HOMOTOPY THEORY

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For these notes, we will follow [2], [1] and [3].

1. Cofibrations

For this section, we will follow chapter VII.1 in [1].

One of the fundamental questions in topology is the "extension problem". Namely, given a map $g\colon A \to Y$ defined on a subspace A of X, when can we extend this map to all of X.
This cannot always be done - for example, as is the case with $A = Y = S^n$ and $X = D^{n+1}$ choosing the map to be any degree -1 map.

Question 1.1. Is the extension problem a *homotopy-theoretic* problem? That is, does the answer depend only on the homotopy class of g?

The answer is: generally not. For example, we can take $X = [0,1]\,, A = \{0\} \cup \left\{\frac{1}{n} \mid n = 1, 2, \ldots\right\}$ and $Y = CA$, the cone on A. Choosing g to be the inclusion of A into Y, this cannot be extended to X as the extension would be discontinuous at $\{0\}$. However, $g \simeq g'$ with g' being the constant map of A to the vertex of the cone, and g' easily extends to X by the constant map.

It turns out, however, that under some very mild conditions on the spaces, the problem becomes homotopy theoretic. We will now discuss this.

Definition 1.2 (Homotopy extension property)**.** Let (X, A) and Y be given spaces. Then (X, A) is said to have the *homotopy extension property* with respect to Y if the following diagram can always be completed to be commutative.

$$\begin{tikzcd}
A \times I \cup X \times \{0\} \arrow[r] \arrow[d, hook] & Y \\
X \times I \arrow[ur, dashed] &
\end{tikzcd}$$

One can also depict this by the following diagram:

$$\begin{tikzcd}
A \times \{0\} \arrow[rr, hook] \arrow[dd, hook] & & A \times I \arrow[dl] \arrow[dd, hook] \\
& Y & \\
X \times \{0\} \arrow[ur] \arrow[rr] & & X \times I \arrow[ul, dashed]
\end{tikzcd}$$

If (X, A) has the homotopy extension property with respect to Y, then the extensibility of maps $g\colon A \to Y$ depends only on the homotopy class of g. For suppose $H\colon g \simeq g'$ and g' can be extended to $\tilde{g'}\colon X \to Y$, then define the map $A \times I \cup X \times \{0\}$ by $\tilde{g'} \times \{0\}$ on $X \times \{0\}$ and H on $A \times I$. The homotopy extension property for the pair (X, A) then guarantees the existence of a map $G\colon X \times I \to Y$ which equals g on $A \times \{1\}$, so $H(-, 1) : X \to Y$ extends g.

Definition 1.3 (Cofibration)**.** Let $f\colon A \to X$ be a map. Then f is called a *cofibration* if one can always fill in the following commutative diagram given the solid arrows:

$$\begin{tikzcd}
A \times \{0\} \arrow[rr, hook] \arrow[dd, "f \times \mathrm{id}"] & & A \times I \arrow[dl] \arrow[dd, "f \times \mathrm{id}"] \\
& Y & \\
X \times \{0\} \arrow[ur] \arrow[rr, hook] & & X \times I \arrow[ul, dashed]
\end{tikzcd}$$

for *any* space Y.

Note. If f is an inclusion, the this is the same as the homotopy extension property for all Y. That attribute is sometimes referred to as the *absolute homotopy extension property.*

Lemma 1.4. *If $f\colon A \to X$ is a cofibration, then the inclusion $\iota\colon f(A) \hookrightarrow X$ is a cofibration with $f(A)$ inheriting the subspace topology.*

Proof. If f is a cofibration, then for any Y, there following diagram can be filled out given the solid arrows

$$\begin{tikzcd}
A \times \{0\} \arrow[rr, hook] \arrow[dd, "f \times \mathrm{id}"] & & A \times I \arrow[dl] \arrow[dd, "f \times \mathrm{id}"] \\
& Y & \\
X \times \{0\} \arrow[ur] \arrow[rr] & & X \times I \arrow[ul, dashed, "F"]
\end{tikzcd}$$

And thus we can fill the following diagram as well

$$\begin{tikzcd}
f(A) \times \{0\} \arrow[rr, hook] \arrow[dd, hook, "\iota \times \mathrm{id}"] & & f(A) \times I \arrow[dl, "F|_{f(A) \times I}"'] \arrow[dd, hook, bend left, "\iota \times \mathrm{id}"] \\
& Y & \\
X \times \{0\} \arrow[ur] \arrow[rr, hook] & & X \times I \arrow[ul, dashed, "F"]
\end{tikzcd}$$

By definition then $\iota\colon f(A) \hookrightarrow X$ is a cofibration. $\square$

Note. Note that the converse is not true since we will see later in a problem that a cofibration is an embedding, so it is easy to construct a counter example, for example by choosing a well-pointed space (see definition later) and then choosing any space A which is not a single point and the collapsing map $A \to X$ to the base point.

Theorem 1.5. *For an inclusion $A \subset X$, the following are equivalent:*

1. *The inclusion map $A \hookrightarrow X$ is a cofibration.*
2. *$A \times I \cup X \times \{0\}$ is a retract of $X \times I$.*

Proof. If the inclusion is a cofibration, then choosing $Y = A \times I \cup X \times \{0\}$ with all arrows being inclusions in the diagram of a cofibration, we obtain a map $X \times I \to A \times I \cup X \times \{0\}$ which is the identity on $A \times I \cup X \times \{0\}$.
Conversely, if $A \times I \cup X \times \{0\}$ is a retract of $X \times I$, then we can always complete the diagram by mapping $X \times I \to A \times I \cup X \times \{0\} \to Y$ where the second map takes the maps $A \times I \to Y$ and $X \times \{0\} \to Y$ from the diagram. □

Corollary 1.6. *If A is a subcomplex of a CW-complex X, then the inclusion $A \hookrightarrow X$ is a cofibration.*

Proof. We want to construct a retraction $X \times I \to A \times I \cup X \times \{0\}$. We will do so by constructing a retraction $\left(\left(A \cup X^{(r)}\right) \times I\right) \cup (X \times \{0\}) \to (A \times I) \cup (X \times \{0\})$ by induction on r. If it has been defined on the $(r-1)$-skeleton, then extending it over an r-cell is simply a matter of extending a map on $S^{r-1} \times I \cup D^r \times \{0\}$ over $D^r \times I$ which can be done since the pair $\left(D^r \times I, S^{r-1} \times I \cup D^r \times \{0\}\right)$ is homeomorphic to $(D^r \times I, D^r \times \{0\})$. See Figure 1

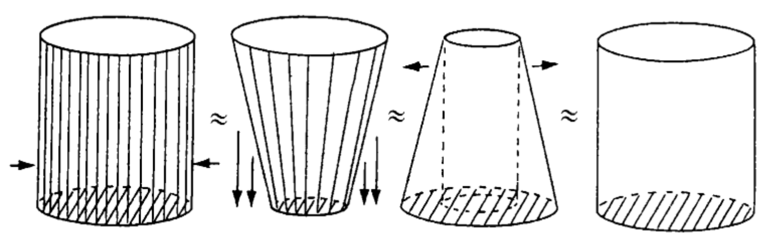

Figure 1. A homeomorphism of pairs.

These maps for each cell fit together to give a map on the r-skeleton because of the weak topology on $X \times I$. The union of these maps for all r gives a map on $X \times I$, again because of the weak topology on $X \times I$. □

Theorem 1.7. *Assume that $A \subset X$ is closed and that there exists a neighborhood U of A and a map $\varphi\colon X \to I$ such that*

1. *$A = \varphi^{-1}(0)$.*
2. *$\varphi(X - U) = \{1\}$.*
3. *U deforms to A through X with A fixed. That is, there is a map $H\colon U \times I \to X$ such that $H(a,t) = a$ for all $a \in A$, $H(u,0) = 0$, and $H(u,1) \in A$ for all $u \in U$.*

Then the inclusion $A \hookrightarrow X$ is a cofibration. The converse also holds.

Proof. We may assume that $\varphi = 1$ on a neighborhood of $X - U$ by replacing φ with $\min(2\varphi, 1)$. It suffices to show that there exists a retract $\Phi\colon U \times I \to X \times \{0\} \cup A \times I$

since then the map

$$r(x,t) = \begin{cases} \Phi\left(x, t\left(1-\varphi(x)\right)\right), & x \in U \\ (x,0), & x \notin U \end{cases}$$

gives a retraction $X \times I \to A \times I \cup X \times \{0\}$.
We define Φ by

$$\Phi(u,t) = \begin{cases} H\left(u, \frac{t}{\varphi(u)}\right) \times \{0\}, & \varphi(u) > t \\ H(u,1) \times \{t - \varphi(u)\}, & \varphi(u) \leq t. \end{cases}$$

The only thing that needs checking here is that Φ is continuous at points $(u,0)$ such that $\varphi(u) = 0$, i.e., points $(a,0)$ for $a \in A$ - indeed here the expression for $\varphi(u) > t$ is not defined.
Recall that a map $f\colon X \to Y$ is continuous if for every point $x \in X$ and any neighborhood U of $f(x)$, there exists a neighborhood V of x such that $f(V) \subset U$. So let W be a neighborhood of $a = H(a,t)$. Then there exists a neighborhood $V \subset W$ containing a such that $H(V \times I) \subset W$, by assumption of H being continuous. So for $t < \varepsilon$ for some ε and $u \in V$, we have $\Phi(u,t) \in W \times [0,\varepsilon]$. Hence Φ is continuous.

To prove the converse, suppose that the inclusion $A \hookrightarrow X$ is a cofibration. Equivalently, $A \times I \cup X \times \{0\}$ is a retract of $X \times I$. Let $r\colon X \times I \to A \times I \cup X \times \{0\}$ be this retraction. Let $s(x) = r(x,1)$ and set $U = s^{-1}(A \times (0,1])$. Let p_X, p_I be the projections of $X \times I$ to its factors. Then put $H = p_X \circ r|_{U \times I}\colon U \times I \to X$. Now, $H(a,t) = p_X \circ r|_{U\times I}(a,t) = p_X(a,t) = a$ for all $a \in A$ and $t \in I$; $H(u,0) = p_X \circ r|_{U\times I}(u,0) = p_X(u,0) = u$, and $H(u,1) = p_X \circ r|_{U\times I}(u,1) = u$ forces $(u,1) \in A \times I$, hence $u \in A$. Thus, H satisfies condition (3).
For (1) and (2), let $\varphi(x) = \max_{t\in I} |t - p_I r(x,t)|$ which is possible since I is compact. Then $x \in \varphi^{-1}(0)$ implies that $\max_{t \in I} |t - p_I r(x,t)| = 0$, so for all $t \in I$, we have $|t - p_I r(x,t)| = 0$, so $r(x,t) \in A \times \{t\}$ for all $t \in (0,1]$. Then $r(x,0) = \lim_{n\to\infty} r\left(x, \frac{1}{n}\right) \in A \times I$ since $A \times I$ is closed. But $(x,0) = r(x,0)$, so $x \in A$. Conversely, for any $x \in A$, clearly, $\varphi(x) = 0$ since $r(x,t) = (x,t)$ for all $t \in I$. This shows that φ satisfies (1). For (2), we have that for $x \in X - U$, with $U = s^{-1}(A \times (0,1])$, we have $r(x,1) = s(x) \notin A \times (0,1]$, so $r(x,1) \in X \times \{0\}$. Hence $\varphi(x) = \max_{t\in I} |t - p_I r(x,t)| = 1$, giving (2).
It remains to show that φ is continuous. Let $f(x,t) = |t - p_I r(x,t)|$ and $f_t = (x,t)$ all of which are continuous. Then

$$\varphi^{-1}\left((-\infty, b]\right) = \{x \mid f(x,t) \leq b \text{ for all } t\} = \bigcap_{i \in I} f_t^{-1}\left((-\infty,b]\right).$$

is an intersection of closed sets and so is closed. Similarly,

$$\varphi^{-1}\left([a,\infty)\right) = \{x \mid f(x,t) \geq a \text{ for some } t\} = p_X\left(f^{-1}\left([a,\infty)\right)\right)$$

which si also closed since p_X is closed as a projection and I is compact. Since the complements of the intervals of the form $[a,\infty)$ and $(-\infty,b]$ give a subbase for the topology of $\mathbb{R}$, this shows that φ is continuous.

□

Next, we recall that for a map $f\colon X \to Y$, the mapping cylinder M_f is defined as

$$M_f = \left((X \times I) \sqcup Y\right) / \left((x,0) \sim f(x)\right).$$

Consider the inclusion $\iota\colon X \hookrightarrow M_f$ where we include X as $X \times \{1\}$. Consider the map $\varphi\colon Mf \to I$ given by $\varphi(x,t) = 1 - 2t$ for $t \geq \frac{1}{2}$ and $\varphi(x,t) = 1$ on the rest of M_f. Choosing $U = X \times (\frac{1}{3}, 1]$, U clearly deformations retracts to $X \times \{1\}$ and satisfies the conditions of Theorem 1.7, hence the inclusion $X \hookrightarrow M_f$ is a cofibration. Also, the retraction $r\colon M_f \to Y$ is a homotopy equivalence with the homotopy inverse being the inclusion $Y \hookrightarrow M_f$. The diagram

$$\begin{tikzcd} X \arrow[rr, "\iota"] \arrow[dr, "f"'] & & M_f \arrow[dl, "r", "\simeq"'] \\ & Y & \end{tikzcd}$$

commutes. Thus any map f is a cofibration up to a homotopy equivalence of spaces. Recall also that the mapping cone of a map $f\colon X \to Y$ is defined as

$$C_f := M_f / X \times \{1\} \cong M_f \cup CX.$$

In the case of an inclusion $\iota\colon A \hookrightarrow X$, we have $C_\iota = X \cup CA$.

There is a map $C_\iota \xrightarrow{h} X/A$, defined as the composite of the quotient map $X \cup CA \to X \cup CA/CA$ composed with the inverse of the homeomorphism $X/A \to X \cup CA/CA$.

Question 1.8. Is h a homotopy equivalence?

Theorem 1.9. *If $A \subset X$ is closed and the inclusion $\iota\colon A \to X$ is a cofibration, then $h\colon C_\iota \to X/A$ is a homotopy equivalence. In fact, it is a homotopy equivalence of pairs*

$$(X/A, *) \simeq (C_\iota, CA) \simeq (C_\iota, v),$$

where v is the vertex of the cone.

Proof. The mapping cone $C_\iota = X \cup CA$ consists of three different types of points: the vertex $v = \{A \times \{1\}\}$, the rest of the cone $\{(a,t) \mid 0 \leq t < 1\}$ where $(a,0) = a \in A \subset X$, and points in X itself, which we identify with $X \times \{0\}$.

Define $f\colon A \times I \cup X \times \{0\} \to C_\iota$ as the collapsing map and extend f to $\overline{f}\colon X \times I \to C_\iota$ using that f is a cofibration. Then $\overline{f}\,(a,1) = v, \overline{f}(a,t) = (a,t)$ and $\overline{f}(x,0) = x$.

Let $\overline{f}_t = \overline{f}|_{X \times \{t\}}$. Since $\overline{f}_1(A) = \{v\}$, we can factorize $\overline{f}_1\colon X \to C_\iota$ as $g \circ j$ where $j\colon X \to X/A$ is the quotient map and $g\colon X/A \to C_\iota$ is the induced map

$$\begin{tikzcd} X \arrow[d, "j"] \arrow[dr, "\overline{f}_1"] & \\ X/A \arrow[r, dashed, "g"] & C_\iota. \end{tikzcd}$$

where g is induced and continuous by definition of the quotient topology.

We claim that g is a homotopy equivalence with homotopy inverse h. First, we prove that $hg \simeq \mathrm{id}_{X/A}$.

Note that taking the composite $h\overline{f}_t\colon X \to X/A$ gives a homotopy between $h\overline{f}_0$ and $h\overline{f}_1$. For all t, this homotopy takes A to the point $\{A\}$. Thus, it factors to give a homotopy

$$hgj = h\overline{f}_1 \simeq h\overline{f}_0 = j$$

Let $H\colon X \times I \to X/A$ be the homotopy between hgj and j, so $H(x,0) = hgj(x)$ and $H(x,1) = j(x)$. Then the map $\overline{H}\colon X/A \times I \to X/A$ defined by $\overline{H}([x], t) = H(x,t)$ defines a homotopy between hg and $\mathrm{id}_{X/A}$, so $hg \simeq \mathrm{id}_{X/A}$.

Next, we will show that $gh \simeq \mathrm{id}_{C_\iota}$. Consider $W = (X \times I) / (A \times \{1\})$ and the maps illustrated in Figure 2.

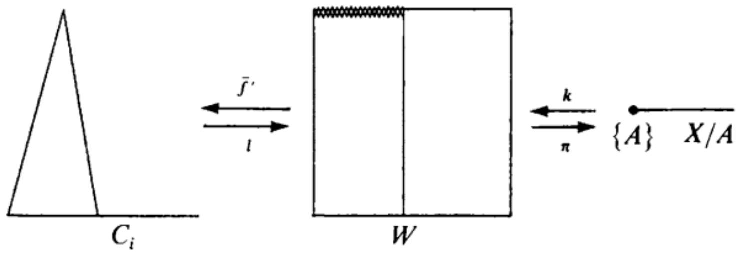

FIGURE 2.

The map $\overline{f}'$ is induced by $\overline{f}$. The map k is the "top face" map. From this, we see that

$$\begin{aligned} \overline{f}' \circ l &= \mathrm{id} \\ \pi \circ k &= \mathrm{id} \\ k \circ \pi &\simeq \mathrm{id} \\ \overline{f}' \circ k &= g \\ \pi \circ l &= l. \end{aligned}$$

Hence $gh = \overline{f}' k\pi l \simeq \overline{f}' l = \mathrm{id}$. $\square$

Example 1.10 (A non example)**.** An example of when the result of Theorem 1.6 does not hold is with $A = \{0\} \cup \left\{\frac{1}{n} \mid n = 1, 2, \ldots\right\}$ and $X = [0, 1]$. In this case, C_ι is not homotopy equivalent to X/A which is a one-point union of a countably infinite sequence of circles with radii going to zero.
C_i has homeomorphs of circles joined along edges. However, the circles do not tend to a point ,so any prospective homotopy equivalence $X/A \to C_\iota$ would be discontinuous at the image of $\{0\}$ in X/A.

