

Announcements

- read def 1.1-1.6
- PSI due Friday

Econ 204 2023

Lecture 1

Outline

1. Introductions
2. About the Course and Other Administrative Details
3. Methods of Proof
4. Equivalence Relations
5. Cardinality

Introductions

Welcome

- 204
- Berkeley Economics
- UC Berkeley
- Berkeley
- California

- US...

Introductions

- Chris Shannon
- Bruno Smaniotto
- Anna Vakarova

About the Course

(sharp)

- **Schedule:** Lectures MTWThF 9:00 - 11:30 am (~~Berkeley~~ time), often going over so don't schedule anything before 12:00

Discussion Sections: MTWThF 1:00 - 3:00 pm (first section today)

Office hours: Chris Shannon MTWThF 11:30 - 12:30 (end of lecture + 1 hour), also by appointment

Bruno + Anna MTWThF 3:00 - 5:00 pm

- **Final Exam:** Wednesday August 16 9am - 12pm

- **Prerequisites:** Math 53-54 at Berkeley or equivalent
 - 4 semesters college mathematics
 - linear algebra
 - multivariable calculus
 - rigorous approach - theorems stated carefully and some proofs given
 - stream for engineers and scientists

Course requirements:

- problems sets: 6 total
(no late problem sets...no exceptions)
- exam
- reading/working on your own

Grade: 10% problem sets (5 highest scores out of 6), 90% final exam

Grading in First Year Economics Courses:

- median grade = B+ : solid command of material
- A and A- are very good grades, A+ for truly exceptional work
- B : ready to go on to further work...a B in 204 means you are ready to go on to 201a/b, 202a/b, 240a/b
- B- : very marginal, but we won't make you take the class again. B- in 204 means you will have a very hard time in 201a/b. Recommend you take Math 53 and 54 this year, maybe Math 104, come back next year to retake 204 and

take 201a/b. B- is a passing grade, but you must maintain a B average

- C: not passing. Definitely not ready for 201a/b, 202a/b, 240a/b. Take Math 53-54 this year, maybe Math 104, retake 204 next year
- 204 with at least a B- (or a waiver from 204 requirement) is a strictly enforced prerequisite for enrollment in 201a/b
- F: means you didn't take the final exam. Be sure to withdraw if you don't or can't take the final.

Resources:

Book: de la Fuente, *Mathematical Methods and Models for Economists*

Lecture notes: for every lecture + supplements for several topics

Be sure to read Corrections Handout with dIF

Seek out other references

This class is not normal...

- lectures
- expectations
- no devices (laptops, phones, etc.) during lectures
- basic covid precautions

Goals for 204

- reduce heterogeneity of math backgrounds for students in Econ graduate classes
- advance everyone's math skills and knowledge
- present some particular concepts and results used in first-year economics courses 201a/b, 202a/b, 240a/b
- challenge everyone - so not everyone will understand everything

- develop basic math skills and knowledge needed to work as a professional economist and read academic economics
- develop ability to read and evaluate purported proofs...essential for reading and working in all branches of economics - theoretical, empirical, experimental
- develop ability to compose simple proofs...essential to working in all branches of economics - theoretical, empirical, experimental
- cover selected material from real analysis and linear algebra at moderate level of abstraction (considerably more advanced and abstract than Math 53 + 54)

- **not** to review Math 53 + 54. If you are weak on this material, take Math 53-54 this year, and take 204 next year.

Learning by Doing

- to learn this sort of mathematics you need to do more than just read the book and notes and listen to lectures
- active reading: work through each line, be sure you know how to get from one line to the next
- active listening: follow each step as we work through arguments in class
- working problems: the most valuable part of the class

- working in groups strongly encouraged...
- but, always try to work through all of the problems before talking to others
- everyone must write up their own solutions
- best test of understanding: can you explain it to others

Methods of Proof

What is a proof? The million dollar question...

Main Methods of Proof:

- deduction
- contraposition
- induction
- contradiction

We'll examine each of these in turn.

Proof by Deduction

Proof by Deduction: A list of statements, the last of which is the statement to be proven. Each statement in the list is either

- an axiom: a fundamental assumption about mathematics, or part of definition of the object under study; or
- a previously established theorem; or
- follows from previous statements in the list by a valid rule of inference

Proof by Deduction

Example: Prove that the function $f(x) = x^2$ is continuous at $x = 5$.

Recall from one-variable calculus that $f(x) = x^2$ is continuous at $x = 5$ means

$$\underbrace{\forall \varepsilon > 0}_{\text{blue wavy}} \underbrace{\exists \delta > 0}_{\text{blue wavy}} \text{ s.t. } |x - 5| < \delta \Rightarrow |f(x) - f(5)| < \varepsilon$$

That is, “for every $\varepsilon > 0$ there exists a $\delta > 0$ such that whenever x is within δ of 5, $f(x)$ is within ε of $f(5)$.”

