Math Review
Summer 2016

Topic 1

1. Introduction to mathematical notations and logic

1.1. Mathematical notation

We start by getting acquainted (or re-acquainted for some of you) to the basic mathematical notations that you will see in economics.

$\forall$	For all...
$\exists$	There exists...
$\nexists$	There does not exist...
$\therefore$	Therefore...
$\because$	Because...
$\neg$	Negation
$\equiv$	Identical to or the same as… For example, we write $f \equiv g$ if $f(x) = g(x)$ for all x
$\Longrightarrow$	A $\Longrightarrow$ B means: “A implies B, “If A then B or "A is sufficient condition for B”
$\Leftrightarrow$	A $\Leftrightarrow$B means “A if and only if B”,“A is equivalent to B” or “A is a necessary and sufficient condition for B”
$A \subset B$	"B strictly contains A" or “A is a proper subset of B”
$A \subseteq B$	“B contains A” or “A is a subset of B”
$\in$ ($\notin$)	In... (Not in...) or an element of... (Not an element of...)
■	Bonus: End of proof, Q.E.D.

Anybody knows what Q.E.D means?

The last three notations deal with sets. Formally, a set is a collection of well-defined and distinct objects (usually numbers). For example, the set A is completely determined by the elements in A, where:

$$A = \{x : x \in A\}.$$

We will touch more on sets in the next section.

1.2. Numbers

The different sets of numbers in mathematics are:

Natural numbers: $\mathbb{N} = \{1, 2, 3, \dots\}$
Integers: $\mathbb{Z} = \{\dots, -3, -2, -1, 0, 1, 2, 3, \dots\}$
Rational numbers: $\mathbb{Q} = \{\frac{p}{q} : p, q \in \mathbb{Z}\}$

Q: What do you think is missing in this definition of rational numbers? It has something to do with q.

$\mathcal{A}$:

Real numbers: $\mathbb{R} = \{all\ decimals\}$
Complex numbers: $\mathbb{C} = \{a + bi : a, b \in \mathbb{R}, i = \sqrt{-1}\}$

1.2.1. Intervals in ℝ

These are the four sets of intervals in the real line:

Closed interval: $[a, b] = \{x \in \mathbb{R} : a \leq x \leq b\}$
Open interval: $(a, b) = \{x \in \mathbb{R} : a < x < b\}$
Right-half closed or left-half open $(a, b] = \{x \in \mathbb{R} : a < x \leq b\}$
Other: $[a, \infty) = \{x \in \mathbb{R} : a \leq x\}$

where ∞ denotes infinity. We also have $-\infty$ for negative infinity.

1.3. Necessity and sufficiency

Before, jumping into proofs, we establish what we really mean by necessity and sufficiency. Necessary and sufficient have two very different meanings.

- If you advance that "**A is necessary for B**," this is what is entailed:
  - "A is implied by B" ($A \Leftarrow B$)
  - For B to be true requires A to be true <u>or</u> equally, A is required to have B.

Example. Let A be the set "x is an integer less than 9" and let B be the set "x is an integer less than 7". Then A is implied by B, because "x is an integer less than 9" is implied by the statement "x is an integer less than 7".

- If you advance that "**A is sufficient for B**," this is what is entailed:
  - "A implies B" ($A \Longrightarrow B$)
  - Whenever A holds, B must hold.

Example. If Sally gets a 100% in all her graded assignments (**A**), she gets a pass in the class (**B**). Getting 100% in all assignments is a sufficient condition to pass the class. But Sally may very well get an 88% in Homework#7 and still get an A in the class.

Contrapositive form:

Suppose we know that $A \Longleftarrow B$ is true. Then, as A is necessary for B, when A is not true, then B cannot be true.

$\mathcal{Q}$: Look back at your table of notations, how can you write this contrapositive form for A and B?

$\mathcal{A}$:

Example. Let A="x is an integer less than 9" and B= "x is an integer less than 7". As we saw earlier, A is implied by B. Now, we form the contrapositives, so ¬A= "x is not an integer less than 9" and ¬B= "x is not an integer less than 7". This implies ¬A ⇒¬B is a true statement.

1.4. Theorems and proofs

A mathematical proof is used to show the validity of a specified statement. A proof uses logic and deductive reasoning to show that the statement is always true. Proofs are usually statements take the form "*if A then B.*" There are three types of proofs that are frequently used. I have them down here by their popularity (in my opinion) in the first year micro series.

1.4.1. Proof by contradiction

This is a very powerful form of proof. In a proof by contradiction you show that "if not B then not A." Logically, this is what it means:

$$A \Longrightarrow B$$
$$\equiv$$
$$\neg\, A \text{ and } \neg B$$
$$\equiv$$
$$\neg\, B \Longrightarrow \neg A$$

All these three statements are *all equivalent.*

A good proof by contradiction has the following steps:

Step 1: Assume B is false
Step 2: Show that A must also be false.

