\text{pr}_1(x_1) = r(g)$ and $\text{pr}_1(x_2) = s(g)$ on arrows.

Example 3.15. An equivalence from the identity functor on $G$ to a functor $F: G \to G$ is $\Phi \in C(G^0, G^1)$ with $s \circ \Phi = \text{id}_{G^0}$, $r \circ \Phi = F^0$, and
\begin{equation}
F^1(g) = \Phi(r(g)) \cdot g \cdot \Phi(s(g))^{-1} \quad \text{for all} \quad g \in G^1.
\end{equation}

Conversely, let $\Phi$ be any section for $G^1 \to G^0$. Then $F^0 = r \circ \Phi$ and (5.5) define an endomorphism $\text{Ad}(\Phi) = F: G \to G$ such that $\Phi$ is a natural transformation $\text{id}_{G^0} \Rightarrow F$. Functors $F: G \to G$ that are naturally equivalent to the identity functor are called inner.

The horizontal product of $\Phi_1: \text{id}_{G^0} \Rightarrow \text{Ad}(\Phi_1)$ for $i = 1, 2$ is a natural transformation
\begin{equation}
\Phi_1 \circ \Phi_2: \text{id}_{G^0} \Rightarrow \text{Ad}(\Phi_1) \circ \text{Ad}(\Phi_2).
\end{equation}

Here
\begin{equation}
\Phi_1 \circ \Phi_2(x) := \Phi_1(r \circ \Phi_2(x)) \cdot \Phi_2(x) \quad \text{for all} \quad x \in G^0.
\end{equation}

This product on sections for $s$ gives a monoid with unit $u: x \mapsto 1_x$. The map $A$ from this monoid to the submonoid of inner endomorphisms of $G$ is a unital homomorphism, that is, $\text{Ad}(\Phi_1 \circ \Phi_2) = \text{Ad}(\Phi_1) \circ \text{Ad}(\Phi_2)$ and $\text{Ad}(1) = \text{id}_G$.

Definition and Lemma 3.16. The following are equivalent for a section $\Phi$ of $s$:
1. $\Phi$ is invertible for the horizontal product $\circ$;
2. $\text{Ad}(\Phi)$ is an automorphism;
3. $r \circ \Phi$ is invertible in $C$.

Sections of $s$ with these equivalent properties are called bisections.

Proof. Let $\Phi$ be invertible for $\circ$ with inverse $\Phi^{-1}$. Then $\text{Ad}(\Phi^{-1})$ is inverse to $\text{Ad}(\Phi)$, so $\text{Ad}(\Phi)$ is an automorphism of $G$. Then $r \circ \Phi = \text{Ad}(\Phi)^0 \in C(G^0, G^0)$ is invertible in $C$. Conversely, if $\alpha := r \circ \Phi$ is invertible in $C$, then $\Phi^{-1}(x) := \Phi(\alpha^{-1}(x))^{-1}: G^0 \to G^1$ has $s(\Phi^{-1}(x)) = r(\Phi(\alpha^{-1}(x))) = \alpha^{-1}(x) = x$, so it is a section, and both $\Phi \circ \Phi^{-1} = 1_x$ and $\Phi^{-1} \circ \Phi = 1_x$. We have shown $(1) \Rightarrow (2) \Rightarrow (3) \Rightarrow (1)$. \hfill \Box

We may think of a section as a subobject $\Phi(G^0) \subseteq G^1$ such that $s$ restricts to an isomorphism $\Phi(G^0) \cong G^0$. Being a bisection means that both $s$ and $r$ restrict to isomorphisms $\Phi(G^0) \cong G^0$. This explains the name “bisection.”

Isomorphisms of groupoids with natural transformations between them form a strict 2-groupoid. Thus the automorphisms of $G$ with natural transformations between them form a strict 2-group or, equivalently, a crossed module. The crossed module combines automorphisms of $G$ and bisections because the latter are the natural transformations from the identity functor to another automorphism of $G$. The crossed module involves the horizontal product $\circ$ on bisections and the composition $\circ$ on automorphisms, and the group homomorphism $\text{Ad}$ from bisections to automorphisms; another piece of structure is the conjugation action of automorphisms on bisections, given by conjugation:

$$F \bullet \Phi := 1_F \circ \Phi \circ 1_{F^{-1}}: \text{id}_G = F \circ \text{id}_G \circ F^{-1} \Rightarrow F \text{Ad}(\Phi)F^{-1}.$$ 

By the definition of the horizontal product, we have

$$F \bullet \Phi(x) = F^1(\Phi(x)) \quad \text{for all} \quad x \in G^0.$$ 

The crossed module conditions $\text{Ad}(F \bullet \Phi) = F \text{Ad}(\Phi)F^{-1}$ and $\text{Ad}(\Phi_1) \bullet \Phi_2 = \Phi_1 \circ \Phi_2 \circ \Phi_1^{-1}$ are easy to check.
3.6. Vague functors. The functor \( p_i : G(X) \to G \) from Example 3.13 is not an isomorphism, but should be an equivalence of groupoids. When we formally invert these functors, we arrive at the following definition:

**Definition 3.17.** Let \( G \) and \( H \) be groupoids in \( C \). A vague functor from \( G \) to \( H \) is a triple \( (X, p, F) \) where \( X \in \in C, p : X \to G^0 \) is a cover, and \( F : G(X) \to H \) is a functor, with \( G(X) \) defined in Example 3.9.

An isomorphism between two vague functors \( (X_i, p_i, F_i) \), \( i = 1, 2 \), is an isomorphism \( \varphi \in C(X_1, X_2) \) with \( p_2 \circ \varphi = p_1 \) and \( F_2 \circ \varphi_* = F_1 \), where \( \varphi_* : G(X_1) \to G(X_2) \) is the functor given on objects by \( \varphi \) and on arrows by \( \varphi^*(x_1, g, x_2) = (\varphi(x_1), g, \varphi(x_2)) \) for all \( x_1, x_2 \in X, g \in G^1 \) with \( p_1(x_1) = r(g), p_1(x_2) = s(g) \), and \( p(x_3) = s(g) \).

Remark 3.18. Vague functors or similar constructs are often called anafunctors (see [9] and the references there), but we find the justification for this name rather weak. Since we also want to study related equivalences, which we do not want to call anaequivalences, we suggest “vague functor” as a new name.

Pronk [77], Carchedi [3], Roberts [39] and several other authors use spans of functors like we do, but with weak equivalences instead of hypercovers. As a consequence, they use the weak instead of the strong pull-back to compose spans. Roberts’ [39] Proposition 6.4] together with Theorem 3.29 below shows that localising at hypercovers or at all (almost) weak equivalences gives the same result.

We are going to compose vague functors. Let \( G_1, G_2 \) and \( G_3 \) be groupoids in \( (C, T) \) and let \( (X_{ij}, p_{ij}, F_{ij}) \) for \( ij = 12 \) and \( ij = 23 \) be vague functors from \( G_i \) to \( G_j \). Their product \( (X_{13}, p_{13}, F_{13}) \) is the vague functor from \( G_1 \) to \( G_3 \) given by

\[
X_{13} := X_{12} \times_{p_{12}, G_2, p_{23}} X_{23},
\]
\[
p_{13} := p_{12} \circ p_1 : X_{13} \to X_{12} \to G^0,
\]
\[
F_{13} := F_{12} \circ F_{1} : G_1(X_{13}) \cong G_1(X_{12})(X_{23}) \to G_2(X_{23}) \to G_3.
\]

Thus \( F_{13}^0(x_1, x_2) = F_{12}^0(x_2) \) for all \( x_1 \in X_{12}, x_2 \in X_{23} \) with \( F_{12}^0(x_1) = p_{23}(x_2) \) and \( F_{13}^1(x_1, x_2, g, x_3, x_4) = F_{12}^1(x_2, F_{1}^1(x_1, x_3, x_4)) \) for all \( x_1, x_3 \in X_{12}, x_2, x_4 \in X_{23}, g \in G^1 \) with \( F_{12}^1(x_2) = p_{23}(x_2), F_{1}^0(x_1) = p_{23}(x_3), p_{12}(x_1) = r(g), p_{12}(x_3) = s(g) \). The map \( p_{13} : X_{13} \to X_{12} \) is a cover because \( p_{23} \) is one. Hence \( p_{13} \) is a cover as a composite of covers.

**Lemma 3.19.** The composition of vague functors is associative up to isomorphism; the associator comes from the canonical isomorphism

\[
(X_{12} \times_{p_{12}, G_2, p_{23}} X_{23}) \times_{p_{13}, G_1, p_{34}} X_{34} \sim X_{12} \times_{p_{12}, G_2, p_{23} \circ p_{13}} X_{34} \sim X_{13} \times_{p_{13}, G_2, p_{34}} X_{34}.
\]

The identity functor viewed as a vague functor with \( X = G^0 \) and \( p = id_{G^0} \) is a unit for this composition, up to the natural isomorphisms \( Y \times_{G^0} G^0 \cong Y \cong G^0 \times_{G^0} Y \).

**Proof.** The proof is routine.

Since fibre products are, in general, only associative up to the canonical isomorphism in the above lemma, vague functors do not form a category; together with their isomorphisms, they give a bicategory. We now incorporate natural transformations into this bicategory.
To simplify notation, we usually ignore the associators in Lemma 3.19 from now on, assuming that fibre products are strictly associative.

**Definition 3.20.** Let $G$ and $H$ be groupoids in $C$ and let $(X_1, p_1, F_1)$ and $(X_2, p_2, F_2)$ be vague functors from $G$ to $H$. Let $X := X_1 \times_{p_1, G, p_2} X_2$ and let $p := p_1 \circ p_1 = p_2 \circ p_2 : X \to G^0$. We get functors $F_1 \circ (pr_1)_* : G(X) \to H$ and $F_2 \circ (pr_2)_* : G(X) \to H$. A vague natural transformation $\Phi : F_1 \circ (pr_1)_* \Rightarrow F_2 \circ (pr_2)_\ast$:

\[
\begin{array}{ccc}
X & \xrightarrow{pr_1} & X_1 \\
pr_2 \downarrow & & \downarrow p_1 \\
X_2 & \xrightarrow{p} & G^0 \\
\end{array}
\quad
\begin{array}{ccc}
G(X) & \xrightarrow{(pr_1)_*} & G(X_1) \\
\Phi & \underset{\sim}{\Rightarrow} & \Phi \\
G(X_2) & \xrightarrow{(pr_2)_\ast} & H \\
\end{array}
\]

The natural transformation $\Phi$ is a map $\Phi : X \to H^1$ with $s \circ \Phi = F_1^0 \circ pr_1 : X \to H^0$, $r \circ \Phi = F_2^0 \circ pr_2 : X \to H^0$, and

$$\Phi(x_1, x_2) \cdot F_1^1(x_1, g, x_3) = F_2^1(x_2, g, x_4) \cdot \Phi(x_3, x_4)$$

for all $x_1, x_3 \in X_1$, $x_2, x_4 \in X_2$, $g \in G^1$ with $p_1(x_1) = p_2(x_2) = r(g)$ and $p_1(x_3) = p_2(x_4) = s(g)$.

**Example 3.21.** Let $(X_i, p_i, F_i)$ for $i = 1, 2$ be vague functors from $G$ to $H$ and let $\phi : X_1 \to X_2$ be an isomorphism between them. Then

$$\Phi(x_1, x_2) := F_1^1(\phi^{-1}(x_2), 1_{p_1(x_1)}, x_1) = F_2^1(x_2, 1_{p_2(x_2)}, \phi(x_1))$$

for all $x_1 \in X_1$, $x_2 \in X_2$ with $p_1(x_1) = p_2(x_2)$ is a natural transformation from $(X_1, p_1, F_1)$ to $(X_2, p_2, F_2)$.

**Lemma 3.22.** Let $F_1, F_2 : G \to H$ be functors and let $p : X \to H^0$ be a cover. Let $p_* : G(X) \to G$ be the induced hypercover. Then natural transformations $F_1 \circ p_* \Rightarrow F_2 \circ p_*$ are in canonical bijection with natural transformations $F_1 \Rightarrow F_2$.

**Proof.** A natural transformations $\Phi : F_1 \Rightarrow F_2$ induces a natural transformation $\Phi \circ 1_{p_*} : F_1 \circ p_* \Rightarrow F_2 \circ p_*$ by the horizontal product; explicitly, $\Phi \circ 1_{p_*}$ is the map $\Phi \circ p : X \to G^0 \to H^1$. To show that this canonical map $\Phi \Rightarrow \Phi \circ 1_{p_*}$ is bijective, we must prove that any natural transformation $\Psi : F_1 \circ p_* \Rightarrow F_2 \circ p_* : G(X) \Rightarrow H^1$ factors uniquely through $p$ and a map $\Phi : G^1 \to H^1$; the latter is then automatically a natural transformation $F_1 \Rightarrow F_2$ because $p_*^1 : G(X)^1 \to G^1$ is a cover, hence an epimorphism, and the conditions for a natural transformation hold after composing with $p$.

Since $\Psi$ is natural with respect to all arrows $(x_1, 1_{p(x_1)}, x_2)$ in $G(X)$ for $x_1, x_2 \in X$ with $p(x_1) = p(x_2)$, we get $\Psi(x_1) = \Psi(x_2)$ if $p(x_1) = p(x_2)$. Since the pretopology is subcanonical and $p$ is a cover, $\Psi$ factors uniquely through $p : X \to G^0$. $\square$

**Theorem 3.23.** Groupoids in $(C, T)$, vague functors and natural transformations of vague functors with the composition of vague functors described above form a bicategory with invertible 2-arrows.

**Proof.** We must compose natural transformations of vague functors vertically and horizontally. We reduce this to the same constructions for ordinary natural transformations: the reduction explains why the conditions for a bicategory hold.

Let $(X_i, p_i, F_i)$ be three vague functors from $G$ to $H$ and let $\Phi_{ij} : (X_i, p_i, F_i) \Rightarrow (X_j, p_j, F_j)$ for $ij = 12, 23$ be natural transformations to compose vertically. Let $X_{ij} := X_1 \times_{p_1, G, p_2} X_j$ and $p_{ij} := p_1 \circ p_1 = p_j \circ p_2 : X_{ij} \to G^0$ for $ij = 12, 13, 23$. Let $X_{123} := X_1 \times_{p_1, G, p_2} X_2 \times_{p_2, G, p_3} X_3$ and $p_{123} := p_1 \circ p_1 = p_2 \circ p_2 = p_3 \circ p_3 : X \to G^0$. 

The given natural transformations are maps \( \Phi_{12} : X_{12} \to H^1 \) and \( \Phi_{23} : X_{23} \to H^1 \) with, among others, where the first functor is associated to the coordinate projection \( s \).

Similarly, if \( \Phi \) comes from an isomorphism of vague functors \( \Phi_{12} : X_{12} \to X_2 \) as in Example 3.24 then the composite \( \Phi_{13} \) above is

\[
\Phi_{13} : X_1 \times_{p_1,H^0,p_2} X_3 \xrightarrow{\varphi_{12} \times_{q_0,p_3} \varphi_{23}} X_2 \times_{p_2,H^0,p_3} X_3 \xrightarrow{\Phi_{23}} H^1.
\]

Similarly, if \( \Phi_{23} \) comes from an isomorphism of vague functors \( \varphi_{23} : X_2 \to X_3 \), then the vertical product \( \Phi_{13} \) is

\[
\Phi_{13} : X_1 \times_{p_1,H^0,p_2} X_3 \xrightarrow{\varphi_{12}} X_2 \times_{p_2,H^0,p_3} X_3 \xrightarrow{\varphi_{23}^{-1}} X_1 \xrightarrow{\Phi_{12}} H^1.
\]

As a consequence, the natural transformation corresponding to the identity isomorphism of a vague functor is a unit for the vertical product.

Since arrows in groupoids are invertible, any natural transformation of vague functors has an inverse exchange the order of the factors in the fibre product and compose \( \Phi \) with the inversion map on \( H^1 \). This is an inverse for the vertical product above. Thus all 2-arrows are invertible.

When we further compose with a natural transformation \( \Phi_{34} : (X_3,p_3,F_3) \Rightarrow (X_4,p_4,F_4) \), then we may first construct a natural transformation on the fibre product \( X_{1234} \) of all four \( X_i \). Then by Lemma 3.22 this factors uniquely through the covers \( X_{1234} \Rightarrow X_{124} \) and \( X_{1234} \Rightarrow X_{134} \), and then further through the covers \( X_{124} \Rightarrow X_1 \) and \( X_{134} \Rightarrow X_{14} \). The resulting map on \( X_{14} \) does not depend on whether we factor through \( X_{124} \) or \( X_{134} \) first. Thus the vertical product is associative.

Now we turn to the horizontal product. Let \( K \) be a third groupoid in \((C,T)\); let \( (X_i,p_i,F_i) \) for \( i = 1,2 \) be vague functors \( G \Rightarrow H \) and let \( (Y_i,q_i,E_i) \) for \( i = 1,2 \) be vague functors \( H \Rightarrow K \); let \( \Phi : (X_1,p_1,F_1) \Rightarrow (X_2,p_2,F_2) \) and \( \Psi : (Y_1,q_1,E_1) \Rightarrow (Y_2,q_2,E_2) \) be natural transformations. The horizontal product \( \Psi \circ \Phi \) must be a natural transformation of vague functors \( E_1 \circ F_1 \Rightarrow E_2 \circ F_2 \). We are going to reduce it to an ordinary horizontal product of natural transformations of composable functors. To make our functors composable, we pass to larger fibre products.

First, let

\[
Y := Y_1 \times_{q_1,H^0,q_2} Y_2, \quad E_i := E_i \circ (pr_j)_* : H(Y) \to H(Y_i) \to K;
\]

by definition, \( \Psi \) is a natural transformation of functors \( \Psi : E_1 \Rightarrow E_2 \). Secondly, let

\[
Y_i X_j := Y_i \times_{q_i,H^0,F_i} X_j
\]

for \( i,j \in \{1,2\} \) and

\[
YX := Y_1 X_1 \times_{G \times G} Y_2 X_1 \times_{G \times G} Y_1 X_2 \times_{G \times G} Y_2 X_2 \cong (Y \times_{q_1,H^0,F_1} X_1) \times_{G \times G} (Y \times_{q_2,H^0,F_2} X_2).
\]

Let \( \tilde{E}_i : G(YX) \to H(Y) \) be the composite functors \( G(YX) \to G(Y \times_{G \times G} X_i) \to H(Y) \), where the first functor is associated to the coordinate projection \( YX \Rightarrow Y \times_{G \times G} X_i \) and the second functor is \( F_i(Y) \). The natural transformation of vague functors \( \Phi \) induces a natural transformation of ordinary functors \( \Phi_{F_1} : \tilde{F}_1 \Rightarrow \tilde{F}_2 \).
Now the natural transformations of ordinary functors \( \Psi \) and \( \Phi \) may be composed horizontally in the usual way, giving a natural transformation \( E_1 \circ \bar{F}_1 \Rightarrow E_2 \circ \bar{F}_2 \). The composite functor \( \bar{E}_1 \circ \bar{F}_2 : G(YX) \to K \) and the composite vague functor \( E_1 \circ F_2 \) are related as follows: the latter is given by a functor \( E_1 \circ F_2 : G(Y_i X_j) \to K \), and we get \( \bar{E}_1 \circ \bar{F}_2 \) by composing \( E_1 \circ F_2 \) with the functor \( G(YX) \to G(Y_i X_j) \) associated to the coordinate projection \( YX \to Y_i X_j \). Now Lemma \[3.24\] shows that the natural transformation \( \Psi \circ \Phi \) descends to a natural transformation of vague functors \( E_1 \circ \bar{F}_1 \Rightarrow E_2 \circ \bar{F}_2 \). This defines the horizontal product.

It is routine to see that the horizontal product is associative and commutes with the vertical product (exchange law). For each proof, we replace vague functors by ordinary functors defined over suitable fibre products, and first get the desired equality of natural transformations on this larger fibre product. Then Lemma \[3.22\] shows that it holds as an equality of natural transformations of vague functors.

The composition of vague functors is associative and unital up to canonical isomorphisms of vague functors by Lemma \[3.22\]. These isomorphisms give natural transformations by Example \[3.21\]. These are natural with respect to natural transformations of vague functors and satisfy the usual coherence conditions; this follows from the simplifications of the vertical product with isomorphisms in \[3.7\] and \[5.5\].

**Theorem 3.24.** The bicategory of vague functors is the localisation of the bicategory of groupoids, functors and natural transformations at the class of hypercovers. More explicitly, let \( \mathcal{D} \) be a bicategory and let \( E \) be a functor from the category of groupoids with functors as arrows to \( \mathcal{D} \) that maps hypercovers to equivalences. Then \( E \) extends to a functor on the bicategory of vague functors; for any two such extensions of \( E \), there is a natural transformation between them, which is trivial on groupoids and ordinary functors.

**Proof.** Since we use hypercovers instead of weak equivalences between groupoids and cannot rely on abstract results on bicategories of fractions, our proof is more direct than similar arguments in \[3.7\] and \[3.9\]. We only sketch some of the ideas here.

Let \((X, p, F)\) be a vague functor from \( G \) to \( H \). Since \((X, p, F) \circ p_* = F\), any extension must satisfy \( \bar{E}(X, p, F) \circ E(p_*) \cong E(F) \), and since \( E(p_*) \) is invertible, there is a unique choice for \( \bar{E}(X, p, F) \) up to 2-arrows, namely, \( E(F) \circ E(p_*)^{-1} \) for some quasi-inverse \( E(p_*)^{-1} \) of the equivalence \( E(p_*) \). Now let \( \Phi : (X_1, p_1, F_1) \Rightarrow (X_2, p_2, F_2) \) be a vague natural transformation. Let \( X := X_1 \times_{p_1, G^0, p_2} X_2 \) and \( \bar{p}_i := p_i \circ \text{pr}_i \), \( \bar{F}_i := F_i \circ (\text{pr}_i)_* \), for \( i = 1, 2 \). By definition, \( \Phi \) is an ordinary natural transformation \( \Phi : \bar{F}_1 \Rightarrow \bar{F}_2 \), to which we may apply \( \bar{E} \). Since \( \text{pr}_i \) for \( i = 1, 2 \) are covers and \( (p_*)_* \circ (\text{pr}_i)_* = (p_i \circ \text{pr}_i)_* \), we get canonical 2-arrows

\[
\bar{E}(X_1, p_1, F_1) \cong \bar{E}(X, \bar{p}_1, \bar{F}_1) \xrightarrow{E(\Phi)} \bar{E}(X, \bar{p}_2, \bar{F}_2) \cong \bar{E}(X_2, p_2, F_2).
\]

We use this to define \( \bar{E} \) on 2-arrows.

Composing a vague functor with an identity functor literally does nothing, so it is trivial to find the unit transformations for \( \bar{E} \). When we compose two vague functors \((X, p, F_1)\) from \( G \) to \( H \) and \((Y, q, F_2)\) from \( H \) to \( K \), then we implicitly use \( q_* \circ \bar{F}_1(Y) = F_1 \circ \bar{q}_* \) for the cover \( \bar{q}_* = \text{pr}_1 : X \times_{F_1^0, H^0, \bar{q}} Y \to X \) to rewrite \( F_2 \circ q_*^{-1} \circ \bar{F}_1 \circ \text{pr}_1^{-1} = F_2 \circ \bar{F}_1(Y) \circ \bar{q}_*^{-1} \circ \text{pr}_1^{-1} = F_2 \circ \bar{F}_1(Y) \circ (p \circ \bar{q})^{-1} \); thus the product is given by \((X \times_{F_1^0} Y, \bar{q}, F_2 \circ \bar{F}_1(Y))\). Using the functoriality of \( \bar{E} \) for ordinary functors, we get canonical invertible 2-arrows

\[
E(q_*) \circ E(F_1(Y)) \cong E(q_* \circ F_1(Y)) = E(F_1 \circ \bar{q}) \cong E(F_1) \circ E(\bar{q}).
\]
We are going to provide necessary and sufficient conditions for this that are easier an isomorphism. Since being an isomorphism is a local property by Proposition 2.4, along this cover gives the map (3.10) for the functor $q$. A routine computation shows that this map from arrows to 2-arrows and the trivial map $G \to \text{id}_E$ from objects to arrows satisfy the appropriate coherence conditions for a natural transformation $E \Rightarrow E'$. Thus the extension is unique up to natural equivalence.

3.7. Vague equivalences and vague isomorphisms. An arrow $f: G \to H$ in a bicategory is an equivalence if there are an arrow $g: H \to G$ and invertible 2-arrows $g \circ f = \text{id}_G$ and $f \circ g = \text{id}_H$.

**Definition 3.25.** Equivalences in the bicategory of vague functors are called vague equivalences.

Vague natural transformations may be far from being “isomorphisms.” This makes it non-trivial to decide whether a given vague functor is a vague equivalence. We are going to provide necessary and sufficient conditions for this that are easier to check.

**Definition 3.26.** A vague isomorphism between two groupoids $G$ and $H$ in $(\mathcal{C}, \mathcal{T})$ is given by an object $X \in \mathcal{C}$, covers $p: X \to G^0$ and $q: X \to H^0$, and a groupoid isomorphism $F: p^*(G) \to q^*(H)$ with $F^0 = \text{id}_X$. A vague functor from $G$ to $H$ lifts to a vague isomorphism if it is equivalent (through a vague natural transformation) to $(X, p, q, F)$ for a vague isomorphism $(X, p, q, F)$.

**Definition 3.27.** A functor $F: G \to H$ is essentially surjective if the map

$$r_X: G_0 \times_{F^0, H^0, F} H^1 \to H^0, \quad (g, x) \mapsto s(x),$$

is a cover. It is almost essentially surjective if the map is a cover locally (see Definition 2.23). It is fully faithful if the fibre product $G_0 \times_{F^0, H^0, F} H^1 \times_{s, H^0, F^0} G^0$ exists in $\mathcal{C}$ and the map

$$G^1 \to G_0 \times_{F^0, H^0, F} H^1 \times_{s, H^0, F^0} G^0, \quad g \mapsto (r(g), F^1(g), s(g)),$$

is an isomorphism in $\mathcal{C}$. It is almost fully faithful if there is some cover $q: Y \to H^0$ for which the functor $q^*(F)$ is fully faithful.

It is trivial that essentially surjective functors are almost essentially surjective and fully faithful functors are almost fully faithful. The converse holds under Assumption 2.6.

**Lemma 3.28.** If Assumption 2.6 holds, then any almost essentially surjective functor is essentially surjective. An essentially surjective and almost fully faithful functor is fully faithful.

**Proof.** Assumption 2.6 says that a map that is locally a cover is a cover, so an almost essentially surjective functor is essentially surjective. The fibre product $G_0 \times_{F^0, H^0, F} H^1$ always exists because $r$ is a cover. If $F$ is essentially surjective, then $s: G_0 \times_{F^0, H^0, F} H^1 \to H^0$ is a cover, so the fibre product $(G_0 \times_{F^0, H^0, F} H^1) \times_{s, H^0, F^0} G^0$ exists. Let $q: Y \to H^0$ be a cover such that $q^*(F)$ is fully faithful. The projection $pr_{234}: Y \times_{q, H^0, F^0} G_0 \times_{F^0, H^0, F} H^1 \times_{s, H^0, F^0, F} G_0 \times_{F^0, H^0, q} Y \to G_0 \times_{F^0, H^0, F} H^1 \times_{s, H^0, F^0} G^0$ is a cover because $q$ is a cover. The pull-back of the map (3.10) for the functor $F$ along this cover gives the map for the functor $q^*(F)$, which is assumed to be an isomorphism. Since being an isomorphism is a local property by Proposition 2.4.
the functor $F$ is fully faithful if $q'(F)$ is fully faithful. (This conclusion holds whenever the fibre product $G^0 \times_{F^0, H^0, r} H^1 \times_{s, H^0, F} G^0$ exists.) \hfill \Box

Theorem 3.29. Let $(X, p, F)$ be a vague functor from $G$ to $H$. Then the following are equivalent:

1. $(X, p, F)$ is a vague equivalence;
2. the functor $F: G(X) \to H$ is almost fully faithful and almost essentially surjective;
3. $(X, p, F)$ lifts to a vague isomorphism.

If Assumption 2.6 holds, then we may replace $(2)$ by the condition that $F$ is fully faithful and essentially surjective – the usual definition of a weak equivalence.

The proof of the theorem will occupy the remainder of this subsection. The last statement is Lemma 3.31. We will show the implications $(1) \Rightarrow (2) \Rightarrow (3) \Rightarrow (1)$.

We start with the easiest implication: $(3) \Rightarrow (1)$. The main point here is the following example:

Example 3.30. Let $G$ be a groupoid in $(C, T)$ and let $p: X \to G^0$ be a cover. The hypercover $p_*: G(X) \to G$ is a vague equivalence. Its quasi-inverse is the vague functor $(X, p, \text{id}_G(X))$ from $G$ to $G(X)$. The composite functor $G \to G(X) \to G$ is the vague functor $(X, p, p_*)$. The unit section $X \to G(X)$ gives a natural transformation between $(X, p, p_*)$ and the identity vague functor $(G^0, \text{id}_{G^0}, \text{id}_G)$ on $G$. The other composite functor $G \to G \to G(X)$ is the vague functor $(X \times_{G^0} X, \text{pr}_1, (\text{pr}_2)_*)$. It is naturally equivalent to the identity on $G(X)$ because the functors $(\text{pr}_2)_*$ and $(\text{pr}_1)_*$ from $G(X \times_{G^0} X)$ to $G(X)$ are naturally equivalent.

If $F \cong q_* \circ \tilde{F}$ for a cover $q: X \to H^0$ and an isomorphism $\tilde{F}$, then the functors $F: G(X) \to H$ and $p_*: G(X) \to G$ are vague equivalences by Example 3.30. Since $(X, p, F) \circ p_* \cong F: G(X) \to H$, we have $(X, p, F) \cong F \circ (p_*)^{-1}$, so $(X, p, F)$ is a vague equivalence as well; here $\cong$ denotes equivalence of vague functors. Thus $(3)$ implies $(1)$ in Theorem 3.29.

Now we show $(2) \Rightarrow (3)$. The following lemma explains why (almost) fully faithful functors are related to hypercovers.

Lemma 3.31. A functor $F: G(X) \to H$ is isomorphic to a hypercover if and only if it is (almost) fully faithful and $F^0: X \to H^0$ is a cover.

Here “isomorphic” means that there is an isomorphism $G(X) \cong q^*(H)$ intertwining $F$ and the hypercover $q_*: q^*(H) \to H$.

Proof. If $F^0$ is a cover, then $F$ is essentially surjective, so $F$ is almost fully faithful if and only if $F$ is fully faithful by Lemma 3.28.

Let $F$ be fully faithful and let $F^0: X \to H^0$ be a cover. Since $F$ is fully faithful, the map $(r, F^1, s): G(X)^1 \cong X \times_{F^0, H^0, r} H^1 \times_{s, H^0, F} X$ is an isomorphism. This isomorphism together with the identity map on $X$ is a groupoid isomorphism from $G(X)$ to $(F^0)^*(H)$ that intertwines $F$ and $q_*$. Conversely, if $F \cong q_*$, then $F$ is fully faithful and $F^0$ is a cover because $q$ is one. \hfill \Box

Now assume that $F: G(X) \to H$ is almost fully faithful and almost essentially surjective. Then there is a cover $q: Y \to H^0$ such that the map

$$\text{pr}_3: XHY := X \times_{F^0, H^0, r} H^1 \times_{s, H^0, q} Y \to Y$$

is a cover. Then so is $q \circ \text{pr}_3: XHY \to H^0$. The projection $\text{pr}_1: XHY \to X$ is a cover because $q$ and $r$ are covers. Hence the vague functor $(X, p, F)$ is equivalent to $(XHY, p \circ \text{pr}_1, F \circ (\text{pr}_1)_*)$. This functor maps $(x, h, y) \mapsto F^0(x)$ on objects and
between the resulting fibre products. The conjugation map

\[ (z_1, x_1, h_1, y_1, g, x_2, h_2, y_2, z_2) \mapsto (z_1, x_1, y_1, h_1, F^1(x_1, g, x_2), x_2, h_2, y_2, z_2) \]

is an isomorphism. Adding extra variables \( y_1, y_2 \in Y, h_1, h_2 \in H^1 \) with \( (x_1, h_1, y_i) \in XHY \) for \( i = 1, 2 \) gives an isomorphism

\[ (z_1, x_1, h_1, y_1, h, x_2, h_2, y_2, z_2) \mapsto (z_1, x_1, y_1, h, h^{-1}_1 h h_2, x_2, h_2, y_2, z_2) \]

is an isomorphism between suitable fibre products as well, with inverse

\[ (z_1, x_1, h_1, y_1, h, x_2, h_2, y_2, z_2) \mapsto (z_1, x_1, y_1, h, h h_2^{-1}, x_2, h_2, y_2, z_2). \]

Composing these isomorphisms gives the map

\[ (z_1, x_1, h_1, y_1, g, x_2, h_2, y_2, z_2) \mapsto (z_1, x_1, y_1, h, h, h, h_2, x_2, h_2, y_2, z_2). \]

Since this is an isomorphism, \( G \) is almost fully faithful.

Since \( G \) is almost fully faithful and \( G^0 \) is a cover, \( G \) is isomorphic to a hypercover by Lemma 3.32. Thus \( (X, p, F) \) lifts to a vague isomorphism. This finishes the proof that \([2]\Rightarrow[3]\) in Theorem 3.29.

Finally, we show that \([1]\) implies \([2]\) in Theorem 3.29; this is the most difficult part of the theorem. A vague equivalence is given by vague functors \( (X, p, F) : G \to H \) and \( (Y, q, E) : H \to G \) and natural transformations \( \Psi : (X, p, F) \circ (Y, q, E) \Rightarrow \text{id}_H \) and \( \Phi : (Y, q, E) \circ (X, p, F) \Rightarrow \text{id}_G \), which are automatically invertible. More explicitly, \( \Psi : Y \times_{E^0, G^0, p} X \to H^1 \) is a vague natural transformation from \( F \circ p^*E \) to \( \text{id}_H \); that is, \( \Psi(y, x) \in H^1 \) is defined for all \( y \in Y, x \in X \) with \( E^0(y) = p(x) \) and is an arrow in \( H^1 \) with \( s(\Psi(y, x)) = F^0(x) \) and \( t(\Psi(y, x)) = q(y) \); and for all \( (x_1, y_1, h, y_2, x_2) \in X \times_{p, G^0, E^0} Y \times_{q, H^1, q} Y \times E^0, G^0, p \times \)

\[ \Psi(y_1, x_1) \cdot F^1(x_1, E^1(y_1, h, y_2), x_2) = h \cdot \Psi(y_2, x_2); \]

and \( \Phi : X \times_{F^0, H^1, q} Y \to G^1 \) is a natural transformation from \( E \circ q^*F \) to \( \text{id}_G \), that is, \( \Phi(x, y) \in G^1 \) is defined for all \( x \in X, y \in Y \) with \( F^0(x) = q(y) \) and is an arrow in \( G^1 \) with \( s(\Phi(x, y)) = E^0(y) \) and \( t(\Phi(x, y)) = p(x) \); and for all \( (y_1, x_1, g, x_2, y_2) \in Y \times_{p, H^1} Y \times_{q, G^1, q} G^1 \times_{s, G^0, p} X \times_{F^0, H^1, q} Y \),

\[ \Phi(x_1, y_1) \cdot E^1(y_1, F^1(x_1, g, x_2), y_2) = g \cdot \Phi(x_2, y_2). \]
Lemma 3.33. There is a unique map $a: X \times_{f^0,H^p,r} H^1 \times_{s,H^p,q} Y \to G^1$ with

\begin{equation}
(a(x_1, h, y_2) = \Phi(x_1, y_1) \cdot E^1(y_1, h, y_2)
\end{equation}

for all $x_1 \in X$, $h \in H^1$, $y_1, y_2 \in Y$ with $F^0(x_1) = r(h) = q(y_1)$, $s(h) = q(y_2)$.

