

MONOIDAL CATEGORIES

1. INTRODUCTION

In this notes we study monoidal categories. We introduce this notion and prove some important consequence of its axioms in the first section. Next we discuss monoidal functors and we present useful result about monoidal adjoint pairs (Theorem 3.3). Third section contains rigorous and formal proofs of Mac Lane's coherence and strictness theorems. In the fourth section we are concerned with notions of dual pairs and rigid objects. Finally we introduce symmetric monoidal categories and symmetric monoidal functors in the closing section.

Throughout the notes our foundation is Tarski-Grothendieck system described in [Mon19, Introduction]. We indicate each usage of Tarski's axiom for the reader's convenience.

We explain now some conventions concerning notation that we use in this notes. There are two ways of denoting values of functions. In *prefix notation* a function symbol f precedes its arguments x_1, x_2, \dots, x_n and the expression is $f(x_1, x_2, \dots, x_n)$ (parentheses are standard in the prefix notation). On the other hand *infix notation* is used when a symbol f of a function is placed between each pair of arguments x_1, x_2, \dots, x_n and the expression is $x_1 f x_2 f \dots f x_n$. For real life example note that $x_1 + x_2 + \dots + x_n$ is written in infix notation. Infix notation can be also used in the case of functors. For example let $\otimes : \mathcal{C} \times \mathcal{C} \rightarrow \mathcal{C}$ be a functor and let \mathcal{C} be a category. Then using infix notation we can write the value of \otimes on objects X, Y of \mathcal{C} as $X \otimes Y$. We can also consider the composition $\otimes \cdot \langle \otimes, 1_{\mathcal{C}} \rangle : \mathcal{C} \times \mathcal{C} \times \mathcal{C} \rightarrow \mathcal{C}$ and we can write its value on objects X, Y and Z of \mathcal{C} as $(X \otimes Y) \otimes Z$.

2. MONOIDAL CATEGORIES

Definition 2.1. Let \mathcal{C} be a category. Suppose that $\otimes : \mathcal{C} \times \mathcal{C} \rightarrow \mathcal{C}$ is a functor (we use infix notation for it), I is an object of \mathcal{C} , $\alpha_{X,Y,Z} : X \otimes (Y \otimes Z) \rightarrow (X \otimes Y) \otimes Z$ is an isomorphism natural in objects X, Y, Z of \mathcal{C} and $l_X : I \otimes X \rightarrow X$, $r_X : X \otimes I \rightarrow X$ are isomorphisms natural in object X of \mathcal{C} . Assume that *Mac Lane's pentagon*

$$\begin{array}{ccc}
 X \otimes (Y \otimes (Z \otimes T)) & \xrightarrow{1_X \otimes \alpha_{Y,Z,T}} & X \otimes ((Y \otimes Z) \otimes T) \\
 \downarrow \alpha_{X,Y,Z \otimes T} & & \downarrow \alpha_{X,Y \otimes Z, T} \\
 (X \otimes Y) \otimes (Z \otimes T) & & (X \otimes (Y \otimes Z)) \otimes T \\
 \searrow \alpha_{X \otimes Y, Z, T} & & \swarrow \alpha_{X, Y, Z} \otimes 1_T \\
 & ((X \otimes Y) \otimes Z) \otimes T &
 \end{array}$$

is commutative for any objects X, Y, Z, T in \mathcal{C} and that *unit triangle*

$$\begin{array}{ccc}
 X \otimes (I \otimes Y) & \xrightarrow{\alpha_{X,I,Y}} & (X \otimes I) \otimes Y \\
 \downarrow 1_X \otimes l_Y & & \downarrow r_X \otimes 1_Y \\
 & X \otimes Y &
 \end{array}$$

is commutative for any objects X, Y in \mathcal{C} . Then $(\otimes, I, \alpha, l, r)$ is called a *monoidal structure on \mathcal{C}* and $(\mathcal{C}, \otimes, I, \alpha, r, l)$ is called a *monoidal category*. If α, l, r are identities, then we say that $(\mathcal{C}, \otimes, I, \alpha, r, l)$ is a *strict monoidal category*.

Proposition 2.2. *Let $(\mathcal{C}, \otimes, I, \alpha, l, r)$ be a monoidal category. Then triangles*

$$\begin{array}{ccc} I \otimes (X \otimes Y) & \xrightarrow{\alpha_{I,X,Y}} & (I \otimes X) \otimes Y \\ & \searrow l_{X \otimes Y} \quad \swarrow l_X \otimes 1_Y & \\ & X \otimes Y & \end{array} \quad \begin{array}{ccc} X \otimes (Y \otimes I) & \xrightarrow{\alpha_{X,Y,I}} & (X \otimes Y) \otimes I \\ & \searrow 1_X \otimes r_Y \quad \swarrow r_{X \otimes Y} & \\ & X \otimes Y & \end{array}$$

are commutative for every pair X, Y of objects of \mathcal{C} .

Proof. We prove that the first triangle commutes (commutativity of the second can be proved by the similar method). Pick objects X, Y and consider the following diagram.

$$\begin{array}{ccccc} (I \otimes I) \otimes (X \otimes Y) & \xleftarrow{\alpha_{I,I,X \otimes Y}} & I \otimes (I \otimes (X \otimes Y)) & \xrightarrow{1_I \otimes \alpha_{I,X,Y}} & I \otimes ((I \otimes X) \otimes Y) \\ & \searrow r_I \otimes 1_{X \otimes Y} & \downarrow 1_I \otimes l_{X \otimes Y} & \swarrow 1_I \otimes (l_X \otimes 1_Y) & \\ & & I \otimes (X \otimes Y) & & \\ & \searrow \alpha_{I \otimes I, X, Y} & \downarrow \alpha_{I, X, Y} & \swarrow \alpha_{I, I \otimes X, Y} & \\ & & (I \otimes X) \otimes Y & & \\ & \swarrow (r_I \otimes 1_X) \otimes 1_Y & & \searrow (1_I \otimes l_X) \otimes 1_Y & \\ ((I \otimes I) \otimes X) \otimes Y & \xleftarrow{\alpha_{I, I, X} \otimes 1_Y} & (I \otimes (I \otimes X)) \otimes Y & & \end{array}$$