Corollary 1.11. *If $A \subset X$ is closed and the inclusion $A \hookrightarrow X$ is a cofibration, then the map $j\colon (X, A) \to (X/A, *)$ induces isomorphisms*

$$H_*(X, A) \xrightarrow{\cong} H_*(X/A, *) \cong \tilde{H}_*(X/A)$$

and

$$\tilde{H}^*(X/A) \cong H^*(X/A, *) \xrightarrow{\cong} H^*(X, A).$$

Proof. We have $H_*(X/A, *) \cong H_*(C_\iota, CA)$ by Theorem 1.9. And since $C_\iota = X \cup A \times \left[0, \frac{1}{2}\right]$ and $CA = A \times \left[0, \frac{1}{2}\right]$, where we collapse $A \times \left\{\frac{1}{2}\right\}$ in both, and attach $A \times \left[0, \frac{1}{2}\right]$ along $A \times \{0\}$ in $X \cup A \times \left[0, \frac{1}{2}\right]$, we obtain

$$H_*(C_\iota, CA) \cong H_*\left(X \cup A \times \left[0, \frac{1}{2}\right], A \times \left[0, \frac{1}{2}\right]\right) \cong H_*(X, A)$$

since $\left(X \cup A \times \left[0, \frac{1}{2}\right], A \times \left[0, \frac{1}{2}\right]\right) \simeq (X, A)$ by deformation retracting $A \times \left[0, \frac{1}{2}\right]$ down to $A \times \{0\} \subset X$. $\square$

1.0.1. *Interlude on pointed-spaces and operations on spaces.* We recall some important constructions:

Definition 1.12 (Unreduced Suspension)**.** For a space X, the *unreduced suspension* ΣX is the quotient obtained from $X \times I$ by collapsing $X \times \{0\}$ to one point and $X \times \{1\}$ to another point.

Note. We have $\Sigma S^n = S^{n+1}$.

Definition 1.13 (Suspension of a map)**.** Given a map $f\colon X \to Y$, we can suspend f to $\Sigma f\colon \Sigma X \to \Sigma Y$ by letting Σf be the induced map on the quotients:

$$\begin{array}{ccc} X \times I & \xrightarrow{f \times \mathrm{id}} & Y \times I \\ \downarrow & & \downarrow \\ \Sigma X & \xrightarrow{\Sigma f} & \Sigma Y \end{array}$$

Definition 1.14 (Reduced Suspension)**.** For a space X, the *reduced suspension* SX is the quotient

$$SX = X \times I / \left(X \times \partial I \cup \{*\} \times I \right).$$

Definition 1.15 (Reduced Suspension of a map)**.** The reduced suspension of a map $f\colon X \to Y$ is the induced map on the reduced suspensions of X and Y :

$$\begin{array}{ccc} X \times I & \xrightarrow{f \times \mathrm{id}} & Y \times I \\ \downarrow & & \downarrow \\ SX & \xrightarrow{Sf} & SY \end{array}$$

Exercise 1.16. For any homology theory, show that there is a natural isomorphism $\tilde{H}_I(X) \overset{\cong}{\to} \tilde{H}_{i+1}(\Sigma X)$. Here, natural means that for a map $f\colon X \to Y$, and its suspension $\Sigma f\colon \Sigma X \to \Sigma Y$, the following diagram commutes:

$$\begin{array}{ccc} \tilde{H}_i(X) & \xrightarrow{\cong} & \tilde{H}_{i+1}(\Sigma X) \\ \downarrow f_* & & \downarrow (\Sigma f)_* \\ \tilde{H}_i(Y) & \xrightarrow{\cong} & \tilde{H}_{i+1}(\Sigma Y) \end{array}$$

Definition 1.17 (Wedge Sum/one-point union)**.** Given two pointed spaces $(X, x_0), (Y, y_0)$, we define the *wedge sum* $X \vee Y$ to be

$$X \vee Y = X \sqcup Y / \left(x_0 \sim y_0 \right),$$

i.e., the quotient of the disjoint union identifying x_0 and y_0 to a single point.

Definition 1.18 (Smash Product)**.** Inside the product $X \times Y$ of two pointed space $(X, x_0), (Y, y_0)$, we have natural copies of X and Y by $X \times \{y_0\}$ and $\{x_0\} \times Y$, respectively. These two copies intersect only at the point (x_0, y_0), so their union can be identified with the wedge sum $X \vee Y$. I.e., $X \vee Y = X \times \{y_0\} \cup \{x_0\} \times Y$. We define the *smash product* $X \wedge Y$ to be the quotient $X \times Y / X \vee Y$.

If $f\colon X \to Y$ is a pointed map, then the reduced mapping cylinder of f is defined as the quotient space M_f of $(X \times I) \cup Y$ modulo the relations identifying $(x, 0) \sim f(x)$ and the set $\{*\} \times I$ to the base point of M_f.
The reduced mapping cone is the quotient of the reduced mapping cylinder M_f

obtained by identifying the image of $X \times \{1\}$ to a point, the base point.

The circle S^1 is defined as $I/\partial I$ with base point $\{\partial I\}$.
The reduced suspension of a pointed space X is $SX = X \wedge S^1$. It can also be considered as the quotient space $X \times I/\left(X \times \partial I \cup \{*\} \times I\right)$

Definition 1.19 (Well-pointed space)**.** A base point $x_0 \in X$ is said to be *nondegenerate* if the inclusion $\{x_0\} \hookrightarrow X$ is a cofibration. A pointed Hausdorff space X with nondegenerate base point is said to be *well-pointed*.

It is clear that any manifold or CW-complex satisfies Theorem 1.7 with A being any point of the space. Hence any manifold or CW-complex is well-pointed.

Example 1.20 (Pointed space that is not well-pointed)**.** Taking the pointed space $X = \{0\} \cup \left\{\frac{1}{n} \mid n \in \mathbb{N}\right\}$ with base point 0, this space is not well-pointed. This can for example be seen because it fails to satisfy Theorem 1.5 - any retraction would break continuity at $(0, 1)$.

Example 1.21. If $A \hookrightarrow X$ is a cofibration, then X/A with base point $\{A\}$ is well-pointed, as follows from Theorem 1.7.

Theorem 1.22. *If X is well-pointed, then so are the reduced cone CX and the reduced suspension SX. Moreover, the collapsing map $\Sigma X \to SX$, of the unreduced suspension to the reduced suspension, is a homotopy equivalence.*

Proof. Denote the base point of X by $*$. Consider the homeomorphism

$$h\colon\ (I \times I, I \times \{0\} \cup \partial I \times I) \xrightarrow{\cong} (I \times I, I \times \{0\})$$

which clearly exists. For example, take Figure 3

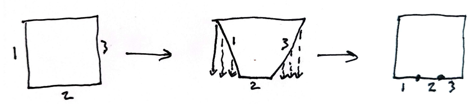

Figure 3.

Then the induced homeomorphism

$$\mathrm{id}_X \times h\colon X \times I \times I \xrightarrow{\cong} X \times I \times I$$

carries $X \times I \times \{0\} \cup X \times \partial I \times I$ to $X \times I \times \{0\}$. Hence it takes $A = X \times I \times \{0\} \cup X \times \partial I \times I \cup \{*\} \times I \times I$ to $X \times I \times \{0\} \cup \{*\} \times I \times I$. Therefore, the pair $(X \times I \times I, A)$ is homeomorphic to the pair $I \times (X \times I, X \times \{0\} \cup \{*\} \times I)$. Now, X is well-pointed, so $X \times \{0\} \cup \{*\} \times I$ is a retract of $X \times I$ by Theorem 1.5 and the definition of well-pointed. It follows that A is a retract of $X \times I \times I$. By another application of 1.5, then the inclusion $X \times \partial I \cup \{*\} \times I \hookrightarrow X \times I$ is a cofibration. Hence the quotient by this, $SX = X \times I/\left(X \times \partial I \cup \{*\} \times I\right)$ is well-pointed, using the quotient of the above inclusion.

Next consider the homeomorphism $(I \times I, I \times \{0\} \cup \{1\} \times I) \xrightarrow{\cong} (I \times I, I \times \{0\})$ which can be seen similarly. The induced homeomorphism

$$1 \times h\colon X \times I \times I \xrightarrow{\cong} X \times I \times I$$

takes $A := X \times \{1\} \times I \cup \{*\} \times I \times I \cup X \times I \times \{0\}$ to $X \times I \times \{0\} \cup \{*\} \times I \times I$. Thus the pair $(X \times I \times I, A)$ is homeomorphic to $I \times (X \times I, X \times \{0\} \cup \{*\} \times I)$. Just as above, we have that $X \times \{0\} \cup \{*\} \times I$ is a retract of $X \times I$, so it follows that A is a retract of $X \times I \times I$. Thus the inclusion $X \times \{1\} \cup \{*\} \times I \hookrightarrow X \times I$ is a cofibration, which shows that $CX = X \times I / (X \times \{1\} \cup \{*\} \times I)$ is well-pointed.

The fact that $X \times \partial I \cup \{*\} \times I \hookrightarrow X \times I$ is a cofibration gives that there exists a neighborhood U of $X \times \partial I \cup \{*\} \times I$ and a map $\varphi \colon X \times I \to I$ that satisfy Theorem 1.7. We obtain an induced map $\overline{\varphi} \colon \Sigma X \to I$ which satisfies the same conditions, so $I \times \times \{*\} \times I \hookrightarrow X \times I / \{X \times \{0\}, X \times \{1\}\} = \Sigma X$ is a cofibration. Now Theorem 1.9 implies that $\Sigma X \cup CI = C_\iota \to \Sigma X / I$ is a homotopy equivalence. Hence we obtain that $\Sigma X \simeq \Sigma X \cup CI \simeq \Sigma X / I = SX$, via the collapsing map.

□

Problem 1.23. Find $H_* \left(\mathbb{P}^2, \mathbb{P}^1\right)$ using methods or results from this section.

Solution. Consider $\mathbb{P}^2$ as S^2 quotiented by the relation $x \simeq -x$. Then we can think of $\mathbb{P}^1$ as $S^1 \subset S^2$ under this relation. We want to show that the inclusion $\mathbb{P}^1 \hookrightarrow \mathbb{P}^2$ is a cofibration. Using Theorem 1.7, it suffices to find a neighborhood U of $\mathbb{P}^1 \subset \mathbb{P}^2$ and a map $\overline{\varphi} \colon \mathbb{P}^2 \to I$ such that the conditions of the theorem are satisfied. We construct a preliminary map on S^2 towards this end. Define $\varphi \colon S^2 \to I$ to be $\varphi(x) = \min\{1, 2|x_3|\}$, where x_3 is the last coordinate of x. Since $\varphi(x) = \varphi(-x)$, φ induces a map $\overline{\varphi} \colon \mathbb{P}^2 \to I$ such that the diagram

$$\begin{tikzcd} S^2 \arrow[d] \arrow[dr, "\varphi"] & \\ \mathbb{P}^2 \arrow[r, "\overline{\varphi}"] & I \end{tikzcd}$$

commutes. Letting U be the image under the quotient map of $\left\{x \in S^2 \mid |x_3| < \frac{1}{2}\right\}$, this becomes an open set in $\mathbb{P}^2$ since the above set is saturated with respect to the quotient map. It is also clear that U and $\overline{\varphi}$ satisfy the conditions of the theorem, hence the inclusion $\mathbb{P}^1 \hookrightarrow \mathbb{P}^2$ is a cofibration. By Corollary 1.11, we obtain that $H_*\left(\mathbb{P}^2, \mathbb{P}^1\right) \cong \tilde{H}_*\left(\mathbb{P}^2/\mathbb{P}^1\right)$. But $\mathbb{P}^2/\mathbb{P}^1 \cong S^2$, so $H_*\left(\mathbb{P}^2, \mathbb{P}^1\right) \cong \tilde{H}_*\left(S^2\right)$. Now simply recall that

$$\tilde{H}_p\left(S^2\right) \cong \begin{cases} \mathbb{Z}, & p = 2 \\ 0, & p \neq 2. \end{cases}$$

□

Problem 1.24. Find $H_*\left(T^2, \{*\} \times S^1 \cup S^1 \times \{*\}\right)$ using methods from this section.

Solution. If we can show that the inclusion $A := \{*\} \times S^1 \cup S^1 \times \{*\} \hookrightarrow T^2$ is a cofibration, then we will again obtain that $H_*(T^2, A) \cong \tilde{H}_*\left(T^2/A\right) \cong \tilde{H}_*\left(S^2\right)$. But we have a CW-structure on the torus given by the square with identified sides. With this identificaiton, A simple becomes the 1-skeleton, hence it is a subcomplex, so by Corollary 1.6, the inclusion $A \hookrightarrow T^2$ is a cofibration. This finishes the solution. □

Problem 1.25. For a space X, consider the pair (CX, X). What do the results of this section tell you about the homology of these, and related, spaces?

Solution. We can define a map $\varphi \colon CX \to I$ by $\varphi(x, t) = t$. Choosing $A = X = X \times \{0\} \subset CX$ and $U = CX - \{v\}$ where v is the vertex, this satisfies the conditions in Theorem 1.7 (H can be defined by $H((x,t_0),t) = (x,t_0)(1-t) + (x,0)t$). Hence the inclusion $X \hookrightarrow CX$ is a cofibration, so we know that $H_*(CX,X) \cong \tilde{H}_*(CX/X)$. Similarly, one can show that the inclusion $X \hookrightarrow \Sigma X$ is a cofibration, so $H_*(\Sigma X, X) \cong \tilde{H}_*(\Sigma X/X) \cong \tilde{H}_*(\Sigma X \vee \Sigma X)$ and $H_*(SX,X) \cong \tilde{H}_*(SX \vee SX)$.

Problem 1.26. If $f\colon A \to X$ is a cofibration then show that f is an embedding. If X is also Hausdorff, then show that $f(A)$ is closed in X.

Proof. Since f is a cofibration, the following diagram can be filled out, inducing a map $g\colon X \times I \to M_f$:

$$\begin{tikzcd}
A \times \{0\} \arrow[rr, hook] \arrow[dd, "f\times\mathrm{id}"] & & A \times I \arrow[dl, "q"] \arrow[dd, "f\times\mathrm{id}"] \\
& M_f & \\
X \times \{0\} \arrow[rr, hook] \arrow[ur, "q"] & & X \times I \arrow[ul, "g"]
\end{tikzcd}$$

By construction, we have that $q\colon A \times \{1\} \hookrightarrow M_f$ is an embedding, so letting $l\colon q(A \times \{1\}) \to A \times \{1\}$ be the inverse map, we have $l \circ g|_{f(A)\times\{1\}} \circ (f \times \mathrm{id}) = \mathrm{id}_{A\times\{1\}}$. Likewise, $(f \times \mathrm{id}) \circ l \circ g|_{f(A)\times\{1\}}$, since $g(f(a),t) = q(a,t)$, we have that $l \circ g|_{f(A)\times\{1\}}(f(a),1) = (a,t)$, hence $(f \times \mathrm{id}) \circ l \circ g|_{f(A)\times\{1\}} = \mathrm{id}_{f(A)\times\{1\}}$. Therefore, $f \times \mathrm{id}$ is a homeomorphism $A \times \{1\} \overset{\cong}{\to} f(A) \times \{1\}$, so $f\colon A \overset{\cong}{\to} f(A)$ is a homeomorphism.

By Lemma 1.4 and Theorem 1.5, we have that there exists a retraction $r\colon X \times I \to X \times \{0\} \cup f(A) \times I$.

Lemma 1.27. *If a space X is Hausdorff and there exists a retraction $r\colon X \to A$, then A is closed.*

Proof. Let $x \in X - A$ be a limit point of A. Let U, V be open disjoint neighborhoods of x and $r(x)$. Then $r^{-1}(V)$ is open and contains x, so let $U' = U \cap r^{-1}(V)$. Now $U \cap A \cap r^{-1}(V) = \varnothing$ since otherwise $U \cap A = r(U \cap A) \subset V$ contradicting $U \cap V = \varnothing$. But then U' is an open neighborhood of x that is disjoint from A, contradicting x being a limit point of A. Thus $\overline{A} = A$. $\square$

Using this Lemma, we find that since $X \times I$ is Hausdorff and $r\colon X \times I \to X \times \{0\} \cup f(A) \times I$ is a retraction, $X \times \{0\} \cup f(A) \times I$ is closed in $X \times I$. Now, $f(A) \times \{1\} = X \times \{1\} \cap (X \times \{0\} \cup f(A) \times I)$, so since $X \times \{1\}$ is closed in $X \times I$, $f(A) \times \{1\}$ is by definition closed in $X \times \{0\} \cup f(A) \times I$ in the subspace topology. Hence it is also closed in $X \times I$. Now we use another lemma:

Lemma 1.28. *If Y is a compact space, then the projection $X \times Y \to X$ is a closed map.*

Proof. Let $W \subset X \times Y$ be closed and set $W' = X \times Y - W$. Note that $x_0 \in \pi_X(W)$ if and only if $\exists y_0 \in Y$ such that $(x_0, y_0) \in W$. Thus $x_0 \notin \pi_X(W)$ if and only if $\{x_0\} \times Y \subset W'$.
By the tube lemma, $x_0 \notin \pi_X(W)$ if and only if W' contains some tube $N \times Y$ about $\{x_0\} \times Y$ where N is an open neighborhood of x_0 in X. But then $N = \pi(N \times Y) \subset$

$X - \pi(W)$ is an open neighborhood of x_0 in $X - \pi(W)$. Hence $X - \pi(W)$ is open, so $\pi(W)$ is closed. $\square$

Noting that $\{1\} \subset I$ is compact, we can apply this Lemma to $f(A) \times \{1\}$ to obtain that $f(A)$ is closed in X. This completes the proof.

$\square$

Problem 1.29. Let $\iota\colon A \hookrightarrow X$, the inclusion of A in X, be a cofibration and A be a contractible space. Show that the quotient map $X \to X/A$ is a homotopy equivalence.

Proof. Let $H\colon A \times I \to A$ be the contraction of A where $H(a,0) = a$ and $H(a,1) = a_0 \in A$. Consider the diagram

$$\begin{tikzcd}
A \times \{0\} \arrow[rr] \arrow[dd, "\iota\times\mathrm{id}"] & & A \times I \arrow[dl, "H"] \arrow[dd, "\iota\times\mathrm{id}"] \\
& X & \\
X \times \{0\} \arrow[rr] \arrow[ur, "\mathrm{id}"] & & X \times I \arrow[ul, "\tilde{H}"]
\end{tikzcd}$$

Then since $\tilde{H}(a,t) \in A$ for all t, the composition $q\tilde{H}\colon X \times I \to X/A$ sends A to a point at all times, hence factors as $X \times I \overset{q\times\mathrm{id}}{\to} X/A \times I \to X/A$. Denote the latter map by $\overline{H}\colon X/A \times I \to X/A$. Then $q\tilde{H} = \overline{H}\,(q \times \mathrm{id})$. When $t = 1$, we have $\tilde{H}\,(A,1)$ equal to a point, so $\tilde{H}\,(-,1)$ induces a map $g\colon X/A \to X$ with $gq = \tilde{H}\,(-,1)$. It follows that $qg = \overline{H}(-,1)$ since $qg\,(\overline{x}) = qgq(x) = q\tilde{H}(x,1) = \overline{H}\,(q(x),1) = \overline{H}\,(\overline{x},1)$. Now the maps g and q are inverse homotopy equivalences since $gq = \tilde{H}(-,1) \simeq \tilde{H}(-,0) = \mathrm{id}_X$ and $qg = \overline{H}(-,1) \simeq \overline{H}(-,0) = \mathrm{id}_{X/A}$. $\square$

1.0.2. *Some Applications of the HEP.*

Proposition 1.30. *Suppose* (X, A) *and* (Y, A) *satisfy the HEP, and* $f\colon X \to Y$ *is a homotopy equivalence with* $f|_A = \mathrm{id}$. *Then* f *is a homotopy equivalence* $\mathrm{rel}\, A$.