The following map is an isomorphism:

$$(pr_1, a, pr_3): X \times_{f^0,H^p,r} H^1 \times_{s,H^p,q} Y \cong X \times_{p,G^0,r} G^1 \times_{s,G^0,E^0} Y.$$ 

Proof. The fibre products $X \times_{f^0,H^p,r} H^1 \times_{s,H^p,q} Y$ and $Y \times_{q,H^p,p^0} X \times_{f^0,H^p,r} H^1 \times_{s,H^p,q} Y$ exist because $r$ and $q$ are covers. The fibre product $X \times_{p,G^0,r} G^1 \times_{s,G^0,E^0} Y$ exists because $p$ and $s$ are covers. Equation (3.13) defines a map $\hat{a}: Y \times_{q,H^p,p^0} X \times_{f^0,H^p,r} H^1 \times_{s,H^p,q} Y \to G^1$. We must check that $\hat{a}$ factors through the projection $pr_{234}$. Since $q$ is a cover, so is $pr_{234}$. Since our pretopology is subcanonical, $\hat{a}$ factors through this cover if and only if $\hat{a} \circ \pi_1 = \hat{a} \circ \pi_2$, where $\pi_1, \pi_2$ are the two canonical projections

$$(Y \times_{q,H^p,p^0} X \times_{f^0,H^p,r} H^1 \times_{s,H^p,q} Y) \times_{pr_{234}, pr_{1345}} (Y \times_{q,H^p,p^0} X \times_{f^0,H^p,r} H^1 \times_{s,H^p,q} Y) \to Y \times_{q,H^p,p^0} X \times_{f^0,H^p,r} H^1 \times_{s,H^p,q} Y.$$ 

We may identify $\pi_1, \pi_2$ with the two coordinate projections

$$pr_{2345}, pr_{1345}: Y \times_{q,H^p,q} Y \times_{q,H^p,p^0} X \times_{f^0,H^p,r} H^1 \times_{s,H^p,q} Y \Rightarrow Y \times_{q,H^p,p^0} X \times_{f^0,H^p,r} H^1 \times_{s,H^p,q} Y.$$ 

Hence $\hat{a}$ factors through $pr_{234}$ if and only if $\hat{a}(y_1, x_1, h, y_2) = \hat{a}(y_1', x_1, h, y_2)$ for all $y_1, y_1', y_2 \in Y$, $x_1 \in X$, $h \in H^1$ with $q(y_1) = q(y_1') = F^0(x_1) = r(h)$, $s(h) = q(y_2)$.

Equivalently,

$$\Phi(x_1, y_1) \cdot E^1(y_1, h, y_2) = \Phi(x_1, y_1') \cdot E^1(y_1', h, y_2)$$

for $y_1, y_1', x_1, h, y_2$ as above. Since $E^1(y_1', h, y_2) = E^1(y_1', 1_{q(y_1)}, y_1) \cdot E^1(y_1, h, y_2)$, and $q(y_1) = q(y_1') = F^0(x_1)$, this is equivalent to

$$\Phi(x_1, y_1) = \Phi(x_1, y_1') \cdot E^1(y_1', 1_{q(y_1)}, y_1) = \Phi(x_1, y_1') \cdot E^1(y_1, F^1(x_1, 1_{p(x_1)}, x_1), y_1).$$

This equation is a special case of the naturality condition (3.12) for $\Phi$. This finishes the proof that $\hat{a}$ factors through a unique map $a: X \times_{f^0,H^p,r} H^1 \times_{s,H^p,q} Y \to G^1$.

Since $r(a(x_1, h, y_2)) = r(\Phi(x_1, y_2)) = p(x_1)$ and $s(a(x_1, h, y_2)) = s(E^1(y_1, h, y_2)) = E^0(y_2)$, the map $(pr_1, a, pr_3)$ maps $X \times_{f^0,H^p,r} H^1 \times_{s,H^p,q} Y$ to $X \times_{p,G^0,r} G^1 \times_{s,G^0,E^0} Y$.

The property of being an isomorphism is local by Proposition 2.24. Thus the map $(pr_1, a, pr_3)$ is an isomorphism if and only if the following pull-back along a cover induced by $q$ is an isomorphism:

$$(pr_1, pr_2, \hat{a}, pr_4): Y \times_{q,H^p,p^0} X \times_{f^0,H^p,r} H^1 \times_{s,H^p,q} Y \Rightarrow Y \times_{q,H^p,p^0} X \times_{p,G^0,r} G^1 \times_{s,G^0,E^0} Y.$$ 

Here we have simplified the pull-back using the construction of $a$ through $\hat{a}$. Actually, to construct a map in the opposite direction, we add even more variables and study the map

$$\beta: X \times_{p,H^p,E^0} Y \times_{q,H^p,p^0} X \times_{f^0,H^p,r} H^1 \times_{s,H^p,q} Y \times_{E^0,G^0,p} X \times_{f^0,H^p,q} Y \to X \times_{p,H^p,E^0} Y \times_{q,H^p,p^0} X \times_{p,G^0,r} G^1 \times_{s,G^0,E^0} Y \times_{E^0,G^0,p} X \times_{f^0,H^p,q} Y,$$

$$(x_3, y_1, x_1, h, y_2, x_2, y_3) \mapsto (x_3, y_1, x_1, \Phi(x_1, y_1) \cdot E^1(y_1, h, y_2), y_2, x_2, y_3).$$

Since $p$ and $q$ are covers, the fibre products above exist and $\beta$ is a pull-back of $(pr_1, a, pr_4)$ along a cover. By Proposition 2.24, it suffices to prove that $\beta$ is invertible.
In the opposite direction, we have the map defined elementwise by
\[ \gamma(x_3, y_1, x_1, g, y_2, x_2, y_3) := F^1(x_1, g, x_2) \cdot \Psi(y_2, x_2)^{-1}; \]
the product is well-defined because \( s(F^1(x_1, g, x_2)) = F^0(x_2) = s(\Psi(y_2, x_2)) \), and it has range and source \( r(F^1(x_1, g, x_2)) = F^0(x_1) \) and \( r(\Psi(y_2, x_2)) = q(y_2) \), respectively, so \( (x_3, y_1, x_1, F^1(x_1, g, x_2) \cdot \Psi(y_2, x_2)^{-1}, y_2, x_2, y_3) \) belongs to the domain of \( \beta \). We compute
\[
\begin{align*}
\beta \circ \gamma(x_3, y_1, x_1, g, y_2, x_2, y_3) &= \Phi(x_1, y_1) \cdot E^1(y_1, F^1(x_1, g, x_2) \cdot \Psi^{-1}(y_2, x_2), y_2) \\
&= \Phi(x_1, y_1) \cdot E^1(y_1, F^1(x_1, g, x_2), y_3) \cdot E^1(y_3, \Psi(y_2, x_2)^{-1}, y_2) \\
&= g \cdot \Phi(x_2, y_3) \cdot E^1(y_3, \Psi(y_2, x_2)^{-1}, y_2), \\
\gamma \circ \beta(x_3, y_1, x_1, h, y_2, x_2, y_3) &= F^1(x_1, \Phi(x_1, y_1) \cdot E^1(y_1, h, y_2), x_2) \cdot \Psi(y_2, x_2)^{-1} \\
&= F^1(x_1, \Phi(x_1, y_1), x_3) \cdot F^1(x_3, E^1(y_1, h, y_2), x_2) \cdot \Psi(y_2, x_2)^{-1} \\
&= F^1(x_1, \Phi(x_1, y_1), x_3) \cdot \Psi(y_1, x_3)^{-1} \cdot h.
\end{align*}
\]
The first map multiplies \( g \) from the right with some complicated element \( \xi \) of \( G^1 \) with \( r(\xi) = s(\xi) = s(g) \); the crucial point is that \( \xi \) does not depend on \( q \), so the map \( g \mapsto g \cdot \xi \) is a well-defined inverse for \( \beta \circ \gamma \). Similarly, the map \( \gamma \circ \beta \) is invertible because it multiplies \( h \) on the left with some element \( \eta \) of \( H^1 \) with \( s(\eta) = r(\eta) = r(h) \). Thus \( \beta \) is both left and right invertible, so it is invertible.

\[ \square \]

Lemma 3.34. \textit{The projection} \( \text{pr}_3 : XHY := X \times_{F^0, H^0} \times_{H^0, H^0} \times_{H^0, q} Y \to Y \) \textit{is a cover.}

Proof. The isomorphism in Lemma \ref{lem:iso} allows us to replace \( \text{pr}_3 : XHY \to Y \) by \( \text{pr}_3 : XGY := X \times_{p, G^0} \times_{H^0, G^0} \times_{H^0, q} Y \to Y \). Since \( p : X \to G^0 \) and \( s : G^1 \to G^0 \) are covers, so are the induced maps \( \text{pr}_{3q} : XGY \to GY \) and \( \text{pr}_2 : GY \to Y \). Hence so is their composite \( \text{pr}_3 : XGY \to Y \).

\[ \square \]

Lemma 3.35. \textit{The functor} \( F : G(X) \to H \) \textit{is almost essentially surjective.}

Proof. We consider the following diagram
\[ \begin{array}{ccc}
X \times_{F^0, H^0, p} H^1 & \xrightarrow{\text{pr}_Y} & Y \\
\downarrow \text{pr}_{12} & & \downarrow q \\
X \times_{p, G^0, p} H^1 & \xrightarrow{s \circ \text{pr}_{H^1}} & H^0
\end{array} \]

Lemma \ref{lem:prY-cover} shows that \( \text{pr}_Y \) is a cover. The map \( q \) is a cover by assumption. Thus \( s \circ \text{pr}_{H^1} \) is locally a cover, meaning that \( F \) is almost essentially surjective.

\[ \square \]

Lemma 3.36. \textit{The functor} \( F : G(X) \to H \) \textit{is almost fully faithful.}

Proof. We claim that \( q^*(F) \) is fully faithful for the given cover \( q : Y \to H^0 \), that is, the map
\[
\begin{align*}
\beta : Y \times_{q, H^0, p} X \times_{p, G^0} G^1 \times_{s, G^0, p} X \times_{p, H^0, q} Y & \to Y \times_{q, H^0, p} X \times_{p, H^0} H^1 \times_{s, H^0, q} Y \times_{q, H^0, p} X, \\
(y_1, x_1, g, y_2, y_3) & \mapsto (y_1, x_1, F^1(x_1, g, x_2), y_2, x_2),
\end{align*}
\]
is an isomorphism. The fibre product on the right exists because by Lemma \ref{lem:prY-cover}.

An element of the codomain of \( \beta \) is given by \( y_1, y_2 \in Y, x_1, x_2 \in X, h \in H^1 \) with
\[ q(y_1) = F^0(x_1) = \tau(h), \ q(y_2) = F^0(x_2) = s(h). \] Hence \( E^1(y_1, h, y_2), \ \Phi(x_1, y_1) \) and \( \Phi(x_2, y_2) \) are well-defined arrows in \( G^1 \), and their ranges and sources match so that

\[ \gamma(y_1, x_1, h, x_2, y_2) := \Phi(x_1, y_1) \cdot E^1(y_1, h, y_2) \cdot \Phi(x_2, y_2)^{-1} \in G^1 \]

is well-defined and has range \( \tau(\Phi(x_1, y_1)) = p(x_1) \) and source \( s(\Phi(x_2, y_2)) = p(x_2) \).

We get a map

\[ \tilde{\gamma} : Y \times_{q,H^p,F^0} X \times_{F^0,H^p,q} H^1 \times_{s,H^p,F^0} X \times_{F^0,H^p,q} X \rightarrow Y \times_{q,H^p,F^0} X \times_{p,G^0,r} G^1 \times_{s,G^0,p} X \times_{F^0,H^p,q} Y, \]

\[ ((y_1, x_1, h, x_2, y_2)) \mapsto (y_1, x_1, \gamma(y_1, x_1, h, x_2, y_2), x_2, y_2). \]

The map \( \tilde{\gamma} \circ \beta \) is the identity on \( Y \times_{q,H^p,F^0} X \times_{p,G^0,r} G^1 \times_{s,G^0,p} X \times_{F^0,H^p,q} Y \) by the naturality condition \( \text{[3.12]} \).

We are going to show that the composite \( \beta \circ \tilde{\gamma} \) is invertible (and hence the identity because \( \beta \circ \beta \) is the identity). Elementwise, \( \beta \circ \tilde{\gamma} \) maps \((y_1, x_1, h, x_2, y_2)\) to \((y_1, x_1, \eta(y_1, x_1, h, x_2, y_2), x_2, y_2)\) with

\[ \eta(y_1, x_1, h, x_2, y_2) = F^1(x_1, \Phi(x_1, y_1) \cdot E^1(y_1, h, y_2) \cdot \Phi(x_2, y_2)^{-1}, x_2) \]

To show that \( \beta \circ \tilde{\gamma} \) is an isomorphism, we pull \( \beta \circ \tilde{\gamma} \) back to the map on

\[ X \times_{p,G^0,F^0} Y \times_{q,H^p,F^0} X \times_{F^0,H^p,q} X \rightarrow Y \times_{q,H^p,F^0} X \times_{p,G^0,r} G^1 \times_{s,G^0,p} X \times_{F^0,H^p,q} Y \times_{p,G^0,F^0} X \]

that sends \((x_3, y_1, x_1, h, x_2, y_2, x_4)\) to \((x_3, y_1, x_1, \eta(y_1, x_1, h, x_2, y_2), x_2, y_2, x_4)\). Since \( p : X \rightarrow G^0 \) is a cover, Proposition \( \text{[2.4]} \) shows that \( \beta \circ \tilde{\gamma} \) is an isomorphism if and only if this new map is an isomorphism. Using the extra variables \( x_3, x_4 \), we may simplify \( \eta \):

\[ \eta(y_1, x_1, h, x_2, y_2) = F^1(x_1, \Phi(x_1, y_1) \cdot E^1(y_1, h, y_2) \cdot \Phi(x_2, y_2)^{-1}, x_2) \]

\[ = F^1(x_1, \Phi(x_1, y_1), x_3) \cdot F^1(x_3, E^1(y_1, h, y_2), x_4) \cdot F^1(x_4, \Phi(x_2, y_2)^{-1}, x_2) \]

\[ = F^1(x_1, \Phi(x_1, y_1), x_3) \cdot \Psi(y_1, x_4) \cdot F^1(x_4, \Phi(x_2, y_2)^{-1}, x_2). \]

This map is invertible because \( \eta \) multiplies \( h \) on the left and right by expressions that do not depend on \( h \): the inverse maps \((x_3, y_1, x_1, h, x_2, y_2, x_4)\) to

\[ (x_3, y_1, x_1, \Psi(y_1, x_3) \cdot F^1(x_1, \Phi(x_1, y_1), x_3)^{-1} \cdot h \times F^1(x_2, \Phi(x_2, y_2), x_4) \cdot \Psi(y_2, x_4)^{-1}, x_2, y_2, x_4). \]

Thus \( \beta \circ \tilde{\gamma} \) is invertible. It follows that \( \beta \) is invertible, so that \( F \) is almost fully faithful.

This finishes the proof that \( \text{[1]} \) implies \( \text{[2]} \) in Theorem \( \text{[3.29]} \) and hence the proof of the theorem.

4. **Groupoid actions**

Let \( \mathcal{C} \) be a category with coproducts and \( \mathcal{T} \) a subcanonical pretopology on \( \mathcal{C} \).

**Definition and Lemma 4.1.** Let \( G = (G^0, G^1, r, s, m) \) be a groupoid in \((\mathcal{C}, \mathcal{T})\). A (right) \( G \)-**action** in \( \mathcal{C} \) is \( X \in \mathcal{C} \) with \( s \in \mathcal{C}(X, G^0) \) (anchor) and \( m \in \mathcal{C}(X \times_{s,G^0} G^1, X) \) (action), denoted multiplicatively as \( \cdot \), such that

1. \( s(x \cdot g) = s(g) \) for all \( x \in X \), \( g \in G^1 \) with \( s(x) = \tau(g) \);
2. \( (x \cdot g_1) \cdot g_2 = x \cdot (g_1 \cdot g_2) \) for all \( x \in X \), \( g_1, g_2 \in G^1 \) with \( s(x) = \tau(g_1) \); \( s(g_1) = \tau(g_2) \);
3. \( x \cdot 1_s(x) = x \) for all \( x \in X \).

This definition does not depend on \( \mathcal{T} \). In the presence of (1) and (2), the third condition is equivalent to

1. \( m : X \times_{s,G^0} G^1 \rightarrow X \) is an epimorphism;
2. \( m : X \times_{s,G^0} G^1 \rightarrow X \) is a cover;
We have not yet tried to carry over some of the usual constructions with sheaves. An action where the anchor map is a cover is called a sheaf over $G$.

**Remark** 4.2. Conditions (1)–(3) imply $(x \cdot g)^{-1} \cdot g = x \cdot (g^{-1} \cdot g) = x \cdot 1_{s(x)} = x$ for all $x \in X$, $g \in G^1$ with $s(x) = s(g)$ and $(x \cdot g) \cdot g^{-1} = x$ for $x \in X$, $g \in G^1$ with $s(x) = r(g)$. Hence the elementwise formula $(x, g) \mapsto (x \cdot g^{-1}, g)$ gives an inverse for the map in $(3'')$. Thus (3) implies $(3'')$ in the presence of (1) and (2).

Assume $(3'')$. The map $pr_{1} : X \times_{s,G^0} G^1 \to X$ is a cover because $s : G^1 \to G^0$ is a cover. Composing with the isomorphism in $(3'')$ shows that $m$ is a cover. Covers are epimorphisms because the pretopology is subcanonical. Thus

$(1)\rightarrow(3)\Rightarrow(3'')\Rightarrow(3') \Rightarrow (3')$.

Since $(x \cdot g) \cdot 1_{s(g)} = x \cdot (g \cdot 1_{s(g)}) = x \cdot g$ for all $x \in X$, $g \in G^1$ with $s(x) = r(g)$, the map $f : X \to X$, $x \mapsto x \cdot 1_{s(x)}$, satisfies $f \circ m = m$. If $m$ is an epimorphism, this implies $f = id_X$. Thus $(3')$ implies (3).

**Remark** 4.2. Sheaves over a Lie groupoid are equivalent to groupoid actions with an étale anchor map (see [30]). Sheaf theory only works well for étale groupoids, however. If we work in the category of smooth manifolds or topological spaces with étale surjections as covers, then the above definition of a sheaf is almost equivalent to the usual one. We also require the anchor map to be surjective, which restricts to sheaves for which all stalks are non-empty; this seems a rather mild restriction. We have not yet tried to carry over some of the usual constructions with sheaves to non-étale groupoids using the above definition.

The class of groupoid actions with a cover as anchor map certainly deserves special consideration, but it is not a good idea to require this for all actions. Then we would also have to require this for bibundles and, in particular, for bibundle functors. Hence we could only treat covering bibundle functors, where both anchor maps are covers. But the bibundle functor associated to a functor need not be covering: this happens if and only if the functor is essentially surjective. As a result, vague functors and bibundle functors would no longer be equivalent.

**Definition** 4.3. Let $X$ and $Y$ be right $G$-actions. A $G$-equivariant map or briefly G-map $X \to Y$ is $f \in \mathcal{C}(X, Y)$ with $s(f(x)) = s(x)$ for all $x \in X$ and $f(x \cdot g) = f(x) \cdot g$ for all $x \in X$, $g \in G^1$ with $s(x) = r(g)$.

The $G$-actions and $G$-maps form a category, which we denote by $\mathcal{C}(G)$. Let $\mathcal{C}_T(G) \subseteq \mathcal{C}(G)$ be the full subcategory of $G$-sheaves.

**Definition** 4.4. Let $X$ be a $G$-action and $Z \in \mathcal{C}$. A map $f \in \mathcal{C}(X, Z)$ is $G$-invariant if $f(x \cdot g) = f(x)$ for all $x \in X$, $g \in G^1$ with $s(x) = r(g)$.

4.1. Examples.

**Example** 4.5. Any groupoid $G$ acts on $G^0$ by $s = id_{G^0}$ and $r(g) \cdot g = s(g)$ for all $g \in G^1$.

**Proposition** 4.6. $G^0$ is a final object in $\mathcal{C}(G)$ and $\mathcal{C}_T(G)$.

**Proof.** For any $G$-action $X$, the source map $s$ is a $G$-map, and it is the only $G$-map $X \to G^0$. Since identity maps are covers, $G^0$ belongs to $\mathcal{C}_T(G)$. □

**Example** 4.7. View $Y \in \mathcal{C}$ as a groupoid as in Example 3.7. A $Y$-action on $X$ is equivalent to a map $X \to Y$, namely, the anchor map of the action; the multipication map $X \times_Y Y \to X$ must be the canonical isomorphism. A $Y$-map between actions $s_i : X_i \to Y$, $i = 1, 2$, of $Y$ is a map $f : X_1 \to X_2$ with $s_2 \circ f = s_1$. Thus $\mathcal{C}(Y)$ is the slice category $(\mathcal{C} \downarrow Y)$ of objects in $\mathcal{C}$ over $Y$.
Example 4.8. Let \( G \) be a group in \((\mathcal{C}, \mathcal{T})\), that is, \( G^0 \) is a final object. Then there is a unique map \( X \to G^0 \) for any \( X \in \mathcal{C} \). Since this unique map is the only choice for the anchor map, a \( G \)-action is given by the multiplication map \( X \times G^1 \to X \) alone. This defines a group action if and only if \((x \cdot g_1) \cdot g_2 = x \cdot (g_1 \cdot g_2)\) for all \( x \in X, g_1, g_2 \in G^1 \), and \( x \cdot 1 = x \) for all \( x \in X \); the unit element 1 is defined in Example 3.10.

4.2. Transformation groupoids.

Definition and Lemma 4.9. Let \( X \) be a right \( G \)-action. The transformation groupoid \( X \rtimes G \) in \((\mathcal{C}, \mathcal{T})\) is the groupoid with objects \( X \), arrows \( X \times_{s \in G^0} G^1 \), range \( \text{pr}_1 \), source \( m \), and multiplication defined by

\[
(x_1, g_1) \cdot (x_2, g_2) := (x_1, g_1 \cdot g_2)
\]

for all \( x_1, x_2 \in X, g_1, g_2 \in G^1 \) with \( s(x_1) = r(g_1), s(x_2) = r(g_2) \), and \( x_1 \cdot g_1 = x_2 \), that is, \( s(x_1, g_1) = r(x_2, g_2) \) in \( X \); then \( r(x_1) = r(g_1 \cdot g_2) \), so that \((x_1, g_1) \cdot g_2 \in X \times_{s \in G^0} G^1 \).

This is a groupoid in \((\mathcal{C}, \mathcal{T})\) with unit map and inversion given by \( 1_x := (x, 1_{s(x)}) \) and \((x, g)^{-1} := (x, g^{-1}) \). It acts on \( X \) with anchor map \( s = \text{id}_X : X \to X \), by \( x \cdot (x, g) := x \cdot g \) for all \( x \in X, g \in G^1 \) with \( s(x) = r(g) \).

Proof. The range map \( \text{pr}_1 : X \times_{s \in G^0} G^1 \to X \) of \( X \rtimes G \) is a cover because \( r : G^1 \to G^0 \) is a cover; Lemma 4.1 shows that the source map \( m \) of \( X \rtimes G \) is a cover as well. The remaining properties are routine computations. The action of \( X \rtimes G \) on \( X \) is a special case of Example 4.5. \( \square \)

Proposition 4.10. Let \( X \) be a \( G \)-action. An action of the transformation groupoid \( X \rtimes G \) on an object \( Y \in \mathcal{C} \) is equivalent to an action of \( G \) on \( Y \) together with a \( G \)-map \( f : Y \to X \). Furthermore,

\[
Y \rtimes (X \rtimes G) \cong Y \rtimes G,
\]

a map \( Y \to Z \) is \( X \rtimes G \)-invariant if and only if it is \( G \)-invariant, and a map between two \( X \rtimes G \)-actions is \( X \rtimes G \)-equivariant if and only if it is \( G \)-equivariant.

Proof. An action of \( X \rtimes G \) on \( Y \) is given by an anchor map \( f : Y \to X \) and a multiplication map

\[
Y \times f, \text{pr}_1 (X \times_{s \in G^0} G^1) \to Y.
\]

We compose \( f \) with \( s_X : X \to G^0 \) to get an anchor map \( s_Y : Y \to G^0 \), and we compose the multiplication map with the canonical isomorphism

\[
X \times_{s_Y, G^0} G^1 \cong Y \times f, \text{pr}_1 (X \times_{s \in G^0} G^1)
\]

to get a \( G \)-action on \( Y \): \( y \cdot g := y \cdot f(y), g \) for all \( y \in Y, g \in G^1 \) with \( s(f(y)) = r(g) \). It is routine to check that this is an action of \( G \). The map \( f \) is \( G \)-equivariant: \( s_X \circ f = s_Y \) by construction, and \( f(y \cdot g) = s_X \circ c(f(y), g) = f(y) \cdot g \).

Conversely, given a \( G \)-action on \( Y \) and a \( G \)-equivariant map \( f : X \to Y \), we define an action of \( X \rtimes G \) by taking \( f \) as the anchor map and \( y \cdot (x, g) := y \cdot g \) for all \( y \in Y, x \in X, g \in G^1 \) with \( f(y) = x, s(x) = r(g) \). These two processes are inverse to each other. Since both constructions are natural, \( X \rtimes G \) and \( G \)-invariance are equivalent for maps between \( X \rtimes G \)-actions.

The transformation groupoids \( Y \rtimes (X \rtimes G) \) and \( Y \rtimes G \) have the same objects \( Y \), and isomorphic arrows by \( (4.1) \). This isomorphism also intertwines their range, source and multiplication maps, so both transformation groupoids for \( Y \) are isomorphic. The isomorphism \( (4.1) \) also implies that \( X \rtimes G \) and \( G \)-invariance are equivalent. \( \square \)
4.3. Left actions and several commuting actions. Let $G$-actions and $G$-maps between them are defined similarly; but we denote anchor maps for left actions by $r: X \to G^0$ instead of $s$.

**Lemma 4.11.** The categories of left and right $G$-actions are isomorphic.

**Proof.** We turn a right $G$-action $(s, m)$ on $X$ into a left $G$-action by $r = s$ and $g \cdot x := x \cdot g^{-1}$ for $g \in G^1$, $x \in X$ with $r(g^{-1}) = s(g) = r(x)$. A left $G$-action gives a right one by $s = r$ and $x \cdot g := g^{-1} \cdot x$ for $x \in X$, $g \in G^1$ with $s(x) = r(g) = s(g^{-1})$. A map is equivariant for left actions if and only if it is equivariant for the corresponding right actions, so this is an isomorphism of categories.

**Definition 4.12.** Let $G$ and $H$ be groupoids in $(\mathcal{C}, \mathcal{T})$. A $G, H$-bibundle is $X \in \mathcal{C}$ with a left $G$-action and a right $H$-action such that $s(g \cdot x) = s(x)$, $r(x \cdot h) = r(x)$, and $(g \cdot x) \cdot h = g \cdot (x \cdot h)$ for all $g \in G^1$, $x \in X$, $h \in H^1$ with $s(g) = r(x)$, $s(x) = r(h)$. Let $\mathcal{C}(G, H)$ be the category with $G, H$-bibundles as objects and $G, H$-maps — maps $X \to Y$ that are equivariant for both actions — as arrows.

A $G, H$-bibundle also has a **transformation groupoid** $G \ltimes X \rtimes H$ with objects $X$ and arrows

\[(G \ltimes X \rtimes H)^1 := G^1 \ltimes_{s, G^0, r} X \ltimes_{s, H^0, r} H^1;\]

\[r(g, x, h) := g \cdot x, s(g, x, h) := x \cdot h, \text{ and}\]

\[(g_1, x_1, h_1) \cdot (g_2, x_2, h_2) := (g_1 \cdot g_2, g_2^{-1} \cdot x_1, h_1 \cdot h_2) = (g_1 \cdot g_2, x_2 \cdot h_1^{-1}, h_1 \cdot h_2)\]

for all $g_1, g_2 \in G^1$, $x_1, x_2 \in X$, $h_1, h_2 \in H^1$ with $s(g_1) = r(x_1)$, $s(x_1) = r(h_1)$ for $i = 1, 2$ and $x_1 \cdot h_1 = g_2 \cdot x_2$, so that $g_2^{-1} \cdot x_1 = x_2 \cdot h_1^{-1}$.

**Remark 4.13.** Assume Assumption 2.8 Then the product of two groupoids in $(\mathcal{C}, \mathcal{T})$ is again a groupoid in $(\mathcal{C}, \mathcal{T})$: the range and source maps are again covers by Lemma 2.10. The category $\mathcal{C}(G, H)$ is isomorphic to $\mathcal{C}(G \ltimes H)$: actions of $G$ and $H$ determine an action of $G \ltimes H$ by $x \cdot (g, h) := g^{-1} \cdot x \cdot h$ for $x \in X$, $g \in G^1$, $h \in H^1$ with $r(g) = s(x)$, $s(x) = r(h)$. Here we use that $(g, h) \in G^1 \times H^1$ is equivalent to $g \in G^1$ and $h \in H^1$. The transformation groupoid $G \ltimes X \rtimes H$ is naturally isomorphic to the transformation groupoid $G \ltimes (G \ltimes H)$ via $(g, x, g^{-1}, h)$.

More generally, we may consider an object of $\mathcal{C}$ with several groupoids acting on the left and several on the right, with all actions commuting. We single out $G, H$-bibundles because they are the basis of several bicategories of groupoids.

4.4. Fibre products of groupoid actions. Let $X_1$, $X_2$ and $Y$ be $G$-actions and let $f_i: X_i \to Y$ for $i = 1, 2$ be $G$-maps. Assume that the fibre product $X := X_1 \times_{f_1, Y, f_2} X_2$ exists in $\mathcal{C}$ (this happens, for instance, if $f_1$ or $f_2$ is a cover).

**Lemma 4.14.** There is a unique $G$-action on $X$ for which both coordinate projections $pr_i: X \to X_i$, $i = 1, 2$, are equivariant. With this $G$-action, $X$ becomes a fibre product in the category of $G$-actions.

**Proof.** We define a $G$-action on $X$ as follows. The anchor map $s: X \to G^0$ is defined by

\[s(x_1, x_2) := s(x_1) = s(f_1(x_1)) = s(f_2(x_2)) = s(x_2),\]

the multiplication by $(x_1, x_2) \cdot g := (x_1 \cdot g, x_2 \cdot g)$ for all $x_1, x_2 \in X_1$, $g \in G^1$ with $f_1(x_1) = f_2(x_2)$ and $s(x_1, x_2) = r(g)$. This elementwise formula defines a map $(X_1 \times_{f_1, Y, f_2} X_2) \ltimes_{s, G^0, r} G^1 \to X_1 \times_{f_1, Y, f_2} X_2$ by taking $? = (X_1 \times_{f_1, Y, f_2} X_2) \ltimes_{s, G^0, r} G^1$.

Routine computations show that this defines a $G$-action on $X$. The coordinate projections $X \to X_i$ for $i = 1, 2$ are $G$-equivariant by construction, and the above formulas are clearly the only ones that make this happen. Finally, a map $h: W \to X$
is a $G$-map if and only if $h_i := pr_i o h$ for $i = 1, 2$ are $G$-maps, and two $G$-maps $h_i : W \to X_i$ combine to a $G$-map $W \to X$ if and only if $f_1 o h_1 = f_2 o h_2$. Thus $X$ has the property of a fibre product in the category $\mathcal{C}(G)$.

\[ \square \]

4.5. **Actors: another category of groupoids.** A functor $G \to H$ between two groupoids does not induce a functor $\mathcal{C}(H) \to \mathcal{C}(G)$. (The only general result is Proposition 7.6 which gives a functor $\mathcal{C}_T(H) \to \mathcal{C}(G)$ on the subcategory of sheaves.) Here we introduce actors, a different type of groupoid morphisms that are equivalent to functors $\mathcal{C}(H) \to \mathcal{C}(G)$ with some extra properties. In the context of locally compact groupoids, these were studied by Buneci (see [5,6]) because they induce morphisms between groupoid $C^*$-algebras. In the context of Lie groupoids and Lie algebroids, these were studied under the name of comorphisms (see [10, 26] Definition 4.3.16 and the references there).

**Definition 4.15.** Let $G$ and $H$ be groupoids in $\langle \mathcal{C}, T \rangle$. An actor from $G$ to $H$ is a left $G$-action on $H^1$ that commutes with the right multiplication action of $H$ on $H^1$.

Other authors exchange left and right in the above definition. The following generalises [7 Lemma 4.3]:

**Proposition 4.16.** An actor from $G$ to $H$ is equivalent to a pair consisting of a left action of $G$ on $H^0$ and a functor $G \times H^0 \to H$ that is the identity on objects.

**Proof.** Let $r_{G^0} : H^1 \to G^0$ and $m : G^1 \times_{G^0} r_{G^0} H^1 \to H^1$ define an actor from $G$ to $H$. Since the left and right actions on $H^1$ commute, we have $r_{G^0}(h_1 \cdot h_2) = r_{G^0}(h_1)$ for all $h_1, h_2 \in H^1$ with $s(h_1) = r_{G^0}(h_2)$. Thus $r_{G^0}(h) = r_{G^0}(h \cdot h^{-1}) = r_{G^0}(1_{r_{G^0}(h)})$.

With the map $r^0 : H^0 \to G^0$ defined by $r^0(x) := r_{G^0}(1_x)$ for $x \in H^0$, this becomes $r_{G^0} = r^0 o r_{G^0}$.

The map $r^0$ is the anchor map of a $G$-action on $H^0$. The action $G^1 \times_{G^0} r_{G^0} H^0 \to H^0$ is defined elementwise by $g \cdot x := r_{G^0}(g \cdot 1_x)$. We have $r^0(g \cdot x) = r_{G^0}(1_{r_{G^0}(x)}) = r_{G^0}(1_{r_{G^0}(g \cdot 1_x)}) = r_{G^0}(g \cdot 1_x) = r(g)$ and $1_{r_{G^0}(x)} \cdot x = x$ for all $x \in H^0$. Furthermore, $r_{G^0}(g \cdot h) = r_{G^0}(g \cdot h^{-1}) = g \cdot r_{G^0}(h)$ for all $g \in G^1$, $h \in H^1$ with $s(g) = r_{G^0}(h)$. Hence $(g_1 \cdot g_2) \cdot x = g_1 \cdot (g_2 \cdot x)$ for all $g_1, g_2 \in G^1$, $x \in H^0$ with $s(g_1) = r(g_2)$, $s(g_2)(x) = r^0(x)$.

The map $F^1 : G^1 \times_{G^0} r_{G^0} H^0 \to H^1$, $(g, x) \mapsto g \cdot 1_x$, together with the identity map on $H^0$ is a functor $F : G \times H^0 \to H$. This functor determines the actor because $g \cdot h = (g \cdot 1_{r_{G^0}(h)}) \cdot h = F(g, r_{G^0}(h)) \cdot h$ for all $g \in G^1$, $h \in H^1$ with $s(g) = r_{G^0}(h)$.

