Symmetric Monoidal ∞-Categories

- Note: we will call $(\infty, 1)$-categories ∞-categories. Sorry Tom, it's just convenient.
- Main references: [4], [5], [2], [1], [3].

1 Pseudofunctors, opfibrations, and symmetric monoidal categories

1.1 Pseudofunctors to Cat are Grothendieck opfibrations

- Grothendieck op-fibrations correspond to pseudofunctors to **Cat**.

The below gives an example to complement [2].

Example of a pseudofunctor to **Cat**: Let $\mathcal{C}$ be a category with pullbacks. Recall that for a map $f : C \to D$ in $\mathcal{C}$, we define a pullback functor

$$\begin{array}{rcl} f^* : \quad \mathcal{C}_{/D} & \to & \mathcal{C}_{/C}, \\ (h : X \to D) & \mapsto & (f^*h : P \to C), \end{array}$$

where we have formed a pullback

$$\begin{tikzcd} P \arrow[r, "h^*f"] \arrow[d, "f^*h"'] & X \arrow[d, "h"] \\ C \arrow[r, "f"'] & D \end{tikzcd}$$

in $\mathscr{C}$. For any map

$$\begin{tikzcd} X \arrow[rr, "\phi"] \arrow[dr, "h"'] & & X' \arrow[dl, "h'"] \\ & D & \end{tikzcd}$$

from h to h' in $\mathcal{C}_{/D}$, we define $f^*\phi$ to be the unique map making the diagram below commute.

$$\begin{tikzcd} X \arrow[rr, "\phi"] \arrow[dr, "h"'] & & X' \arrow[dl, "h'"] \\ & D & \\ P \arrow[uu, "h^*f"] \arrow[rr, dashed, "f^*\phi"] \arrow[dr, "f^*h"'] & & P' \arrow[uu, "h'^*f"'] \arrow[dl, "f^*h'"] \\ & C \arrow[uu, "f"'] & \end{tikzcd}$$

Now, we may wish to define a functor

$$\begin{aligned} F : \mathcal{C}^{\mathrm{op}} &\to \mathbf{Cat}, \\ C &\mapsto \mathcal{C}_{/C}, \end{aligned}$$

which sends a map $f : C \to D$ in $\mathcal{C}$ to a pullback functor $f^* : \mathcal{C}_{/D} \to \mathcal{C}_{/C}$. However a problem arises when we check that F respects composition: suppose $f : C \to D$, $g : D \to E$ are maps in $\mathcal{C}$. Then

$$F(g \circ f)(h : X \to E) = (g \circ f)^* h : P \to C,$$

corresponding to the pullback

$$\begin{tikzcd} P \arrow[r, "h^*(g\circ f)"] \arrow[d, "(g\circ f)^* h"'] & X \arrow[d, "h"] \\ C \arrow[r, "g\circ f"'] & E \end{tikzcd}$$

in $\mathcal{C}$. On the other hand,

$$(F(g) \circ F(f))(h : X \to E) = f^*(g^* h) : P'' \to C,$$

which corresponds to the diagram below.

$$\begin{tikzcd} P'' \arrow[r, "(g^*h)^* f"] \arrow[d, "f^*(g^*h)"'] & P' \arrow[r, "h^* g"] \arrow[d, "g^* h"] & X \arrow[d, "h"] \\ C \arrow[r, "f"'] & D \arrow[r, "g"'] & E \end{tikzcd}$$

The outer square is indeed a pullback square, since the inner two squares are, so we have a unique isomorphism $P \cong P''$. However, we do not in general have equality. This is because pullbacks are only unique up to unique isomorphism, and in defining a pullback functor we made arbitrary (and not necessarily compatible) choices of P, P' and P''. Thus, we have not defined a functor $\mathcal{C}^{\mathrm{op}} \to \mathbf{Cat}$, rather, we have defined what is known as a *pseudofunctor*.

(definition of a pseudofunctor)

The above example is one way in which pseudofunctors into **Cat** naturally arise; another common example is the pseudofunctor

$$\begin{aligned} \mathbf{CRing} &\to \mathbf{Cat} \\ R &\mapsto R\text{-}\mathbf{Mod}, \end{aligned}$$

which sends a ring homomorphism $\phi : R \to S$ to the functor $- \otimes_R S : R\text{-}\mathbf{Mod} \to S\text{-}\mathbf{Mod}$ (extension of scalars). However, to give the data of a pseudofunctor $F : \mathcal{C} \to \mathbf{Cat}$, we must specify not only the functions $\mathrm{ob}(\mathcal{C}) \to \mathrm{ob}(\mathbf{Cat})$ and $\mathrm{Hom}_{\mathcal{C}}(X, Y) \to \mathrm{Hom}_{\mathbf{Cat}}(F(X), F(Y))$ for each $X, Y \in \mathcal{C}$, but also natural isomorphisms

$$F(\mathrm{id}_X) \cong \mathrm{id}_{F(X)}, \quad F(g \circ f) \cong F(g) \circ F(f).$$

That's a pain, let's use Grothendieck opfibrations instead.

The definitions below are from [1].