First note that all morphism in the diagram are isomorphisms. The outer pentagon in the diagram commutes, since it is an instance of the Mac Lane's pentagon. Moreover, the two triangles denoted by \circlearrowright commute, since one is an instance of the unit triangle and the other is an image of an instance of the unit triangle under the functor $(-) \otimes Y$. Finally, the two squares denoted by \circlearrowright are commutative according to the naturality of α . This implies that the triangle denoted by \circlearrowleft is commutative. This triangle is precisely the image under the functor $I \otimes (-)$ of the first triangle in the statement. Since this $I \otimes (-)$ is an equivalence of categories, it follows that the first triangle in the statement is commutative. \square

Let \mathcal{C} be a category. By abuse of language we say that \mathcal{C} is a monoidal category when we have a certain monoidal structure on \mathcal{C} in mind. Also when we deal with two (or more) monoidal categories \mathcal{C} and \mathcal{D} we often use the same symbols to denote their monoidal structures. In these cases (as usual in categorical considerations) context helps us to avoid possible confusion.

3. MONOIDAL FUNCTORS, TRANSFORMATIONS AND ADJUNCTIONS

Definition 3.1. Let \mathcal{C} and \mathcal{D} be monoidal categories. Suppose that $F : \mathcal{C} \rightarrow \mathcal{D}$ is a functor, $\tau_{X,Y} : F(X) \otimes F(Y) \rightarrow F(X \otimes Y)$ is an morphism natural in pairs of objects X, Y of \mathcal{C} and $\phi : I \rightarrow F(I)$ is a morphism in \mathcal{D} . Assume that the diagram

$$\begin{array}{ccc}
 F(X) \otimes (F(Y) \otimes F(Z)) & \xrightarrow{\alpha_{F(X), F(Y), F(Z)}} & (F(X) \otimes F(Y)) \otimes F(Z) \\
 \downarrow 1_{F(X)} \otimes \tau_{Y,Z} & & \downarrow \tau_{X,Y} \otimes 1_{F(Z)} \\
 F(X) \otimes F(Y \otimes Z) & & F(X \otimes Y) \otimes F(Z) \\
 \downarrow \tau_{X,Y \otimes Z} & & \downarrow \tau_{X \otimes Y, Z} \\
 F(X \otimes (Y \otimes Z)) & \xrightarrow{F(\alpha_{X,Y,Z})} & F((X \otimes Y) \otimes Z)
 \end{array}$$

is commutative for any objects X, Y, Z in \mathcal{C} and diagrams

$$\begin{array}{ccc}
 I \otimes F(X) & & F(X) \otimes I \\
 \downarrow \phi \otimes 1_{F(X)} & \searrow l_{F(X)} & \downarrow 1_{F(X)} \otimes \phi \\
 F(I) \otimes F(X) & & F(X) \otimes F(I) \\
 \downarrow \tau_{I,X} & \nearrow F(l_X) & \downarrow \tau_{X,I} \\
 F(I \otimes X) & & F(X \otimes I) \\
 & \nearrow F(l_X) & \nearrow F(r_X) \\
 & F(X) & F(X)
 \end{array}$$

are commutative for every object X in \mathcal{C} . Then a triple (F, τ, ϕ) is called a *weak monoidal functor*. Moreover, if τ is a natural isomorphism and ϕ is an isomorphism, then we say that (F, τ, ϕ) is a *strong monoidal functor*. Finally, we say that (F, τ, ϕ) is a *strict monoidal functor* if τ and ϕ are identities.

If \mathcal{C} and \mathcal{D} are monoidal categories and (F, τ, ϕ) is a (weak, strong, strict) monoidal functor, where $F : \mathcal{C} \rightarrow \mathcal{D}$ is the underlying functor, then by the usual abuse of language we say that $F : \mathcal{C} \rightarrow \mathcal{D}$ is a (weak, strong, strict) monoidal functor.

Definition 3.2. Let \mathcal{C} and \mathcal{D} be monoidal categories. Suppose that (F, τ^F, ϕ^F) and (G, τ^G, ϕ^G) are (weak, strong, strict) monoidal functors. Let $\sigma : F \rightarrow G$ be a natural transformation. Assume that the square

$$\begin{array}{ccc}
 F(X) \otimes F(Y) & \xrightarrow{\sigma_X \otimes \sigma_Y} & G(X) \otimes G(Y) \\
 \downarrow \tau_{X,Y}^F & & \downarrow \tau_{X,Y}^G \\
 F(X \otimes Y) & \xrightarrow{\sigma_{X \otimes Y}} & G(X \otimes Y)
 \end{array}$$

is commutative for every pair X, Y of objects in \mathcal{C} and also that the triangle

$$\begin{array}{ccc}
 F(I) & \xrightarrow{\sigma_I} & G(I) \\
 \nwarrow \phi^F & & \nearrow \phi^G \\
 & I &
 \end{array}$$

commutes. Then σ is a *natural transformation of monoidal functors* or a *monoidal transformation*.

The next theorem is not used in the remaining part of this notes and we left some commutative diagram manipulations in its proof as exercises for the reader.