Conversely, a left $G$-action on $H^0$ and a functor $F : G \times H^0 \to H$ yield an actor by taking the anchor map $r^0 o r_{G^0} : H^1 \to H^0 \to G^0$ and the multiplication $g \cdot h := F(g, r_{G^0}(h)) \cdot h$.

**Proposition 4.16** shows that actors $G \to H$ are usually not functors $G \to H$, and vice versa. The intersection of both types of morphisms is described in the following example:

**Example 4.17.** Let $F : G \to H$ be a functor with invertible $F^0 \in \mathcal{C}(G^0, H^0)$. Then we define an associated actor by $r_F : H^1 \to G^1$, $g \mapsto (F^0)^{-1}(r_H(g))$, and $g \cdot h := F^1(g) \cdot h$ for all $g \in G^1$, $h \in H^1$ with $r(h) = s(F^1(g)) = F^0(s(g))$. Conversely, if an actor has the property that the associated anchor map $r : H^0 \to G^0$ is invertible, then we may identify $G \times H^0 \cong G$ and get a functor $G \to H$ by Proposition 4.16. The actor associated to this functor is the one we started with.
Proposition 4.18. An actor from $G$ to $H$ induces a functor $\mathcal{C}(H) \to \mathcal{C}(G)$ that does not change the underlying objects in $\mathcal{C}$. Furthermore, $H$-invariant maps are also $G$-invariant. Any functor $\mathcal{C}(H) \to \mathcal{C}(G)$ with these extra properties comes from an actor. Thus groupoids as objects and actors as arrows form a category, and $G \to \mathcal{C}(G)$ is a contravariant functor on this category.

Proof. We use categories of left actions during the proof. Describe an actor as in Proposition 1.10 as a $G$-action on $H^0$ with a functor $F: H^0 \to G$. Let $X$ be a left $H$-action. Then we define a left $G$-action on $X$ by taking the anchor map $r^0 \circ r : X \to H^0 \to G^0$ and the multiplication $g \cdot x := F^1(g,t(x)) \cdot x$ for all $g \in G^1, x \in X$ with $s(g) = r^0(t(x))$. This action is the unique one with $r_{G^0}(h \cdot x) = r_{G^0}(h)$ and $g \cdot (h \cdot x) = (g \cdot h) \cdot x$ for all $g \in G^1, h \in H^1, x \in X$ with $s(g) = r_{G^0}(h), s(h) = t(x)$.

Routine computations show that the above formulas define a $G$-action on $X$ in a natural way so as to give a functor $\mathcal{C}(H) \to \mathcal{C}(G)$, and that $H$-invariant maps $f : X \to Z$ remain $G$-invariant.

Conversely, let $F : \mathcal{C}(H) \to \mathcal{C}(G)$ be a functor that does not change the underlying object of $\mathcal{C}$ and that preserves invariant maps. That is, $F$ equips any left $H$-action $X$ with a left $G$-action, such that $H$-maps remain $G$-maps and $H$-invariant maps remain $G$-invariant. When we apply $F$ to the left multiplication action on $H^1$, we get a left $G$-action on $H^1$. We claim that this commutes with the right multiplication action of $H^1$, so that we have an actor, and that this actor induces the functor $F$. Let $X$ be any left $H$-action. Let $H$ act on $HX := H^1 \times_{s,H^0} X$ by $h_1 \cdot (h_2, x) := (h_1 h_2, x)$ for all $h_1, h_2 \in H^1, x \in X$ with $s(h_1) = r(h_2), s(h_2) = t(x)$. Equip $HX$ with the $G$-action from $F(HX)$. Routine computations show that the maps $p_1 : HX \to H^1$ and $m : HX \to X$ are $H$-equivariant and the map $p_2 : HX \to X$ is $H$-invariant. By assumption, $p_1$ and $m$ are $G$-equivariant and $p_2$ is $G$-invariant. The statements for $p_1$ and $p_2$ mean that $g \cdot (h, x) = (g \cdot h, x)$ for all $g \in G^1, h \in H^1, x \in X$ with $s(g) = r_{G^0}(h), s(h) = t(x)$. The $G$-equivariance of $m$ gives $g \cdot m(h, x) = m(g \cdot (h, x)) = m(g \cdot h, x)$ or brief $g \cdot (h \cdot x) = (g \cdot h) \cdot x$ for $g, h, x$ as above. For $X = H^1$, this says that the left $G$-action on $G^1$ commutes with the right $H$-action by multiplication, so that we have an actor. For general $X$, we get $g \cdot x = g \cdot (1_{r(x)} \cdot x) = (g \cdot 1_{t(x)}) \cdot x$, so the $G$-action given by $F$ is the one from this actor. We also see that the functor $F$ determines the actor uniquely.

Since the composite of two functors $\mathcal{C}(H) \to \mathcal{C}(G)$ and $\mathcal{C}(K) \to \mathcal{C}(H)$ that does not change the underlying object of $\mathcal{C}$ and preserves invariant maps again has the same properties, it must come from an actor. Thus actors may be composed. More explicitly, given actors $G \to H$ and $H \to K$, there is a unique right $G$-action on $K^1$ with $(g \cdot h) \cdot k = g \cdot (h \cdot k)$ for all $k \in K^1, h \in H^1, g \in G^1$ with $s(g) = r_{G^0}(h)$ and $s(h) = r_{G^0}(k)$. This left action gives the actor from $G$ to $K$ that corresponds to the composite functor $\mathcal{C}(K) \to \mathcal{C}(G)$.

Proposition 4.19. An actor is invertible if and only if it is associated to an isomorphism of categories.

Proof. The anchor maps $H^0 \to G^0$ are composed when we compose actors. Since this anchor map is the identity for the identity actor, the anchor map $H^0 \to G^0$ for an invertible actor must be invertible in $\mathcal{C}$. The identification between actors $G \to H$ with invertible anchor map $H^0 \to G^0$ and functors acting identically on objects in Example 3.14 is compatible with the compositions on both sides. Thus invertible actors are the same as invertible functors, that is, isomorphisms of categories.

In order to enrich actors to a 2-category, we study automorphisms of $H^1$ that preserve the right $H$-action:
Proposition 4.20. The right H-maps $\phi : H^1 \to H^1$ are exactly the maps of the form $h \mapsto \Phi(r(h)) \cdot h$ for a section $\Phi : H^0 \to H^1$ of $s$. This map is invertible if and only if $\Phi$ is a bisection.

Proof. In the following, “section” always means a section of $s$. It is clear that left multiplication with a section defines an H-map. Furthermore, the map from sections to H-maps is a homomorphism for the horizontal product $(\ref{eq:horizontal})$ of sections, so a bisection gives an invertible map on $H^1$. It remains to prove the converse. Let $\phi : H^1 \to H^1$ be an H-map and let $h \in H^1$. Then $s(\phi(h)) = s(h)$, so Lemma $3.13$ gives a unique $\omega_h$ with $\phi(h) = \omega_h \cdot h$. This defines a map $\omega : H^1 \to H^1$ with $s \circ \omega = r$ and $\omega(h) \cdot h = \phi(h)$ for all $h \in H^1$. Since $\phi(h_1 \cdot h_2) = \phi(h_1) \cdot h_2$ for all $h_1, h_2 \in H^1$ with $s(h_1) = r(h_2)$, we get $\omega(h_1 \cdot h_2) = \omega(h_1)$. This implies $\omega = \phi \circ r$ for a map $\Phi : H^0 \to H^1$, compare the proof of Proposition $3.16$. We have $s \circ \Phi = id_{H^1}$, so $\Phi$ is a section, and $\phi(h) = \Phi(r(h)) \cdot h$ for all $h \in H^1$ by construction. The section $\Phi$ is uniquely determined by $\phi$.

If $\phi$ is invertible, its inverse is also an H-map and hence associated to some section $\Psi$. Since the map $\Phi \mapsto \phi$ is injective, $\Phi$ is invertible in the monoid of sections, hence it is a bisection by Lemma $3.10$. \hfill $\Box$

Let $m_1, m_2$ be two actors from G to H, that is, left actions of G on H that commute with the right multiplication action. A 2-arrow from $m_1$ to $m_2$ is a G,H-bibundle map $(H^1, m_1) \to (H^1, m_2)$. By Proposition $4.20$ this is the same as a section $\Phi$ of H with

$$\Phi(r(g \cdot h)) \cdot (g \cdot h) = g \cdot 2 (\Phi(r(h)) \cdot 1) h$$

for all $g \in G^1$, $h \in H^1$ with $s(g) = r_{G,1}(r(h))$. Composing the G,H-maps associated to sections $\Phi_1$ and $\Phi_2$ gives the G,H-map associated to the section $\Phi_1 \circ \Phi_2$ defined in $(\ref{eq:horizontal})$.

Proposition 4.21. There is a strict 2-category with groupoids in $(\mathcal{C}, \mathcal{T})$ as objects, actors as arrows, sections $\Phi$ as above as 2-arrows, the usual composition of actors and the usual unit actors, and with the product $\circ$ for sections as vertical product. The equivalences in this 2-category are precisely the isomorphisms of categories.

Proof. It remains to construct the horizontal product. Let G, H and K be groupoids, let $m_1, m_2 : G \rightrightarrows H$ and $m'_1, m'_2 : H \rightrightarrows K$ be actors, let $\Phi : H^0 \to H^1$ and $\Psi : K^0 \to K^1$ be sections with

$$\Phi(r(g \cdot h)) \cdot (g \cdot h) = g \cdot 2 (\Phi(r(h)) \cdot 1) h, \quad \Psi(r(h \cdot k)) \cdot (h \cdot k) = h \cdot 2 (\Psi(r(k)) \cdot 1) k$$

for all $g \in G^1$, $h \in H^1$, $k \in K^1$ with $s(g) = r_{G,1}(r(h))$ and $s(h) = r_{H,1}(r(k))$, respectively. Then $\Psi \bullet \Phi : K^0 \to K^1$, $x \mapsto \Phi(r_{H,1}(x)) \cdot \Psi(x)$, is a section for K that gives a 2-arrow from the composite $m'_1 \circ m_1$ to $m'_2 \circ m_2$.

An equivalence $\alpha : G \to H$ in this 2-category has a quasi-inverse $\beta : H \to G$ and invertible 2-arrows $id_G \Rightarrow \beta \circ \alpha$ and $id_H \Rightarrow \alpha \circ \beta$. Being invertible, they correspond to bisections. Then it follows that the actors $\beta \circ \alpha$ and $\alpha \circ \beta$ come from inner automorphisms of G and H, respectively, as in Example 4.17. Thus $\beta \circ \alpha$ and $\alpha \circ \beta$ are isomorphisms in the 1-category of actors. This implies that $\alpha$ is an isomorphism in the 1-category of actors. Now Proposition 4.14 shows that $\alpha$ is an isomorphism of categories. \hfill $\Box$

5. PRINCIPAL BUNDLES

Definition 5.1. Let G be a groupoid in $(\mathcal{C}, \mathcal{T})$. A G-bundle (over Z) is a G-action $(X, s, m)$ with a G-invariant map $p : X \to Z$ (bundle projection). A G-bundle is principal if

1. $p$ is a cover;
(2) the following map is an isomorphism:
\[(p_1, m) : X \times_{s, G^0, r} G^1 \sim \to X \times_{f, p, Z, p} X, \quad (x, g) \mapsto (x, x \cdot g).\]
The isomorphism \[(5.1)\] is equivalent to the elementwise statement that for \(x_1, x_2 \in X\) with \(p(x_1) = p(x_2)\), there is a unique \(g \in G^1\) with \(s(x_1) = r(g)\) and \(x_1 \cdot g = x_2\); this translation is proved like Lemma 3.6.

**Definition 5.2.** Let \(G\) be a groupoid and \(X\) a \(G\)-action in \((C, T)\). The orbit space projection \(p_X : X \to X/G\) is the coequaliser of the two maps \(p_1, m : X \times_{s, G^0, r} G^1 \rightrightarrows X\).

While the coequaliser need not exist in \(C\), it always exists in the category of presheaves over \(C\).

**Lemma 5.3.** Let \(X\) with bundle projection \(p : X \to Z\) be a principal \(G\)-action. Then \(p\) is equivalent to the orbit space projection \(X \to X/G\), which therefore exists in \(C\) and is a cover. The orbit space projection is always \(G\)-invariant, and condition (3\(''\)) in Definition 4.1 follows from (5.1).

**Proof.** Since the pretopology is subcanonical, the cover \(p : X \to Z\) is the coequaliser of \(p_1, p_2 : X \times_{p, Z, p} X \rightrightarrows X\), and these two maps are covers. By the isomorphism (5.1), \(p\) is the coequaliser of \(p_1, m : X \times_{s, G^0, r} G^1 \rightrightarrows X\) as well, and both \(p_1\) and \(m\) are covers. Thus \(p\) is an orbit space projection and \(m\) is automatically a cover; the latter is Definition 3.4(3\(''\)). \(\square\)

5.1. Examples.

**Example 5.4.** Let \(Y\) be a 0-groupoid, let \(X \to Y\) be a \(Y\)-action, and let \(p = \text{id}_X\). This is a principal \(Y\)-bundle.

**Example 5.5.** Let \(p : X \to Z\) be a cover and let \(G\) be its covering groupoid (see Example 3.8). The canonical action of \(G\) on its objects \(X\) is given by \(s = \text{id}_X\) and \(x_1 \cdot (x_1, x_2) := x_2\) for all \(x_1, x_2 \in X\) with \(p(x_1) = p(x_2)\) (see Example 4.5). Together with the bundle projection \(p : X \to Z\), this is a principal bundle: the map \(X \times_{s, X, p_1} (X \times_{p, Z, p} X) \to X \times_{p, Z, p} X\) defined elementwise by \((x_1, (x_1, x_2)) \mapsto (x_1, x_2)\) is an isomorphism.

5.2. Pull-backs of principal bundles.

**Proposition 5.6.** Let \(f : \tilde{Z} \to Z\) be a map in \(C\) and let \((X, s, p, m)\) be a principal \(G\)-bundle over \(Z\). Then there are a principal \(G\)-bundle \((\tilde{X}, \tilde{s}, \tilde{p}, \tilde{m})\) over \(\tilde{Z}\) and a \(G\)-map \(\tilde{f} : \tilde{X} \to X\) with \(p \circ \tilde{f} = f \circ \tilde{p}\). These are unique in the following sense: for any principal \(G\)-bundle \((X', \hat{s}', \hat{p}', \hat{m}')\) over \(Z\) and \(G\)-map \(\hat{f}' : X' \to X\), there is a unique isomorphism of principal \(G\)-bundles \(\varphi : X \to X'\) with \(f' \circ \varphi = f\).

This principal \(G\)-bundle is called the pull-back of \((X, s, p, m)\) along \(f\).

**Proof.** Let \(\tilde{X} := \tilde{Z} \times_{f, Z, p} X\), \(\tilde{s} := s \circ p_1 : \tilde{X} \to G^0\) and \(\tilde{p} := p_1 : \tilde{X} \to \tilde{Z}\). The fibre product \(\tilde{X}\) exists and \(\tilde{p}\) is a cover because \(p\) is a cover. Let
\[m : \tilde{X} \times_{s', G^0, r} G^1 = \tilde{Z} \times_{f, Z, p} X \times_{s, G^0, r} G^1 \to \tilde{X} \times_{f, Z, p} X = \tilde{X};\]
this map is well-defined because \(\tilde{p} \circ m = p \circ p_1\).

Routine computations show that \((\tilde{X}, \tilde{s}, \tilde{m})\) is a \(G\)-action and that \(\tilde{p} \circ \tilde{m} = \tilde{p} \circ p_1\). The map \((5.1)\) with tildes is the pull-back along \(f\) of the same map without tildes, where we use the canonical maps from both sides to \(Z\). Since pull-backs of isomorphisms remain isomorphisms, \((\tilde{X}, \tilde{Z}, \tilde{s}, \tilde{m}, \tilde{p})\) is a principal \(G\)-bundle over \(\tilde{Z}\). The second coordinate projection \(\tilde{f} : \tilde{X} \to X\) is a \(G\)-map with \(p \circ \tilde{f} = f \circ \tilde{p}\).

Let \((\hat{X}', \hat{s}', \hat{p}', \hat{m}')\) be another principal \(G\)-bundle over \(Z\) with a \(G\)-map \(\hat{f}' : \hat{X}' \to X\) with \(p \circ \hat{f}' = f \circ \hat{p}'\). Then \(\varphi := (\hat{p}', \hat{f}') : \hat{X}' \to X\) is a \(G\)-map with \(\hat{p} \circ \varphi = \hat{p}'\), and it
is the only G-map with this extra property. The proof will be finished by showing that \( \varphi \) is an isomorphism.

Since \( \tilde{p}' : \tilde{X}' \to \tilde{Z} \) is a cover, so is its pull-back along \( \tilde{p} : \tilde{X} \to \tilde{Z} \). Identifying \( \tilde{X}' \times_{\tilde{p}', \tilde{Z}, \tilde{p}} \tilde{X} \cong \tilde{X}' \times_{f', \tilde{Z}, p} \tilde{X} \), this cover becomes the map

\[
\tilde{p}' \times_{\tilde{Z}} \id_{\tilde{X}} : \tilde{X}' \times_{f', \tilde{Z}, p} \tilde{X} \to \tilde{X} \times_{f, \tilde{Z}, p} \tilde{X}, \quad (x_1, x_2) \mapsto (\tilde{p}'(x_1), x_2).
\]

Since \( \tilde{p}' \times_{\tilde{Z}} \id_{\tilde{X}} \) is a cover, the fibre product of the following two maps exists:

\[
\tilde{X}' \times_{f', \tilde{Z}, p} \tilde{X} \xrightarrow{\tilde{p}' \times_{\tilde{Z}} \id_{\tilde{X}}} \tilde{X} \xleftarrow{\tilde{p}} \tilde{X}'.
\]

An element of this fibre product is a triple \( x_1 \in \tilde{X}', x_2 \in X, x_3 \in \tilde{X}' \) with \( f(\tilde{p}'(x_1)) = p(x_2), f'(x_3) = x_2, \tilde{p}'(x_3) = \tilde{p}'(x_1) \). Then \( p(x_2) = p(f'(x_3)) = f(\tilde{p}'(x_1)) = f(\tilde{f}'(x_1)). \) Since \( X \) is a principal G-bundle over \( \tilde{Z} \), there is a unique \( g \in G \) with \( s(x_2) = r(g) \) and \( \tilde{f}'(x_1) = x_2 \cdot g \). Since \( \tilde{X}' \) is a principal G-bundle over \( \tilde{Z} \) and \( \tilde{p}'(x_3) = \tilde{p}'(x_1) \), there is also a unique \( g' \in G \) with \( s'(x_1) = r(g') \) and \( x_1 \cdot g' = x_3 \). Then \( x_2 = \tilde{f}'(x_3) = \tilde{f}'(x_1) \cdot g' = \tilde{f}'(x_1) \cdot g' \), so \( g = g' \). Thus \( x_3 = \tilde{f}'(x_1) \cdot g \) is uniquely determined by \( x_1 \) and \( x_2 \). That is, the pull-back of \( \varphi \) along the cover \( \tilde{p}' \times_{\tilde{Z}} \id_{\tilde{X}} \) is an isomorphism. This implies that \( \varphi \) is an isomorphism by Proposition 2.3.

**Proposition 5.7.** Let \( X_1 \) and \( X_2 \) be principal G-bundles over \( Z_1 \) and \( Z_2 \), respectively. Then a G-map \( f : X_1 \to X_2 \) induces a G-map \( f/G : Z_1 \to Z_2 \). The map \( f \) is an isomorphism if and only if \( f/G \) is. If \( f/G \) is a cover, so is \( f \). Conversely, under Assumption 2.4 \( f \) is a cover if and only if \( f/G \) is.

**Proof.** Since \( Z_i \) is the orbit space of \( X_i \) and orbit spaces are constructed naturally, the G-map \( f \) induces a map \( f/G : Z_1 \to Z_2 \). Since \( p_2 \circ f = f/G \circ p_1 \), \( X_1 \) must be the pull-back of \( X_2 \) along \( f/G \) by Proposition 5.6. That is, the diagram

\[
\begin{array}{ccc}
X_1 & \xrightarrow{f} & X_2 \\
p_1 & & p_2 \\
Z_1 & \xleftarrow{f/G} & Z_2
\end{array}
\]

is a fibre-product diagram. Proposition 2.3 shows that \( f \) is an isomorphism if and only if \( f/G \) is one. By the pretology axioms, \( f \) is a cover if \( f/G \) is, and the converse holds under Assumption 2.4.

**Proposition 5.8.** Consider a commuting square of G-maps between principal G-bundles and the corresponding maps between their base spaces:

\[
\begin{array}{ccc}
X_1 & \xrightarrow{\gamma_2} & X_2 \\
\gamma_3 & & \delta_2 \\
X_3 & \xrightarrow{\delta_3} & X_4
\end{array} \quad \begin{array}{ccc}
Z_1 & \xrightarrow{\beta_2} & Z_2 \\
\beta_3 & & \alpha_3 \\
Z_3 & \xrightarrow{\alpha_2} & Z_4
\end{array}
\]

The first square is a fibre-product square if and only if the second one is.

**Proof.** Assume first that the square of \( Z_i \) is a fibre-product square. Let \( x_2 \in X_2, x_3 \in X_3 \) satisfy \( x_4 := \delta_2(x_2) = \delta_3(x_3) \). We must show that there is a unique \( x_1 \in X_1 \) with \( \gamma_i(x_1) = x_i \) for \( i = 2, 3 \). Let \( z_i := p_i(x_i) \in Z_i \), then \( \alpha_2(z_2) = p_4(\delta_2(x_2)) = p_4(\delta_3(x_3)) = \alpha_3(z_3) \). Since \( Z_1 \) is the pull-back of \( \alpha_2, \alpha_3 \) by assumption, we get a unique \( z_1 \in Z_1 \) with \( \beta_i(z_1) = z_i \) for \( i = 2, 3 \). Proposition 5.6 shows that \( X_1 \to Z_1 \) is the pull-back of \( X_4 \to Z_4 \) along \( \alpha_1 \circ \beta_1 : Z_1 \to Z_4 \), and similarly for \( X_4 \to Z_4 \) for \( i = 2, 3 \). Thus \( x_4 \in X_4 \) and \( z_1 \in X_1 \) determine a unique element \( x_1 \in X_1 \) with
$p_1(x_1) = z_1$ and $\delta_i \gamma_i(x_1) = x_4$ for $i = 2, 3$. We claim that this is the unique element of $X_i$ with $\gamma_i(x_1) = x_1$ for $i = 2, 3$.

Any element of $X_i$ with $\gamma_i(x_1) = x_i$ for $i = 2, 3$ will also satisfy $p_1(x_1) = z_1$ and $\delta_i \gamma_i(x_1) = x_4$ for $i = 2, 3$, so uniqueness is clear. Since $X_i \to Z_i$ is the pull-back of $X_1 \to Z_1$ for $i = 2, 3$, the element $x_i \in X_i$ is uniquely determined by $z_i = p_i(x_1)$ and $x_4 = \delta_i(x_1)$. Since $p_i(\gamma_i(x_1)) = \beta_i p_i(x_1) = \beta_1(z_1) = z_1 = p_i(x_1)$ and $\delta_i(\gamma_i(x_1)) = x_3 = \delta_1(x_1)$, we get $x_i = \gamma_i(x_1)$ as desired. Hence we get a bijection between $x_1 \in X_1$ and pairs $x_2 \in X_2, x_3 \in X_3$ with $\delta_2(x_2) = \delta_3(x_3)$. This is the elementwise statement corresponding to $X_1 \cong X_2 \times X_3$.

Now assume, conversely, that $X_1 \cong X_2 \times X_3$. We are going to show that $Z_1 \cong Z_2 \times Z_3$. This means that, for all $x \in C$, the map

$$C(x, Z_1) \to \{(z_2, z_3) \in C(x, Z_2) \times C(x, Z_3) \mid \alpha_2 z_2 = \alpha_3 z_3\}$$

is a bijection. Let $z_i : ? \to Z_i$ for $i = 2, 3, 4$ with $\alpha_2 z_2 = z_4 = \alpha_3 z_3$ be given. The $G$-maps $X_i \to Z_i$ for $i = 2, 3$ give isomorphisms between $X_i \to Z_i$ and the pull-back of $X_4 \to Z_4$ along $\alpha_1$. Pulling back further along the maps $z_i$ shows that the three pull-backs of the principal $G$-bundles $X_i \to Z_i$ along $z_i$ for $i = 2, 3, 4$ are canonically isomorphic principal $G$-bundles over $z_i$. Let $z_i \to ?$ be this unique principal $G$-bundle over $z_i$. By Proposition 5.8, the maps $z_i$ for $i = 2, 3, 4$ lift uniquely to $x_i : ? \to X_i$. These liftings still satisfy $\gamma_2 x_2 = x_4 = \gamma_3 x_3$ because the lifting of $z_4$ is unique.

Since $X_1 \cong X_2 \times X_3$, $X_1$ is a fibre product in the category of $G$-actions by Lemma 1.14, the unique map $x_i : ? \to X_1$ with $\delta_i x_1 = x_i$ for $i = 2, 3$ is a $G$-map. Thus it induces a map $z_1 : ? \to Z_1$ by Proposition 5.7. The naturality of this construction implies $\beta_i z_1 = z_i$ for $i = 2, 3$. Any map $z_i' : ? \to Z_1$ with $\beta_i z_i' = z_i$ for $i = 2, 3$ lifts to a map $x_i' = (z_1', x_i) : ? \to X_1 \times Z_1$. Since $X_1 \cong X_2 \times X_3$, we must have $x_i' = x_1$, which gives $z_i' = z_1$. Hence there is a unique map $z_1 : ? \to Z_1$ with $\beta_i z_1 = z_i$ for $i = 2, 3$, as desired.

5.3. Locality of principal bundles. We formulate now how it means for principal bundles to be a “local” notion. Let $G$ be a groupoid in $(C, T)$ and let $s : X \to G^0$, $p : X \to Z$, and $m : X \times_{s,G^0,G} G^1 \to X$ be maps. We pull back this data along a cover $f : Z \to Z$ as follows. Let $X := \tilde{Z} \times_{f,Z} X$, $s := \tilde{s} \circ pr_2 : \tilde{X} \to G^0$, $p := pr_1 : \tilde{X} \to \tilde{Z}$ and

$$\tilde{m} : \tilde{X} \times_{\tilde{s},G^0,G} G^1 = \tilde{Z} \times_{f,Z} \tilde{X} \times_{s,G^0,G} G^1 \xrightarrow{id_{\tilde{Z}} \times_{f,Z} m} \tilde{Z} \times_{f,Z} \tilde{X} = \tilde{X};$$

this map is well-defined if $p \circ m = p \circ pr_1$.

Proposition 5.9. The data $(\tilde{X}, \tilde{Z}, \tilde{s}, \tilde{m}, \tilde{p})$ is a well-defined principal $G$-bundle over $\tilde{Z}$ if and only if $(X, Z, s, m, p)$ is a principal $G$-bundle over $Z$.

Put in a nutshell, principality for $G$-bundles is a local property.

Proof. If $(X, s, m, p)$ is a principal $G$-bundle over $Z$, then Proposition 5.8 shows that $(\tilde{X}, \tilde{s}, \tilde{m}, \tilde{p})$ is a principal $G$-bundle over $\tilde{Z}$.

Now assume that $(\tilde{X}, \tilde{s}, \tilde{m}, \tilde{p})$ is a principal $G$-bundle over $\tilde{Z}$. We are going to show that $(X, s, m, p)$ is a principal $G$-bundle over $Z$. For $m$ to be well-defined, we need $p \circ m = p \circ pr_1$ or $p(x \cdot g) = p(x)$ for all $x \in \tilde{X}$, $g \in G^1$ with $s(x) = r(g)$. Since $f$ is a cover, so is the map $\tilde{X} \times_{\tilde{s},G^0,G} G^1 \to X \times_{s,G^0,G} G^1$ it induces. Since $T$ is subcanonical, this map is an epimorphism. Now we get $s \circ m = s \circ pr_2 : \tilde{X} \times_{\tilde{s},G^0,G} G^1 \to G^0$ because composing $s \circ m$ and $s \circ pr_2$ with the cover $\tilde{X} \times_{\tilde{s},G^0,G} G^1 \to X \times_{s,G^0,G} G^1$ gives the same map $s \circ m = s \circ pr_2$. A similar, more complicated argument shows that $m$ is associative because $m$ is associative and both multiplications are intertwined by covers $\tilde{X} \times_{\tilde{s},G^0,G} G^1 \times_{\tilde{s},G^0,G} G^1 \to \tilde{X} \times_{\tilde{s},G^0,G} G^1 = \tilde{X} \times_{\tilde{s},G^0,G} G^1 \to \tilde{X} \times_{\tilde{s},G^0,G} G^1 \to \tilde{X} \times_{\tilde{s},G^0,G} G^1$. 

and $\tilde{X} \to X$. Similarly, we get the unitality condition for the multiplication, so $(X, s, m)$ is a $G$-action.

It remains to verify that the map 

$$(m, pr_1): X \times_{s,G^0,r} G^1 \to X \times_{p,Z,p} X$$

is an isomorphism. Since the coordinate projection $\tilde{X} \to X$ is a cover, so is the induced map $X \times_{p,Z,p} \tilde{X} \to X \times_{p,Z,p} X$. The pull-back of $(m, pr_1)$ along this map is equivalent to the map 

$$(\tilde{m}, pr_1): \tilde{X} \times_{\tilde{s},G^0,r} G^1 \to \tilde{X} \times_{p,Z,p} \tilde{X},$$

where we identify 

$$\tilde{X} \times_{p,Z,p} \tilde{X} \cong X \times_{p,Z,f \circ \beta} X,$$

$$(X \times_{s,G^0,r} G^1) \times_{X \times_{Z,\beta} X} (X \times_{p,Z,f \circ \beta} X) \cong \tilde{X} \times_{\tilde{s},G^0,r} G^1$$

in the obvious way. The map (5.2) is an isomorphism because $\tilde{X}$ is principal. This implies that $(m, pr_1)$ is an isomorphism because the property of being an isomorphism is local by Proposition 2.4. \hfill $\Box$

### 5.4. Basic actions and covering groupoids.

**Definition 5.10.** A groupoid action or sheaf that, together with some bundle projection, is part of a principal bundle is called basic. A groupoid is called basic if its canonical action on $G^0$ in Example 4.5 is basic.

We call such actions “basic” because they have a well-behaved base and because “principal groupoid” already has a different meaning for topological groupoids (it means that the action on $G^0$ is free).

**Proposition 5.11.** A $G$-action $X$ is basic if and only if the transformation groupoid $X \times G$ is isomorphic to a covering groupoid.

**Proof.** Let $X$ be basic with bundle projection $p: X \to Z$. Then (5.1) provides an isomorphism $(X \times G)^1 \cong X \times_{p,Z,p} X$. Together with the identity on objects, this is an isomorphism of groupoids from $X \times G$ to the covering groupoid of $p$. Conversely, let $X \times G$ be isomorphic to a covering groupoid. We may assume that the isomorphism is the identity on objects, so that the cover whose covering groupoid we take is a map $p: X \to Z$. Since the maps $pr_1$ and $m$ in (5.1) are the range and source maps of $X \times G$, the isomorphism of groupoids from $X \times G$ to the covering groupoid of $p$ must be given by $(x, g) \mapsto (x, x \cdot g)$ on arrows; thus (5.1) is an isomorphism. \hfill $\Box$

**Corollary 5.12.** A $G$-action on $X$ is basic if and only if its transformation groupoid $X \times G$ is basic.

**Proof.** The criterion in Proposition 5.11 depends only on $X \times G$. \hfill $\Box$

**Corollary 5.13.** An action of a transformation groupoid $X \times G$ is basic if and only if the restriction of the action to $G$ is basic.

**Proof.** Proposition 4.11 shows that $Y \times (X \times G) \cong Y \times G$, so the assertion follows from Corollary 5.12. \hfill $\Box$

**Lemma 5.14.** Let $Y$ carry an action of a transformation groupoid $X \times G$, equip it with the resulting $G$-action. Then $Y/(X \times G) \cong Y/G$.

**Proof.** Proposition 4.11 shows that the invariant maps for both actions are the same, hence so are the orbit spaces. \hfill $\Box$
6. Bibundle functors, actors, and equivalences

Let $G$ and $H$ be groupoids in $(\mathcal{C}, \mathcal{T})$. We describe several important classes of $G, H$-bibundles:

**Definition 6.1.** A **bibundle equivalence from $G$ to $H$** is a $G, H$-bibundle $X$ such that both the left and right actions are principal bundles with bundle projections $s: X \to H^0$ and $r: X \to G^0$, respectively. We call $G$ and $H$ **equivalent** if there is a bibundle equivalence from $G$ to $H$.

A **bibundle functor from $G$ to $H$** is a $G, H$-bibundle $X$ such that the right $H$-action is a principal bundle with bundle projection $r: X \to G^0$. A bibundle functor is **covering** if the anchor map $s: X \to H^0$ is a cover.

A **bibundle actor from $G$ to $H$** is a $G, H$-bibundle $X$ such that the right $H$-action is basic and a sheaf, that is, $s: X \to H^0$ is a cover.

Bibundle functors are also called generalised morphisms or Hilsum–Skandalis morphisms, and bibundle equivalences just equivalences or Morita equivalences. We will show later that for sufficiently nice pretopologies, bibundle functors and actors are precisely the products of bibundle equivalences with functors and actors, respectively (see Sections 6.2 and 7.4). This justifies the names above.

The anchor map $r: X \to G^0$ of a bibundle functor is always a cover because it is the bundle projection of a principal action. For an equivalence $X$, both anchor maps $r: X \to G^0$ and $s: X \to H^0$ are covers for the same reason. Thus bibundle equivalences are covering bibundle functors. A bibundle functor is a bibundle actor as well if and only if it is covering. The following diagram illustrates the relations between these notions:

```
| bibundle functor |
|-------------------|
| covering bibundle functor |
| bibundle equivalence |
| bibundle actor |
```

**Example 6.2.** Let $G$ be a groupoid in $(\mathcal{C}, \mathcal{T})$. Then $G$ acts on $G^1$ on the left and right by multiplication. These actions turn $G^1$ into a bibundle equivalence from $G$ to itself, so equivalence of groupoids is a reflexive relation. First, the two actions commute by associativity, so they form a $G, G$-bibundle; secondly, the right multiplication action gives a principal $G$-bundle with bundle projection $s: G^1 \to G^0$ by (3.3); thirdly, the left action gives a principal $G$-bundle with bundle projection $r: G^1 \to G^0$ by (3.4).

The assumptions that $r$ and $s$ be covers and the conditions (3.3) and (3.4) in the definition of a groupoid are necessary and sufficient for this unit bibundle equivalence to work.

Left and right actions of groupoids are equivalent by Lemma 4.11. Left and right principal bundles are also equivalent in the same way. Thus a $G, H$-bibundle $X$ gives an $H, G$-bibundle $X^*$, which is the same object of $\mathcal{C}$ with the two anchor maps exchanged and $h \cdot x \cdot g := g^{-1} \cdot x \cdot h^{-1}$; this is a bibundle equivalence if and only if $X$ is one. Thus equivalence of groupoids is a symmetric relation. Transitivity seems to require an extra assumption in order to compose bibundle equivalences, see Section 7.

