1. Fixed Points for Functions
2. Brouwer’s Fixed Point Theorem
3. Fixed Points for Correspondences
4. Kakutani’s Fixed Point Theorem
5. Separating Hyperplane Theorems
Exam 9-12 Weds Aug 17
* start at 9 am sharp (not Berkeley time)
* 3106 Etcheverry Hall

- no notes, books, etc
- bring your own exam book or paper
- no machines may be used during the exam for any reason
  (phones, laptops, tablets, smart watches, etc)
- exam like problem sets (adjusted for time)
- like previous exams
- show what you know
Schedule for Office Hours

Chris: Thursday: 12:10 - 12:30
     Friday: end of class + 1 hour

Monday: 9 - 11
        open, drop in

* 4:30 - 6:30: sign up*

  sign up outside 511 Evans
  or by emailing me

* sign up for Monday afternoon*
  timed by Monday at 11
Fixed Points for Functions

Definition 1. Let $X$ be a nonempty set and $f : X \to X$. A point $x^* \in X$ is a fixed point of $f$ if $f(x^*) = x^*$.

$x^*$ is a fixed point of $f$ if it is “fixed” by the map $f$. 
$f(x) = y$

$x_1 = f(x_1)$

$\text{graph of } f$

$45^\circ$

$x = y$

$x_1$
Fixed Points for Functions

Examples:

1. Let $X = \mathbb{R}$ and $f : \mathbb{R} \to \mathbb{R}$ be given by $f(x) = 2x$. Then $x = 0$ is a fixed point of $f$ (and is the unique fixed point of $f$).

2. Let $X = \mathbb{R}$ and $f : \mathbb{R} \to \mathbb{R}$ be given by $f(x) = x$. Then every point in $\mathbb{R}$ is a fixed point of $f$ (in particular, fixed points need not be unique).

3. Let $X = \mathbb{R}$ and $f : \mathbb{R} \to \mathbb{R}$ be given by $f(x) = x + 1$. Then $f$ has no fixed points.
4. Let $X = [0, 2]$ and $f : X \to X$ be given by $f(x) = \frac{1}{2}(x + 1)$. Then

\[
\begin{align*}
  f(x) &= \frac{1}{2}(x + 1) = x \\
  \iff x + 1 &= 2x \\
  \iff x &= 1
\end{align*}
\]

So $x = 1$ is the unique fixed point of $f$. Notice that $f$ is a contraction (why?), so we already knew that $f$ must have a unique fixed point on $\mathbb{R}$ from the Contraction Mapping Theorem.

5. Let $X = [0, \frac{1}{4}] \cup [\frac{3}{4}, 1]$ and $f : X \to X$ be given by $f(x) = 1 - x$. Then $f$ has no fixed points.

\[
X = 1 - x \iff x = \frac{1}{2} \notin X
\]
6. Let $X = [-2, 2]$ and $f : X \to X$ be given by $f(x) = \frac{1}{2}x^2$. Then $f$ has two fixed points, $x = 0$ and $x = 2$. If instead $X' = (0, 2)$, then $f : X' \to X'$ but $f$ has no fixed points on $X'$.

7. Let $X = \{1, 2, 3\}$ and $f : X \to X$ be given by $f(1) = 2$, $f(2) = 3$, $f(3) = 1$ (so $f$ is a permutation of $X$). Then $f$ has no fixed points.

8. Let $X = [0, 2]$ and $f : X \to X$ be given by

$$f(x) = \begin{cases} 
  x + 1 & \text{if } x \leq 1 \\
  x - 1 & \text{if } x > 1 
\end{cases}$$

Then $f$ has no fixed points.

\[ x \neq x+1 \quad \forall x \in [0,2] \]
\[ x \neq x-1 \]
A Simple Fixed Point Theorem

**Theorem 1.** Let $X = [a, b]$ for $a, b \in \mathbb{R}$ with $a < b$ and let $f : X \rightarrow X$ be continuous. Then $f$ has a fixed point.

