STAT 230

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These are my notes for the Probability course at the University of Waterloo (STAT 230). They are pretty similar to the online lecture content
You will find that these aren't very useful as notes, in the sense that they are not significantly shorter than the content in the lecture content, they're really just a way for me to type down the content I am learning and absorb it.
Thanks to Prof. Dan Wolczuk for providing me with the macros to typeset this LaTeX document.

Week 1

1 Introduction to Probability

Probability

- A strong likely hood or chance of something
- The relative possibility an event will occur
- The ratio of the number of actual occurrences to the total number of possible occurences

In this course we will consider so-called "random" experiments that have several possible outcomes and are repeatable

Definitions of Probability

Definition Classical Definition of Probability

Let $\mathcal{S}$ be the set of all possible distinct outcomes of a random experiment. Then the probability of an event, provided that all outcomes are equally likely, is

$$\frac{\textit{Number of ways the event can occur}}{\textit{Total number of outcomes in } \mathcal{S}}$$

Definition Relative Frequency Definition

The probability of an event in an experiement is the (limiting) proportion or fraction of times the event occurs in a very long (theoretically infinite) series of (independent) repetitions of the experiement

Definition Subjective Probability

The probability of an event is a 'best guess' by a person making the statement of the chances that the event will happen (e.g., 30% chance of rain)

The classical definition and the relative frequency definition are **consistent** with one another if we are careful in constructing our model.

Characteristics of a Random Experiment

- It should have more than one possible outcome
- We should be able to repeat the experiment under similar/identical conditions
- It *may* have equally likely outcomes

Probability Models

- A sample space of all possible outcomes of a random experiement must be defined
- A set of events is defined. An event is a subset of the sample space, to which we can assign a probability
- A way of assigning probabilites, which are numbers between 0 and 1, to events is specified.

2 Random Experiments and Sample spaces

When we repeat the experiement under *controlled conditions*, (repetitions are called **trials** of the experiment) different outcomes may occur

Definition
Random Experiment

Properties of a Random experiment

- We should be able to repeat it
- Different outcomes may occur on different trials even if the conditions are the same
- Outcomes have probabilities associated with them

A sample space, $\mathcal{S}$, is the set of distinct outcomes for an experiement or process, with the property that in a single trial, one and only one of these outcomes occurs

Definition
Sample Space

The sample space is a set and the outcomes in a sample space are called **sample points** or **points**

A **discrete sample space**, $\mathcal{S}$, is one with a **finite** number of sample points or **countably many** sample points

Definition
Discrete Sample Space

A set, $\mathcal{S}$, is countable if the elements can be put in a 1-1 correspondency with the positive integers

Definition
Countable

E.g. A **countably infinite** set is the sample space of a coin tossing experiment that ends on the event that a Tails occurs. The set

$$\mathcal{S} = \{T, HT, HHT, HHHT, ...\}$$

is countably infinite as we can form a 1-1 correspondence of each sample point with the positive integers, and since it is countable, it is discrete
Example of an **uncountably infinite** set is the sample space

$$\mathcal{S} = [0, \infty)$$

which has an infinite number of sample points, they **can not** be put into a 1-1 correspondence with the positive integers. The sample space $\mathcal{S}$ is not discrete

3 Probability Models and Events

An **event**, A, defined on a discrete sample space, $\mathcal{S}$, is a subset of $\mathcal{S}$. i.e. $A \subset \mathcal{S}$ — Definition: Event

If the event $A \subset \mathcal{S}$ consists of only one sample point this A is called a **simple event** — Definition: Simple Event

If the event $A \subset \mathcal{S}$ consists of two or more sample points then A is called a **compound event**. A is said to **occur** on a trial of the experiment if one of the simple events in A occurs — Definition: Compound Event

Let $\mathcal{S} = \{a_1, a_2, a_3, ...\}$ be a discrete sample space
Let $P(a_1), P(a_2), P(a_3), ...$ be a set of numbers associated with the sample points $a_1, a_2, a_3, ...$ such that:
1) $0 \leq P(a_i) \leq 1, i = 1, 2, ...$
2) $\sum_{i=1} P(a_i) = 1$
Then $P(a_i)$ is called a probability
The set $\{P(a_i), i = 1, 2, ...\}$ is called the **probability distribution on $\mathcal{S}$** — Definition: Probability Distribution on $\mathcal{S}$