**Example 6.3.** Let $p: X \to Z$ be a cover in $(\mathcal{C}, \mathcal{T})$. View $Z$ as a groupoid with only identity arrows and let $G$ be the covering groupoid of $p$. Then $G$ and $Z$ are equivalent.
The equivalence bibundle is $X$, with the canonical right action of $G$ on its object space and with the left $Z$-action given by the anchor map $p$. The right $G$-action on $X$ with $p$ as bundle projection gives a principal $G$-bundle by Example 4.7. The left $Z$-action is given simply by its anchor map $p$, and any such action gives a principal bundle with the identity map $X \to X$ as bundle projection; the identity is also the right anchor map.

Conversely, if $X$ is a bibundle equivalence from a groupoid $G$ to a 0-groupoid $Z$, then is isomorphic to the covering groupoid of the anchor map $pX \to Z$.

**Example 6.4.** More generally, let $p_i : X_i \to Z$ for $i = 1, 2$ be two covers and let $G_1$ and $G_2$ be their covering groupoids. Let $X := X_1 \times_{p_i, Z, p_j} X_2$, $r := pr_1 : X \to X_1 = G_1^0$ and $s := pr_2 : X \to X_2 = G_2^0$, and define the multiplication maps by $(x_1, y_1) \cdot (y_1, y_2) := (x_1, y_2) \cdot (x_2, y_2) := (x_1, y_2)$ for $x_1, y_1 \in X_1$, $x_2, y_2 \in X_2$ with $p_1(x_1) = p_1(y_1) = p_2(x_2) = p_2(y_2)$. Then $X$ is a bibundle equivalence from $G_1$ to $G_2$. This shows that equivalence of groupoids is a transitive relation among covering groupoids.

**Example 6.5.** Let $Y$ be an object of a groupoid $G$ viewed as a groupoid. An action of $G$ on $Y$ is the same as a map to $Y$ by Example 4.7. Thus a $G$-$Y$-bibundle is the same as a (left) $G$-action $X$ with a $G$-invariant map $f : X \to Y$.

A bibundle functor $G \to Y$ is, up to isomorphism, the same as a $G$-equivariant map $G^0 \to Y$ because of the assumption that $r$ induces an isomorphism $X = X/Y \sim G^0$. A bibundle functor $Y \to G$ is the same as a principal $G$-bundle over $Y$.

A bibundle actor $G \to Y$ is the same as a $G$-action $X$ with a $G$-invariant cover $X \to Y$. A bibundle actor $Y \to G$ is the same as a principal $G$-bundle $X$ over some space $Z$ with a map $Z \to Y$, such that the anchor map $s : X \to G^0$ is a cover.

Let $Y_1$ and $Y_2$ be two objects of a groupoid $G$. Then a $Y_1, Y_2$-bibundle is a span $Y_1 \leftarrow X \rightarrow Y_2$ in $C$. This is

- a bibundle functor if and only if the map $Y_1 \leftarrow X$ is invertible;
- a bibundle equivalence if and only if both maps $Y_1 \leftarrow X \rightarrow Y_2$ are isomorphisms;
- a bibundle actor if and only if the map $X \rightarrow Y_2$ is a cover.

Example 6.5 shows that a groupoid is equivalent to a 0-groupoid if and only if it is basic. By Proposition 5.11, a groupoid is basic if and only if it is isomorphic to a covering groupoid.

### 6.1 From functors to bibundle functors

Let $G$ and $H$ be groupoids in $(C, T)$ and let $F : G \to H$ be a functor, given by $F^i \in C(G^i, H^i)$ for $i = 0, 1$. We are going to define an associated bibundle functor $X_F$ from $G$ to $H$ (see also [30]).

Since $r : H^1 \to H^0$ is a cover, the fibre product $X_F = X := G^0 \times_{F^0, H^0, r} H^1$ exists and the coordinate projection $pr_1 : X \to G^0$ is a cover. This map is the anchor map for a left $G$-action on $X$ defined elementwise by $g \cdot (x, h) := (r(g), F^1(g) \cdot h)$ for all $g \in G^1$, $x \in G^0$, $h \in H^1$ with $s(g) = x$, $r(h) = F^0(x) = F^0(s(g)) = s(F^1(g))$. The map $s : X \to H^0$, $(x, h) \mapsto s(h)$, for $x \in G^0$, $h \in H^1$ with $F^0(x) = r(h)$ is the anchor map for a right $H$-action defined elementwise by $(x, h_1) \cdot h_2 := (x, h_1 \cdot h_2)$ for all $x \in G^0$, $h_1, h_2 \in H^1$ with $F^0(x) = r(h_1)$ and $s(h_1) = r(h_2)$.

**Lemma 6.6.** The $G, H$-bibundle $X$ is a bibundle functor.

**Proof.** The left and right actions on $X$ commute. For $x \in G^0$, $h_1, h_2, y \in H^1$ with $F^0(x) = r(h_1) = r(h_2)$ we have $s(h_1) = r(y)$ and $(x, h_1) \cdot y = (x, h_2)$ if and only if $y = h_1^{-1} \cdot h_2$. Hence there is a unique such $y$, proving the isomorphism 5.11 for the $H$-bundle $r : X \to G^0$. Since $r : X \to G^0$ is a cover as well, the right $H$-action together with $r$ is a principal $H$-bundle. \[\square\]
We may generalise the construction above as follows. Let $F: G \to H$ be a functor and let $Y$ be a bundle functor from $H$ to $K$. We may then construct a bundle functor $F^*(Y)$ from $G$ to $K$. The bundle functor $X_F$ is the special case where $Y = H^1$ is the identity bundle functor on $H$. The only change in the construction is to replace $H^1$ by $Y$ everywhere. Thus the underlying object of $C$ is $F^*(Y) := G^0 \times_{H^0,Y} Y$; this exists in $C$ and the coordinate projection $\text{pr}_1 = s: F^*(Y) \to G^0$ is a cover because $r: Y \to H^0$ is a cover.

The same formulas as above define a left $G$-action and a right $K$-action on $Y$.

### Proposition 6.7.
The bundle functor associated to $F$ is covering if and only if $F$ is essentially surjective, and an equivalence if and only if $F$ is essentially surjective and fully faithful.

**Proof.** The right anchor map of $X_F$ is given by $(x, h) \mapsto s(h)$ for $x \in G^0$, $h \in H^1$ with $F^0(x) = r(h)$; this is exactly the map that is required to be a cover in order for $F$ to be essentially surjective. The bundle $X_F$ is a bundle equivalence if and only if the right anchor map is a cover and the following map is invertible:

$$\varphi: G^1 \times_{s,G^0,r} X_F \to X_F \times_{s,H^0,r} X_F, \quad (g, x) \mapsto (g \cdot x, x).$$

The domain and codomain of $\varphi$ are naturally isomorphic to $G^1 \times_{F^0,H^0,r} H^1$ and $G^0 \times_{r,G^0,r} F^0 \times_{s,H^0,r} G^0$, respectively, and $\varphi$ is given elementwise by $\varphi(g, h) = (r(g), F^1(g \cdot h, s, h), s(g))$ for all $g \in G^1$, $h \in H^1$ with $F^0(s(g)) = r(h)$.

If $\varphi$ is invertible, then the first component of $\varphi^{-1}$ applied to $(x_1, h, 1_{s(h)}, x_2)$ for $x_1, x_2 \in G^0$, $h \in H^1$ with $F^0(x_1) = r(h)$, $F^0(x_2) = s(h)$, gives an inverse to the map $\psi$ in \(\text{3.10}\). Conversely, if $\psi$ is invertible, then so is $\varphi$ with $\varphi^{-1}(x_1, h_1, h_2, x_2) = (\psi^{-1}(x_1, h_1, h_2^{-1}, x_2), h_2)$. \(\square\)

### Example 6.8.

Let $p: X \to G^0$ be a cover. The hypercover $p_*: G(X) \to G$ is an equivalence functor.

### 6.2. From bundle functors to vague functors.

Let $X$ be a bundle functor between two groupoids $G$ and $H$ in $(\mathcal{C}, T)$. We are going to turn it into a vague functor $G \to H$. We take $r: X \to G^0$ as the cover that is part of a vague functor. It remains to define a functor $F: G(X) \to H$ using the $G,H$-bundle $X$.

### Proposition 6.9.

Let $X$ be a bundle functor $G \to H$. There is a natural isomorphism of groupoids $G(X) \cong G \ltimes X \times H$ that acts identically on objects.

**Proof.** Both groupoids $G \ltimes X \times H$ and $G(X)$ have object space $X$. Their arrow spaces are $G^1 \times_{s,G^0,r} X \times_{s,H^0,r} H^1$ and $X \times_{r,G^0} G^1 \times_{s,\mathcal{C},r} X$, respectively. We define

$$F^1: G^1 \times_{s,G^0,r} X \times_{s,H^0,r} H^1 \to X \times_{r,G^0} G^1 \times_{s,\mathcal{C},r} X$$

elementwise by $F^1(g, x, h) := (g \cdot x, g, x \cdot h)$ for all $g \in G^1$, $x \in X$, $h \in H^1$ with $s(g) = r(x)$, $s(x) = r(h)$; this is well-defined because then $g \cdot x$ and $x \cdot h$ are defined and $r(g \cdot x) = r(g)$ and $s(g) = r(x) = r(x \cdot h)$. Furthermore, $r(F^1(g, x, h)) = g \cdot x = r(g, x, h)$, $s(F^1(g, x, h)) = x \cdot h = s(g, x, h)$ and $F^1(g_1, x_1, h_1) \cdot F^1(g_2, x_2, h_2) = (g_1, x_1, g_1 \cdot g_2, x_2 \cdot h_2) = F^1(g_1 \cdot g_2, g_2^{-1}, x_1, h_1 \cdot h_2)$ for all $g_1, g_2 \in G^1$, $x_1, x_2 \in X$, $h_1, h_2 \in H^1$ with $s(g_i) = r(x_i)$, $s(x_i) = r(h_i)$ and $x_1 \cdot h_1 = g_2 \cdot x_2$. Thus $F^1$ together with the identity on arrows is a functor. It remains to show that $F^1$ is an invertible map in $\mathcal{C}$. 
Let \( x_1, x_2 \in X \), \( g \in G^1 \) satisfy \( r(x_1) = g \cdot x_1 \). Then \( x := g^{-1} \cdot x_1 \) is well-defined and \( r(x) = s(g) = r(x_2) \). Since \( X \) with bundle projection \( r \) is a principal \( H \)-bundle, there is a unique \( h \in H^1 \) with \( s(x) = r(h) \) and \( x_2 = x \cdot h \). Thus \( F^1(g, x, h) = (x_1, g, x_2) \). Furthermore, the element \((g, x, h)\) is unique with this property, so \( F^1 \) is invertible by the Yoneda Lemma.

We compose the isomorphism \( G(X) \xrightarrow{\sim} G \rtimes X \rtimes H \) in Proposition 6.9 with the functor \( G \times X \rtimes H \to H \) that is \( s: X \to H \) on objects and the coordinate projection \( \operatorname{pr}_3: (G \times X \rtimes H)^1 \to H^1 \) on arrows. This yields a functor \( F_X: G(X) \to H \), given on \( G(X)^0 = X \) by \( s \) and on \( G(X)^1 = X \times_{r, G^0, r} G^1 \times_{s, G^0, s} X \) by

\[
F_X^1(g \cdot x, g, x, h) := h
\]

for all \( g \in G^1 \), \( x \in X \), \( h \in H^1 \) with \( s(g) = r(x) \), \( s(x) = r(h) \); Proposition 6.9 says that any \((x_1, g, x_2) \in X \times_{r, G^0, r} G^1 \times_{s, G^0, s} X \) may be rewritten as \( x_1 = g \cdot x_1 \), \( x_2 = x \cdot h \) for unique \( g, x, h \) as above.

The triple \((X, r, F_X)\) is a vague functor from \( G \) to \( H \).

**Corollary 6.10.** An equivalence bibundle \( X \) from \( G \) to \( H \) induces an isomorphism \( G(X) \xrightarrow{\sim} H(X) \), that is, a vague isomorphism between \( G \) and \( H \).

**Proof.** If \( X \) is an equivalence bibundle from \( G \) to \( H \), then we may exchange left and right and get another equivalence bibundle \( X^* \) from \( H \) to \( G \). Proposition 6.9 applied to \( X \) and \( X^* \) gives groupoid isomorphisms

\[
r^*(G) = G(X) \xrightarrow{\sim} G \times X \times H \xrightarrow{\sim} H(X) = s^*(H). \]

**Lemma 6.11.** Let \( F: G \to H \) be a functor. This gives rise first to a bibundle functor \( X_F: G \to H \), secondly to a vague functor \((X_F, r_F, \tilde{F})\) from \( G \) to \( H \), where \( r_F: X_F \to G^0 \) is the left anchor map of \( X_F \). This vague functor is equivalent to \((G^0, \operatorname{id}_{G^0}, F), \) that is, to \( F \) viewed as a vague functor.

**Proof.** We have \( X_F = G^0 \times_{F^0, \operatorname{id}_{G^0}} H^1 \) with \( r_F = \operatorname{pr}_1 \). The functor \( \tilde{F}: G(X_F) \to H \) is given elementwise by

\[
\tilde{F}^1(x, h) := s(h), \quad \tilde{F}^1((x_1, h_1), g, (x_2, h_2)) = h_1^{-1} \cdot F^1(g) \cdot h_2
\]

for all \( x, x_1, x_2 \in G^0 \), \( h, h_1, h_2 \in H^1 \), \( g \in G^1 \) with \( F^0(x) = r(h) \), \( F^0(x_1) = r(h_1) \), \( F^0(x_2) = r(h_2) \), \( x_1 = r(g) \), \( x_2 = s(g) \). The map \( \Phi: X_F \to H^1 \), \( (x, h) \mapsto h \), is a natural transformation \( \tilde{F} \Rightarrow F \) because of the following commuting diagram in \( H^1 \):

\[
\begin{array}{ccc}
F^0(x_2) - F^0(x) & \xrightarrow{F^0(s)} & F^0(r) - F^0(x_1) \\
F^1(h_2) & \xrightarrow{F^1} & F^1(h_1) \\
& \xrightarrow{s} & s(h_1)
\end{array}
\]

\[
\begin{array}{cc}
r(h_2) - r(h) & \xrightarrow{F^0} F^0(r_2) - F^0(r_1) \\
h_2 & \xrightarrow{h_1} h_1
\end{array}
\]

7. Composition of bibundles

The composition of bibundle functors and actors requires an extra assumption on the pretopology. We first formulate this assumption in several closely related ways and then use it to compose the various types of bibundles.
7.1. Assumptions on covering groupoid actions. Let $\mathcal{T}$ be a subcanonical pretopology on $\mathcal{C}$.

**Assumption 7.1.** Any action of a covering groupoid in $(\mathcal{C}, \mathcal{T})$ is basic.

**Assumption 7.2.** Any sheaf over a covering groupoid in $(\mathcal{C}, \mathcal{T})$ is basic.

Assumption 7.1 is obviously weaker than Assumption 7.2. We will use Assumptions 7.1 and 7.2 to compose bibundle functors and equivalences. The stronger Assumptions 2.6 and 7.2 to compose bibundle actions defined below.) Proposition 5.6 and 5.7 yield a bijection between maps $\mathcal{G}$-actions and bibundle equivalences on $\mathcal{C}$ functors.

**Proposition 7.3.** The following are equivalent:

1. Let $G$ be a groupoid, $X_1$ and $X_2$ $G$-actions and $f: X_1 \rightarrow X_2$ a $G$-map. If $X_2$ is basic, then so is $X_1$.
2. Any action of a basic groupoid is basic.
3. Any action of a covering groupoid is basic.
4. Let $p: X \rightarrow Z$ be a cover, let $G$ be its covering groupoid, and let $Y$ be a $G$-action. Then there are $\tilde{Z} \in \mathcal{C}$ and a map $f: \tilde{Z} \rightarrow Z$ such that $Y \cong \tilde{Z} \times_{f, Z, \pi} X$ with $G$ acting on $\tilde{Z} \times_{f, Z, \pi} X$ by $(z, x_1) \cdot (x_1, x_2) := (z, x_2)$, as in Proposition 5.6.
5. Let $p: X \rightarrow Z$ be a cover and let $G$ be its covering groupoid. Then the functor $C(Z) \rightarrow C(G)$ induced by the equivalence bibundle $X$ between $G$ and the 0-groupoid $Z$ is an equivalence of categories.

**Proof.** (1) $\Rightarrow$ (2): Let $G$ be a basic groupoid and let $X$ be a $G$-action. Let $X_2 = G^0$ and let $f = s: X \rightarrow X_2$ be the anchor map. Since $f$ is a $G$-map and the $G$-action on $G^0$ is basic by assumption, (1) gives that the $G$-action on $X$ is also basic.

(2) implies (3) because covering groupoids are basic (Example 7.5).

(3) implies (1): the $G$-action on $X_1$ and the map $f$ combine to an action of $X_2 \times G$ on $X_1$. The groupoid $X_2 \times G$ is isomorphic to a covering groupoid by Proposition 5.11. Hence its action on $X_1$ is basic by (3). Corollary 5.13 shows that the action of $G$ on $X_1$ is basic as well.

(4) $\iff$ (3): The action of the covering groupoid of $p$ on $X$ is basic by Example 5.1. Hence its pull-back along $f: \tilde{Z} \rightarrow Z$ remains a basic action by Proposition 5.2. Thus the actions described in (4) are basic, so (4) implies (3). Conversely, let $X$ be a basic $G$-action for the covering groupoid of $p$: $X \rightarrow Z$. Let $p: X \rightarrow \tilde{Z}$ be the bundle projection. The anchor map $f := \bar{s}: X \rightarrow X = G^0$ of the $G$-action on $X$ is a $G$-map. It induces a map $\bar{f} = f/G: \tilde{Z} \rightarrow Z$ by Proposition 5.7. Proposition 5.6 shows that $X$ is isomorphic to $\tilde{Z} \times_{f, Z, \pi} X$ with the canonical action. Thus (3) implies (4).

A $Z$-action is the same as a map $\tilde{Z} \rightarrow Z$. The covering groupoid $G$ of $p: X \rightarrow Z$ is equivalent to the 0-groupoid $Z$ by Example 6.3. The functor $C(Z) \rightarrow C(G)$ induced by this equivalence is, by definition, the pull-back construction described in (4). (This is indeed a special case of the composition of bibundle equivalences with actions defined below.) Propositions 5.6 and 5.7 yield a bijection between maps $\tilde{Z}_1 \rightarrow \tilde{Z}_2$ and $G$-maps $\tilde{Z}_1 \times_Z X \rightarrow \tilde{Z}_2 \times_Z X$. This means that the functor $C(Z) \rightarrow C(G)$ is fully faithful. Condition (4) means that it is essentially surjective. A fully faithful functor is an equivalence if and only if it is essentially surjective.

**Proposition 7.4.** The following are equivalent:
(1) Let \( G \) be a groupoid, \( X_1 \) and \( X_2 \) \( G \)-actions and \( f : X_1 \to X_2 \) a cover that is also a \( G \)-map. If \( X_2 \) is basic, then so is \( X_1 \).

(2) Any sheaf over a basic groupoid is basic.

(3) Any sheaf over a covering groupoid is basic.

(4) Let \( p : X \to Z \) be a cover, let \( G \) be its covering groupoid. Let \( Y \) be a \( G \)-sheaf.

Then there are \( \hat{Z} \in \mathcal{C} \) and a map \( f : \hat{Z} \to Z \) such that \( Y \cong \hat{Z} \times_{f, Z, p} X \) with \( G \) acting on \( \hat{Z} \times_{f, Z, p} X \) by \((z, x_1) \cdot (x_1, x_2) := (z, x_2)\), as in Proposition 5.6. Assumption 2.6 is equivalent to the statement that the map \( f \) in (4) is automatically a cover.

\[ \text{Proof.} \] The proof is the same as for Proposition 7.4. Assumption 2.6 is necessary and sufficient for the map \( f \) in (4) to be a cover because each fibre-product situation (2.4) in which \( q \) is a cover gives rise to a situation as in (4). \( \square \)

Let \( p : X \to Z \) be a cover and let \( G \) be its covering groupoid. Then the equivalence \( \mathcal{C}(T)(Z) \to \mathcal{C}(G) \) between the 0-groupoid \( Z \) and \( G \). By Proposition 7.4, Assumptions 2.6 and 7.1 together are equivalent to the statement that this functor \( \mathcal{C}(T) \to \mathcal{C}(G) \) is an equivalence of categories.

Proposition 7.5. Let \( \mathcal{T} \) and \( \mathcal{T}' \) be pretopologies on \( \mathcal{C} \) with \( \mathcal{T} \subseteq \mathcal{T}' \). Let \( \mathcal{T}' \) be subcanonical; then so is \( \mathcal{T} \). If \( \mathcal{T}' \) satisfies Assumption 7.1, then so does \( \mathcal{T} \). If \( \mathcal{T}' \) satisfies Assumption 7.2, then so does \( \mathcal{T} \).

\[ \text{Proof.} \] Let \( p : X \to Z \) be a cover in \( \mathcal{T} \) and let \( G \) be its covering groupoid. Let \( Y \) be a \( G \)-action. Since \( \mathcal{T} \subseteq \mathcal{T}' \), \( p \) is also a cover in \( \mathcal{T}' \). Proposition 7.4(4) for the pretopology \( \mathcal{T}' \) shows that there is a map \( f : \hat{Z} \to Z \) such that \( Y \cong \hat{Z} \times_{f, Z, p} X \) with \( G \) acting by \((z, x_1) \cdot (x_1, x_2) := (z, x_2)\). This action is basic also in \((\mathcal{C}, \mathcal{T})\). The proof of the second statement is similar. \( \square \)

Often a category admits many different pretopologies. Proposition 7.5 shows that we do not have to check Assumptions 7.1 and 7.2 for all pretopologies, it suffices to look at a maximal one among the interesting pretopologies.

7.2. Composition of bibundle functors and actors.

Proposition 7.6. Let \( G \) and \( H \) be groupoids in \((\mathcal{C}, \mathcal{T})\). Under Assumption 7.1, a bibundle actor \( X \) from \( G \) to \( H \) induces a functor \( \mathcal{C}(H) \to \mathcal{C}(G) \), \( Y \mapsto X \times_H Y \).

Under Assumption 7.2, a \( G, H \)-bibundle \( X \) with basic action of \( H \) induces a functor \( \mathcal{C}(T)(H) \to \mathcal{C}(G) \), \( Y \mapsto X \times_H Y \).

Both constructions are natural in \( X \), that is, a \( G, H \)-map \( X_1 \to X_2 \) induces a natural \( G \)-map \( X_1 \times_H Y \to X_2 \times_H Y \). Assume Assumption 2.6. If the \( G, H \)-map \( f : X_1 \to X_2 \) and the \( H \)-map \( g : Y_1 \to Y_2 \) are covers, then so is the induced map \( f \times_H g : X_1 \times_H Y_1 \to X_2 \times_H Y_2 \).

If Assumptions 7.2 and 2.6 hold, then \( X \times_H Y \in \mathcal{C}(G) \) if \( X \) is a \( G, H \)-bibundle actor and \( Y \in \mathcal{C}(T)(H) \).

\[ \text{Proof.} \] The proofs for bibundle functors and actors are almost the same. The first difference is that the fibre product \( XY := X \times_{s, H^0} Y \) exists in \( \mathcal{C} \) for different reasons: if \( X \) is a bibundle actor, then \( s : X \to H^0 \) is a cover, and otherwise \( Y \in \mathcal{C}(T)(H) \) means that \( s : Y \to H^0 \) is a cover.
There is an obvious left action of $G$ on $XY$ with anchor map $r_{XY} := r \circ \text{pr}_X : XY \to X \to G^0$ and multiplication map
\[ G^1 \times_{s,G^0} r_{XY} XY \to XY \]
given elementwise by $g \cdot (x,y) := (g \cdot x, y)$ for $g \in G^1$, $x \in X$, $y \in Y$ with $s(g) = r(x)$, $s(x) = s(y)$. We equip $XY$ with the unique right $H$-action for which the coordinate projections $\text{pr}_X : XY \to X$ and $\text{pr}_Y : XY \to Y$ are $H$-maps (see Lemma 4.14). Elementwise, we have $s(x,y) = s(x) = s(y)$ and $(x,y) \cdot h = (x \cdot h, y \cdot h)$ for all $x \in X$, $y \in Y$, $h \in H^1$ with $s(x) = s(y) = r(h)$.

The actions of $G$ and $H$ on $XY$ clearly commute, and the map on objects
\[ C(G,H) \times C(H) \to C(G,H), \quad X,Y \mapsto XY, \]
is part of a bifunctor; that is, a $G,H$-map $X_1 \to X_2$ and an $H$-map $Y_1 \to Y_2$ induce a $G,H$-map $X_1Y_1 \to X_2Y_2$.

The coordinate projection $\text{pr}_X : XY \to X$ is an $H$-map and $X$ is a basic $H$-action by assumption. In the first case, Proposition 7.3(1) shows that $XY$ is a basic $H$-action. In the second case, the cover $r : Y \to H^0$ induces a cover $XY \to X$; then Proposition 7.4(1) shows that $XY$ is a basic $H$-action. Let $p : XY \to Z$ be the bundle projection of this basic action. We also write $Z = X \times_Y Y$.

Recall that a $G,H$-map $f : X_1 \to X_2$ and an $H$-map $g : Y_1 \to Y_2$ induce a $G,H$-map $f \times_{H^0} g : X_1Y_1 \to X_2Y_2$. By Proposition 5.7, this induces a map $f \times_H g : X_1 \times_H Y_1 \to X_2 \times_H Y_2$. Thus the construction of $X \times_H Y$ is bifunctorial. If $f$ and $g$ are covers, then so is the induced map $f \times_H g$; this is a general property of pretopologies. By Proposition 5.7, the map $f \times_H g$ induced by this on the base spaces of principal bundles is a cover as well if Assumption 2.6 holds.

It remains to push the $G$-action on $XY$ down to a natural $G$-action on $Z$. Let $W := X/H$. The anchor map $s : X \to G^0$ descends to a map $s_W : W \to G^0$ because it is $H$-invariant. Proposition 5.7 gives a unique map $pr_X/H : Z \to W$, which we compose with $s_W$ to get a map $r_Z : Z \to G^0$. This is the anchor map of the desired action. It is the unique map with $r \circ pr_X = r_Z \circ pr_Y : XY \to G^0$.

Pulling back the principal $H$-bundle $XY \to Z$ along $pr_Z : G^1 \times_{s,G^0} r_Z Z \to Z$ gives
\[ G^1 \times_{s,G^0} r_Z Z \times_Z XY \cong G^1 \times_{s,G^0} r_Z XY \]
with its usual $H$-action. This is a principal bundle over $G^1 \times_{s,G^0} r_Z Z$ by Proposition 5.6. By Proposition 5.7, the left $G^1$-action $G^1 \times_{s,G^0} r_Z XY \to XY$ induces a map $m_Z : G^1 \times_{s,G^0} r_Z Z \to Z$ on the bases of these principal bundles. It is routine to see that $r_Z$ and $m_Z$ define a left $G$-action on $Z$, using the corresponding facts for $XY$ and passing to orbit spaces by Proposition 5.7. Thus $X \times_H Y$ becomes a left $G$-action. This $G$-action is natural in the sense that the maps $f \times_H g$ defined above are $G$-equivariant.

If $X$ is a $G,H$-bibundle function and $Y \in C_T(H)$, then $pr_X : XY \to X$ is a cover because $s : Y \to H^0$ is one. Since $r : X \to G^0$ for bibundle functors, the composite map $XY \to G^0$ is a cover as well. The map $XY \to X \times_H Y$ is a cover as the bundle projection of a principal bundle. Assumption 2.7 shows that the induced map $X \times_H Y \to G^0$ is a cover, so $X \times_H Y \in C_T(G)$.

Proposition 7.7. The quotient $X/H$ for a $G,H$-bibundle $X$ with basic action of $H$ inherits a natural $G$-action.

Proof. This is shown during the proof of Proposition 7.6. We are dealing with the special case $Y = H^0$, where $XY \cong X$, so that $X \times_H H^0 \cong X/H$. No extra assumption about actions of covering groupoids is needed. □
Proposition 7.8. Assume Assumptions 7.2 and 2.6.

Let $G$, $H$ and $K$ be groupoids in $(C, T)$. Let $X$ and $Y$ be bibundle functors from $G$ to $H$ and from $H$ to $K$, respectively. Then $X \times_H Y$ is a bibundle functor from $G$ to $K$ in a natural way with respect to $G$, $H$-maps $X_1 \to X_2$ and $H$, $K$-maps $Y_1 \to Y_2$. If both $X$ and $Y$ are bibundle equivalences, then so is $X \times_H Y$.

Assume also Assumption 2.7. Then if both bibundle functors $X$ and $Y$ are covering, so is $X \times_H Y$.

Assume Assumptions 7.1 and 2.7. Let $X$ and $Y$ be bibundle actors from $G$ to $H$ and from $H$ to $K$, respectively. Then $X \times_H Y$ is a bibundle actor from $G$ to $K$ in a natural way with respect to $G$, $H$-maps $X_1 \to X_2$ and $H$, $K$-maps $Y_1 \to Y_2$.

Proof. Since right and left actions of $H$ are equivalent, Proposition 7.3 also works for a left $H$-action on $Y$. All cases of composition considered fall into one of the two cases of Proposition 7.6 which provides $X \times_H Y$ with a natural $G$-action.

A right $K$-action on $X \times_H Y$ is constructed like the left $G$-action in the proof of Proposition 7.6. First, $XY$ carries a right $K$-action that commutes with the actions of $G$ and $H$: the anchor map is $s \circ \rho_Y: XY \to Y \to K^0$ and the multiplication is $id_X \times_{s \circ \rho_Y} \rho_Y: XY \times_{s \circ \rho_Y} K^0 \to XY$. Proposition 7.4 shows that this $K$-action descends from $XY$ to $X \times_H Y$. A routine inspection of this construction shows that the actions of $G$ and $K$ on $X \times_H Y$ commute.

It remains to show that the $G$, $K$-bibundle $X \times_H Y$ is a bibundle functor, bibundle equivalence, covering bibundle functor, or bibundle actor if both $X$ and $Y$ are, under appropriate assumptions on $(C, T)$. We consider the case of bibundle functors first. We must show that the $r: X \times_H Y \to G^0$ is a principal $K$-bundle.

It is clear that the anchor map $r: X \times_H Y \to G^0$ is $K$-invariant. We claim that it is a cover. The map $\rho_X: XY \to X$ is a cover because $r: Y \to H^0$ is one. Hence so is the induced map $\rho_X/H: X \times_H Y \to X/H \cong G^0$ by Proposition 7.4. Here we need Assumption 2.6. This map is the anchor map $r: X \times_H Y \to G^0$.

We must also show that the map
\[(m, \rho_Y): (X \times_H Y) \times_{s \circ \rho_Y} K^1 \to (X \times_H Y) \times_{s \circ \rho_Y} (X \times_H Y)\]
is an isomorphism. Since $r: Y \to H^0$ is a principal $K$-bundle, its pull-back along $s: X \to H^0$ is a principal $K$-bundle $\rho_X: XY \to X$. This means that the map
\[(m, \rho_Y): (X \times_H Y) \times_{s \circ \rho_Y} K^1 \to (X \times_H Y) \times_{s \circ \rho_Y} (X \times_H Y)\]
is an isomorphism.

Pulling $XY \to X \times_H Y$ back along $r: K^1 \to K^0$ gives a principal $H$-bundle $XY \times_{s \circ \rho_Y} K^1 \to (X \times_H Y) \times_{s \circ \rho_Y} K^1$. Proposition 5.8 shows that $XY \times_{s \circ \rho_Y} X \times_{s \circ \rho_Y} XY$ is a principal $H$-bundle over $(X \times_H Y) \times_{s \circ \rho_Y} (X \times_H Y)$. Hence (7.2) is the map on the base spaces induced by the $H$-equivariant isomorphism (7.2). Thus (7.1) is an isomorphism as well by Proposition 5.7. This finishes the proof that $X \times_H Y$ is a bibundle functor if $X$ and $Y$ are. We have used Assumptions 7.1 and 2.6.

If both $X$ and $Y$ are bibundle equivalences, then the same arguments as above for the right $K$-action apply to the left $G$-action on $X \times_H Y$. They show that $s: X \times_H Y \to K^0$ is a principal $G$-bundle. Thus $X \times_H Y$ is a bibundle equivalence if $X$ and $Y$ are.

Assume now that $s: X \to H^0$ and $s: Y \to K^0$ are covers. Then so are $\rho_Y: XY \to Y$ and the composite map $XY \to Y \to K^0$. Since the bundle projection $XY \to X \times_H Y$ is a cover as well, Assumption 2.7 gives that the anchor map $X \times_H Y \to K^0$ is a cover. Thus a product of covering bibundle functors is again a covering bibundle functor. Furthermore, the right anchor map for a product of two bibundle actors is a cover. It remains to show that the right action on the product of two bibundle actors is basic.
Since the $K$-action on $Y$ is basic, we may form its base $W \cong Y/K$ and get a principal $K$-bundle $p: Y \to W$. Proposition 7.3 shows that the $H$-action on $Y$ descends to $W$.

Now we may also form the $G$-action $X \times_H W$, and the cover $p$ induces a cover $q: X \times_H Y \to X \times_H W$ by Proposition 7.6; here we need Assumption 2.6. The map (7.3) $XY \times_{K^0, r} K^1 \to XY \times_W XY$ is an isomorphism because $p: Y \to W$ is a principal $K$-bundle, which we have pulled back to $XY$. The spaces in (7.3) are total spaces of principal $H$-bundles over $(X \times_H Y) \times_{K^0, r} K^1$ and $(X \times_H Y) \times_{X \times_H W} (X \times_H Y)$, respectively. Proposition 7.6 shows that the induced map $(X \times_H Y) \times_{K^0, r} K^1 \to (X \times_H Y) \times_{X \times_H W} (X \times_H Y)$ on the bases is also an isomorphism. Hence the induced $K$-action on $X \times_H Y$ is basic with bundle projection $q$.

Remark 7.9. The proof above shows that $(X \times_H Y)/K \cong X \times_H (Y/K)$ whenever the actions of $H$ on $X$ and of $K$ on $Y$ are basic and suitable assumptions about $(C, T)$ hold to ensure that $X \times_H Y$ and $X \times_H (Y/K)$ exist and $q: X \times_H Y \to X \times_H (Y/K)$ is a cover.

**Proposition 7.10.** The compositions defined above under suitable assumptions are associative in the following sense:

1. For bibundle functors or bibundle actors $X$ from $G$ to $H$, $Y$ from $H$ to $K$, and $Z$ from $K$ to $L$, there is a natural isomorphism $(X \times_H Y) \times_K Z \cong X \times_H (Y \times_K Z)$; these associators for four composable bibundle functors or actors make the usual pentagon diagram commute.

2. For bibundle actors $X$ from $G$ to $H$ and $Y$ from $H$ to $K$, and a $K$-action $Z$, there is a natural isomorphism $(X \times_H Y) \times_K Z \cong X \times_H (Y \times_K Z)$.

**Proof.** Literally the same argument proves both statements. The usual fibre product $XYZ := X \times_{H^0, r} Y \times_{K^0, r} Z$ is associative up to very canonical isomorphisms, which we drop from our notation to simplify. This space carries commuting actions of $H$ and $K$ by $(x, y, z) \cdot h = (x \cdot h, h^{-1} \cdot y, z)$ and $(x, y, z) \cdot k = (x \cdot y \cdot k, k^{-1} \cdot z)$ for $x \in X$, $y \in Y$, $z \in Z$, $h \in H^1$, $k \in K^1$ with $s(x) = r(y) = r(h)$, $s(y) = r(z) = r(k)$.