Definition 1.1.1. Let $p : X \to \mathcal{C}$ be a functor, and let $f : c \to d$ be a morphism in $\mathcal{C}$. A morphism Φ in X lying over f is *p-cocartesian* if for any other morphism Ψ of X lying over f, there exists a morphism I of X such that $p(I) = \mathrm{id}_d$ and $\Psi = I \circ \Phi$.

Definition 1.1.2. Let $p : X \to \mathcal{C}$ be a functor. Then p is a *Grothendieck opfibration* if for any morphism of $\mathcal{C}$ and any lift of its source, there is a p-cocartesian morphism with that course lying over it.

1.2 Symmetric monoidal categories are special pseudofunctors to Cat

- Now that we know how to move between pseudofunctors to **Cat** and opfibrations, let's write the data of a symmetric monoidal category as a pseudofunctor to **Cat**.

1.3 ...which are special opfibrations

- The above implies there's some category $\mathcal{D}$ such that opfibrations $\mathcal{D} \to \mathrm{Fin}_*$ are the same as symmetric monoidal categories. Let's see what $\mathcal{D}$ is.
- (Usual) definition of symmetric monoidal category and translation into the language of op-fibrations into Fin_*, running example of $\mathbf{Vect}_k$ with $\otimes$ or $\times$.
- Possibly mention swapping out $\mathbf{Fin}_*$ for Δ^{op} gives a monoidal category rather than a symmetric monoidal category (how do we get a braided monoidal category?)
- Correspondence of symmetric monoidal functors with morphisms of opfibrations.

The construction below is in [4].

Let $(\mathcal{C}, \otimes)$ be a symmetric monoidal category. We define a new category $\mathcal{C}^{\otimes}$, whose objects are finite (possibly empty) sequences of objects of $\mathcal{C}$, denoted by $[C_1, ..., C_n]$. A morphism

$$[C_1, ..., C_n] \to [C'_1, ..., C'_m]$$

consists of a subset $S \subseteq \{1, ..., n\}$, a map of finite sets $\alpha : S \to \{1, ..., m\}$, and a collection of morphisms $\{f_j : \bigotimes_{i \in \alpha^{-1}\{j\}} C_i \to C'_j\}_{1 \leq j \leq m}$ in $\mathcal{C}$.

For two morphisms $f : [C_1, ..., C_n] \to [C'_1, ..., C'_m]$ and $g : [C'_1, ..., C'_m] \to [C''_1, ..., C''_l]$, determining two subsets $S \subseteq \{1, ..., n\}$ and $T \subseteq \{1, ..., m\}$ and maps $\alpha : S \to \{1, ..., m\}$, $\beta : T \to \{1, ..., l\}$, the composition $g \circ f$ is given by the subset $U = \alpha^{-1}T \subseteq \{1, ..., n\}$, the map $\beta \circ \alpha : U \to \{1, ..., l\}$ and the maps

$$\left\{ \bigotimes_{i \in (\beta \circ \alpha)^{-1}\{k\}} C_i \cong \bigotimes_{j \in \beta^{-1}\{k\}} \bigotimes_{i \in \alpha^{-1}\{j\}} C_i \to \bigotimes_{j \in \beta^{-1}\{k\}} C'_j \to C''_k \right\}_{1 \leq k \leq l}.$$

For example, let

$$f : [C_1, C_2, C_3, C_4] \to [C'_1, C'_2, C'_3]$$

be a morphism in $\mathcal{C}^{\otimes}$ consisting of the subset $\{1, 2, 3\} \subseteq \{1, 2, 3, 4\}$, the map

$$\begin{aligned} \alpha : \{1, 2, 3\} &\to \{1, 2, 3\}, \\ 1 &\mapsto 1, \\ 2 &\mapsto 2, \\ 3 &\mapsto 3, \end{aligned}$$

and morphisms

$$f_1 : C_1 \to C'_1, \quad f_2 : C_2 \otimes C_3 \to C'_2, \quad f_3 : \mathbf{1} \to C'_3,$$

and let

$$g : [C'_1, C'_2, C'_3] \to [C''_1, C''_2, C''_3]$$

be a morphism in $\mathcal{C}^{\otimes}$ consisting of the subset $\{1,2,3\} \subseteq \{1,2,3\}$, the map

$$\beta : \{1,2,3\} \to \{1,2,3\},$$
$$1,2,3 \mapsto 3,$$

and morphisms

$$g_1 : \mathbf{1} \to C_1'', \quad g_2 : \mathbf{1} \to C_2'', \quad g_3 : C_1' \otimes C_2' \otimes C_3' \to C_3''.$$

Then the composition $g \circ f$ consists of the subset $\alpha^{-1}\{1,2,3\} = \{1,2,3\} \subseteq \{1,2,3,4\}$, the map

$$\beta \circ \alpha : \{1,2,3\} \to \{1,2,3\},$$
$$1,2,3 \mapsto 3,$$

and the morphisms

$$(g \circ f)_1 = g_1, \quad (g \circ f)_2 = g_2, \quad (g \circ f)_3 = g_3 \circ (f_1 \otimes f_2 \otimes f_3).$$

(really?)