Corollary 1.31. *If* (X, A) *satisfy the HEP and the inclusion* $A \hookrightarrow X$ *is a homotopy equivalence, then* A *is a deformation retract of* X.

Corollary 1.32. *A map* $f\colon X \to Y$ *is a homotopy equivalence if and only if* X *is a deformation retract of the mapping cylinder* M_f. *Hence, two space* X *and* Y *are homotopy equivalence if and only if there is a third space containing both* X *and* Y *as deformation retracts.*

2. The Compact-Open Topology

Recall that Y^X denotes the *set* of *continuous* functions $X \to Y$.

Definition 2.1. The *compact-open topology* on Y^X is the topology generated by the sets $M(K,U) = \left\{f \in Y^X \mid f(K) \subset U\right\}$ where $K \subset X$ is compact and $U \subset Y$ is open.

Generated here means that these sets form a *subbasis* for the open sets.

Lemma 2.2. *Let $\mathcal{K}$ be a collection of compact subsets of X containing a neighborhood base at each point of X. Let $\mathcal{B}$ be a subbasis for the open sets of Y. Then the collection*

$$\{M(K,U) \mid K \in \mathcal{K}, B \in \mathcal{B}\}$$

forms a subbasis for the compact-open topology on Y^X.

Proof. Recall first that a subbasis is a collection whose union is the whole space and such that the collection of finite intersections of elements of the subbasis form a basis.
In particular, noting that $M(K,U) \cap M(K,V) = M(K, U \cap V)$, this implies that it suffices to consider the case when $\mathcal{B}$ is a basis.
So to show that the collection in question is a subbasis, it suffices to show that given $f \in M(K,U)$, there exist $K_1, \ldots, K_n \in \mathcal{K}$ and $U_1, \ldots, U_n \in \mathcal{B}$ such that $f \in \bigcap_{i=1}^n M(K_i, U_i) \subset M(K,U)$.
For each $x \in K$, there is an open set $U_x \in \mathcal{B}$ with $f(x) \in U_x \subset U$ (since $\mathcal{B}$ was assumed to be a basis), and there exists a neighborhood $K_x \in \mathcal{K}$ of x such that $f(K_x) \subset U_x$ (since f is continuous and $\mathcal{K}$ was assumed to contain a neighborhood base at each point of X). Thus $f \in M(K_x, U_x)$. Now, covering K with these sets $K \subset \bigcup_{x \in K} K_x$. By compactness of K, there exists a finite subcover $K \subset K_{x_1} \cup \ldots \cup K_{x_n}$. Then $f \in \bigcap_{i=1}^n M(K_{x_i}, U_{x_i}) \subset M(K,U)$. □

Proposition 2.3. *For X locally compact Hausdorff, the "evaluation map" $e\colon Y^X \times X \to Y$, defined by $e(f,x) = f(x)$, is continuous.*

Proof. Let $(f,x) \in Y^X \times X$ and U a neighborhood of $f(x) \in Y$. Now we make use of the following lemma:

Lemma 2.4. *If X is a locally compact Hausdorff space, then each neighborhood of a point $x \in X$ contains a compact neighborhood of X. In particular, X is completely regular.*

Proof. Let C be a compact neighborhood of x and U an arbitrary neighborhood of x. Since X is Hausdorff, C is closed, so $(X-U) \cap C$ is a closed subspace of C, hence compact. Now, for each point $z \in (X-U) \cap C$, choose, by Hausdorffness, open neighborhoods U'_z, V'_z of z and x, respectively, and consider $W' := \bigcup_{z \in (X-U) \cap C} U'_z$. Since this is open, $C - W'$ is closed hence compact. Furthermore, it is contained in U and contains x.

Alternative proof due to Bredon: Let C be a compact neighborhood of x and U an arbitrary neighborhood of x. Let $V \subset C \cap U$ be open with $x \in V$. Then $\overline{V} \subset C$ is compact Hausdorff, hence regular, so there exists a neighborhood $N \subset V$ of x in C which is closed in $\overline{V}$ and hence closed in X. Since N is closed in the compact space

C, it is compact. Since N is a neighborhood of x in $\overline{V}$ and since $N = N \cap V$, N is a neighborhood of x in the open set V and hence in X. $\square$

By Lemma 2.4, there exists a compact neighborhood K of x such that $f(K) \subset U$. Hence $f \in M(K, U)$, and $e(M(K, U) \times K) \subset U$. This finishes the proof. $\square$

Theorem 2.5. *Let X be locally compact Hausdorff and Y and T arbitrary Hausdorff spaces. Given a function $f \colon X \times T \to Y$, define, for each $t \in T$, the function $f_t \colon X \to Y$ by $f_t(x) = f(x, t)$. Then f is continuous if and only if both of the following conditions hold:*

1. *Each f_t is continuous*
2. *The function $T \to Y^X$ taking $t \mapsto f_t$ is continuous.*

Proof. The "if" implication follows from the fact that f is the composition

$$X \times T \overset{(x,t) \mapsto (f_t, x)}{\longrightarrow} Y^X \times X \overset{e}{\to} Y.$$

Now the evaluation map is continuous by Proposition 2.3 since X is assumed to be locally compact Hausdorff and since f_t is assumed to be continuous for all t by condition (1); and $(x, t) \mapsto (f_t, x)$ is continuous since $t \mapsto f_t$ is assumed to be continuous by condition (2).
Conversely, for the "only if" implication, (1) follows from the fact that f_t is the composition

$$X \overset{x \mapsto (x,t)}{\to} X \times T \overset{f}{\to} Y.$$

To prove (2), let $t \in T$ be given and $f_t \in M(K, U)$. It suffices to find a neighborhood W of t in T such that $t' \in W$ implies that $f_{t'} \in M(K, U)$ (i.e., it suffices to prove conditions for continuity for a subbasis only). For $x \in K$, there are open neighborhoods $V_x \subset X$ of x and $W_x \subset T$ of t such that $f(V_x \times W_x) \subset U$. By compactness, $K \subset V_{x_1} \cup \ldots \cup V_{x_n} =: V$ for some V_{x_i}. Let $W = \bigcap_{i=1}^n W_{x_i}$. Then $f(K \times W) \subset f(V \times W) \subset U$. So $t' \in W$ implies that $f_{t'} \in M(K, U)$ as claimed. $\square$

Note. This theorem implies that a homotopy $X \times I \to Y$ with X locally compact is the same thing as a path $I \to Y^X$ when we give Y^X the compact-open topology.

Note. This is precisely the reason why, when we define $\mathrm{MCG}(X)$, we define it as $\pi_0 \operatorname{Homeo}^+(X, \partial X)$ where we equip $\operatorname{Homeo}^+(X, \partial X)$ with the subspace topology inherited from X^X in the compact-open topology. By the above theorem, a path $I \to \operatorname{Homeo}^+(X, \partial X)$ given as $t \mapsto \gamma_t$ is continuous if and only if the associated function $\gamma \colon X \times I \to X$ given by $\gamma(x, t) = \gamma_t(x)$ is continuous. But since each γ_t is a self-homeomorphism of X, this just tells us that γ is an isotopy of X. So path components of $\operatorname{Homeo}^+(X, \partial X)$ correspond to isotopy classes of orientation-preserving self-homeomorphisms of X fixing the boundary point-wise.

Theorem 2.6 (The Exponential Law)**.** *Let X and T be locally compact Hausdorff spaces and let Y be an arbitrary Hausdorff space. Then there is the homeomorphism*

$$Y^{X \times T} \overset{\cong}{\to} \left(Y^X\right)^T$$

taking $f \mapsto f^*$ where $f^*(t)(x) = f(x, t) = f_t(x)$.

Proof. By Theorem 2.5, the assignment $f \mapsto f^*$ is a bijection.
We must show it and its inverse to be continuous. Let $U \subset Y$ be open and $K \subset X, K' \subset T$ be compact. Then

$$\begin{aligned} f \in M\left(K \times K', U\right) &\iff \left(t \in K', x \in K \implies f_t(x) = f(x,t) \in U\right) \\ &\iff \left(t \in K' \implies f_t \in M\left(K, U\right)\right) \\ &\iff f^* \in M\left(K', M\left(K,U\right)\right). \end{aligned}$$

Now, the $K \times K'$ are compact subsets of $X \times T$, and the collection of all these over $X \times T$ contain a neighborhood basis at each point since X and T are both assumed to be locally compact. By Lemma 2.2, the collection

$$\left\{M\left(K \times K', U\right) \mid U \subset Y \text{ open}, K \subset X, K' \subset T \text{ both compact}\right\}$$

forms a subbasis for the compact-open topology on $Y^{X \times T}$. Also, the $M\left(K,U\right)$ give a subbasis for Y^X and therefore the $M\left(K', M\left(K,U\right)\right)$ form a subbasis for the topology on $\left(Y^X\right)^T$. Since we showed that these subbases correspond to one another under the exponential correspondence, the theorem is proved. □

Proposition 2.7. *If X is locally compact Hausdorff and Y and W are Hausdorff, then there is the homeomorphism*

$$Y^X \times W^X \xrightarrow{\cong} \left(Y \times W\right)^X$$

given by $(f,g) \mapsto f \times g$.

Proof. It is clearly a bijection. If $K, K' \subset X$ are compact and $U \subset Y$ and $V \subset W$ are open, then

$$\begin{aligned} (f,g) \in M\left(K,U\right) \times M\left(K',V\right) &\iff \left(x \in K \implies f(x) \in U\right) \text{ and } \left(x \in K' \implies g(x) \in V\right) \\ &\iff \left((x,y) \in K \times K' \implies f \times g(x,y) \in U \times V\right) \\ &\iff f \times g \in M\left(K, U \times W\right) \cap M\left(K', U \times W\right). \end{aligned}$$

so $(f,g) \mapsto f \times g$ is an open map.
Also $(f,g) \in M(K,U) \times M(K,V) \iff f \times g \in M\left(K, U \times V\right)$ which implies that the function is continuous. □

Proposition 2.8. *If X and T are locally compact Hausdorff spaces and Y is an arbitrary Hausdorff space, then there is the homeomorphism*

$$Y^{X \sqcup T} \xrightarrow{\cong} Y^X \times Y^T$$

taking $f \mapsto (f \circ \iota_X, f \circ \iota_T)$.

Proof. The map is clearly well-defined and injective. Also, given $(f,g) \in Y^X \times Y^T$, we can define a function $f \cup g \colon X \sqcup T \to Y$ by f on X and g on T, and clearly, $f \cup g \mapsto (f,g)$ under the correspondence, giving surjectivity. We must show that it is continuous and has continuous inverse.
Let $f \colon X \sqcup T \to Y$ and suppose $(f \circ \iota_X, f \circ \iota_T) \in M\left(K,U\right) \times M\left(K',V\right)$. Then $f \in M\left(K,U\right) \cap M\left(K',V\right)$ which is an open set that is mapped precisely to $M\left(K,U\right) \times M\left(K',V\right)$. Hence $f \mapsto (f \circ \iota_X, f \circ \iota_T)$ is continuous.

Conversely, note that under the correspondence, $M\left(C \sqcup C', U\right)$ is mapped to $M(C,U) \times M(C',U)$, so the map is also open. □

Theorem 2.9. *For X locally compact and both X and Y Hausdorff, Y^X is a covariant functor of Y and a contravariant functor of X from* Top *to* Top.

3. Homotopy Groups

3.1. **Homotopy.** We follow chapter 14 of [1] for this subsection.

To start of, we recall the basic definitions of homotopies.

Definition 3.1 (Homotopy)**.** Two maps $f_0, f_1 \colon X \to Y$ are said to be *homotopic* if there exists a homotopy $F \colon X \times I \to Y$ such that $F(x, 0) = f_0(x)$ and $F(x, 1) = f_1(x)$ for all $x \in X$.

Definition 3.2 (Homotopy equivalence)**.** A map $f \colon X \to Y$ is said to be a *homotopy equivalence* if it is an isomorphism in hTop.

Lemma 3.3 (Reparametrization Lemma)**.** *Let φ_1, φ_2 be maps $(I, \partial I) \to (I, \partial I)$ which are equal on ∂I. Let $F \colon X \times I \to Y$ be a homotopy and let $G_i(x, t) = F(x, \varphi_i(t))$ for $i = 1, 2$. Then $G_1 \simeq G_2 \operatorname{rel} X \times \partial I$.*

We shall use c to denote the constant homotopy.

Proposition 3.4. *$F * c \simeq F \operatorname{rel} X \times \partial I$ and $c * F \simeq F \operatorname{rel} X \times \partial I$.*

Definition 3.5. If $F \colon X \times I \to Y$ is a homotopy, then we define $F^{-1} \colon X \times I \to Y$ by $F^{-1}(x, t) = F(x, 1 - t)$.

Note that F^{-1} is precisely the inverse to F in hTop.

Proposition 3.6. *For any homotopies F, G, H for which the concatenations are defined, we have*

$$(F * G) * H \simeq F * (G * H) \operatorname{rel} X \times \partial I.$$

Proposition 3.7. *For homotopies F_1, F_2, G_1, G_2, if $F_1 \simeq F_2 \operatorname{rel} X \times \partial I$ and $G_1 \simeq G_2 \operatorname{rel} X \times \partial I$, then $F_1 * G_1 \simeq F_2 * G_2 \operatorname{rel} X \times \partial I$.*

Note that all of the discussion of concatenation of homotopies goes through with no difficulties for the cases in which all homotopies are relative to some subspace $A \subset X$ or are homotopies of pairs $(X, A) \to (Y, B)$.
It follows that homotopy between maps of pairs $(X, A) \to (Y, B)$ is an equivalence relation. The set of homotopy classes of these maps is commonly denoted by $[X, A; Y, B]$ or just $[X; Y]$ if $A = \varnothing$.

Theorem 3.8. *If $f_0 \simeq f_1 \colon X \to Y$ then $M_{f_0} \simeq M_{f_1} \operatorname{rel} X + Y$ and $C_{f_0} \simeq C_{f_1} \operatorname{rel} Y +$ vertex.*

To show this, one needs the following basic topological proposition:

Proposition 3.9. *If $f \colon X \to Y$ is a quotient map and K is locally compact Hausdorff, then $f \times 1 \colon X \times K \to Y \times K$ is a quotient map.*

Proof of Theorem 3.8. First, let $F \colon X \times I \to Y$ be the homotopy between f_0 and f_1. Now define $h \colon M_{f_0} \to M_{f_1}$ by $h(y) = y$ for $y \in Y$ and

$$h(x, t) = \begin{cases} F(x, 2t), & t \leq \frac{1}{2} \\ (x, 2t - 1), & \frac{1}{2} \leq t. \end{cases}$$

Define $k\colon M_{f_1} \to M_{f_0}$ likewise by the identity on Y nad

$$k\left(x,t\right) = \begin{cases} F^{-1}\left(x,2t\right), & t \leq \frac{1}{2} \\ (x,2t-1), & \frac{1}{2} \leq t \end{cases}.$$

Then the composition $kh\colon M_{f_0} \to M_{f_1}$ is the identity on Y and $F * \left(F^{-1} * E\right)$ on the cylinder portion, where $E\colon X \times I \to M_{f_0}$ is induced by the identity on $X \times I \to X \times I$. This is homotopic to the identity $\operatorname{rel} X \times \{1\} + Y$. Similarly for hk. In now remains to check the continuity of this homotopy. We have a homotopy $M_{f_0} \times I \to M_{f_0}$. We now claim that $M_{f_0} \times I \cong M_{f_0 \times I}$. Indeed then, using that $M_{f_0 \times I} = \frac{X \times I \times I \sqcup Y \times I}{((x,0,k)\sim(f_0(x),k)}$, it suffices to show continuity of the composition $X \times I \times I \sqcup Y \times I \to M_{f_0} \times I \to M_{f_0}$. For on $Y \times I$, it is the constant homotopy and on $X \times I \times I$ it is $F * \left(F^{-1} * E\right) \simeq E \operatorname{rel} X \times \partial I$. Now, that $M_{f_0} \times I \cong M_{f_0 \times I}$ follows from Proposition 3.9.

□

Let $f\colon X \to Y$. If $\varphi\colon Y \to Y'$ is a map, then there is the induced map $F\colon M_f \to M_{\varphi \circ f}$ induced from φ on Y and the identity on $X \times I$.

Theorem 3.10. *If $\varphi\colon Y \to Y'$ is a homotopy equivalence then so is $F\colon (M_f, X) \to (M_{\varphi\circ f}, X)$ and hence so is $F\colon C_f \to C_{\varphi \circ f}$.*

Proof. Let $\psi\colon Y' \to Y$ be a homotopy inverse of φ and let $G\colon M_{\varphi\circ f} \to M_{\psi\circ\varphi\circ f}$ be the map induced by ψ on Y' and the identity on $X \times I$. The composition $GF\colon M_f \to M_{\psi\circ\varphi\circ f}$ is induced from $\psi \circ \varphi\colon Y \to Y$ and the identity on $X \times I$. Let $H\colon Y \times I \to Y$ be a homotopy from id to $\psi \circ \varphi$; i.e., $H(y,0) = y$ and $H(y,1) = \psi\varphi(y)$. By the proof of Theorem 3.8, there is a homotopy equivalence $h\colon M_f \to M_{\psi\circ\varphi\circ f} \operatorname{rel} X$ given by $h(y) = y$ and

$$h(x,t) = \begin{cases} H\left(f(x),2t\right), & t \leq \frac{1}{2} \\ (x,2t-1), & t \geq \frac{1}{2} \end{cases}.$$

We claim that $h \simeq GF \operatorname{rel} X$. Indeed, the homotopy H can be extended to $M_f \times I \to M_{\psi\circ\varphi\circ f}$ by putting

$$H\left((x,s),t\right) = \begin{cases} H\left(f(x),2s+t\right), & 2s+t \leq 1 \\ \left(x, \frac{2s+t-1}{t+1}\right), & 2s+t \geq 1 \end{cases}.$$

Then $H\left(-,0\right) = h$ and $H\left(-,1\right) = GF$, so since GF is a homotopy equvalence, so is h. Define $F'\colon M_{\psi\circ\varphi\circ f} \to M_{\varphi\circ\psi\circ\varphi\circ f}$ as the induced map on mapping cones with φ on Y and the identity on $X \times I$. Then similarly, $F'G$ is a homotopy equivalence. If k is a homotopy inverse of GF then $GFk \simeq \mathrm{id}$. If k' is a homotopy inverse of $F'G$ then $k'F'G \simeq \mathrm{id}$. Thus G has a right and left homotopy inverse: $R = Fk$ and $L = k'F'$. Then $R = \mathrm{id} \circ R \simeq (LG)\, R = L\,(GR) \simeq L \circ \mathrm{id} = L$, so $R \simeq L$. That is, G has a homotopy inverse. Therefore, G is a homotopy equivalence. Since G and GF are homotopy equivalences, so is F. □

Problem 3.11. [1, Ex 14.1] Let $S^2 \cup A$ denote the union of the unit 2-sphere and the line segment joining the north and south poles. Show that $S^2 \vee S^1 \simeq S^2 \cup A$.

