1 The fibration zoo

If the reader thought that the theory of Kan fibrations was vibrant, they are in for a treat.

Let $f: K \to S$ be a morphism of simplicial sets.

- We call the morphism f a Kan fibration if it has the right lifting property with respect to all horn inclusion $\Lambda^n_i \to \Delta^n$ with $0 \leq i \leq n$.
- We call the morphism f a left fibration if it has the right lifting property with respect to all horn inclusion $\Lambda^n_i \to \Delta^n$ with $0 \leq i < n$.
- We call the morphism f a right fibration if it has the right lifting property with respect to all horn inclusion $\Lambda^n_i \to \Delta^n$ with $0 < i \leq n$.
- We call the morphism f an inner fibration if it has the right lifting property with respect to all horn inclusion $\Lambda^n_i \to \Delta^n$ with $0 < i < n$.

We will use the following terminology.

- The morphism f is anodyne if it has the left-lifting property with respect to all Kan fibrations.
- The morphism f is left anodyne if it has the left-lifting property with respect to all left fibrations.
- The morphism f is right anodyne if it has the left-lifting property with respect to all right fibrations.
- The morphism f is inner anodyne if it has the left-lifting property with respect to all inner fibrations.

Unable to leave well enough alone, we now define the following additional notions.

Definition 1 (Cartesian fibration)**.** Let $f: K \to S$ be a morphism of simplicial sets. The morphism f is a Cartesian fibration if the following conditions are satisfied.

- The morphism f is an inner fibration
- For every $h: x \to y$ in S and $\tilde{y} \in K_0$ there is a f-Cartesian morphism $\tilde{h}: \tilde{x} \to \tilde{y}$ such that $f(\tilde{h}) = h$.
- A f-Cartesian edge in K is an edge $f: x \to y$ such that the map

  $$K_{/f} \to K_{/y} \underset{S_{/f(y)}}{\times} S_{/p(f)}$$

  is a trivial Kan fibration.

Theorem 2. Let f be a trivial fibration. Then f is a Kan fibration.

Proof. Let f be a trivial fibration, and consider the following lifting problem.

$$\begin{tikzcd} \Lambda^n_i \arrow[r] \arrow[d] & K \arrow[d] \\ \Delta^n \arrow[r] & S \end{tikzcd}$$

Restricting to the face opposite i, we find the lifting problem

$$\begin{tikzcd} \partial\Delta^{\{1,\dots,n\}} \arrow[r] \arrow[d] & K \arrow[d] \\ \Delta^{\{1,\dots,n\}} \arrow[r] \arrow[ur, dashed] & S \end{tikzcd}$$

which has a dashed solution. This allows us to turn our map $\Lambda^n_i \to K$ to a map $\partial\Delta^n \to K$ making the folowing diagram commute.

$$\begin{tikzcd} \partial\Delta^n \arrow[r] \arrow[d] & K \arrow[d] \\ \Delta^n \arrow[r] \arrow[ur, dashed] & S \end{tikzcd}$$

which has a dashed lift. □

Note 3. A map $f\colon X \to Y$ is a left fibration if and only if $f^{\mathrm{op}}\colon X^{\mathrm{op}} \to Y^{\mathrm{op}}$ is a a right fibration. Thus, it suffices to study left fibrations; the theory of right fibrations is dual.

Lemma 4. Let $p\colon \mathcal{C} \to \mathcal{D}$ be a left fibration of infinity categories, and let $\tilde{f}\colon \bar{x} \to p(y)$ be an equivalence in $\mathcal{D}$, and $y \in \mathcal{C}_0$. Then there exists $f\colon x \to y$ so that $p(f) = \bar{f}$.

Lemma 5. Consider morphisms of simplicial sets as follows

$$\bar{K} \hookrightarrow K \xrightarrow{p} X \xrightarrow{q} S$$

where q is an inner fibration. Let $r = p \circ q$, $\bar{p} = p|_{\bar{K}}$, $\bar{r} = r|_{\bar{K}}$. Then the induced map

$$S_{p/} \to X_{\bar{p}/} \underset{S_{\bar{p}/}}{\times} S_{r/}$$

is an inner fibration. If q is a left fibration, then the map is a left fibration.

Corollary 6. Let $\mathcal{C}$ be an infinity category, and let $p\colon K \to \mathcal{C}$ be a diagram in $\mathcal{C}$. Then the map $\mathcal{C}_{/p} \to \mathcal{C}$ is a left fibration, and $\mathcal{C}_{/p}$ is an infinity category.

