Note on

Homological Algebra

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Abstract

This note is on homological algebra with a homotopy-theoretical perspective and aims to introduce a framework for homotopy theory based on the notion of dg-categories. Such a framework, as I know, is a special case of the full general machinery of infinite-category theory and thus should be thought as well-known fact or even common sense.

Contents

§ 1 Homotopy theory for topological spaces

Before going to the main topics of this note, let's take a glance to the homotopy theory. One can refer to either a standard textbook on algebraic topology like [1], or a homotopy-first textbook like [2], or the wonderful textbook [3]. For further reading, refer [4].

1.1 Let $f, g\colon X \to Y$ be two (continues) maps between topological spaces, a **(left) homotopy** $\Phi\colon f \Rightarrow g$ is a commutative diagram (in the category of topological spaces) of the form

$$\begin{tikzcd} X \arrow[d, "{(\mathrm{id},\delta_0)}"'] \arrow[dr, "f"] & \\ X \times I \arrow[r, dashed, "\Phi"] & Y \\ X \arrow[u, "{(\mathrm{id},\delta_1)}"] \arrow[ur, "g"'] & \end{tikzcd}$$

where I is the unit interval $[0,1]$ and δ_0 (resp. δ_1) is the inclusion $\{0\} \hookrightarrow I$ (resp. $\{1\} \hookrightarrow I$). If such a homotopy exists, then we say f and g are **homotopic**, denoted by $f \simeq g$. Let $x_0 \in X$ and $y_0 \in Y$ be base points and suppose f and g preserve the base point. Then Φ is called a **based homotopy** if $\Phi(x_0, t) = y_0$ for all $t \in I$. More generally, let $A \subset X$ and $B \subset Y$ be subspaces and $f|_A = g|_A$ and $f(A) \subset B$. Then Φ is called a **relative homotopy** or **homotopy rel** A if $\Phi(x, t) = f(x)$ for all $x \in A$. To emphasize the base point x_0, or the subspace A, we use the notations $f \simeq_{x_0} g$ or $f \simeq_A g$ to denote that f and g are **based homotopic** or **homotopic rel** A.

The set $\mathrm{Map}(X, Y)$ of all continues maps from X to Y, equipped with the compact-open topology, is called the **mapping space** from X to Y. If X is a good topological space, for instant a locally compact Hausdorff space, then there is a natural bijection

$$\mathrm{Map}(Z \times X, Y) \cong \mathrm{Map}\big(Z, \mathrm{Map}(X, Y)\big),$$

where $Z \times X$ carries the product topology. If this is the case, then the exponential law implies that there is a natural bijection between the set of homotopy classes of maps $X \to Y$ and the set of path-components of $\mathrm{Map}(X, Y)$. This set will be denoted by $[X, Y]$, called the **free homotopy class set**.

Let $A \subset X$ and $B \subset Y$ be subspaces. The **product** of the pairs (X, A) and (Y, B) is the pair $(X \times Y, X \times B \cup A \times Y)$. The subspace $\mathrm{Map}(X, A; Y, B)$ of $\mathrm{Map}(X, Y)$ consists of those maps $f\colon X \to Y$ satisfying $f(A) \subset B$. It is called the **(relative) mapping space** from (X, A) to (Y, B). There is a special subspace of it, which consists of those factoring through B, thus can be identified to $\mathrm{Map}(X,B)$. Again, if (X,A) is good enough, then there is a natural bijection

$$\mathrm{Map}\big(Z\times X, Z\times A\cup C\times X; Y, B\big) \cong \mathrm{Map}\big(Z, C; \mathrm{Map}(X,A;Y,B), \mathrm{Map}(X,B)\big).$$

Let $(Z.C)$ be $(I,\varnothing)$, then we see that if (X,A) is good enough, then there is a natural bijection between the set of relative homotopy classes of maps $(X,A)\to(Y,B)$ and the set of path-components of $\mathrm{Map}(X,A;Y,B)$. This set is denoted by $[X,A;Y,B]$, called the **relative homotopy class set**.

Let (X,x_0) and (Y,y_0) are pointed spaces, i.e. topological spaces with a base point. The subspace $\mathrm{Map}(X,x_0;Y,y_0)$ is simply denoted by $\mathrm{Map}_*(X,Y)$, called the **(based) mapping space**. (In many case, the base point is clear or irrelevant to the discussion, we should simplify our notation by just write X instead of (X,x_0).) If X is good enough, from the previous paragraph, there is a natural bijection between the set of based homotopy classes of based maps $X\to Y$ and the set of path-components of $\mathrm{Map}_*(X,Y)$. This set will be denoted by $[X,Y]_*$, or $\langle X,Y\rangle$, called the **based homotopy class set**. Beside the Cartesian product, there is another *tensor product* of pointed spaces, which is the **smash product** $X\wedge Y$: it is precisely the pointed space obtained from the pair $(X\times Y, X\vee Y)$ by modulo the later, where $X\vee Y$ is the wedge sum. There is a natural base point of $\mathrm{Map}_*(X,Y)$, that is the map $\widetilde{y_0}\colon X\to\{y_0\}$. In the case X is good enough, there is a natural bijection

$$\mathrm{Map}_*(Z\wedge X, Y)\cong \mathrm{Map}_*(Z,\mathrm{Map}_*(X,Y)).$$

1.2 Before going further, notice that the natural objection

$$\mathrm{Map}(X\times I, Y)\cong \mathrm{Map}\big(X,\mathrm{Map}(I,Y)\big)$$

gives another equivalent definition of homotopy: let $f,g\colon X\to Y$ be two maps between topological spaces, a **right homotopy** $\Phi\colon f\Rightarrow g$ is a commutative diagram of the form

$$\begin{tikzcd} & Y \\ X \arrow[ur, "f"] \arrow[r, dashed, "\Phi"] \arrow[dr, "g"'] & \mathrm{Map}(I,Y) \arrow[u, "\mathrm{ev}_0"'] \arrow[d, "\mathrm{ev}_1"] \\ & Y \end{tikzcd}$$

where ev_0 (resp. ev_1) is the evaluation at $0\in I$ (resp. $1\in I$).

1.3 One can also define the notion of based homotopy using pure diagrammatic language. Write Y_+ for the pointed space obtained as the union of Y and a disjoint base point $*$. Note that if X is a pointed space, then $X\wedge Y_+$

can be identified with the one obtained from the pair $(X \times Y, \{*\} \times Y)$ and $\mathrm{Map}_*(Y_+, X)$ can be identified as $\mathrm{Map}(Y, X)$ specified the base point to be the map collapsing to the base point of X. Let $f, g\colon X \to Y$ be two based maps between pointed spaces. A **based homotopy** $\Phi\colon f \Rightarrow g$ can be defined as a commutative diagram of the form

$$\begin{tikzcd} X \arrow[d, "\mathrm{id} \wedge \delta_0"'] \arrow[dr, "f"] & \\ X \wedge I_+ \arrow[r, dashed, "\Phi"] & Y \\ X \arrow[u, "\mathrm{id} \wedge \delta_1"] \arrow[ur, "g"'] & \end{tikzcd}$$

where inclusions δ_i are viewed as $\{i\}_+ \hookrightarrow I_+$. Using the natural bijection for pointed spaces, a **based right homotopy** can be defined as the same commutative diagram for right homotopy with additional requirement that all maps involved must be based.

Remark The functor $Y \mapsto Y_+$ is in fact the left adjoint of the forgetful functor from **Top** to $\mathbf{Top}_*$, the category of pointed spaces with based maps.

1.4 The topological spaces with continuous maps form a category **Top**. However, this category lost informations since it ignores the topologies on the mapping spaces. A better category is the one obtained by replacing every mapping space by the corresponding homotopy class set[1]. This can be done since homotopy respect the composition of maps. The result category is called **the homotopy category** $\mathcal{H}$. Two topological spaces are said to be **(strong) homotopy equivalent** if they are isomorphic in $\mathcal{H}$.

Similar discussion apply to relative and pointed spaces.

1.5 Let (X, x_0) be a pointed space. Then a **(based) loop** on (X, x_0) is a base-point-preserving map from $(S^1, *)$, where $*$ is a fixed base point of S^1, to it. $\mathrm{Map}_*(S^1, X)$ is called the **loop space** on it, denoted by $\Omega(X, x_0)$ or simply ΩX. There is a natural "multiplication" on this space: any two such loops can be concatenated to obtain a third loop. Although this "multiplication" is not associative, it does induce an associative multiplication on the quotient set $\pi_1(X, x_0)$ of it by modulo the based homotopies. The set $\pi_1(X, x_0)$ then carries a group structure and is called the **fundamental group** of (X, x_0).

Similarly, one can define the **n-th homotopy group** as $\pi_n(X, x_0) = [S^n, X]_*$ with the addition induced by $c\colon S^n \to S^n \vee S^n$ where c collapses a

[1] There is an issue that the notion of homotopy class sets, although can be defined for arbitrary topological spaces, does not behave well unless the topological space is good enough. Therefore, it is better to work on a subcategory of **Top** consisting of *good topological spaces*, or on a *convenient category of topological spaces* instead of **Top**. For the purpose of this note, we ignore this issue.

equator S^{n-1} (containing the base point) in S^n to the base point. As the notation suggests, $\pi_0(X, x_0)$ should be $[S^0, X]_*$, where S^0 is the 0-sphere, i.e. the set of two points with one of them being the base point. Note that there is no natural group structure on it anymore. Since S^0 is merely a set of two points and one of them must be mapped to x_0, the space $\mathrm{Map}_*(S^0, X)$ is homeomorphic to $\mathrm{Map}(\mathrm{pt}, X)$ and hence X itself. Thus $\pi_0(X, x_0)$ actually has nothing to do with x_0 and is precisely the set of path-components of X.

Note that for (X, A) a pair of space and subspace and (Y, y_0) a pointed space, there is a canonical bijection $[X, A; Y, y_0] \cong [X/A, [A]; Y, y_0]$. Thus the n-the homotopy group can also be defined as $[I^n, \partial I^n; X, x_0]$ with the addition induced by concatenation (there are n different ways to do this, but by the *Eckmann-Hilton argument*, they all give the same commutative binary operation on the homotopy class set). This characterization is easier to compute.

1.6 Note that we have a natural bijection

$$\mathrm{Map}_*(X \wedge S^1, Y) \cong \mathrm{Map}_*(X, \Omega Y)$$

for any pointed spaces X and Y. Let ΣX denote the pointed space $X \wedge S^1$. It is called the **suspension** of X. From this we get

$$\pi_n(X) = [\Sigma^n S^0, X]_* = \pi_0(\Omega^n X).$$

1.7 We can always view the loop space $\Omega(X, x_0)$ as a subspace of $\mathrm{Map}(I, X)$ by identify it as $\mathrm{Map}(I, \partial I; X, x_0)$. Note that there are two canonical maps from $\mathrm{Map}(I, X)$ to X: one maps $f\colon I \to X$ to $f(0)$, another to $f(1)$. If we ignore the issue that concatenation is not strict associative, those data defines a *topological groupoid*. To fix this issue, we can consider $[I, X]$ instead of $\mathrm{Map}(I, X)$. Then the result construction is a *groupoid*, called the **fundamental groupoid** of X and denoted by $\Pi_1(X)$. If X is good enough (locally path-connected and locally simply-connected), then $[I, X]$ has a natural topology on it and $\Pi_1(X)$ becomes a *topological groupoid*.

In any case, using those two maps, we obtain a bundle $[I, X] \to X \times X$ whose fiber at any point (x_0, x_0) in the diagonal is precisely $\pi_1(X, x_0)$. Thus, if we pullback it along the diagonal map $\Delta\colon X \to X \times X$, we obtain a bundle above X, or equivalently a sheaf on X. This is another realization of the notion of *fundamental groupoid*.