**Proof.** Let $g : [a, b] \rightarrow \mathbb{R}$ be given by

$$g(x) = f(x) - x$$

If either $f(a) = a$ or $f(b) = b$, we’re done. So assume $f(a) > a$ and $f(b) < b$. Then

$$g(a) = f(a) - a > 0$$

$$g(b) = f(b) - b < 0$$

$g$ is continuous, so by the Intermediate Value Theorem, $\exists x^* \in (a, b)$ such that $g(x^*) = 0$, that is, such that $f(x^*) = x^*$. □
a discontinuous function might have no fixed points
Brouwer’s Fixed Point Theorem

**Theorem 2** (Thm. 3.2. Brouwer’s Fixed Point Theorem). Let $X \subseteq \mathbb{R}^n$ be nonempty, compact, and convex, and let $f : X \to X$ be continuous. Then $f$ has a fixed point.

$X \subseteq \mathbb{R}^n$ is **convex** if for $x, y \in X$ and $\alpha \in [0,1]$:

$$\alpha x + (1-\alpha)y \in X$$

$X$ convex

D not convex
Sketch of Proof of Brouwer

Consider the case when the set $X$ is the unit ball in $\mathbb{R}^n$, i.e.

$$X = B_1[0] = B = \{x \in \mathbb{R}^n : \|x\| \leq 1\}.$$ 

Let $f : B \to B$ be a continuous function. Recall that $\partial B$ denotes the boundary of $B$, so $\partial B = \{x \in \mathbb{R}^n : \|x\| = 1\}$.

**Fact:** Let $B$ be the unit ball in $\mathbb{R}^n$. Then there is no continuous function $h : B \to \partial B$ such that $h(x') = x'$ for every $x' \in \partial B$.

See J. Franklin, Methods of Mathematical Economics, for an elementary (but long) proof.
\( h: \mathbb{R} \to \mathbb{R} \text{ with } x' = h(x') \forall x' \in \partial B \)
Now to establish Brouwer’s theorem, suppose, by way of contradiction, that \( f \) has no fixed points in \( B \). Thus for every \( x \in B \), \( x \neq f(x) \).

Since \( x \neq f(x) \) for every \( x \), we can carry out the following construction. For each \( x \in B \), construct the line segment originating at \( f(x) \) and going through \( x \). Let \( g(x) \) denote the intersection of this line segment with \( \partial B \).

This construction is well-defined, and gives a continuous function \( g : B \to \partial B \). Furthermore, if \( x' \in \partial B \), then \( x' = g(x') \). That is, \( g|_{\partial B} = \text{id}_{\partial B} \). Since there are no such functions by the fact above, we have a contradiction. Therefore there exists \( x^* \in B \) such that \( f(x^*) = x^* \), that is, \( f \) has a fixed point in \( B \).
where \( u = \frac{x - f(x)}{\|x - f(x)\|} \)

and

\[ t = -x \cdot u + \sqrt{1 - x \cdot x + (x \cdot u)^2} \]

\[ x' = f(x) \]

\[ x' = g(x') \]

\[ x^* = f(x^*) \]

\[ x^* = f(x^*) \text{ not defined if } x^* = f(x^*) \]

\[ x \neq f(x) \]
\[ f(x) = x \]
Fixed Points for Correspondences

**Definition 2.** Let $X$ be nonempty and $\Psi : X \to 2^X$ be a correspondence. A point $x^* \in X$ is a fixed point of $\Psi$ if $x^* \in \Psi(x^*)$.

Note here that we do not require $\Psi(x^*) = \{x^*\}$, that is $\Psi$ need not be single-valued at $x^*$. So $x^*$ can be a fixed point of $\Psi$ but there may be other elements of $\Psi(x^*)$ different from $x^*$. 
Examples:

1. Let $X = [0, 4]$ and $\Psi : X \to 2^X$ be given by

$$\Psi(x) = \begin{cases} 
[x + 1, x + 2] & \text{if } x < 2 \\
[0, 4] & \text{if } x = 2 \\
[x - 2, x - 1] & \text{if } x > 2 
\end{cases}$$

Then $x = 2$ is the unique fixed point of $\Psi$.  

2. Let $X = [0, 4]$ and $\Psi : X \to 2^X$ be given by

$$\Psi(x) = \begin{cases} 
[x + 1, x + 2] & \text{if } x < 2 \\
[0, 1] \cup [3, 4] & \text{if } x = 2 \\
[x - 2, x - 1] & \text{if } x > 2 
\end{cases}$$

Then $\Psi$ has no fixed points.
$x \in \Psi(x^*)$ where graph $\Psi$ entered

$y = x + 2$

$y = x + 1$

$y = x - 2$

$2 \in \Psi(2) = [0, 4]$
$2 \not\in \Psi(2) = [0, 1) \cup [3, 4]$

Note: $\Psi$ is nice in both cases
Kakutani’s Fixed Point Theorem

Theorem 3. (Thm. 3.4’. Kakutani’s Fixed Point Theorem) Let $X \subseteq \mathbb{R}^n$ be a non-empty, compact, convex set and $\Psi : X \to 2^X$ be an upper hemi-continuous correspondence with non-empty, convex, compact values. Then $\Psi$ has a fixed point in $X$.