To prove the claim, we must systematically verify that this definition is satisfied.

Proof. Let $\varepsilon > 0$ be given. Let

$$\delta = \min \left\{ 1, \frac{\varepsilon}{11} \right\} > 0 \quad \Rightarrow \quad \delta \leq \frac{\varepsilon}{11}$$

Where did that come from ? Suppose $|x - 5| < \delta$. Since $\delta \leq 1$, $4 < x < 6$, so $9 < x + 5 < 11$ and $|x + 5| < 11$. Then

$$\begin{aligned} |f(x) - f(5)| &= |x^2 - 25| \\ &= |(x + 5)(x - 5)| \\ &= |x + 5||x - 5| \\ &< 11 \cdot \delta \\ &\leq 11 \cdot \frac{\varepsilon}{11} \\ &= \varepsilon \end{aligned}$$

Thus, we have shown that for every $\varepsilon > 0$, there exists $\delta > 0$ such that $|x - 5| < \delta \Rightarrow |f(x) - f(5)| < \varepsilon$, so f is continuous at $x = 5$. \square

P, Q, S statements

Proof by Contraposition

Recall some basics of logic.

"not P"

$\neg P$ means "P is false."

"and"

$P \wedge Q$ means " P is true *and* Q is true."

"or"

$P \vee Q$ means " P is true *or* Q is true (or possibly both)."

$\neg P \wedge Q$ means $(\neg P) \wedge Q$; $\neg P \vee Q$ means $(\neg P) \vee Q$.

"implies"

$P \Rightarrow Q$ means "whenever P is satisfied, Q is also satisfied."

Formally, $P \Rightarrow Q$ is equivalent to $\neg P \vee Q$.

Proof by Contraposition

The *contrapositive* of the statement $P \Rightarrow Q$ is the statement $\neg Q \Rightarrow \neg P$.

Theorem 1. $P \Rightarrow Q$ is true if and only if $\neg Q \Rightarrow \neg P$ is true.

\Rightarrow : *Proof.* Suppose $P \Rightarrow Q$ is true. Then either P is false, or Q is true (or possibly both). Therefore, either $\neg P$ is true, or $\neg Q$ is false (or possibly both), so $\neg(\neg Q) \vee (\neg P)$ is true, that is, $\neg Q \Rightarrow \neg P$ is true.

\Leftarrow : Conversely, suppose $\neg Q \Rightarrow \neg P$ is true. Then either $\neg Q$ is false, or $\neg P$ is true (or possibly both), so either Q is true, or P is false (or possibly both), so $\neg P \vee Q$ is true, so $P \Rightarrow Q$ is true. \square

Claim: $P(n)$ true $\forall n \geq n_0$

- Base case: show $P(n_0)$ true for n_0
- Induction step: Assume $P(n)$ true for $n \geq n_0$
- Show $P(n+1)$ true

Proof by Induction

We illustrate with an example:

Theorem 2. For every $n \in \mathbb{N}_0 = \{0, 1, 2, 3, \dots\}$,

$\mathbb{N}_0 = \mathbb{N} \cup \{0\}$

$$\sum_{k=1}^n k = \frac{n(n+1)}{2}$$

i.e. $1 + 2 + \dots + n = \frac{n(n+1)}{2}$.

Proof. **Base step** $n = 0$: LHS = $\sum_{k=1}^0 k =$ the empty sum = 0. RHS = $\frac{0 \cdot 1}{2} = 0$

So the claim is true for $n = 0$.

Induction step: Suppose

$$\sum_{k=1}^n k = \frac{n(n+1)}{2} \text{ for some } n \geq 0$$

We must show that

$$\sum_{k=1}^{n+1} k = \frac{(n+1)((n+1)+1)}{2}$$

$$\begin{aligned}
\text{LHS} &= \sum_{k=1}^{n+1} k \\
&= \sum_{k=1}^n k + (n+1) \\
&= \frac{n(n+1)}{2} + (n+1) \text{ by the Induction hypothesis} \\
&= (n+1) \left(\frac{n}{2} + 1 \right) \\
&= \frac{(n+1)(n+2)}{2} \\
\text{RHS} &= \frac{(n+1)((n+1)+1)}{2} \\
&= \frac{(n+1)(n+2)}{2} = \text{LHS}
\end{aligned}$$

So by mathematical induction, $\sum_{k=1}^n k = \frac{n(n+1)}{2}$ for all $n \in \mathbf{N}_0$. \square

Claim : $P \Rightarrow Q$

Suppose not Q ...