Proof. Take $X = \mathcal{C}$, $S = \Delta^0$, and $\bar{K} = \emptyset$. This tells us that the map

$$\mathcal{C}_{p/} \to \mathcal{C}$$

is a left fibration. Thus, the composition

$$\mathcal{C}_{p/} \to \mathcal{C} \to *$$

is the composition of a left fibration and an inner fibration, so is itself an inner fibration. □

Corollary 7. Let $f: x \to y$ be a morphism in an ∞-category $\mathcal{C}$. Then f is an equivalence if and only if for every $n \geq 2$ and left horn $h: \Lambda_0^n \to \mathcal{C}$, with $h|_{\{0,1\}} = f$, h admits a filler.

Theorem 8. The following are equivalent for an ∞-category $\mathcal{C}$.

- The homotopy category $\mathrm{h}\mathcal{C}$ is a groupoid.
- Every left horn in $\mathcal{C}$ has a filler.
- Every right horn has a filler.
- $\mathcal{C}$ is a Kan complex.

Corollary 9. All fibers of a left fibration are Kan complexes.

1.1 The classical Grothendieck construction

Definition 10 (Grothendieck construction). Let $\mathcal{D}$ be a small category, and let $\chi: \mathcal{D} \to$ **Grpd**. The Grothendieck construction consists of the following data the following data.

- A category $\mathcal{C}_\chi$
- A functor $\pi: \mathcal{C}_\chi \to \mathcal{D}$

The category $\mathcal{C}_\chi$ is as follows.

- **Objects:** Pairs (d, x), where $d \in \mathcal{D}$ and $x \in \chi(d)$.
- **Morphisms:** A morphism $(d, x) \to (d', x')$ consists of
  - A morphism $f: d \to d'$ in $\mathcal{D}$
  - An isomorphism $\alpha: \chi(f)(x) \simeq x'$

The functor π is the forgetful functor to $\mathcal{D}$.

The Grothendieck construction can be understood in the following way. The functor χ gives us a way of associating a groupoid to each object $d \in \mathcal{D}$. Each of these groupoids is itself a category, and has its own objects. The idea of the Grothendieck construction is to throw all of these objects together into one big category. To keep track of where each object x comes from, we think of x as ordered pairs (d, x), where the $x \in \chi(d)$. The functor π simply remembers where each x came from.

For two objects x and $\tilde{x}$ from the same $\chi(d)$, the morphisms $(d, x) \to (d, \tilde{x})$ are simply the morphisms between x and $\tilde{x}$. For an object x' from a different groupoid $\chi(d')$, the morphisms $(d, x) \to (d', x')$ come from translating, using χ and a morphism $d \to d'$, morphisms in $\chi(d)$ into morphisms in $\chi(d')$.

Example 11. Let G and H be a groups, and $\mathbf{B}G$ and $\mathbf{B}H$ their delooping groupoids. Let $\phi: G \to H$ be a group homomorphism, or equivalently a functor $\mathbf{B}G \to \mathbf{B}H$. This can also be taken to be a functor $\mathbf{B}G \to$ **Grpd**.

The Grothendieck construction consists of a category with one object, whose morphisms consist of an element $g \in G$

There is also a contravariant version of the Grothendieck construction, consisting of the following.

Definition 12 (contravariant Grothendieck construction)**.** For any functor $\mathcal{D}^{\mathrm{op}} \to \mathrm{Grpd}$, the contravariant Grothendieck construction consists of the following.

1. A category $\mathcal{C}^{\chi}$
2. A functor $\pi\colon \mathcal{C}^{\chi} \to \mathcal{D}$.

The category $\mathcal{C}^{\chi}$ is as follows.

- The objects of $\mathcal{C}^{\chi}$ are be pairs (d, x), with $d \in \mathcal{D}$ and $x \in \chi(d)$.
- The morphisms $(d', x') \to (d, x)$ are pairs (f, α), where $f\colon d' \to d$ and $\alpha\colon x' \to F(f)(x)$.

There is the following relationship between the covariant and contravariant Grothendieck constructions. $\mathcal{C}^{\chi} = \mathcal{C}_{\chi}^{\mathrm{op}}$.

Example 13. Let $X\colon \mathcal{D}^{\mathrm{op}} \to \mathbf{Set}$ be a diagram of sets, which we interpret as discrete groupoids. Then there is an equivalence of categories between the contravariant construction and the slice category $\mathcal{D}/X$.

The objects of $\mathcal{D}/X$ are pairs (d, α), where $d \in \mathcal{D}$ and $\alpha\colon \mathrm{Hom}_{\mathcal{D}}(-, d) \Rightarrow X$. The morphisms $(d, \alpha) \to (d', \beta)$ are morphisms $f\colon d \to d'$ such that the diagram

$$\begin{tikzcd} \mathrm{Hom}_{\mathcal{D}}(-, d) \arrow[rr, Rightarrow, "f\circ-"] \arrow[dr, Rightarrow, "\alpha"'] & & \mathrm{Hom}_{\mathcal{D}}(-, d') \arrow[dl, Rightarrow, "\beta"] \\ & X & \end{tikzcd} \tag{1.1}$$

commutes.