It is clear that the fundamental groupoid $\Pi_1(X)$ encodes the information of homotopies between points, i.e. paths connecting them, and is essentially (up to equivalences of categories) determined by $\pi_0(X)$ and $\pi_1(X, x_0)$ with x_0 go through a presenting system of $\pi_0(X)$.

1.8 Then one may try to obtain a higher analogy of fundamental groupoids. That is a *functorial* construction $\Pi(X)$ for each topological space X, which encodes the information of not only homotopies between points, but homotopies between homotopies, homotopies between those between homotopies and so on. Moreover, $\Pi(X)$ must be essentially determined by $\pi_0(X)$ and $\pi_n(X, x_0)$ for all n with x_0 go through a presenting system of $\pi_0(X)$. This object is called the **homotopy type** or **fundamental ∞-groupoid** of X.

The later terminology suggests it should be an ∞-groupoid, i.e. an ∞-category with all morphisms invertible. Ideally, for a given topological space X, its points should be the objects of $\Pi(X)$, homotopies between them should be 1-morphisms of $\Pi(X)$, homotopies between 1-morphisms should be 2-morphisms and so on. Conversely, there is a requirement of ∞-category theory called the **homotopy hypothesis**, which states that the ∞-category of ∞-groupoid is equivalent (in the sense of ∞-category theory) to the ∞-category of homotopy types.

A naïve approach is just define an ∞-groupoid as a topological space and an ∞-category as a category enriched over $\mathcal{H}$. However, this does not work due to the reason below.

1.9 Let $f\colon X \to Y$ be a map between topological spaces. We can view it as a based map by choosing a base point x_0 of X. Then, by composing with f, we obtain natural maps $\mathrm{Map}_*(S^n, X) \to \mathrm{Map}_*(S^n, Y)$ and hence homomorphisms $f_*\colon \pi_n(X) \to \pi_n(Y)$ for all n. f is called a **weak homotopy equivalence** if f_* is an isomorphism for all n and all choices of base point. Two topological spaces are said to be **weak homotopy equivalent**, or have the same **(weak) homotopy type** if there is a zigzag of weak homotopy equivalences between them. By the homotopy hypothesis, if $f\colon X \to Y$ is weak homotopy equivalence, then the induces morphism $f_*\colon \Pi(X) \to \Pi(Y)$ must be an equivalent of ∞-groupoid, or an isomorphism in $\mathcal{H}$.

It is not difficult to show that homotopy equivalences are weak homotopy equivalences. However, the converse is not true. Therefore to get the correct ∞-category theory, the homotopy category $\mathcal{H}$ should be modified such that two topological spaces are weak homotopy equivalent if and only if they are isomorphic in $\mathcal{H}$.

One way to do this is to restrict $\mathcal{H}$ to a suitable subcategory such that:

1) in this subcategory, every weak homotopy equivalence becomes an isomorphism;

2) every topological space is weak homotopy equivalent to an object in this subcategory.

1.10 There is a special class of topological spaces called **CW complexes**. For which we have

Whitehead theorem Every weak homotopy equivalence between CW complexes is a strong homotopy equivalence.

CW approximation Every topological space admits a weak homotopy equivalence from a CW complex to it.

Cellular approximation Every maps of CW complexes is homotopic to a cellular map, i.e. preserving the skeletons.

Thus, a good modification of $\mathcal{H}$ is to restrict it to the subcategory of CW complexes.

With this modification, we can built an ∞-category theory satisfying the homotopy hypothesis. To summary[2]:

- **The homotopy category** $\mathcal{H}$ is the category of CW complexes whose morphisms are homotopy classes of maps between CW complexes. Furthermore, such a morphism can be presented by a cellular map.
- Hence, an **∞-groupoid** is a CW complex and an **∞-category** is a category enriched over $\mathcal{H}$. This definition gives naturally a notion of **homotopy category** of an ∞-category, which is the plain category obtained by apply the *change of base categories* $\pi_0 \colon \mathcal{H} \to \mathbf{Set}$.
- The **fundamental ∞-groupoid** of a topological space is then the CW approximation of it.

The above version of ∞-category theory provided a good framework to study homotopy theory and has the advantage that it is pretty geometric. However, it also has some disadvantages: it is not algebraic enough for general application and the constructions in CW complex theory involves cumbersome and irrelevant choices. Another well-developed ∞-category theory can be find in [5]. An axiomatic approach to ∞-category theory can be find in a book in progress [6].

1.11 Leaving the general ∞-category theory aside, let's return to the homotopy theory of topological spaces. First of first, the category **Top** of topological spaces now can be viewed as an ∞-category. Note that, in our setting, the **Hom space** from X to Y is not $\mathrm{Map}(X, Y)$, but its CW approximation. Let's denote it by $\mathcal{H}om(X, Y)$.

1.12 A significant feature of ∞-category theory is it admits **homotopy limits** and **homotopy colimits**. To see the difference between those notions and *limits/colimits*, let's consider a simple diagram: $\bullet \to \bullet$. A digram of this shape in **Top** is just a continuous map $f \colon X \to Y$. It is easy to see that the limit (resp. colimit) of it is just X (resp. Y).

However, when consider homotopy limit of it, one looks at the category of *homotopy triangle above* f. An object of this category is a space T (called

[2] But there is still some pathological issue in this framework. A really correct definition needs to replace **Top** by a convenient category of topological spaces.

the *vertex*) together with a triangle

$$\begin{tikzcd} T \arrow[d] \arrow[dr] & \\ X \arrow[r, "f"'] \arrow[ur, phantom, "\Leftarrow"] & Y \end{tikzcd}$$

where the bold arrow denoted a homotopy. If $S \to T$ is a continuous map, then by composing it with a homotopy triangle above f with vertex T, we obtain a homotopy triangle above f with vertex S. A *morphism* between homotopy triangles is such a continuous map. Then the *homotopy limit* of the diagram $X \xrightarrow{f} Y$ is the terminal object in this category.

To spell out the homotopy limit, we translate the homotopy triangles into usual commutative diagrams

$$\begin{tikzcd} & Y \\ T \arrow[ur] \arrow[r] \arrow[d] & \mathrm{Map}(I, Y) \arrow[u, "\mathrm{ev}_0"'] \arrow[d, "\mathrm{ev}_1"] \\ X \arrow[r, "f"] & Y \end{tikzcd}$$

which is equivalent to the following diagram.

$$\begin{tikzcd} T \arrow[r] \arrow[d] & \mathrm{Map}(I, Y) \arrow[d, "\mathrm{ev}_1"] \\ X \arrow[r, "f"] & Y \end{tikzcd}$$

Therefore, the homotopy limit of the diagram $X \xrightarrow{f} Y$ is the pullback of $\mathrm{ev}_1 \colon \mathrm{Map}(I, Y) \to Y$ along f. More concretely, it is the space

$$Nf := \big\{(x, \gamma) \in X \times \mathrm{Map}(I, Y) : f(x) = \gamma(1)\big\}$$

equipped with the subspace topology. This space is called the **mapping path space** of f. It is clear that Nf is not homeomorphic to X in general. However, they are homotopy equivalent.

The similar story happens to the dual situation, where the homotopy triangle is eventually translated into the following diagram.

$$\begin{tikzcd} X \arrow[r, "f"] \arrow[d, "\delta_0"'] & Y \arrow[d] \\ X \times I \arrow[r] & T \end{tikzcd}$$

Therefore, the homotopy colimit of the diagram $X \xrightarrow{f} Y$ is the pushout of $\delta_0 \colon X \to X \times I$ along f. More concretely, it is the quotient space

$$\mathrm{Cly}(f) := X \times I \coprod Y / \sim,$$

where $\sim$ is generated by $(x, 0) \sim f(x)$. This space is called the **mapping cylinder** of f. It is clear that $\mathrm{Cly}(f)$ is not homeomorphic to X in general. However, they are homotopy equivalent.

Remark Note that in the above diagrams, one can invert the orientation of I, i.e. switch ev_0 and ev_1 (resp. δ_0 and δ_1), while the resulting space is homeomorphic to the one defined there.

1.13 However, the *homotopy limits/colimits* are even not limits/colimits in the homotopy category. To see this, let's consider the diagram $\bullet \to \bullet \leftarrow \bullet$. A diagram of this shape in **Top** is a pair of continuous maps $X \xrightarrow{f} Y \xleftarrow{g} Z$. Then a *homotopy square to* it is such a diagram

$$\begin{tikzcd}
T \arrow[r] \arrow[d] & Z \arrow[d, "g"] \arrow[dl, Rightarrow, dashed] \\
X \arrow[r, "f"'] & Y
\end{tikzcd}$$

where the dashed arrow denote a homotopy. Such a homotopy diagram is equivalent to the following commutative diagram.

$$\begin{tikzcd}
Z \arrow[r, "g"] & Y \\
T \arrow[u] \arrow[r] \arrow[d] & \mathrm{Map}(I, Y) \arrow[u, "\mathrm{ev}_0"'] \arrow[d, "\mathrm{ev}_1"] \\
X \arrow[r, "f"] & Y
\end{tikzcd}$$

Hence, the homotopy limit of the diagram $X \xrightarrow{f} Y \xleftarrow{g} Z$ is the fiber product of Nf and Ng over $\mathrm{Map}(I, Y)$, that is the space

$$X \times_Y^h Z := \big\{(x, \gamma, z) \in X \times \mathrm{Map}(I, Y) \times Z : f(x) = \gamma(1), g(z) = \gamma(0)\big\}.$$

This space is called the **homotopy fiber product**, or the **homotopy pullback** of g along f.

Dually, one can consider the digram $X \xleftarrow{f} Y \xrightarrow{g} Z$ and the homotopy colimit of it is the fiber coproduct of $\mathrm{Cly}(f)$ and $\mathrm{Cly}(g)$ under $Y \times I$, which is the quotient space

$$X \amalg_Y^h Z := X \coprod (Y \times I) \coprod Z / \sim,$$

where $\sim$ is generated by $f(y) \sim (y, 0)$ and $(y, 1) \sim g(y)$. This is called the **homotopy fiber coproduct**. the **homotopy pushout** of f along g.

1.14 Now, let's consider a special case of previous constructions: where Z is the singleton pt. In this case, we can identify $X \times_Y^h \mathrm{pt}$ with the space

$$\mathrm{Fib}(f) := \{(x, \gamma) \in X \times \mathrm{Map}(I, Y) : f(x) = \gamma(1), \gamma(0) = *\},$$

where $*$ is the image of pt in Y. This space is called the **homotopy fiber** of f at the point $* \in Y$. We can identify $X \amalg_Y^h \mathrm{pt}$ as the quotient space

$$\mathrm{Cofib}(f) := X \coprod (Y \times I)/\sim,$$

where $\sim$ is generated by $f(y) \sim (y, 0)$ and $(y, 1) \sim (y', 1)$. This space is called the **homotopy cofiber** of f, or the **mapping cone** of f with notation Cf.

1.15 Let's consider a even more special case: both X and Z are singleton pt and mapping to the same point $*$ of Y. In this case, we can surprisingly identify $\mathrm{pt} \times_Y^h \mathrm{pt}$ with the loop space ΩY by viewing Y as the pointed space with the base point $*$. It is clear that the loop space of a topological space is in general not contractible.

Besides, we can identify $\mathrm{pt} \amalg_Y^h \mathrm{pt}$ as the quotient space

$$SY := Y \times I/\sim,$$

where $\sim$ is generated by $(y, i) \sim (y', i)$ for $i = 0, 1$. This space is called the **unreduced suspension** of Y. Let $Y = S^1$, it is clear that $SS^1 = S^2$, which is not contractible. Note that if Y is pointed as a base point $*$, then SY admits a distinguish subspace $\{*\} \times I$ and the quotient by modulo this subspace is the pointed space ΣY.