We get $X \times_H Y \times_K Z$ from $XYZ$ by first taking the base space $X \times_{H^0} (Y \times_K Z)$ for the basic $K$-action on $XYZ$ and then taking the orbit space of the resulting basic $H$-action on $X \times_{H^0} (Y \times_K Z)$. Remark 7.3 implies that $X \times_H Y \times_K Z$ is naturally isomorphic to $(X \times_H Y \times_{K^0} Z)/K$. The latter is, in turn, naturally isomorphic to $((X \times_H Y) \times_{K^0} Z)/K$, which is $(X \times_H Y) \times_K Z$ by definition. This provides the desired associator.

The associator is characterised uniquely by the statement that it is lifted by the associator $(X \times_{H^0} Y) \times_{K^0, r} Z \to X \times_{H^0, r} (Y \times_{K^0, r} Z)$. Since the latter associators clearly make the associator pentagon commute, the same holds for the induced maps on the quotients.

**Remark 7.11.** Assume Assumption 2.8 about a final object $\star$. Then a left $G$-action $X$ is the same as a bibundle actor from $G$ to $\star$. The functor $\mathcal{C}(H) \to \mathcal{C}(G)$ defined by a bibundle actor $X$ from $G$ to $H$ in Proposition 7.6 is equivalent to the composition of bibundle actors $G \to H \to \star$ under this identification. Thus the second statement in Proposition 7.10 is a special case of the first one.

**Proposition 7.12.** The bibundle equivalence $G^1$ from $G$ to itself is a unit both for the composition of bibundle functors and bibundle actors, up to natural isomorphisms $X \times_G G^1 \cong X$ and $G^1 \times_G Y \cong Y$ for a bibundle functor or actor $X$ to $G$ and a bibundle functor or actor $Y$ out of $G$. 
Proof. The bibundle equivalence $G^1$ is constructed in Example 6.2. Pulling the principal left $G$-bundle $s: G^1 \to G^0$ back along the anchor map $s: X \to G^0$ gives a principal left $G$-bundle $X \times_{s, G^0, s} G^1 \to X$; here the action of $G$ is by $g_1 \cdot (x, g_2) := (x, g_1 \cdot g_2)$. The map $X \times_{s, G^0, s} G^1 \to X \times_{s, G^0, s} G^1$, $(x, g) \mapsto (x \cdot g^{-1}, g)$, is an isomorphism with inverse $(x, g) \mapsto (x, g)$. It intertwines the $G$-action on $X \times_{s, G^0, s} G^1$ with the action of $G$ on $X \times_{s, G^0, s} G^1$ by $g_1 \cdot (x, g_2) := (x, g_1 \cdot g_2)$. These isomorphic $G$-actions have isomorphic orbit spaces, and the orbit space for the latter is $X \times_G G^1$. Hence the multiplication map $X \times_{s, G^0, s} G^1 \to X$, $(x, g) \mapsto x \cdot g$, induces an isomorphism $X \times_G G^1 \cong X$. Similarly, the multiplication map $G^1 \times_{s, G^0, s} Y \to Y$, $(g, y) \mapsto g \cdot y$, induces an isomorphism $G^1 \times_G Y \cong Y$. \hfill \square

Putting together the results above gives the following theorem:

**Theorem 7.13.** Assume Assumptions 2.7 and 7.1. Then there is a bicategory with groupoids in $(C, T)$ as objects, bibundle functors from $G$ to $H$ as arrows, maps of $G, H$-bibundles as 2-arrows between arrows $G \to H$, maps in reverse order as composition, $G^1$ as unit arrow on $G$, the associator and unitors from Propositions 7.10 and 7.12, and composition of maps as vertical product of 2-arrows; the horizontal product of 2-arrows $f: X_1 \Rightarrow X_2$ for $X_1, X_2: G \Rightarrow H$ and $g: Y_1 \Rightarrow Y_2$ for $Y_1, Y_2: H \Rightarrow K$ is $f \times H g$. All 2-arrows in this bicategory are invertible.

Assume Assumptions 2.7 and 7.1. Then almost all of the above holds for bibundle actors, except that 2-arrows need no longer be invertible. Furthermore, the covering bibundle functors form a sub-bicategory of both.

**Proof.** It is a routine consequence of the propositions above that bibundle functors, bibundle equivalences, bibundle actors, and covering bibundle functors are the arrows in bicategories, with the 2-arrows and compositions as asserted.

We show that 2-arrows between bibundle functors are equivalences. Let $X_1$ and $X_2$ be bibundle functors from $G$ to $H$ and let $f: X_1 \Rightarrow X_2$ be a $G, H$-map. Then the induced map $f / H: X_1 / H \Rightarrow X_2 / H$ is the identity map on $G^0$, $G$-equivariance and because $X_i / H \cong G^0$ by assumption. Since $f / H$ is an isomorphism, so is $f$ by Proposition 5.7. This argument fails for bibundle actors because their definition does not determine $X_i / G$. \hfill \square

**Remark 7.14.** Assume Assumption 2.8. Then Assumptions 7.1 and 7.4 are necessary to compose bibundle actors.

By Remark 7.11, we may identify $C(G)$ for a groupoid $G$ with the category of bibundle actors $G \to X \to X$ and 2-arrows between them. Let $p: X \Rightarrow Z$ be a cover and let $G$ be its covering groupoid. The functor $C(Z) \to C(G)$, $Y \mapsto Y \times_Z X$, in Proposition 7.35 composes with the bibundle equivalence $X$ from $Z$ to $G$. Exchanging left and right in $X$ gives a bibundle equivalence $X^* : G \to Z$, such that $X^* \times_Z X \cong G^1$ and $X \times_G X^* \cong Z$. That is, $X^*$ is inverse to $X$. If we can compose bibundle actors, we can compose them with bibundle equivalences as well, and the latter composition must be an equivalence. Hence the existence of a composition of bibundle actors implies Proposition 7.35 and thus Assumption 7.4.

Now consider also a map $f : Z \Rightarrow Y$ such that $f \circ p: X \Rightarrow Y$ is a cover. Then $X$ with its usual left action of $G$ and right action of $Y$ by $f \circ p$ is a covering bibundle functor from $G$ to $Y$, and hence a bibundle actor. Composing it with the equivalence $X^*$ gives the bibundle functor $Z \Rightarrow G \Rightarrow Y$ from the map $f$. This is a bibundle actor if and only if it is a covering bibundle functor if and only if $f$ is a cover. Thus Assumption 7.4 is necessary for composites of bibundle actors to exist, and also for composites of covering bibundle functors to remain covering bibundle functors.
7.3. Bibundle functors versus vague functors.

**Theorem 7.15.** The construction of vague functors from bibundle functors in Section 6.2 is part of an equivalence from the bicategory of bibundle functors to the bicategory of vague functors; this equivalence acts identically on objects.

This theorem requires Assumptions 2.6 and 7.2 in order for the bicategory of bibundle functors to be defined. Related results for Lie groupoids and topological groupoids (with suitable covers) are proved by Pronk [37] and Carchedi [8]. Pronk develops a general calculus of fractions in bicategories for such purposes.

**Proof.** Let $G$ and $H$ be groupoids in $(C, T)$. We show first that the groupoid of vague functors from $G$ to $H$ with natural transformations of vague functors as arrows is equivalent to the groupoid of bibundle functors from $G$ to $H$ with $G,H$-maps between them as arrows. Secondly, we check that this equivalence is compatible with the composition of arrows in the appropriate weak sense.

The vague functor associated to a bibundle functor $X$ from $G$ to $H$ is $(X, r, F_X)$, where $F_X^0 := s: X \to H^0$ on objects and $F_X^2: X \times_{r, G^0, s} G^1 \times_{s, H^0, r} X \to H^2$ is determined by the elementwise formula $F_X^2(g \cdot x, g, g \cdot h) = h$ for all $x \in X, g \in G^1, h \in H^1$ with $s(g) = r(x), s(x) = r(h)$ (see the proof of Proposition 6.3).

Conversely, let $(X, p, F)$ be a vague functor from $G$ to $H$. We have built bibundle functors from functors in Section 6.1. In particular, $p_*: G(X) \to G$ gives a bibundle functor $X \times_p G^0, r G^1$ from $G(X)$ to $G$, and $F: G(X) \to H$ gives a bibundle functor $X \times_{F^0, H^0, r} H^1$ from $G(X)$ to $H$. The bibundle functor $X \times_{p, G^0, r} G^1$ from $G(X)$ to $G$ is a bibundle equivalence (Example 6.3): exchanging the left and right actions on $X \times_{p, G^0, r} G^1$ gives a quasi-inverse bibundle functor $(X \times_{p, G^0, r} G^1)^* \to G(X)$.

We map the vague functor $(X, p, F)$ to the bibundle functor

$$\beta(X, p, F) := (X \times_{p, G^0, r} G^1)^* \times_{G(X)} (X \times_{F^0, H^0, r} H^1).$$

This is the orbit space of the right action of $G(X)$ on the fibre product

$$(X \times_{p, G^0, r} G^1)^* \times_X (X \times_{F^0, H^0, r} H^1) \cong G^1 \times_{s, G^0, p} X \times_{F^0, H^0, r} H^1$$

with anchor map $s(g, x, h) := x$ and

$$(g_1, x_1, h_1) \cdot (x_1, g_2, x_2) := (g_1 \cdot g_2, x_2, F^1(x_1, g_2, x_2)^{-1} \cdot h)$$

for all $g_1, g_2 \in G^1, x_1, x_2 \in X, h \in H^1$ with $s(g_1) = p(x_1) = r(g_2), F^0(x_1) = r(h), p(x_2) = s(g_2)$; the $G$, $H$-action on $\beta(X, p, F)$ is induced by the obvious $G$, $H$-action

$$g_1 \cdot (g_2, x_1, h_1) \cdot h_2 := (g_1 \cdot g_2, x_1, h_1 \cdot h_2)$$

on $G^1 \times_{s, G^0, r} X \times_{F^0, H^0, r} H^1$.

We claim that these two maps between bibundle functors and vague functors are inverse to each other up to natural 2-arrows. First we start with a vague functor $X$, turn it into a vague functor $(X, r, F_X)$ and then turn that into a bibundle functor $(G^1 \times_{s, G^0, r} X \times_{s, H^0, r} H^1)/G(X)$. We claim that the map

$$G^1 \times_{s, G^0, r} X \times_{s, H^0, r} H^1 \to X, \quad (g, x, h) \mapsto g \cdot x \cdot h,$$

descends to an isomorphism $\beta(X, r, F_X) \cong X$; it is clear that this isomorphism is a $G,H$-map. We must show that $(g_1, x_1, h_1), (g_2, x_2, h_2) \in G^1 \times_{s, G^0, r} X \times_{s, H^0, r} H^1$ satisfy $g_1 \cdot x_1 \cdot h_1 = g_2 \cdot x_2 \cdot h_2$ if and only if there is $(x_3, g_3, x_4) \in G(X)^3$ with $s(g_1) = p(x_1) = r(g_2), F^0(x_1) = r(h_1), p(x_2) = s(g_2)$; the $G^1$-entry in $(g_1, x_1, h_1) \cdot (x_3, g_3, x_4)$ is $g_1 \cdot g_3$, so we must have $g_3 = g_1^{-1} \cdot g_2$. Since $s(g_1^{-1}) = r(g_1) = r(g_1 \cdot x_1 \cdot h_1)$ and $r(g_2) = r(g_2 \cdot x_2 \cdot h_2)$, this product is well-defined if $g_1 \cdot x_1 \cdot h_1 = g_2 \cdot x_2 \cdot h_2$. Furthermore, $r(g_1^{-1} \cdot g_2) = s(g_1) = r(x_1)$ and $s(g_1^{-1} \cdot g_2) = s(g_2) = r(x_2)$, so that
that $\Psi$ is well-defined as a map from vague functors to bibundle functors, it remains to show that the map from $\Psi$ to $\beta(X, r, F_X)$ is natural.

Next we start with a vague functor $(X, p, F)$, take the associated bibundle functor

$$Y := (G^1 \times_{s,Gr^0, p} X \times F^0, H^1) / G(X),$$

and construct a vague functor from that. This vague functor contains the cover $g: Y \to G^0$ induced by the map $G^1 \times_{s,Gr^0, X \times F^0, H^0, r} H^1 \to G^0$, $(g, x, h) \mapsto r(g)$, and a functor $E: G(Y) \to H$. This functor is described elementwise by $E^g([x, h]) = s(h)$ for $g \in G^1$, $h \in H^1$, $x \in X$ with $s(g) = p(x)$, $F^0(x) = r(h)$ and

$$E^g([x, h]) := F^1(x_1, g_1^{-1} \cdot g \cdot g_2, x_2) \cdot h$$

for $g, g_1, g_2 \in G^1$, $h_1, h_2 \in H^1$, $x_1, x_2 \in X$ with $s(g_1) = p(x_1)$, $s(g_2) = p(g)$; here $[g, x, h]$ stands for the image of $(g, x, h)$ in $G^1 \times_{s,Gr^0, X \times F^0, H^0, r} H^1$ under the quotient map to $Y$. The constructions above show that there is a unique functor $E$ with these properties.

We describe a canonical natural transformation $\Psi$ from $(Y, q, E)$ to $(X, p, F)$; this is a map from $X \times_{p, Gr^0, q} Y$ to $H^1$ with suitable properties. Elementwise, $\Psi$ is determined uniquely by

$$\Psi([\tilde{x}, [g, x, h]]) = F^1(\tilde{x}, g, x) \cdot h: s(h) \xrightarrow{\Delta} r(h) = F^0(x) \xrightarrow{F^1(\tilde{x}, g, x)} F^0(\tilde{x})$$

for $\tilde{x}, x \in X$, $g \in G^1$, $h \in H^1$ with $s(g) = p(x)$, $F^0(x) = r(h)$, $p(\tilde{x}) = r(g)$. We must check that this is well-defined and that it gives a natural transformation.

For well-definedness, we use that $X \times_{p, Gr^0} Y$ is the orbit space of the $G(X)$-action on $X \times_{p, Gr^0, p} G^1 \times_{s, Gr^0, X \times F^0, H^0, r} H^1$ on the last three legs; this follows as in the construction of the left $G$-action on $X \times Y$ in the proof of Proposition 7.4. It is clear that $\Psi$ is well-defined as a map $X \times_{p, Gr^0} G^1 \times_{s, Gr^0} X \times F^0, H^0, r) H^1 \to H^1$. This map is $G(X)$-invariant because

$$F^1(\tilde{x}, g_1^{-1} \cdot g \cdot g_2, x_2) \cdot F^1(x_1, g_2, x_2)^{-1} \cdot h = F^1(\tilde{x}, g_1, x_1) \cdot h$$

for $\tilde{x}, x_1, x_2 \in X$, $g_1, g_2 \in G^1$, $h \in H^1$ with $p(\tilde{x}) = r(g_1)$, $s(g_1) = p(x_1) = r(g_2)$, $F^0(x_1) = r(h)$, $s(g_2) = p(x_2)$, so that $(x_1, g_2, x_2) \in G(X)$ and $(\tilde{x}, g_1, x_1, h) \in X \times_{p, Gr^0} G^1 \times_{s, Gr^0} X \times F^0, H^0, r) H^1$.

Naturality of $\Psi$ follows because for $(\tilde{x}_i, g_i, x_i, h_i) \in X \times_{p, Gr^0} G^1 \times_{s, Gr^0} X \times F^0, H^0, r) H^1$ for $i = 1, 2$, $g \in G^1$, with $r(g) = p(\tilde{x}_1)$, $s(g) = p(\tilde{x}_2)$, the following diagram in $H$ commutes:

$$\begin{array}{ccc}
    s(h_1) & r(h_1) & F^0(x_1) \\
    h_1^{-1} F^1(x_1, g_1^{-1} \cdot g_2, x_2) & F^0(x_1) \\
    s(h_2) & r(h_2) & F^0(x_2) \\
    h_2^{-1} F^1(x_2, g_2^{-1} \cdot g_1 \cdot g_2, x_2) & F^0(x_2) \\
    F^1(\tilde{x}_1, g, \tilde{x}_2) & F^0(\tilde{x}_2) \\
\end{array}$$

the two rows give $\Psi$ and the left and right vertical maps give $E^1$ and $F^1$ for an arrow in $G(X \times_{Gr^0} Y$.

We have now constructed an equivalence between the groupoids of bibundle functors and vague functors from $G$ to $H$. To check that we have an equivalence of bicategories, it remains to show that the map from vague functors to bibundle functors is compatible with composition of vague functors up to natural $G, H$-maps. The identity (vague) functor on a groupoid $G$ is clearly mapped to the unit bibundle functor on $G$.

The first step is to show that the composition of bibundle functors gives the usual composition for ordinary functors. Let $F_2: G \to H$ and $F_1: H \to K$ be functors. Let
\(\beta(F_2)\) and \(\beta(F_1)\) be the associated bibundle functors. We claim that \(\beta(F_1 \circ F_2)\) is naturally isomorphic to \(\beta(F_2) \times_h \beta(F_1)\) as a \(G, K\)-action. The underlying objects are \(G^0 \times_f F_1^g H, r, K^1\) for \(\beta(F_1 \circ F_2)\) and
\[
(G^0 \times f_2^g H, r, H^1) \times_h (H^0 \times f_1^g K, r, K^1)
\]
for \(\beta(F_2) \times_h \beta(F_1)\); the latter is the orbit space of a canonical \(H\)-action on
\[
(G^0 \times f_2^g H, r, H^1) \times_h (H^0 \times f_1^g K, r, K^1) \cong G^0 \times f_2^g H, r, H^1 \times f_1^g K, r, K^1.
\]
The isomorphism is induced by the map
\[
\alpha: G^0 \times f_2^g H, r, H^1 \times f_1^g K, r, K^1 \rightarrow G^0 \times f_2^g H, r, K^1, \quad (x, h, k) \mapsto (x, F_1(h) \cdot k),
\]
for \(x \in G^0, h \in H^1, k \in K^1\) with \(F_2(q)(x) = r(h), F_0^1(q(h)) = s(F_1^1(h)) = r(k)\). Since \(r: H^1 \rightarrow H^0\) is a cover, so is the coordinate projection \(G^0 \times f_2^g H, r, H^1 \rightarrow G^0\). The pull-back of this cover along the coordinate projection \(G^0 \times f_2^g H, r, K^1 \rightarrow G^0\) is a cover as well, and this pull-back is exactly \(\alpha\). Thus \(\alpha\) is a cover. We must also show that \(\alpha\) induces an isomorphism
\[
(G^0 \times f_2^g H, r, H^1) \times_h (H^0 \times f_1^g K, r, K^1) \rightarrow G^0 \times f_2^g H, r, K^1.
\]
We show that \(\alpha\) is the bundle projection of a principal \(H\)-bundle. This means that if \((x_i, h_i, k_i) \in G^0 \times f_2^g H, r, H^1 \times f_1^g K, r, K^1\) for \(i = 1, 2\), then there is \(h \in H^1\) with
\[
(x_2, h_2, k_2) = (x_1, h_1, k_1) \cdot h := (x_1, h_1 \cdot F_1^1(h) \cdot k_1)
\]
if and only if \(\alpha(x_1, h_1, k_1) = \alpha(x_2, h_2, k_2)\). Indeed, the only possible choice is \(h = h_1^{-1} \cdot h_2\), and this does the trick if and only if \(x_1 = x_2\) and \(F_1^1(h_1) \cdot k_1 = F_1^1(h_2) \cdot k_2\). This provides an isomorphism
\[
(7.4) \quad \beta(F_2) \times_h \beta(F_1) \cong \beta(F_1 \circ F_2)
\]
for two functors \(F_1\) and \(F_2\).

Now consider vague functors \((X, p, F)\) from \(G\) to \(H\) and \((Y, q, E)\) from \(H\) to \(K\). Their composition is the vague functor \((X \times f_0^g H, q, Y, p \circ q \circ E \circ \hat{F}), \) where \(\hat{q} = \bar{p}_1: X \times f_0^g H, q, Y \rightarrow X\) and \(\hat{F}: G(X \times f_0^g H, q, Y) \rightarrow H(Y)\) is induced by \(F\). The bibundle functors associated to \((X, p, F)\) and \((Y, q, E)\) are \(\beta(F) \times H(X) \beta(p)\ast\) and \(\beta(E) \times H(Y) \beta(q)\ast\), respectively; here \(\ast\) means to exchange left and right actions for a bibundle equivalence. We have an equality of functors \(q_\ast \circ \hat{F} = F \circ q_\ast\) by construction. Hence the isomorphisms (7.4) above induce first an isomorphism
\[
\beta(q_\ast)^{-1} \times G(X \times q_\ast Y) \beta(\hat{F}) \cong \beta(F) \times_h \beta(q_\ast)^{-1}
\]
and then an isomorphism
\[
\beta(X, p, F) \times_h \beta(Y, q, E) := \beta(p_\ast)^{-1} \times \times G(X) \beta(F) \times_h \beta(q_\ast)^{-1} \times H(Y) \beta(E)
\]
\[
\cong \beta(p_\ast)^{-1} \times G(X) \beta(q_\ast)^{-1} \times G(X \times q_\ast Y) \beta(\hat{F}) \times H(Y) \beta(E)
\]
\[
\cong \beta((p \circ q_\ast)^{-1} \times G(X \times q_\ast Y) \beta(E \circ \hat{F})
\]
\[
= \beta((Y, q, E) \circ (X, p, F)).
\]

Thus the compositions of vague functors and bibundle functors agree up to the 2-arrows above. It remains to show that these isomorphisms of bibundle functors are natural with respect to natural transformations of vague functors and that they satisfy the coherence conditions needed for a functor between bicategories (see [25]). All this is routine computation and left to the reader. \(\square\)
7.4. Decomposing bibundle actors. Let $G$ and $H$ be groupoids and let $X$ be a bibundle actor from $G$ to $H$. We will decompose $X$ into an ordinary actor from $G$ to an auxiliary groupoid $K$ and a bibundle equivalence from $K$ to $H$:

**Proposition 7.16.** Assume Assumptions 2.6 and 7.2. Any bibundle actor is a composite of an actor and a bibundle equivalence.

The groupoid $K$ is defined using only the right $H$-action on $X$, in such a way that $X$ is a bibundle equivalence from $K$ to $G$. The construction follows one for locally compact groupoids in [32, p. 5].

**Proof.** The fibre product $X \times_{s,H^0,s} X$ exists and the coordinate projections

$$
pr_1, pr_2 : X \times_{s,H^0,s} X \rightrightarrows X
$$

are covers because $s : X \rightrightarrows H^0$ is a cover by assumption. We let $K^0 := X/H$ and

$$
K^1 := (X \times_{s,H^0,s} X)/H,
$$

where $H$ acts diagonally on $X \times_{s,H^0,s} X$, that is, $(x_1, x_2) \cdot h := (x_1 \cdot h, x_2 \cdot h)$ if $x_1, x_2 \in X$, $h \in H^1$ with $s(x_1) = s(x_2) = r(h)$. Assumption 7.2 ensures that this action is basic because $pr_1$ and $pr_2$ are $H$-maps and the $H$-action on $X$ is basic. The range and source maps $r, s : K^1 \rightrightarrows K^0$ are induced by the coordinate projections $pr_1$ and $pr_2$ above and are covers by Proposition 5.7; here we need Assumption 5.8. Using Proposition 5.8 we may identify

$$
K^1 \times_{s,K^0,s} K^1 \cong ( (X \times_{s,H^0,s} X) \times (X \times_{s,H^0,s} X))/H
\cong (X \times_{s,H^0,s} X \times_{s,H^0,s} X)/H.
$$

The multiplication map of $K^1$ is the map on the base induced by the $H$-map $(pr_1, pr_2) : X \times_{s,H^0,s} X \times_{s,H^0,s} X \rightrightarrows X \times_{s,H^0,s} X$. Proposition 5.8 also implies the isomorphisms (7.5) and (5.11) for $K$, so that $K$ is a groupoid in $(\mathcal{C}, T)$.

We are going to construct a canonical actor from $G$ to $K$. Let the groupoid $G$ act on $X \times_{s,H^0,s} X$ by $g \cdot (x_1, x_2) := (g \cdot x_1, x_2)$ for all $g \in G^1$, $x_1, x_2 \in X$ with $s(g) = r(x_1)$ and $s(x_1) = s(x_2)$; this is well-defined because $s(g \cdot x_1) = s(x_1)$. This $G$-action commutes with the diagonal $H$-action and hence descends to a $G$-action on the $H$-orbit space $K^1$ by Proposition 7.3. The resulting $G$-action on $K^1$ commutes with the right multiplication action because $g \cdot [x_1, x_3] = [g \cdot x_1, x_3] = (g \cdot [x_1, x_2]) \cdot [x_2, x_3]$ for all $g \in G^1$, $x_1, x_2, x_3 \in X$ with $s(g) = r(x_1)$, $s(x_1) = s(x_2) = s(x_3)$.

We are going to construct a left $K$-action on $X$ such that $X$ becomes a bibundle equivalence from $K$ to $H$. Its anchor map is the bundle projection $p : X \rightrightarrows X/H$. The action $(X \times_{s,H^0,s} X)/H \rightrightarrows X$ is induced by the map $X \times_{s,H^0,s} X \rightrightarrows X$ that is given elementwise by $(x_1, x_2) \cdot h := x_1 \cdot h$ for all $x_1, x_2 \in X$, $h \in H^1$ with $s(x_1) = s(x_2) = r(h)$; this defines a map on $X \times_{s,H^0,s} X \times_{p,X/H,H^0} X$ because there is $h \in H^1$ with $x_3 = x_2 \cdot h$ whenever $x_2, x_3 \in X$ satisfy $p(x_2) = p(x_3)$. We have $(X \times_{s,H^0,s} X)/H \times_{p,X/H,H^0} X \cong (X \times_{s,H^0,s} X \times_{p,X/H,H^0} X)/H$, where $H$ acts on $X \times_{s,H^0,s} X \times_{p,X/H,H^0} X$ by $(x_1, x_2, x_3) \cdot h := (x_1 \cdot h, x_2 \cdot h, x_3)$. The multiplication map defined above is $H$-invariant for this action, hence it descends to a map $K^1 \times_{s,K^0,p} X \rightrightarrows X$.

Let $H$ act on $K^1 \times_{s,K^0,p} X$ by $(k, x) \cdot h := (k \cdot x \cdot h)$. This action is basic with

$$
(K^1 \times_{s,K^0,p} X)/H \cong K^1 \times_{s,K^0,p} (X/H) \cong K^1,
$$

by Remark 7.4. Thus the $H$-map

$$
(7.5) \quad K^1 \times_{s,K^0,p} X \rightrightarrows X \times_{s,H^0,s} X, \quad (k, x) \mapsto (k \cdot x, x),
$$

induces an isomorphism $(K^1 \times_{s,K^0,p} X)/H \cong (X \times_{s,H^0,s} X)/H$ on the bases of principal $H$-bundles. Hence the map in (7.3) is an isomorphism as well by Proposition 5.7. Thus $s : X \rightrightarrows H^0$ and the $K$-action on $X$ form a principal $K$-bundle. Thus we have turned $X$ into a bibundle equivalence from $K$ to $H$. 

The actor from $G$ to $K$ is also a bibundle actor. Its composite with the bibundle equivalence $X$ from $K$ to $H$ is $X$ as a right $H$-action because $K^1 \times_K X \cong X$ for any bibundle actor $X$ from $K$ to $H$. The induced action of $G$ on the composite is the given one because $g \cdot [x,x] \cdot x = [g \cdot x,x] \cdot x = g \cdot x$ for all $g \in G^1$, $x \in X$, where we interpret $[x,x] \in K^1$. This shows that the actor and the bibundle equivalence constructed above compose to the given bibundle actor $X$.

We conclude that the category of bibundle actors is the smallest one that contains both bibundle equivalences and actors and where the composition is given by $\times_H$.

Now let $X$ be a covering bibundle functor. Equivalently, $X$ is a bibundle actor and the range map induces an isomorphism $\pi_1 X^r \cong G^0$. In the above construction, this means that $K^0 = G^0$, so that the actor from $G$ to $K$ acts identically on objects. Such actors are exactly the ones that are also functors, by Proposition 4.11.

7.5. The symmetric imprimitivity theorem.

Theorem 7.17. Let $G$ and $H$ be groupoids and $X$ a $G,H$-bibundle with basic actions of $G$ and $H$. This induces a left action of $G$ on $X/H$ and a right action of $H$ on $G\backslash X$, and $X$ becomes a bibundle equivalence from $G \times (X/H)$ to $(G\backslash X) \times H$.

Proof. The induced $G$-action on $X/H$ exists by Proposition 7.7. The bundle projection $s' \colon X \to X/H$ is a $G$-map. Hence the $G$-action on $X$ and $s'$ combine to a left action of $G \times (X/H)$ on $X$ with anchor map $s'$ by Proposition 4.10. This left action is basic with the same orbit space $G\backslash X$ by Corollary 5.13 and Lemma 5.14 because the $G$-action on $X$ is basic. Exchanging left and right, the same arguments give an $H$-action on $G\backslash X$ and a basic right action of $(G\backslash X) \times H$ on $X$ with anchor map $r' \colon X \to G\backslash X$ and orbit space $X/H$. The actions of $G \times (X/H)$ and $(G\backslash X) \times H$ on $X$ commute because the actions of $G$ and $H$ commute, $s'$ is $H$-invariant, and $r'$ is $G$-invariant. Hence they form a bibundle equivalence.

This theorem generalises the symmetric imprimitivity theorem for actions of locally compact groups by Green and Rieffel [48] and provides many important examples of bibundle equivalences between transformation groupoids.

Example 7.18. Assume Assumption 2.8 and let $G$ be a group in $C$. Let $H \hookrightarrow G$ and $K \hookrightarrow G$ be “closed subgroups” of $G$; we mean by this that the restrictions of the multiplication actions on $G$ to $H$ and $K$ are basic. Since the left and right multiplication actions commute, $G$ is an $H,K$-bibundle. We get an induced bibundle equivalence $H \times (G/K) \sim (H^1 \times G) \times K$.

7.6. Characterising composites of bibundle functors.

Proposition 7.19. Let $G$, $H$, $K$ be groupoids in $C$. Let $X \colon G \to H$, $Y \colon H \to K$, and $W \colon G \to K$ be bibundle functors. Then isomorphisms $X \times_H Y \cong W$ are in canonical bijection with $G,K$-maps $m \colon X \times_{s,H^r} Y \to W$ with $m(x \cdot h,y) = m(x,h \cdot y)$ for all $x \in X$, $h \in H^1$, $y \in Y$ with $s(x) = r(h)$, $s(h) = r(y)$. If $m$ is such a map, then $m$ is a cover and the following map is an isomorphism:

\[ (pr_1,m) : X \times_{s,H^r} Y \to X \times_{r,G^0} W, \quad (x,y) \mapsto (x,m(x,y)). \]

Proof. Any $G,K$-map $X \times_H Y \to W$ is an isomorphism by Theorem 7.13. Since $X \times_H Y$ is the orbit space of an $H$-action on $X \times_{s,H^r} Y$, a $G,K$-map $X \times_H Y \to W$ is equivalent to an $H$-invariant $G,K$-map $X \times_{s,H^r} Y \to W$. It remains to show that $\pi_1$ is always an isomorphism.

Since $X$ is a principal $H$-bundle over $G^1$, its pull-back $X \times_{r,G^0} W$ along $r : W \to G^1$ is a principal $H$-bundle over $W$ with bundle projection $pr_2$ by Proposition 5.10. Here $H$ acts on $X \times_{r,G^0} W$ by $s(x,w) = s(x)$ and $(x,w) \cdot h := (x \cdot h, w)$ for all $x \in X$, $w \in W$, $h \in H^1$ with $r(x) = r(w)$, $s(x) = r(h)$. By definition of the composition,
$X \times_{s,1} Y \rightarrow X \times_Y Y$ is a principal $H$-bundle as well. We compute that $(pr_1, m)$ is an $H$-map:

$$(pr_1, m)((x, y) \cdot h) = (pr_1, m)(x \cdot h, h^{-1} \cdot y)$$

$$= (x \cdot h, m(x \cdot h, h^{-1} \cdot y)) = (x \cdot h, m(x, y)) = (x, m(x, y)) \cdot h$$

for all $x \in X, y \in Y$, $h \in H^1$ with $s(x) = r(y) = r(h)$. Proposition 7.7 shows that (7.6) is an isomorphism if and only if the induced map $X \times_H Y \rightarrow W$ is an isomorphism.

Since $r: X \rightarrow G^0$ is a cover, so is the induced map $pr_2: X \times_{r,G^0} W \rightarrow W$. Composing this with the isomorphism (7.6) shows that $m$ is a cover. □

We have seen some special cases of the isomorphism (7.6) before. First, the condition (3.4) in the definition of a groupoid is equivalent to $G^1 \times_G G^1 \cong G^1$. Secondly, the condition (5.1) for a principal bundle is equivalent to $X \times_G G^1 \cong X$ for a principal $G$-bundle $X \rightarrow Z$ viewed as a bibundle functor from $Z$ to $G$. We will use this similarity to simplify the description of the quasi-category of groupoids and bibundle functors in Section 8.

Condition (3′′′) in Definition 4.1 is equivalent to $G^1 \times_G X \cong X$ for any left $G$-action $X$.

**Remark 7.20.** The proof of Proposition 7.19 does not use Assumption 7.1. For any subcanonical pretopology $(C, T)$, if $G, H, K$ are groupoids, $X, Y, H: H \rightarrow K$ and $W: G \rightarrow K$ bibundle functors, and $m: X \times_{s,1} Y \rightarrow W$ an $H$-invariant $G$-map and a cover such that (7.6) is an isomorphism, then $m$ is the bundle projection of a principal $H$-bundle, so that $X \times_H Y$ exists and is isomorphic to $W$.

### 7.7. Locality of basic actions

We now reformulate Assumption 4.4 in a way similar to the locality of principal bundles in Proposition 7.9.

Let $G$ be a groupoid, $X$ a right $G$-action, $f: Z \rightarrow Z$ a cover, $Z, \tilde{Z} \in C$, and let $\varphi: X \rightarrow Z$ be some $G$-invariant map. Then we may pull back $X$ along $f$ to a $G$-action $\tilde{X}$: let $\tilde{X} := \tilde{Z} \times_f Z, \varphi X$ (this exists because $f$ is a cover) and define the $G$-action on $\tilde{X}$ by $s(z, x) := s(x)$ and $(z, x) \cdot g := (z, x \cdot g)$ for all $z \in Z, x \in X, g \in G^1$ with $f(z) = \varphi(x), s(x) = r(g)$.

**Proposition 7.21.** In the above situation, if $X$ is a basic $G$-action, then so is $\tilde{X}$. Under Assumption 2.4, Assumption 4.4 is equivalent to the following converse statement: in the above situation, $X$ is basic if $\tilde{X}$ is.

**Proof.** If $X$ is a basic $G$-action, let $Z_0$ be its base and $p: X \rightarrow Z_0$ its bundle projection. There is a unique map $\varphi_0: Z_0 \rightarrow Z$ with $\varphi_0 \circ p = \varphi$ because $\varphi$ is $G$-invariant and $p$ is the orbit space projection by Lemma 6.3. Let $\tilde{Z}_0 := \tilde{Z} \times_{f, Z, \varphi_0} Z_0$. Then $\tilde{X}$ is naturally isomorphic to the pull-back $\tilde{Z}_0 \times_{pr_2, Z_0, p} X$. The induced $G$-action on this together with the projection to $\tilde{Z}_0$ is a principal bundle by Proposition 5.8. Thus $\tilde{X}$ is basic if $X$ is.