Consider any such morphism f. The above diagram commutes if and only if it commutes component-wise, i.e. if for each c, the diagram below commutes.

$$\begin{tikzcd} \mathrm{Hom}_{\mathcal{D}}(c, d) \arrow[rr, "f\circ-"] \arrow[dr, "\alpha_c"'] & & \mathrm{Hom}_{\mathcal{D}}(c, d') \arrow[dl, "\beta_c"] \\ & X(c) & \end{tikzcd} \tag{1.2}$$

In particular, it commutes when $c = d$. Following the identity id_d around, we find that morphisms f making the above diagram commute satisfy the following equality.

$$\begin{tikzcd} \mathrm{id}_d \arrow[rr, mapsto] \arrow[dr, mapsto] & & f \arrow[dl, mapsto] \\ & \alpha_d(\mathrm{id}_d) = \beta_d(f) & \end{tikzcd}$$

By the naturality of the Yoneda embedding, we have that

$$\beta_d(f) = X(f)(\beta_{d'}(\mathrm{id}_{d'})),$$

so

$$\alpha_d(\mathrm{id}_d) = X(f)(\beta_{d'}(\mathrm{id}_{d'})). \tag{1.3}$$

We can specify a functor $\mathcal{D}/X \longrightarrow \mathcal{C}^X$ on objects by sending

$$(d, \alpha) \mapsto (d, \alpha_b(\mathrm{id}_b)),$$

and on morphisms $f\colon (d, \alpha) \longrightarrow (d', \beta)$ commute by sending

$$f \mapsto (f, \mathrm{id}_{X(f)(\beta_{d'}(\mathrm{id}_{d'}))}).$$

We are allowed to use the above identity map preciesly because it is an isomorphism

$$\alpha_d(\mathrm{id}_d) \longrightarrow X(f)(\beta_{d'}(d'))$$

as shown in Equation 1.3.

The fully faithfulness of the Yoneda embedding implies that the map between the objects of $\mathcal{D}/X$ and the objects of $\mathcal{C}^X$ is a bijection. We will now construct a functor $\mathcal{C}^X \longrightarrow \mathcal{D}/X$, defined on objects to be the inverse of the one defined above, i.e. sending a pair (d, x) to the pair (d, α^x), where α^x is the natural transformation uniquely specified by $\alpha^x_d(\mathrm{id}_d) \mapsto x \in X(d)$.

Our inverse functor acts on any morphism (f, ϕ) by forgetting ϕ. It only remains to check that this provides a well-defined map of morphisms, as f has to make Diagram 1.1 commute. We can check that this is so by following a general morphism $g\colon c \longrightarrow d$ around Diagram 1.2, finding the following condition.

$$\begin{tikzcd}
g \arrow[rr, mapsto] \arrow[dr, mapsto] & & f \circ g \arrow[dl, mapsto] \\
& \alpha_c(g) \overset{!}{=} \beta_c(f \circ g) &
\end{tikzcd}$$

By naturality of the Yoneda embedding, we have

$$\alpha_c(g) = (Xg)(\alpha_d(\mathrm{id}_d)), \qquad \beta_c(f \circ g) = X(f \circ g)(\beta_{d'}(\mathrm{id}_{d'})) = (Xg \circ Xf)(\beta_{d'}(\mathrm{id}_{d'})),$$

so our condition equivalently reads

$$Xg(\alpha_d(\mathrm{id}_d)) = Xg((Xf)(\beta_{d'}(\mathrm{id}_{d'}))).$$

This is true because by definition of f,

$$\alpha_d(\mathrm{id}_d) = (Xf)(\beta_{d'}(\mathrm{id}_{d'})).$$

The two functors defined in this way are manifestly each other's inverses, hence provide an isomorphism of categories, which is stronger than what we are looking for.

1.1.1 When can we invert the classical Grothendieck construction?

Suppose we are given a functor $F\colon \mathcal{C} \to \mathcal{D}$ exhibiting $\mathcal{C}$ as cofibered in groupoids over $\mathcal{D}$. By Lemma 27, each of the fibers $\mathcal{C}_d$ is a groupoid. We may hope that we could reverse the Grothendieck construction by defining a functor $\mathcal{D} \to \mathbf{Grpd}$ defined on objects by $d \mapsto \mathcal{C}_d$.

We almost can. For any morphism $f\colon d \to d'$ in $\mathcal{D}$, we can build functor $f_!\colon \mathcal{C}_d \to \mathcal{C}_{d'}$ as follows.

