DEGREE OF MAPS $f: S^n \to S^n$

Let $f: S^n \to S^n$ be a map. Then f induces $f_*: \tilde{H}_n(S^n) \to \tilde{H}_n(S^n)$.

Since $\tilde{H}_n(S^n) \cong \mathbb{Z}$, there exists precisely one $d \in \mathbb{Z}$, such that $f_*(a) = da \quad \forall a \in \mathbb{Z}$.

This number d is called the **DEGREE of f** and is denoted $\deg(f) \in \mathbb{Z}$.

SIMPLE PROPERTIES OF DEGREE

1. $\deg(id) = 1$
2. $S^n \xrightarrow{f} S^n \xrightarrow{g} S^n \Rightarrow \deg(g \circ f) = \deg g \cdot \deg f$
3. If $f \simeq g : S^n \to S^n \Rightarrow \deg(f) = \deg(g)$.

Proof

1. follows since $(id)_* = id$.

② follows since $(g\circ f)_* = g_* \circ f_*$

③ If $f \simeq g$, then $f_* = g_*$, so $\deg(f) = \deg(g)$.

PROPOSITION

Let $S^n \subset \mathbb{R}^{n+1}$ be the n-dim sphere, write the elements of S^n as $(x_0, \dots, x_n)$.
Let $f: S^n \to S^n$ be the map

$$f(x_0, \dots, x_n) := (-x_0, x_1, \dots, x_n).$$

Then $\deg(f) = -1$.

Proof

Let $n = 0$. Then $f: \{-1, 1\} \to \{-1, 1\}$ is the map $f(-1) = 1$, $f(1) = -1$.

$$\begin{tikzcd}
H_0(\{-1\}) \oplus H_0(\{1\}) \arrow[r, "\cong", "②"'] & H_0(S^0) \arrow[d, "\varepsilon_*"] \\
\mathbb{Z} \oplus \mathbb{Z} \arrow[r] & \mathbb{Z}
\end{tikzcd}$$

$$(a, b) \longmapsto a + b \in \mathbb{Z}$$

the kernel of the above map

$$
\begin{array}{ccc}
\tilde{H}_0(S^0) & \xleftarrow[\cong]{g} & \{(a,-a),\, a\in\mathbb{Z}\} \subset \mathbb{Z}\oplus\mathbb{Z} \\
\Big\downarrow f_* & & \Big\downarrow \quad (a,-a) \mapsto (-a,a) \quad \cong\mathbb{Z} \\
\tilde{H}_0(S^0) & \xrightarrow[g^{-1}]{} & \{(a,-a),\, a\in\mathbb{Z}\} \subset \mathbb{Z}\oplus\mathbb{Z} \quad \cong\mathbb{Z}
\end{array}
$$

From this it immediately follows that

$\deg(f) = -1$.

Now we proceed by induction.

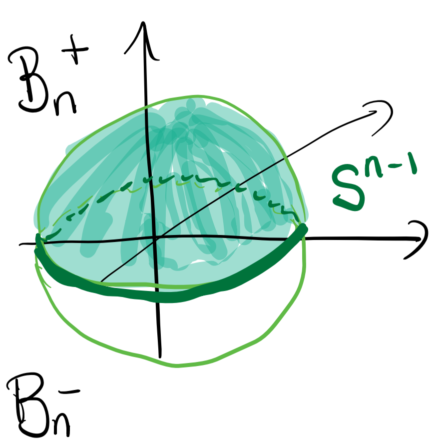
Let $n \geq 1$. Suppose that the statement is true for S^k $\forall\ 0 \leq k < n$.

We now prove it for n.

Consider

$$B_+^n = \{(x_0, \dots, x_n) \in S^n : x_n \geq 0\}$$

$$B_-^n = \{(x_0, \dots, x_n) \in S^n : x_n \leq 0\}$$



We have

$$f(B_\pm^n) = B_\pm^n$$

$$f(S^{n-1}) = S^{n-1}$$

$$\begin{tikzcd}
\tilde{H}_n(S^n) \arrow[r, "\cong"] \arrow[d, "f_*"] & H_n(S^n, B^n_+) \arrow[d, "f_*"] & H_n(B^n_-, S^{n-1}) \arrow[l, "\cong", "\text{excision + homotopy}"'] \arrow[r, "\cong", "\text{LES of a pair}"'] \arrow[d, "f_*"] & \tilde{H}_{n-1}(S^{n-1}) \arrow[d, "(f|_{S^{n-1}})_*"] \\
\tilde{H}_n(S^n) \arrow[r, "\cong"'] & H_n(S^n, B^n_+) & H_n(B^n_-, S^{n-1}) \arrow[l, "\cong"'] \arrow[r, "\cong"] & \tilde{H}_{n-1}(S^{n-1})
\end{tikzcd}$$

By induction $\deg(f|_{S^{n-1}}) = -1 \Rightarrow$ all vertical maps are multiplications by -1. $\blacksquare$

COROLLARY

Let $0 \leq i \leq n$, $\tau_i : S^n \to S^n$,

$$\tau_i(x_0, \dots, x_n) := (x_0, \dots, -x_i, \dots, x_n).$$

Then $\deg(\tau_i) = -1$.