**Proof. (sketch)** Here, the idea is to use Brouwer’s theorem after appropriately approximating the correspondence with a function. The catch is that there won’t necessarily exist a continuous selection from $\Psi$, that is, a continuous function $f : X \to X$ such that $f(x) \in \Psi(x)$ for every $x \in X$. If such a function existed, then by applying Brouwer to $f$ we would have a fixed point of $\Psi$ (because if $\exists x^* \in X$ such that $x^* = f(x^*)$, then $x^* = f(x^*) \in \Psi(x^*)$).
? f : x ↦ x such that f(x) ∈ ψ(x) ∀x and f continuous

ψ(x) convex ∀x ∈ X
Instead, we look for a weaker type of approximation. Let $X \subset \mathbb{R}^n$ be a non-empty, compact, convex set, and let $\Psi : X \to 2^X$ be an uhc correspondence with non-empty, compact, convex values. For every $\varepsilon > 0$, define the $\varepsilon$ ball about graph $\Psi$ to be

$$B_\varepsilon(\text{graph } \Psi) = \left\{ z \in X \times X : d(z, \text{graph } \Psi) = \inf_{(x,y) \in \text{graph } \Psi} d(z, (x,y)) < \varepsilon \right\}$$

Here $d$ denotes the ordinary Euclidean distance in $\mathbb{R}^n$. If $\Psi$ is an uhc correspondence, then for every $\varepsilon > 0$ there exists a continuous function $f_\varepsilon : X \to X$ such that $\text{graph } f_\varepsilon \subseteq B_\varepsilon(\text{graph } \Psi)$. 
Now by letting $\varepsilon \to 0$, this means that we can find a sequence of continuous functions $\{f_n\}$ such that $\text{graph } f_n \subseteq B_1(\text{graph } \Psi)$ for each $n$. By Brouwer’s Fixed Point Theorem, each function $f_n$ has a fixed point $\hat{x}_n \in X$, and

$$(\hat{x}_n, \hat{x}_n) = (\hat{x}_n, f_n(\hat{x}_n)) \in \text{graph } f_n \subseteq B_1(\text{graph } \Psi)$$

for each $n$. So for each $n$ there exists $(x_n, y_n) \in \text{graph } \Psi$ such that

$$d(\hat{x}_n, x_n) < \frac{1}{n} \quad \text{and} \quad d(\hat{x}_n, y_n) < \frac{1}{n}$$

Since $X$ is compact, $\{\hat{x}_n\}$ has a convergent subsequence $\{\hat{x}_{n_k}\}$, with $\hat{x}_{n_k} \to \hat{x} \in X$. Then $x_{n_k} \to \hat{x}$ and $y_{n_k} \to \hat{x}$. Since $\Psi$ is uhc and closed-valued, it has closed graph, so $(\hat{x}, \hat{x}) \in \text{graph } \Psi$. Thus $\hat{x} \in \Psi(\hat{x})$, that is, $\hat{x}$ is a fixed point of $\Psi$. \qed
Separating Hyperplane Theorems

**Theorem 4** (1.26, Separating Hyperplane Theorem). Let $A, B \subseteq \mathbb{R}^n$ be nonempty, disjoint convex sets. Then there exists a nonzero vector $p \in \mathbb{R}^n$ such that

$$p \cdot a \leq p \cdot b \quad \forall a \in A, b \in B$$
\[ H = \{ z \in \mathbb{R}^n : p \cdot z = c \} \]

\[ p \cdot a \leq c \quad \forall a \in A \]

\[ p \cdot b \geq c \quad \forall b \in B \]
∃ p ∈ R^n, p ≠ 0, s.t. p ⋅ a ≤ p ⋅ b \forall x \in A \forall y \in B

