Lecture # 7

Outline:

1) Review from last time
2) Brouwer's Fixed point theorem
3) Borsuk - Ulam Theorem

Section 1: Review

Definition: A closed curve in S^1 = circle is a ② continuous ① map $\gamma : S^1 \longrightarrow S^1$.

① We send every pt in S^1 to a point in S^1.

② "Continuous" = we send points infintesimally close together in S^1 to points infintesimally close together in S^1.

↪ We map S^1 into S^1 w/ out ripping or cutting it

Remark: Equivalently, a map $\gamma : S^1 \longrightarrow S^1$ may be viewed as a continuous map

$$\gamma : [0, 2\pi] \longrightarrow S^1$$

w/

$$\gamma(0) = \gamma(2\pi)$$

↳ i.e., a map of a circle is just a map of an interval that connects up at its end points.

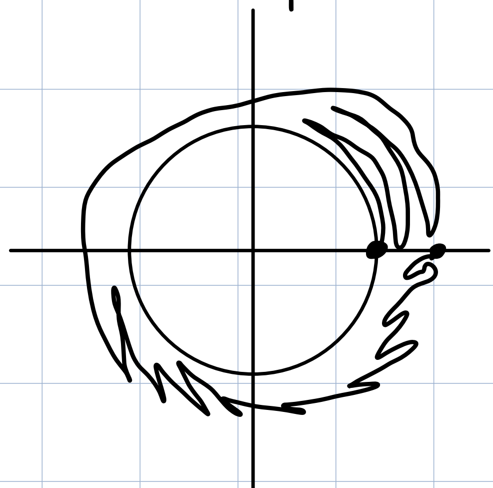
↳ Intuitively, $\gamma : S^1 \to S^1$ gives a way of wrapping/laying a string onto a circle such that you can tie together its ends.

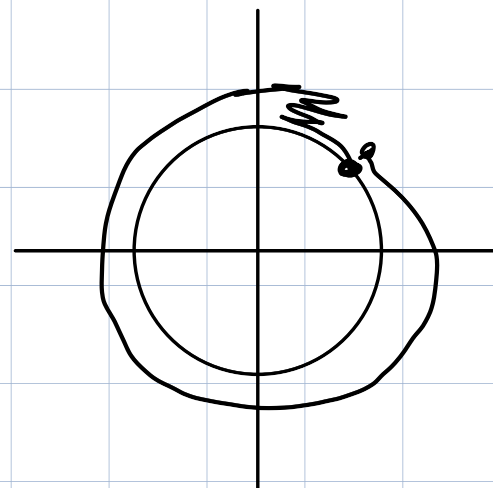
Example: 1) $\gamma_n : [0, 2\pi] \longrightarrow S^1$ given by

$$\gamma(t) = (\cos(nt), \sin(nt))$$

$\rightsquigarrow$ γ_n wraps n-times around the circle.

2) Crazier examples





Lemma: (Curve Lifting) Given a closed curve $\gamma : S^1 \to S^1$, there exists a function $f : [0, 2\pi] \to \mathbb{R}$ st

1) $f(0) = f(2\pi) + 2\pi \cdot n$ for some integer n
2) $\gamma(t) = (\cos(f(t)), \sin(f(t)))$

↪ f is called a lift of γ to $\mathbb{R}$.

Idea: $f(t)$ = Accumulated angle of rotation of $\gamma(t)$ measured w/ respect to $(1,0)$

↪ rotate clockwise angle decreases

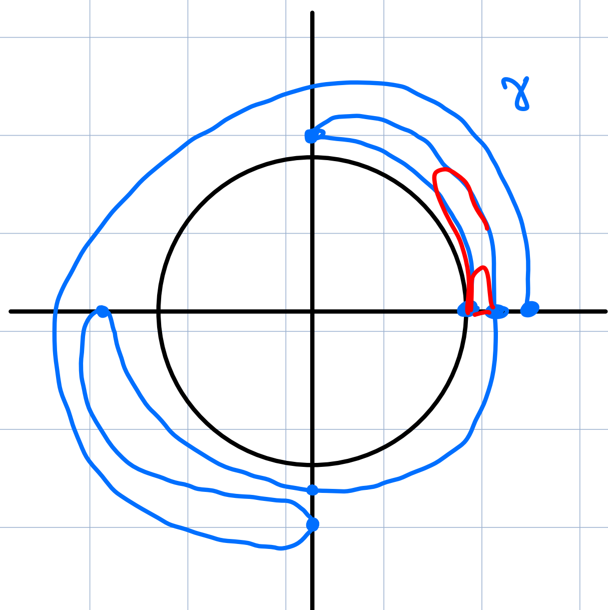
↪ rotate counterclockwise angle increases