Proof

Show that $\tau_i \simeq \tau_{i-1} \simeq \dots \simeq \tau_0$. (exercise) HW

$\Rightarrow \deg \tau_i = \deg \tau_0$

Hint for the homotopy: 2D case

$$\begin{bmatrix}-1&0\\0&-1\end{bmatrix}\underbrace{\begin{bmatrix}-1&0\\0&1\end{bmatrix}}_{\tau_0}=\underbrace{\begin{bmatrix}1&0\\0&-1\end{bmatrix}}_{\tau_1}$$

by angles

rotation in the 2-D plane by 180 deg.

$$H((x_0,x_1),t)=\begin{bmatrix}\cos(\pi t)&-\sin(\pi t)\\ \sin(\pi t)&\cos(\pi t)\end{bmatrix}\begin{bmatrix}-x_0\\ x_1\end{bmatrix}\qquad t\in[0,1]$$

$$H((x_0,x_1),0)=\begin{bmatrix}1&0\\0&1\end{bmatrix}\begin{bmatrix}-x_0\\ x_1\end{bmatrix}=(-x_0,x_1)=\tau_0(x_0,x_1)$$

$$H((x_0,x_1),1)=\begin{bmatrix}-1&0\\0&-1\end{bmatrix}\begin{bmatrix}-x_0\\ x_1\end{bmatrix}=(x_0,-x_1)=\tau_1(x_0,x_1)$$

IMPORTANT EXAMPLE

(the antipodal map)

Let $\sigma: S^n \to S^n$ be the map

$$\sigma(x) := -x.$$

Then $\deg \sigma = (-1)^{n+1}$.

Proof

$\sigma = \tau_0 \circ \tau_1 \circ \dots \circ \tau_n$

$\Rightarrow \deg \sigma = \deg \tau_0 \cdot \deg \tau_1 \cdots \deg \tau_n$

$= (-1)^{n+1}$

$\boxtimes$

COROLLARY

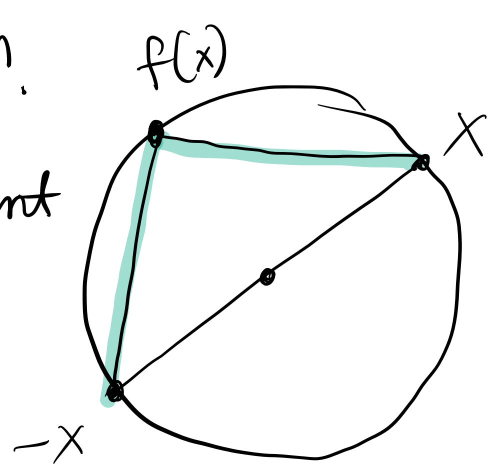
If n = even $\Rightarrow \sigma \not\simeq id$.

COROLLARY

Let n be even and $f: S^n \to S^n$. Then there exists $x \in S^n$, s.t. $f(x) = \pm x$.

Proof

Suppose by contradiction that $f(x) \neq x$, $f(x) \neq -x$ $\forall x \in S^n$.



the straight segment in B^{n+1} connecting x to $f(x)$ does not pass through 0.

The same also holds for the segment connecting $-x$ to $f(x)$.

Consider $F: S^n \times I \to S^n$
$G: S^n \times I \to S^n$:

the denominators never vanish $\forall x \in S^n$, $t \in [0,1]$

$$F(x,t) := \frac{t f(x) + (1-t)x}{\| t f(x) + (1-t) x \|}$$

$$G(x,t) := \frac{t \cdot (-x) + (1-t) f(x)}{\| t \cdot (-x) + (1-t) f(x) \|}$$

F is a homotopy between id & f.
G is a homotopy between f & the antipodal map.

$\Rightarrow \deg(f) = 1$ & $\deg(f) = (-1)^{n+1} = -1$

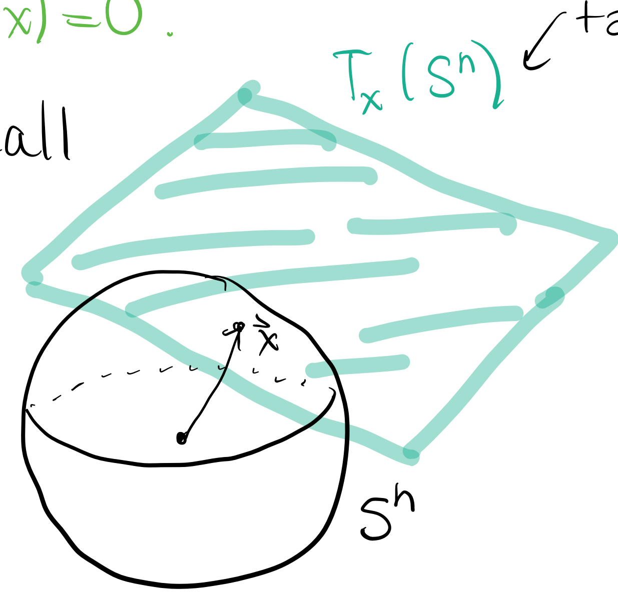
n is even

Contradiction.