1.16 Recall that if $D \colon \mathcal{I} \to \mathcal{C}$ is a diagram in a category $\mathcal{C}$, then there are natural isomorphisms of sets

$$\begin{aligned} \mathrm{Hom}_{\mathcal{C}}(-, \lim D) &\cong \lim \mathrm{Hom}_{\mathcal{C}}(-, D), \\ \mathrm{Hom}_{\mathcal{C}}(\mathrm{colim}\, D, -) &\cong \lim \mathrm{Hom}_{\mathcal{C}}(D, -). \end{aligned}$$

Analogously, if $D \colon \mathcal{I} \to \mathcal{C}$ is a diagram in a ∞-category $\mathcal{C}$, then there should be natural equivalences of (functors to) ∞-groupoids[3]

$$\begin{aligned} \mathcal{H}om_{\mathcal{C}}(-, \mathrm{holim}\, D) &\simeq \mathrm{holim}\, \mathcal{H}om_{\mathcal{C}}(-, D), \\ \mathcal{H}om_{\mathcal{C}}(\mathrm{hocolim}\, D, -) &\simeq \mathrm{holim}\, \mathcal{H}om_{\mathcal{C}}(D, -). \end{aligned}$$

Therefore, since we have worked out the homotopy limits/colimits of previous diagrams, we can make the following definitions in an arbitrary ∞-category $\mathcal{C}$.

[3] However, the right-hand side is not a CW complex in general. Hence one needs to replace it by its CW approximation and makes the statements meaningful only for weak homotopy equivalences. Consequently, the notions of homotopy limits/colimits make sense only up to weak homotopy equivalences.

- Let $f\colon X \to Y$ be a morphism in $\mathcal{C}$. Then a **mapping path object** is an object Nf inducing a natural equivalence of ∞-groupoids

$$\mathcal{H}om_{\mathcal{C}}(T, Nf) \simeq N\,\mathcal{H}om_{\mathcal{C}}(T, f),$$

  where the continuous map $\mathcal{H}om_{\mathcal{C}}(T,f)\colon\ \mathcal{H}om_{\mathcal{C}}(T,X) \to \mathcal{H}om_{\mathcal{C}}(T,Y)$ is given by composing with f, for each object T of $\mathcal{C}$. Dually, a **mapping cylinder object** is an object $\mathrm{Cly}(f)$ inducing a natural equivalence of ∞-groupoids

$$\mathcal{H}om_{\mathcal{C}}\big(\mathrm{Cly}(f), T\big) \simeq P\,\mathcal{H}om_{\mathcal{C}}(f, T)$$

  for each object T of $\mathcal{C}$.

- Let $X \xrightarrow{f} Y \xleftarrow{g} Z$ be two morphisms in $\mathcal{C}$. Then a **homotopy fiber product** is a object $X \times^h_Y Z$ inducing a natural equivalence of ∞-groupoids

$$\mathcal{H}om_{\mathcal{C}}(T, X \times^h_Y Z) \simeq \mathcal{H}om_{\mathcal{C}}(T, X) \times^h_{\mathcal{H}om_{\mathcal{C}}(T,Y)} \mathcal{H}om_{\mathcal{C}}(T, Z),$$

  where the right-hand side is obtained from the diagram

$$\mathcal{H}om_{\mathcal{C}}(T, X) \xrightarrow{f_*} \mathcal{H}om_{\mathcal{C}}(T, Y) \xleftarrow{g_*} \mathcal{H}om_{\mathcal{C}}(T, Z),$$

  for each object T of $\mathcal{C}$.

- As special cases of previous, we have the notions of **homotopy fiber** and **loop space object** (also called **looping**) in $\mathcal{C}$.

- Let $X \xleftarrow{f} Y \xrightarrow{g} Z$ be two morphisms in $\mathcal{C}$. Then a **homotopy fiber coproduct** is a object $X \amalg^h_Y Z$ inducing a natural equivalence of ∞-groupoids

$$\mathcal{H}om_{\mathcal{C}}(X \amalg^h_Y Z, T) \simeq \mathcal{H}om_{\mathcal{C}}(X, T) \times^h_{\mathcal{H}om_{\mathcal{C}}(Y,T)} \mathcal{H}om_{\mathcal{C}}(Z, T),$$

  where the right-hand side is obtained from the diagram

$$\mathcal{H}om_{\mathcal{C}}(X, T) \xrightarrow{f^*} \mathcal{H}om_{\mathcal{C}}(Y, T) \xleftarrow{g^*} \mathcal{H}om_{\mathcal{C}}(Z, T),$$

  for each object T of $\mathcal{C}$.

- As special cases of previous, we have the notions of **homotopy cofiber** and **suspension object** in $\mathcal{C}$.

1.17 Apply the previous to the ∞-category $\mathbf{Top}_*$, we obtain the following constructions.

- The **mapping path space** of a based map $f\colon (X,x_0)\to(Y,y_0)$ is the same space as Nf with the base point $(x_0,\widetilde{y_0})$, where $\widetilde{y_0}$ is the constant path at y_0.
- The **(reduced) mapping cylinder** of a based map $f\colon (X,x_0)\to(Y,y_0)$ is the quotient space

$$\mathrm{Cly}(f) := X\times I\coprod Y/\sim,$$

where $\sim$ is generated by $(x,0)\sim f(x)$ and $(x_0,t)\sim(x_0,t')$, with the base point the class of $(x_0,0)$.

- The **homotopy fiber product** of a pair of based maps $(X,x_0)\xrightarrow{f}(Y,y_0)\xleftarrow{g}(Z,z_0)$ is the same space as $X\times^h_Y Z$ with the base point $(x_0,\widetilde{y_0},z_0)$.
- In particular, the **homotopy fiber** of a based map $f\colon (X,x_0)\to(Y,y_0)$ is the same space as $\mathrm{Fib}(f)$ with the base point $(x_0,\widetilde{y_0})$.
- In particular, the **looping** of pointed space (X,x_0) is the loop space ΩX with the based point the constant loop at x_0.
- The **(reduced) homotopy fiber coproduct** of based maps $(X,x_0)\xleftarrow{f}(Y,y_0)\xrightarrow{g}(Z,z_0)$ is the quotient space

$$X\amalg^h_Y Z := X\coprod(Y\times I)\coprod Z/\sim,$$

where $\sim$ is generated by $f(y)\sim(y,0)$, $(y,1)\sim g(y)$ and $(y_0,t)\sim(y_0,t')$, with the base point the class of (y_0,t).

- In particular, the **(reduced) homotopy cofiber** of a based map $f\colon (X,x_0)\to(Y,y_0)$ is the quotient space

$$\mathrm{Cofib}(f) := X\coprod(Y\times I)/\sim,$$

where $\sim$ is generated by $f(y)\sim(y,0)$, $(y,1)\sim(y',1)$ and $(y_0,t)\sim(y_0,t')$, with the base point the class of (y_0,t).

- In particular, the **(reduced) suspension** of pointed space (X,x_0) is the suspension ΣX.

1.18 Let $f\colon X\to Y$ be a map between topological spaces. The preimage $f^{-1}(y_0)$ of $y_0\in Y$ is called the **fiber** of X at the point y_0. Viewing f as a based map by specifying y_0 as the base point of Y, the notion of fiber is similar to the notion of kernel: let $f\colon A\to B$ be a homomorphism between abelian groups, then the kernel is the preimage $f^{-1}(0)$.

Note that in the category of pointed spaces, the singleton pt is both an initial and terminal object, hence is a *zero object*. Let $\mathcal{C}$ be a category having pullbacks and a zero object $\mathbf{0}$. For $f\colon A \to B$ a morphism in $\mathcal{C}$, its **kernel** is the pullback of the zero morphism $\mathbf{0} \to B$ along f.

$$\begin{tikzcd} \mathrm{Ker}(f) \arrow[r] \arrow[d] & \mathbf{0} \arrow[d] \\ A \arrow[r, "f"] & B \end{tikzcd}$$

Dually, if $\mathcal{C}$ has pushouts, the **cokernel** of f is the pushout of the zero morphism $A \to \mathbf{0}$ along f.

$$\begin{tikzcd} A \arrow[r, "f"] \arrow[d] & B \arrow[d] \\ \mathbf{0} \arrow[r] & \mathrm{Coker}(f) \end{tikzcd}$$

A sequence $A \xrightarrow{f} B \xrightarrow{g} C$ is called a **left exact sequence** if A is the kernel of g, a **right exact sequence** if C is the cokernel of f and a **short exact sequence** if both of previous are true.

In the category of pointed sets, or pointed spaces, we further have the notion of *exact sequence*: a sequence $X \xrightarrow{f} Y \xrightarrow{g} Z$ is said to be **exact** at Y if $\mathrm{im}(f) = \ker(g)$.

1.19 Let $\mathcal{C}$ be a category with terminal object pt. Then the category under pt has a zero object pt $\to$ pt. This category is denoted by $\mathcal{C}_*$. An object $x_0\colon \mathrm{pt} \to X$ in $\mathcal{C}_*$ is called a **pointed object** in $\mathcal{C}$, viewed as an object X in $\mathcal{C}$ with the **base point** x_0. A morphism in $\mathcal{C}_*$ is called a **based morphism**.

Suppose $\mathcal{C}$ has limits and colimits. Then we have the followings.

- The forgetful functor sending each pointed object (X, x_0) to X has a left adjoint $+\colon \mathcal{C} \to \mathcal{C}_*$ sending each object X to the pointed object $(X_+, *)$, where X_+ is the coproduct of X and pt and $*$ is the morphism $\mathrm{pt} \to X \amalg \mathrm{pt}$.

- Therefore the limits of pointed objects can be computed in the category $\mathcal{C}$: it is precisely the limit together with the unique morphism obtained from the base points by the universal property.

- Secondly, the colimits of pointed objects are obtained by apply the functor $+$ to the colimits of their underlying objects.

- The coproduct of two pointed objects X, Y is called the **wedge sum** of them, denoted by $X \vee Y$. Clearly, there is canonical morphism $X \times Y \to X \vee Y$. The cokernel of this morphism is called the **smash product** and denoted by $X \wedge Y$.

Suppose $\mathcal{C}$ is further *Cartesian closed*, i.e. the functor $X \times -$ has a right adjoint $[X, -]$.

- Then the smash product gives $\mathcal{C}_*$ a closed symmetric monoidal structure: the unit is pt_+ and the internal Hom object $[X, Y]_*$ is obtained as the pullback of the morphism $\mathrm{pt} \to [\mathrm{pt}, Y]$ along $[X, Y] \to [\mathrm{pt}, Y]$ with the base point obtained from the morphism $\mathrm{pt} \to [X, Y]$ whose adjunct is the composition $\mathrm{pt} \times X \to \mathrm{pt} \to Y$

1.20 Now, let $\mathcal{C}$ be a ∞-category having terminal object pt. Then we can define the ∞-category $\mathcal{C}_*$ of pointed objects as previous. Suppose $\mathcal{C}$ has homotopy pullbacks and homotopy pushouts. A sequence $X \xrightarrow{f} Y \xrightarrow{g} Z$ of is called a **fibration sequence** if X is a homotopy fiber of g and a **cofibration sequence** if Z is a homotopy cofiber of f. Unlike left/right exact sequences, fibration/cofibration sequences are automatically long.