Let $f\colon d \to d'$, and let $c \in \mathcal{C}_d$. By property 2 in Definition 17, we can find an object $c' \in \mathcal{C}_{d'}$ and a morphism $\bar{f}\colon c \to c'$ in $\mathcal{C}$ such that $F(\bar{f}) = f$. Define $f_!(c) = c'$, and $f_!()$

The above discussion means that the Grothendieck construction defines the following correspondence.

$$\left\{\substack{F\colon \mathcal{C}\to\mathcal{D} \text{ exhibits } \mathcal{C} \\ \text{as cofibered in groupoids}}\right\} \overset{\simeq}{\longleftrightarrow} \left\{\substack{\text{pseudofunctors} \\ \mathcal{D}\to\mathbf{Grpd}}\right\}$$

1.1.2 Fibrance and cofibrance in groupoids

Example 14. The Grothendieck construction

$$\pi\colon \mathcal{C}_\chi \to \mathcal{D}$$

exhibits $\mathcal{D}$ as cofibered over groupoids. We simply transcribe the definition, making the necessary changes as we go along.

In ordered for π to exhibit $\mathcal{C}_\chi$ as cofibered in groupoids over $\mathcal{D}$, we have to check the following.

1. For every $(d, x) \in \mathcal{C}_\chi$ and every morphism
$$\eta\colon d \to d' \qquad \text{in } \mathcal{D}$$
there exists a lift
$$\tilde{\eta} = (f, \alpha)\colon (d, x) \to (d', x') \qquad \text{in } \mathcal{C}_\chi$$
such that
$$\pi(\tilde{\eta}) = f\colon d \to d' = \eta.$$

2. For every morphism $\eta\colon (x, d) \to (x', d')$ in $\mathcal{C}$ and every object $(x'', d'') \in \mathcal{C}$, the map
$$\mathcal{C}_\chi((d', x') \to (d'', x'')) \to \mathcal{C}_\chi((d, x), (d'', x'')) \underset{\mathcal{D}(d,d'')}{\times} \mathcal{D}(d', d'')$$
is a bijection.

What do these mean?

1. We need to construct from our map $\eta\colon d \to d'$ an isomorphism
$$\alpha\colon \chi(f)(x) \simeq x'$$
for some x'. We can pick $x' = \chi(f)(x)$. Then $\tilde{\eta} = (f, \alpha)$ does the job. Indeed, $\pi(f, \alpha) = f$ as required.
2. Draw a picture. Given the data of
    - A morphism

Example 15. The contravariant Grothendieck construction exhibits $\mathcal{C}^{\chi} \to \mathcal{D}$ as fibered in groupoids over $\mathcal{D}$.

To see this, we need to make the following checks.

- **Check:** For every $(d, x) \in \mathcal{C}^{\chi}$, and every morphism $\eta\colon d' \to d$ in $\mathcal{D}$, we should be able to find some object $x' \in \chi(d')$ and a morphism $(f, \alpha)\colon (d', x') \to (d, x)$.

  Solution: We can pick $f = \eta$, $x' = \chi(f)(x)$, and $\alpha = \mathrm{id}_{x'}$.
- **Check:** Fixing any diagram
$$\begin{tikzcd} & (d',x') \arrow[dr, "(g,\alpha)"] & \\ (d'',x'') \arrow[rr, "(\eta,\beta)"'] & & (d,x) \end{tikzcd}$$
  in $\mathcal{C}^{\chi}$, for any morphism $f\colon d'' \to d'$ making the below left diagram commute, we should be able to find a morphism $(f, \gamma)\colon (d'', x'') \to (d', x')$ making the below right diagram commute.
$$\begin{tikzcd} & d' \arrow[dr, "g"] & \\ d'' \arrow[ur, dashed, "f"] \arrow[rr, "\eta"'] & & d \end{tikzcd} \quad \rightsquigarrow \quad \begin{tikzcd} & (d',x') \arrow[dr, "(g,\alpha)"] & \\ (d'',x'') \arrow[ur, dashed, "(f,\gamma)"] \arrow[rr, "(\eta,\beta)"'] & & (d,x) \end{tikzcd}$$
  Solution: We need a morphism $\gamma\colon x'' \to \chi(f)(x')$ making the above diagram commute.

  Using the data available to us, we can create the following diagram in $\chi(d'')$.
$$\begin{tikzcd} & \chi(f)(x') \arrow[dr, "\chi(f)(\alpha)"] & \\ x'' \arrow[rr, "\beta"'] & & \chi(\eta)(x) \end{tikzcd}$$
  Note that we are entitled to draw $\chi(f)(\alpha)$ terminating at $\chi(\eta)(x)$ because
$$\chi(f)(\chi(g)(x)) = \chi(g \circ f)(x) = \chi(\eta)(x).$$
  Because $\chi(d'')$ is a groupoid, we get the morphism γ via
$$\gamma = (\chi(f)(a))^{-1} \circ \beta.$$