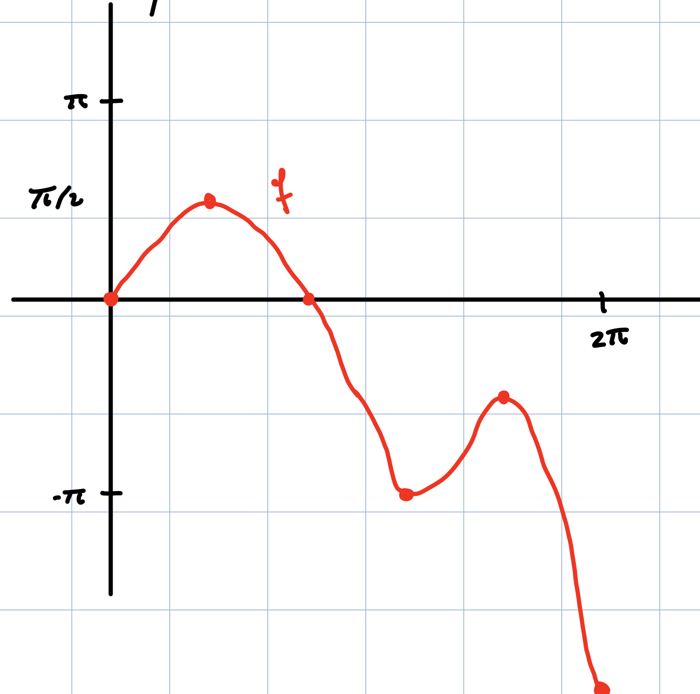
Example: 1) A lift of γ_n is given by $f(t) = n \cdot t$

2)

$$\deg(\gamma) = \frac{f(2\pi) - f(0)}{2\pi} = \frac{-2\pi - 0}{2\pi} = -1$$

y-axis = accumulated angle.





Definition: The degree of a closed curve $\gamma : S^1 \to S^1$ is

$$\deg(\gamma) = \left(f(2\pi) - f(0)\right)/2\pi$$

where f is any lift of γ to $\mathbb{R}$.

↪ This did not depend on the choice of lift

Remark: 1) Intuitively, $\deg(\gamma)$ = signed # of times γ completely wraps around the circle

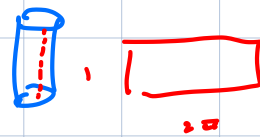
↪ signed: wraps clockwise = negative wrap

wraps counter clockwise = positive wrap

Example: 1) $\deg(\gamma_n) = n$

2) See above examples.

Definition: Two closed curves $\beta : S^1 \to S^1$ and $\gamma : S^1 \to S^1$ are <u>homotopic</u> if there is a continuous map $H : [0,1] \times S^1 \to S^1$ satisfying



1) $H(0,t) = \beta(t)$

2) $H(1,t) = \gamma(t)$

Remark: Equivalently, $H : [0,1] \times [0, 2\pi] \to S^1$ w/

1) $H(0,t) = \beta(t)$

2) $H(1,t) = \gamma(t)$

3) $H(s,0) = H(s, 2\pi)$

Remark: 1) H parameterizes a family of curves that interpolates between β and γ.

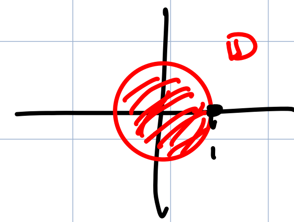
2) Intuitively, H parameterizes how we can push, compress, deform the image of β in S^1 to the image of γ in S^1.