Proof. Define two maps $f_0, f_1\colon \{0,1\} \to S^2$ where $f_0(t) = (\cos(2\pi t), \sin(2\pi t), 0)$ and f_1 is the constant map at $(1,0,0)$. Then $f_0 \simeq f_1$, so $C_{f_0} \simeq C_{f_1}$. Now, $C_{f_0} = S^2 \cup A$ while $C_{f_1} = S^2 \vee S^1$. □

Problem 3.12. [1, Ex 14.2] Show that the union of a 2-sphere and a flat unit 2-cell through the origin is homotopically equivalent to the one-point union of two 2-spheres.

Proof. A 2-cell is contractible, an a 2-sphere with a 2-cell inside it is precisely the cone of the map $S^1 \sqcup S^1 \to S^1$ with the identity on both. By [1, Thm 14.19], this is homotopy equivalent to the cone on $S^1 \sqcup S^1 \to \{*\}$ which is $S^2 \vee S^2$. $\square$

Problem 3.13. Show that the union of a standard 2-torus with two disks, one spanning a latitudinal circle and the other spanning a longitudinal circle of the torus, is homotopically equivalent to a 2-sphere.

Proof. Using the identification of the torus as the quotient space of I^2 in the usual way, we can choose on spanning circle to be a 2-cell attached along $\{0\} \times I$ and the other to be a 2-cell attached along $I \times \{0\}$. These are contractible, and the quotient space becomes a 2-sphere. $\square$

3.2. **Homotopy Groups.** Recall that $[X, A; Y, B]$ denotes the set of homotopy classes of maps $X \to Y$ carrying A into B such that A goes into B during the entire homotopy.
To make a group then, we can select a point $y_0 \in Y$ and consider the set

$$[X \times I, X \times \partial I; Y, \{y_0\}]$$

In this case, the operation of concatenation of homotopies makes this set into a group. It is technically also better to choose a basepoint $x_0 \in X$ and consider

$$[X \times I, \{x_0\} \times I \cup X \times \partial I; Y, \{y_0\}] .$$

For the moment, let us set $A = \{x_0\} \times I \cup X \times \partial I$. Then maps $X \times I \to Y$ which carry A into $\{y_0\}$ are in bijective correspondence with maps $(X \times I)/A \to Y$ which take the point $\{A\}$ into $\{y_0\}$.

Definition 3.14 (Reduced Suspension)**.** We define the *reduced suspension* of X to be

$$SX = (X \times I)/A = (X \times I) / (\{x_0\} \times I \cup X \times \partial I)$$

The set of homotopy classes of pointed maps of a pointed space X to a pointed space Y with homotopies preserving the base points will be denoted by $[X; Y]_*$.
Thus $[SX; Y]_*$ is in canonical bijective correspondence with $[X \times I, A; Y, \{y_0\}]$.
Now, suppose we have pointed maps $f, g \colon SX \to Y$. Then they induce homotopies $f', g' \colon X \times I \to Y$ by precomposing with the quotient map $X \times I \to SX$. We can then define $f' * g' \colon X \times I \to Y$ as usual. The resulting pointed map $SX \to Y$ will be denoted $f * g$. Geometrically, $f * g$ is obtained by putting f on the bottom and g on the top of the one-point union $SX \vee SX$ and composing the resulting map $SX \vee SX \to Y$ with the map $SX \to SX \vee SX$ obtained by collapsing the middle parameter value $\frac{1}{2}$ copy of X in SX to the base point.
For a map $f \colon (SX, \{A\}) \to (Y, \{y_0\})$, we denote its homotopy class in $[SX; Y]_*$ by $[f]$, and we define

$$[f]\,[g] = [f * g]$$

Under this operation, the set $[SX; Y]_*$ becomes a group.

Proposition 3.15. *The reduced suspension gives $SS^{n-1} \cong S^n$.*

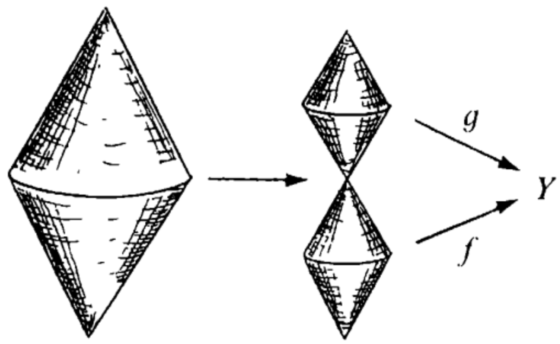

FIGURE 4. The product of two map classes $SX \to Y$.

Thus, we can define S^n as the n-fold reduced suspension of S^0. As a special case, the set $[S^n; Y]_*$ then becomes a group for $n > 0$.

Definition 3.16 (n th homotopy group)**.** We define

$$\pi_n(Y, y_0) = [S^n; Y]_*$$

with this operation.

3.2.1. *A different way of defining $\pi_n(Y, y_0)$.* Note that reduced suspension supplies a parameter in $[0,1]$ and the space S^n as constructed is the quotient space of I^n obtained by collapsing the boundary of the cube to a point. Pointed maps $S^n \to Y$ are in bijective correspondence with maps $I^n \to Y$ taking ∂I^n to the base point of Y. This is a more traditional way of defining $\pi_n(Y)$. This becomes the group of homotopy classes of maps $(I^n, \partial I^n) \to (Y, \{y_0\})$ with the operation being

$$f * g(t_1, \ldots, t_n) = \begin{cases} f(2t_1, t_2, \ldots, t_n), & t_1 \in \left[0, \frac{1}{2}\right] \\ g(2t_1 - 1, t_2, \ldots, t_n), & t_1 \in \left[\frac{1}{2}, 1\right] \end{cases}.$$

Proposition 3.17. *For $n \geq 2$, $\pi_n(X, x_0)$ is abelian.*

Proof. Consider the homotopy in Figure 5. We begin by shrinking the domains of f and g to smaller subcubes of I^n, where the region outside is mapped to the basepoint. This allows us to move the boxes around in a continuous manner. The rest is clear. □

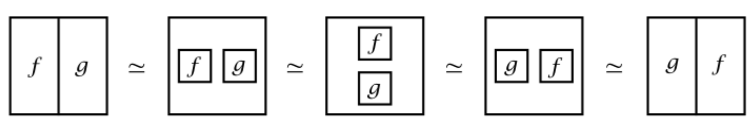

FIGURE 5. The homotopy in question

Next, we want to show that following:

Proposition 3.18. *If X is path-connected, then $\pi_n(X, x_0) \cong \pi_n(X, x_1)$ for any two $x_0, x_1 \in X$.*

For this, we introduce an action of π_1 on π_n.

Definition 3.19 (The action of π_1 on π_n)**.** Given a path $\gamma\colon I \to X$ from x_0 to x_1, we associate to a map $f\colon (I^n, \partial I^n) \to (X, x_1)$ the map $\gamma f\colon (I^n, \partial I^n) \to (X, x_0)$ by shrinking the domain of f to a smaller concentric cube in I^n, then inserting the path γ on each radial segment in the shell between this smaller cube and ∂I^n. See Figure 6

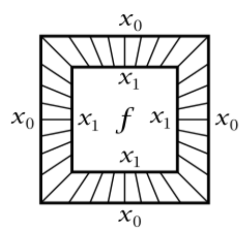

FIGURE 6. Depiction of γf.

Note. We have the following properties

(1) $\gamma (f + g) \simeq \gamma f + \gamma g$.
(2) $(\gamma\eta) f \simeq \gamma (\eta f)$.
(3) $\mathrm{id} f \simeq f$, where id denotes the constant path.

To see (1), first deform f and g to be constant on the right and left halves of I^n, respectively, producing maps which we may call $f+0$ and $0+g$, then we can excise a progressively wider symmetric middle slab of $\gamma(f+0)+\gamma(0+g)$ (which can be seen on the left in Figure 7) until it becomes $\gamma (f+g)$ (shown on the right).

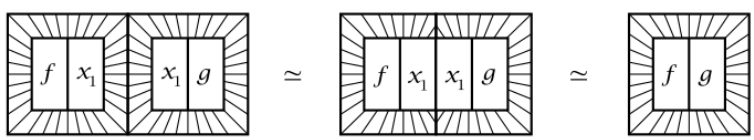

FIGURE 7.

Now if $\beta_\gamma\colon \pi_n(X, x_1) \to \pi_n(X, x_0)$ is the change-of-basepoint transformation, $\beta_\gamma [f] = [\gamma f]$, then the above note shows that β_γ is a group isomorphism. This proves Proposition 3.18. If we restrict attention to loops γ at x_0, then since $\beta_{\gamma\eta} = \beta_\gamma \beta_\eta$, the map $[\gamma] \mapsto \beta_\gamma$ defines a homomorphism from $\pi_1 (X, x_0)$ to $\mathrm{Aut}(\pi_n (X, x_0))$ called the *action of* π_1 *on* π_n .

Note. For $n > 1$, this action makes $\pi_n(X, x_0)$ into a module over the group ring $\mathbb{Z} [\pi_1 (X, x_0)]$.

Definition 3.20 (Simple/abelian spaces)**.** A space with trivial π_1 action on π_n is called 'n-simple', and 'simple' means ' n-simple for all n '. We call a space *abelian* if it has trivial action of π_1 on all homotopy groups π_n.

Proposition 3.21 (π_n is a functor)**.** *A map* $\varphi\colon (X, x_0) \to (Y, y_0)$ *induces a map* $\varphi_*\colon \pi_n (X, x_0) \to \pi_n (Y, y_0)$ *defined by* $\varphi_* [f] = [\varphi f]$. *It is immediate from the definitions that* φ_* *is well-defined and a homomorphism for* $n \geq 1$. *The functorial properties are also clear.*

Corollary 3.22. *Homotopy equivalent spaces have isomorphic homotopy groups.*

Proposition 3.23. *A covering space projection* $p\colon \left(\tilde{X}, \tilde{x}_0\right) \to (X, x_0)$ *induces isomorphisms* $p_*\colon \pi_n\left(\tilde{X}, \tilde{x}_0\right) \to \pi_n(X, x_0)$ *for all* $n \geq 2$.

Proof. Since S^n is path-connected and locally path-connected, and simply connected for $n \geq 2$, we find that any map $(S^n, s_0) \to (X, x_0)$ lifts to a map $(S^n, s_0) \to \left(\tilde{X}, \tilde{x}_0\right)$ when $n \geq 2$. This gives surjectivity of p_*. For injectivity, suppose $p_*[f] = [0]$ where $f\colon (S^n, s_0) \to \left(\tilde{X}, \tilde{x}_0\right)$. Let $c_{\tilde{x}_0}$ be the constant map at $\tilde{x}_0$. Then $p_*[\tilde{x}_0] = [0]$, so by uniqueness of the lifting theorem, $[f] = [c_{\tilde{x}_0}] = [0]$. ☐

Definition 3.24 (Aspherical)**.** Spaces with $\pi_n = 0$ for all $n \geq 2$ are called *aspherical.*

Corollary 3.25. S^1, T^n *and* K *are aspherical since they have contractible covering spaces.*

Proposition 3.26.

$$\pi_n\left(\prod_\alpha X_\alpha\right) \cong \prod_\alpha \pi_n(X_\alpha)$$

Next we define relative homotopy groups.

Definition 3.27 (Relative homotopy groups)**.** Regard I^{n-1} as a face of I^n with the last coordinate $s_n = 0$ and let J^{n-1} be the closure of $\partial I^n - I^{n-1}$. Then we define

$$\pi_n(X, A, x_0) := \left[I^n, \partial I^n, J^{n-1}; X, A, x_0\right]$$

We shall leave $\pi_0(X, A, x_0)$ undefined for now.

We can define a sum operation on $\pi_n(X, A, x_0)$ in the same way as for $\pi_n(X, x_0)$, except now the coordinate s_n now must remain free, so we must use one of the other coordinates. Thus we must have at least one other coordinate to define the same operation. So $\pi_n(X, A, x_0)$ is a group for $n \geq 2$, and it is abelian for $n \geq 3$. For $n = 1$, we have $I^1 = [0, 1], I^0 = \{0\}$ and $J^0 = \{1\}$, so $\pi_1(X, A, x_0) = [I, \{0\}, \{1\}; X, A, x_0]$ is the set of homotopy classes of paths in X from a varying point in A to the fixed basepoint $x_0 \in A$. In general, this is not a group in any natural way.

Now, we saw before that $\pi_n(X, x_0)$ can be regarded as homotopy classes of maps $(S^n, x_0) \to (X, x_0)$. Similarly, collapsing J^{n-1} to a point, converts $\left(I^n, \partial I^n, J^{n-1}\right)$ to $\left(D^n, S^{n-1}, s_0\right)$. In this case, addition is done by the map $c\colon D^n \to D^n \vee D^n$ collapsing $D^{n-1} \subset D^n$ to a point.

Theorem 3.28 (Compression criterion)**.** *A map* $f\colon \left(D^n, S^{n-1}, s_0\right) \to (X, A, x_0)$ *represents zero in* $\pi_n(X, A, x_0)$ *if and only if it is homotopic* $\operatorname{rel} S^{n-1}$ *to a map with image contained in* A.

Proof. Suppose we have a homotopy $\operatorname{rel} S^{n-1}$ from f to a map g, so $[f] = [g]$ in $\pi_n(X, A, x_0)$. Viewing g as a map $\left(D^n, S^{n-1}, s_0\right) \to (X, A, x_0)$ whose image is contained in A, we can construct the homotopy $H\colon D^n \times I \to X$ by $H(x,t) = g\left((1-t)x + s_0 t\right)$ which is a homotopy from g to the constant map at x_0, hence $[g] = 0$ in $\pi_n(X, A, x_0)$.
Conversely, if $[f] = 0$ via a homotopy $F\colon D^n \times I \to X$ such that $F(x,0) = f(x)$ and $F(x,1) = x_0$ for all $x \in D^n$ and $F(x,t) \in A$ for all x with $|x| = 1$ as well as $F(s_0, t) = x_0$ for all t. We can construct a homotopy using F by restricting F to a family of n-disks in $D^n \times I$ starting with $D^n \times \{0\}$ and ending with the disk $D^n \times \{1\} \cup S^{n-1} \times I$, and where all the disks throughout the family have the same boundary. See Figure 8 for a depiction of this homotopy.

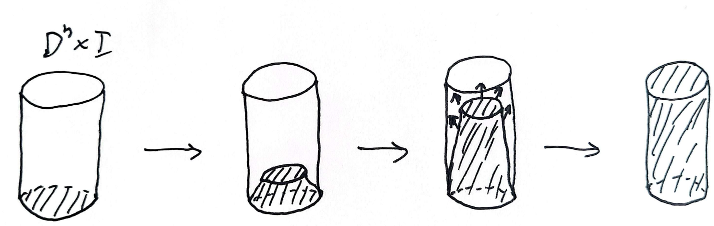

FIGURE 8.

This completes the proof. □

Next, some things that carry over: a map $\varphi\colon (X, A, x_0) \to (Y, B, y_0)$ induces maps $\varphi_*\colon \pi_n(X, A, x_0) \to \pi_n(Y, B, y_0)$ which are homomorphisms when $n \geq 2$ and have properties analogous to those in the absolute case: $(\varphi\psi)_* = \varphi_*\psi_*$, $(\mathrm{id}_{(X,A,x_0)})_* = \mathrm{id}_{\pi_n(X,A,x_0)}$, and if $\varphi \simeq \psi$ through maps $(X, A, x_0) \to (Y, B, y_0)$, then $\varphi_* = \psi_*$.

3.2.2. *LES of relative homotopy groups.* Probably the most useful feature of relative homotopy groups $\pi_n(X, A, x_0)$ is that they fit into a long exact sequence

$$\ldots \to \pi_n(A, x_0) \xrightarrow{i_*} \pi_n(X, x_0) \xrightarrow{j_*} \pi_n(X, A, x_0) \xrightarrow{\partial} \pi_{n-1}(A, x_0) \to \ldots \to \pi_0(X, x_0).$$

Here i and j are the inclusions $(A, x_0) \hookrightarrow (X, x_0)$ and $(X, x_0, x_0) \hookrightarrow (X, A, x_0)$. The map ∂ comes from restricting maps $\left(I^n, \partial I^n, J^{n-1}\right) \to (X, A, x_0)$ to I^{n-1} (the face of I^n with the last coordinate $s_n = 0$), or equivalently, by restricting maps $\left(D^n, S^{n-1}, s_0\right) \to (X, A, x_0)$ to S^{n-1}. The map ∂, called the *boundary map*, is a homomorphism when $n > 1$. In fact, we can show the following theorem

Theorem 3.29 (LES of relative homotopy groups)**.** *Given $x_0 \in B \subset A \subset X$, the sequence of relative homotopy groups*

$$\ldots \to \pi_n(A, B, x_0) \xrightarrow{i_*} \pi_n(X, B, x_0) \xrightarrow{j_*} \pi_n(X, A, x_0) \xrightarrow{\partial} \pi_{n-1}(A, B, x_0) \to \ldots \to \pi_1(X, A, x_0)$$

is exact and natural. In the case when $B = \{x_0\}$, we have that the LES

$$\ldots \to \pi_n(A, x_0) \xrightarrow{i_*} \pi_n(X, x_0) \xrightarrow{j_*} \pi_n(X, A, x_0) \xrightarrow{\partial} \pi_{n-1}(A, x_0) \to \ldots \to \pi_0(X, x_0).$$

is exact and natural.