1.2 Left fibrations

Lemma 16. Consider simplicial sets and morphisms as follows.

$$\begin{tikzcd} K_0 \arrow[r, hook] \arrow[rr, bend right, "p_0"'] \arrow[rrr, bend left, "r_0"] & K \arrow[r, "p"] \arrow[rr, bend left, "r"] & X \arrow[r, "q"] & S \end{tikzcd}$$

We can translate a lifting problem of the first type into a lifting problem of the second.

$$\begin{tikzcd} A \arrow[r] \arrow[d] & X_{p/} \arrow[d] \\ B \arrow[r] \arrow[ur, dashed] & X_{p_0/} \times_{S_{r_0/}} S_{r/} \end{tikzcd} \qquad \begin{tikzcd} K \star A \coprod_{K_0 \star A} K_0 \star B \arrow[r] \arrow[d] & X \arrow[d] \\ K \star B \arrow[r] \arrow[ur, dashed] & S \end{tikzcd}$$

1.3 Left fibrations and cofibrancy in groupoids

Since left fibrations are of the form

$$\{\Lambda^n_i \hookrightarrow \Delta^n \mid n \geq 1, 0 \leq i < n\}_\perp,$$

Proposition **??** implies that they are closed under pullback.

Let $F\colon X \to Y$ be a left fibration of simplicial sets. For $x \in X$, the fiber

1.3.1 Cofibrancy in groupoids

Definition 17 (cofibrant in groupoids)**.** Let $F\colon \mathcal{C} \to \mathcal{D}$ be a functor. We say that f exhibits $\mathcal{C}$ as cofibrant in groupoids over $\mathcal{D}$ if the following conditions are satisfied.

1. For every $c \in \mathcal{C}$ and every morphism

$$\eta\colon F(c) \to d \qquad \text{in } \mathcal{D}$$

there exists a morphism

$$\tilde{\eta}\colon c \to \tilde{d} \qquad \text{in } \mathcal{C}$$

such that $F(\tilde{\eta}) = \eta$.

2. For every morphism $\eta\colon c \to c'$ in $\mathcal{C}$ and every object $c'' \in \mathcal{C}$, the map

$$\mathcal{C}(c', c'') \to \mathcal{C}(c, c'') \underset{\mathcal{D}(F(c), F(c''))}{\times} \mathcal{D}(F(c'), F(c'')).$$

is a bijection.

Let us unravel what the second condition means. The second set is the following pullback.

$$\begin{tikzcd} * \arrow[r] \arrow[d] & \mathcal{D}(F(c'), F(c'')) \arrow[d, "\eta"] \\ \mathcal{C}(c, c'') \arrow[r, "F"'] & \mathcal{D}(F(c), F(c'')) \end{tikzcd}$$

Its elements are pairs

$$(f, \bar{g}), \qquad \text{where} \quad f : c \to c'' \quad \text{and} \quad \bar{g} \colon F(c') \to F(c'')$$

such that

$$F(f) = \bar{g} \circ F(\eta).$$

The bijection above is defined as follows. Starting on the LHS with a morphism $h \colon c' \to c''$, build the following commutative diagram.

$$\begin{tikzcd} & c' \arrow[dr, "h"] & \\ c \arrow[ur, "\eta"] \arrow[rr, "h \circ \eta"'] & & c'' \end{tikzcd}$$

We can read off a map $f = h \circ \eta \colon c \to c''$ and a map $\bar{g} = F(h) \colon F(c') \to F(c'')$, and indeed $F(f) = \bar{g} \circ F(\eta)$, giving us an element of the RHS.

The fact that this is a bijection means that the above operation is invertible. Fixing a morphism $\eta \colon c \to c'$ and an object c'', whenever we have the following data:

- A morphism $g \colon c \to c''$ as follows

$$\begin{tikzcd} & c' & \\ c \arrow[ur, "\eta"] \arrow[rr, "\bar{g}"'] & & c'' \end{tikzcd}$$

- A map $\bar{h} \colon F(c') \to F(c'')$ making the following diagram commute

$$\begin{tikzcd} & F(c') \arrow[dr, "\bar{h}"] & \\ F(c) \arrow[ur, "F(\eta)"] \arrow[rr, "F(g)"'] & & F(c'') \end{tikzcd}$$

we can lift $\bar{h}$ to a morphism h in $\mathcal{C}$ making the following diagram commute.

$$\begin{tikzcd} & c' \arrow[dr, "h"] & \\ c \arrow[ur, "\eta"] \arrow[rr, "g"'] & & c'' \end{tikzcd}$$

Lemma 18. Let $F: \mathcal{C} \to \mathcal{D}$ be a functor exhibiting $\mathcal{C}$ as cofibered in groupoids over $\mathcal{D}$. Let f be a morphism in $\mathcal{C}$ such that $F(f) = \mathrm{id}$. Then f is an isomorphism.