Theorem: Two closed curves $\beta : S^1 \to S^1$ and $\gamma : S^1 \to S^1$ are homotopic if and only if $\deg(\beta) = \deg(\gamma)$

Section 2: Brouwer's Fixed Point Theorem

Definition: $\mathbb{D} = \{(x,y) \text{ in } \mathbb{R}^2 \mid x^2+y^2 \leq 1\}$

= unit disk in the plane



Theorem: Given a continuous map $f: \mathbb{D} \longrightarrow \mathbb{D}$, there exists a point (x,y) in $\mathbb{D}$ such that $f(x,y) = (x,y)$

↳ ie, f has a fixed point.

Proof:

1) Suppose by way of contradiction that f does <u>not</u> have any fixed points.

2) Define a map $r : \mathbb{D} \longrightarrow S^1$ as follows:

   a) Consider the ray from $f(x,y)$ to (x,y)

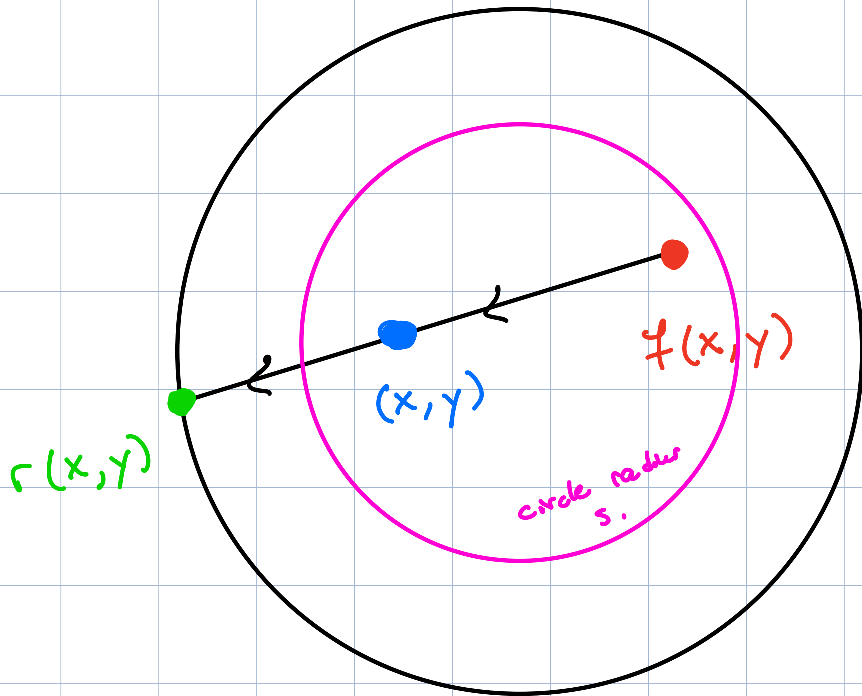
   b) follow the ray until you hit the boundary of the disk, which is a circle

   c) Set $r(x,y)$ = point where ray meets the boundary

   ↳ Note, that to get such a ray we needed $f(x,y) \neq (x,y)$

3) Note, r is continuous.

Picture:



4) Define $\gamma : S^1 \to S^1$ as follows:

Take S^1, include it into boundary of $\mathbb{D}$, and then apply the map $r : \mathbb{D} \to S^1$.

5) Define $\beta : S^1 \to S^1$ as follows:

Take S^1, map it to $(0,0)$ in $\mathbb{D}$, and then apply the map $r : \mathbb{D} \to S^1$.

6) By construction, $\deg(\gamma) = \underline{1}$

7) β is a constant map, so $\deg(\beta) = 0$

8) Define a homotopy $H : \overset{s}{[0,1]} \times \overset{t}{S^1} \longrightarrow S^1$ as follows:

$$H(s,t) = r\big(s \cdot \cos(t),\ s \cdot \sin(t)\big)$$

9) $H(0,t) = r(0,0) = \beta(t)$

10) $H(1,t) = \big(\cos(t), \sin(t)\big) = \gamma(t)$

11) $\Rightarrow$ γ is homotopic to β

$\Rightarrow$ $1 = \deg(\gamma) = \deg(\beta) = 0$

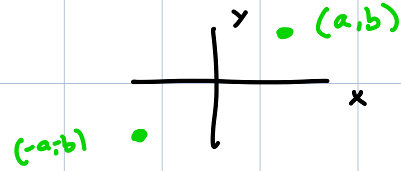
a contradiction

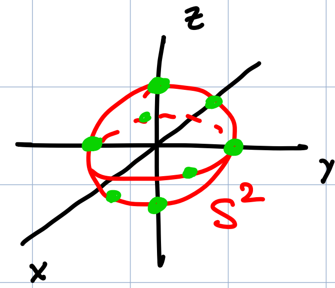
12) $\Rightarrow$ $f(x,y) = (x,y)$ for at least some (x,y) in $\mathbb{D}$. $\square$

Exercise: Given a continuous function $f : [0,1] \longrightarrow [0,1]$, there exists $x \in [0,1]$ such that $f(x) = x$.

Hint:
1) You could use the intermediate value theorem
2) <u>or</u> try to replicate the proof of Brouwer's fixed point theorem but in one lower dimension.

Section 3: Borsuk-Ulam Theorem





Definition:

- $S^2 = \{(x,y,z) \text{ in } \mathbb{R}^3 \mid x^2+y^2+z^2=1\}$

  $= \text{unit sphere in } \mathbb{R}^3$

- The antipodal point of (x,y,z) in S^2 is the point $(-x,-y,-z)$

Theorem: Given a continuous map $f: S^2 \to \mathbb{R}^2$, there exists a point (x,y,z) in S^2 such that

$$f(x,y,z) = f(-x,-y,-z)$$

Example: $f : S^2 \to \mathbb{R}^2$ via a location an earth is mapped to (temperature, humidity).

So the thm $\Rightarrow$ there exists antipodal locations on the earth w/ the same temperature and humidity.

Definition: The norm of a point (x,y) in $\mathbb{R}^2$ is

$$|(x,y)| = \sqrt{x^2 + y^2}$$

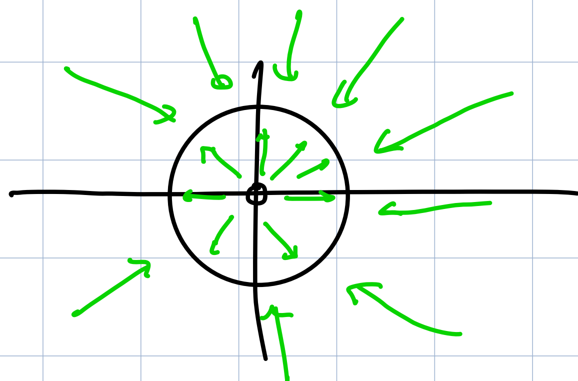
$\leftrightarrow$ distance of (x,y) from the origin $(0,0)$.

Remark: If $(x,y) \neq (0,0)$, then

$$\frac{(x,y)}{|(x,y)|} = \left(\frac{x}{|(x,y)|}, \frac{y}{|(x,y)|} \right)$$

lies on $S^1 \subset \mathbb{R}^2$

↪ We've just scaled in (x,y) according to its distance from the origin so that its new distance from the origin is 1, ie, it lies on S^1.



Proof:

1) Suppose by way of contradiction that

$$f(x,y,z) \neq f(-x,-y,-z)$$

for all (x,y,z) in S^2.

2) Define $g : S^2 \to \mathbb{R}^2$ via

$$g(x,y,z) = f(x,y,z) - f(-x,-y,-z)$$

(temp., hum) — (temp, hum)

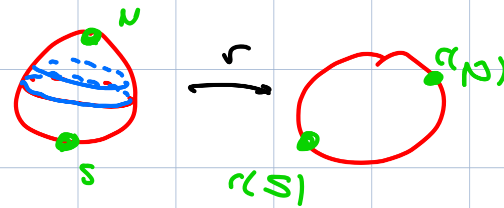
↳ By (1), $g \neq (0,0)$.