Theorem 3.3. *Let \mathcal{C}, \mathcal{D} be monoidal categories and let $F : \mathcal{C} \rightarrow \mathcal{D}$ be a strong monoidal functor. Suppose that $G : \mathcal{D} \rightarrow \mathcal{C}$ is a right adjoint functor to F . Assume that $\eta : 1_{\mathcal{C}} \rightarrow GF$ and $\xi : FG \rightarrow 1_{\mathcal{D}}$ are unit and counit of this adjunction, respectively. Then there exists a unique structure of a weak monoidal functor on G such that η and ξ are monoidal transformations.*

Proof. Denote the strong monoidal structure on F by (τ^F, ϕ^F) . Fix a pair X, Y of objects of \mathcal{D} . According to the universal property of $\xi_{X \otimes Y}$ there exists a unique morphism $\tau_{X,Y}^G : G(X) \otimes G(Y) \rightarrow G(X \otimes Y)$ that makes the following diagram commutative.

$$\begin{array}{ccc} F(G(X \otimes Y)) & \xleftarrow{F(\tau_{X,Y}^G)} & F(G(X) \otimes G(Y)) \\ \xi_{X \otimes Y} \downarrow & & \downarrow (\tau_{G(X), G(Y)}^F)^{-1} \\ X \otimes Y & \xleftarrow{\xi_X \otimes \xi_Y} & F(G(X)) \otimes F(G(Y)) \end{array}$$

We left to the reader verification that $\tau_{X,Y}^G$ is natural both in X and Y . Next according to the universal property of ξ_I there exists a unique morphism $\phi^G : I \rightarrow G(I)$ such that the following triangle is commutative.

$$\begin{array}{ccc} F(G(I)) & \xleftarrow{F(\phi^G)} & F(I) \\ \xi_I \downarrow & \nearrow (\phi^F)^{-1} & \\ I & & \end{array}$$

Now we verify that (G, τ^G, ϕ^G) is a weak monoidal functor. For this we need to check that for any objects X, Y, Z in \mathcal{D} the following diagram

$$\begin{array}{ccc} G(X) \otimes (G(Y) \otimes G(Z)) & \xrightarrow{\alpha_{G(X), G(Y), G(Z)}} & (G(X) \otimes G(Y)) \otimes G(Z) \\ 1_{G(X)} \otimes \tau_{Y,Z}^G \downarrow & & \downarrow \tau_{X,Y}^G \otimes 1_{G(Z)} \\ G(X) \otimes G(Y \otimes Z) & & G(X \otimes Y) \otimes G(Z) \\ \tau_{X,Y \otimes Z}^G \downarrow & & \downarrow \tau_{X \otimes Y, Z}^G \\ G(X \otimes (Y \otimes Z)) & \xrightarrow{G(\alpha_{X,Y,Z})} & G((X \otimes Y) \otimes Z) \end{array}$$

is commutative. Now definition of τ^G (details are left to the reader) implies that

$$\xi_{(X \otimes Y) \otimes Z} \cdot F\left(G(\alpha_{X,Y,Z}) \cdot \tau_{X,Y \otimes Z}^G \cdot (1_{G(X)} \otimes \tau_{Y,Z}^G)\right) = \xi_{(X \otimes Y) \otimes Z} \cdot F\left(\tau_{X \otimes Y, Z}^G \cdot (\tau_{X,Y}^G \otimes 1_{G(Z)}) \cdot \alpha_{G(X), G(Y), G(Z)}\right)$$

By universal property of $\xi_{(X \otimes Y) \otimes Z}$, we deduce that the hexagonal diagram above is commutative. Using exactly the same trick (we apply F and use the universal property of ξ_X) we show that triangles

$$\begin{array}{ccc}
I \otimes G(X) & & G(X) \otimes I \\
\downarrow \phi^G \otimes 1_{G(X)} & \searrow l_{G(X)} & \downarrow 1_{G(X)} \otimes \phi^G \\
G(I) \otimes G(X) & & G(X) \otimes G(I) \\
\downarrow \tau_{I,X}^G & \nearrow G(l_X) & \downarrow \tau_{X,I}^G \\
G(I \otimes X) & & G(X \otimes I)
\end{array}$$

are commutative for every object X in \mathcal{D} . This shows that (G, τ^G, ϕ^G) is a weak monoidal functor. Note also that τ^G and ϕ^G are uniquely defined in such a way that ξ automatically is a monoidal transformation. This proves that (τ^G, ϕ^G) is the unique structure of a weak monoidal functor on G that makes ξ a monoidal transformation. It remains to verify that η is a monoidal transformation with respect to (G, τ^G, ϕ^G) and (F, τ^F, ϕ^F) . This also can be done by the same trick (apply F and use universality of ξ). For instance let us write the complete proof of the fact that $\eta_I = G(\phi^F) \cdot \phi^G$. First we apply F to the right hand side and then we compose it with $\xi_{F(I)}$. We obtain

$$\xi_{F(I)} \cdot F(G(\phi^F)) \cdot F(\phi^G) = \phi^F \cdot \xi_I \cdot F(\phi^G) = \phi^F \cdot (\phi^F)^{-1} = 1_{F(I)} = \xi_{F(I)} \cdot F(\eta_I)$$

Thus by universal property of $\xi_{F(I)}$, we deduce that $\eta_I = G(\phi^F) \cdot \phi^G$. \square

4. COHERENCE AND STRICTNESS FOR MONOIDAL CATEGORIES

The idea of coherence originated in algebraic topology. We refer the reader to interesting and enlightening article [Mac63] for history and intuition behind this important concept. Let $(\mathcal{C}, \otimes, I, \alpha, l, r)$ be a monoidal category. Coherence theorem states that appropriate diagrams involving α, l, r , identities and their tensor products commute. To make this precise one needs to put considerable effort in constructing these diagrams in a formal way. This is our task in this section.

A magma consists of a set S equipped with binary operation (we use infix notation for it)

$$\square : S \times S \rightarrow S$$

and distinguished element $e \in S$. Morphism of magmas is a map of sets preserving binary operations and distinguished elements. The category of magmas is denoted by **Mgm**. According to [BDR94, Corollary 3.7.8] the forgetful functor $|-| : \mathbf{Mgm} \rightarrow \mathbf{Set}$ admits a left adjoint. This means that for every set there exists a free magma generated by this set.