Proof. Let $f: c \to c'$ in $\mathcal{C}_d$ be a morphism such that $F(f) = \mathrm{id}_d$. Then we can form the following commutative diagram.

$$\begin{tikzcd} & c' & \\ c \arrow[ur, "f"] \arrow[rr, "\mathrm{id}"'] & & c \end{tikzcd}$$

When mapped to $\mathcal{D}$, we find the following very simple diagram, with a dashed filler.

$$\begin{tikzcd} & d \arrow[dr, dashed, "\mathrm{id}"] & \\ d \arrow[ur, "\mathrm{id}"] \arrow[rr, "\mathrm{id}"'] & & d \end{tikzcd}$$

Lifting this gives us a left inverse $\tilde{f}$ to f. Pulling the same trick with $\tilde{f}$ gives us a left inverse $\hat{f}$ to $\tilde{f}$. Then

$$\begin{aligned} f \circ \tilde{f} &= \mathrm{id} \\ \hat{f} \circ f \circ \tilde{f} &= \hat{f} \\ \hat{f} &= f, \end{aligned}$$

so $\tilde{f}$ is both a left and a right inverse for f, i.e. f is an isomorphism. □

Corollary 19. Let $F: \mathcal{C} \to \mathcal{D}$ exhibit $\mathcal{C}$ as cofibered in groupoids over $\mathcal{D}$. Then the fibers of F are groupoids.

Proof. The morphisms in the fiber $\mathcal{C}_d$ are precisely those which are mapped to the identity id_d. □

Lemma 20. Let $F: \mathcal{C} \to \mathcal{D}$ be a functor exhibiting $\mathcal{C}$ as cofibered in groupoids over $\mathcal{D}$. Let f be a morphism in $\mathcal{C}$ such that $F(f)$ is an equivalence. Then f is an equivalence.

Definition 21 (coCartesian morphism)**.** Let $F: \mathcal{C} \to \mathcal{D}$ be a functor of small categories. A morphism $f: c \to c'$ is said to be F-coCartesian if, for every $c'' \in \mathcal{C}$, the map

$$\mathcal{C}(c', c'') \to \mathcal{C}(c, c'') \times_{\mathcal{D}(F(c), F(c''))} \mathcal{D}(F(c'), F(c''))$$

is a bijection.

Definition 22 (coCartesian fibration)**.** A functor $F: \mathcal{C} \to \mathcal{D}$ is said to be a coCartesian fibration if, for each $x \in \mathcal{C}$ and every morphism $\tilde{f}: F(x) \to y$ in $\mathcal{D}$, there exists a coCartesian morphism $f: x \to \tilde{y}$ such that $F(f) = \tilde{f}$.

The reader has probably guessed the next sentence: "There is a dual notion."

Definition 23 (fibrant in groupoids)**.** Let $F\colon \mathcal{C} \to \mathcal{D}$ be a functor. We say that f exhibits $\mathcal{C}$ as fibrant in groupoids over $\mathcal{D}$ if the following conditions are satisfied.

1. For every $c' \in \mathcal{C}$ and every morphism

$$\eta\colon d \to F(c') \qquad \text{in } \mathcal{D}$$

there exists a morphism

$$\tilde{\eta}\colon \tilde{d} \to c' \qquad \text{in } \mathcal{C}$$

such that $F(\tilde{\eta}) = \eta$.

2. For every morphism $\eta\colon c \to c'$ in $\mathcal{C}$ and every object $c'' \in \mathcal{C}$, the map

$$\mathcal{C}(c', c'') \to \mathcal{C}(c, c'') \underset{\mathcal{D}(F(c),F(c''))}{\times} \mathcal{D}(F(c'), F(c'')).$$

is a bijection.

1.4 The starred smash

Definition 24 (starred smash)**.** Let $f : A \to A'$, $g\colon B \to B'$ be two morphisms of simplicial sets. Define a morphism $f \overset{\star}{\wedge} g$ using the universal property for pushouts as follows.

$$\begin{tikzcd}
A \star B \arrow[r, "f\star\mathrm{id}"] \arrow[d, "\mathrm{id}\star g"'] & A' \star B \arrow[d, hook] \arrow[ddr, bend left, "\mathrm{id}\star g"] & \\
A \star B' \arrow[r, hook] \arrow[drr, bend right, "f\star\mathrm{id}"'] & A' \star B \coprod_{A\star B} A \star B' \arrow[dr, dashed, "f \overset{\star}{\wedge} g"] & \\
& & A' \star B'
\end{tikzcd}$$

Proposition 25. We have the following facts.

1. If f is right anodyne, then $f \overset{\star}{\wedge} g$ and $f \wedge g$ are inner anodyne.
2. If f is left anodyne, then $f \overset{\star}{\wedge} g$ and $f \wedge g$ are left anodyne.
3. If f is anodyne, then $f \overset{\star}{\wedge} g$ is a Kan fibration.