(some intuition on this, tensor along the fibres, etc)

Claim: the forgetful functor

$$\begin{aligned} p : \quad \mathcal{C}^{\otimes} \quad &\to \ \mathrm{Fin}_*, \\ [C_1, ..., C_n] &\mapsto \ \langle n \rangle_* \end{aligned}$$

is an opfibration. (It almost tautologically is).

1.4 Generalisation to ∞-categories

- Translation of the above into ∞-categorical language.
- A functor $p : D \to C$ between ordinary categories is a Grothendieck opfibration if and only if the induced functor $N(p) : N(D) \to N(C)$ on nerves is a cocartesian fibration.
- Some examples (nerve of an ordinary symmetric monoidal category, currently trying to find more examples – many people talk about **Sp**, but it seems like I'd need a lot of background to understand this).
- If an ∞-category has finite (co)products, there is a (co)cartesian monoidal structure on $\mathcal{C}$.
- Algebra objects in monoidal (∞-)categories
- Possibly generalisation to ∞-operads, depending on how much the above comes to or if I find anything fun to do with symmetric monoidal ∞-categories.

Definition 1.4.1 ([1], Def 2.1). A functor $p : X \to Y$ between ∞-categories is an *inner fibration* if for all $n \geq 2$, all $0 < k < n$, and any solid arrow commutative square

$$\begin{tikzcd} \Lambda^n_k \arrow[r] \arrow[d, hook] & X \arrow[d, "p"] \\ \Delta^n \arrow[r] \arrow[ur, dashed] & Y \end{tikzcd}$$

there exists a dotted lift.

(Stupid note to self, very obvious but I forget it every now and again):

- If $X : \Delta^{\mathrm{op}} \to \mathbf{Set}$ is a simplicial set, and $\Delta^0 : \Delta^{\mathrm{op}} \to \mathbf{Set} := \mathrm{Hom}(-, [0])$, then a map $F : X \to \Delta^0$ is a natural transformation $(F_n : X_n \to *)_{n\in\mathbb{N}_0}$. That is, such a natural transformation is a family of maps down to a point. In other words, there's only really one natural transformation, so we really *can* view Δ^0 as a point.

Example 1.4.2 ([1], Ex 2.2). Let $p : X \to \Delta^0$ be the canonical map, and suppose we have the diagram below, such that the outer square commutes.

$$\begin{tikzcd}
\Lambda^n_k \arrow[r] \arrow[d, hook] & X \arrow[d, "p"] \\
\Delta^n \arrow[r] \arrow[ur, dashed, "\phi"'] & \Delta^0
\end{tikzcd}$$

The lower triangle commutes automatically, so the statement that p is an inner fibration is equivalent to the statement that for all $n \geq 2$, all $0 < k < n$, and any map $\Lambda^n_k \to X$, there exists a dotted lift.

$$\begin{tikzcd}
\Lambda^n_k \arrow[r] \arrow[d, hook] & X \\
\Delta^n \arrow[ur, dashed] &
\end{tikzcd}$$

That is, X is an ∞-category.

Now, since any element $y \in Y_0$ can be viewed as a copy of Δ^0, the above discussion tells us that the fibre $p^{-1}\{y\}$ is an ∞-category.

Definition 1.4.3 ([1], Def 3.1). Let $p : X \to Y$ be an inner fibration. An edge $f : \Delta^1 \to X$ of X is *p-cocartesian* if for all $n \geq 2$, any extension

$$\begin{tikzcd}
\Delta^{\{0,1\}} \arrow[r, "f"] \arrow[d, hook] & X \\
\Lambda^n_0 \arrow[ur, "F"'] &
\end{tikzcd}$$

and any solid arrow commutative diagram

$$\begin{tikzcd}
\Lambda^n_0 \arrow[r, "F"] \arrow[d, hook] & X \arrow[d, "p"] \\
\Delta^n \arrow[r] \arrow[ur, dashed] & Y
\end{tikzcd}$$

a dotted lift exists.

Definition 1.4.4. Let $p : X \to Y$ be an inner fibration. Then p is a cocartesian fibration if for any edge $\phi : y \to y'$ in Y_1, and for every $x \in X_0$ lying over y, there exists a p-cocartesian edge $f : x \to x'$ of X lying over ϕ.

This is a test to check pushing to GitHub is working as expected.

References

[1] Clark Barwick and Jay Shah. 'Fibrations in ∞-Category Theory'. In: *2016 MATRIX Annals*. Springer Cham, 2018, pp. 17–42.

[2] Julius Frank. *Symmetric monoidal ∞-categories*. 2021. URL: https://homepages.abdn.ac.uk/markus.upmeier/pages/JuliusMay13.pdf.

[3] Moritz Groth. *A Short Course on ∞-Categories*. 2015. arXiv: 1007.2925 [math.AT].

[4] Jacob Lurie. *Higher Algebra*. 2017. URL: https://www.math.ias.edu/~lurie/papers/HA.pdf.

[5] Jacob Lurie. *Higher Topos Theory*. 2008. arXiv: math/0608040 [math.CT].