Let S be a set and let \mathbf{M}_S be a free magma generated by this set with operation \square and distinguished element e . We define a magma \mathbf{A}_S and a directed graph

$$\mathbf{A}_S \xrightleftharpoons[t]{s} \mathbf{M}_S$$

in which s, t are morphisms of magmas. The magma \mathbf{A}_S is a free magma generated by the set of symbols:

$$1_v \text{ for } v \in \mathbf{M}_S \setminus \{e\}, l_v, l_v^{-1}, r_v, r_v^{-1} \text{ for } v \in \mathbf{M}_S \text{ and } \alpha_{v,w,u}, \alpha_{v,w,u}^{-1} \text{ for } v, w, u \in \mathbf{M}_S.$$

By abuse of language we denote the binary operation of \mathbf{A}_S by \square . Its distinguished element is denoted by 1_e . Now it remains to define morphisms s, t . For this we define

$$s(1_v) = v = t(1_v), s(l_v) = t(l_v^{-1}) = e \square v, t(l_v) = s(l_v^{-1}) = v, s(r_v) = t(r_v^{-1}) = v \square e, t(r_v) = s(r_v^{-1}) = v,$$

$$s(\alpha_{v,w,u}) = t(\alpha_{v,w,u}^{-1}) = v \square (w \square u), t(\alpha_{v,w,u}) = s(\alpha_{v,w,u}^{-1}) = (v \square w) \square u$$

for every $v, w, u \in \mathbf{M}_S$ and we extend these maps of sets to morphisms of magmas according to the fact that \mathbf{A}_S is free. We also define an automorphism $i : \mathbf{A}_S \rightarrow \mathbf{A}_S$ by

$$i(1_v) = 1_v, i(l_v) = l_v^{-1}, i(l_v^{-1}) = l_v, i(r_v) = r_v^{-1}, i(r_v^{-1}) = r_v, i(\alpha_{v,w,u}) = \alpha_{v,w,u}^{-1}, i(\alpha_{v,w,u}^{-1}) = \alpha_{v,w,u}$$

for every $v, w, u \in \mathbf{M}_S$ and we extend this map of sets to a magma endomorphism according to the fact that \mathbf{A}_S is free. We have $i^2 = 1_{\mathbf{A}_S}$ and hence i is an automorphism. Moreover, we have $s \cdot i = t$ and $t \cdot i = s$. Now we construct a groupoid \mathbf{Syn}_S . Objects of \mathbf{Syn}_S are elements of \mathbf{M}_S . Morphisms of \mathbf{Syn}_S are paths in the directed graph defined above modulo relation that asserts that edges 1_v for $v \in \mathbf{M}_S$ in the graph are identity morphisms in \mathbf{Syn}_S and for every edge η in the graph its inverse in \mathbf{Syn}_S is $i(\eta)$. Next \square define a functor $\square : \mathbf{Syn}_S \times \mathbf{Syn}_S \rightarrow \mathbf{Syn}_S$ and we have distinguished object e in \mathbf{Syn}_S .

Proposition 4.1. *Let S be a set and let the graph*

$$\mathbf{A}_S \begin{array}{c} \xrightarrow{s} \\ \xrightarrow{t} \end{array} \mathbf{M}_S$$

with the automorphism $i : \mathbf{A}_S \rightarrow \mathbf{A}_S$ and the groupoid \mathbf{Syn}_S be as defined above. Suppose that \mathcal{C} is a monoidal category. Then every function f that assigns to elements of S objects of \mathcal{C} can be uniquely extended to a functor $F_f : \mathbf{Syn}_S \rightarrow \mathcal{C}$ such that

$$F_f(e) = I, F_f(v \square w) = F_f(v) \otimes F_f(w), F_f(l_v) = l_{F_f(v)}, F_f(r_v) = r_{F_f(v)}, F_f(\alpha_{v,w,u}) = \alpha_{F_f(v), F_f(w), F_f(u)}$$

for any $v, w, u \in \mathbf{M}_S$.

Proof. First using [Mon19, Introduction] we may enlarge our base universe so that \mathcal{C} is a small category. This does not affect construction of \mathbf{Syn}_S so without loss of generality we assume that \mathcal{C} is small category. Note that \otimes and I give rise to a magma structure on the set of objects of \mathcal{C} . This implies that f can be uniquely extended to a morphism $F_f : \mathbf{M}_S \rightarrow \text{ob}(\mathcal{C})$ of magmas. This is uniquely defined so that $F_f(e) = I$ and $F_f(v \square w) = F_f(v) \otimes F_f(w)$ for every $v, w \in \mathbf{M}_S$. We assign

$$F_f(1_v) = 1_{F_f(v)}$$

for $v \in \mathbf{M}_S \setminus \{e\}$ and

$$F_f(l_v) = l_{F_f(v)}, F_f(l_v^{-1}) = l_{F_f(v)}^{-1}, F_f(r_v) = r_{F_f(v)}, F_f(r_v^{-1}) = r_{F_f(v)}^{-1},$$

$$F_f(\alpha_{v,w,u}) = \alpha_{F_f(v), F_f(w), F_f(u)}, F_f(\alpha_{v,w,u}^{-1}) = \alpha_{F_f(v), F_f(w), F_f(u)}^{-1}$$

for any $v, w, u \in \mathbf{M}_S$. One can also view the set of morphisms of \mathcal{C} as a magma with respect to binary operation \otimes and 1_I . This implies that F_f can be extended to a morphism $F_f : \mathbf{A}_S \rightarrow \text{Mor}(\mathcal{C})$ of magmas. Now F_f is a morphism of directed graphs

$$\mathbf{A}_S \begin{array}{c} \xrightarrow{s} \\ \xrightarrow{t} \end{array} \mathbf{M}_S$$

and

$$\text{Mor}(\mathcal{C}) \begin{array}{c} \xrightarrow{\text{dom}} \\ \xrightarrow{\text{cod}} \end{array} \text{ob}(\mathcal{C})$$

Moreover, $F_f(\eta)^{-1}$ is identical to $F_f(i(\eta))$ for every η in \mathbf{A}_S . Since morphisms of \mathbf{Syn}_S are paths in the first graph modulo the relation that asserts that 1_v for $v \in \mathbf{M}_S$ are identities and for every edge η in the graph its inverse in \mathbf{Syn}_S is $i(\eta)$, we deduce that F_f can be uniquely extended to a functor $F_f : \mathbf{Syn}_S \rightarrow \mathcal{C}$ having all properties expressed in the statement. \square

Let \mathcal{C} be a monoidal category and S be a subset of the class of its objects. We denote by $F_S : \mathbf{Syn}_S \rightarrow \mathcal{C}$ the unique functor corresponding to the inclusion of S into the class of objects in \mathcal{C} by means of Proposition 4.1.