3) Define a map $r : S^2 \to S^1$ as follows:

$$r(x,y,z) = g(x,y,z) / |g(x,y,z)|$$

4) Note, $\boxed{r(x,y,z) = -r(-x,-y,-z)}$

$\hookrightarrow$ ie, r sends antipodal points on S^2 to antipodal points on S^1.



$$-r(-x,-y,-z)$$

$$= \frac{-g(-x,-y,-z)}{|g(-x,-y,-z)|}$$

$$= \frac{-\left(f(-x,-y,-z) - f(x,y,z)\right)}{|f(-x,-y,-z) - f(x,y,z)|}$$

$$= \frac{\left(f(x,y,z) - f(-x,-y,-z)\right)}{|f(x,y,z) - f(-x,-y,-z)|}$$

$$= r(x,y,z)$$

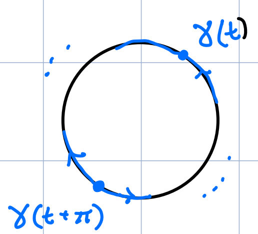
4) Define a curve $\gamma : [0, 2\pi] \longrightarrow S^1$ via

$$\gamma(t) = r\,(\cos(t),\ \sin(t),\ 0)$$

5) Notice that

$$\begin{aligned}\gamma(t+\pi) &= r\,(\cos(t+\pi),\ \sin(t+\pi),\ 0)\\ &= r\,(-\cos(t),\ -\sin(t),\ 0)\\ &= -r\,(\cos(t),\ \sin(t),\ 0)\\ &= -\gamma(t)\end{aligned}$$

6) $\Rightarrow$ $\gamma(t+\pi)$ is always on the opposite side of the circle as $\gamma(t)$



7) Let f be a lift of γ

8) Let $\beta(t) := \gamma(t+\pi)$.

9) Note $f(t+\pi)$ is a lift of β.

10) (6) $\Rightarrow f(t) - f(t+\pi) =$ odd multiple of π, say $k \cdot \pi$

11) $f(0) = f(\pi) + k\pi = f(2\pi) + 2k\pi$

12) $$\Rightarrow \deg(\gamma) = \frac{f(2\pi) - f(0)}{2\pi} = k \neq 0$$

13) But γ is homotopic to a constant curve

$\hookrightarrow$ shrink equator down to southpole and apply r.

$\Rightarrow \deg(\gamma) = 0$, a contradiction

14) $\Rightarrow f(x,y,z) = f(-x,-y,-z)$ for some (x,y,z) $\square$

Theorem: Let A_0, A_1, A_2 be subsets of S^2 that cover S^2 w/ the condition that each point in S^2 is contained in only one of these subsets. There exists a point (x,y,z) in S^2 such that both (x,y,z) and $(-x,-y,-z)$ are contained in the same A_i.

Proof: 1) Define the function $d_i : S^2 \longrightarrow \mathbb{R}$ via

$$d_i(x,y,z)$$

$$= \min \{ \text{dist}((x,y,z),(x',y',z')) \mid (x',y',z') \text{ in } A_i \}$$

= minimum distance needed to travel from (x,y,z) to get into A_i

2) Note, if $d_i(x,y,z)=0$, then (x,y,z) is in A_i.

if $d_i(x,y,z)\neq 0$, then (x,y,z) is not in A_i.

3) Define $f: S^2 \longrightarrow \mathbb{R}^2$ via

$$f(x,y,z) = (d_0(x,y,z), d_1(x,y,z))$$

4) By Borsuk-Ulam, there exists (x,y,z) such that

$$f(x,y,z) = f(-x,-y,-z)$$

$$\Rightarrow \quad d_0(x,y,z) = d_0(-x,-y,-z)$$

$$d_1(x,y,z) = d_1(-x,-y,-z)$$

5) If $d_0(x,y,z)=0$, then $d_0(-x,-y,-z)=0$

$\Rightarrow$ (x,y,z) and $(-x,-y,-z)$ are in A_0

If $d_1(x,y,z)=0$, then $d_1(-x,-y,-z)=0$

$\Rightarrow$ (x,y,z) and $(-x,-y,-z)$ are in A_1.

6) If $d_0(x,y,z)\neq 0$, $d_1(x,y,z)\neq 0$

$\Rightarrow$ Neither (x,y,z) nor $(-x,-y,-z)$ is in A_0 or A_1

7) $\Rightarrow$ (x,y,z) and $(-x,-y,-z)$ are in A_2. $\square$