We start with a simple math example, and later we will go through a slightly more involved example from micro theory after completing Topic 2.

Example. Prove that $\sqrt{2}$ is irrational.

We could jump to Steps 1 and 2 but let's be a little more careful.

<u>Define related concepts</u>: What form do rational numbers take?

<u>Think of some different examples</u>? Any cases I am forgetting?

<u>Anything we can redefine to get started on a proof by contradiction</u>? It is often helpful to reframe some concepts.

<u>Proof</u>:

Step 1: <u>Assume to the contrary</u> that $\sqrt{2}$ is rational. Thus we can write

$$\sqrt{2} = \frac{p}{q}$$

Moreover, let p and q have no common divisor > 1, that is, $\frac{p}{q}$ is in the lowest terms. Then we have:

$$\left(\sqrt{2}\right)^2 = \frac{p^2}{q^2}$$

which implies:

$$2q^2 = p^2$$

Step 2: Because $p, q \in \mathbb{Z}$ we have $p^2, q^2 \in \mathbb{Z}$. An integer k is even if $2n = k$ so, by definition, p^2 must be an even integer. The square of an odd number is always odd so because p^2 is even it must also hold that p is even. Because p is even there exists $n \in \mathbb{Z}$ such that $2n = p$
Thus:

$$2q^2 = (2n)^2 = 4n^2$$
$$q^2 = 2n^2$$

You can apply the same logic as above to show that q must also be even. But if both p and q are even then the fraction $\frac{p}{q}$ cannot be in lowest terms since both integers are divisible by 2, a contradiction. Therefore $\sqrt{2}$ is has to be irrational. ■

1.4.2. Proof by construction

In proof by construction you use true statements to construct the actual statement that you wish to prove. Suppose we have the theorem "A ⇒ B". Here, A is called the premise and B the conclusion. In a constructive proof we assume that A is true, deduce various consequences of that, and use them to show that B must also hold. This proof technique is a little less structured, as it is more dependent on the nature of the statement you are trying to prove Proof by construction follows these two steps:

Step 1: State what you wish to show (i.e. your claim)
Step 2: Use valid logic and parameters to construct the statement.
Step 3: Conclusion. This is optional, you can re-state the goal if desired.

Example: Prove that if a and b are consecutive integers, then the sum $a + b$ is odd.

Proof.

$\mathcal{Q}$: How would you approach this simple proof as a proof by contradiction?

$\mathcal{A}$:

1.4.3. Proof by Induction

Proof by induction is another great method in which we use recursion to demonstrate an infinite number of facts in a finite amount of space. In other words, you wish to show that some statement, S, is true for all n, S_n. To prove this general statement with induction we follow two steps:

> *Step 1*: Show that a propositional form is true for some basis case. It is typical to begin by showing that either S_0 is true or S_1 is true for example.
> *Step 2*: Assume that S_k is true for some k. This assumption is called the inductive hypothesis. Prove that S_{k+1} is also true, using the assumption that S_k is true.

I will just skim over this proof by induction and leave it as mostly as a reading material for you *(if we have time we will reference this again when going through tips for writing proofs)*

Example. Prove that $1 + 2 + 3 + \cdots + n = \frac{n(n+1)}{2}$ for all $n \in \mathbb{N}$.

<u>Proof</u>:
Step 1: Consider the case where $n = 1$. Then we have:

$$1 = \frac{1(1+1)}{2} = 1$$

and the statement holds.
Step 2.a: Now assume that for some $n = k \geq 1$. We have the following hold:

$$1 + 2 + 3 + \cdots + k = \frac{k(k+1)}{2}$$

Step 2.b: We now wish to show that is true for $n = k + 1$, that is:

$$1 + 2 + 3 + \cdots + k + (\boldsymbol{k} + \mathbf{1}) = \frac{(k+1)(k+2)}{2}?$$

We know from our inductive hypothesis that $1 + 2 + 3 + \cdots + k = \frac{k(k+1)}{2}$. Plugging this into the equation into the above, we have:

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

Thus we have shown that the statement also holds for $k + 1$ which implies that $1 + 2 + 3 + \cdots + n = \frac{n(n+1)}{2}$ for all $n \in \mathbb{N}$. ■

General tips for approaching and writing proofs:

- As much as possible, use complete sentences when writing your proof. When writing a proof for a homework, exam or prelim, be as legible as possible. This holds for all parts of submitted work, and especially for proofs.
- Always remember to define any variables you introduce.
- It's a good practice to say what type of proof you are using (e.g. Proof by contradiction) to help your reader.
- Overly wordy proofs may result in more likelihood for errors – keep things concise and simple.
- Avoid the use of words such as *obviously*, *clearly*, *as we know*, etc. State what is clear and obvious to you as it may not be for the reader. You might see these words in your micro notes, but I would personally stay clear of these.
- If asked to prove $A \Leftrightarrow B$, that is "A if and only if B" then you must remember to complete both directions of the proof. You must prove "*if A then B*" and "*if B then A*."