Theorem 4.2 (Mac Lane's coherence result). *Let \mathcal{C} be a monoidal category and S be a subset of the class of its objects. Then the functor $F_S : \mathbf{Syn}_S \rightarrow \mathcal{C}$ sends any two parallel arrows in \mathbf{Syn}_S to the same arrow in \mathcal{C} .*

Proof. Suppose that \mathcal{D} is a monoidal category and suppose that a triple $(F : \mathcal{C} \rightarrow \mathcal{D}, \tau, \phi)$ is a strong monoidal functor. Let f be a function given by the restriction of the functor F to a set S . Then f maps S into a class of objects of \mathcal{D} . There exists a unique functor $F_f : \mathbf{Syn}_S \rightarrow \mathcal{D}$ that extends f and satisfies properties described in Proposition 4.1. Next for every $v \in \mathbf{M}_S$ we define an isomorphism $\sigma_v : F_f(v) \rightarrow F(F_S(v))$. This is done by induction. We define $\sigma_e = \phi$ and $\sigma_s = 1_{F(s)}$ for every $s \in S$. Next if σ_v and σ_w are defined for some $v, w \in \mathbf{M}_S$, then we define

$$\sigma_{v \square w} = \tau_{F_S(v), F_S(w)} \cdot (\sigma_v \otimes \sigma_w)$$

Now we prove that for any $v, w \in \mathbf{M}_S$ and morphism $\eta : v \rightarrow w$ in \mathbf{Syn}_S the square

$$(*) \quad \begin{array}{ccc} F_f(v) & \xrightarrow{F_f(\eta)} & F_f(w) \\ \sigma_v \downarrow & & \downarrow \sigma_w \\ F(F_S(v)) & \xrightarrow{F(F_S(\eta))} & F(F_S(w)) \end{array}$$

is commutative. Since each morphism in \mathbf{Syn}_S can be decomposed into edges in \mathbf{A}_S , we derive that it suffices to check commutativity of $(*)$ for an edge in \mathbf{A}_S . Now the proof goes by induction. If η is 1_v for some $v \in \mathbf{M}_S$ then the commutativity of $(*)$ boils down to the fact that $\sigma_v = \phi$. Next assume that $\eta = l_v$ for some $v \in \mathbf{M}_S$, then we have a commutative diagram

$$\begin{array}{ccc} F_f(e \square v) & \xrightarrow{F_f(l_v)} & F_f(v) \\ \downarrow = & & \downarrow = \\ I \otimes F_f(v) & \xrightarrow{l_{F_f(v)}} & F_f(v) \\ \downarrow 1_I \otimes \sigma_v & & \downarrow \sigma_v \\ I \otimes F(F_S(v)) & \xrightarrow{l_{F(F_S(v))}} & F(F_S(v)) \\ \downarrow \tau_{I, F_S(v)} \cdot (\phi \otimes 1_{F(F_S(v))}) & & \downarrow 1_{F(F_S(v))} \\ F(I \otimes F_S(v)) & \xrightarrow{F(l_{F_S(v)})} & F(F_S(v)) \\ \downarrow = & & \downarrow = \\ F(F_S(e \square v)) & \xrightarrow{F(F_S(l_v))} & F(F_S(v)) \end{array}$$

Indeed, the commutativity of the top square follows by definition of F_f , the second square from the top commutes, since $l_X : I \otimes X \rightarrow X$ is natural, the second square from the bottom commutes as F is monoidal and finally the bottom square is commutative according to definition of F_S . Now the outer square in the diagram is an instance of $(*)$ for $\eta = l_v$. This also gives the commutativity of $(*)$ for $\eta = l_v^{-1}$. Similarly one can prove the commutativity of $(*)$ for $\eta = r_v$ and $\eta = r_v^{-1}$. Now suppose that $\eta = \alpha_{v,w,u}$ for some $v, w, u \in \mathbf{M}_S$. We have a commutative diagram

$$\begin{array}{ccc}
F_f(v \sqcap (w \sqcap u)) & \xrightarrow{F_f(\alpha_{v,w,u})} & F_f((v \sqcap w) \sqcap u) \\
\downarrow = & & \downarrow = \\
F_f(v) \otimes (F_f(w) \otimes F_f(u)) & \xrightarrow{\alpha_{F_f(v), F_f(w), F_f(u)}} & (F_f(v) \otimes F_f(w)) \otimes F_f(u) \\
\downarrow \sigma_v \otimes (\sigma_w \otimes \sigma_u) & & \downarrow (\sigma_v \otimes \sigma_w) \otimes \sigma_u \\
F(F_S(v)) \otimes (F(F_S(w)) \otimes F(F_S(u))) & \xrightarrow{\alpha_{F(F_S(v)), F(F_S(w)), F(F_S(u))}} & (F(F_S(v)) \otimes F(F_S(w))) \otimes F(F_S(u)) \\
\downarrow 1_{F(F_S(v))} \otimes \tau_{F_S(w), F_S(u)} & & \downarrow \tau_{F_S(v), F_S(w)} \otimes 1_{F(F_S(u))} \\
F(F_S(v)) \otimes F(F_S(w) \otimes F_S(u)) & & F(F_S(v) \otimes F_S(w)) \otimes F(F_S(u)) \\
\downarrow \tau_{F_S(v), F_S(w) \otimes F_S(u)} & & \downarrow \tau_{F_S(v) \otimes F_S(w), F_S(u)} \\
F(F_S(v) \otimes (F_S(w) \otimes F_S(u))) & \xrightarrow{F(\alpha_{F_S(v), F_S(w), F_S(u)})} & F((F_S(v) \otimes F_S(w)) \otimes F_S(u)) \\
\downarrow = & & \downarrow = \\
F(F_S(v \sqcap (w \sqcap u))) & \xrightarrow{F(F_S(\alpha_{v,w,u}))} & F(F_S((v \sqcap w) \sqcap u))
\end{array}$$