Indeed, let $f\colon X \to Y$ be a based morphism of pointed objects in $\mathcal{C}$. Then, we have the fibration sequence

$$\mathrm{Fib}(f) \xrightarrow{i} X \xrightarrow{f} Y.$$

Consider the *reversed* homotopy fiber $\bar{\mathrm{Fib}}(i)$ of i. To see what does this means and why we need this, look at the following diagram

$$\begin{tikzcd}
\bar{\mathrm{Fib}}(i) \arrow[r] \arrow[d] & \mathrm{Fib}(f) \arrow[r] \arrow[d, "i"'] \arrow[dl, Rightarrow, dashed] & \mathrm{pt} \arrow[d] \arrow[dl, Rightarrow, dashed] \\
\mathrm{pt} \arrow[r] & X \arrow[r, "f"] & Y
\end{tikzcd}$$

where the right square exhibits $\mathrm{Fib}(f)$ as the homotopy fiber of f while the left square, instead of exhibiting $\bar{\mathrm{Fib}}(i)$ as the homotopy fiber of i which is the homotopy pullback of $\mathrm{pt} \to X$ along i, exhibits $\bar{\mathrm{Fib}}(i)$ as the homotopy pullback of i along $\mathrm{pt} \to X$. Note that, by pasting the two squares, the rectangle becomes a homotopy square and exhibits $\bar{\mathrm{Fib}}(i)$ as the homotopy pullback of $\mathrm{pt} \to Y$ along itself, i.e. the *loop space object* ΩY. Note that, by our construction, the reversed homotopy fiber and the homotopy fiber are canonically isomorphic[4]. Therefore we have anther fibration sequence

$$\Omega Y \longrightarrow \mathrm{Fib}(f) \xrightarrow{i} X.$$

[4] In fact, since the notions of homotopy limits only make sense up to weak homotopy equivalences, the statement here is literally wrong. However, it is true that the constructions of reversed homotopy fiber (which is given by just invert I in the construction of the homotopy fiber) and the homotopy fiber given in **Top** and $\mathbf{Top}_*$ are canonically homeomorphic.

If we keep going, obtaining the following diagram

$$
\begin{tikzcd}
\Omega X \arrow[r] \arrow[d, "-\Omega f"'] & \mathrm{pt} \arrow[d] \arrow[dl, Rightarrow, dashed] & \\
\Omega Y \arrow[r] \arrow[d] & \mathrm{Fib}(f) \arrow[r] \arrow[d, "i"'] \arrow[dl, Rightarrow, dashed] & \mathrm{pt} \arrow[d] \arrow[dl, Rightarrow, dashed] \\
\mathrm{pt} \arrow[r] & X \arrow[r, "f"] & Y
\end{tikzcd}
$$

where the $-\Omega f$ denotes the *reversed* loop morphism. The reversion appear due to the reversed homotopy in the left-below square.

Therefore, if we have a fibration sequence $X \xrightarrow{f} Y \xrightarrow{g} Z$, then we have a *long fibration sequence*

$$\cdots \longrightarrow \Omega X \xrightarrow{-\Omega f} \Omega Y \xrightarrow{-\Omega g} \Omega Z \longrightarrow X \xrightarrow{f} Y \xrightarrow{g} Z.$$

The similar story applies to cofibration sequences. If we have a cofibration sequence $X \xrightarrow{f} Y \xrightarrow{g} Z$, then we have a *long cofibration sequence*

$$X \xrightarrow{f} Y \xrightarrow{g} Z \longrightarrow \Sigma X \xrightarrow{-\Sigma f} \Sigma Y \xrightarrow{-\Sigma g} \Sigma Z \longrightarrow \cdots .$$

1.21 Let $f\colon X \to Y$ be a morphism in $\mathcal{C}_*$. The adjunction of Σ and Ω gives rise to the following commutative diagram.

$$
\begin{tikzcd}
 & \Sigma\Omega\mathrm{Fib}(f) \arrow[r] \arrow[d] & \Sigma\Omega X \arrow[r] \arrow[d] & \Sigma\Omega Y \arrow[r] \arrow[d] & \Sigma\Omega\mathrm{Cofib}(f) \arrow[r] \arrow[d] & \Sigma\Omega\Sigma X \arrow[d] \\
\Omega Y \arrow[r] \arrow[d] & \mathrm{Fib}(f) \arrow[r] \arrow[d] & X \arrow[r] \arrow[d] & Y \arrow[r] \arrow[d] & \mathrm{Cofib}(f) \arrow[r] \arrow[d] & \Sigma X \\
\Omega\Sigma\Omega Y \arrow[r] & \Omega\Sigma\mathrm{Fib}(f) \arrow[r] & \Omega\Sigma X \arrow[r] & \Omega\Sigma Y \arrow[r] & \Omega\Sigma\mathrm{Cofib}(f) &
\end{tikzcd}
$$

Considering the following homotopy commutative diagram:

$$
\begin{tikzcd}
\mathrm{Fib}(f) \arrow[r] \arrow[d] & \mathrm{pt} \arrow[d] \arrow[dl, Rightarrow, dashed] \\
X \arrow[r] \arrow[d] & Y \arrow[d] \arrow[dl, Rightarrow, dashed] \\
\mathrm{pt} \arrow[r] & \mathrm{Cofib}(f)
\end{tikzcd}
$$

one see that there are homotopy equivalence:

$$\mathrm{Fib}(f) \xrightarrow{\sim} \Omega\mathrm{Cofib}(f), \qquad \Sigma\mathrm{Fib}(f) \xrightarrow{\sim} \mathrm{Cofib}(f).$$

Together with the triangle identities for the $\Sigma \dashv \Omega$, we obtain the following commutative diagram

$$\begin{tikzcd}
& \Sigma\Omega\mathrm{Fib}(f) \arrow[r] \arrow[d] & \Sigma\Omega X \arrow[r] \arrow[d] & \Sigma\Omega Y \arrow[r] \arrow[d] & \Sigma\mathrm{Fib}(f) \arrow[r] \arrow[d] & \Sigma X \arrow[d, equal] \\
\Omega Y \arrow[r] \arrow[d, equal] & \mathrm{Fib}(f) \arrow[r] \arrow[d] & X \arrow[r] \arrow[d] & Y \arrow[r] \arrow[d] & \mathrm{Cofib}(f) \arrow[r] \arrow[d] & \Sigma X \\
\Omega Y \arrow[r] & \Omega\mathrm{Cofib}(f) \arrow[r] & \Omega\Sigma X \arrow[r] & \Omega\Sigma Y \arrow[r] & \Omega\Sigma\mathrm{Cofib}(f) &
\end{tikzcd}$$

where the top row is the suspension of a fiber sequence and the bottom row is the looping of a cofiber sequence.

1.22 It turns out that the functor $[Z,-]_*\colon \mathbf{Top}_* \to \mathbf{Set}_*$ is left exact for any pointed space Z. In particular, π_0 is left exact. So, if we have a fiber sequence of pointed spaces

$$\cdots \longrightarrow \Omega^2 Z \longrightarrow \Omega X \xrightarrow{-\Omega f} \Omega Y \xrightarrow{-\Omega g} \Omega Z \longrightarrow X \xrightarrow{f} Y \xrightarrow{g} Z.$$

Notice that $\pi_0(\Omega^n X) = \pi_n(X)$. Then we get a long exact sequence of pointed sets

$$\begin{aligned}\cdots \longrightarrow \pi_2(X) \xrightarrow{f_*} \pi_2(Y) \xrightarrow{g_*} \pi_2(Z) \longrightarrow& \\ \pi_1(X) \xrightarrow{f_*} \pi_1(Y) \xrightarrow{g_*} \pi_1(Z) \longrightarrow \pi_0(X) &\xrightarrow{f_*} \pi_0(Y) \xrightarrow{g_*} \pi_0(Z).\end{aligned}$$

Moreover, since π_0 is left exact, the above maps preserve group structures if there exists one.

For $\mathcal{C}$ an ∞-category and C any object in $\mathcal{C}_*$, the functor $\mathcal{H}om_{\mathcal{C}_*}(C,-)$ is left exact, i.e. preserves homotopy limits. Hence, if we have a fiber sequence of pointed objects

$$\cdots \longrightarrow \Omega^2 Z \longrightarrow \Omega X \xrightarrow{-\Omega f} \Omega Y \xrightarrow{-\Omega g} \Omega Z \longrightarrow X \xrightarrow{f} Y \xrightarrow{g} Z.$$

Then we get a fiber sequence of pointed spaces

$$\begin{aligned}&\cdots \longrightarrow \mathcal{H}om_{\mathcal{C}_*}(C,\Omega^2 Z) \longrightarrow \mathcal{H}om_{\mathcal{C}_*}(C,\Omega X) \xrightarrow{f_*} \mathcal{H}om_{\mathcal{C}_*}(C,\Omega Y) \xrightarrow{g_*} \\ &\mathcal{H}om_{\mathcal{C}_*}(C,\Omega Z) \longrightarrow \mathcal{H}om_{\mathcal{C}_*}(C,X) \xrightarrow{f_*} \mathcal{H}om_{\mathcal{C}_*}(C,Y) \xrightarrow{g_*} \mathcal{H}om_{\mathcal{C}_*}(C,Z),\end{aligned}$$

and thus a long exact sequence of pointed sets

$$\begin{aligned}&\cdots \longrightarrow \pi_0\,\mathcal{H}om_{\mathcal{C}_*}(C,\Omega^2 Z) \longrightarrow \\ &\quad \pi_0\,\mathcal{H}om_{\mathcal{C}_*}(C,\Omega X) \xrightarrow{f_*} \pi_0\,\mathcal{H}om_{\mathcal{C}_*}(C,\Omega Y) \xrightarrow{g_*} \pi_0\,\mathcal{H}om_{\mathcal{C}_*}(C,\Omega Z) \\ &\qquad \longrightarrow \pi_0\,\mathcal{H}om_{\mathcal{C}_*}(C,X) \xrightarrow{f_*} \pi_0\,\mathcal{H}om_{\mathcal{C}_*}(C,Y) \xrightarrow{g_*} \pi_0\,\mathcal{H}om_{\mathcal{C}_*}(C,Z),\end{aligned}$$

where the maps preserve (possibly exist) group structures. Dually, the functor $\mathcal{H}om_{\mathcal{C}_*}(-, C)$ sends homotopy colimits to homotopy limits. Hence, if we have a cofiber sequence of pointed objects

$$X \xrightarrow{f} Y \xrightarrow{g} Z \longrightarrow \Sigma X \xrightarrow{-\Sigma f} \Sigma Y \xrightarrow{-\Sigma g} \Sigma Z \longrightarrow \Sigma^2 X \longrightarrow \cdots .$$

Then we get a fiber sequence of pointed spaces

$$\begin{aligned} \cdots \longrightarrow \mathcal{H}om_{\mathcal{C}_*}(\Sigma^2 X, C) \longrightarrow \mathcal{H}om_{\mathcal{C}_*}(\Sigma Z, C) \xrightarrow{g^*} \mathcal{H}om_{\mathcal{C}_*}(\Sigma Y, C) \xrightarrow{f^*} \\ \mathcal{H}om_{\mathcal{C}_*}(\Sigma X, C) \longrightarrow \mathcal{H}om_{\mathcal{C}_*}(Z, C) \xrightarrow{g^*} \mathcal{H}om_{\mathcal{C}_*}(Y, C) \xrightarrow{f^*} \mathcal{H}om_{\mathcal{C}_*}(X, C), \end{aligned}$$

and thus a long exact sequence of pointed sets

$$\begin{aligned} \cdots \longrightarrow \pi_0\, \mathcal{H}om_{\mathcal{C}_*}(\Sigma^2 X, C) \longrightarrow \\ \pi_0\, \mathcal{H}om_{\mathcal{C}_*}(\Sigma Z, C) \xrightarrow{g^*} \pi_0\, \mathcal{H}om_{\mathcal{C}_*}(\Sigma Y, C) \xrightarrow{f^*} \pi_0\, \mathcal{H}om_{\mathcal{C}_*}(\Sigma X, C) \\ \longrightarrow \pi_0\, \mathcal{H}om_{\mathcal{C}_*}(Z, C) \xrightarrow{g^*} \pi_0\, \mathcal{H}om_{\mathcal{C}_*}(Y, C) \xrightarrow{f^*} \pi_0\, \mathcal{H}om_{\mathcal{C}_*}(X, C), \end{aligned}$$

where the maps preserve (possibly exist) group structures. The above two exact sequences are related by the following identification of pointed sets

$$\pi_0\, \mathcal{H}om_{\mathcal{C}_*}(\Sigma^n X, Y) = \pi_0\, \mathcal{H}om_{\mathcal{C}_*}(X, \Omega^n Y) = \pi_n\, \mathcal{H}om_{\mathcal{C}_*}(X, Y).$$