Proof. Exactness at $\pi_n(X, B, x_0)$ *:* the composition $j_* i_*$ is zero because any map $\left(I^n, \partial I^n, J^{n-1}\right) \to (A, B, x_0)$ is zero in $\pi_n(X, A, x_0)$ by the compression criterion (Theorem 3.28). To see that $\ker j_* \subset \operatorname{im} i_*$, let $f\colon \left(I^n, \partial I^n, J^{n-1}\right) \to (X, B, x_0)$ represent zero in $\pi_n(X, A, x_0)$. Using the compression criterion again, we then get that f is homotopic $\operatorname{rel} \partial I^n$ to a map with image in A, hence the class $[f] \in \pi_n(X, B, x_0)$ is indeed in the image of i_*. We conclude that $\ker j_* = \operatorname{im} i_*$, obtaining exactness at $\pi_n(X, B, x_0)$.
Exactness at $\pi_n(X, A, x_0)$*:* for a map $[f] \in \operatorname{im} j_*$, we have that j_* maps ∂I^n into B, hence in particular $I^{n-1} \subset \partial I^n$ into B, so $\partial j_*[f]$ represents a homotopy class in $\pi_{n-1}(A, B, x_0)$ with image in B, but then by the compression criterion, $\partial j_*[f] = 0$ in $\pi_{n-1}(A, B, x_0)$, so $\operatorname{im} j_* \subset \ker \partial$. Conversely, suppose $\partial[f] = 0$. By the compression criterion, representatives of $\partial[f]$ are homotopic $\operatorname{rel} \partial I^{n-1}$ to a map with image in B. In particular, $f|_{I^{n-1}}$ is homotopic to a map with image in B via a homotopy $F\colon I^{n-1} \times I \to A \operatorname{rel} \partial I^{n-1}$. We can tack F onto f to get a new map $\left(I^n, \partial I^n, J^{n-1}\right) \to (X, B, x_0)$ which, as a map $\left(I^n, \partial I^n, J^{n-1}\right) \to (X, A, x_0)$ is homotopic to f by the homotopy that tacks on increasingly longer initial segments of F. See Figure 9. Hence $[f] \in \operatorname{im} j_*$.

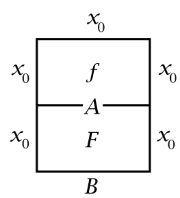

FIGURE 9.

Exactness at $\pi_n(A, B, x_0)$ *:* First, $i_*\partial$ is zero since the restriction of a map $f\colon \left(I^{n+1}, \partial I^{n+1}, J^n\right) \to (X, A, x_0)$ to I^n is homotopic $\operatorname{rel} \partial I^n$ to a constant map via f itself (a similar picture to Figure 8 works).
Conversely, if B is a point, then a nullhomotopy $f_t\colon (I^n, \partial I^n) \to (X, x_0)$ of $f_0\colon (I^n, \partial I^n) \to (A, x_0)$ gives a map $F\colon \left(I^{n+1}, \partial I^{n+1}, J^n\right) \to (X, A, x_0)$ with $\partial([F]) = [f_0]$. So in this case, the proof is finished. For a general B, let F be a nullhomotopy of $f\colon \left(I^n, \partial I^n, J^{n-1}\right) \to (A, B, x_0)$ through maps $\left(I^n, \partial I^n, J^{n-1}\right) \to (X, B, x_0)$ and let g be the restriction of F to I^{n-1} in $I^{n-1} \times I = I^n$ (see the first of the pictures in Figure 10). Next reparametrize the n th and $(n+1)$ st coordinates as in the second picture. Then we find that f with g tacked on is in the image of ∂. But as before, tacking g onto f gives the same element of $\pi_n(A, B, x_0)$

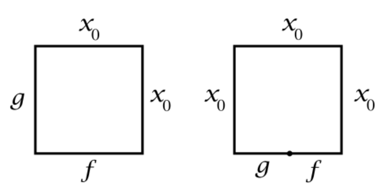

FIGURE 10.

$\square$

Corollary 3.30. *Consider the inclusion* $\iota\colon X = X\times\{0\} \hookrightarrow CX$. *Then* $\pi_n\left(CX, X, x_0\right) \cong \pi_{n-1}\left(X, x_0\right)$ *for all* $n \geq 1$. *Taking* $n = 2$, *we can thus realize an group* G, *abelian or not, as a relative* π_2 *by choosing* X *to have* $\pi_1(X) \cong G$.

There are also change-of-basepoint isomorphisms β_γ for relative homotopy groups. One takes a path γ in $A \subset X$ from x_0 to x_1 which induces $\beta_\gamma\colon \pi_n(X, A, x_1) \to \pi_n(X, A, x_0)$ by setting $\beta_\gamma\left([f]\right) = [\gamma f]$, where γf is depicted in Figure 11.

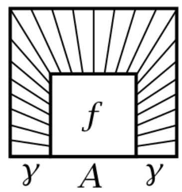

FIGURE 11.

Restricting to loops at the basepoint, the association $\gamma \mapsto \beta_\gamma$ defines an action of $\pi_1\left(A, x_0\right)$ on $\pi_n\left(X, A, x_0\right)$ analogous to the action of $\pi_1\left(X, x_0\right)$ on $\pi_n(X, x_0)$.

3.3. **Problem set 1.**

3.3.1. *Exercises.*

Exercise 3.31 (The action of the fundamental gorup, part 2)**.** Let X be a path-connected, semi-locally simply-connected space with basepoint x and $p\colon \tilde{X} \to X$ its universal cover. Show that for $n \geq 2$ and $\tilde{x} \in X$ with $p(\tilde{x}) = x$, the isomorphism $p_* = \pi_n(p)\colon \pi_n\left(\tilde{X}, \tilde{x}\right) \cong \pi_n(X, x)$ allows us to identify the action of $\pi_1(X, x)$ on $\pi_n(X, x)$ with the action of $\pi_1(X, x)$ on $\pi_n\left(\tilde{X}, \tilde{x}\right)$ induced by the group of deck transformations, i.e., the natural action of $\pi_1(X, x)$ on $\tilde{X}$. In particular, make the statement precise.

Proof. We want to show that for $[\gamma] \in \pi_1(X, x)$ and $[f] \in \pi_n(X, x)$, if $\tilde{g}$ is the lift for γ starting at $\tilde{x}_0$, and $\tilde{f}\colon (S^n, s_0) \to \left(\tilde{X}, \tilde{x}_0\right)$ is the lift of f, then $p_*\left(\tilde{\gamma}\tilde{f}\right) = \gamma f$. But this follows directly from how $\tilde{\gamma}\tilde{f}$ and γf we constructed. Namely, applying p to the square used in the definition, we see that we obtain γf from $\tilde{\gamma}\tilde{f}$ since $p \circ \tilde{\gamma} = \gamma$ and $p \circ \tilde{f} = f$. □

Exercise 3.32. Let X and Y be pointed spaces and $n \geq 2$. Show that the inclusion $X \vee Y \hookrightarrow X \times Y$ induces a surjection $\pi_n(X \vee Y) \to \pi_n(X \times Y)$ for all n. Furthermore, this exhibits $\pi_n(X \times Y)$ as a retract of $\pi_n(X \vee Y)$ for all n. (Is this also true for $n = 1$?)

Proof. a □

3.3.2. *Problems.*

Problem 3.33. Fix an isomorphism $H_n(S^n) \cong \mathbb{Z}$. We define the degree $\deg f$ of a map $f\colon S^n \to S^n$ to be the integer such that $f_*\colon H_n(S^n) \to H_n(S^n)$ sends 1 to $\deg f \in \mathbb{Z}$.

(1) Show that taking the degree of a map $S^n \to S^n$ induces a well-defined map
$$\deg\colon \pi_n(S^n) \to \mathbb{Z}$$
(2) Show that deg is a group homomorphism.
(3) Show that the map deg is surjective.
(4) Suppose that $n \geq 2$. Show that $\pi_n(S^n) \cong \mathbb{Z} \times A$ for some abelian group A.

Proof. (1) Let $[f] \in \pi_n(S^n)$ and suppose f, f' are two representatives of this class. Then f and f' are homotopic by definition, so $f_* = (f')_* : \mathbb{Z} = H_n(S^n) \to H_n(S^n) = \mathbb{Z}$ are equal. In particular, $\deg f = f_*(1) = (f')_*(1) = \deg f'$. So the map is well-defined.

(2) To show that degree is a group homomorphism, we must show that $\deg(f + g) = \deg f + \deg g$.

For this, we will show a couple of results.

Proposition 3.34. *Let $X = S^n_1 \vee \ldots \vee S^n_k$ for $n > 0$. Then the homomorphism $H_n(S^n_1) \oplus \ldots \oplus H_n(S^n_k) \to H_n(X)$ induced by the inclusion maps is an isomorphism whose inverse is induced by the projections $X \to S^n_i$.*

To prove this proposition, we must show the following lemma.

Lemma 3.35. *Let X be a Hausdorff space and let $x_0 \in X$ be a point having a closed neighborhood N in X of which $\{x_0\}$ is a strong deformation retract. Let Y be a Hausdorff space and let $y_0 \in Y$. Define $X \vee Y = X \times \{y_0\} \cup \{x_0\} \times Y$. Then the inclusion maps induce isomorphisms $\tilde{H}_i(X) \oplus \tilde{H}_i(Y) \cong \tilde{H}_i(X \vee Y)$ whose inverse is induced by the projections of $X \vee Y$ to X and Y.*

Proof of lemma. Consider $A = X$ and $U = X - N$ which is open, and $\overline{U} \subset A$. Then by excision, $H_*(X \vee Y, X) \cong H_*(N \cup Y, N) \cong \tilde{H}_*(Y)$

Consider the LES of the triple $(X \vee Y, \{x_0\} \times Y, \{x_0\} \times \{y_0\})$. We obtain

$$\ldots \to H_p(\{x_0\} \times Y, (x_0, y_0)) \xrightarrow{i_*} H_p(X \vee Y, (x_0, y_0)) \xrightarrow{j_*} H_p(X \vee Y, \{x_0\} \times Y) \to \ldots$$

Since $\pi_Y \circ i = \mathrm{id}_{\{x_0\} \times Y}$, i_* is injective.

Furthermore, we have

$$H_p(X \vee Y, (x_0, y_0)) \xrightarrow{(\pi_X)_*} H_p(\{x_0\} \times Y, (x_0, y_0)) \cong H_p(X \vee Y, \{x_0\} \times Y)$$

so $j_* = (\pi_X)_*$ under these identifications, so, in particular, j_* is surjective. Therefore, our exact sequence is a SES:

$$0 \to H_p(Y, pt) \xrightarrow{i_*} H_p(X \vee Y, pt) \xrightarrow{j_*} \underbrace{H_p(X \vee Y, Y)}_{\cong H_p(X, pt)} \to 0$$

It remains to show that this SES is split, but since $\pi_X \circ \iota_X = \mathrm{id}_{\{x_0\} \times X}$, we have that ι_{X*} provides a section.

$\square$

Proof of proposition. This follows by induction on the lemma. $\square$

Next, suppose that $E_1, \ldots, E_k$ are disjoint open subsets of S^n, each homeomorphic to $\mathbb{R}^n$ for $n > 0$. Let $f\colon S^n \to Y$ be a map which takes $S^n - \bigcup E_i$ to y_0. Then f factors through the quotient space $S^n / (S^n - \bigcup E_i) \cong S_1^n \vee \ldots \vee S_k^n$ where $S_i^n = S^n / (S^n - E_i)$:

$$f\colon S^n \xrightarrow{g} S_1^n \vee \ldots \vee S_k^n \xrightarrow{h} Y$$

Let $\iota_j\colon S_j^n \hookrightarrow S_1^n \vee \ldots \vee S_k^n$ be the j th inclusion and let $p_j\colon S_1^n \vee \ldots \vee S_k^n \to S_j^n$ be the j th projection. Then by the proposition, $\sum_j \iota_{j*} p_{j*} = \mathrm{id}_*\colon H_n(S_1^n \vee \ldots \vee S_k^n) \to H_n(S_1^n \vee \ldots \vee S_k^n)$. Let $g_j = p_j \circ g\colon S^n \to S_j^n$ and $h_j = h \circ \iota_j\colon S_j^n \to Y$ and let $f_j = h_j \circ g_j\colon S^n \to Y$. That is, f_j is the map which is f on E_j and maps the complement of E_j to the basepoint y_0.

Theorem 3.36. *In the above situation, $f_* = \sum_{j=1}^k f_{j*}\colon H_n(S^n) \to H_n(Y)$.*

Proof of theorem. We have $f_* = h_* \circ g_* = \sum_j h_* i_{j*} p_{j*} g_* = \sum_j h_{j*} g_{j*} = \sum_j f_{j*}$. $\square$

Now we get back to showing that $\deg(f+g) = \deg f + \deg g$.

Note that by way of defining $f + g$, this essentially maps I^n by f on the left half and g on the right half with the boundary mapping to the base point x_0. In particular, this factors through the quotient $I^n \to I^n / \partial I^n \cong S^n$, where now the two halves can be interpreted as, say, the upper and lower hemispheres. In particular, the equator is by assumption also mapped to x_0, so we can quotient further by $S^n \to S^n \vee S^n$ by "pinching" the equator to a point. This is essentially what the proposition above describes. In particular, $f+g$ can be covered by the two open hemispheres and maps the equator to x_0, so by the theorem, we have $(f+g)_* = f_* + g_*$, i.e., $\deg(f+g) = (f+g)_*(1) = f_*(1) + g_*(1) = \deg f + \deg g$, as we wanted to show.

(3) Next we show that deg is surjective. First note that $\deg \mathrm{id} = \mathrm{id}_*(1) = 1$ by functoriality since $\mathrm{id}_* = \mathrm{id}_{H_n(S^n)}$. By functoriality, we thus hit all of $\mathbb{Z}$. More precisely, $\deg(*_n \mathrm{id}) = n$ for $n \in \mathbb{N}$ as deg is a homomorphism. Also $\deg(*_n(-\mathrm{id})) = -n$ for $n \in \mathbb{N}$ and $\deg(c_{x_0}) = 0$, so deg is surjective.

(4) Let $n \geq 2$. We have a SES

$$0 \to \ker \deg \to \pi_n(S^n) \overset{\deg}{\to} \mathbb{Z} \to 0.$$

Since $\mathbb{Z}$ is projective, this splits, so $\pi_n(S^n) \cong \mathbb{Z} \oplus \ker \deg$. But $\ker \deg$ is a subgroup of $\pi_n(S^n)$ which is abelian, hence is itself abelian.

□

Problem 3.37. Fix $n \geq 1$. We say that a space X is *n-connected* if it is non-empty, path-connected, and $\pi_k(X, x) = 0$ for all $1 \leq k \leq n$ and $x \in X$. For (X, x_0) a pointed, path-connected space, show that the following are equivalent:

(1) X is n-connected.
(2) $\pi_k(X, x_0) = 0$ for all $1 \leq k \leq n$.
(3) Every map $S^k \to X$ can be extended to a map $D^{k+1} \to X$ for all $k \leq n$.
(4) Every map $S^k \to X$ is homotopic to a constant map for all $k \leq n$.

Proof. ($1 \implies 2$): this follows since X being n-connected means that $\pi_k(X, x) = 0$ for all $x \in X$ and all $1 \leq k \leq n$, hence in particular for x_0.
($2 \implies 3$) : Let $f\colon S^k \to X$ be a map. Then f represents some homotopy class $[f] \in \pi_k(X, x_0)$. But since $\pi_k(X, x_0) = 0$, f is homotopic to the constant map at $x_0 \operatorname{rel} s_0$. Let $H\colon S^k \times I \to X$ be this homotopy. Define $\tilde{f}\colon D^{k+1} \to X$ by $\tilde{f}(x) = H(x, \|x\|)$. Then $\tilde{f}$ is continuous as a composite of continuous maps and $\tilde{f}|_{S^k}(-) = H(-, 1) = f(-)$, so $\tilde{f}$ indeed extends f.
($3 \implies 4$) : Let $f\colon S^k \to X$ be a map. Extends f to a map $\tilde{f}\colon D^{k+1} \to X$. Define now a homotopy $H\colon S^k \times I \to X$ by $H(x, t) = \tilde{f}(xt)$. This is continuous and $H(x, 1) = \tilde{f}(x) = f(x)$ while $H(x, 0) = \tilde{f}(0) \in X$ is constant. Hence this gives a homotopy between f and $c_{\tilde{f}(0)}$.

($4 \implies 3$) : Let $f\colon S^k \to X$ be a given map. By assumption, there exists a homotopy $H\colon S^k \times I \to X$ such that $H(-, 1) = f(-)$ and $H(-, 0) = c$ where c is some constant map at a point in X. But then H factors through the quotient

$$\begin{tikzcd} S^k \times I \arrow[d] \arrow[dr, "H"] & \\ D^{k+1} \arrow[r, "\tilde{H}"'] & X \end{tikzcd}$$

where we identify $S^k \times \{0\}$ to a point. But then $\tilde{H}|_{S^k}(-) = H(-, 1) = f(-)$, so $\tilde{H}$ extends f.

($3 \implies 2$) : Let $[f] \in \pi_k(X, x_0)$ and f a representative. We want to show that f is homotopic to the constant map at x_0 relative ∂I^k. Extend f to a map $\tilde{f}\colon D^{k+1} \to X$, and let $H\colon S^k \times I \to X$ be given by $H(x,t) = \tilde{f}(ts_0 + (1-t)x)$. This gives a homotopy between f and the constant map at x_0.

$(2 \implies 1)$: the only thing that requires showing is that given that $\pi_k(X, x_0) = 0$ for all k, we then have $\pi_k(X, x) = 0$ for all k and all $x \in X$. But this is precisely what the given hint says we are allowed to assume since X is path connected. So we are done. $\square$

Problem 3.38 (n-connected in the relative case)**.** The following four conditions are equivalent for $i > 0$:

(1) Every map $\left(D^i, \partial D^i\right) \to (X, A)$ is homotopic $\operatorname{rel} \partial D^i$ to a map $D^i \to A$.
(2) Every map $\left(D^i, \partial D^i\right) \to (X, A)$ is homotopic through such maps to a map $D^i \to A$.
(3) Every map $\left(D^i, \partial D^i\right) \to (X, A)$ is homotopic through such maps to a constant map $D^i \to A$.
(4) $\pi_i\left(X, A, x_0\right) = 0$ for all $x_0 \in A$.

When $i = 0$, we did not define the relative π_0, and (1)-(3) are each equivalent to saying that each path-component of X contains points in A since D^0 is a point and ∂D^0 is empty. The pair (X, A) is called *n-connected* if (1)-(4) hold for $0 < i \le n$ and (1)-(3) hold for $i = 0$.