Indeed, the first square from the top commutes by definition of F_f , the second square from the top is commutative, since $\alpha_{X,Y,Z} : X \otimes (Y \otimes Z) \rightarrow (X \otimes Y) \otimes Z$ is natural, the second from the bottom commutes according to the fact that F is monoidal and finally the bottom square is commutative by definition of F_S . Now the outer square is an instance of (*) for $\eta = \alpha_{v,w,u}$. This also gives the commutativity of (*) for $\eta = \alpha_{v,w,u}^{-1}$. Thus we know that (*) is commutative for η in the generating set of \mathbf{A}_S . It remains to check that if $\eta = \beta \sqcap \gamma$ and instances of (*) commute both for β and γ , then the instance of (*) for η is commutative. Suppose that $\beta : v \rightarrow u$, $\gamma : w \rightarrow z$ for some $v, w, u, z \in \mathbf{M}_S$. We have a commutative diagram

$$\begin{array}{ccc}
F_f(v \sqcap w) & \xrightarrow{F_f(\beta \sqcap \gamma)} & F_f(u \sqcap z) \\
\downarrow = & & \downarrow = \\
F_f(v) \otimes F_f(w) & \xrightarrow{F_f(\beta) \otimes F_f(\gamma)} & F_f(u) \otimes F_f(z) \\
\downarrow \sigma_v \otimes \sigma_w & & \downarrow \sigma_u \otimes \sigma_z \\
F(F_S(v)) \otimes F(F_S(w)) & \xrightarrow{F(F_S(\beta)) \otimes F(F_S(\gamma))} & F(F_S(u)) \otimes F(F_S(z)) \\
\downarrow \tau_{F_S(v), F_S(w)} & & \downarrow \tau_{F_S(u), F_S(z)} \\
F(F_S(v) \otimes F_S(w)) & \xrightarrow{F(F_S(\beta) \otimes F_S(\gamma))} & F(F_S(u) \otimes F_S(z)) \\
\downarrow = & & \downarrow = \\
F(F_S(v \sqcap w)) & \xrightarrow{F(F_S(\beta \sqcap \gamma))} & F(F_S(u \sqcap z))
\end{array}$$

Indeed, the first square from the top commutes by definition of F_f , the second square from the top is commutative, since instances of (*) for β and γ are commutative, the second square from the bottom is commutative according to the fact that $\tau_{X,Y} : F(X \otimes Y) \rightarrow F(X) \otimes F(Y)$ is natural, and

finally the bottom square is commutative by definition of F_S . This proves that $(*)$ is commutative for every morphism in \mathbf{Syn}_S .

Let $\eta, \xi : v \rightarrow w$ be parallel morphisms in \mathbf{Syn}_S . Then commutativity of $(*)$ for both η and ξ imply that

$$F(F_S(\eta)) = \sigma_w \cdot F_f(\eta) \cdot \sigma_v^{-1}, F(F_S(\xi)) = \sigma_w \cdot F_f(\xi) \cdot \sigma_v^{-1}$$

If \mathcal{D} is a strict monoidal category, then $F_f(v) = F_f(w)$ and

$$F_f(\eta) = 1_{F_f(v)} = 1_{F_f(w)} = F_f(\xi)$$

This last equality follows by decomposing each morphism in \mathbf{Syn}_S into edges in \mathbf{A}_S and then by induction on complexity of an edge in \mathbf{A}_S . Thus if \mathcal{D} is strict, we derive that $F(F_S(\eta)) = F(F_S(\xi))$. Therefore, in order to prove the theorem it suffices to construct a faithful, strong monoidal functor $F : \mathcal{C} \rightarrow \mathcal{D}$ into a strict monoidal category. For this consider the category $\mathbf{End}(\mathcal{C}) = \mathbf{Fun}(\mathcal{C}, \mathcal{C})$ of endofunctors of \mathcal{C} . The functor (in infix notation)

$$\circ : \mathbf{End}(\mathcal{C}) \times \mathbf{End}(\mathcal{C}) \rightarrow \mathbf{End}(\mathcal{C})$$

that sends endofunctors $F : \mathcal{C} \rightarrow \mathcal{C}$ and $G : \mathcal{C} \rightarrow \mathcal{C}$ to their composition $F \circ G$ makes $\mathbf{End}(\mathcal{C})$ a strict monoidal category with $1_{\mathcal{C}}$ serving as the unit. We define a functor $\Phi : \mathcal{C} \rightarrow \mathbf{End}(\mathcal{C})$ by formula $\Phi(X) = X \otimes (-)$ for every object X in \mathcal{C} and $\Phi(f) = f \otimes (-)$ for every morphism f in \mathcal{C} . Next we define $\tau_{X,Y} : \Phi(X) \circ \Phi(Y) \rightarrow \Phi(X \otimes Y)$ for objects X, Y in \mathcal{C} by formula $\tau_{X,Y} = \alpha_{X,Y,-}$. Finally we define $\phi : 1_{\mathcal{C}} \rightarrow \Phi(I)$ by $\phi = l^{-1}$. A triple (Φ, τ, ϕ) is a monoidal functor. Indeed, commutative diagrams asserting that (Φ, τ, ϕ) is monoidal are Mac Lane's pentagon, unit triangle and the first triangle in 2.2. The functor Φ is faithful. Indeed, if we have $\Phi(f) = \Phi(g)$ for some parallel morphisms f, g in \mathcal{C} , then this implies that $f \otimes 1_I = g \otimes 1_I$ and hence $f = g$. \square

Corollary 4.3. *Let $(\mathcal{C}, \otimes, I, \alpha, l, r)$ be a monoidal category. Then $l_I = r_I$.*

Proof. This follows from Theorem 4.2. We have $l_I = F_{\emptyset}(l_e) = F_{\emptyset}(r_e) = r_I$. \square

As another consequence of Theorem 4.2 we obtain Mac Lane's strictness theorem.