§ 2 Chain complexes

2.1 Let I be a set and $\mathcal{C}$ a category. An ***I*-graded object** in $\mathcal{C}$ is a functor from I, viewed as a discrete category, to $\mathcal{C}$. Hence the category of I-graded objects is denoted by $\mathcal{C}^I$. In plain words, an I-graded object is a family of objects $\{X_i\}_{i\in I}$ in $\mathcal{C}$ indexed by I. We denote it by $X_\bullet$ or simply X if there is no ambiguity. A **morphism** between I-graded objects $f\colon X \to Y$ is thus a family of morphisms $\{f\colon X_i \to Y_i\}_{i\in I}$ in $\mathcal{C}$ indexed by I. In other words,

$$\mathrm{Hom}_{\mathcal{C}^I}(X,Y) = \prod_{i\in I} \mathrm{Hom}_{\mathcal{C}}(X_i, Y_i).$$

Let $\iota\colon \mathcal{C} \to \mathcal{C}^I$ be the functor sending each object Y to the I-graded object $\underline{Y}$ whose each degree is Y. Then we have a functor

$$\mathrm{Hom}_{\mathcal{C}^I}(X,\iota)\colon \mathcal{C} \longrightarrow \mathbf{Set}.$$

Suppose $\mathcal{C}$ has direct sums, then the above functor can be represented by the direct sum

$$\bigoplus_{i\in I} X_i.$$

We call it the representative of X and denoted also by X.

2.2 Now, suppose G is a commutative monoid. Let X be a G-graded object and g an element of G. The ***g*-twisted object** of X is the G-graded object $X(g)$ defined as

$$X(g)_u := X_{g+u}, \quad \forall u \in G.$$

Let X, Y be two G-graded objects. A morphism from X to $Y(g)$ is called a ***g*-twisted morphism** from X to Y. The 0-twisted morphisms are the usual morphisms can called **homogeneous morphisms**. The G-graded set defined by

$$\mathrm{Hom}(X,Y)_g := \mathrm{Hom}_{\mathcal{C}^G}(X, Y(g))$$

is called the ***G*-graded Hom**.

2.3 Now, suppose $\mathcal{A}$ is an *abelian tensor category.* For A, B two G-graded objects in $\mathcal{A}$, their **tensor product** is defined by

$$(A\otimes B)_g := \bigoplus_{u+v=g} (A_u \otimes B_v), \quad \forall g \in G.$$

In this way, $\mathcal{A}^G$ becomes an abelian tensor category. If furthermore $\mathcal{A}$ is *closed*, admitting internal Hom bifunctor $[-,-]\colon \mathcal{A}^{\mathrm{op}} \times \mathcal{A} \to \mathcal{A}$. Then $\mathcal{A}^G$ can be viewed as a $\mathcal{A}$-enriched category by setting the *Hom-object* as

$$\underline{\mathrm{Hom}}_{\mathcal{A}^G}(A,B) := \prod_{g\in G} [A_g, B_g].$$

Moreover, we define the **internal G-graded Hom-object** by

$$[A, B]_g := \underline{\mathrm{Hom}}_{\mathcal{A}^G}(A, B(g)).$$

The internal G-graded Hom-objects turn to be the *internal Hom-objects* in $\mathcal{A}^G$ and we have the following (enriched) adjunctions:

$$\begin{aligned}
\mathrm{Hom}_{\mathcal{C}^G}(A \otimes B, C) &\cong \mathrm{Hom}_{\mathcal{C}^G}(A, [B, C]), \\
\underline{\mathrm{Hom}}_{\mathcal{C}^G}(A \otimes B, C) &\cong \underline{\mathrm{Hom}}_{\mathcal{C}^G}(A, [B, C]), \\
[A \otimes B, C] &\cong [A, [B, C]].
\end{aligned}$$

(However, to prove the above statements, one needs to deal with $\mathcal{A}^G$-enrichment first and then apply the obverse *change of base categories* $\mathcal{A}^G \to \mathcal{A}$.)

2.4 Let $\mathcal{C}$ be a category admitting a *zero object* 0.

- A **chain complex** in $\mathcal{C}$ is a graded object endowed with a (-1)-twisted endomorphism ∂, called the **boundary operator** or **codifferential**, such that $\partial \circ \partial = 0$. We use the notation $X_\bullet$ to indicate it is a chain complex.

- Dually, a **cochain complex** in $\mathcal{C}$ is a graded object endowed with a 1-twisted endomorphism d, called the **differential** or **coboundary operator**, such that $\mathrm{d} \circ \mathrm{d} = 0$. We use the notation $X^\bullet$ to indicate it is a cochain complex.

- Let $X_\bullet$, $Y_\bullet$ be two chain complexes. A **chain morphism** $f \colon X_\bullet \to Y_\bullet$ between them is a homogeneous morphism such that the following diagrams commute.

$$\begin{tikzcd}
\cdots \arrow[r] & X_n \arrow[r, "\partial_n"] \arrow[d, "f_n"] & X_{n-1} \arrow[r] \arrow[d, "f_{n-1}"] & \cdots \\
\cdots \arrow[r] & Y_n \arrow[r, "\partial_n"] & Y_{n-1} \arrow[r] & \cdots
\end{tikzcd}$$

- Dually, let $X^\bullet, Y^\bullet$ be two cochain complexes. A **cochain morphism** $f \colon X^\bullet \to Y^\bullet$ between them is a homogeneous morphism such that the following diagrams commute.

$$\begin{tikzcd}
\cdots \arrow[r] & X^n \arrow[r, "\mathrm{d}^n"] \arrow[d, "f^n"] & X^{n+1} \arrow[r] \arrow[d, "f^{n+1}"] & \cdots \\
\cdots \arrow[r] & Y^n \arrow[r, "\mathrm{d}^n"] & Y^{n+1} \arrow[r] & \cdots
\end{tikzcd}$$

The category of chain complexes (resp. cochain complexes) in $\mathcal{C}$ with chain morphisms (resp. cochain morphisms) between them is denoted by $\mathbf{Ch}_*(\mathcal{C})$ (resp. $\mathbf{Ch}^*(\mathcal{C})$). Note that this category also has a zero object $\underline{0}$ whose each degree is 0.

2.5 A chain complex $X_\bullet$ is said to be

- **connective** if $X_n = 0$ for all $n < 0$;
- **coconnective** if $X_n = 0$ for all $n > 0$;
- **bounded above** if $X_n = 0$ for sufficiently large n;
- **bounded below** if $X_n = 0$ for sufficiently small n;
- **bounded** if it is both bounded above and bounded below.

The full subcategory of $\mathbf{Ch}_*(\mathcal{C})$ spanned by connective (resp. coconnective, bounded above, bounded below, bounded) chain complexes is denoted by $\mathbf{Ch}_c(\mathcal{C})$ or $\mathbf{Ch}_{\geqslant 0}(\mathcal{C})$ (resp. $\mathbf{Ch}_{\leqslant 0}(\mathcal{C})$, $\mathbf{Ch}_-(\mathcal{C})$, $\mathbf{Ch}_+(\mathcal{C})$, $\mathbf{Ch}_b(\mathcal{C})$).

Dually, a cochain complex $X^\bullet$ is said to be

- **coconnective** if $X^n = 0$ for all $n < 0$;
- **connective** if $X^n = 0$ for all $n > 0$;
- **bounded above** if $X^n = 0$ for sufficiently large n;
- **bounded below** if $X^n = 0$ for sufficiently small n;
- **bounded** if it is both bounded above and bounded below.

The full subcategory of $\mathbf{Ch}^*(\mathcal{C})$ spanned by connective (resp. coconnective, bounded above, bounded below, bounded) chain complexes is denoted by $\mathbf{Ch}^c(\mathcal{C})$ or $\mathbf{Ch}^{\leqslant 0}(\mathcal{C})$ (resp. $\mathbf{Ch}^{\geqslant 0}(\mathcal{C})$, $\mathbf{Ch}^-(\mathcal{C})$, $\mathbf{Ch}^+(\mathcal{C})$, $\mathbf{Ch}^b(\mathcal{C})$).

2.6 Any chain complex $X_\bullet$ can be transformed into a cochain complex by

$$X^n := X_{-n}, \qquad \mathrm{d}^n := \partial_{-n}$$

and *vice versa*. Thus we can identify the following two categories

$$\mathbf{Ch}_*(\mathcal{C}) \cong \mathbf{Ch}^*(\mathcal{C})$$

and safely use the notation $\mathbf{Ch}(\mathcal{C})$ instead of $\mathbf{Ch}_*(\mathcal{C})$ or $\mathbf{Ch}^*(\mathcal{C})$ to denote those categories. In this sense, we can safely use the terminology **complex** to indicate both chain complexes and cochain complexes, and **morphism of complexes** to indicate both chain morphisms and cochain morphisms.

On the other hand, one can see that chain complexes in $\mathcal{C}$ are the same as cochain complexes in $\mathcal{C}^{\mathrm{op}}$, hence

$$\mathbf{Ch}_*(\mathcal{C})^{\mathrm{op}} = \mathbf{Ch}^*(\mathcal{C}^{\mathrm{op}}).$$

So we can canonically identify $\mathbf{Ch}(\mathcal{C}^{\mathrm{op}})$ and $\mathbf{Ch}(\mathcal{C})^{\mathrm{op}}$.

Restricting the full subcategories mentioned before, we have the following natural isomorphisms

$$\mathbf{Ch}_{\geqslant 0}(\mathcal{C})^{\mathrm{op}} = \mathbf{Ch}^{\geqslant 0}(\mathcal{C}^{\mathrm{op}}) \cong \mathbf{Ch}_{\leqslant 0}(\mathcal{C}^{\mathrm{op}}),$$
$$\mathbf{Ch}_{\leqslant 0}(\mathcal{C})^{\mathrm{op}} = \mathbf{Ch}^{\leqslant 0}(\mathcal{C}^{\mathrm{op}}) \cong \mathbf{Ch}^{\geqslant 0}(\mathcal{C}^{\mathrm{op}}).$$

Therefore, we can identify connective (resp. coconnective) chain complexes with connective (resp. coconnective) cochain complexes and call simply call them *connective (resp. coconnective) complexes*. In practice, the terminology **connective complexes** often refers to connective chain complexes while **coconnective complexes** to coconnective cochain complexes.