3.4. **Whitehead's Theorem.**

Theorem 3.39 (Whitehead's Theorem)**.** *If a map $f\colon X \to Y$ between connected CW complexes induces isomorphisms $f_*\colon \pi_n(X) \to \pi_n(Y)$ for all n, then f is a homotopy equivalence. In case f is the inclusion of a subcomplex $X \hookrightarrow Y$, the conclusion is stronger: X is a deformation retract of Y.*

The proof will require the following lemma:

Lemma 3.40 (Compression Lemma)**.** *Let (X, A) be a CW pair and let (Y, B) be any pair with $B \neq \varnothing$. For each n such that $X - A$ has cells of dimension n, assume that $\pi_n\left(Y, B, y_0\right) = 0$ for all $y_0 \in B$. Then every map $f\colon (X, A) \to (Y, B)$ is homotopic* $\operatorname{rel} A$ *to a map $X \to B$. When $n = 0$, the condition that $\pi_n\left(Y, B, y_0\right) = 0$ for all $y_0 \in B$ is to be regarded as saying that (Y, B) is 0-connected.*

Proof of lemma. Assume inductively that f has already been homotoped to take the skeleton X^{k-1} to B. Let Φ be the caracteristic (attaching) map of cell e^k of $X - A$. Then the composition $f\Phi\colon \left(D^k, \partial D^k\right) \to (Y, B)$ is in some class in $\pi_k\left(Y, B, y_0\right) = 0$, so it can be homotoped into $B \operatorname{rel} \partial D^k$ by the compression criterion when $k > 0$, or by (Y, B) being 0-connected for $k = 0$ (this is condition (3) in Problem 3.38). This homotopy of $f\Phi$ induces a homotopy $\operatorname{rel} X^{k-1}$ on the quotient space $X^{k-1} \cup e^k$ of $X^{k-1} \sqcup D^k$. Doing this for all k-cells of $X - A$ simultaneously, and taking the constant homotopy on A, we obtain a homotopy of $f|_{X^k \cup A}$ to a map into B. Since the inclusion of a subcomplex into a CW-complex is a cofibration, $f|_{X^k \cup A}$ extends to all of X (essentially the homotopy extension property). This completes the inductive step in the finite dimensional CW-complex case. In the general case, we perform the homotopy of the inductive step during the t-interval $\left[1 - \frac{1}{2^k}, 1 - \frac{1}{2^{k+1}}\right]$. Any finite skeleton X^k is eventually stationary under these homotopies, hence we have a well-defined homotopy $f_t, t \in [0, 1]$ with $f_1(X) \subset B$. $\square$

Proof of Whitehead's Theorem, 3.39. Let's tackle the case when f is the inclusion of a subcomplex first. Consider then the LES of the pair (Y, X). Since f by assumption induces isomorphisms on all homotopy groups, $f_*\colon \pi_*(X) \to \pi_*(Y)$, the relative homotopy groups $\pi_*(Y, X)$ are zero. Applying the lemma now to the identity map $(Y, X) \to (Y, X)$, we obtain a homotopy of the identity $\mathrm{id}\colon Y \to Y$ to a map $Y \to X$ which is relative to X. That is, we obtain a deformation retract of Y onto X.

For the general case, recall that a map $f\colon X \to Y$, can be considered as the composition of the inclusion $X \hookrightarrow M_f$ and the retraction $M_f \to Y$. Since the retraction is a homotopy equivalence, it suffices to show that M_f deformation retracts onto X if f induces isomorphisms on homotopy groups, or equivalently, if the relative groups $\pi_n(M_f, X)$ are all zero (since $M_f \simeq Y$). If f is cellular - i.e., takes the n-skeleton of X to the n-skeleton of Y for all n - then (M_f, X) is a CW pair and we can apply the first paragraph of the proof.
If f is not cellular, we can either apply Theorem 4.8 in [2] which says that f is homotopic to a cellular map, or we can use the following argument.
First, using that $\pi_n(M_f, X) = 0$ for all n, apply the Compression Lemma to the inclusion $(X \cup Y, X) \hookrightarrow (M_f, X)$ to obtain a homotopy of the inclusion to a map into $X \operatorname{rel} X$. The inclusion $X \cup Y \hookrightarrow M_f$ can be seen to be a cofibration using Theorem 1.7, so the pair $(M_f, X \cup Y)$ satisfies the homotopy extension property. So the homotopy in question extends to a homotopy from the identity of M_f to a map $g\colon M_f \to M_f$ taking $X \cup Y$ into $X \operatorname{rel} X$. However, we first of all do not know that this homotopy is $\operatorname{rel} X$ nor that g maps all of M_f into X.
So we apply the Compression lemma again to the composition

$$(X \times I \sqcup Y, X \times \partial I \sqcup Y) \to (M_f, X \cup Y) \xrightarrow{g} (M_f, X),$$

to get a homotopy $\operatorname{rel} X \times \partial I \sqcup Y$ of g to a map $X \times I \sqcup Y \to X$. In particular, this homotopy passes through the quotient $X \times I \sqcup Y \to M_f$, so we get a homotopy of $g \operatorname{rel} X \times \partial I \cup Y$ to a map $M_f \to X$.
Composing the homotopy from the identity of M_f to g with this homotopy, we get a deformation retraction of M_f onto X. □

Note. Whitehead's theorem requires a map $f\colon X \to Y$ which induces isomorphisms on homotopy groups. Thus it does not apply simply to any two CW complexes X and Y with isomorphic homotopy groups since there might not exist such a map. For examples where this is the case, see [2, p. 348].

Corollary 3.41. *If X is a CW complex with $\pi_n(X) = 0$ for all $n \geq 0$, then $X \simeq \{0\}$.*

Proof. The inclusion of a 0-cell into the complex induces an isomorphism on homotopy groups, so by Whitehead's theorem, the complex deformation retracts to the 0-cell. □

Lemma 3.42 (Extension Lemma)**.** *Given a CW pair (X, A) and a map $f\colon A \to Y$ with Y-path connected, then f can be extended to a map $X \to Y$ if $\pi_{n-1}(Y) = 0$ for all n such that $X - A$ has cells of dimension n.*

Proof. Suppose that f has been extended over the $(n-1)$-skeleton. Then an extension over an n-cell exists if and only if the composition of the cell's attaching map $S^{n-1} \to X^{n-1}$ with $f\colon X^{n-1} \to Y$ is nullhomotopic, which it is if $\pi_{n-1}(Y) = 0$. □

3.5. **Cellular Approximation.**

Definition 3.43 (Cellular maps)**.** A map $f\colon X \to Y$ between CW complexes, satisfying $f(X^n) \subset Y^n$ for all n, is called a *cellular map*.

Theorem 3.44 (Cellular Approximation Theorem)**.** *Every map $f\colon X \to Y$ of CW complexes is homotopic to a cellular map. If f is already cellular on a subcomplex $A \subset X$, then homotopy map be taken to be stationary on A.*

Recall the following about simplicial maps and simplicial approximations:

Definition 3.45 (Simplicial map)**.** Let K and L be simplicial complexes. A function $s\colon |K| \to |L|$ is called *simplicial* if it takes simplexes of K linearly onto simplexes of L.

Definition 3.46 (Carrier of $f(x)$)**.** Given a map $f\colon |K| \to |L|$ between polyhedra and a point $x \in |K|$, the point $f(x)$ lies in the interior of a unique simplex of L. Call this simplex the *carrier* of $f(x)$.

Definition 3.47 (Simplicial Approximation)**.** A simplicial map $s\colon |K| \to |L|$ is a simplicial approximation of $f\colon |K| \to |L|$ if $s(x)$ lies in the carrier of $f(x)$ for each $x \in |K|$.

Theorem 3.48 (Simplicial approximation theorem)**.** *Let $f\colon |K| \to |L|$ be a map between polyhedra. If m is chosen large enough, there is a simplicial approximation $s\colon |K^m| \to |L|$ to $f\colon |K^m| \to |L|$.*

Thus we may view cellular approximation as a CW analog of simplicial approximation since simplicial maps are cellular. Simplicial maps are much more rigid than cellular maps, however, and the core proof of cellular approximation will be a weaker form of simplciial approximation.

But first, a nice corollary:

Corollary 3.49. *$\pi_n\left(S^k\right)$ for $n < k$.*

Proof. If S^n and S^k are given their usual CW structure of a single 0-cell and then an n- or k-cell, respectively, then by the Cellular Approximation Theorem, any pointed map $S^n \to S^k$ is based homotopic to a cellular map, and hence maps the n-skeleton of S^n into the n-skeleton of S^k. But the n-skeleton of S^k is just the 0-cell. That is, any map $S^n \to S^k$ is based nullhomotopic, so $\pi_n\left(S^k\right) = 0$. $\square$

Proof of Cellular Approximation Theorem. Long. To do $\square$

Example 3.50 (Cellular Approximation for Pairs)**.** Every map $f\colon (X, A) \to (Y, B)$ of *CW* pairs can be deformed through maps $(X, A) \to (Y, B)$ to a cellular map. This follows from the theorem by first deforming the restriction $f\colon A \to B$ to be cellular, then extending this to a homotopy of f on all of X, then deforming the resulting map to be cellular staying fixed on A. As a further refinement, the homotopy of f can be taken to be stationary on any subcomplex of X where f is already cellular.

Corollary 3.51 (Geometric Version of n-connectedness)**.** *A CW pair (X, A) is n-connected if all the cells in $X - A$ have dimension greater than n. In particular, the pair (X, X^n) is n-connected, hence the inclusion $X^n \hookrightarrow X$ induces isomorphisms on π_i for $i < n$ and a surjection on π_n.*

Proof. Recall that (X, A) is n-connected if every map $\left(D^i, \partial D^i\right) \to (X, A)$ is homotopic through such maps to a map $D^i \to A$. Now let $f\left(D^i, \partial D^i\right) \to (X, A)$ be any map. Then by the Cellular Approximation theorem for Pairs, f is homotopic through maps $\left(D^i, \partial D^i\right) \to (X, A)$ to a cellular map, $\tilde{f}\colon \left(D^i, \partial D^i\right) \to (X, A)$. But by assumption, all cells in $X - A$ have dimension greater than $n \geq i$. Hence $\tilde{f}$ maps D^i into A. The last part of the statement now follows from the LES

$$\ldots \to \pi_n(X^n) \xrightarrow{\iota_*} \pi_n(X) \to \underbrace{\pi_n\left(X, X^n\right)}_{0} \to \pi_{n-1}(X^n) \xrightarrow{\iota_*} \pi_{n-1}(X) \to \underbrace{\pi_{n-1}\left(X, X^n\right)}_{0} \to \ldots$$

□

3.6. **CW Approximation.**

Definition 3.52 (Weak Homotopy Equivalence)**.** A map $f\colon X \to Y$ is called a *weak homotopy equivalence* if it induces isomorphisms $\pi_n\left(X, x_0\right) \to \pi_n\left(Y, f(x_0)\right)$ for all $n \geq 0$ and all choices of basepoint x_0.

Remark (Reformulation of Whitehead's Theorem)*.* Whitehead's Theorem thus says that a weak homotopy equivalence between CW complexes is, in fact, a homotopy equivalence.

Definition 3.53 (CW Approximation)**.** For a space X, a weak homotopy equivalence $f\colon Z \to X$, where Z is a CW complex, is called a *CW approximation* to X.

Remark. CW approximations to a given space X are unique up to homotopy equivalence since if $f\colon Z \to X$ and $f'\colon Z' \to X$ are CW approximations, then consider the composition $Z \to X \hookrightarrow M_{f'}$. Since $f'\colon Z' \to X$ is assumed to be a weak homotopy equivalence, we find by the relative LES that $\pi_n(M_f, Z') \cong \pi_n\left(X, Z'\right) = 0$ for all $n \geq 0$, so by the Compression Lemma (with A chosen to be the basepoint of Z), we find that the map $Z \to X \hookrightarrow M_{f'}$ is homotopic to a map $Z \to Z' \subset M_{f'}$ relative to the basepoint. But taking π_n of $Z \to X \to M_{f'} \to Z'$, we get $\pi_n(Z) \xrightarrow{\cong} \pi_n(X) \xrightarrow{\cong} \pi_n(M_{f'}) \xrightarrow{\cong} \pi_n\left(Z'\right)$ where $\pi_n(X) \xrightarrow{\cong} \pi_n(M_{f'})$ follows from $\iota\colon X \simeq M_{f'}$ being a homotopy equivalence; $\pi_n\left(M_{f'}\right) \xrightarrow{\cong} \pi_n(Z')$ follows from the homotopy that we got from the compression lemma, and the first isomorphism $f_*\colon \pi_n(Z) \xrightarrow{\cong} \pi_n(X)$ follows from f being a weak homotopy equivalence. Applying Whitehead's theorem, we find that this composition is a homotopy equivalence $Z \simeq Z'$.

Proposition 3.54. *Every space X has a CW approximation $f\colon Z \to X$. If X is path-connected, Z can be chosen to have a single* 0*-cell, with all other cells attached by basepoint-preserving maps. Thus every connected CW complex is homotopy equivalent to a CW complex with these additional properties.*

Proof. The construction of a CW approximation $f\colon Z \to X$ is inductive, so we first describe the induction step. Suppose we are given a CW complex A with a map $f\colon A \to X$ and suppose we have chosen a basepoint 0-cell a_γ in each component of A. Then for an integer $k \geq 0$, we will attach k-cells to A to form a CW complex B with a map $f\colon B \to X$ extending f such that

- For each basepoint a_γ, the induced map $f_*\colon \pi_i\left(B, a_\gamma\right) \to \pi_i\left(X, f\left(a_\gamma\right)\right)$ is injective for $i = k - 1$ (when $k > 0$) and surjective for $i = k$.

We do this in two steps (the first step is omitted when $k = 0$):

(1) We have been given a CW complex A and a map $f\colon A \to X$ alongside basepoints a_γ. Now for each nontrivial element α of the kernel $\ker f_*$ ranging over all basepoints, choose a map $\varphi_\alpha\colon \left(S^{k-1}, s_0\right) \to (A, a_\gamma)$ representing

α. We may assume that the φ_α are all cellular (by the Cellular Approximation Theorem) where S^{k-1} is given its standard CW structure with s_0 as a 0-cell. Attaching cells e^k_α to A via the maps φ_α then produces a CW complex. Now, $f \circ \varphi_\alpha$ is nullhomotopic, so f extends over the cell e^k_α.

(2) Choose maps $f_\beta \colon S^k \to X$ representing all nontrivial elements of $\pi_k\left(X, f(a_\gamma)\right)$ for all the a_γ 's Then attach cells e^k_β to A via the constant maps at the appropriate basepoints a_γ and extend f over the resulting spheres S^k_β via f_β.

By the construction, then surjectivity of $f_* \colon \pi_i\left(B, a_\gamma\right) \to \pi_i\left(X, f(a_\gamma)\right)$ for $i = k$ follows. Now let α be in the kernel of $f_* \colon \pi_{k-1}(B, a_\gamma) \to \pi_{k-1}\left(X, f(a_\gamma)\right)$, and let $h \colon S^{k-1} \to B$ be a cellular map that represent α. Since h is cellular, its image is contained in the $(n-1)$-skeleton of B which is a subskeleton (could be all) of A. Since h has image in A, it is in the kernel of $f_* \colon \pi_{k-1}(A, a_\gamma) \to \pi_{k-1}\left(X, f(a_\gamma)\right)$ and thus it is homotopic to some φ_α and therefore nullhomotopic in B.

Note. In step (1), it suffices to attach cells for just the generators of the kernels when $k > 1$, and just for the generators of $\pi_k\left(X, f(a_\gamma)\right)$ in step (2) when $k > 0$.

Note. If the given map $f \colon A \to X$ happened to already be injective or surjective on π_i for some $i < k-1$ or $i < k$, respectively, then this remains true after attaching the k-cells. This is because attaching k-cells does not affect π_i if $i < k-1$, by cellular approximation, not does it affect surjectivity on any π_i, simply because the same maps still hold and work.

Now to construct a CW approximation $f \colon Z \to X$, one can start with A consisting of one point for each path-component of X, with $f \colon A \to X$ mapping each of these points to the corresponding path-component. This gives a bijection on π_0 by construction, hence it provides us with the inductive base case. Now we can attach 1-cells to A to create a surjection on π_1 for each path-component, then 2-cells to improve this to an isomorphism on π_1 and a surjection on π_2 and so forth for each successive π_i in turn. After all cells have been attached, on has a CW complex Z with a weak homotopy equivalence $f \colon Z \to X$. $\square$

Example 3.55. One can apply this technique to produce a CW approximation to a pair (X, X_0) also. First one constructs a CW approximation $f_0 \colon Z_0 \to X_0$, then one starts with the composition $Z_0 \to X_0 \hookrightarrow X$ and attaches cells to Z_0 to create a weak homotopy equivalence $f \colon Z \to X$ extending f_0. Then we get

$$\begin{tikzcd}
\pi_n(Z_0) \arrow[r] \arrow[d, "\cong"] & \pi_n(Z) \arrow[r] \arrow[d, "\cong"] & \pi_n(Z, Z_0) \arrow[r] \arrow[d] & \pi_{n-1}(Z_0) \arrow[r] \arrow[d, "\cong"] & \pi_{n-1}(Z) \arrow[d, "\cong"] \\
\pi_n(X_0) \arrow[r] & \pi_n(X) \arrow[r] & \pi_n(X, X_0) \arrow[r] & \pi_{n-1}(X_0) \arrow[r] & \pi_{n-1}(X)
\end{tikzcd}$$

By the five-lemma, it follows that $\pi_n\left(Z, Z_0\right) \to \pi_n\left(X, X_0\right)$ is an isomorphism for each n.

Proposition 3.56. *If (X, A) is an n-connected CW pair, then there exists a CW pair $(Z, A) \simeq (X, A)\,\mathrm{rel}\,A$ such that all cells of $Z - A$ have dimension greater than n.*

Proof. Starting with the inclusion $A \hookrightarrow X$, attach cells of dimension $n+1$ and higher to A to produce a CW complex Z and a map $f\colon Z \to X$ using the procedure of Proposition 3.54. In particular then by the Proposition proof, f_* induces an injection of π_n and isomorphisms on all higher homotopy groups. Now, the induced map on π_n is also surjective since it is true for $A \hookrightarrow Z \xrightarrow{f} X$ as (X, A) is n-connected and hence $\pi_n(A) \xrightarrow{\cong} \pi_n(X)$ is an isomorphism. Since f is equal to this inclusion on the n-skeleton, this gives that f_* is also surjective. By cellular approximation $A \hookrightarrow Z$ induces an isomorphism on homotopy groups in dimensions below n, and likewise n-connectedness does the same for $A \hookrightarrow X$. But then since

$$\begin{tikzcd}
\pi_n(A) \arrow[r, "\iota_*", "\cong"'] \arrow[rr, bend right, "\iota_*", "\cong"'] & \pi_n(Z) \arrow[r, "f_*"] & \pi_n(X)
\end{tikzcd}$$

commutes, we find that f_* is also an isomorphism on all $n \geq 0$. Thus f is a weak homotopy equivalence, and hence a homotopy equivalence by Whitehead's theorem.

To see that f is a homotopy equivalence $\operatorname{rel} A$, we could apply Proposition 1.30, but here is an alternative argument. Let W be the quotient space of the mapping cylinder M_f obtained by collapsing each segment $\{a\} \times I$ to a point, for $a \in A$. Assuming f has been made cellular, W is a CW complex (why?) containing X and Z as subcomplexes, and W deformation retracts to X just as M_f does. Also, $\pi_i(W, Z) = 0$ for all i since f induces isomorphisms on all homotopy groups (by the LES), so W deformation retracts onto Z by Whitehead's Theorem (Theorem 3.39). The deformation retract of W onto X and the deformation retract of W onto Z are stationary on A, hence give a homotopy equivalence $X \simeq Z \operatorname{rel} A$. □

Example 3.57 (Postnikov Towers)**.** For each connected CW complex X and each integer $n \geq 1$, we can construct a CW complex X_n containing X as a subcomplex such that

(1) $\pi_i(X_n) = 0$ for $i > n$.
(2) The inclusion $X \hookrightarrow X_n$ induces an isomorphism on π_i for $i \leq n$.