Theorem 4.4 (Mac Lane's strictness result). *Let \mathcal{C} be a monoidal category. Then there exists a strict monoidal category $\mathbf{Strict}(\mathcal{C})$ and a strict monoidal functor $F : \mathcal{C} \rightarrow \mathbf{Strict}(\mathcal{C})$ such that F is full, faithful and surjective on objects.*

Proof. According to [Mon19, Introduction] we may enlarge our base universe so that \mathcal{C} is a small category. Denote by I unit and by \otimes functor (as usual we use infix notation for it) in \mathcal{C} . Let S be a set of objects of \mathcal{C} . Let \mathbf{Syn}_S be the groupoid and $F_S : \mathbf{Syn}_S \rightarrow \mathcal{C}$ be the functor defined above. Let X, Y be objects of \mathcal{C} . We write $X \sim_{\mathbf{syn}} Y$ if and only if there exists an arrow $\eta : v \rightarrow w$ in \mathbf{Syn}_S such that $F_S(v) = X$ and $F_S(w) = Y$. Next suppose that $f : X \rightarrow Y$ and $g : Z \rightarrow T$ are morphisms of \mathcal{C} . Then we write $f \equiv_{\mathbf{syn}} g$ if and only if there exist arrows β and γ in \mathbf{Syn}_S such that $F_S(\beta) \cdot f = g \cdot F_S(\gamma)$. Since \mathbf{Syn}_S is a groupoid, both $\sim_{\mathbf{syn}}, \equiv_{\mathbf{syn}}$ are equivalence relations. Now the following assertions hold.

- (1) Suppose that f_1 and f_2 are morphisms in \mathcal{C} such that $\text{cod}(f_1) \sim_{\mathbf{syn}} \text{dom}(f_2)$. Then there exist $g_1 \equiv_{\mathbf{syn}} f_1$ and $g_2 \equiv_{\mathbf{syn}} f_2$ such that $\text{cod}(g_1) = \text{dom}(g_2)$.
- (2) If $f_1 \equiv_{\mathbf{syn}} g_1$, $f_2 \equiv_{\mathbf{syn}} g_2$ and compositions $f_2 \cdot f_1$, $g_2 \cdot g_1$ exist, then $f_2 \cdot f_1 \equiv_{\mathbf{syn}} g_2 \cdot g_1$.
- (3) If f is a morphism in \mathcal{C} and $X \sim_{\mathbf{syn}} \text{dom}(f)$, $Y \sim_{\mathbf{syn}} \text{cod}(f)$, then there exists a unique morphism $g : X \rightarrow Y$ in \mathcal{C} such that $g \equiv_{\mathbf{syn}} f$.
- (4) If $X_1 \sim_{\mathbf{syn}} X_2$ and $Y_1 \sim_{\mathbf{syn}} Y_2$, then $X_1 \otimes Y_1 \sim_{\mathbf{syn}} X_2 \otimes Y_2$.
- (5) If $f_1 \equiv_{\mathbf{syn}} g_1$ and $f_2 \equiv_{\mathbf{syn}} g_2$, then $f_1 \otimes f_2 \equiv_{\mathbf{syn}} g_1 \otimes g_2$.

Indeed, assertions (1), (4) and (5) hold since \mathbf{Syn}_S is a groupoid and assertions (2), (3) are consequences of Theorem 4.2. Let X be an object of \mathcal{C} and let f be a morphism in \mathcal{C} . Then we denote by $[X]_{\sim_{\text{syn}}}$ and $[f]_{\equiv_{\text{syn}}}$ their equivalence classes. Now we define a category $\mathbf{Strict}(\mathcal{C})$. Its objects are equivalence classes of \sim_{syn} and its morphisms are equivalence classes of \equiv_{syn} . Now if $f : X \rightarrow Y$ is a morphism in \mathcal{C} , then $[f]_{\equiv_{\text{syn}}}$ is in $\text{Mor}_{\mathbf{Strict}(\mathcal{C})}([X]_{\sim_{\text{syn}}}, [Y]_{\sim_{\text{syn}}})$. Suppose that $[f_1]_{\equiv_{\text{syn}}}$ and $[f_2]_{\equiv_{\text{syn}}}$ are morphisms in $\mathbf{Strict}(\mathcal{C})$ such that $[\text{cod}(f_1)]_{\sim_{\text{syn}}} = [\text{dom}(f_2)]_{\sim_{\text{syn}}}$ i.e. they form a composable pair of morphisms in $\mathbf{Strict}(\mathcal{C})$. Then we define

$$[f_2]_{\equiv_{\text{syn}}} \cdot [f_1]_{\equiv_{\text{syn}}} = [g_2 \cdot g_1]_{\equiv_{\text{syn}}}$$

where $g_1 \equiv_{\text{syn}} f_1$, $g_2 \equiv_{\text{syn}} f_2$ and $\text{cod}(g_1) = \text{dom}(g_2)$. This is always possible by (1) and is a well defined operation according to (2). Next the associativity of such defined composition follows from the associativity in \mathcal{C} and identities in $\mathbf{Strict}(\mathcal{C})$ are equivalence classes of identities in \mathcal{C} . Hence $\mathbf{Strict}(\mathcal{C})$ is a category. We also have a functor $F : \mathcal{C} \rightarrow \mathbf{Strict}(\mathcal{C})$ given by $X \mapsto [X]_{\sim_{\text{syn}}}$ for every object X in \mathcal{C} and $f \mapsto [f]_{\equiv_{\text{syn}}}$ for every morphism f in \mathcal{C} . According to (3) functor F is full and faithful. Clearly it is surjective on objects. Next according to (4) and (5) the following are well defined