Convexity needed: no hyperplane separates A \& B
Separating a Point from a Set

**Theorem 5.** Let \( Y \subseteq \mathbb{R}^n \) be a nonempty convex set and \( x \notin Y \). Then there exists a nonzero vector \( p \in \mathbb{R}^n \) such that

\[
p \cdot x \leq p \cdot y \quad \forall y \in Y
\]

**Proof.** We sketch the proof in the special case that \( Y \) is compact. We will see that in this case we actually get a stronger conclusion:

\[
\exists p \in \mathbb{R}^n, p \neq 0 \text{ s.t. } p \cdot x < p \cdot y \quad \forall y \in Y
\]

Choose \( y_0 \in Y \) such that \( |y_0 - x| = \inf\{|y - x| : y \in Y\} \); such a point exists because \( Y \) is compact, so the distance function \( g(y) = |y - x| \) assumes its minimum on \( Y \). Since \( x \notin Y, x \neq y_0 \), so \( y_0 - x \neq 0 \). Let \( p = y_0 - x \). The set

\[
H = \{z \in \mathbb{R}^n : p \cdot z = p \cdot y_0\}
\]
\[ p \cdot y - (y_0 - x) \cdot y = y_0 \cdot y - x \cdot y \]

is the hyperplane perpendicular to \( p \) through \( y_0 \). See [Figure 12].

Then

\[
\begin{align*}
p \cdot y_0 &= (y_0 - x) \cdot y_0 \\
&= (y_0 - x) \cdot (y_0 - x + x) \\
&= (y_0 - x) \cdot (y_0 - x) + (y_0 - x) \cdot x \\
&= |y_0 - x|^2 + p \cdot x \\
&\geq |y_0 - x|^2 + p \cdot x \\
&> p \cdot x
\end{align*}
\]

We claim that

\[ y \in Y \Rightarrow p \cdot y \geq p \cdot y_0 > p \cdot x \]

If not, suppose there exists \( y \in Y \) such that \( p \cdot y < p \cdot y_0 \). Given \( \alpha \in (0, 1) \), let

\[ w_\alpha = \alpha y + (1 - \alpha)y_0 \]
Since $Y$ is convex, $w_\alpha \in Y$. Then for $\alpha$ sufficiently close to zero,

\[
|x - w_\alpha|^2 = |x - \alpha y - (1 - \alpha)y_0|^2
\]
\[
= |x - y_0 + \alpha(y_0 - y)|^2
\]
\[
= |-p + \alpha(y_0 - y)|^2
\]
\[
= |p|^2 - 2\alpha p \cdot (y_0 - y) + \alpha^2|y_0 - y|^2
\]
\[
= |p|^2 + \alpha(-2p \cdot (y_0 - y) + \alpha|y_0 - y|^2)
\]
\[
< |p|^2 \quad \text{for } \alpha \text{ close to 0, as } p \cdot y_0 > p \cdot y
\]
\[
= |y_0 - x|^2
\]

Thus for $\alpha$ sufficiently close to zero,

\[
|w_\alpha - x| < |y_0 - x|
\]

which implies $y_0$ is not the closest point in $Y$ to $x$, contradiction. \qed
\[ \exists y \in Y \text{ s.t. } p \cdot y < p \cdot y_0. \]
The general version of the Separating Hyperplane Theorem can be derived from this special case by noting that if \( A \cap B = \emptyset \), then \( 0 \notin A - B = \{a - b : a \in A, b \in B\} \).
Strict Separation

For the special case of $Y$ compact and $X = \{x\}$, we actually could strictly separate $Y$ and $X$:

$x \notin Y \Rightarrow \exists p \in \mathbb{R}^n, p \neq 0 \text{ s.t. } p \cdot x < p \cdot y \quad \forall y \in Y$

When can we do this in general? Will require additional assumptions...
A, B nonempty, disjoint, convex \Rightarrow \\
\exists p \in \mathbb{R}^n, p \neq 0 \text{ s.t. } p \cdot a \leq p \cdot b \, \forall a \in A \, \forall b \in B \\
\\nBut \quad p \cdot \bar{c} = p \cdot \bar{b} \quad \text{for some} \, \bar{c} \in A \quad \bar{b} \in B
Strict Separation

Theorem 6. (Strict Separating Hyperplane Theorem) Let $A, B \subseteq \mathbb{R}^n$ be nonempty, disjoint, closed, convex sets. Then there exists a nonzero vector $p \in \mathbb{R}^n$ such that

$$p \cdot a < p \cdot b \quad \forall a \in A, b \in B$$