Idea. Take X and fill out any spheres of dimension $> n$ by filling them in.

Indeed, we attach $(n+2)$-cells to X using cellular maps $S^{n+1} \to X$ that generate $\pi_{n+1}(X)$ to form a space with π_{n+1} trivial. Then for this space, we attach $(n+3)$-cells to make π_{n+2} trivial, and so on. The result is a CW complex X_n with the desired properties. The inclusion $X \hookrightarrow X_n$ extends to a map $X_{n+1} \to X$ since X_{n+1} is obtained from X by attaching cells of dimension $n+3$ and greater, and $\pi_i(X_n) = 0$ for $i > n$, so we can apply the Extension Lemma (Lemma 3.42). Thus we get a commutative diagram as follows:

$$
\begin{tikzcd}
 & \vdots \arrow[d] \\
 & X_3 \arrow[d] \\
 & X_2 \arrow[d] \\
X \arrow[r] \arrow[ur] \arrow[uur] & X_1
\end{tikzcd}
$$

This is called a *Postnikov tower* for X. One can regard the spaces X_n as truncations of X which provides successively better approximations to X as n increases.

4. Methods of Calculation

4.1. Excision for Homotopy Groups.

Theorem 4.1. *Let X be a CW complex decomposed as the union of subcomplexes A and B with nonempty connected intersection $C = A \cap B$. If (A, C) is m-connected and (B, C) is n-connected, $m, n \geq 0$, then the map $\pi_i(A, C) \to \pi_i(X, B)$ induced by inclusion is an isomorphism for $i < m + n$ and a surjection for $i = m + n$.*

Corollary 4.2 (Freudenthal Suspension Theorem)**.** *The unreduced suspension map $\pi_i(S^n) \to \pi_{i+1}\left(S^{n+1}\right)$, induced by the suspension map $S^n \to \Sigma S^n \cong S^{n+1}$, is an isomorphism for $i < 2n - 1$ and a surjection for $i = 2n - 1$. More generally, this holds for the suspension $\pi_i(X) \to \pi_{i+1}(\Sigma X)$ whenever X is an $(n-1)$-connected CW complex.*

Proof of Corollary. Decompose the unreduced suspension $\Sigma X = (X \times I) / (X \times \{0\}, X \times \{1\})$ as the union of two cones C_+X and C_-X intersecting in a copy of X. Recall that a map $f \colon X \to Y$ induces a suspended map $\Sigma f \colon \Sigma X \to \Sigma Y$. Now, if we consider f to be any map $f \colon (S^n, s_0) \to (X, x_0)$, then we have a suspended map

$$
\begin{tikzcd}
S^n \times I \arrow[r, "f \times \mathrm{id}"] \arrow[d] & X \times I \arrow[d] \\
S^{n+1} \cong \Sigma S^n \arrow[r, "\Sigma f"] & \Sigma X
\end{tikzcd}
$$

So, in particular, Σf is some class in $\pi_{n+1}(\Sigma X)$. Define the suspension homomorphism $\pi_i(X) \to \pi_{i+1}(\Sigma X)$ to be the map that sends f to Σf. This is a homomorphism (why?).

The unreduced suspension map is the same as the map

$$\pi_i(X) \cong \pi_{i+1}(C_+X, X) \to \pi_{i+1}(\Sigma X, C_-X) \cong \pi_{i+1}(\Sigma X).$$

(why?) where the two isomorphisms come from the LES of pairs and the middle map is induced by inclusion. The first map $\pi_i(X) \to \pi_{i+1}(C_+X, X)$ takes a map $\left(I^i, \partial I^n\right) \to (X, x_0)$ to the map $\left(I^{n+1}, \partial I^{n+1}, J^n\right) \to (C_+X, X, x_0)$ constructed by extending the given map radially to correspond with the height of C_+X. So one face of I^{n+1} will be mapped to the vertex of C_+X.

Including this into $(\Sigma X, C_- X)$ gives the middle homomorphism, and then the map $\pi_{i+1}(\Sigma X, C_- X) \to \pi_{i+1}(\Sigma X)$ is simply the identity on our map.
From the LES of $(C_\pm X, X)$, we see that this pair is n-connected if X is $(n-1)$-connected. Then Theorem 4.1 gives that the middle map is an isomorphism for $i+1 < 2n$ and surjective for $i+1 = 2n$.

□

Example 4.3 ($\pi_n(\bigvee_\alpha S^n_\alpha)$)**.** We want to show that $\pi_n(\bigvee_\alpha S^n_\alpha)$ for $n \geq 2$ is free abelian with basis the homotopy classes of the inclusions $S^n_\alpha \hookrightarrow \bigvee_\alpha S^n_\alpha$.
Suppose first that there are only *finitely many* summands S^n_α. Then we can regard $\bigvee_\alpha S^n_\alpha$ as the n-skeleton of the product $\prod_\alpha S^n_\alpha$, where S^n_α is given the usual CW structure and $\prod_\alpha S^n_\alpha$ has the product CW structure. (See Hatcher appendix A).
By construction then $\prod_\alpha S^n_\alpha$ has cells only in dimensions a multiple of n, so the pair $(\prod_\alpha S^n_\alpha, \bigvee_\alpha S^n_\alpha)$ is $(2n-1)$-connected by Corollary 3.51. So from the LES for the pair, we see that the inclusion $\bigvee_\alpha S^n_\alpha \hookrightarrow \prod_\alpha S^n_\alpha$ induces an isomorphism on homotopy groups in dimensions $\leq 2n-1$. Next we have $\pi_n(\prod_\alpha S^n_\alpha) \cong \bigoplus_\alpha \pi_n(S^n_\alpha) \cong \bigoplus_\alpha \mathbb{Z}$, a free abelian group with basis the inclusions $S^n_\alpha \hookrightarrow \prod_\alpha S^n_\alpha$, so pulling this back along the isomorphism $\pi_n(\bigvee_\alpha S^n_\alpha) \cong \pi_n(\prod_\alpha S^n_\alpha)$, the same is true for $\bigvee_\alpha S^n_\alpha$. This proves the claim when there are finitely many S^n_α's.
When there are infinitely many summands S^n_α, consider the homomorphism $\Phi\colon \bigoplus_\alpha \pi_n(S^n_\alpha) \to \pi_n(\bigvee_\alpha S^n_\alpha)$ induced by the inclusions $S^n_\alpha \hookrightarrow \bigvee_\alpha S^n_\alpha$. Then Φ is surjective since any map $f\colon S^n \to \bigvee_\alpha S^n_\alpha$ has compact image contained in the wedge sum of finitely many S^n_α's, so by the finite case already proved, $[f]$ is in the image of Φ.
Similarly, a nullhomotopy of f has compact image contained in a finite wedge sum of S^n_α's, so the finite case also implies that Φ is injective.

Proposition 4.4. *If a CW pair (X, A) is r-connected and A is s-connected, with $r, s \geq 0$, then the map $\pi_i(X, A) \to \pi_i(X/A)$ induced by the quotient map $X \to X/A$ is an isomorphism for $i \leq r+s$ and a surjection for $i = r+s+1$.*

Proof. Consider $X \cup CA$. Since A is closed and the inclusion $A \hookrightarrow X$ is a cofibration (since these are CW complexes), the map $h\colon C_\iota = X \cup CA \to X/A$ is a homotopy equivalence by Theorem 1.9. So we have a commutative diagram

$$\begin{tikzcd}
\pi_i(X,A) \arrow[r] & \pi_i(X \cup CA, CA) \arrow[r] & \pi_i(X \cup CA/CA) = \pi_i(X/A) \\
& \pi_i(X \cup CA) \arrow[u, "\cong"] \arrow[ur, "\cong"] &
\end{tikzcd}$$

where the vertical isomorphism comes from the LES of the pair $(X \cup CA, CA)$. Now, applying Theorem 4.1 to $(A, B) = (X, CA)$, since (X, A) is r-connected and (CA, A) is $(s+1)$-connected, we find that the homomorphism $\pi_i(X, A) \to \pi_i(X \cup CA, CA)$ induced by the inclusion is an isomorphism for $i < r+s+1$ and a surjection for $i = r+s+1$, which proves the result. □

Example 4.5 (Construction of spaces with a particular group as π_n)**.** Suppose X is obtained from a wedge of spheres $\bigvee_\alpha S^n_\alpha$ by attaching cells e^{n+1}_β via basepoint-preserving maps $\varphi_\beta\colon S^n \to \bigvee_\alpha S^n_\alpha, n \geq 2$. By cellular approximation, we know that $\pi_i(X) = 0$ for $i < n$, and we shall show that $\pi_n(X)$ is the quotient of the free abelian group $\pi_n(\bigvee_\alpha S^n_\alpha) \cong \bigoplus_\alpha \mathbb{Z}$ by the subgroup generated by the classes $[\varphi_\alpha]$. Any subgroup can be realized in this way, by choosing maps φ_β to represent a set

of generators for the subgroup. Let $X = (\bigvee_\alpha S^n_\alpha) \bigcup_\beta e^{n+1}_\beta$.
Then the LES of the pair $(X, \bigvee_\alpha S^n_\alpha)$ gives

$$\pi_{n+1}\left(X, \bigvee_\alpha S^n_\alpha\right) \xrightarrow{\partial} \pi_n\left(\bigvee_\alpha S^n_\alpha\right) \to \pi_n(X) \to 0.$$

so

$$\pi_n(X) \cong \pi_n\left(\bigvee_\alpha S^n_\alpha\right) / \operatorname{im} \partial$$

The quotient $X/\bigvee_\alpha S^n_\alpha$ is a wedge of spheres S^{n+1}_β, so by Proposition 4.4 and Example 4.3, the map $\pi_{n+1}(X, \bigvee_\alpha S^n_\alpha) \to \pi_{n+1}(X/\bigvee_\alpha S^n_\alpha) \cong \pi_{n+1}\left(\bigvee_\beta S^{n+1}_\beta\right)$ is an isomorphism, so $\pi_{n+1}(X, \bigvee_\alpha S^n_\alpha)$ is free with basis the caracteristic maps φ_β of the cells e^{n+1}_β. The boundary map ∂ takes these to the classes $[\varphi_\beta]$, so the result follows.

4.1.1. *Eilenberg-MacLane Spaces.*

Definition 4.6 (Eilenberg-MacLane space, $K(G,n)$)**.** A space X having just one nontrivial homotopy group $\pi_n(X) \cong G$ is called an *Eilenberg-MacLane space* $K(G,n)$.

Given arbitrary G and n, and assuming G is abelian if $n > 1$, we can construct a CW complex $K(G,n)$. To begin, construct the CW complex X from Example 4.5. Then X is an $(n-1)$- conneted CW complex of dimension $n+1$ such that $\pi_n(X) \cong G$ by construction. Hence we just need to fix all homotopy groups of dimension greater than n. By Example 3.57, we can construct a CW complex X_n containing X as a subcomplex such that $\pi_n(X_n) \cong \pi_n(X) \cong G$ while $\pi_k(X_n) \cong 0$ for all $k \neq n$.

4.2. **The Hurewicz Theorem.**

Theorem 4.7. *If a space X is $(n-1)$-connected, $n \geq 2$, then $\tilde{H}_i(X) = 0$ for $i < n$ and $\pi_n(X) \cong H_n(X)$. If a pair (X, A) is $(n-1)$-connected, $n \geq 2$, with A simply connected and nonempty, then $H_i(X, A) = 0$ for $i < n$ and $\pi_n(X, A) \cong H_n(X, A)$.*

4.3. **Problem Set 2.**

Problem 4.8. Let $T = S^1 \times S^1$ be the torus and $i\colon D^2 \hookrightarrow T$ and embedding of the unit disk that is disjoint from $S^1 \times \{s_0\}$. Define $A := \left(S^1 \times \{s_0\}\right) \cup i\left(S^1\right) \subset T$. Let $x_0 = (s_0, s_0)$ and $x_1 \in i\left(S^1\right)$.

(1) Draw a picture of (X, A) and the two points x_0 and x_1.
(2) Construct an explicit bijection of sets $\pi_1(T, A, x_1) \cong \mathbb{Z}^2 \sqcup \mathbb{Z}$.
(3) Compute the relative homotopy groups $\pi_2(T, A, x_0)$ and $\pi_2(T, A, x_1)$.

Solution. (1)

FIGURE 12. Note that in this figure, A are the parts drawn without the interior of the disk $i(D^2)$.

(2) Recall that
$$\pi_n(T, A, x_1) = \left[I^n, \partial I^n, J^{n-1}; T, A, x_1\right].$$
Thus $\pi_1(T, A, x_1)$ becomes the set of homotopy classes of maps $(I, \{0,1\}, \{1\}) \to (T, A, x_1)$. That is, the set of paths in T starting at a point in A and ending at x_1 up to homotopy through such paths.
For any map $f\colon (I, \{0\}, \{1\}) \to (T, A, \{x_1\})$, can lift this to the universal cover since I is simply connected. Let $\tilde{f}\colon (I, \{0\}, \{1\}) \to \left(\mathbb{R}^2, p^{-1}(A), p^{-1}(\{x_1\})\right)$. Now, $p^{-1}(A)$ can be visualized as tiling $\mathbb{R}^2$ by tiles as the left picture in Figure 12, each tile of course contains precisely one element of the fiber $p^{-1}(\{x_1\})$. For the lift $\tilde{f}$, we choose a base point $\tilde{x_1}$ in $p^{-1}(\{x_1\})$. By the lifting theorem, there now exists a unique lift, call it $\tilde{f}\colon (I, \{1\}) \to \left(\mathbb{R}^2, \{\tilde{x_1}\}\right)$, such that $f = p \circ \tilde{f}$. Now, $f(0) \in A$ is the only condition, so $\tilde{f}(0)$ lies in $p^{-1}(A)$. Homotopies through maps which start in A for f correspond in the universal cover to letting $\tilde{f}(0)$ run freely through its path component in $p^{-1}(A)$. We can construct a bijection $\pi_0\left(p^{-1}(A)\right) \cong \mathbb{Z}^2 \sqcup \mathbb{Z}$ by identifying the component of $p^{-1}\left(i\left(S^1\right)\right) \cap [n, n+1] \times [m, m+1]$ with $(n, m) \in \mathbb{Z}^2$ and identifying the vertical line in $p^{-1}\left(S^1 \times \{s_0\}\right) \cap [n, n+1)$ with $n \in \mathbb{Z} \subset \mathbb{Z}^2 \sqcup \mathbb{Z}$. This is obviously bijective. We can always homotopy f to be a straight-line in the universal cover, so the only thing that determines the equivalence class of f, given that $\tilde{f}$ ends at $\tilde{x_1}$, is which path component in $\mathbb{Z}^2 \sqcup \mathbb{Z}$ it start in. This gives an injective map $\varphi\colon \pi_1(T, A, x_1) \to \mathbb{Z}^2 \sqcup \mathbb{Z}$. To see that it is surjective, it is clear that choosing $\tilde{x_1}$ as above and choosing any point in the path component corresponding to an element $x \in \mathbb{Z}^2 \sqcup \mathbb{Z}$, taking the straight line between these two points gives a path $\tilde{f}\colon I \to \mathbb{R}^2$ such that $f := p \circ \tilde{f}$ gives a path $[f] \in \pi_1(T, A, x_1)$, and, by construction, $\varphi([f]) = x$.
Thus $\pi_1(T, A, x_1) \cong \mathbb{Z}^2 \sqcup \mathbb{Z}$.

(3) Let $\iota\colon A \to T$ be the inclusion. Then using the LES of relative homotopy groups, we have that

$$\pi_2(T, x_i) \to \pi_2(T, A, x_i) \to \pi_1(A, x_i) \xrightarrow{\iota_*} \pi_1(T, x_i)$$

is exact for $i = 0, 1$. For $i = 0, 1$, $\pi_1(A, x_i) \cong \mathbb{Z}$ and $\pi_1(T, x_i) \cong \mathbb{Z}^2$, while $\pi_2(T, x_i) \cong \pi_2(S_1) \times \pi_2(S^1) \cong 1$ for both $i = 0, 1$. Hence $\pi_2(T, A, x_i) \cong \ker \iota_*$. First, suppose $i = 0$. Then ι induces the map $\mathbb{Z} \cong \pi_1(A, x_0) \to \pi_1(T, x_0) \cong \mathbb{Z}^2$ given by $n \mapsto (0, n)$, so $\ker \iota_*$ is trivial in this case, so $\pi_2(T, A, x_0) \cong 0$. Suppose now that $i = 1$. Then any loop in the image of ι_* is clearly based nullhomotopic by contracting $i(D^2)$ to the point x_1. Thus $\ker \iota_* = \pi_1(A, x_1) \cong \pi_1(S^1) \cong \mathbb{Z}$. So $\pi_2(T, A, x_1) \cong \mathbb{Z}$.

Problem 4.9.
1. Compute $\pi_1(S^1 \vee S^2)$ and describe the universal cover of $S^1 \vee S^2$.
2. Show that $\pi_2(S^1 \vee S^2)$ is isomorphic to $\bigoplus_{\mathbb{Z}} \mathbb{Z}$.
3. Explicitly describe the action of $\pi_1(S^1 \vee S^2)$ on $\bigoplus_{\mathbb{Z}} \mathbb{Z} \cong \pi_2(S^1 \vee S^2)$.

Solution. (1) The universal cover of $S^1 \vee S^2 =: X$, which we will denote $\tilde{X}$, is clearly $\mathbb{R}$ with a copy of S^2 attached to each integer of $\mathbb{R}$.
Let A_1 be the S^1 part together with a small open neighborhood of the base point in S^2, and likewise, A_2 be S^2 together with a small open neighborhood of the base point in S^1 - here the base points are the points that get identified in the construction of $S^2 \vee S^1$. Applying van Kampen, we find that $\pi_1(S^2 \vee S^1) \cong \pi_1(S^1) * \pi_1(S^2)/N$ where N is generated by all elements of the form $i_{12}(w) i_{21}(w)^{-1}$ for $w \in \pi_1(A_1 \cap A_2)$. But $A_1 \cap A_2$ is contractible, so $N \cong 0$. Since $\pi_1(S^1) \cong \mathbb{Z}$ and $\pi_1(S^2) \cong 0$, we conclude that $\pi_1(S^2 \vee S^1) \cong \mathbb{Z}$.