COROLLARY

Let $\vec{v}$ be a tangent vector field to S^n. If $n =$ even, then $\exists\, x \in S^n$ with $\vec{v}(x) = 0$.

Recall



$u \in \mathbb{R}^{n+1}$ is in $T_x(S^n) \iff u \perp x$, ie $T_x(S^n) = x^\perp$.

A tangent vector field is $\{\vec{v}(x)\}_{x \in S^n}$ s.t. $\vec{v}(x) \in T_x(S^n)$ / $\vec{v}(x)$ and x are orthogonal in $\mathbb{R}^{n+1}$.

Proof

Suppose that $\vec{v}(x) \neq 0 \quad \forall\, x \in S^n$.

Consider $f : S^n \to S^n$, $f(x) = \dfrac{\vec{v}(x)}{\|\vec{v}(x)\|}$.

Clearly, $\forall\, x \quad f(x) \in T_x(S^n)$.

But both x & $-x$ are in $(T_x(S^n))^\perp$.

$\Rightarrow f(x) \neq x, -x \quad \forall x$. this is a contradiction with the previous corollary.

APPLICATION

$n=2$, S^2 = Earth's surface

$\vec{v}(x)$ = velocity of the wind at $x \in$ Earth

$\Rightarrow$ at any given moment, $\exists$ a point $x \in$ Earth where the wind does <u>not</u> blow.

Exercise: Show that S^{2k-1} (odd dim sphere) <u>does</u> have a nowhere vanishing vector field. (HW exercise)

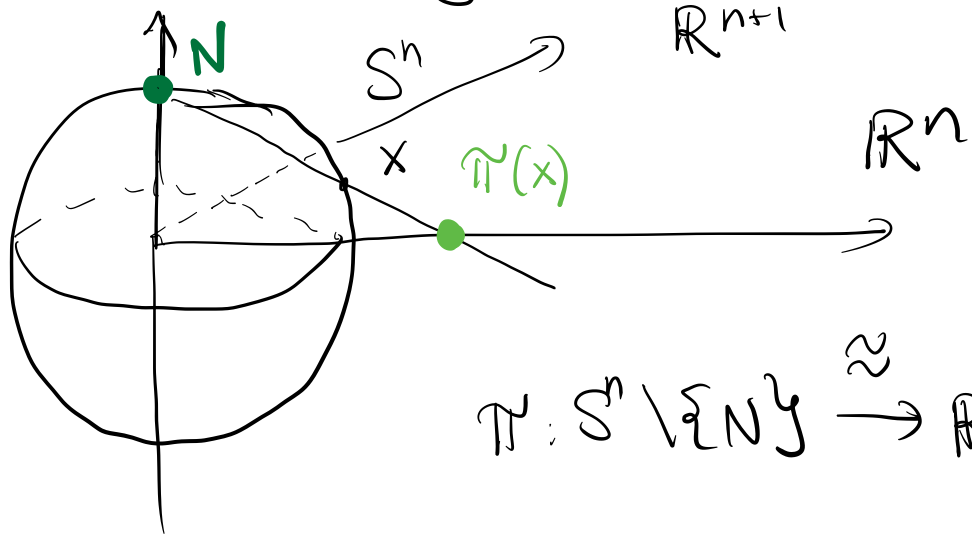
CALCULATION OF DEGREES

Consider maps $S^n \to S^n$ defined as follows.

$S^n \approx \mathbb{R}^n \cup \{\infty\}$ (one-point compactification)

open sets of the original space + nbhd of $\{\infty\}$ [complement of a comp-set $\cup \{\infty\}$]

Recall the stereographic projection



$$\pi : S^n \setminus \{N\} \xrightarrow{\approx} \mathbb{R}^n$$

π extends to a homeomorphism that we denote by $\hat{\pi} : S^n \to \mathbb{R}^n \cup \{\infty\}$ (HW exercise)

Now fix a non-singular $n \times n$ matrix A. ($\det A \neq 0$). View A as a homeomorphism $A : \mathbb{R}^n \to \mathbb{R}^n$, $x \mapsto A \cdot x$. (invertible since A is non-singular).

A extends to a homeo.

$$\mathbb{R}^n \cup \{\infty\} \longrightarrow \mathbb{R}^n \cup \{\infty\}$$

(HW exercise)

Denote this extension by

$$\hat{A} : \mathbb{R}^n \cup \{\infty\} \longrightarrow \mathbb{R}^n \cup \{\infty\}.$$