The function $P(*)$ has the sample space $\mathcal{S}$ as its domain, the condition $\sum P(a_i) = 1$ reflects the idea that when the process or experiment happens, one or other of the simple events $a_i \in \mathcal{S}$ must occur. (The sum shows that it is certain the total probability of an outcome coming from the defined events in the sample space is 1, and hence 0 for anything outside the sample space). Events consisting of a single a_i in the sample space are referred to as **simple events**

Let $\mathcal{S}$ be a discrete sample space and let A be an event defined on $\mathcal{S}$, i.e. $A \subset \mathcal{S}$
Then $P(A)$, the probability of event A, is the sum of the probabilities corresponding to the sum of all the simple events that make up A, $P(A) = \sum_{a \in A} P(a)$ — Definition: Probability of an Event

According to this definition $P(A) = P(a_1) + P(a_2)$ would be the probability of a compound event $A = \{a_1, a_2\}$
Note that for any event $A, 0 \leq P(A) \leq 1$

A discrete sample space $\mathcal{S} = \{a_1, a_2, ...\}$ together with a probability distribution $\{P(a_i), i = 1, 2...\}$ is referred to as a **discrete probability model** — Definition: Discrete Probability Model

The odds in favour of an event A is the probability the event occurs divided by the probability it does not occur or $\frac{P(A)}{1-P(A)}$. The odds against the vent is the reciprocal, $\frac{1-P(A)}{P(A)}$ — Definition: Odds

4 Counting Techniques

When all the simple events have the same probability, for any even $A \subset \mathcal{S}$, **Definition** $P(A)$ for equi-probable outcomes

$$P(A) = \frac{\textit{number of points in } A}{N(\textit{number of points in } \mathcal{S})}$$

Suppose we can do job 1 in p ways and job 2 in q ways. Then we can do either job 1 **OR** job 2 (but not both), in a total of $p + q$ ways **Definition** Addition Rule

Suppose we can do job 1 in p ways and, for each of these ways, we can do job 2 in q ways. Then we can do both job 1 **AND** job 2, in a total of pq distinct ways **Definition** Multiplication Rule

Some useful combinatorial symbols

• $n^{(k)} = n(n-1)(n-2)...(n-k+1)$ (also written as ${}^nP_r$)
$= \textit{number of arrangements of } n \textit{ different elementes taken } k \textit{ at a time}$

• $n! = n(n-1)...(2)(1)$
$= \textit{number of arrangements (permutations) of } n \textit{ different elements taken } n \textit{ at a time}$

• $n^k = n...n$
$= \textit{number of arrangements of } n \textit{ elements taken } k \textit{ at a time allowing repeats}$

• By definition $0^0 = 1,\ \textit{and } 0! = 1,\ \textit{therefore } 0^{(0)} = 1$

• Note $n^{(k)} = \frac{n!}{(n-k)!}$ when $k \geq 0$ is an integer

• Note that $n^{(k)}$ is also defined for a real number n, with k as a non-negative integer (e.g. $e^{(3)} = e(e-1)(e-2), 3^{(4)} = 3 \times 2 \times 1 \times 0$)

Definition n choose k

$$\binom{n}{k} = \frac{n^{(k)}}{k!} = \frac{n!}{(n-k)!k!} = {}^nC_k$$

If n is a positive integer and k is a non-negative integer such that $k \leq n$ then ${}^nC_k$ is the number of subsets (combinations) of k elements which may be selected from a set containing n elements

Definition Multinomial Coefficients

$$\binom{n}{n_1, ..., n_k} = \frac{n!}{n_1!...n_k!}$$

Week 2

Sets and Probability

Suppose $\mathcal{S}$ is a sample space for an experiment
Let $A, B, C, A_1, A_2, ...$ be events defined on $\mathcal{S}$

The union of A and B (written $A \cup B$) is the set of all points which are in either A or B or both — Definition: Union of Two Sets

The intersection of A and B (written $A \cap B$) is the set of all points which are in both A and B — Definition: Intersection of Two Sets

The complement of A (written $\bar{A}$) is the set of all points in $\mathcal{S}$ which are not in A — Definition: Complement of a Set

De Morgan's Laws

The complement of the union is the intersection of the complements:

$$\overline{(A \cup B)} = \overline{A} \cap \overline{B}$$

The complement of the intersection is the union of the complements:

$$\overline{(A \cap B)} = \overline{A} \cup \overline{B}$$

Definition: Mutually Exclusive

Two events A and B are **mutually exclusive** if $A \cap B = \emptyset$, where $\emptyset$ is the empty set
The events $A_1, ..., A_k$ are called **(pairwise) mutually exclusive** if $A_i \cap A_j = \emptyset, \forall i, j$ with $i \neq j$
In general mutually exclusive events are such that no two events overlap