We also have the following natural isomorphisms

$$\mathbf{Ch}_{-}(\mathcal{C})^{\mathrm{op}} = \mathbf{Ch}^{-}(\mathcal{C}^{\mathrm{op}}) \cong \mathbf{Ch}_{+}(\mathcal{C}^{\mathrm{op}}),$$
$$\mathbf{Ch}_{+}(\mathcal{C})^{\mathrm{op}} = \mathbf{Ch}^{+}(\mathcal{C}^{\mathrm{op}}) \cong \mathbf{Ch}_{-}(\mathcal{C}^{\mathrm{op}}),$$
$$\mathbf{Ch}_{b}(\mathcal{C})^{\mathrm{op}} = \mathbf{Ch}^{b}(\mathcal{C}^{\mathrm{op}}) \cong \mathbf{Ch}_{b}(\mathcal{C}^{\mathrm{op}}).$$

Hence, we can identify bounded above (resp. bounded below) chain complexes with bounded below (resp. bounded above) cochain complexes. In this sense bounded above and bounded below chain complexes are dual notions while the notion of bounded complexes is self-dual.

We say a complex $X_\bullet$ is **concentrated** at degree $n_1, \cdots, n_k$ if $X_i = 0$ unless $i = n_1, \cdots, n_k$. It is clear that concentrated complexes are bounded complexes and *vice versa*.

2.7 There are many ways to embed $\mathcal{C}$ into the category $\mathbf{Ch}(\mathcal{C})$. Let X be an object in $\mathcal{C}$.

- The complex $\underline{X}_\bullet$ has X at its every degree and 0 as its boundary operator.
- The complex $X[n]$ concentrated at degree $-n$ with component X.
- We simply denote $X[0]$ by X if there is no ambiguity.

The notation $X[n]$ suggests that this complex is obtained by apply a **translation of degree n** functor to the complex X.

In the case $\mathcal{C}$ is an additive category, the functor $[n]$ is defined as follows. Let $X_\bullet$ be a complex. Then the complex $X[n]_\bullet$ is defined by

$$X[n]_i := X_{n+i}, \qquad \partial_{X[n]} := (-1)^n \partial_X, \qquad \forall i \in \mathbb{Z}.$$

Let f be a chain morphism. Then the chain morphism $f[n]$ is defined by $f[n]_i = f_{n+i}$ for all $i \in \mathbb{Z}$.

2.8 When $\mathcal{C} = \mathbf{Ab}$, the category of abelian groups, we simply denote $\mathbf{Ch}(\mathbf{Ab})$ by $\mathbf{Ch}$. More generally, let k be a ring and $\mathcal{C} = k\mathbf{Mod}$, the category of k-modules, we simply denote $\mathbf{Ch}(k\mathbf{Mod})$ by $\mathbf{Ch}(k)$. The notations for subcategories $\mathbf{Ch}_c$, $\mathbf{Ch}_{\geqslant 0}$, $\mathbf{Ch}_{\leqslant 0}$, $\mathbf{Ch}_{-}$, $\mathbf{Ch}_{+}$ and $\mathbf{Ch}_b$ are similar.

2.9 From now on, let $\mathcal{A}$ be an abelian category. When $\mathcal{A}$ is **Ab** or k**Mod**, we can talk about *elements* of an object. For general abelian tensor category, a **global element** of an object refers to a morphism from the unit to it, and a **(general) element** refers to a morphism from arbitrary object.

Let $(C_\bullet, \partial)$ be a chain complex in $\mathcal{A}$.

- The n-th **cycle object** of $C_\bullet$ is $Z_n(C) := \operatorname{Ker} \partial_n$, whose elements are called **n-cycles**.
- The n-th **boundary object** of $C_\bullet$ is $B_n(C) := \operatorname{Im} \partial_{n+1}$, whose elements are called **n-boundaries**.

Since $\partial \circ \partial = 0$, the inclusion $B_n(C) \rightarrowtail C_n$ factors through $Z_n(C)$.

- The cokernel of the resulted inclusion $B_n(C) \rightarrowtail Z_n(C)$ is called the n-th **homology object** of $C_\bullet$ and denoted by $H_n(C)$. The elements of $H_n(C)$ are called **homology classes**.

Dually, let $(C^\bullet, \mathrm{d})$ be a cochain complex in $\mathcal{A}$.

- The n-th **cocycle object** of $C^\bullet$ is $Z^n(C) := \operatorname{Ker} \mathrm{d}_n$, whose elements are called **n-cocycles**.
- The n-th **coboundary object** of $C^\bullet$ is $B^n(C) := \operatorname{Im} \mathrm{d}_{n-1}$, whose elements are called **n-coboundaries**.

Since $\mathrm{d} \circ \mathrm{d} = 0$, the inclusion $B^n(C) \rightarrowtail C^n$ factors through $Z^n(C)$.

- The cokernel of the resulted inclusion $B^n(C) \rightarrowtail Z^n(C)$ is called the n-th **cohomology object** of $C^\bullet$ and denoted by $H^n(C)$. The elements of $H^n(C)$ are called **cohomology classes**.

The above constructions extend to the following additive functors

$$\begin{aligned} Z_\bullet, B_\bullet, H_\bullet \colon \mathbf{Ch}_*(\mathcal{A}) &\longrightarrow \mathcal{A}^{\mathbb{Z}}, \\ Z^\bullet, B^\bullet, H^\bullet \colon \mathbf{Ch}^*(\mathcal{A}) &\longrightarrow \mathcal{A}^{\mathbb{Z}}. \end{aligned}$$

In particular, any chain morphism $f \colon C_\bullet \to D_\bullet$ (resp. cochain morphism $f \colon C^\bullet \to D^\bullet$) induces a homogeneous morphism

$$H(f) \colon H_\bullet(C) \to H_\bullet(D). \qquad (\text{resp. } H(f) \colon H^\bullet(C) \to H^\bullet(D))$$

Obviously, if f is an isomorphism, then so is $H(f)$. But the converse may not be true. A chain morphism (resp. cochain morphism) f is called a **quasi-isomorphism** if $H(f)$ is an isomorphism. A chain complex $C_\bullet$ (resp. cochain complex $C^\bullet$) is said to be **acyclic** if it is *quasi-isomorphic* to 0.

2.10 Since complexes is a special kind of diagrams, the limits and colimits in $\mathbf{Ch}(\mathcal{A})$ are computed degree-wisely. Note that filtered colimits commute with finite limits and all colimits, hence by the construction of the functors $B_\bullet, Z_\bullet$ and $H_\bullet$ (resp. $B^\bullet, Z^\bullet$ and $H^\bullet$), they preserve filtered colimits.

2.11 Suppose $\mathcal{A}$ is an abelian tensor category. Let $C_\bullet$, $D_\bullet$ be two complexes. Then there exists a natural boundary operator ∂ on the tensor product $(C \otimes D)_\bullet$ of their underlying $\mathbb{Z}$-graded objects. The resulted complex is called the **Koszul product** of $C_\bullet$ and $D_\bullet$. By its construction, we only need to define the following morphisms

$$C_p \otimes D_q \xrightarrow{\partial^{(1)}_{p,q}} C_{p-1} \otimes D_q, \qquad C_p \otimes D_q \xrightarrow{\partial^{(2)}_{p,q}} C_p \otimes D_{q-1}.$$

Note that the condition $\partial \circ \partial = 0$ requires that the following two morphisms must be negative to each other.

$$C_p \otimes D_q \xrightarrow{\partial^{(2)}_{p,q}} C_p \otimes D_{q-1} \xrightarrow{\partial^{(1)}_{p,q-1}} C_{p-1} \otimes D_{q-1},$$
$$C_p \otimes D_q \xrightarrow{\partial^{(1)}_{p,q}} C_{p-1} \otimes D_q \xrightarrow{\partial^{(2)}_{p-1,q}} C_{p-1} \otimes D_{q-1}.$$

The common convention is

$$\partial^{(1)}_{p,q} := \partial_p \otimes \mathrm{id}_{D_q}, \qquad \partial^{(2)}_{p,q} := (-1)^p \, \mathrm{id}_{C_p} \otimes \partial_q.$$

In element notation, it reads

$$\partial(x \otimes y) = \partial x \otimes y + (-1)^{|x|} x \otimes \partial y,$$

where $|x|$ denotes the degree of x. Then one can verify that the above construction makes $\mathbf{Ch}(\mathcal{A})$ into an abelian tensor category with the unit $\mathbf{1}$, which is $\mathbf{1}[0]_\bullet$ with $\mathbf{1}$ the unit of $\mathcal{A}$, and with the non-trivial braiding $\gamma(C, D)_\bullet \colon (C \otimes D)_\bullet \to (D \otimes C)_\bullet$ whose component in each degree is

$$(-1)^{pq} \gamma(C_p, D_q) \colon C_p \otimes D_q \longrightarrow D_q \otimes C_p,$$

where γ is the braiding in $\mathcal{A}$.

Remark One can see that $C[n]_\bullet$ is precisely $(\mathbf{1}[n] \otimes C)_\bullet$. This could be a reason why one may dislike the common convention. However, if we use $(C \otimes D)_\bullet$ to denote what usually means $(D \otimes C)_\bullet$, then (using the element notation) the boundary operator reads as

$$\partial(x \otimes y) = (-1)^{|y|} \partial x \otimes y + x \otimes \partial y.$$

In a middle way, we use the notation $(C \otimes^\gamma D)_\bullet$ to denote $(D \otimes C)_\bullet$. Under this convention, we have $C[n]_\bullet = (C \otimes^\gamma \mathbf{1}[n])_\bullet$.

2.12 Suppose further $\mathcal{A}$ is a closed abelian tensor category. Let $C_\bullet$, $D_\bullet$ be two complexes. Then there exists a natural boundary operator ∂ on the internal Hom $[C, D]_\bullet$ of their underlying $\mathbb{Z}$-graded objects. The resulted complex is called the **Koszul Hom-complex** of $C_\bullet$ and $D_\bullet$. By its construction, we only need to define the following morphisms

$$[C_p, D_q] \xrightarrow{\partial^{(1)}_{-p,q}} [C_{p+1}, D_q], \qquad [C_p, D_q] \xrightarrow{\partial^{(2)}_{-p,q}} [C_p, D_{q-1}].$$

Note that the condition $\partial \circ \partial = 0$ requires that the following two morphisms must be negative to each other.

$$[C_p, D_q] \xrightarrow{\partial^{(2)}_{-p,q}} [C_p, D_{q-1}] \xrightarrow{\partial^{(1)}_{-p,q-1}} [C_{p+1}, D_{q-1}],$$
$$[C_p, D_q] \xrightarrow{\partial^{(1)}_{-p,q}} [C_{p+1}, D_q] \xrightarrow{\partial^{(2)}_{-p-1,q}} [C_{p+1}, D_{q-1}].$$

The common convention is

$$\partial^{(1)}_{-p,q} := -(-1)^{-p+q}[\partial_{p+1}, D_q], \qquad \partial^{(2)}_{-p,q} := [C_p, \partial_q].$$

In element notation, it reads

$$(\partial f)(x) = \partial f(x) - (-1)^{|f|} f(\partial x).$$

Then one can verify that this construction together with previous ones makes $\mathbf{Ch}(\mathcal{A})$ a closed abelian tensor category.

Remark The functor $- \otimes^\gamma C$ admits a right adjoint $[C_\gamma -]$ which gives another, although equivalent to the above one, closed abelian tensor category structure. The complex $[C_\gamma D]_\bullet$ is defined as follows. Its components are the same as $[C, D]_\bullet$ and the boundary operator reads

$$(\partial f)(x) = (-1)^{|x|}\big(\partial f(x) - f(\partial x)\big).$$

This construction is convenient for some purpose and will be used later.

2.13 Let $\mathcal{A}$ be an abelian tensor category. We have seen that so is $\mathbf{Ch}(\mathcal{A})$. Moreover, since the full subcategories $\mathbf{Ch}_-(\mathcal{A})$, $\mathbf{Ch}_+(\mathcal{A})$, $\mathbf{Ch}_b(\mathcal{A})$ are closed under finite limits and colimits and Koszul product, they are also abelian tensor categories. As for the full subcategories $\mathbf{Ch}_{\geqslant 0}(\mathcal{A})$ and $\mathbf{Ch}_{\leqslant 0}(\mathcal{A})$, we use the following proposition.