Proof. Consider the set

$$\mathcal{S} = \{f \mid f \overset{\star}{\wedge} g \text{ is inner anodyne}\}.$$

That is, f consists of precisely those maps such that the lifting

$$\begin{tikzcd}
A_0 \star B \coprod_{A_0 \star B_0} A \star B_0 \arrow[r] \arrow[d, "f \hat{\star} g"'] & X \arrow[d, "\text{inner fibration}"] \\
A \star B \arrow[r] \arrow[ur, dashed] & Y
\end{tikzcd}$$

has a solution

By a result analogous to Odious Lemma **??**, we have immediately that such a lifting problem is equivalent to the following.

□

We have the following ‘perpendicular statements’ (whatever that means).

Fact 26. Consider morphisms of simplicial sets as follows

$$\bar{K} \hookrightarrow K \xrightarrow{p} X \xrightarrow{q} S$$

where q is an inner fibration. Let $r = p \circ q$, $\bar{p} = p|_{\bar{K}}$, $\bar{r} = r|_{\bar{K}}$. Denote the

$$S_{/p} \to X_{/\bar{p}} \underset{S_{/\bar{p}}}{\times} S_{/r}.$$

1.4.1 Cofibration in groupoids

We would like to find the correct ∞-categorical notion of being cofibered in groupoids.

Lemma 27. Let $F\colon \mathcal{C} \to \mathcal{D}$ be a functor exhibiting $\mathcal{C}$ as cofibered in groupoids over $\mathcal{D}$. Then for each $d \in \mathcal{D}$, the fiber $\mathcal{C}_d$ defined by the pullback below is a groupoid.

$$\begin{tikzcd}
\mathcal{C}_d \arrow[r] \arrow[d] & \mathcal{C} \arrow[d, "F"] \\
\{d\} \arrow[r, hook] & \mathcal{D}
\end{tikzcd}$$

Proof. Every morphism in $\mathcal{C}_d$ is by definition mapped to id_d, so by □

Theorem 28. Let $F\colon \mathcal{C} \to \mathcal{D}$ be a functor. Then F exhibits $\mathcal{C}$ as cofibered in groupoids over D if and only if $N(F)\colon N(\mathcal{C}) \to N(\mathcal{D})$ is a left fibration.

Proof. Suppose F is a left fibration. We examine some horn filling conditions in small degrees. First, consider a horn filling

$$\begin{tikzcd}
\Lambda^1_0 \arrow[r] \arrow[d] & N(\mathcal{C}) \arrow[d] \\
\Delta^1 \arrow[r] & N(\mathcal{D})
\end{tikzcd}$$

The commutativity conditions tell us that we have the following solid diagrams in $\mathcal{C}$ and $\mathcal{D}$ respectively.

$$x \qquad \xrightarrow{F} \qquad F(x) \xrightarrow{\bar{f}} \bar{y}$$

A dashed lift

$$\begin{tikzcd}
\Lambda^1_0 \arrow[r] \arrow[d] & N(\mathcal{C}) \arrow[d] \\
\Delta^1 \arrow[r] \arrow[ur, dashed] & N(\mathcal{D})
\end{tikzcd}$$

gives us the following dashed data.

$$x \overset{f}{\dashrightarrow} y \qquad \xrightarrow{F} \qquad F(x) \xrightarrow{\bar{f}} \bar{y}$$

Thus, the first condition of Definition 17 is satisfied.

Similarly, a horn filling problem $\Lambda^2_0 \to \Delta^2$ gives us the following solid data, while a lift gives us the dashed data.

$$\begin{tikzcd}
& y \arrow[dr, dashed, "g"] & \\
x \arrow[ur, "f"] \arrow[rr, "h"'] & & z
\end{tikzcd}
\qquad
\begin{tikzcd}
& F(y) \arrow[dr, "\bar{g}"] & \\
F(x) \arrow[ur, "F(f)"] \arrow[rr, "F(h)"'] & & F(z)
\end{tikzcd}$$

This says that there exists a lift as required, but not that it is unique.