Definition: Probability Set function, Axioms of Probability

Suppose the function P associates a real value, $P(A)$, with each event A defined on a sample space $\mathcal{S}$ such that

1. $0 \leq P(A)$ for every event A
2. $P(S) = 1$
3. If $A_1, A_2, ...$ is a sequence of mutually exclusive events, then $P(A_1 \cup ... \cup A_n) = \sum_{i=1}^{n} P(A_i)$

then P is called a **probability set function** and $P(A)$ is called the probability of A

(1) - (3) are called the **Axioms of Probability**. These three axioms of probability are sufficient to allow a mathematical structure (the calculus of probability) to be developed.
Note: It does not matter if we assign the probabilities according to the classical, long-run relative frequency or subjective approach as long as the three axioms holds.

Theorem Properties of Probabilities

Suppose $\mathcal{S}$ is a sample space for an experiment
Let $A, B, C, A_1, A_2, ...$ be events defined on $\mathcal{S}$
Then:

1. $0 \leq P(A) \leq 1$

$$P(A) = \sum_{a \in A} P(a) \leq \sum_{all\ a} P(a) = P(\mathcal{S}) = 1$$

2. **Probability of the Complement of an Event:**
$P(\overline{A}) = 1 - P(A)$ which implies $P(\emptyset) = 1 - P(\mathcal{S}) = 0$

$$\sum_{all\ a} P(a) = \sum_{a \in A} P(a) + \sum_{a \in \overline{A}} P(a) \Rightarrow 1 = P(A) + P(\overline{A})$$

3. **Probability of a subset of an Event:**
If $A \subset B$, then $P(A) \leq P(B)$

$$P(A) = \sum_{a \in A} P(a) \leq \sum_{a \in B} P(a) = P(B)$$

4. **Probability of the Union of Two Mutually Exclusive Events:**
Let A and B be mutually exclusive events
Then $P(A \cup B) = P(A) + P(B)$

$$P(A \cup B) = \sum_{a \in A \cup B} P(a) = \sum_{a \in A} P(a) + \sum_{a \in B} P(a) = P(A) + P(B)$$

(Note: This works since for any $a \in B, a \notin A$ and for any $a \in A, a \notin B$)

5. **Probability of the Union of Mutually Exclusive Events:**
Let $A_1, ..., A_n$ be mutually exclusive events
Then $P(A_1 \cup ... \cup A_n) = \sum_{i=1}^{n} P(A_i)$

$$A_i \cap A_j = \emptyset, i \neq j$$

6. For any two events A and B,
$P(A \cup B) = P(A) + P(B) - P(A \cap B)$

$$P(A) + P(B) = P(A \cup B) + P(A \cap B)$$

(This is since when we add $P(A)$ and $P(B)$ we end up double counting the points at the intersection, once when we count $P(A)$ and a second time when we count $P(B)$, so we subtract the intersection to make it count just once)

7. For any three events A, B and C,
$P(A \cup B \cup C) = P(A) + P(B) + P(C) - P(A \cap B) - P(A \cap C) - P(B \cap C) + P(A \cap B \cap C)$

Independent Events

Events A and B are **independent events** if and only if $P(A \cap B) = P(A)P(B)$. If they are not independent, we call the events **dependent**

Definition
Two Independent Events

Note: $P(A \cap B)$ can be written as $P(AB)$

Independent events are such that the ratios

$$\frac{P(A \cap B)}{P(B)} = \frac{P(A)}{P(S)} = P(A)$$

The events $A_1, ..., A_n$ are independent if and only if
$P(A_{i_1} \cap ... \cap A_{i_k}) = P(A_{i_1})...P(A_{i_k})$ for all sets $(i_1, ..., i_k)$ of distinct subscripts chosen from $(1, ..., n)$

Definition
n Independent Events

It is not sufficient for events to just be pairwise independent. All groupings have to be independent.

A and B are independent events if and only if $\overline{A}$ and B are independent events. Similarly A and $\overline{B}$ or $\overline{A}$ and $\overline{B}$

Theorem

Proof:
Note that $B = (A \cap B) \cup (\overline{A} \cap B)$, where $A \cap B$ and $\overline{A} \cap B$ are mutually exclusive events
So $P(B) = P(A \cap B) + P(\overline{A} \cap B)$. Therefore,

$$P(\overline{A} \cap B) = P(B) - P(A \cap B) = P(B) - P(A)P(B) = P(B)(1 - P(A)) = P(\overline{A})P(B)$$