(2) To compute $\pi_2(S^1 \vee S^2)$, it suffices to compute π_2 of its universal cover since these are isomorphic. The universal cover is $\mathbb{R}$ with S^2 attached at each integer. Since $\mathbb{R} \simeq \{*\}$, the universal cover is homotopy equivalent to $\vee_{\mathbb{Z}} S^2$ for example by using proposition 0.16 and 0.17 in Hatcher.
Since homotopy groups are invariant under based homotopy equivalences, it suffices to compute $\pi_2(\bigvee_{\mathbb{Z}} S^2)$.
But $\bigvee_{\mathbb{Z}} S^2$ is 1-connected, so if $\tilde{H}_2(\bigvee_{\mathbb{Z}} S^2) \cong H_2(\bigvee_{\mathbb{Z}} S^2)$ is nonzero, then by the Hurewicz theorem, we will obtain that $\pi_2(\bigvee_{\mathbb{Z}} S^2) \cong H_2(\bigvee_{\mathbb{Z}} S^2)$. Now, we can give $\bigvee_{\mathbb{Z}} S^2$ a Δ-complex (or cellular) structure with a single 0-simplex and a 2-simplex for each S^2 in $\bigvee_{\mathbb{Z}} S^2$. The associated simplicial chain complex then becomes

$$\ldots \to 0 \to \bigoplus_{\mathbb{Z}} \mathbb{Z} \to 0 \to \mathbb{Z} \to 0 \to \ldots$$

with 0 everywhere else. In particular then $H_2(\bigvee_{\mathbb{Z}} S^2) \cong \oplus_{\mathbb{Z}} \mathbb{Z}$ since there cannot be any cancellation from the maps. Since the Hurewicz isomorphism takes $f \in \pi_2(\bigvee_{\mathbb{Z}} S^2)$, to $f_*[1] \in H_2(\bigvee_{\mathbb{Z}} S^2)$ for $[1] \in H_2(S^2)$ a generator, we find that through our proof using the Δ-complex of $\bigvee_{\mathbb{Z}} S^2$, we found that the inclusions $S^2 \hookrightarrow \bigvee_{\mathbb{Z}} S^2$ in fact induce generators on homology: i.e., the images of the different inclusions $\iota_i\colon H_2(S_i^2) \hookrightarrow H_2(\bigvee_{i \in \mathbb{Z}} S_i^2) \cong \bigoplus_{\mathbb{Z}} \mathbb{Z}$ generate $\bigoplus_{\mathbb{Z}} \mathbb{Z}$, and hence also $\pi_2(\bigvee_{\mathbb{Z}} S^2)$ under the Hurewicz isomorphism.

(3) Recall that the action of $\pi_1\left(S^1 \vee S^2\right)$ on $\pi_n\left(S^1 \vee S^2\right)$ makes $\pi_n\left(S^1 \vee S^2\right)$ into a $\mathbb{Z}\left[\pi_1\left(S^1 \vee S^2\right)\right]$-module. We saw that $\pi_1\left(S^1 \vee S^2\right) \cong \mathbb{Z}$. Let γ be a loop that goes once around the S^1 factor. This generates $\pi_1\left(S^1 \vee S^2\right) \cong \mathbb{Z}$, so it suffices to describe the action of γ on $\pi_2\left(S^1 \vee S^2\right)$ since π_2 now becomes a $\mathbb{Z}[\gamma]$-module under this action. Since also $\pi_2\left(S^1 \vee S^2\right) \cong \bigoplus_{\mathbb{Z}} \mathbb{Z}$, it suffices to describe the action of γ on an arbitrary basis element of $\bigoplus_{\mathbb{Z}} \mathbb{Z}$, say, corresponding to the image under p_* of some an inclusion of some $S^2 \hookrightarrow \tilde{X}$. Suppose we choose the inclusion α into the S^2 attached to $1_n \in \mathbb{Z}_n$.
Then $p_*\alpha = [\eta_n \xi] = 1_n \in \mathbb{Z}_n$ where η_n is the loop that winds around the S^1 factor n times and ξ is the inclusion $S^2 \hookrightarrow S^1 \vee S^2$.
In particular then $\gamma p_* \alpha = [\eta_{n+1}\xi] = 1_{n+1} \in \mathbb{Z}_{n+1}$.

This completes the description, but I will also give an alternative description just for completeness where I expound on some details between the homomorphisms $H_2\left(\bigvee_{\mathbb{Z}} S^2\right) \cong \pi_2\left(\bigvee_{\mathbb{Z}} S^2\right) \cong \pi_2\left(S^1 \vee S^2\right)$ that underlies the above explanation. We will use the correspondence between the π_1 action on $\pi_n(X)$ and its action on $\pi_n\left(\tilde{X}\right)$ where $\tilde{X}$ was the universal covering space.
To this end, we have previously shown the following:

Lemma 4.10. *Let $p\colon \tilde{X} \to X$ be the universal cover of a path-connected space X. Under the isomorphism $\pi_n(X) \cong \pi_n(\tilde{X})$, for $n \geq 2$, the action of $\pi_1(X)$ on $\pi_n(X)$ corresponds to the action of $\pi_1(X)$ on $\pi_n\left(\tilde{X}\right)$ induced by the action of $\pi_1(X)$ on $\tilde{X}$ as deck transformations. More precisely, for $\gamma \in \pi_1(X, x_0), \alpha \in \pi_n\left(\tilde{X}, \tilde{x}_0\right), \tilde{\gamma}$ the lift of γ, and γ_* the homomorphism induced by the action of γ on $\tilde{X}$, we have $\gamma p_*(\alpha) = p_*\left(\beta_{\tilde{\gamma}}\left(\gamma_*(\alpha)\right)\right)$.*

Let $\alpha \in \pi_2\left(\tilde{X}\right)$ be the element corresponding under the isomorphism $\pi_2(X) \cong \pi_2(\tilde{X})$ to the class of our chosen inclusion $S^2 \hookrightarrow \bigvee_{\mathbb{Z}} S^2$. That is, α is the inclusion of S^2 into one of the S^2 in the universal cover. To understand $\gamma p_*(\alpha)$, we can thus look at $p_*\left(\beta_{\tilde{\gamma}}\left(\gamma_*(\alpha)\right)\right)$. Now, $\gamma_*(\alpha)$ will simply be the inclusion of S^2 to the S^2 "above" the previous one in the universal cover. So if we previously included our S^2 into the S^2 attached to $n \in \mathbb{R} \subset \tilde{X}$, then $\gamma_*(\alpha)$ corresponds to including S^2 into the S^2 attached to $n+1 \in \mathbb{R} \subset \tilde{X}$. Then $\beta_{\tilde{\gamma}}$ is simply the change-or-basepoint transformation depicted in the picture on page 341 in Hatcher. I.e., it essentially shrinks α and attaches it inside a larger square where we put $\tilde{\gamma}$ on each radial line in-between the squares. If we understand our isomorphism $\pi_2\left(\bigvee_{\mathbb{Z}} S^2\right) \cong \bigoplus_{i \in \mathbb{Z}} \mathbb{Z}_i$ as the generator for $\mathbb{Z}_i$ corresponding under the Hurewicz isomorphism to the inclusion of S^2 into the sphere attached to $i \in \mathbb{Z}$, then we find that $\alpha \mapsto \beta_{\tilde{\gamma}}\left(\gamma_*(\alpha)\right)$ precisely sends $\alpha = 1_n \in \mathbb{Z}_n$ to $1_{n+1} \in \mathbb{Z}_{n+1}$. Under p_*, this may be interpreted again as sending $1_n \mapsto 1_{n+1}$ when n corresponds to $[\eta\xi]$ where η is the loop that winds around the S^1 factor n times and ξ is the inclusion of $S^2 \hookrightarrow S^1 \vee S^2$.

Problem 4.11. Let (X, A, x_0) be a pointed pair such that the inclusion $i\colon A \hookrightarrow X$ is based nullhomotopic (the nullhomotopy preserves the basepoint). The goal is to show that for $n \geq 2$, there is an isomorphism of groups:

$$\pi_n(X, A, x_0) \cong \pi_n(X, x_0) \times \pi_{n-1}(A, x_0).$$

(1) Show that there is an exact sequence of groups
$$1 \to \pi_n(X, x_0) \xrightarrow{j_*} \pi_n(X, A, x_0) \xrightarrow{\partial_*} \pi_{n-1}(A, x_0) \to 1.$$
(2) Using a based nullhomotopy $H\colon A \times [0,1] \to X$, construct a natural group morphism
$$r_*\colon \pi_n(X, A, x_0) \to \pi_n(X, x_0)$$
such that $r_* \circ j_* = 1$.

(3) Show that for any short exact sequence of groups
$$1 \to A \xrightarrow{\alpha} B \xrightarrow{\beta} C \to 1$$
such that α admits a retraction, there is a group isomorphism
$$B \cong A \times C.$$
Conclude the desired isomorphism.

Proof. (1) From the LES for relative homotopy groups, we obtain that
$$\pi_n(A, x_0) \xrightarrow{i_*} \pi_n(X, x_0) \xrightarrow{j_*} \pi_n(X, A, x_0) \xrightarrow{\partial_*} \pi_{n-1}(A, x_0) \xrightarrow{i_*} \pi_{n-1}(X, x_0)$$
is exact. For $n \geq 2$, all the sets in the exact sequence are groups and the maps are group homomorphisms. Since homotopic maps relative to the base point induce the same maps on homotopy groups, we find by assumption that $i_* = 0$. Therefore,
$$1 \xrightarrow{0} \pi_n(X, x_0) \xrightarrow{j_*} \pi_n(X, A, x_0) \xrightarrow{\partial_*} \pi_{n-1}(A, x_0) \xrightarrow{0} 1$$
is exact.

(2) Let $[f] \in \pi_n(X, A, x_0)$ and consider a representative $f\colon (D^n, S^{n-1}, s_0) \to (X, A, x_0)$. We put f on the bottom of a cylinder $D^n \times \{0\} \subset D^n \times I$. Now $H(f(x), t)$ gives a homotopy $S^{n-1} \times I \to X$, so we can use this on $S^{n-1} \times I \subset D^n \times I$ of the cylinder. Now we use that $D^n \times \{0\} \cup S^{n-1} \times I \cong D^n$ (see Figure 13). Denote this homeomorphism by $\varphi\colon D^n \to D^n \times \{0\} \cup S^{n-1} \times I$.

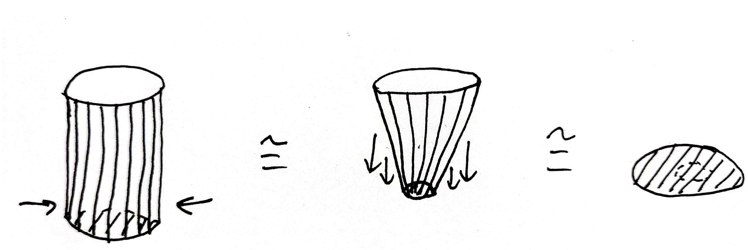

Figure 13.

Define $h\colon S^{n-1} \times I$ by $h(x,t) = H(f(x), t)$ and define $h \cup f\colon D^n \times \{0\} \cup S^{n-1} \times I$ by f on $D^n \times \{0\}$ and h on $S^{n-1} \times I$. Then define $h \cup f \circ \varphi\colon D^n \to X$. Now $h \cup f \circ \varphi$ maps ∂D^n to x_0, so it factors through the quotient $D^n \to S^n$ and induces a map $\Gamma\colon (S^n, pt) \to (X, x_0)$, where pt is the point that the boundary collapses to. This is well-defined since if $f \simeq f' \operatorname{rel} s_0$ through a homotopy $F\colon D^n \times I \to X$, then $\tilde{h}(x,t,s) = H(F(x,s), t)$ gives a map $S^{n-1} \times I \times I$ - and this homotopy is constant on the boundary $S^{n-1} \times \{1\}$. Then taking $\tilde{h} \cup F\colon \left(D^n \times \{0\} \cup S^{n-1} \times I\right) \times I \cong D^{n-1} \times \{0\} \times I \cup S^{n-1} \times I \times I \to X$, we obtain a homotopy $\tilde{h} \cup F \circ \varphi\colon D^n \times I \to X$ which is constant on the boundary throughout, hence induces the desired homotopy $S^n \times I \to X$ between Γ and Γ' rel $\{pt\}$.

To see that it is a group morphism, see Figure 14. Here the top left picture depicts Γ obtained from $f + g \in \pi_n(X, A, x_0)$. The bottom left picture represents $\Gamma_f + \Gamma_g$, where Γ_f is obtained from f by the above procedure and Γ_g is obtained from g by the procedure. Hence $r_*([f] + [g]) = r_*([f]) + r_*([g])$.

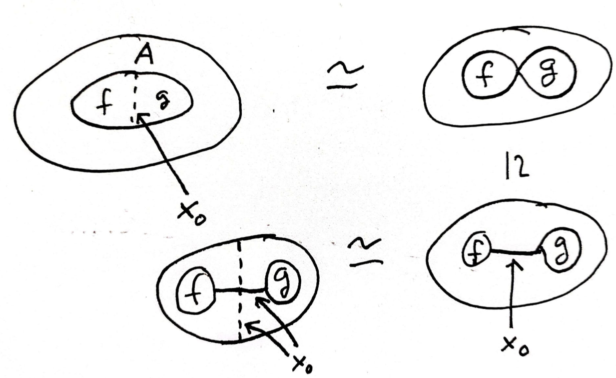

FIGURE 14.

Naturality amounts to showing that r_* defines a natural transformation from $\pi_n(-,-,-)$ to $\pi_n(-,-)$ on the category of based pairs (X, A) such that $A \hookrightarrow X$ is based nullhomotopic. That is, that given a map $f\colon (X, A, x_0) \to (Y, B, y_0)$, with both $A \hookrightarrow X$ and $B \hookrightarrow Y$ based nullhomotopic, the diagram

$$\begin{array}{ccc} \pi_n(X, A, x_0) & \xrightarrow{r_*} & \pi_n(X, x_0) \\ \downarrow{\scriptstyle f_*} & & \downarrow{\scriptstyle f_*} \\ \pi_n(Y, B, y_0) & \xrightarrow{r_*} & \pi_n(Y, y_0) \end{array}$$

commutes.

Now, if $H\colon A \times I \to X$ is the based nullhomotopy of $A \hookrightarrow X$ and $G\colon B \times I \to Y$ is the based nullhomotopy of $B \hookrightarrow Y$, then for $[f] \in \pi_n(X, A, x_0)$, we get the situation of Figure 15. In the central part, these maps agree - namely they are $f \circ g$. We are thus asking for a homotopy between $f \circ H(g(x), t)$ and $G(f \circ g(x), t)$. So we want a map $L\colon S^{n-1} \times I \times I \to X$. We may assume without loss of generality that H and G map $S^{n-1} \times \{0\}$ to x_0 and y_0, respectively, instead of $S^{n-1} \times \{1\}$. Now we let L be given by

$$L(x, t, s) \begin{cases} f \circ H(g(x), (1-2s)t), & s \in \left[0, \frac{1}{2}\right] \\ G(f \circ g(x), 2s-1), & s \in \left[\frac{1}{2}, 1\right]. \end{cases}$$

This gives naturality.

Now, for $[f] \in \pi_n(X, x_0)$, we have that the boundary is already mapped to x_0, so $H(f(x), t)$ is constant on $S^{n-1} \times I$ since H is relative the basepoint. Hence

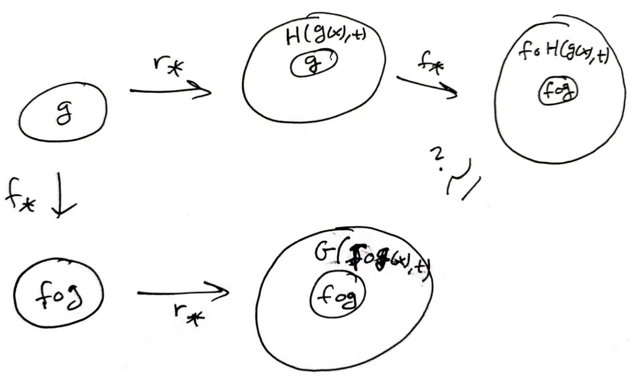

FIGURE 15.

$\Gamma \simeq f$ as depicted in Figure 16 where Γ is obtained from $j_* [f]$ which is simply $[f] \in \pi_n (X, A, x_0)$.

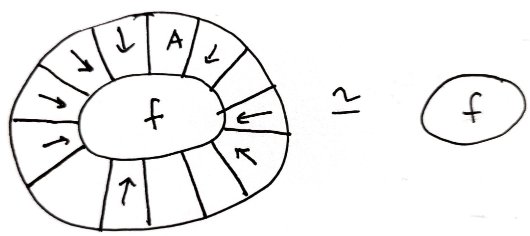

FIGURE 16.

This shows that $r_* \circ j_* = \mathrm{id}$ which was what we wanted to show.

(3) Suppose

$$1 \to A \overset{\alpha}{\to} B \overset{\beta}{\to} C \to 1$$

is a short exact sequence and let $s \colon B \to A$ be a retraction - i.e., $s \circ \alpha = \mathrm{id}$. We claim that $\varphi \colon B \to A \times C$ by $\varphi(b) = (s(b), \beta(b))$ is an isomorphism. Firstly, it is clearly a group homomorphism since s and β are assumed to be group homomorphisms. Next, for injectivity, if $\varphi(b) = 0$, then $s(b) = 0$ and $\beta(b) = 0$. But by exactness then there exists $a \in A$ such that $\alpha(a) = b$. Thus $a = \mathrm{id}(a) = s \circ \alpha(a) = s(b) = 0$. But then since α is a group homomorphism, it takes 0 to 0, so $b = \alpha(a) = \alpha(0) = 0$. This gives injectivity.
For surjectivity, let $(a, c) \in A \times C$. Since β is surjective by exactness of the SES, there exists $b \in B$ such that $\beta(b) = c$. Then $s(\alpha(a) - \alpha \circ s(b) + b) = a - s(b) + s(b) = a$ while $\beta (\alpha(a) - \alpha \circ s(b) + b) = \beta(b) = c$ since $\beta \circ \alpha = 0$. Hence $\varphi (\alpha(a - s(b)) + b) = (a, c)$, so φ is also surjective.
To conclude the desired isomorphism of the problem, we simply note that by (1)

and (2), we precisely have an exact sequence where j_* admits a retraction, so by (3), we get an isomorphism

$$\pi_n\,(X, A, x_0) \cong \pi_n(X, x_0) \times \pi_{n-1}(A, x_0).$$

$\square$

References

[1] Glen E. Bredon. *Topology and geometry*. **volume** 139. Graduate Texts in Mathematics. Corrected third printing of the 1993 original. Springer-Verlag, New York, 1997, **pages** xiv+557. ISBN: 0-387-97926-3.

[2] Allen Hatcher. *Algebraic topology*. Cambridge University Press, Cambridge, 2002, **pages** xii+544. ISBN: 0-521-79160-X; 0-521-79540-0.

[3] Oscar Randal-Williams. *Homotopy Theory*. 2021. URL: https://www.dpmms.cam.ac.uk/~or257/teaching/notes/HomotopyTheory.pdf.