Proof by Contradiction

Assume the negation of what is claimed, and work toward a contradiction.

Theorem 3. *There is no rational number q such that $q^2 = 2$.*

integers *rationals*

Proof. Suppose $q^2 = 2$ where $q \in \mathbf{Q}$. Then we can write $q = \frac{m}{n}$ for some integers $m, n \in \mathbf{Z}$. Moreover, we can assume that m and n have no common factor; if they did, we could divide it out.

$$2 = q^2 = \frac{m^2}{n^2}$$

Therefore, $m^2 = 2n^2$, so m^2 is even.

We claim that m is even. If not, then m is odd, so $m = 2p + 1$ for some $p \in \mathbf{Z}$. Then

$$\begin{aligned} \underline{m^2} &= (2p + 1)^2 \\ &= 4p^2 + 4p + 1 \\ &= 2(2p^2 + 2p) + 1 \end{aligned}$$

which is odd, contradiction. Therefore, m is even, so $m = 2r$ for some $r \in \mathbf{Z}$.

$$\begin{aligned} m^2 &= 4r^2 = (2r)^2 \\ &= m^2 \\ &= 2n^2 \\ \Rightarrow n^2 &= 2r^2 \end{aligned}$$

So n^2 is even, which implies (by the argument given above) that n is even. Therefore, $n = 2s$ for some $s \in \mathbf{Z}$, so m and n have a

common factor, namely 2, contradiction. Therefore, there is no rational number q such that $q^2 = 2$. \square

Binary Relations

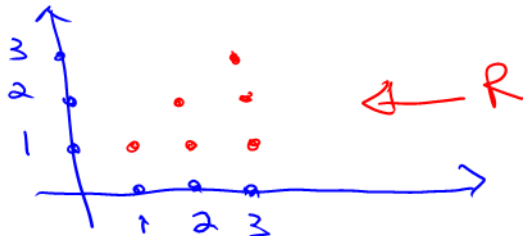
Definition 1. A binary relation R from X to Y is a subset $R \subseteq X \times Y$. We write xRy if $(x, y) \in R$ and "not xRy " if $(x, y) \notin R$. $R \subseteq X \times X$ is a binary relation on X . $\neg (xRy)$

Example: Suppose $f : X \rightarrow Y$ is a function from X to Y . The binary relation $R \subseteq X \times Y$ defined by

$$xRy \iff f(x) = y$$

is exactly the graph of the function f . A function can be considered a binary relation R from X to Y such that for each $x \in X$ there exists exactly one $y \in Y$ such that $(x, y) \in R$.

Example: Suppose $X = \{1, 2, 3\}$ and R is the binary relation on X given by $R = \{(1, 1), (2, 1), (2, 2), (3, 1), (3, 2), (3, 3)\}$. This is the binary relation "is weakly greater than," or \geq .



$$[x] = \{y : xRy\} = \{1, 2, 3\}$$

Equivalence Relations

Definition 2. A binary relation R on X is

(i) reflexive if $\forall x \in X, xRx$

(ii) symmetric if $\forall x, y \in X, xRy \Leftrightarrow yRx$

(iii) transitive if $\forall x, y, z \in X, (xRy \wedge yRz) \Rightarrow xRz$

Definition 3. A binary relation R on X is an equivalence relation if it is reflexive, symmetric and transitive.

Equivalence Relations

Definition 4. Given an equivalence relation R on X , write

$$[x] = \{y \in X : xRy\}$$

$[x]$ is called the equivalence class containing x .

The set of equivalence classes is the quotient of X with respect to R , denoted X/R . " $X \text{ mod } R$ "

Example: The binary relation \geq on \mathbf{R} is not an equivalence relation because it is not symmetric.

Example: Let $X = \{a, b, c, d\}$ and

$$R = \{(a, a), (a, b), (b, a), (b, b), (c, c), (c, d), (d, c), (d, d)\}$$

R is an equivalence relation (why?) and the equivalence classes of R are $\{a, b\}$ and $\{c, d\}$. $X/R = \{\{a, b\}, \{c, d\}\}$

$$[a] = \{a, b\}$$

$$[b] = \{a, b\}$$

$$[c] = \{c, d\}$$

$$[d] = \{c, d\}$$

$$[a] = \{a, b, c\}$$

$$[b] = \{a, b\}$$

Equivalence Relations

The equivalence classes of an equivalence relation form a *partition* of X : every element of X belongs to exactly one equivalence class.

Theorem 4. *Let R be an equivalence relation on X . Then $\forall x \in X, x \in [x]$. Given $x, y \in X$, either $[x] = [y]$ or $[x] \cap [y] = \emptyset$.*

Proof. If $x \in X$, then xRx because R is reflexive, so $x \in [x]$.