Conversely, assume that $\tilde{X}$ is a basic $G$-action. First, we also assume that Assumptions 2.7 and 7.1 hold. Since $f$ is a cover, so is $pr_2: \tilde{X} \rightarrow X$. The map $pr_2$ is a $G$-map as well, so the $G$-action and $pr_2$ give a right $X \times G$-action on $\tilde{X}$ by Proposition 4.10. This action is basic by Corollary 6.15 and because the $G$-action is assumed basic. The advantage of the right $X \times G$-action over the right $G$-action is that its anchor map $pr_2$ is a cover.

Let $H$ be the covering groupoid of $f$. It acts on $\tilde{X}$ on the left with anchor map $pr_1$ and action $(z_1, z_2) \cdot (z_2, x) := (z_1, x)$ for all $z_1, z_2 \in \tilde{Z}, x \in X$ with $f(z_1) = f(z_2) = $
\( \varphi(x) \). This action commutes with the right \( X \times G \)-action. Thus \( \tilde{X} \) is a bibundle actor from \( H \) to \( G \). Proposition \([7,3]\) allows us to compose bibundle actors. In particular, we may compose \( \tilde{X} \) with the bibundle equivalence \( Z \) from \( Z \) to \( H \) (see Example \([6,3]\)).

The composite is \( H \tilde{X} \cong X \) because the pull-back of the principal \( H \)-bundle \( Z \rangle Z \) along \( \varphi \) gives a principal \( H \)-bundle \( \tilde{X} \rangle X \).

Since the isomorphism is the coordinate projection, the induced \( X \times G \)-action on \( \tilde{X} \rangle X \) is the one we started with. Since this composite of bibundle actors is again a bibundle actor from \( Z \) to \( X \times G \), we conclude that \( X \) is a basic right \( X \times G \)-action. Hence it is a basic right \( G \)-action by Corollary \([5,13]\). Thus being basic is a local property of groupoid actions.

Now assume that basic actions are local. Let \( f : \tilde{Z} \rangle Z \) be a cover and let \( G \) be its covering groupoid. Let \( \tilde{X} \rangle X \) be a \( G \)-action. We want to show that \( X \) is basic as well, by proving that it is locally basic. Composing the anchor map \( s : X \rangle Z \) with \( f \) gives a \( G \)-invariant map \( \varphi := f \circ s : X \rangle Z \). The pull-back of the \( G \)-action \( X \rangle X \) along \( f \) gives \( \tilde{X} \rangle X \times_{\varphi} Z \) with \( G \)-action by \( (x, z) \mapsto (x \cdot (z_1, z_2), z) \) for all \( x \in X \), \( z, z_1, z_2 \in \tilde{Z} \) with \( \varphi(x) = f(z) = f(z_1) = f(z_2) \), \( z_1 = s(x) \).

The multiplication \( m : X \times_{\tilde{G}} G \Rightarrow X \) is a cover by \((3'')\) in Definition \([4,1]\). Identifying

\[
X \times_{\tilde{G}} G \cong X \times_{s, \tilde{G}} Z \times \tilde{G} \cong X \times_{f \circ s, Z} Z \rangle \tilde{Z},
\]

this cover becomes \( q : \tilde{X} \rangle X \), \( (x, z) \mapsto x \cdot (s(x), z) \). We claim that \( q \) is the bundle projection of a principal \( G \)-bundle. If \( (x_1, z_1), (x_2, z_2) \in X \) with \( x_1 \cdot (s(x_1), z_1) = x_2 \cdot (s(x_2), z_2) \), then \( f(s(x_1)) = f(z_1), f(s(x_2)) = f(z_2) \), and \( z_1 = s(x_1) \cdot (s(x_1), z_1)) = s(x_2) \cdot (s(x_2), z_2) = z_2 \). Thus

\[
(x_1, z_1) \cdot (s(x_1), s(x_2) = (x_1, z_1) \cdot (s(x_1), z_1) \cdot (z_2, s(x_2)) = (x_2, z_2).
\]

Furthermore, if \( (x_1, z_1) \cdot (z_3, z_4) = (x_2, z_2) \), then \( z_3 = s(x_1) \) and \( z_4 = s(x_2) \), so \((s(x_1), s(x_2))\) is the unique element of \( G \) with this property. Thus the map \([5,1]\) is an isomorphism and \( \tilde{X} \rangle X \) is a principal \( G \)-bundle. Since \( \tilde{X} \) is the pullback of the \( G \)-action \( X \rangle \) along the cover \( f \), any \( G \)-action is locally basic. Therefore, if all locally basic actions are basic, then Assumption \([4,4]\) follows.

7.8. Equivalences in bibundle functors and actors.

**Proposition 7.22.** Let \( G \) and \( H \) be groupoids and let \( X : G \rangle H \) be a bibundle equivalence in \((\mathcal{C}, T)\). Then there are canonical isomorphisms of bibundle equivalences \( X \times_H X^* \cong G^1 \) and \( X^* \times_G X \cong H^1 \).

**Proof.** Since \( r : X \rangle H^0 \) is a left principal \( G \)-bundle, the map \( G^1 \times_{s, G^0} X \Rightarrow X \times_{s, H^0, s} X, (g, x) \mapsto (x, g \cdot x) \), is an isomorphism. The inverse is of the form \( (x_1, x_2) \mapsto (x_1, m(x_1, x_2)) \) for a map \( m : X \times_{s, H^0, s} X \Rightarrow G^1 \), Identifying \( X \times_{s, H^0, s} X \cong X \times_{s, H^0, s} X^*, \) the criterion of Proposition \([7,19]\) applied to \( m \) shows that \( X \times_{H} X^* \cong G^1 \). Explicitly, the isomorphism is induced by \( m \), so it maps the class of \((x_1, x_2) \in X \times_{s, H^0, s} X^* \) to the unique \( g \in G^1 \) with \( g \cdot x_2 = x_1 \).

The same reasoning for \( X^* \) instead of \( X \) gives \( X^* \times_{G} X \cong H^1 \).

**Theorem 7.23.** The equivalences in the bicategories of bibundle functors and bibundle actors are exactly the bibundle equivalences. Furthermore, if \( Y : H \Rightarrow G \) is quasi-inverse to \( X : G \Rightarrow H \), then \( Y \cong X^* \) is obtained from \( X \) by exchanging left and right actions.

We require Assumptions \([2,6]\) and \([7,4]\) for the bibundle functor case and Assumptions \([2,7]\) and \([7,1]\) for the bibundle actor case because otherwise the bicategories in question need not be defined (Theorem \([7,14]\)).

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**Theorem 7.15.** By Theorem 3.29, the equivalences in the bicategory of vague functors are exactly those vague functors that lift to a vague isomorphism. Since the equivalence to bibundle functors maps vague isomorphisms to bibundle equivalences, we conclude that the equivalences in the bicategories of bibundle functors are exactly the bibundle equivalences.

Without Assumption 2.6 something goes wrong at this point because a fully faithful functor that is only almost essentially surjective but not essentially surjective is an equivalence in the bicategory of vague functors, but the associated bibundle functor is no bibundle equivalence by Proposition 6.7.

It is clear that bibundle equivalences are equivalences in the bicategory of bibundle actors. Conversely, let $X$ be an equivalence in this bicategory. Proposition 7.16 decomposes $X$ as a product of a bibundle equivalence and an actor. Thus it suffices to show that an actor that is an equivalence in the bicategory of bibundle actors is already an isomorphism of categories.

Let $m : G^i \times_{s_i G^j, r_i} H^j \to H^j$ be an actor that is an equivalence in the bicategory of bibundle actors. Let $Y$ be its quasi-inverse. Thus $m H^i \times_Y Y \cong G^i$ as $G, G$-bibundles. Since there is a natural isomorphism of right $G$-actions $H^i \times_Y Y \cong Y$, we get $Y \cong G^i$ as a right $G$-action. Thus $Y$ is an actor. When we view actors as bibundle actors, the 2-arrows are exactly the $G, H$-maps $H^i \to H^j$. These are the same 2-arrows that we already used in the bicategory of actors. Any equivalence in this bicategory is an isomorphism of categories by Proposition 7.21. Since the 2-arrows are the same in both bicategories, we conclude that our original actor is an isomorphism of categories.

**Proof.** The bicategories of bibundle functors and vague functors are equivalent by Theorem 7.15. By Theorem 3.29, the equivalences in the bicategory of vague functors are exactly those vague functors that lift to a vague isomorphism. Since the equivalence to bibundle functors maps vague isomorphisms to bibundle equivalences, we conclude that the equivalences in the bicategories of bibundle functors are exactly the bibundle equivalences.

8. THE QUASI-CATEGORY OF BIBUNDLE FUNCTORS

Let $\mathcal{C}$ be a category with coproducts and with a pretopology $\mathcal{T}$ that satisfies Assumptions 2.6 and 7.2. Theorem 7.13 shows that groupoids in $(\mathcal{C}, \mathcal{T})$ with bibundle functors as arrows and $G, H$-maps as 2-arrows form a bicategory with invertible 2-arrows. Its nerve is a quasi-category in the sense of André Joyal [22], that is, a simplicial set satisfying all inner Kan conditions; furthermore, coming from a bicategory, it satisfies inner unique Kan conditions in dimensions above 3. This quasi-category contains essentially the same information as the bicategory.

We are going to describe this quasi-category in a more elementary way, without mentioning groupoids and bibundle functors. The main point is the similarity between the conditions (5.1), (3.4) and (7.6) in the definitions of groupoids, principal bundles, and the composition of bibundle functors. An $n$-simplex in $\mathcal{B}r$ consists of

- $X_i \in \mathcal{C}$ for $0 \leq i \leq n$;
- $X_{ij} \in \mathcal{C}$ for $0 \leq i \leq j \leq n$;
- $r_{ij} \in \mathcal{C}(X_{ij}, X_i)$ and $s_{ij} \in \mathcal{C}(X_{ij}, X_j)$ for $0 \leq i \leq j \leq n$;
- $m_{ijk} \in \mathcal{C}(X_{ij} \times_{s_{ij}, X_j, r_{jk}} X_{jk}, X_{ik})$ for $0 \leq i \leq j \leq k \leq n$;

such that the following conditions hold:

1. $r_{ij}$ is a cover for all $0 \leq i \leq j \leq n$; hence the domain $X_{ij} \times_{s_{ij}, X_j, r_{jk}} X_{jk}$ of $m_{ijk}$ is well-defined;
2. $s_{ij}$ is a cover for all $0 \leq i \leq n$;
3. $r_{ij} \circ m_{ijk} = r_{ij} \circ \text{pr}_1$ and $s_{ij} \circ m_{ijk} = s_{jk} \circ \text{pr}_2$ on $X_{ij} \times_{X_j, X_{jk}} X_{jk}$ for all $0 \leq i \leq j \leq k \leq n$; briefly, $r(x \cdot y) = r(x)$ and $s(x \cdot y) = s(y)$;
(4) (associativity) for $0 \leq i \leq j \leq k \leq l \leq n$, the following diagram commutes:

$$
\begin{array}{c}
\xymatrix{
X_{ij} \times_{X_j} X_{jk} \times_{X_k} X_{kl} \ar[r]^-{\id_{X_{ij} \times_{X_j} X_{jk}}} & X_{ij} \times_{X_j} X_{jk} \times_{X_k} X_{kl} \\
X_{ik} \times_{X_i} X_{kl} \ar[u]^-{m_{ijk} \times_{X_k} \id_{X_{kl}}} \ar[r]^-{m_{ikl}} & X_{il} \ar[u]^-{m_{ijl}}
}
\end{array}
$$

briefly, $(x \cdot y) \cdot z = x \cdot (y \cdot z)$;

(5) the following maps are isomorphisms for all $0 \leq i \leq j \leq k \leq n$ with $i = j$ or $j = k$:

$$(\pr_1, m_{ijk}) : X_{ij} \times_{s_j} X_{j}, r_{jk} X_{jk} \to X_{ij} \times_{r_j}, X_{j}, r_{jk} X_{jk}, \quad (x, y) \mapsto (x, x \cdot y),$$

(6) the following maps are isomorphisms if $0 \leq i \leq j \leq k$:

$$(m_{ijk}, \pr_2) : X_{ij} \times_{s_i} X_{i}, r_{jk} X_{jk} \to X_{ik} \times_{s_i} X_{i}, s_{jk} X_{jk}, \quad (x, y) \mapsto (x, y).$$

An order-preserving map $\varphi : \{0, \ldots, n\} \to \{0, \ldots, m\}$ induces $\varphi^* : \Sigma^m \to \Sigma^n$; take $X_{\varphi(i)}, X_{\varphi(i)\varphi(j)}, r_{\varphi(i)\varphi(j)}, s_{\varphi(i)\varphi(j)}, m_{\varphi(i)\varphi(j)\varphi(k)}$. Thus $\Sigma^*$ is a simplicial set.

Why is this the nerve of the bicategory of bibundle functors?

To begin with, for each $0 \leq i \leq n$, there is a groupoid $G_i$ with objects $X_i$ and arrows $X_{ij}$, range $r_{ij}$, source $s_{ij}$, and multiplication $m_{ijk}$. The conditions above for equal indices amount to the conditions of Definition 3.2.

Next, $X_i$ with left anchor map $r_{il} : X_{il} \to X_{i}$, right anchor map $s_{il} : X_{il} \to X_{i}$, left action $m_{iil}$ and right action $m_{ill}$ in a $G_i, G_l$-bibundle; the associativity condition (4) for $i = j = k \leq l$ says that the left action is associative, the one for $i \leq j = k = l$ says that the right action is associative, the one for $i = j \leq k = l$ says that both actions commute; and for $i = j \leq k \leq l$ says that the left $G_l$-action satisfies (3") in Definition 4.1 and (6) for $i \leq j = k = l$ says that the right $G_l$-action satisfies condition (3") in Definition 4.1

The conditions (1) for $i \leq k$ and (5) for $i \leq j = k$ say that the right $G_k$-action on $X_{ik}$ with bundle projection $r_{ik} : X_{ik} \to X_i$ is a principal bundle; thus $X_{ik}$ is a bibundle functor from $G_i$ to $G_k$. By construction, $X_{ij}$ is the identity bibundle functor on $G_i$.

The associativity conditions (4) for $0 \leq i = j \leq k \leq l \leq n$, $0 \leq i \leq j = k \leq l \leq n$, and $0 \leq i \leq j \leq k = l \leq n$ and (3) say that the maps $m_{ijk} : X_{ij} \times_{X_j} X_{jk} \to X_{ik}$ are $G_l$-invariant $G_i, G_k$-maps. Hence they induce isomorphisms of $G_i, G_k$-bibundles

$$(m_{ijk}) : X_{ij} \times_{G_i} X_{jk} \to X_{ik}$$

by Proposition 7.19. Proposition 7.19 also shows that the maps $m_{ijk}$ are covers for all $0 \leq i \leq j \leq k \leq n$ and that the map in (5) is an isomorphism also for $i < j < k$.

By construction, $m_{ijk} : G_i^l \times_{G_i} X_{ik} \to X_{jk}$ and $m_{ikl} : X_{ik} \times_{G_k} G_l^k \to X_{ik}$ are the canonical isomorphisms. Finally, for $0 \leq i \leq j \leq k \leq l \leq n$, the associativity condition (4) is equivalent to the following commutative diagram of isomorphisms of bibundle functors:

$$
\begin{array}{c}
\xymatrix{
X_{ij} \times_{G_j} X_{jk} \times_{G_k} X_{kl} \ar[r]^-{\id_{X_{ij} \times_{G_j} X_{jk}}} & X_{ij} \times_{G_j} X_{jk} \times_{G_k} X_{kl} \\
X_{ij} \times_{G_j} X_{jl} \ar[u]^-{m_{ijk} \times_{G_k} \id_{X_{kl}}} \ar[r]^-{m_{ijk}} & X_{il} \ar[u]^-{m_{ijl}}
}
\end{array}
$$

Rewriting our $n$-simplices in terms of the groupoids $G_i$, bibundle functors $X_{ij} : G_i \to G_j$ and isomorphisms of bibundle functors $m_{ijk} : X_{ij} \times_{G_j} X_{jk} \to X_{ik}$ gives us precisely the definition of the nerve of the bicategory of bibundle functors. It is well-known that the nerve of a bicategory satisfies the Kan condition Kan(2,1) and the
unique Kan conditions Kan!\((n,j)\) for \(n \geq 3\) and \(1 \leq j \leq n - 1\) (and also for \(n \geq 5\) and \(j = 0\) or \(j = n\)). Of course, this only holds under Assumptions 2.6 and 7.1 because otherwise we do not have a bicategory.

The quasi-category associated to the sub-bicategory of covering bibundle functors is defined similarly; in addition, we require the maps \(s_{ij}\) to be covers for all \(0 \leq i \leq j \leq n\).

The quasi-category associated to the sub-bicategory of bibundle equivalences is defined similarly, with the following extra conditions:

- the maps \(s_{ij}\) should be covers for all \(0 \leq i \leq j \leq n\);
- the maps in (5) and (6) should be isomorphisms if \(0 \leq i \leq j \leq k \leq n\) and \(i = j\) or \(j = k\).

With this symmetric form of the above axioms, we may reverse the order of 0, \ldots, \(n\) and thus show that \(s_{ij}: X_{ij} \rightarrow X_{ij}\) is a principal \(G\)-bundle.

Proposition 7.19 shows that the maps in (5) and (6) are automatically isomorphisms if \(0 \leq i < j < k \leq n\) if this is assumed for \(i = j\) or \(j = k\). So for the quasi-category of bibundle equivalences, we may require (5) and (6) for all \(0 \leq i \leq j \leq k \leq n\). This stronger condition is less technical and provides a very satisfactory description of the quasi-category of groupoids in \((C,T)\) with bibundle equivalences. Since bibundle equivalences are invertible up to 2-arrows, this is a weak 2-groupoid. Thus the corresponding quasi-category also satisfies the outer Kan conditions Kan\(2,j\) for \(j = 0,2\) and Kan\!\!\!\!\!\!(n,j)\) for \(n \geq 3, j = 0, n\).

9. Examples of categories with pretopology

In this section, we discuss pretopologies on different categories and check whether they satisfy our extra assumptions. We also describe basic actions in each case. We begin with a trivial pretopology on an arbitrary category.

Example 9.1. Let \(C\) be any category and let \(T\) be the class of all isomorphisms in \(C\). This is a subcanonical pretopology satisfying Assumptions 2.6 and 2.7. All groupoids in \((C,T)\) are 0-groupoids by Example 3.7 so there are no interesting examples of groupoids. Assumption 7.1 is trivial. Assumption 2.8 on final objects usually fails.

In this section, unlike the previous ones, elementwise statements are meant naively, with elements of sets in the usual sense.

9.1. Sets and surjections. Let \(\text{Sets}\) be the category of sets.

Proposition 9.2. The class \(T_{\text{surj}}\) of surjective maps in \(\text{Sets}\) is a subcanonical, saturated pretopology satisfying Assumptions 2.6, 2.7, 7.1, and 7.2. The subcategory of non-empty sets satisfies the same assumptions and also Assumption 2.8.

Thus all the theory developed above applies to groupoids in \((\text{Sets}, T_{\text{surj}})\). We are going to prove this and characterise basic actions in \((\text{Sets}, T_{\text{surj}})\).

The category \(\text{Sets}\) is complete and therefore closed under fibre products. In the fibre-product situation (2.1), if \(g: U \rightarrow X\) is surjective, then so is the induced map \(\text{pr}_1: Y \times_{f,X,g} U \rightarrow Y\). The isomorphisms in \(\text{Sets}\) are the bijections and belong to \(T_{\text{surj}}\). Let \(f_1: X \rightarrow Y\) and \(f_2: Y \rightarrow Z\) be composable maps. If \(f_1\) and \(f_2\) are surjective, then so is \(f_2 \circ f_1\). Thus surjective maps in \(\text{Sets}\) form a pretopology.

If \(f_2 \circ f_1\) is surjective, then so is \(f_2\). Hence the pretopology \(T_{\text{surj}}\) is saturated, and Assumptions 2.7 and 2.6 follow. A map in \(\text{Sets}\) is a coequaliser if and only if it is surjective. Thus the pretopology \(T_{\text{surj}}\) is subcanonical, and it is the largest subcanonical pretopology on \(\text{Sets}\). Any set with a single element is a final object, and any map to it from a non-empty set is surjective, hence a cover. Hence Assumption 2.8 holds for non-empty sets, but not if we include the empty set. Since a
fibre-product of non-empty sets along a surjective map is never empty, surjections still form a pretopology on the subcategory of non-empty sets, and it still satisfies the same assumptions. Since Assumption 2.8 does not play an important role for our theory, it is a matter of taste whether one should remove the empty set or not.

A groupoid in \((\text{Sets}, \mathcal{T}_{\text{surj}})\) is just a groupoid in the usual sense; the surjectivity of the range and source maps is no condition because the unit map is a one-sided inverse. Since \(\text{Sets}\) has arbitrary colimits, any \(G\)-action \(X\) has an orbit set \(X/G\) (Definition 5.2). The canonical map \(X \rightarrow X/G\) is always surjective.

**Definition 9.3.** A groupoid action in \(\text{Sets}\) is free if for each \(x \in X\), the only \(g \in G^1\) with \(s(x) = r(g)\) and \(x \cdot g = x\) is \(g = 1_{s(x)}\).

**Proposition 9.4.** A groupoid action in \((\text{Sets}, \mathcal{T}_{\text{surj}})\) is basic if and only if it is free.

*Proof.* Let \(G\) be a groupoid and \(X\) a \(G\)-action in \((\text{Sets}, \mathcal{T}_{\text{surj}})\). The canonical map \(p: X \rightarrow X/G\) is a cover. We have \(p(x_1) = p(x_2)\) for \(x_1, x_2 \in X\) if and only if there is \(g \in G^1\) with \(s(x_1) = r(g)\) and \(x_1 \cdot g = x_2\). Thus the map \(X \times_{s, G^0, r} G^1 \rightarrow X \times_{p, X/G, p} X\) is surjective. It is injective if and only if the action is free. \(\square\)

Hence a groupoid \(G\) in \((\text{Sets}, \mathcal{T}_{\text{surj}})\) is basic if and only if all \(g \in G^1\) with \(s(g) = r(g)\) are units. Equivalently, \(G\) is an equivalence relation on \(G^0\).

We may now finish the proof of Proposition 9.2 by showing that any action of a covering groupoid in \(\text{Sets}\) is basic. Let \(G\) be a covering groupoid and let \(X\) be a \(G\)-action. If \(x \in X\), \(g \in G^1\) satisfy \(s(x) = r(g)\) and \(x \cdot g = x\), then \(s(g) = s(x \cdot g) = s(x) = r(g)\). Then \(g = 1_{s(x)}\) because \(G\) is a covering groupoid. Thus the \(G\)-action \(X\) is free; it is basic by Proposition 9.4. This verifies Assumptions 7.1 and 7.2 for \((\text{Sets}, \mathcal{T}_{\text{surj}})\).

9.2. **Pretopologies on the category of topological spaces.** Let \(\text{Top}\) be the category of topological spaces and continuous maps. This category is complete and cocomplete. In particular, all fibre products exist and any groupoid action has an orbit space. There are several classes of maps in \(\text{Top}\) that give candidates for pretopologies:

1. quotient maps
2. biquotient maps (also called limit lifting maps)
3. maps with global continuous sections
4. maps with local continuous sections
5. maps with local continuous sections and partitions of unities
6. closed surjections
7. proper surjections
8. open surjections
9. surjections with many continuous local sections
10. étale surjections

We shall see that quotient maps and closed surjections do not form pretopologies. The other classes of maps all give subcanonical pretopologies that satisfy Assumptions 2.3 and 2.7. Assumption 2.8 about final objects fails for proper maps and étale maps and holds for the remaining pretopologies, if we remove the empty topological space. The pretopologies \((2)–(5)\) are saturated, \((7)–(10)\) are not saturated. Assumption 7.2 and hence also Assumption 7.2 hold in cases \((3)–(5)\) and \((8)–(10)\). Assumption 7.4 fails for biquotient maps; we do not know whether Assumption 7.2 holds for biquotient maps.
9.2.1. Quotient maps.

**Lemma 9.5.** A continuous map \( f : X \to Y \) is a coequaliser in \( \text{Top} \) if and only if it is a quotient map, that is, \( f \) is surjective and \( A \subseteq Y \) is open if and only if \( f^{-1}(A) \) is open.

**Proof.** Let \( g_1, g_2 : Z \rightrightarrows X \) be two maps. Let \( \sim \) be the equivalence relation on \( X \) generated by \( g_1(z) \sim g_2(z) \) for all \( z \in Z \). Equip \( X/\sim \) with the quotient topology. The coequaliser of \( g_1, g_2 \) is the canonical map \( X \to X/\sim \). Thus coequalisers are quotient maps. Conversely, let \( f : X \to Y \) be a quotient map and define an equivalence relation \( \sim \) on \( X \) by \( x_1 \sim x_2 \) if and only if \( f(x_1) = f(x_2) \). Since \( f \) is a quotient map, the induced map \( X/\sim \to Y \) is a homeomorphism. Viewed as a subset of \( X \times X \), we have \( \sim = X \times f, Y, f X \). Thus \( f \) is a coequaliser of \( \text{pr}_1, \text{pr}_2 : X 	imes f, Y, f X \rightrightarrows X \). \( \square \)

\[ \text{[27] Example 8.4} \] provides a quotient map \( f : X \to Y \) and a topological space \( Z \) such that \( f \times \text{id}_Z \) is no longer a quotient map; thus the pull-back of \( f \) along the quotient map \( \text{pr}_1 : Y \times Z \to Y \) is not a quotient map any more. Thus quotient maps do not form a pretopology on \( \text{Top} \). The spaces in \([27] \) Example 8.4 are Hausdorff spaces, so it does not help to restrict from \( \text{Top} \) to the full subcategory \( \text{Haus-Top} \) of Hausdorff spaces.

9.2.2. Biquotient maps.

**Definition 9.6 \([27]\).** Let \( f : X \to Y \) be a continuous surjection. It is a biquotient map if for every \( y \in Y \) and every open covering \( U \) of \( f^{-1}(y) \) in \( X \), there are finitely many \( U \) for which the subsets \( \text{f}(U) \) cover some neighbourhood of \( y \) in \( Y \).

**Definition 9.7 \([16,17]\).** The map \( f \) is limit lifting if every convergent net in \( Y \) lifts to a convergent net in \( X \). More precisely, let \( (I, \leq) \) be a directed set and let \( (y_i)_{i \in I} \) be a net in \( Y \) converging to some \( y \in Y \). A lifting of this convergent net is a directed set \( (J, \leq) \) with a surjective order-preserving map \( \varphi : J \to I \) and a net \( (x_j)_{j \in J} \) in \( X \) with \( f(x_j) = y_{\varphi(j)} \) for all \( j \in J \), converging to some \( x \in X \) with \( f(x) = y \).

**Proposition 9.8 \([27]\).** Biquotient maps are the same as limit lifting maps.

We will use both characterisations of these maps where convenient.

**Proposition 9.9.** The biquotient maps \( \text{T_{biqu}} \) form a subcanonical, saturated pretopology that satisfies Assumptions \([2.6,2.7]\) but not Assumption \([2.1]\). It satisfies Assumption \([2.8]\) if we remove the empty space from the category.

**Proof.** It is clear that isomorphisms are limit lifting. Let \( f_1 : X \to Y \) and \( f_2 : Y \to Z \) be composable maps. If \( f_1 \) and \( f_2 \) are limit lifting, then so is \( f_2 \circ f_1 \) by lifting in two steps; and if \( f_2 \circ f_1 \) is limit lifting, then so is \( f_2 \) by first lifting a convergent net along \( f_2 \circ f_1 \) and then applying the continuous map \( f_1 \). Thus we have a saturated pretopology, and Assumptions \([2.6,2.7]\) follow.

Next we claim that pull-backs inherit the property of being limit lifting. In the fibre-product situation \([2.1]\), assume that \( g : U \to X \) is limit lifting. Let \( (y_i)_{i \in I} \) be a net in \( Y \) that converges to some \( y \in Y \). Then \( f(y_i) \) converges to \( f(y) \) in \( X \). Since \( g \) is limit lifting, there is an order-preserving map \( \varphi : J \to I \) and a net \( \langle u_j \rangle_{j \in J} \) in \( U \) with \( g(u_j) = f(y_{\varphi(j)}) \) for all \( j \in J \), converging to some \( u \in U \) with \( g(u) = f(y) \). Then \( (y_{\varphi(j)}, u_j) \) is a net in \( Y \times f, X, g U \) that converges towards \( (y, u) \). Thus \( \text{pr}_1 : Y \times f, X, g U \to Y \) is limit lifting. This completes the proof that \( \text{T_{biqu}} \) is a pretopology. Limit lifting maps are quotient maps, hence coequalisers, so this pretopology is subcanonical.

A space with a single element is a final object in \( \text{Top} \), and any map from a non-empty space to it is limit lifting. Thus Assumption \([2.8]\) also holds if we exclude the
empty space. The following counterexample to Assumption 7.1 will finish the proof of Proposition 9.8.

Example 9.10. We first recall [22, Example 8.4]. Let $X$ be the disjoint union of $X_1 = (0, 1)$ and $X_2 = \{0, \frac{1}{3}, \frac{1}{7}, \frac{1}{11}, \ldots\}$. Let $\tau_1$ be the obvious topology on $X$. $X_1$ and $X_2$ are open and carry the subspace topologies from $\mathbb{R}$. We will later introduce another topology $\tau_2$ on $X$.

Let $Y$ be the quotient space of $X$ by the relation that identifies $\frac{1}{2}$ in $X_1$ and $X_2$, and let $f: X \to Y$ be the quotient map. This is a quotient map that is not limit lifting. As a set, $Y = [0, 1]$. The topology on $Y$ is the usual one on the subset $(0, 1)$; a subset $U$ of $Y$ with $0 \in U$ is a neighbourhood of 0 if and only if there are $n_0 \in \mathbb{N}$ and $\epsilon_n > 0$ for $n \geq n_0$ with $\bigcup_{n \geq n_0} (\frac{1}{n} - \epsilon_n, \frac{1}{n} + \epsilon_n) \subseteq U$.

We now define another topology $\tau_2$ on $X$ for which the map $f: (X, \tau_2) \to Y$ is limit lifting. The subset $X_1 \cup X_2 \setminus \{0\}$ is open in both topologies $\tau_1$ and $\tau_2$, and both restrict to the same topology on $X_1 \cup X_2 \setminus \{0\}$. A subset $U \subseteq X$ is a $\tau_2$-neighbourhood of 0 if $U \cap X_2$ is a neighbourhood of 0 and there are $n_0 \in \mathbb{N}$ and $\epsilon_n > 0$ for all $n \geq n_0$ such that $\bigcup_{n \geq n_0} (\frac{1}{n} - \epsilon_n, \frac{1}{n} + \epsilon_n) \setminus \{\frac{1}{n}\} \subseteq U$. This uniquely determines the topology $\tau_2$.

On the open subset $(0, 1) \subseteq Y$, the inclusion of $X_1$ into $X$ gives a continuous section for $f|_{(0, 1)}$; hence a net in $Y$ that converges to some element of $(0, 1)$ lifts to a net in $X_1 \subseteq X$ that converges in both $(X, \tau_1)$ and $(X, \tau_2)$. Let now $(y_i)_{i \in I}$ be a net in $Y$ converging to 0. We lift it to a net in $X$ by lifting $y_i$ to $y_i \in X_2$ if $y_i \in X_2$, and to $y_i \in X_1$ if $y_i \notin X_2$. This net in $X$ converges to 0 in $X_2$ in the topology $\tau_2$.

The topology $\tau_1$ is finer than $\tau_2$, that is, the identity map on $X$ is a continuous map $(X, \tau_1) \to (X, \tau_2)$. We claim that the identity map
\[(9.1) (X, \tau_1) \times_{f, Y, f} (X, \tau_1) \to (X, \tau_1) \times_{f, Y, f} (X, \tau_2)\]
is a homeomorphism. That is, the topologies $\tau_1$ and $\tau_2$ pull back to the same topology on $(X, \tau_1) \times_{f, Y, f} X$ along the quotient map $f: (X, \tau_1) \to Y$. This also shows that the localities of isomorphisms, Proposition 2.4, fails for quotient maps in $\mathbf{Top}$; this is okay because they do not form a pretopology.

To prove that the map in (9.1) is a homeomorphism, we show that any net in $X \times X$ converges for $\tau_1 \times \tau_2$ also converges for the topology $\tau_1 \times \tau_1$. A net in $X \times Y$ is a pair of nets $(x_{1i})$ and $(x_{2i})$ with $f(x_{1i}) = f(x_{2i})$. We assume that $(x_{1i}, x_{2i})$ is $\tau_1 \times \tau_2$-convergent to $(x_1, x_2)$. Equivalently, $x_{1i}$ has $\tau_1$-limit $x_1$ and $(x_{2i})$ has $\tau_2$-limit $x_2$. We must show that $x_{2i}$ also converges to $x_2$ in the topology $\tau_1$. This is clear if $x_2 \neq 0 \in X_2$ because the topologies $\tau_1$ and $\tau_2$ agree away from 0. Thus we may assume $x_1 = x_2 = 0$. Since $X_2$ is $\tau_1$-open, we have $x_{1i} \in X_2$ for almost all $i$; hence also $f(x_{2i}) = f(x_{1i}) \in X_2$. Since the points $\frac{1}{i}$ in $X_1$ are excluded from the $\tau_2$-neighbourhoods of 0 and $x_{2i}$ converges to 0 in $\tau_2$, this implies $x_{2i} \in X_2$ for almost all $i$ as well. Since $f|_{X_2}$ is injective, we get $x_{1i} = x_{2i}$ for almost all $i$, so $(x_{2i})$ converges in $\tau_1$.

Now let $G$ be the covering groupoid of the limit lifting map $(X, \tau_2) \to Y$. The action of $G$ on its orbit space $(X, \tau_2)$ is basic in $(\mathbf{Top}, T_{\mathbf{biqu}})$ by Example 5.5. The same action on $(X, \tau_1)$ is still a continuous action: the anchor map $(X, \tau_1) \to (X, \tau_2)$ is continuous, and the action map
\begin{align*}
(X, \tau_1) \times_{f, X, f} (X, \tau_2) &\cong (X, \tau_1) \times (X, \tau_2) \times_{f, X, f} (X, \tau_2) \overset{pr_1}{\to} (X, \tau_1)
\end{align*}
is continuous because of the homeomorphism (9.1). This action is, however, not basic because the orbit space projection $(X, \tau_1) \to (X, \tau_1)/G \cong Y$ is not in $T_{\mathbf{biqu}}$. If this action were basic, it would contradict Proposition 6.7 because the $G$-actions on $(X, \tau_1)$ and $(X, \tau_2)$ have the same orbit space $Y$. 
We do not know whether Assumption \(7.2\) holds for \((\text{Top}, T_{\text{biquot}})\). A counterexample would have to be of different nature because a continuous bijection that is also a (bi)quotient map is already a homeomorphism.

**Proposition 9.11.** The pretopology of biquotient maps is the largest subcanonical pretopology on \text{Top}.

**Proof.** We claim that a continuous map \(f : X \to Y\) is biquotient if and only if \(pr_1 : Z \times_{g,Y,f} X \to Z\) is a quotient map for any map \(g : Z \to Y\). We have already seen that biquotient maps form a pretopology; in particular, if \(f\) is biquotient, then \(pr_1 : Z \times_{g,Y,f} X \to Z\) is biquotient and thus quotient. The converse remains to be proved. It implies the proposition because the covers of a subcanonical pretopology on \text{Top} must be quotient maps by Lemma \(9.5\) hence biquotient by our claim.