$$[X]_{\sim_{\text{syn}}} \diamond [Y]_{\sim_{\text{syn}}} = [X \otimes Y]_{\sim_{\text{syn}}}, [f]_{\equiv_{\text{syn}}} \diamond [g]_{\equiv_{\text{syn}}} = [f \otimes g]_{\equiv_{\text{syn}}}$$

and these give rise to a functor $\diamond : \mathbf{Strict}(\mathcal{C}) \times \mathbf{Strict}(\mathcal{C}) \rightarrow \mathbf{Strict}(\mathcal{C})$. Moreover, by construction we derive that $F \cdot F_S$ sends every arrow in \mathbf{Syn}_S to some identity in $\mathbf{Strict}(\mathcal{C})$. This implies that

$$[\alpha_{X,Y,Z}]_{\equiv_{\text{syn}}} : [X]_{\sim_{\text{syn}}} \diamond ([Y]_{\sim_{\text{syn}}} \diamond [Z]_{\sim_{\text{syn}}}) \rightarrow ([X]_{\sim_{\text{syn}}} \diamond [Y]_{\sim_{\text{syn}}}) \diamond [Z]_{\sim_{\text{syn}}}$$

as well as

$$[l_X]_{\equiv_{\text{syn}}} : [I]_{\sim_{\text{syn}}} \diamond [X]_{\sim_{\text{syn}}} \rightarrow [X]_{\sim_{\text{syn}}}, [r_X]_{\equiv_{\text{syn}}} : [X]_{\sim_{\text{syn}}} \diamond [I]_{\sim_{\text{syn}}} \rightarrow [X]_{\sim_{\text{syn}}}$$

are identity morphisms in $\mathbf{Strict}(\mathcal{C})$. Hence $\mathbf{Strict}(\mathcal{C})$ is a strict monoidal category with respect to \diamond and unit $[I]_{\sim_{\text{syn}}}$. By definition of F and $\diamond : \mathbf{Strict}(\mathcal{C}) \times \mathbf{Strict}(\mathcal{C}) \rightarrow \mathbf{Strict}(\mathcal{C})$, we derive that F is a strict monoidal functor. \square

5. SYMMETRIC MONOIDAL CATEGORIES

Definition 5.1. Let \mathcal{C} be a monoidal category. We denote by $(\otimes, \alpha, l, r, I)$ its monoidal structure. Let

$$\gamma_{X,Y} : X \otimes Y \rightarrow Y \otimes X$$

be an isomorphism defined and natural for every pair X, Y of objects in \mathcal{C} . Suppose that

$$\gamma_{Y,X} \cdot \gamma_{X,Y} = 1_{X \otimes Y}$$

for every pair X, Y of objects of \mathcal{C} . Assume also that the diagram

$$\begin{array}{ccc} X \otimes (Y \otimes Z) & \xrightarrow{\alpha_{X,Y,Z}} & (X \otimes Y) \otimes Z \\ \downarrow 1_X \otimes \gamma_{Y,Z} & & \downarrow \gamma_{X,Y} \otimes 1_Z \\ X \otimes (Z \otimes Y) & & (Y \otimes X) \otimes Z \\ \downarrow \alpha_{X,Y,Z} & & \downarrow \alpha_{Y,X,Z}^{-1} \\ (X \otimes Z) \otimes Y & \xrightarrow{\gamma_{X \otimes Z, Y}} & Y \otimes (X \otimes Z) \end{array}$$

is commutative for any objects X, Y, Z in \mathcal{C} and the triangle

$$\begin{array}{ccc}
I \otimes X & \xrightarrow{\gamma_{I,X}} & X \otimes I \\
& \searrow l_X \quad \swarrow r_X & \\
& X &
\end{array}$$

is commutative for every object X in \mathcal{C} . Then we say that $(\mathcal{C}, \otimes, \alpha, l, r, I, \gamma)$ is a *symmetric monoidal category* and γ is called a *symmetry*. Moreover, if α, r, l, γ are identities, then $(\mathcal{C}, \otimes, \alpha, l, r, I, \gamma)$ is called a *strict symmetric monoidal category*.

Let \mathcal{C} be a category. By abuse of language we say that \mathcal{C} is a symmetric monoidal category when we have a certain symmetric monoidal structure on \mathcal{C} in mind. Also when we deal with two or more symmetric monoidal categories we often use the same symbols to denote their symmetries. In each case it should be clear from the context how to distinguish monoidal structures that we consider.

Definition 5.2. Let \mathcal{C} and \mathcal{D} be symmetric monoidal categories. Suppose that (F, τ, ϕ) is a monoidal functor where $F : \mathcal{C} \rightarrow \mathcal{D}$ is the underlying functor. Assume that the following square is commutative for every pair of objects X, Y in \mathcal{C} .

$$\begin{array}{ccc}
F(X \otimes Y) & \xrightarrow{F(\gamma_{X,Y})} & F(Y \otimes X) \\
\tau_{X,Y} \downarrow & & \downarrow \tau_{Y,X} \\
F(X) \otimes F(Y) & \xrightarrow{\gamma_{F(X),F(Y)}} & F(Y) \otimes F(X)
\end{array}$$

Then (F, τ, ϕ) is a *symmetric monoidal functor*.

If \mathcal{C} and \mathcal{D} are symmetric monoidal categories and (F, τ, ϕ) is a symmetric monoidal functor where $F : \mathcal{C} \rightarrow \mathcal{D}$ is the underlying functor, then by the usual abuse of language we say that $F : \mathcal{C} \rightarrow \mathcal{D}$ is a symmetric monoidal functor.

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