Now consider two possible lifts $\bar{g}$ and $\bar{g}'$, arranged into a $(3,0)$-horn as follows.

$$\begin{tikzcd}
x \arrow[r, "f"] \arrow[d, "f"'] \arrow[dr, "h"] & y \arrow[d, "g"] \\
y \arrow[r, "g'"'] & z
\end{tikzcd}
\qquad
\begin{tikzcd}
x \arrow[r, "f"] \arrow[d, "f"'] & y \arrow[d, "g"] \\
y \arrow[r, "g'"'] \arrow[ur, "\mathrm{id}_y"] & z
\end{tikzcd}$$

These correspond to a 3-simplex in $\mathcal{D}$ as follows.

$$\begin{tikzcd}
F(x) \arrow[r, "F(f)"] \arrow[d, "F(f)"'] \arrow[dr, "F(h)"] & F(y) \arrow[d, "\bar{g}'"] \\
F(y) \arrow[r, "\bar{g}"'] & F(z)
\end{tikzcd}
\qquad
\begin{tikzcd}
F(x) \arrow[r, "F(f)"] \arrow[d, "F(f)"'] & F(y) \arrow[d, "\bar{g}'"] \\
F(y) \arrow[r, "\bar{g}"'] \arrow[ur, "\mathrm{id}_{F(y)}"] & F(z)
\end{tikzcd}$$

The lifting properties say that we can fill the above horn, telling us that $g = g'$, i.e. that the lift is unique. $\square$

1.5 The infinity-categorical Grothendieck construction

Definition 29 (fiber over a point)**.** Let $f\colon X \to S$ be a map of simplicial sets, and let $s \in S$. The fiber over s, denoted X_s is the following pullback.

$$\begin{tikzcd} X_s \arrow[r] \arrow[d] & X \arrow[d, "f"] \\ \{s\} \arrow[r, hook] & S \end{tikzcd}$$

Theorem 30. Let $p\colon X \to S$ be a left fibration of simplicial sets. Then the assignment

$$s \mapsto X_s$$

extends to a functor $\mathrm{h}S \to \mathrm{h}\mathcal{S}$, where $\mathcal{S}$ is the category of spaces (Definition **??**).

Proof. By Corollary 9, each fiber X_s is a Kan complex.

Now, let $f\colon s \to s'$ be any morphism in S. Consider the following lifting problem.

$$\begin{tikzcd} \{0\} \times X_s \arrow[rr, hook] \arrow[d, hook] & & X \arrow[d, "p"] \\ \Delta^1 \times X_s \arrow[r] \arrow[urr, dashed, "Lf"] & \Delta^1 \arrow[r, "f"] & S \end{tikzcd}$$

The left-hand morphism is left anodyne because it is the smash product

$$(\{0\} \hookrightarrow \Delta^1) \overset{\star}{\wedge} (\emptyset \hookrightarrow X_s),$$

so we can find a dashed lift. This gives us a map $Lf\colon \Delta^1 \times X_s \to X$ such that $Lf_{\{0\}} = \mathrm{id}_{X_s}$. Restricting to $\{1\} \times X_s$, we get a map $Lf_{\{1\}\times X_s}\colon \{1\} \times X_s \to X_{s'}$, giving us a map

$$\tilde{f}\colon X_s \to X_{s'}.$$

The functor $\mathrm{h}S \to \mathrm{h}\mathcal{S}$ sends $[f] \mapsto [\tilde{f}]$. It remains to check that this is well-defined, i.e. respects □

1.6 More model structures

Let S be a simplicial set.

- Denote by $(\mathbf{Set}_\Delta)_{/S}$ the category of simplicial sets over S.
- Denote by $\mathbf{Set}_\Delta{}^{\mathfrak{C}(S)}$ the category of functors of simplicial categories from $\mathfrak{C}(S) \to \mathbf{Set}_\Delta$.

Theorem 31. There is a Quillen equivalence

$$(\mathbf{Set}_\Delta)_{/S} \leftrightarrow \mathbf{Set}_\Delta{}^{\mathfrak{C}(S)}$$

where $(\mathbf{Set}_\Delta)_{/S}$ is taken to have the covariant model structure, and $\mathbf{Set}_\Delta{}^{\mathfrak{C}(S)}$ is taken to have the projective model structure.

1.7 Some correspondences

$$\left\{\begin{matrix}\text{functors } \mathcal{C}^{\mathcal{X}} \to \mathcal{D} \\ \text{fibered in groupoids}\end{matrix}\right\} \longleftrightarrow \left\{\begin{matrix}\text{pseudofunctors} \\ \mathcal{D} \to \mathbf{Grpd}\end{matrix}\right\} \longleftrightarrow \left\{\begin{matrix}\text{functors } \mathcal{C} \to \mathcal{D} \\ \text{cofibered in groupoids}\end{matrix}\right\}$$

$$\left\{\begin{matrix}\text{coCartesian fibrations} \\ \mathcal{C}^{\mathcal{X}} \to \mathcal{D}\end{matrix}\right\} \longleftrightarrow \left\{\begin{matrix}\text{pseudofunctors} \\ \mathcal{D} \to \mathbf{Grpd}\end{matrix}\right\} \longleftrightarrow \left\{\begin{matrix}\text{coCartesian fibrations} \\ \mathcal{C}^{\mathcal{X}} \to \mathcal{D}\end{matrix}\right\}$$