Assume that \(pr_1\) is a quotient map for any map \(g : Z \to Y\), although \(f\) is not biquotient; we want to arrive at a contradiction. By assumption, there are \(y_\infty \in Y\) and an open covering \(U\) of \(f^{-1}(y_\infty)\) such that for any finite set \(F \subseteq U\), \(\bigcup_{U \in F} f(U)\) is not a neighbourhood of \(y_\infty\). Let \(I\) be the set of pairs \((F,V)\) for a finite subset \(F \subseteq U\) and an open neighbourhood \(V\) of \(y_\infty\) in \(Y\). We order \(I\) by \((F_1,V_1) \leq (F_2,V_2)\) if \(F_1 \subseteq F_2\) and \(V_1 \supseteq V_2\); this gives a directed set. By assumption, \(V \setminus \bigcup_{U \in F} f(U) \neq \emptyset\) for all \((F,V) \in I\); we choose \(y_{F,V} \in V\) in this difference. Since \(y_{F,V} \in V\), \(\lim y_{F,V} = y_\infty\).

Let \(I^+ := I \cup \{\infty\}\), topologised so that any subset of \(I\) is open and a subset \(W\) containing \(\infty\) is open if and only if there is \(i \in I\) with \(j \in W\) for all \(j \geq i\). Let \(Z := \{(i,y) \in I^+ \times Y \mid y = y_i\}\) be the graph of the function \(I^+ \ni i \mapsto y_i \in Y\), equipped with the subspace topology; let \(g : Z \to Y\) be the second coordinate projection. We identify \(Z \times_{g,Y,f} X \cong \{(i,x) \in I^+ \times X \mid f(x) = y_i\}\), \((i,y,x) \mapsto (i,x)\), for \((i,y) \in Z\), \(x \in X\) with \(f(x) = g(i,y) = y\). This bijection is a homeomorphism for the subspace topologies from \(Z \times X \subseteq I^+ \times Y \times X\) and \(I^+ \times X\).

The subset \(S := Z \setminus \{(\infty,y_\infty)\}\) in \(Z\) is not closed because \(\lim_{i \in F}(i,y_i) = (\infty,y_\infty)\). Since the coordinate projection \(Z \times_{g,Y,f} X \to Z\) is assumed to be a quotient map, the preimage \(\hat{S}\) of \(S\) is not closed in \(Z \times_{g,Y,f} X\). Hence there is a net \((i_j,x_{j})_{j \in J}\) in \(\hat{S}\) that converges in \(Z \times_{g,Y,f} X\) towards some point in the complement of \(\hat{S}\), that is, of the form \((\infty,x_\infty)\) with \(x_\infty \in X\) such that \(f(x_\infty) = y_\infty\). That is, \(\lim x_j = x_\infty\) in \(I^+\) and \(x_j = x_\infty\) in \(X\). We have \(f(x_j) = y_j\) because \((i_j,x_j) \in Z \times_{g,Y,f} X\).

Since \(U\) is an open covering of \(f^{-1}(y_\infty)\) and \(f(x_\infty) = y_\infty\), there is \(U \in U\) with \(x_\infty \in U\). Then also \(x_j \in U\) for sufficiently large \(j \in J\). Since \(i_j \to \infty\), there is \(j_0 \in J\) with \(i_j \geq (\{U\},Y)\) for all \(j \geq j_0\); thus \(y_{j_0} \notin f(U)\) for \(j \geq j_0\). Then \(x_j \notin U\) for \(j \geq j_0\), a contradiction. Hence the coordinate projection \(Z \times_{g,Y,f} X \to Z\) cannot be a quotient map.

\(\square\)

**Remark 9.12.** There are several other notions of improved quotient maps, such as triquotient maps (see \([12,29]\)). Triquotient maps also form a subcanonical pretopology satisfying Assumptions \(2.6\) and \(2.7\). The biquotient map \((X,\tau_2) \to Y\) is a triquotient map as well, however. Thus the same counterexample as above shows that Assumption \(7.1\) fails for the pretopology of triquotient maps. The surjective open maps form the largest pretopology on \text{Top} for which we know Assumption \(7.1\).

Now we consider groupoids in \((\text{Top}, T_{\text{biquot}})\). Any map with a continuous section is limit lifting. Since the unit map is a section for the range and source maps in a groupoid, the condition that \(r\) and \(s\) be limit lifting is redundant in the first definition of a groupoid. In the second definition of a groupoid, it is enough to assume that \(r\) and \(s\) are both quotient maps: this suffices to construct a continuous unit map, which then implies that \(r\) and \(s\) are limit lifting.
The category \( \text{Top} \) has arbitrary colimits, so \( X/G \) exists for any \( G \)-action \( X \); it is the set of orbits \( X/G \) with the quotient topology.

**Proposition 9.13.** Let \( T \) be any subcanonical pretopology on \( \text{Top} \). Let \( G \) be a groupoid and \( X \) a \( G \)-action in \( (\text{Top}, T) \).

The \( G \)-action \( X \) is basic if and only if it satisfies the following conditions:

1. The \( G \)-action \( X \) is free;
2. The map \( X \times_{p, X/G, \rho} G \to G^1 \) that maps \( x_1, x_2 \in X \) in the same orbit to the unique \( g \in G^1 \) with \( s(x_1) = r(g) \) and \( x_1 \cdot g = x_2 \) is continuous;
3. The orbit space projection \( X \to X/G \) is in \( T \).

The first two conditions hold for any \( G \)-action of a covering groupoid in \( (\text{Top}, T) \).

**Proof.** By Lemma 5.3 the bundle projection for a basic action must be the orbit space projection \( p : X \to X/G \). For a basic action, this must be a cover. The continuous map \( X \times_{s, G, r} G \to X \times_{p, X/G, \rho} X \), \( (x, g) \mapsto (x, x \cdot g) \), is surjective by the definition of \( X/G \). It is bijective if and only if it is injective if and only if the action is free (see Proposition 9.11). In this case, the inverse map sends \( (x_1, x_2) \in X^2 \) with \( p(x_1) = p(x_2) \) to \( (x_1, g) \) for the unique \( g \in G^1 \) with \( s(x_1) = r(g) \) and \( x_1 \cdot g = x_2 \). This inverse map is continuous if and only if the map \( (x_1, x_2) \mapsto g \) in (2) is continuous. Hence the action is basic if and only if (1)–(3) hold.

Let \( G \) be the covering groupoid of a cover \( f : Y \to Z \). Let \( (x_1, x_2) \in X \) be in the same \( G \)-orbit. Then any \( g \in G^1 \) with \( s(x_1) = r(g) \) and \( x_1 \cdot g = x_2 \) will satisfy \( s(g) = s(x_1 \cdot g) = s(x_2) \), hence \( g = (s(x_1), s(x_2)) \). This is unique and depends continuously on \( x_1, x_2 \), giving (1) and (2) above. \( \Box \)

Hence the only way that covering groupoid actions in \( (\text{Top}, T) \) may fail to be basic is by the orbit space projection not being a cover.

**Example 9.14.** We construct a free groupoid action in \( (\text{Top}, \mathcal{T}_{\text{biqu}}) \) that satisfies (3) in Proposition 9.13 but not (2). Let \( \mathbb{R}_d \) be \( \mathbb{R} \) with the discrete topology. The translation action of \( \mathbb{R}_d \) on \( \mathbb{R} \) with the usual topology is free. Its orbit space has only one point, so the map \( \mathbb{R} \to \mathbb{R}/\mathbb{R}_d \) is a cover. Condition (2) is violated, so the action is not basic.

The transformation groupoid of the non-basic action in Example 9.10 satisfies (1) and (2) in Proposition 9.13 but not (3).

**9.2.3. Hausdorff orbit spaces.** We now replace \( \text{Top} \) by its full subcategory \( \text{Haus-Top} \) of Hausdorff topological spaces. The proof of Proposition 9.11 still works in this subcategory, showing that the biquotient maps form the largest subcanonical pretopology on \( \text{Haus-Top} \). A groupoid in \( (\text{Haus-Top}, \mathcal{T}_{\text{biqu}}) \) is the same as a groupoid in \( (\text{Top}, \mathcal{T}_{\text{biqu}}) \) with Hausdorff spaces \( G^0 \) and \( G^1 \). A \( G \)-action for a Hausdorff groupoid on a Hausdorff space is basic in \( (\text{Haus-Top}, \mathcal{T}_{\text{biqu}}) \) if and only if it is basic in \( (\text{Top}, \mathcal{T}_{\text{biqu}}) \) and the orbit space is Hausdorff. This is not automatic:

**Example 9.15.** Let \( X := [0, 1] \sqcup [0, 1] \) and let \( Y \) be the quotient of \( X \) by the relation that identifies the two copies of \( (0, 1] \). This is a non-Hausdorff, locally Hausdorff space. The quotient map \( X \to Y \) is open and hence biquotient. Therefore, its covering groupoid is basic in \( (\text{Top}, \mathcal{T}_{\text{biqu}}) \) (Example 5.5). This covering groupoid is also a groupoid in \( (\text{Haus-Top}, \mathcal{T}_{\text{biqu}}) \) because its object space \( G^0 = X \) and arrow space \( G^1 = X \times Y \subseteq X \times X \) are both Hausdorff. Since its orbit space is non-Hausdorff, it is not basic in \( (\text{Haus-Top}, \mathcal{T}_{\text{biqu}}) \).

**Proposition 9.16.** Let \( f : X \to Y \) be a biquotient map. The space \( Y \) is Hausdorff if and only if the subset \( X \times_{f,Y,f} X \subseteq X \times X \) is closed.
The first two conditions hold for any $G$-groupoid and $X$-action is basic in $(\text{Top}, T_{\text{biqui}})$. Let $T$ be any subcanonical pretopology on Haus-Top. Let $G$ be a groupoid and $X$ a $G$-action in $(\text{Haus-Top}, T)$. The $G$-action $X$ is basic in $(\text{Haus-Top}, T)$ if and only if it satisfies the following conditions:

1. the $G$-action $X$ is free;
2. the $G$-action $X$ is proper;
3. the orbit space projection $X \to X/G$ belongs to $T$.

The first two conditions hold for any $G$-action of a covering groupoid in $(\text{Haus-Top}, T)$. Let $\mathcal{T}$ be any subcanonical pretopology on Haus-Top. A groupoid $G$ is proper, that is, $G$-action $X$ is basic in $(\text{Haus-Top}, T)$ if $\mathcal{T}$ is Hausdorff, and the orbit space projection $p: X \to X/G$ is in $\mathcal{T}$. Conversely, these three conditions imply that the action is basic in $(\text{Haus-Top}, T)$. If $Y$ is Hausdorff and $f: X \to Y$ is continuous, then $X \times_{f,Y} X = \{(x_1, x_2) \in X \times X \mid f(x_1) = f(x_2)\}$ is closed: if $x_1, x_2 \in X \times X$ with $f(x_1) \neq f(x_2)$, then there are neighbourhoods $U_i$ of $f(x_i)$ in $Y$ for $i = 1, 2$ with $U_1 \cap U_2 = \emptyset$ because $Y$ is Hausdorff; then $f^{-1}(U_1) \times f^{-1}(U_2)$ is a neighbourhood of $(x_1, x_2)$ in $X \times X$ that does not intersect $X \times_{f,Y} X$.

It remains to show that $Y$ is Hausdorff if $X \times_{f,Y} f X$ is closed in $X \times X$ and $f$ is biquotient. We choose $y, y' \in Y$ with $y \neq y'$ and try to separate them by neighbourhoods. If $x, x' \in X$ satisfy $f(x) = y$ and $f(x') = y'$, then $(x, x') \notin X \times_{f,Y} f X$, so there are open neighbourhoods $U_{x,x'}$ and $U'_{x,x'}$ of $x$ and $x'$, respectively, with $U_{x,x'} \times U'_{x,x'} \cap X \times_{f,Y} f X = \emptyset$; that is, $f(U_{x,x'}) \cap f(U'_{x,x'}) = \emptyset$. Choose such neighbourhoods for all $(x, x') \in f^{-1}(y) \times f^{-1}(y')$. For fixed $x$, the open sets $U'_{x,x'}$ for $x' \in f^{-1}(y')$ cover $f^{-1}(y')$. Since $f$ is biquotient, there is a finite set $A_x \subseteq f^{-1}(y')$ such that $V_x := \bigcup_{x' \in A_x} U'_{x,x'}$ is a neighbourhood of $y'$ in $Y$.

Let $U_x := \bigcap_{x' \in A_x} U_{x,x'}$. This is an open neighbourhood of $x$ because $A_x$ is finite. We have $f(U_x) \cap f(U'_{x,x'}) = \emptyset$ for all $x' \in A_x$ and hence $f(U_x) \cap V_x = \emptyset$. Since $f$ is biquotient and the open subsets $U_x, U'_{x,x'}$ cover $f^{-1}(y)$, there is a finite subset $B \subseteq f^{-1}(y)$ such that $\bigcup_{x' \in B} U'_{x,x'}$ is a neighbourhood of $y$ in $Y$. The finite intersection $\bigcap_{x' \in B} V_x$ is a neighbourhood of $y'$ in $Y$. These two neighbourhoods separate $y$ and $y'$. □

**Corollary 9.17.** A topological space $X$ is Hausdorff if and only if the diagonal is a closed subset in $X \times X$.

**Proof.** Apply Proposition 9.16 to the identity map. □
Proposition 9.13 describes when the action is basic in \((\text{Top}, \mathcal{T}_{\text{biqu}})\). An injective continuous map is proper if and only if it is closed, if and only if it is a homeomorphism onto a closed subset (see [2, I.10.1, Proposition 2]). Thus a free action is continuous, is proper if and only if it is closed, if and only if it is a homeomorphism and \(X \times_{p,G,G} X\) is closed in \(X \times X\). The first part of this is the second condition in Proposition 9.13 and the closedness of \(X \times_{p,G,G} X\) in \(X \times X\) is equivalent to \(X/G\) being Hausdorff by Proposition 9.10 because \(p\) is biquotient. Now it is routine to see that (1)–(3) above characterise basic actions in \((\text{Haus-Top}, T)\).

The first two conditions in Proposition 9.13 are automatic for actions of covering groupoids in \((\text{Top}, \mathcal{T}_{\text{biqu}})\). It remains to show that \(X \times_{p,X/G,G} X\) is closed in \(X \times X\) for any action of a covering groupoid in \((\text{Haus-Top}, \mathcal{T}_{\text{biqu}})\). Let \(Y\) and \(Z\) be Hausdorff spaces and let \(f: Y \to Z\) be a biquotient map with covering groupoid \(G\). Thus \(Y = G^0\) and the anchor map on \(X\) is a map \(s: X \to Y\). Since \(Z\) is Hausdorff,

\[
X \times_Z X = \{(x_1, x_2) \in X \times X \mid f(s(x_1)) = f(s(x_2))\}
\]

is a closed subset of \(X \times X\). If \((x_1, x_2) \in X \times_Z X\), then \((s(x_1), s(x_2)) \in G^1\), so \(x'_2 := x_1 \cdot (s(x_1), s(x_2)) \in X\) is defined. This is the unique element in the orbit of \(x_1\) with \(s(x'_2) = s(x_2)\). Thus

\[
X \times_{X/G} X = \{(x_1, x_2) \in X \times_Z X \mid x_1 \cdot (s(x_1), s(x_2)) = x_2\}.
\]

Since \(X\) is Hausdorff and the two maps sending \((x_1, x_2)\) to \(x_1 \cdot (s(x_1), s(x_2))\) and \(x_2\) are continuous, this subset is closed in \(X \times_Z X\) and hence in \(X \times X\).

We may also restrict to other subcategories of topological spaces, still with biquotient maps as covers:

**Proposition 9.21.** Let \(f: X \to Y\) be biquotient. The following properties are inherited by \(Y\) if \(X\) has them:

1. locally quasi-compact;
2. having a countable base;
3. sequential: a subset \(A\) is closed if and only if it is closed under taking limits of convergent sequences in \(A\);
4. Fréchet: the closure of a subset \(A\) is the set of all points that are limits of convergent sequences in \(A\);
5. \(k\)-space: a subset is closed if and only if \(A \cap K\) is relatively compact in \(K\) for any quasi-compact subset \(K\).

**Proof.** That biquotient images inherit the first two properties is stated in [27] Proposition 3.4. The remaining statements follow from [28], which characterises the images of various classes of “nice” spaces under five classes of “quotient maps.” If a property \(P\) characterises the biquotient images of some particular class of “nice” spaces, then \(P\) is inherited by biquotient images because composites of biquotient maps are again biquotient. Composites of biquotient maps with quotient, hereditarily quotient, or countably biquotient maps are also again of the same sort. Hence all the properties in rows 3–6 of the table in [28, p. 93] are preserved under biquotient images. This includes the properties of being sequential, Fréchet, or a \(k\)-space given above, and many less familiar properties.

The classes of spaces in the first row in the table in [28, p. 93] are, however, not closed under biquotient images. This includes the class of locally compact, paracompact spaces and the class of metrisable spaces. [28] shows that any locally compact space is a biquotient image of a locally compact paracompact space (it is a biquotient image of the disjoint union of its compact subsets), while any “bisequential” space is a biquotient image of a metrisable space.
Since orbit space projections of basic actions in \((\text{Top}, T)\) are biquotient, the orbit space \(X/G\) of a basic action in \((\text{Top}, T)\) will inherit the properties listed in Proposition 9.24 from \(X\). Let \(C \subseteq \text{Top}\) be the full subcategory described by this property, say, the full subcategory of k-spaces, and let \(T\) be some pretopology on \(\text{Top}\). It follows that a groupoid action in \((C, T \cap C)\) is basic if and only if it is basic in \((\text{Top}, T)\); the latter is characterised by Proposition 9.13. If we add Hausdorffness, then a groupoid action in \((C \cap \text{Haus-Top}, T \cap C \cap \text{Haus-Top})\) is basic if and only if it is basic in \((\text{Haus-Top}, T \cap \text{Haus-Top})\), which is characterised by Proposition 9.20.

What if we want to restrict to a subcategory that is not closed under biquotient images, say, the category of metrisable topological spaces? An action of a metrisable topological groupoid on a metrisable topological space is basic with respect to a pretopology \(T\) contained in \(T_{\text{biqu}}\) if and only if it satisfies the conditions in Proposition 9.20 or 9.13 and, in addition, \(X/G\) is metrisable.

**Example 9.22.** Let \(Y\) be bisequential and not metrisable. Let \(f: X \to Y\) be a biquotient map with \(X\) metrisable. Then \(X \times f^{-1}(X) \subseteq X \times X\) is again metrisable. Hence the covering groupoid of \(f\) is a groupoid in the category of metrisable topological spaces with biquotient maps as covers. It is not basic in the category of metrisable spaces, however, because its orbit space is not metrisable.

**9.2.4. Covers defined by continuous sections.** Let \(f: X \to Y\) be a continuous map.

**Definition 9.23.** A global continuous section for \(f\) is a continuous map \(\sigma: Y \to X\) with \(f \circ \sigma = \text{id}_Y\). Let \(T_{\text{split}}\) be the class of all continuous maps with a global continuous section.

A local continuous section for \(f\) at \(y \in Y\) is a pair \((U, \sigma)\) consisting of a neighbourhood \(U\) of \(y\) and a continuous map \(\sigma: U \to X\) with \(f \circ \sigma = \text{id}_U\). We call \(f\) locally split if such local continuous sections exist at all \(y \in Y\). Let \(T_{\text{loc.split}}\) be the class of all locally split continuous maps.

We call \(f\) numerically split if there is a numerical open covering \(U\) of \(Y\) with local sections defined on all elements of \(U\); an open covering is numerical if it has a subordinate partition of unity. Let \(T_{\text{num.split}}\) be the class of numerably split maps.

By definition,

\[
T_{\text{split}} \subseteq T_{\text{num.split}} \subseteq T_{\text{loc.split}}.
\]

A local continuous section \(\sigma: U \to X\) for \(f: X \to Y\) at \(y \in Y\) is determined by its image \(S := \sigma(U) \subseteq X\). This is a subset on which \(f\) restricts to a homeomorphism onto a neighbourhood of \(y\) in \(Y\), and any such subset gives a unique local continuous section for \(f\) near \(y\). The subset \(S\) is also called a slice.

**Proposition 9.24.** \(T_{\text{split}}, T_{\text{num.split}}\) and \(T_{\text{loc.split}}\) are subcanonical, saturated pretopologies on \(\text{Top}\) and \(\text{Haus-Top}\) satisfying Assumptions 2.6, 2.7, 7.1 and 7.2. They satisfy 2.3 if we exclude the empty topological space.

**Proof.** Let \(f: Y \to X\) be a continuous map and let \(g: U \to X\) belong to \(T_{\text{split}}, T_{\text{num.split}}\) or \(T_{\text{loc.split}}\), respectively. Let \(W \subseteq X\) be the domain of a local continuous section \(\sigma: W \to U\) for \(g\). Then \((\text{id}, \sigma \circ f): f^{-1}(W) \to Y \times_X U\) is a local continuous section for the coordinate projection \(\text{pr}_1: Y \times_X U \to Y\). If \(W = X\), then we get a global continuous section. If the domains of such local sections cover \(X\), then the subsets \(f^{-1}(W)\) cover \(Y\). If \((\psi_W)_{W \in U}\) is a partition of unity subordinate to \(U\) by domains of local continuous sections, then \((\psi_W \circ f)_{W \in U}\) provides such a partition of unity for the domains of the induced local continuous sections for \(\text{pr}_1: Y \times_X U \to Y\). Thus the map \(\text{pr}_1\) belongs to \(T_{\text{split}}, T_{\text{num.split}}\) or \(T_{\text{loc.split}}\), respectively, if \(g\) does.
It is clear that homeomorphisms are in $\mathcal{T}_{\text{loc.split}}$ and hence in the other classes as well. If $f_2 \circ f_1$ is defined and belongs to $\mathcal{T}_{\text{loc.split}}$, then we may get local sections for $f_2$ by composing local sections for $f_2 \circ f_1$ with the continuous map $f_1$. Since this does not change the domain, we may use the same partition of unity for $f_2$ as for $f_2 \circ f_1$ in the numerably split case. Hence all three pretopologies are saturated, which implies Assumptions 2.6 and 2.7. It is also clear that the constant map from any non-empty space to the one-point space has global continuous sections, which gives Assumption 2.8 for all three pretopologies if we exclude the empty space. A map with local continuous sections must be surjective, and we may use local continuous sections to lift convergent nets. Hence $\mathcal{T}_{\text{loc.split}} \subseteq \mathcal{T}_{\text{biqui}}$, so that the pretopologies are subcanonical.

Let $f: X \to Z$ be a cover in one of our three pretopologies, let $G$ be its covering groupoid, and let $Y$ be a $G$-action. Let $p: Y \to Y/G$ be the orbit space projection. By Proposition 9.13 the $G$-action is basic if and only if $p$ is a cover. The anchor map $s: Y \to X$ of the $G$-action induces a continuous map $s: G: Y/G \to X/G = Z$.

Let $U$ be an open cover of $Z$ by domains of local sections $\sigma_U: U \to X$ for $U \in \mathcal{U}$; in the case of the pretopology $\mathcal{T}_{\text{num.split}}$, we assume a partition of unity $(\psi_U)_{U \in \mathcal{U}}$ subordinate to this cover, and in the case of the pretopology $\mathcal{T}_{\text{split}}$, we assume $\mathcal{U} = \{Z\}$. The subsets $s^{-1}(U)$ for $U \in \mathcal{U}$ form an open cover $s^*(U)$ of $Y/G$ because $s/G$ is continuous; in the case of $\mathcal{T}_{\text{num.split}}$, $(\psi_U \circ (s/G))_{U \in \mathcal{U}}$ is a partition of unity on $Y/G$ subordinate to $s^*(U)$, and in the case of $\mathcal{T}_{\text{split}}$, $s^*(U) = \{Y/G\}$. It remains to construct local continuous sections $\sigma_U^*: s^{-1}(U) \to Y$ for $U \in \mathcal{U}$.

Let $y \in Y$ represent $[y] \in s^{-1}(U) \subseteq Y/G$. Then $s(y) \in f^{-1}(U) \subseteq X$ and $g_y := (s(y), \sigma_U(f(s(y)))) \in G^1$ has $r(g_y) = s(y)$, so that $y \cdot g_y$ is defined in $Y$. This is the unique element in the $G$-orbit of $y$ with $s(y \cdot g_y) \in \sigma_U(U)$. Hence $y \cdot g_y$ depends only on $[y] \in Y/G$, so that we get a continuous map $\sigma_U^*: s^{-1}(U) \to Y$, $[y] \mapsto y \cdot g_y$. This is a continuous section for $p$ on $s^{-1}(U)$ as needed.

Thus our whole theory applies to groupoids in $\mathbf{Top}$ for the three pretopologies above. The range and source maps of a groupoid are automatically in $\mathcal{T}_{\text{split}}$ because the unit map provides a global continuous section. Hence our pretopologies do not restrict the class of topological groupoids. They give different notions of principal bundles, however, and thus different bicategories of bibundle functors, equivalences, and actors.

Let $G$ be a topological groupoid (without condition on the range and source maps) and let $X$ be a $G$-action that satisfies (1) and (2) in Proposition 9.13. Let $p: X \to X/G$ be its orbit space projection. This is a principal $G$-bundle for $T$ if and only if $p \in \mathcal{T}$.

**Lemma 9.25.** The map $p$ is in $\mathcal{T}_{\text{split}}$ if and only if $X$ is isomorphic to a pull-back of the principal $G$-bundle $r: G^1 \to G^0$ along some map $X/G \to G^0$.

**Proof.** By definition, $p \in \mathcal{T}_{\text{split}}$ if and only if it has a global continuous section $\sigma: X/G \to X$. We claim that the map

$$X/G \times_{s \circ \sigma,G^0,r} G^1 \to X, \quad ([x], g) \mapsto \sigma[x] \cdot g,$$

is a homeomorphism; it is clearly a continuous bijection, and the inverse map sends $y \in X$ to $([y], g)$ where $g$ is the unique element of $G^1$ with $s(\sigma[y]) = r(g)$ and $\sigma[y] \cdot g = y$; the map $y \mapsto ([y], g)$ is continuous by (2) in Proposition 9.13.

The homeomorphism (9.3) is $G$-equivariant for the $G$-action on $X/G \times_{s \circ \sigma,G^0,r} G^1$ defined by $([x], g_1) \cdot g_2 = ([x], g_1 \cdot g_2)$. Hence the principal $G$-bundle $X \to X/G$ is isomorphic to the pull-back of the principal $G$-bundle $r: G^1 \to G^0$ along the continuous map $s \circ \sigma: X/G \to G^0$ (Proposition 5.6). Conversely, such pull-backs are principal $G$-bundles in $\mathbf{Top}$, $\mathcal{T}_{\text{split}}$ because $r: G^1 \to G^0$ is a principal $G$-bundle in $\mathbf{Top}$, $\mathcal{T}_{\text{split}}$. 

\[\square\]
Thus the principal $G$-bundles in $(\text{Top}, \mathcal{T}_{\text{split}})$ are precisely the trivial $G$-bundles in the following sense:

**Definition 9.26.** A $G$-bundle $p: X \to Z$ is trivial if it is isomorphic to a pull-back of the $G$-bundle $r: G^1 \to G^0$ along some map $Z \to G^0$.

A $G$-bundle $p: X \to Z$ is locally trivial if there is an open covering $\mathcal{U}$ of $Z$ such that the restriction $p|_{U}: p^{-1}(U) \to U$ is a trivial $G$-bundle for each $U \in \mathcal{U}$.

If $\mathcal{T} = \mathcal{T}_{\text{loc.split}}$, then there is an open covering $\mathcal{U}$ of $X/G$ such that trivialisations as in (9.3) are defined on the $G$-invariant subsets $p^{-1}(U)$ for $U \in \mathcal{U}$. Lemma 9.26 shows that the principal $G$-bundles in $(\text{Top}, \mathcal{T}_{\text{loc.split}})$ are precisely the locally trivial $G$-bundles.

Let $p: X \to Z$ be a locally trivial bundle. We have an open covering $\mathcal{U}$ of $Z$ and continuous maps $\varphi_U: U \to G^0$ and local trivialisations $\tau_U: p^{-1}(U) \to U \times \varphi_U \circ G^0 \circ r G^1$ for all $U \in \mathcal{U}$. These local trivialisations are not unique and therefore do not agree on intersections $U_1 \cap U_2$ for $U_1, U_2 \in \mathcal{U}$. Since any $G$-map between fibres of $r: G^1 \to G^0$ is given by left multiplication with some $g \in G^1$, we get continuous maps $g_{U_1, U_2}: U_1 \cap U_2 \to G^1$ with $\varphi_{U_2}(z) = r(g_{U_1, U_2}(z))$, $\varphi_{U_1}(z) = s(g_{U_1, U_2}(z))$, and $\tau_{U_2} \circ \tau_{U_1}(z, g) = (z, g_{U_1, U_2}(z) \cdot g)$ for all $(z, g) \in (U_1 \cap U_2) \times \varphi_{U_1} \circ G^0 \circ r G^1$. These maps $g_{U_1, U_2}$ satisfy the usual cocycle conditions.

If $\mathcal{T} = \mathcal{T}_{\text{num.split}}$, then principal bundles are locally trivial and, in addition, the open covering by trivialisation charts is numerable. This suffices to construct a continuous classifying map $\varphi: X/G \to BG$ such that $X \to X/G$ is the pull-back of the universal principal bundle $EG \to BG$ along $\varphi$, even if the base space $X/G$ is not paracompact. Classifying spaces for topological groupoids were introduced by Haefliger [15]; Bracho [4] proves that $G$-principal bundles over locally compact topological spaces are classified by continuous maps to $BG$. The local compactness assumption should not be needed here, as shown by the example of principal bundles over topological groups, but we have not found a proof of this in the literature.

**Remark 9.27.** If $X$ is Hausdorff, then continuous local sections for the orbit space projection $X \to X/G$ imply that $X/G$ is locally Hausdorff, that is, every point has a Hausdorff open neighbourhood; but it does not yet imply that $X/G$ is Hausdorff. Indeed, Example 9.16 is also a basic groupoid in $(\text{Top}, \mathcal{T}_{\text{loc.split}})$.

**9.2.5. Closed and proper maps.** A map between topological spaces is closed if it maps closed subsets to closed subsets. A map $f: X \to Y$ is proper if and only if it is closed and $f^{-1}(y) \subseteq X$ is quasi-compact for all $y \in Y$; this is shown in [2] 1.10.2, Théorème 1]. In particular, there are closed maps that are not proper. Thus closed maps are not hereditary for pull-backs and do not form a pretopology.

**Proposition 9.28.** The proper maps form a subcanonical pretopology $\mathcal{T}_{\text{prop}}$ on $\text{Top}$. It satisfies Assumptions 2.6 and 2.7 but not Assumption 2.8.

**Proof.** It is clear that homeomorphisms are proper and that composites of proper or closed maps are again proper or closed, respectively. Let $g: U \to X$ be proper and let $f: Y \to X$ be any map. Let $Z$ be another topological space. Then $g_* := \text{id}_Y \times g \times \text{id}_Z: Y \times U \times Z \to Y \times X \times Z$ is closed. So is its restriction to any subset of the form $g_*^{-1}(S)$ for $S \subseteq Y \times X \times Z$. If $S$ is the product of the graph of $f$ and $Z$, then this restriction is the map $p \times \text{id}_Z: Y \times f \times X, g U \times Z \to Y \times Z$. Since this is closed for any $Z$, $p \times (Y \times f \times X, g U) \to Y$ is proper.

Proper surjections are biquotient maps by [27] Proposition 3.2. Hence they are coequalisers, so the pretopology of proper maps is subcanonical.

Let $f_1: X \to Y$ and $f_2: Y \to Z$ be continuous surjections. If $f_2 \circ f_1$ is closed, then so is $f_2$: for a closed subset $S \subseteq Y$, $f_2(S) = (f_2 \circ f_1)(f_1^{-1}(S))$ because $f_1$ is surjective, and this is closed because $f_1$ is continuous and $f_2 \circ f_1$ is closed. Hence
the proper maps satisfy Assumption 2.7 and thus Assumption 2.6. The map from a space $X$ to the one-point space is proper if and only if $X$ is quasi-compact. Hence Assumption 2.8 fails even if we exclude the empty space.

For a groupoid in $(\mathbf{Top}, T_{\text{prop}})$, the source and range maps must be proper. This restriction is so strong that we seem to get a rather useless class of groupoids. In particular, proper topological groupoids need not be groupoids in $(\mathbf{Top}, T_{\text{prop}})$.

### 9.2.6. Open surjections

A map between topological spaces is open if it maps open subsets to open subsets. The following criterion for open maps is similar to but subtly different from the definition of limit lifting maps:

**Proposition 9.29** ([8], Proposition 1.15). A continuous surjection $f: X \to Y$ between topological spaces is open if and only if, for any $x \in X$, a convergent net $(y_i)$ in $Y$ with $y_i = f(x)$ lifts to a net in $X$ converging to $x$.

**Proposition 9.30.** The class $T_{\text{open}}$ of surjective, open maps in $\mathbf{Top}$ is a subcanonical pretopology that satisfies Assumptions 2.6, 2.7, 7.1 and 7.2 but it is not saturated. It satisfies Assumption 2.8 if we exclude the empty space.

The proof that $T_{\text{open}}$ is a subcanonical pretopology satisfying Assumptions 2.6, 2.7 and 2.8 is similar to the proof for $T_{\text{biqui}}$, using Proposition 9.29 and left to the reader.

The following simple counterexample shows that it is not saturated:

**Example 9.31.** Let $f: X \to Y$ be a continuous map that is not open. Let $f_2 := (f, \text{id}_X): X \sqcup Y \to Y$ and let $f_1: Y \to X \sqcup Y$ be the inclusion map. Then $f_2 \circ f_1$ is the identity map on $Y$, hence a cover. But $f_2$ is not open because $f$ is not open.

Hence the pretopology $T_{\text{open}}$ is not saturated.

Groupoids in $(\mathbf{Top}, T_{\text{open}})$ must have open range and source maps. This is no serious restriction for operator algebraists because they need Haar systems to construct groupoid $C^*$-algebras, and Haar systems cannot exist unless the range and source maps are open. The benefit of this assumption is that it forces the orbit space projections $X \to X/G$ for all $G$-actions to be open:

**Proposition 9.32.** Let $G$ be a groupoid and $X$ a $G$-action in $(\mathbf{Top}, T_{\text{open}})$. The orbit space projection $p: X \to X/G$ is open. All actions of covering groupoids in $(\mathbf{Top}, T_{\text{open}})$ are basic.

**Proof.** Let $U \subseteq X$ be open. Then $p^{-1}(p(U))$ is the set of all $x \cdot g$ with $x \in U$, $g \in G^1$, $s(x) = r(g)$. This is $m((U \times G^1) \cap (X \times_{G^0,G^1} G^1))$, which is open because $(U \times G^1) \cap (X \times_{G^0,G^1} G^1)$ is open in $X \times_{G^0,G^1} G^1$ and $m$ is a cover (open surjection) by Proposition 3.6. Thus $p(U)$ is open in $X/G$, and $p$ is open. Proposition 9.13 characterises basic actions by three conditions, of which two are automatic for actions of covering groupoids. The third condition is that $p$ should be a cover, which is automatic for the pretopology $T_{\text{open}}$. Thus all covering groupoid actions in $(\mathbf{Top}, T_{\text{open}})$ are basic, verifying Assumptions 7.1 and 7.2.