Suppose $x, y \in X$. If $[x] \cap [y] = \emptyset$, we're done. So suppose $[x] \cap [y] \neq \emptyset$. We must show that $[x] = [y]$, i.e. that the elements of $[x]$ are exactly the same as the elements of $[y]$.

Choose $z \in [x] \cap [y]$. Then $z \in [x]$, so xRz . By symmetry, zRx . Also $z \in [y]$, so yRz . By symmetry again, zRy . Now choose $w \in [x]$. By definition, xRw . Since zRx and R is transitive, zRw . By symmetry, wRz . Since zRy , wRy by transitivity again. By symmetry, yRw , so $w \in [y]$, which shows that $[x] \subseteq [y]$. Similarly, $[y] \subseteq [x]$, so $[x] = [y]$. □

Cardinality

Definition 5. *Two sets A, B are numerically equivalent (or have the same cardinality) if there is a bijection $f : A \rightarrow B$, that is, a function $f : A \rightarrow B$ that is 1-1 ($a \neq a' \Rightarrow f(a) \neq f(a')$), and onto ($\forall b \in B \exists a \in A$ s.t. $f(a) = b$).*

Example: $A = \{2, 4, 6, \dots, 50\}$ is numerically equivalent to the set $\{1, 2, \dots, 25\}$ under the function $f(n) = 2n$.

$\mathcal{B} =$

$B = \{1, 4, 9, 16, 25, 36, 49 \dots\} = \{n^2 : n \in \mathbf{N}\}$ is numerically equivalent to \mathbf{N} .

Cardinality

A set is either finite or infinite. A set is *finite* if it is numerically equivalent to $\{1, \dots, n\}$ for some n . A set that is not finite is *infinite*.

[^]ew

In particular, $A = \{2, 4, 6, \dots, 50\}$ is finite, $B = \{1, 4, 9, 16, 25, 36, 49 \dots\}$ is infinite.

A set is *countable* if it is numerically equivalent to the set of natural numbers $\mathbb{N} = \{1, 2, 3, \dots\}$. An infinite set that is not countable is called *uncountable*.

Cardinality

Example: The set of integers \mathbf{Z} is countable.

$$\mathbf{Z} = \{0, 1, -1, 2, -2, \dots\}$$

Define $f : \mathbf{N} \rightarrow \mathbf{Z}$ by

$$f(1) = 0$$

$$f(2) = 1$$

$$f(3) = -1$$

\vdots

"floor"
)

$$f(n) = (-1)^{n+1} \left\lfloor \frac{n}{2} \right\rfloor$$

where $\lfloor x \rfloor$ is the greatest integer less than or equal to x . It is straightforward to verify that f is one-to-one and onto.

Cardinality

Theorem 5. *The set of rational numbers \mathbf{Q} is countable.*

“Picture Proof”:

$$\begin{aligned}\mathbf{Q} &= \left\{ \frac{m}{n} : m, n \in \mathbf{Z}, n \neq 0 \right\} \\ &= \left\{ \frac{m}{n} : m \in \mathbf{Z}, n \in \mathbf{N} \right\}\end{aligned}$$

		m					\dots		
		$f(1)$	$f(2)$	$f(3)$	\dots	\dots	\dots	\dots	
		0	1	-1	2	-2	\dots	\dots	
1	0	\rightarrow 1	\rightarrow -1	\rightarrow 2	\rightarrow -2	\dots	\dots	\dots	
2	0	\swarrow	\nearrow $\frac{1}{2}$	\swarrow $-\frac{1}{2}$	\nearrow 1	\swarrow -1	\dots	\dots	
3	0	\downarrow	\nearrow $\frac{1}{3}$	\swarrow $-\frac{1}{3}$	\nearrow $\frac{2}{3}$	\swarrow $-\frac{2}{3}$	\dots	\dots	
4	0	\downarrow	\nearrow $\frac{1}{4}$	\swarrow $-\frac{1}{4}$	\nearrow $\frac{1}{2}$	\swarrow $-\frac{1}{2}$	\dots	\dots	
5	0	\downarrow	\nearrow $\frac{1}{5}$	\swarrow $-\frac{1}{5}$	\nearrow $\frac{2}{5}$	\swarrow $-\frac{2}{5}$	\dots	\dots	

Go back and forth on upward-sloping diagonals, omitting the

\dots

repeats:

$$\begin{aligned}f(1) &= 0 \\f(2) &= 1 \\f(3) &= \frac{1}{2} \\f(4) &= -1 \\&\vdots\end{aligned}$$

$f : \mathbf{N} \rightarrow \mathbf{Q}$, f is one-to-one and onto.