2.14 Proposition *Let $\mathcal{A}$ be an abelian category. Then*

1. *the inclusion $\mathbf{Ch}_{\geqslant 0}(\mathcal{A}) \hookrightarrow \mathbf{Ch}(\mathcal{A})$ admits a left adjoint $\mathrm{sk}_{\geqslant 0}$ and a right adjoint $\tau_{\geqslant 0}$ and hence is exact;*
2. *the inclusion $\mathbf{Ch}_{\leqslant 0}(\mathcal{A}) \hookrightarrow \mathbf{Ch}(\mathcal{A})$ admits a left adjoint $\mathrm{sk}_{\leqslant 0}$ and a right adjoint $\tau_{\leqslant 0}$ and hence is exact.*

In particular, $\mathbf{Ch}_{\geqslant 0}(\mathcal{A})$ *and* $\mathbf{Ch}_{\leqslant 0}(\mathcal{A})$ *are abelian categories.*

PROOF: The functors $\mathrm{sk}_{\geqslant 0}$ and $\tau_{\geqslant 0}$ are defined as follows.

$$\mathrm{sk}_{\geqslant 0}(C)_n = \begin{cases} C_n & n \geqslant 0, \\ 0 & n < 0; \end{cases}$$

$$\tau_{\geqslant 0}(C)_n = \begin{cases} C_n & n > 0, \\ Z_0(C) & n = 0, \\ 0 & n < 0. \end{cases}$$

The functors $\mathrm{sk}_{\leqslant 0}$ and $\tau_{\leqslant 0}$ are defined similarly. □

Remark The complex $\tau_{\geqslant 0}(C)_\bullet$ is called the **0-th truncation** of $C_\bullet$. Note that this lemma shows that $\tau_{\geqslant 0}$ is a lax functor.

2.15 Let $\mathbf{1}$ be the unit of $\mathcal{A}$. Consider the chain complex $I_\bullet$ defined as

$$\cdots \longrightarrow 0 \longrightarrow \mathbf{1} \xrightarrow{(-\mathrm{id},\mathrm{id})} \mathbf{1} \oplus \mathbf{1} \longrightarrow 0 \longrightarrow \cdots$$

where $\mathbf{1} \oplus \mathbf{1}$ is of degree 0. This complex is called the **standard interval chain complex**. To justify this terminology and give an intuition, consider that the topological interval $[0,1]$ admits the following cellular decomposition: it has a 1-cell *the interior* $e = (0,1)$ and two 0-cells *the endpoints* $v_0 = 0$ and $v_1 = 1$. Then the associated cellular chain complex is the connective complex

$$\cdots \longrightarrow 0 \longrightarrow \mathbb{Z}e \xrightarrow{\partial} \mathbb{Z}v_0 \oplus \mathbb{Z}v_1,$$

where $\partial(e) = v_1 - v_0$. To illustrate, we formally write the complex $I_\bullet$ as

$$\cdots \longrightarrow 0 \longrightarrow \mathbf{1}e \xrightarrow{\partial^I} \mathbf{1}v_0 \oplus \mathbf{1}v_1 \longrightarrow 0 \longrightarrow \cdots .$$

Let $C_\bullet$ be a complex. Let's spell out the complex $(C \otimes I)_\bullet$. First,

$$(C \otimes I)_n = C_{n-1}e \oplus C_n v_0 \oplus C_n v_1.$$

To illustrate, an element (f, x, y) of this object is written as $f\colon x \rightsquigarrow y$, called a **copath** in C_n. Then the boundary operator $\partial_n^{C\otimes I}$ is induced by

$$\partial_n^C \otimes \mathrm{id}_{I_0}, \quad \partial_{n-1}^C \otimes \mathrm{id}_{I_1}, \quad \text{and} \quad (-1)^{n-1}\,\mathrm{id}_{C_{n-1}} \otimes \partial^I.$$

To spell out this boundary operator more concretely, let's use the following notation. Let A_j, B_i $(1 \leqslant j \leqslant n, 1 \leqslant i \leqslant m)$ be objects in $\mathcal{A}$, then the matrix

$$\begin{pmatrix} f_{11} & \cdots & f_{1n} \\ \vdots & \ddots & \vdots \\ f_{m1} & \cdots & f_{mn} \end{pmatrix}$$

denotes the morphism $\bigoplus_{1\leqslant j\leqslant n} A_j \to \bigoplus_{1\leqslant i\leqslant m} B_i$ induced by the following morphisms

$$f_{ij}\colon A_j \to B_i, \qquad 1\leqslant j\leqslant n, 1\leqslant i\leqslant m.$$

Using this notation, the boundary operators can be written as

$$\partial_n^{C\otimes I} = \begin{pmatrix} \partial_{n-1}^C & 0 & 0 \\ (-1)^n & \partial_n^C & 0 \\ (-1)^{n-1} & 0 & \partial_n^C \end{pmatrix}.$$

Withing element notation, this reads

$$\partial(f\colon x \rightsquigarrow y) = \big(\partial f\colon -(-1)^{|f|}f + \partial x \rightsquigarrow (-1)^{|f|}f + \partial y\big).$$

On the other hand, let's spell out the complex $[I, C]_\bullet$. First,

$$[I, C]_n = [\mathbf{1}e, C_{n+1}] \oplus [\mathbf{1}v_0, C_n] \oplus [\mathbf{1}v_1, C_n] =: C_{n+1}e^* \oplus C_n v_0^* \oplus C_n v_1^*.$$

To illustrate, an element (f, x, y) of this object is written as $f\colon x \rightsquigarrow y$, called a **path** in C_n. Then the boundary operator $\partial_n^{[I,C]}$ is induced by

$$[\mathrm{id}_{I_1}, \partial_{n+1}^C], \quad [\mathrm{id}_{I_0}, \partial_n^C], \quad \text{and} \quad -(-1)^n[\partial^I, \mathrm{id}_{C_n}].$$

Using matrix notation, the boundary operators can be written as

$$\partial_n^{[I,C]} = \begin{pmatrix} \partial_{n+1}^C & (-1)^n & (-1)^{n+1} \\ 0 & \partial_n^C & 0 \\ 0 & 0 & \partial_n^C \end{pmatrix}.$$

Withing element notation, this reads

$$\partial(f\colon x \rightsquigarrow y) = \big(\partial f + (-1)^{|f|}(y - x)\colon \partial x \rightsquigarrow \partial y\big).$$

Remark The complex $(C \otimes^\gamma I)_\bullet$ has the same components as $(C \otimes I)_\bullet$ with boundary operator (using the element notation)

$$\partial(f\colon x \rightsquigarrow y) = (-\partial f\colon -f + \partial x \rightsquigarrow f + \partial y).$$

The complex $[C_\gamma D]_\bullet$ has the same components as $[C, D]_\bullet$ with boundary operator

$$\partial(f\colon x \rightsquigarrow y) = (-\partial f + x - y\colon \partial x \rightsquigarrow \partial y).$$

2.16 Dually, one can consider the **standard interval cochain complex** $\hat{I}^\bullet$. It is actually motivated by the cellular cohomology of the interval $[0, 1]$:

$$\mathbb{Z}v_0^* \oplus \mathbb{Z}v_1^* \xrightarrow{\mathrm{d}} \mathbb{Z}e^* \longrightarrow 0 \longrightarrow \cdots,$$

where d is the morphism $(\mathrm{id}, -\mathrm{id})$. To illustrate, we formally write the complex $\hat{I}^\bullet$ as

$$\mathbf{1}v_0^* \oplus \mathbf{1}v_1^* \xrightarrow{\mathrm{d}_I} \mathbf{1}e^* \longrightarrow 0 \longrightarrow \cdots,$$

Apply the equivalence between cochain complexes and chain complexes, one can see that this complex is precisely $[I, \mathbf{1}]_\bullet$, i.e. it is the *weak dual* of $I_\bullet$.

Moreover, let $C^\bullet$ be a complex. Then the complex $(C \otimes \hat{I})^\bullet$ is

$$(C \otimes \hat{I})^n = C^{n-1}e^* \oplus C^n v_0^* \oplus C^n v_1^*.$$

with differential

$$\mathrm{d}^n_{C\otimes\hat{I}} = \begin{pmatrix} \mathrm{d}^{n-1}_C & (-1)^n & (-1)^{n+1} \\ 0 & \mathrm{d}^n_C & 0 \\ 0 & 0 & \mathrm{d}^n_C \end{pmatrix}.$$

Withing element notation, this reads

$$\mathrm{d}(f : x \rightsquigarrow y) = \big(\mathrm{d}f + (-1)^{|f|}(y - x) : \mathrm{d}x \rightsquigarrow \mathrm{d}y\big).$$

Apply the equivalence between cochain complexes and chain complexes, one can see that this complex is precisely $[I, C]_\bullet$.

The reason for this is that $\hat{I}^\bullet$ is indeed the *strong dual* of $I_\bullet$. To see this, let's translate $\hat{I}^\bullet$ into a chain complex. Then the chain complex $(\hat{I} \otimes I)_\bullet$ is concentrated at degree $1, 0, -1$ with components

$$\begin{aligned}
(\hat{I} \otimes I)_1 &= \mathbf{1}v_0^*e \oplus \mathbf{1}v_1^*e, \\
(\hat{I} \otimes I)_0 &= \mathbf{1}e^*e \oplus \mathbf{1}v_0^*v_0 \oplus \mathbf{1}v_1^*v_0 \oplus \mathbf{1}v_0^*v_1 \oplus \mathbf{1}v_1^*v_1, \\
(\hat{I} \otimes I)_{-1} &= \mathbf{1}e^*v_0 \oplus \mathbf{1}e^*v_1.
\end{aligned}$$

The boundary operators are presented by matrices as

$$\partial_1 = \begin{pmatrix} 1 & -1 \\ -1 & 0 \\ 0 & -1 \\ 1 & 0 \\ 0 & 1 \end{pmatrix}, \qquad \partial_0 = \begin{pmatrix} 1 & 1 & -1 & 0 & 0 \\ -1 & 0 & 0 & 1 & -1 \end{pmatrix}.$$

Then the **evaluation** $\mathrm{ev} : \hat{I} \otimes I \to \mathbf{1}$ is the chain morphism given by

$$\mathrm{ev}_1 = 0, \quad \mathrm{ev}_{-1} = 0, \quad \text{and} \quad \mathrm{ev}_0 = \begin{pmatrix} 1 & 1 & 0 & 0 & 1 \end{pmatrix},$$

which can be illustrated by the rule

$$\mathrm{ev}(x^*y) = \delta_{x,y} := \begin{cases} 1 & x = y, \\ 0 & x \neq y. \end{cases}$$

on the other hand, the chain complex $(I \otimes \hat{I})_\bullet$ is concentrated at degree $1, 0, -1$ with components

$$\begin{aligned}
(\hat{I} \otimes I)_1 &= \mathbf{1}ev_0^* \oplus \mathbf{1}ev_1^*, \\
(\hat{I} \otimes I)_0 &= \mathbf{1}ee^* \oplus \mathbf{1}v_0v_0^* \oplus \mathbf{1}v_1v_0^* \oplus \mathbf{1}v_0v_1^* \oplus \mathbf{1}v_1v_1^*, \\
(\hat{I} \otimes I)_{-1} &= \mathbf{1}v_0e^* \oplus \mathbf{1}v_1e^*.
\end{aligned}$$

The boundary operators are presented by matrices as

$$\partial_1 = \begin{pmatrix} -1 & 1 \\ -1 & 0 \\ 1 & 0 \\ 0 & -1 \\ 0 & 1 \end{pmatrix}, \qquad \partial_0 = \begin{pmatrix} -1 & 1 & 0 & -1 & 0 \\ 1 & 0 & 1 & 0 & -1 \end{pmatrix}.$$

To illustrate how the braiding acts, we introduce the following formal rule

$$\gamma(x^*y) = (-1)^{|x||y|} y x^*.$$

Then the **unit morphism** $\iota\colon \mathbf{1} \to I \otimes \hat{I}$ is the chain morphism given by

$$\iota_0 = \begin{pmatrix} 1 & 1 & 0 & 0 & 1 \end{pmatrix}^{\mathrm{t}},$$

where t denotes the transpose of a matrix. Then one can verify that the above data satisfies the axioms of strong duality.