This finishes the proof of Proposition 9.30.

**Corollary 9.33.** Let $G$ be a groupoid and $X$ a $G$-action in $(\mathbf{Top}, T_{\text{open}})$. The following are equivalent:

1. the action is basic with Hausdorff base space $X/G$;
2. the action is free and proper.

**Proof.** This follows from the proof of Proposition 9.20, which still works even if $G$ or $X$ are non-Hausdorff.
The proof of Proposition 9.20 shows that an action is free and proper if and only if it satisfies the first two conditions in Proposition 9.13 and $X \times_{p, X/G, p} X$ is closed in $X \times X$. This is exactly how Henri Cartan defines principal fibre bundles for a topological group $G$ in [9] condition (FP) on page 6-05:

Un espace fibré principal $E$ est un espace topologique $E$, où opère un groupe topologique $G$ (appelé groupe structural), de manière que soit rempli l’axiome suivant :

(FP) : le graphe $C$ de la relation d’équivalence définie par $G$ est une partie fermée de $E \times E$ : pour chaque point $(x, y) \in C$ il existe un $s \in G$ et un seul tel que $x \cdot s = y$ ; en outre, en désignant par $u$ l’application de $C$ dans $G$ ainsi définie, on suppose que $u$ est une fonction continue.

Thus our notion of principal bundle in $(\text{Top}, \mathcal{T}_{\text{open}})$ is the same as Henri Cartan’s. Palais [34] and later authors ([11, 20]) call a locally compact group(oid) action Cartan if it satisfies a condition that, for free actions, is equivalent to the continuity of the map $(x, x \cdot g) \mapsto g$, allowing non-Hausdorff orbit spaces. Cartan himself, however, requires the orbit space to be Hausdorff because he requires the orbit equivalence relation to be closed (Proposition 9.16).

9.2.7. Covers with many local continuous sections.

Definition 9.34. A continuous map $f : X \to Y$ has many local continuous sections if it is surjective and for all $x \in X$ there is an open neighbourhood $U \subseteq Y$ of $f(x)$ and a continuous map $\sigma : U \to X$ with $\sigma(f(x)) = x$ and $f(\sigma(y)) = y$ for all $y \in U$. Let $\mathcal{T}_{\text{loc.sect.}}$ be the class of continuous maps with many local continuous sections.

The difference between this pretopology and $\mathcal{T}_{\text{loc.split.}}$ is that we require local sections with a given $x \in X$ in the image. This forces the map $f$ to be open, so $\mathcal{T}_{\text{loc.sect.}} \subseteq \mathcal{T}_{\text{open}}$, whereas $\mathcal{T}_{\text{loc.split.}} \not\subseteq \mathcal{T}_{\text{open}}$.

Proposition 9.35. The class $\mathcal{T}_{\text{loc.sect.}}$ is a subcanonical pretopology on $\text{Top}$ that satisfies Assumptions 2.6, 2.7, 7.1, and 7.2 but is not saturated. It satisfies Assumption 2.3 if we exclude the empty space.

Proof. The proof is very similar to the proof for the pretopology $\mathcal{T}_{\text{loc.split.}}$ (Proposition 9.14) and therefore left to the reader. The idea of Example 9.31 also shows that $\mathcal{T}_{\text{loc.sect.}}$ is not saturated. Since $\mathcal{T}_{\text{loc.sect.}}$ is contained both in $\mathcal{T}_{\text{loc.split.}}$ and $\mathcal{T}_{\text{open}}$ and both are subcanonical and have the property that actions of covering groupoids are basic, Assumptions 7.1 and hence 7.2 follow from Proposition 7.23.

The topological groupoids in $(\text{Top}, \mathcal{T}_{\text{loc.sect.}})$ are those topological groupoids for which $r$ or, equivalently, $s$ has many local continuous sections. This happens for both maps once it happens for one because of the continuous inversion on $G^1$.

Proposition 9.36. Let $G$ be a groupoid and $X$ a $G$-action in $(\text{Top}, \mathcal{T}_{\text{loc.sect.}})$. Then $X$ is basic in $(\text{Top}, \mathcal{T}_{\text{loc.split.}})$ if and only if it is basic in $(\text{Top}, \mathcal{T}_{\text{loc.split.}})$.

Proof. Since $r : G^1 \to G^0$ is a principal $G$-bundle in $(\text{Top}, \mathcal{T}_{\text{loc.sect.}})$, so are its pullbacks, that is, all trivial bundles. Since the existence of many local continuous sections is a local condition, this extends to locally trivial $G$-bundles. Since the principal $G$-bundle in $(\text{Top}, \mathcal{T}_{\text{loc.split.}})$ are precisely the locally trivial $G$-bundles, they are principal in $(\text{Top}, \mathcal{T}_{\text{loc.sect.}})$ as well. The same then holds for basic actions.

Roughly speaking, if the map $r : G^1 \to G^0$ has many local continuous sections, then we may shift local continuous sections for the quotient map $X \to X/G$ so that a particular point in a fibre is in the image of the local section.
Proposition \[\text{9.36}\] implies that the bicategories of bibundle functors, equivalences, and actors for \((\mathsf{Top}, \mathcal{T}_{\text{loc.sect.}})\) are full sub-bicategories of the corresponding bicategories for \((\mathsf{Top}, \mathcal{T}_{\text{loc.split}})\): we only restrict from all topological groupoids to those where the range and source maps have many local continuous sections.

9.2.8. Étale surjections. A continuous map \(f: X \to Y\) is called étale (or local homeomorphism) if for all \(x \in X\) there is an open neighbourhood \(U\) such that \(f(U)\) is open and \(f|_U : U \to f(U)\) is a homeomorphism for the subspace topologies on \(U\) and \(f(U)\) from \(X\) and \(Y\), respectively. This implies that \(f\) is open. Let \(\mathcal{T}_{\text{et}}\) be the class of étale surjections.

**Proposition 9.37.** The class \(\mathcal{T}_{\text{et}}\) is a subcanonical pretopology on \(\mathsf{Top}\) that satisfies Assumptions \[2.6\] \[2.7\] \[7.1\] and \[7.2\]: it is not saturated and Assumption \[2.8\] fails.

**Proof.** The proof is very similar to that of Proposition \[9.24\] and therefore left to the reader. Unless \(X\) is discrete, the constant map from \(X\) to a point is not étale, so Assumption \[2.8\] fails for \(\mathcal{T}_{\text{et}}\), even if we exclude the empty space. The idea of Example \[9.31\] shows that \(\mathcal{T}_{\text{et}}\) is not saturated. \(\square\)

The groupoids in \((\mathsf{Top}, \mathcal{T}_{\text{et}})\) are precisely the étale topological groupoids.

**Proposition 9.38.** An action of an étale topological groupoid is basic in \((\mathsf{Top}, \mathcal{T}_{\text{et}})\) if and only if it satisfies the first two conditions in Proposition \[9.13\]. A groupoid action in \((\mathsf{Haus-Top}, \mathcal{T}_{\text{et}})\) is basic if and only if it is free and proper.

**Proof.** Let \(G\) be an étale topological groupoid and let \(X\) be a \(G\)-action in \(\mathsf{Top}\) that satisfies the first two conditions in Proposition \[9.13\]. We must prove that the canonical map \(p: X \to X/G\) is étale, that is, the third condition in Proposition \[9.13\] is automatic for the pretopology \(\mathcal{T}_{\text{et}}\). The characterisation of basic actions in \((\mathsf{Haus-Top}, \mathcal{T}_{\text{et}})\) then follows from Proposition \[9.20\].

The first two conditions in Proposition \[9.13\] say that the map

\[
X \times_{s,G,p,G} G^1 \to X \times_{p,X/G,p} X, \quad (x,g) \mapsto (x, x \cdot g),
\]

is a homeomorphism. Since \(G\) is étale, the set of units \(u(G^0)\) is open in \(G^1\). Its image in \(X \times_{p,X/G,p} X\) is the diagonal \((\{(x_1, x_2) \in X \times X \mid x_1 = x_2\})\). Hence any \(x \in X\) has an open neighbourhood \(U \subseteq X\) such that \((U \times U) \cap (X \times_{p,X/G,p} X)\) is the diagonal in \(U\). This means that for \(x_1, x_2 \in U\), \(p(x_1) = p(x_2)\) only if \(x_1 = x_2\). Thus \(p\) is injective on the open subset \(U \subseteq X\). Since \(G\) is an étale groupoid, its range and source maps are open. Hence \(p\) is open by Proposition \[9.32\]. Its restriction to \(U\) is injective, open and continuous, hence a homeomorphism onto an open subset of \(X/G\). \(\square\)

9.3. Smooth manifolds of finite and infinite dimension. We consider the following categories of smooth manifolds of increasing generality:

- \(\text{Mfd}_{\text{fin}}\): finite-dimensional manifolds;
- \(\text{Mfd}_{\text{Hil}}\): Hilbert manifolds;
- \(\text{Mfd}_{\text{Ban}}\): Banach manifolds;
- \(\text{Mfd}_{\text{Fré}}\): Fréchet manifolds;
- \(\text{Mfd}_{\text{lcs}}\): locally convex manifolds.

Such manifolds are Hausdorff topological spaces that are locally homeomorphic to finite-dimensional vector spaces, Hilbert spaces, Banach spaces, Fréchet spaces, or locally convex topological vector spaces, respectively. Paracompactness is a standard assumption for finite-dimensional manifolds, but not for infinite-dimensional ones. The morphisms between all these types of manifolds are smooth maps, meaning maps given in local charts by smooth maps between topological vector spaces. Banach manifolds are treated in Lang’s textbook \[23\], Fréchet manifolds in \[18\] Section 1.4, and locally convex manifolds in \[83\] Appendix A and \[11\] Appendix B. The covers are, in each case, the surjective submersions in the following sense:
Definition 9.39 (see [18] Definition 4.4.8 and [33] Appendix A). Let $X$ and $Y$ be locally convex manifolds. A smooth map is a submersion if for each $x \in X$, there is an open neighbourhood $V$ of $x$ in $X$ such that $U := f(V)$ is open in $Y$, and there is a smooth manifold $W$ and a diffeomorphism $V \cong U \times W$ that intertwines $f$ and the coordinate projection $\text{pr}_1 : U \times W \to U$.

Choosing $U$ small enough, we may achieve that $V$, $U$ and $W$ are locally convex topological vector spaces. So submersions are maps that locally look like projections onto direct summands in locally convex topological vector spaces.

**Proposition 9.40.** Surjective submersions form a subcanonical pretopology on $\text{Mfd}_{\text{cs}}, \text{Mfd}_{\text{Fré}}, \text{Mfd}_{\text{Ban}}, \text{Mfd}_{\text{Hil}}$ and $\text{Mfd}_{\text{Ban}}$. In each case, Assumptions 2.6 and 7.2 hold, and Assumption 2.8 holds if we exclude the empty manifold. The pretopology is not saturated.

**Proof.** That surjective submersions form a pretopology on locally convex manifolds is shown in [33][11]. We briefly recall the argument below. It also works in the subcategories $\text{Mfd}_{\text{fin}}, \text{Mfd}_{\text{Hil}}, \text{Mfd}_{\text{Ban}}$, and $\text{Mfd}_{\text{Fré}}$; more generally, we may use manifolds based on any class $\mathcal{C}$ of topological vector spaces (not necessarily locally convex) that is closed under taking finite products and closed subspaces (this ensures that fibre products of manifolds locally modelled on topological vector spaces in $\mathcal{C}$ still have local models in $\mathcal{C}$).

It is routine to check that isomorphisms are surjective submersions and that composites of surjective submersions are again surjective submersions. If $f_1 : M_1 \to N$ for $i = 1, 2$ are smooth maps and $f_2$ is a submersion, then the fibre-product $M_1 \times_N M_2$ is a smooth submanifold of $M_1 \times M_2$, which satisfies the universal property of a fibre product. With our definition of smooth submersion, the proof is rather trivial, see [18] Theorem 4.4.10] for the case of Fréchet manifolds and [33] Proposition A.3.10 for the general case. The proof also shows that $\text{pr}_2 : M_1 \times M_2 \to M_2$ is a (surjective) submersion if $f_1$ is one, so $\mathcal{T}_{\text{subm}}$ is a pretopology. Our categories of smooth manifolds do not admit fibre products in general, so we must be careful about their representability.

Next we show that $\mathcal{T}_{\text{subm}}$ is subcanonical. A submersion $f : X \to Y$ is open because it is locally open. So our covers are open surjections and hence quotient maps of the underlying topological spaces, since open surjections form a subcanonical pretopology by Proposition 9.30. Thus any smooth map $X \to Z$ that equalises the coordinate projections $X \times_Y X \cong X$ factors through a continuous map $f' : Y \to Z$.

Since any submersion $f$ admits local smooth sections, this map $f'$ is smooth if and only if $f$ is smooth. Hence $f$ is the equaliser of the coordinate projections $X \times_Y X \cong X$ also in the category of smooth manifolds, so the pretopology $\mathcal{T}_{\text{subm}}$ is subcanonical.

The final object is the zero-dimensional one-point manifold, and any map to it from a non-empty manifold is a surjective submersion. So Assumption 2.8 is trivial for all our categories of smooth manifolds if we exclude the empty manifold. The idea of Example 9.31 shows that $\mathcal{T}_{\text{subm}}$ is not saturated on any of our categories.

Now we check Assumption 2.6. Let $f : X \to U$ be a surjective submersion and let $g : Y \to U$ be a smooth map. We have already shown that surjective submersions form a pretopology. So the fibre product $W := X \times_{f,U,g} Y$ exists and the projection $\text{pr}_2 : W \to Y$ is a surjective submersion. Assume that $\text{pr}_1 : W \to X$ is a surjective submersion as well. We are going to show that $g$ is a surjective submersion.

It is clear that $g$ is surjective. The submersion condition is local, so we must check it near some $y \in Y$. Since $f$ is surjective, there is some $x \in X$ with $f(x) = g(y)$, that is, $(x, y) \in W$. Since $f$ is a submersion, there are neighbourhoods $X_0$ of $x$ in $X$ and $U_0$ of $f(x)$ in $U$, a smooth manifold $\Xi_0$, and a diffeomorphism $\alpha : \Xi_0 \times U_0 \cong X_0$.
such that \( f \circ \alpha(\xi, u) = u \) for all \( \xi \in \Xi_0 \), \( u \in U_0 \). Let \( (\xi_0, u_0) = \alpha^{-1}(x) \). The preimage \( W_0 := pr_1^{-1}(X_0) \) in \( W \) is an open submanifold. It is diffeomorphic to the fibre product \( \Xi_0 \times \tilde{U}_0 \times U_0 \) with \( Y_0 := g^{-1}(U_0) \) because \( W \) is a fibre product. The restriction of \( pr_1 \) to \( W_0 \) is still a surjective submersion \( W_0 \to X_0 \) because \( pr_1 \) is one and the condition for submersions is local. Hence we have improved our original fibre-product situation to one where \( f \) is the projection map \( pr_1 : \Xi_0 \times U_0 \to U_0 \). Thus \( W_0 = \Xi_0 \times Y_0 \) is an ordinary product and \( pr_1 : W_0 \to X_0 \) becomes the map
\[
\text{id} \times g_0 : \Xi_0 \times Y_0 \to \Xi_0 \times U_0, \quad (\xi, y_0) \mapsto (\xi, g_0(y_0)),
\]
where \( g_0 : Y_0 \to U_0 \) is the restriction of \( g \).

The map \( \text{id} \times g_0 \) is a submersion by assumption. Hence there are neighbourhoods \( W_1 \) around \( (\xi_0, y_0) \) in \( \Xi_0 \times Y_0 \) and \( X_1 \) around \( (\xi_0, u_0) \) in \( \Xi_0 \times U_0 \), a smooth manifold \( \Omega_1 \), and a diffeomorphism \( \beta : W_1 \to \Omega_1 \times X_1 \) that intertwines \( \text{id} \times g_0 \) and the coordinate projection \( \Omega_1 \times X_1 \to X_1 \). We may shrink \( X_1 \) to be of product type: \( X_1 = \Xi_1 \times U_1 \) for open submanifolds \( \Xi_1 \subseteq \Xi_0 \) and \( U_1 \subseteq U_0 \) and replace \( W_1 \) by the preimage of \( \Omega_1 \) times the new \( X_1 \), so we may assume without loss of generality that \( X_1 \) is of product type. If \( (\xi_1, y_1) \in W_1 \), then
\[
\beta(\xi_1, y_1) = (\omega_1(\xi_1, y_1), \xi_1, g_0(y_1))
\]
for some function \( \omega_1 : W_1 \to \Omega_1 \): the second two components of \( \beta \) are \( \text{id} \times g_0 \) by construction. The subset
\[
Y_1 := \{y \in Y_0 \mid (\xi_0, y) \in W_1\},
\]
is open in \( Y_0 \). We claim that \( \gamma(y_1) := (\omega_1(\xi_0, y_1), g_0(y_1)) \) defines a diffeomorphism from \( Y_1 \) onto \( \Omega_1 \times U_1 \); indeed, if \( (\omega_1, u_1) \in \Omega_1 \times U_1 \), then \( \beta^{-1}(\omega_1, \xi_0, u_1) \) must be of the form \( (\xi_0, y_1) \) for some \( y_1 \in Y_0 \) with \( (\xi_0, y_1) \in W_1 \) because the \( \Xi_0 \)-component of \( \beta(\xi_1, y_1) \) is \( \xi_1 \). Hence the smooth map \( \beta^{-1}|_{\Omega_1 \times \{\xi_0\} \times U_1} \) is inverse to \( \gamma \). The restriction of \( g_0 \) to \( Y_1 \) becomes the coordinate projection \( \Omega_1 \times U_1 \to U_1 \) by construction. Hence \( g : Y \to U \) satisfies the submersion condition near \( y \). This finishes the proof that Assumption \( \text{F}_{\text{subm}} \) holds for \( T_{\text{subm}} \).

Now we check Assumption \( \text{F}_{\text{2}} \). Let \( p : X \to Z \) be a surjective submersion. Let \( G \) be its covering groupoid. Let \( Y \) be a sheaf over \( G \), that is, a \( G \)-action that has a surjective submersion \( s : Y \to X \) as anchor map. We claim that the \( G \)-action on \( Y \) is basic. That is, the orbit space \( Y/G \) is a smooth manifold, the orbit space projection \( Y \to Y/G \) is a surjective submersion, and the sheaf map \( Y \times_{Y/G} G^1 \to Y \times Y/G \) is a diffeomorphism. Since surjective submersions are open, \( G \) becomes a covering groupoid in \( \text{HausTop}, T_{\text{open}} \). We know that Assumption \( \text{F}_{\text{1}} \) holds in that case, so \( Y/G \) is a Hausdorff topological space, the orbit space projection \( Y \to Y/G \) is a continuous open surjection, and the shear map is a homeomorphism.

Since \( p \) and \( s \) are covers, so is \( p \circ s \), so the fibre product \( Y \times_Z Y \) is a smooth submanifold of \( Y \). If \( (y_1, y_2) \in Y \times_Z Y \), then \( (s(y_1), s(y_2)) \in X \times X \) and \( s(y_1) \) and \( s(y_2) \) range and source of \( s(y_1) \) and \( s(y_2) \), respectively. Thus there is a well-defined smooth map
\[
\psi : Y \times_Z Y \to Y \times_X G^1, \quad (y_1, y_2) \mapsto (y_1, s(y_1), s(y_2))).
\]
Composing it with the shear map gives the map
\[
\varphi : Y \times_Z Y \to Y \times_Z Y, \quad (y_1, y_2) \mapsto (y_1, y_1 \cdot (s(y_1), s(y_2))).
\]
Since \( s(y_1) \cdot (s(y_1), s(y_2)) = s(y_1) \) and \( (s(y_1), s(y_1)) \) is an identity arrow, we get \( \varphi^2 = \varphi \). If \( y_1, y_2 \) are in the same \( G \)-orbit, that is, \( y_1 \cdot g = y_2 \) for some \( g \in G^1 = X \times X \), then \( r(g) = s(y_1) \) and \( s(g) = s(y_2) \), so \( g = (s(y_1), s(y_2)) \). Thus \( p(s(y_1)) = p(s(y_2)) \) is necessary for \( y_1 \) and \( y_2 \) to have the same orbit (we write \( y_1 G = y_2 G \). If this
necessary condition is satisfied, then the only arrow in \( G \) that has a chance to map \( y_1 \) to \( y_2 \) is \( (s(y_1), s(y_2)) \), so \( y_1 G = y_2 G \) if and only if \( y_1 \cdot (s(y_1), s(y_2)) = y_2 \). This is equivalent to \( \varphi(y_1, y_2) = (y_1, y_2) \). Thus the image of \( \varphi \) is the subspace \( Y \times_{Y/G} Y \) of \( Y \times Y \), and the restriction of \( \psi \) to \( Y \times_{Y/G} Y \) is a smooth inverse for the shear map. More precisely, this is a smooth inverse once we know that \( Y \times_{Y/G} Y \) is a smooth submanifold of \( Y \times Y \) and hence a smooth submanifold of \( Y \times_{Z} Y \). Thus the condition on the shear map is automatic in our case, and we only have to construct a smooth structure on \( Y/G \) such that the projection \( \pi: Y \to Y/G \) is a submersion.

We first restrict to small open subsets where \( p \) and \( s \) are of product type. Fix \( y \in Y \). We may choose neighbourhoods \( Y_0 \) of \( y \) in \( Y \), \( X_0 \) of \( s(y) \) in \( X \) and \( Z_0 \) of \( p(s(y)) \) in \( Z \), smooth manifolds \( \Omega_0 \) and \( \Xi_0 \), and diffeomorphisms \( Y_0 \cong \Omega_0 \times X_0 \), \( X_0 \cong \Xi_0 \times Z_0 \), such that the maps \( s \) and \( p \) become the projections to the second coordinate, respectively. We identify \( \omega \) by open \( \alpha \)-coordinates. Since \( \alpha \) is a smooth inverse once we know that \( \omega \cdot (\xi, \zeta) \in \omega (\xi, \zeta) \) for a smooth function \( \alpha \) and \( \alpha \)-coordinates. Since \( \psi \) is a smooth inverse once we know that \( \omega \cdot (\xi, \zeta) \in \omega (\xi, \zeta) \) for a smooth function \( \alpha \) and \( \alpha \)-coordinates.
diffeomorphism. Hence the proof that the \( G \)-action on \( Y \) is basic will be finished once we show that coordinate change maps between our local charts on \( Y/G \) are smooth.

The charts on \( Y/G \) are defined in such a way that the projection map \( \pi: Y \to Y/G \) is smooth for each chart and there are smooth sections \( Y/G \ni \Omega \ni U \ni Y \) on the chart neighbourhoods, defined by \((\omega_1, u_1) \mapsto (\omega_1, \xi, u_1) \) in local coordinates. Now take two overlapping charts on \( Y/G \) defined on open subsets \( W_1, W_2 \subseteq Y/G \) with their smooth local sections \( \sigma_i: W_i \to Y \). If \( w \in W_1 \cap W_2 \), then \( \sigma_1(w) \) and \( \sigma_2(w) \) are two representatives of the same \( G \)-orbit. By the discussion above, this means that \( ps(\sigma_1(w)) = ps(\sigma_2(w)) \) and \( \sigma_2(w) = \sigma_1(w) \cdot (s(\sigma_1(w)), s(\sigma_2(w))) \). Thus the coordinate change map from \( W_1 \) to \( W_2 \) is of the form

\[
w \mapsto \pi(\sigma_1(w) \cdot (s(\sigma_1(w)), s(\sigma_2(w))))\]

Since the maps \( \pi, \sigma_i \) and \( s \) are all smooth in our local coordinates, so is the composite map. This finishes the proof that Assumption 7.2 holds for \( \mathcal{T}_{\text{subm}} \). The proof works for all our categories of infinite-dimensional manifolds.

It is unclear whether Assumptions 2.7 and 7.1 hold for Fréchet and locally convex manifolds. The problem is that we lack a general implicit function theorem. Such a theorem is available for Banach manifolds and gives the following equivalent characterisations of submersions:

**Proposition 9.41.** Let \( X \) and \( Y \) be Banach manifolds and let \( f: X \to Y \) be a smooth map. The following are equivalent:

1. \( f \) is a submersion in the sense of Definition 9.39.
2. \( f \) has many smooth local sections, that is, for each \( x \in X \), there is an open neighbourhood \( U \) of \( f(x) \) and a smooth map \( \sigma: U \to X \) with \( \sigma(f(x)) = x \) and \( f \circ \sigma = id_U \);
3. for each \( x \in X \), the derivative \( D_xf: T_xX \to T_{f(x)}Y \) is split surjective, that is, there is a continuous linear map \( s: T_{f(x)}Y \to T_xX \) with \( D_xf \circ s = id_{T_{f(x)}Y} \).

If \( X \) and \( Y \) are Hilbert manifolds, then (3) is equivalent to \( D_xf \) being surjective.

**Proof.** It is trivial that (1) implies (2). Using \( D_{f(x)}\sigma \) as continuous linear section for \( D_xf \), we see that (2) implies (3). The implication from (3) to (1) is [24, Proposition 2.2 in Chapter II]. If \( X \) and \( Y \) are Fréchet manifolds, then the derivative \( D_xf \) is open once it is surjective by the Open Mapping Theorem. If \( D_xf \) is surjective and \( X \) and \( Y \) are Hilbert manifolds, then the orthogonal projection onto \( \ker D_xf \) splits \( X \cong \ker(D_xf) \oplus D_{f(x)}Y \), so (3) follows if \( D_xf \) is surjective and \( X \) and \( Y \) are Hilbert manifolds.

**Proposition 9.42.** On the categories \( \text{Mfd}_{\text{Ban}} \), \( \text{Mfd}_{\text{Hil}} \) and \( \text{Mfd}_{\text{fin}} \), the pretopology \( \mathcal{T}_{\text{subm}} \) also satisfies Assumption 2.7.

**Proof.** Since we work with Banach manifolds or smaller categories, we may use Proposition 9.41 to redefine our covers as surjective smooth maps with many local smooth sections. With this alternative definition of our covers, Assumption 2.7 holds for the same reason as for the pretopology of continuous surjections with many continuous local sections on the category of topological spaces. Let \( X \), \( Y \) and \( Z \) be Banach manifolds and let \( f: X \to Y \) and \( g: Y \to Z \) be smooth maps. We assume that \( g \circ f \) and \( f \) are surjective submersions and want to show that \( g \) is so to. Of course, \( g \) must be surjective if \( g \circ f \) is. Given \( y \in Y \), there is \( x \in X \) with \( f(x) = y \) because \( g \) is surjective, and there is a smooth local section \( \sigma \) for \( g \circ f \) near \( g(y) \) with \( \sigma(g(y)) = x \). Then \( f \circ \sigma \) is a smooth local section for \( g \) with \( f \circ \sigma(g(y)) = y \).
If we redefined submersions of locally convex or Fréchet manifolds using one of the alternative criteria in Proposition 9.41, then the existence of pull-backs along submersions would become unclear.

The next lemma is needed to verify Assumption 7.1 for Banach manifolds.

**Lemma 9.43.** Let $Y$ be a Banach manifold and let $\varphi: Y \to Y$ be a smooth map with $\varphi^2 = \varphi$. The image $\text{im}(\varphi)$ is a closed submanifold of $Y$ and $\varphi: Y \to \text{im}(\varphi)$ is a surjective submersion.

**Proof.** The image is closed because $Y$ is Hausdorff and

$$\text{im}(\varphi) = \{ x \in Y \mid \varphi(x) = x \}.$$ 

We need a submanifold chart for $\text{im}(\varphi)$ near $y \in \text{im}(\varphi)$. We use a chart $\gamma: T_y Y \to Y$, that is, $\gamma$ is a diffeomorphism onto an open neighbourhood of $y$ in $Y$ whose derivative at 0 is the identity map on the Banach space $T_y Y$. It suffices to find a submanifold chart for $\varphi': := \gamma^{-1} \circ \varphi \circ \gamma$, which is an idempotent smooth map on a neighbourhood of 0 in $T_y Y$ with $\varphi'(0) = 0$. Let $D: T_y Y \to T_y Y$ be the derivative of $\varphi'$ at 0, which is a linear map with $D^2 = D$. We may assume that $\varphi'$ is defined on all of $T_y Y$ to simplify notation.

Let $X = \text{im}(D)$, $W = \ker(D)$. The map

$$\Psi: X \oplus W \to T_y Y, \quad (\xi, \eta) \mapsto \varphi'(\xi) + \eta,$$

has the identity map as derivative near $(0,0)$. By the Implicit Function Theorem for Banach manifolds, $\Psi$ is a diffeomorphism between suitable open neighbourhoods of 0 in $X \oplus W$ and $T_y Y$. We have $\Psi(\xi,0) = \varphi'(\xi) \in \text{im}(\varphi')$ for all $\xi \in X$, and

$$\varphi'(\Psi(\xi,\eta)) - \Psi(\xi,\eta) = \varphi'(\varphi'(\xi) + \eta) - \varphi'(\xi) - \eta = D(D\xi + \eta) - D\xi - \eta + O(\|\xi\|^2 + \|\eta\|^2) = -\eta + O(\|\xi\|^2 + \|\eta\|^2).$$

This is non-zero if $\eta \neq 0$ and $\eta, \xi$ are small enough. Hence, for sufficiently small $\xi, \eta$, we have $\Psi(\xi,\eta) \in \text{im}(\varphi')$ if and only if $\eta = 0$. Thus $\Psi$ is a submanifold chart for $\text{im}(\varphi')$ near 0. Its composite with $\gamma$ gives the required submanifold chart for $\text{im}(\varphi)$ near $y$. It is clear from the construction that the map $\varphi: Y \to \text{im}(\varphi)$ has surjective derivative at $y$, hence it is a smooth submersion by Proposition 9.41. □

**Proposition 9.44.** Every action of a covering groupoid in $(\text{Mfd}_{\text{Ban}}, \text{Subm})$ is basic.

**Proof.** Let $p: M \to N$ be a surjective submersion and let $G = (M \times_p N, p M \rightrightarrows N)$ be its covering groupoid (see Example 3.3). Let $G$ act on a smooth manifold $Y$ with anchor map $s: Y \to \mathbb{G}^0$.

Since $p$ has many local smooth sections, we may cover $N$ by open subsets $U_i$, $i \in I$, for which there are smooth local sections $\sigma_i: U_i \to M$ with $p \circ \sigma_i = id_{U_i}$. Then $Y_i := (ps)^{-1}(U_i) \subseteq Y$ is open (and thus an open submanifold of $Y$) and $G$-invariant.

The map

$$\varphi_i: Y_i \to Y_i, \quad y \mapsto y \cdot (s(y), \sigma_i \circ p \circ s(y)),$$

is smooth and maps $y$ to a point $y'$ in the same $G$-orbit with $s(y') \in \sigma_i(U_i)$. If $y'$ and $y''$ belong to the same $G$-orbit, then $s(y') = s(y'')$ implies $y' = y''$ because the only element of $G$ that may map $y'$ to $y''$ is $(s(y'), s(y''))$. Thus $\varphi_i(y)$ is the unique element in the $G$-orbit of $y$ that belongs to $s^{-1}(\sigma_i(U_i))$. Thus $\varphi_i^2 = \varphi_i$.

By Lemma 9.43, $\text{im}(\varphi)$ is a smooth submanifold of $Y$ and $\varphi_i: Y_i \to \text{im}(\varphi_i)$ is a surjective submersion.

If $y_1, y_2 \in Y_i$ satisfy $\varphi_i(y_1) = \varphi_i(y_2)$, then $y_2 = y_1 \cdot (s(y_1), s(y_2))$. Hence the map

$$Y_i \times s, M, \rho_1 (M \times N M) \to Y_i \times \varphi_i Y_i \varphi_i Y_i, \quad (y, (m_1, m_2)) \mapsto (y, y \cdot (m_1, m_2)),$$
is a diffeomorphism with inverse \((y_1, y_2) \mapsto (y_1, (s(y_1), s(y_2)))\). As a consequence, the restriction of the \(G\)-action to \(Y_i\) with the bundle projection \(\varphi_i: Y_i \to \text{im}(\varphi_i)\) is a principal bundle.

It remains to glue together these local constructions. Let \(Y/G\) be the quotient space with the quotient topology. The quotient map \(\pi: Y \to Y/G\) is open by Proposition 9.22 and because submersions are open. Thus the subsets \(\pi(Y_i)\) form an open cover of \(Y/G\). The above argument shows that \(\pi\) restricts to a homeomorphism from \(\text{im}(\varphi_i)\) onto \(\pi(Y_i)\). We claim that there is a unique smooth manifold structure on \(Y/G\) for which the maps \(\pi: \text{im}(\varphi_i) \to Y/G\) become diffeomorphisms onto open subsets of \(Y/G\). We only have to check that the coordinate change maps on \(Y/G\) from \(\text{im}(\varphi_i)\) to \(\text{im}(\varphi_j)\) are smooth maps. This is so because the map

\[Y_i \cap \text{im}(\varphi_j) \to \text{im}(\varphi_i) \cap Y_j, \quad y \mapsto y \cdot (\sigma_i \circ s(y), \sigma_j \circ s(y)),\]

is a diffeomorphism between submanifolds of \(Y_i\), with inverse given by a similar formula. The orbit space projection \(Y \to Y/G\) is a surjective submersion for this smooth manifold structure on \(Y/G\) because this holds locally on each \(Y_i\). The same argument as above shows that the map

\[Y \times_{s,M,pr_1} (M \times_M M) \to Y \times_{Y/G} Y, \quad (y, (m_1, m_2)) \mapsto (y, y \cdot (m_1, m_2)),\]

is a diffeomorphism with inverse \((y_1, y_2) \mapsto (y_1, (s(y_1), s(y_2)))\). Hence \(Y \to Y/G\) is a principal \(G\)-bundle.

As a result, most of our theory works for locally convex manifolds with surjective submersions as covers. This includes the bicategories of vague functors, bibundle functors and bibundle equivalences, but not the bicategories of covering bibundle functors and bibundle actors. We only know that these bicategories exist for Banach, Hilbert and finite-dimensional manifolds.

**Remark 9.45.** An action is basic in the category of finite-dimensional manifolds if and only if it is basic in the category of Hausdorff spaces, if and only if it is free and proper (see Proposition 9.20). This remains true for Hilbert manifolds. For group actions, this is the main result of [21]; groupoid actions may be reduced to group actions using the proof of [43] Lemma 3.11.

For Banach manifolds and, even more generally, for locally convex manifolds, it remains true that basic actions are free and proper, but the converse fails. Here is a counterexample (see also [3] Chapter 3]). Let \(E\) be a Banach space and let \(F\) be a closed subspace without complement, for instance, \(c_0(\mathbb{N}) \subset F^\infty(\mathbb{N})\). Let \(F\) act on \(E\) by inclusion and linear addition. This action is free and proper, and the orbit space projection is the quotient map \(E \to E/F\). The derivative of this map is the same map \(E \to E/F\), which has no linear section by assumption. Hence the orbit space projection is not a cover, so the action is not basic.

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E-mail address: rameyer@uni-math.gwdg.de

E-mail address: zhu@uni-math.gwdg.de

Mathematisches Institut, Georg-August-Universität Göttingen, Bunsenstrasse 3-5, 37073 Göttingen, Germany