Remark In a tensor category $\mathcal{C}$, an object X is **dualizable** if it has a **strong dual** X^*, which is another object in $\mathcal{C}$, and a **(strong) duality**, which is a pair of morphisms $\mathrm{ev}\colon X^* \otimes X \to \mathbf{1}$ (called the **evaluation**) and $\iota\colon \mathbf{1} \to X \otimes X^*$ satisfying the following commutative diagrams

$$\begin{tikzcd}
X^* \otimes (X \otimes X^*) \arrow[r, "\cong"] & (X^* \otimes X) \otimes X^* \arrow[d, "\mathrm{ev} \otimes \mathrm{id}"] \\
X^* \otimes \mathbf{1} \arrow[u, "\mathrm{id} \otimes \iota"] \arrow[r, "\cong"] & \mathbf{1} \otimes X^*
\end{tikzcd}
\qquad
\begin{tikzcd}
(X \otimes X^*) \otimes X \arrow[r, "\cong"] & X \otimes (X^* \otimes X) \arrow[d, "\mathrm{id} \otimes \mathrm{ev}"] \\
\mathbf{1} \otimes X \arrow[u, "\iota \otimes \mathrm{id}"] \arrow[r, "\cong"] & X \otimes \mathbf{1}
\end{tikzcd}$$

where the horizontal isomorphisms are the canonical ones.

Suppose $\mathcal{C}$ is further closed. Then the **weak dual** of an object X is precisely the object $[X, \mathbf{1}]$. If X is dualizable, then the weak dual is also the strong dual X^*. If this is the case, then for any object Y, we have a canonical isomorphism

$$Y \otimes X^* \xrightarrow{\sim} [X, Y].$$

2.17 There are two natural chain morphisms from $\mathbf{1}$ to $I_\bullet$: s_i $(i = 0, 1)$ sends $\mathbf{1}$ to the factor $\mathbf{1}v_i$ in the 0-th degree of $I_\bullet$. Then for any complex $C_\bullet$, we have canonical chain morphisms

$$\iota_i\colon C_\bullet \longrightarrow (C \otimes I)_\bullet \quad (i = 0, 1),$$
$$\mathrm{ev}_i\colon [I, C]_\bullet \longrightarrow [\mathbf{1}, C]_\bullet \cong C_\bullet \quad (i = 0, 1).$$

To illustrate, let's spell out them by element notations:

$$\iota_0(x) = (0\colon x \rightsquigarrow 0), \qquad \iota_1(y) = (0\colon 0 \rightsquigarrow y),$$
$$\mathrm{ev}_0(f\colon x \rightsquigarrow y) = x, \qquad \mathrm{ev}_1(f\colon x \rightsquigarrow y) = y.$$

We also use the same notation for the morphisms $\iota_i\colon C_\bullet \longrightarrow (C \otimes^\gamma I)_\bullet$ and $\mathrm{ev}_i\colon [I_\gamma C]_\bullet \longrightarrow C_\bullet$.

2.18 Let $f, g\colon C_\bullet \to D_\bullet$ be two chain morphisms. As in algebraic topology, a **(left) homotopy** $\Phi\colon f \Rightarrow g$ between them is a commutative diagram of complexes in the form

$$\begin{tikzcd}
C_\bullet \arrow[d, "\iota_0"'] \arrow[dr, "f"] & \\
(C \otimes^\gamma I)_\bullet \arrow[r, dashed, "\Phi"] & D_\bullet \\
C_\bullet \arrow[u, "\iota_1"] \arrow[ur, "g"'] &
\end{tikzcd}$$

and a **right homotopy** is a commutative diagram as follows.

$$\begin{tikzcd}
 & D_\bullet \\
C_\bullet \arrow[ur, "f"] \arrow[r, dashed, "\Phi"] \arrow[dr, "g"'] & {[I_\gamma D]_\bullet} \arrow[u, "\mathrm{ev}_0"'] \arrow[d, "\mathrm{ev}_1"] \\
 & D_\bullet
\end{tikzcd}$$

Using the previous conventions, a left homotopy is of the form

$$\Phi_n = \begin{pmatrix} \phi_{n-1} & f_n & g_n \end{pmatrix},$$

and the fact Φ is a chain morphism is then equivalent to that the 1-twisted morphism $\phi_\bullet$ satisfies the following equality:

$$g_n - f_n = \partial_n \circ \phi_n + \phi_{n-1} \circ \partial_n.$$

This equality can be illustrated as the following diagram.

$$\begin{tikzcd}
\cdots \arrow[r] & C_{n+1} \arrow[r, "\partial_{n+1}"] \arrow[d, shift right, "f_{n+1}"'] \arrow[d, shift left, "g_{n+1}"] & C_n \arrow[r, "\partial_n"] \arrow[dl, "\phi_n"'] \arrow[d, shift right, "f_n"'] \arrow[d, shift left, "g_n"] & C_{n-1} \arrow[r] \arrow[dl, "\phi_{n-1}"'] \arrow[d, shift right, "f_{n-1}"'] \arrow[d, shift left, "g_{n-1}"] & \cdots \\
\cdots \arrow[r] & D_{n-1} \arrow[r, "\partial_n"] & D_n \arrow[r, "\partial_n"] & D_{n-1} \arrow[r] & \cdots
\end{tikzcd}$$

A 1-twisted morphism $\phi_\bullet$ as above is called a **(left) chain homotopy** from f to g, also denoted by $\phi\colon f \Rightarrow g$.

Dually, a right homotopy $\Phi\colon f \Rightarrow g$ is of the form

$$\Phi_n = \begin{pmatrix} \phi_n & f_n & g_n \end{pmatrix}^{\mathrm{t}},$$

and the fact that Φ is a chain morphism is then equivalent to that the 1-twisted morphism $\phi_\bullet$ satisfies the following equality:

$$f_n - g_n = \partial_n \circ \phi_n + \phi_{n-1} \circ \partial_n.$$

A 1-twisted morphism $\phi_\bullet$ as above is called a **right chain homotopy** from f to g, also denoted by $\phi\colon f \Rightarrow g$.

Note that these four notions are equivalent and we'll not distinguish them if no necessary.

2.19 Two chain maps $f, g\colon C_\bullet \rightrightarrows D_\bullet$ are said to be **homotopic**, denoted by $f \simeq g$, if there exists a chain homotopy $\Phi\colon f \Rightarrow g$. A chain morphism $f\colon C_\bullet \to D_\bullet$ is called a **homotopy equivalence** if there exists another chain morphism $g\colon D_\bullet \to C_\bullet$ such that $g \circ f \simeq \mathrm{id}_C$ and $f \circ g \simeq \mathrm{id}_D$. Two chain complexes $C_\bullet, D_\bullet$ are said to be **homotopy equivalent** if there exists a chain homotopy equivalence $f\colon C_\bullet \to D_\bullet$.

In this way, we can form a new category $K(\mathcal{A})$ as follows:

- the objects of $K(\mathcal{A})$ are as of $\mathbf{Ch}(\mathcal{A})$,
- the Hom set $\mathrm{Hom}_{K(\mathcal{A})}(C, D)$ is the quotient set of $\mathrm{Hom}_{\mathbf{Ch}(\mathcal{A})}(C, D)$ modulo homotopies.

This category is called the **homotopy category** of $\mathbf{Ch}(\mathcal{A})$ or $\mathcal{A}$ if there are no ambiguities. In the same way, we have subcategories $K_c(\mathcal{A})$, $K_{\geqslant 0}(\mathcal{A})$, $K_{\leqslant 0}(\mathcal{A})$, $K_-(\mathcal{A})$, $K_+(\mathcal{A})$ and $K_b(\mathcal{A})$.

Given two homotopies $\Phi\colon f \Rightarrow g$ and $\Psi\colon g \Rightarrow h$, then the **vertical composition** of them is more or less the sum of them:

$$\Psi \dot{+} \Phi := (\phi + \psi, f, h).$$

Note that $\Psi \dot{+} \Phi \neq \Phi \dot{+} \Psi$, the later even doesn't make sense. Under this composition rule, the inverse of a homotopy $\Phi\colon f \Rightarrow g$ is the homotopy $-\Phi\colon g \Rightarrow f$ defined as

$$-\Phi := (-\phi, g, f).$$

Given two homotopies Φ, Ψ as below:

$$\begin{tikzcd} C_\bullet \arrow[r, bend left, "f"] \arrow[r, bend right, "g"'] \arrow[r, phantom, "\Downarrow\Phi"] & D_\bullet \arrow[r, bend left, "f'"] \arrow[r, bend right, "g'"'] \arrow[r, phantom, "\Downarrow\Psi"] & E_\bullet \end{tikzcd}$$

the **horizontal composition** is defined as

$$\Psi * \Phi := \Psi \circ g \dot{+} f' \circ \Phi,$$

where the composition $f' \circ \Phi$ should be consider as given by

$$(C \otimes^\gamma I)_\bullet \xrightarrow{\Phi} D_\bullet \xrightarrow{f'} E_\bullet,$$

while the composition $\Psi \circ g$ given by

$$C_\bullet \xrightarrow{g} D_\bullet \xrightarrow{\Psi} [I_\gamma E]_\bullet.$$

Now, consider the following diagram.

$$\begin{tikzcd}
C_\bullet \arrow[r, bend left=60, "f"] \arrow[r, "g" description] \arrow[r, bend right=60, "h"'] \arrow[r, phantom, shift left=4, "\Downarrow\Phi"] \arrow[r, phantom, shift right=4, "\Downarrow\Phi'"] & D_\bullet \arrow[r, bend left=60, "f'"] \arrow[r, "g'" description] \arrow[r, bend right=60, "h'"'] \arrow[r, phantom, shift left=4, "\Downarrow\Psi"] \arrow[r, phantom, shift right=4, "\Downarrow\Psi'"] & E_\bullet
\end{tikzcd}$$

There are two ways to compose them:

$$\Psi' * \Phi' \dotplus \Psi * \Phi \qquad \text{and} \qquad (\Psi' \dotplus \Psi) * (\Phi' \dotplus \Phi).$$

However, those two homotopies do not equal. In fact, there is a homotopy from between them:

References

[1] A. Hatcher. *Algebraic Topology.* Cambridge University Press, 2002.

[2] M. Aguilar et al. *Algebraic Topology from a Homotopical Viewpoint.* Universitext. Springer New York, 2002.

[3] J. May. *A Concise Course in Algebraic Topology.* Chicago Lectures in Mathematics. University of Chicago Press, 1999.

[4] J. May and K. Ponto. *More Concise Algebraic Topology: Localization, Completion, and Model Categories.* Chicago Lectures in Mathematics. University of Chicago Press, 2012.

[5] J. Lurie. *Higher Topos Theory.* Princeton University Press, 2009.

[6] E. Riehl and D. Verity. ∞-*Categories for the Working Mathematician.* in progress, 2018.