MATH 556: PROBABILITY PRIMER

1 DEFINITIONS, TERMINOLOGY, NOTATION

1.1 EVENTS AND THE SAMPLE SPACE

Definition 1.1 An **experiment** is a one-off or repeatable process or procedure for which
(a) there is a well-defined set of *possible* outcomes
(b) the *actual* outcome is not known with certainty.

Definition 1.2 A **sample outcome**, ω, is precisely one of the possible outcomes of an experiment.

Definition 1.3 The **sample space**, Ω, of an experiment is the set of all possible outcomes.

NOTE : Ω is a set in the mathematical sense, so set theory notation can be used. For example, if the sample outcomes are denoted $\omega_1, ..., \omega_k$, say, then

$$\Omega = \{\omega_1, ..., \omega_k\} = \{\omega_i : i = 1, ..., k\},$$

and $\omega_i \in \Omega$ for $i = 1, ..., k$.

The sample space of an experiment can be

- a FINITE list of sample outcomes, $\{\omega_1, ..., \omega_k\}$
- an INFINITE list of sample outcomes, $\{\omega_1, \omega_2, ...\}$
- an INTERVAL or REGION of a real space, $\left\{\omega : \omega \in A \subseteq \mathbb{R}^d\right\}$

Definition 1.4 An **event**, E, is a designated collection of sample outcomes. Event E **occurs** if the actual outcome of the experiment is one of this collection.

Special Cases of Events

The event corresponding to collection of *all* sample outcomes is Ω.

The event corresponding to a collection of *none* of the sample outcomes is denoted $\emptyset$.

i.e. The sets $\emptyset$ and Ω are also events, termed the **impossible** and the **certain** event respectively, and for any event E, $E \subseteq \Omega$.

1.1.1 OPERATIONS IN SET THEORY

Set theory operations can be used to manipulate events in probability theory. Consider events $E, F \subseteq \Omega$. Then the three basic operations are

UNION	$E \cup F$	"E or F or both occur"
INTERSECTION	$E \cap F$	"both E and F occur"
COMPLEMENT	E'	"E does not occur"

Properties of Union/Intersection operators

Consider events $E, F, G \subseteq \Omega$.

COMMUTATIVITY	$E \cup F = F \cup E$ $E \cap F = F \cap E$
ASSOCIATIVITY	$E \cup (F \cup G) = (E \cup F) \cup G$ $E \cap (F \cap G) = (E \cap F) \cap G$
DISTRIBUTIVITY	$E \cup (F \cap G) = (E \cup F) \cap (E \cup G)$ $E \cap (F \cup G) = (E \cap F) \cup (E \cap G)$
DE MORGAN'S LAWS	$(E \cup F)' = E' \cap F'$ $(E \cap F)' = E' \cup F'$

Union and intersection are *binary* operators, that is, they take only two arguments, and thus the bracketing in the above equations is necessary. For $k \geq 2$ events, $E_1, E_2, ..., E_k$,

$$\bigcup_{i=1}^{k} E_i = E_1 \cup ... \cup E_k \qquad \text{and} \qquad \bigcap_{i=1}^{k} E_i = E_1 \cap ... \cap E_k$$

for the union and intersection of $E_1, E_2, ..., E_k$, with a further extension for k *infinite*.

1.1.2 MUTUALLY EXCLUSIVE EVENTS AND PARTITIONS

Definition 1.5 Events E and F are **mutually exclusive** if $E \cap F = \emptyset$, that is, if events E and F cannot both occur. If the sets of sample outcomes represented by E and F are **disjoint** (have no common element), then E and F are mutually exclusive.

Definition 1.6 Events $E_1, ..., E_k \subseteq \Omega$ form a **partition** of event $F \subseteq \Omega$ if
(a) $E_i \cap E_j = \emptyset$ for $i \neq j$, $i, j = 1, ..., k$
(b) $\bigcup\limits_{i=1}^{k} E_i = F$.

so that each element of the collection of sample outcomes corresponding to event F is in *one and only one* of the collections corresponding to events $E_1, ...E_k$.

In Figure 1, we have $\Omega = \bigcup\limits_{i=1}^{6} E_i$. In Figure 2, we have $F = \bigcup\limits_{i=1}^{6} (F \cap E_i)$, but, for example, $F \cap E_6 = \emptyset$.

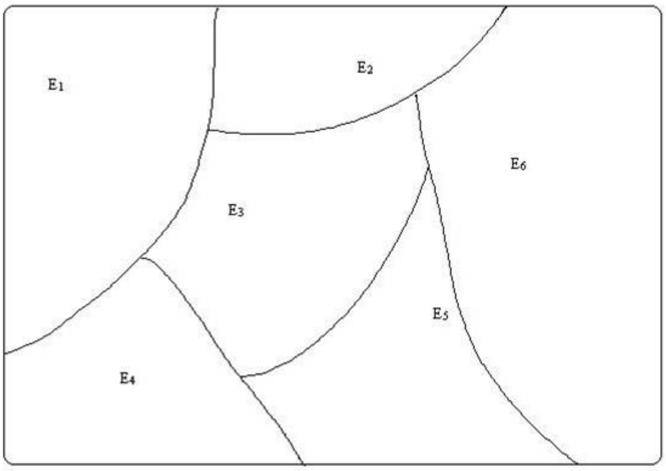

Figure 1: Partition of Ω

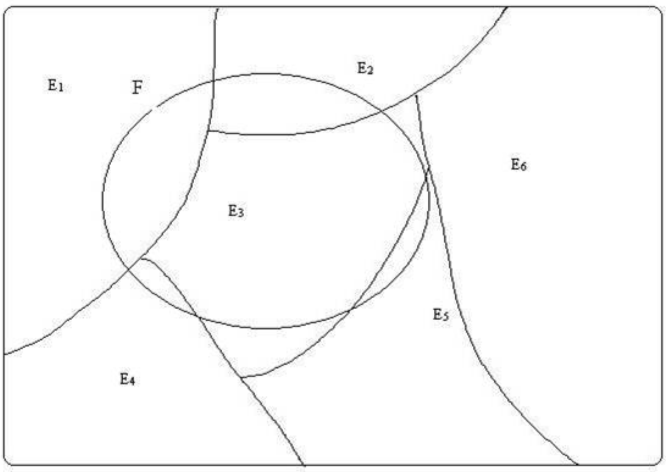

Figure 2: Partition of $F \subset \Omega$

1.2 THE PROBABILITY FUNCTION

Definition 1.7 For an event $E \subseteq \Omega$, the **probability that** E **occurs** is written $P(E)$.

Interpretation : $P(.)$ is a *set-function* that assigns "weight" to collections of possible outcomes of an experiment. There are many ways to think about precisely how this assignment is achieved;

CLASSICAL : "Consider equally likely sample outcomes ..."

FREQUENTIST : "Consider long-run *relative frequencies* ..."

SUBJECTIVE : "Consider personal degree of belief ..."

or merely think of $P(.)$ as a set-function.

1.3 PROPERTIES OF P(.): THE AXIOMS OF PROBABILITY

Consider sample space Ω. Then probability function $P(.)$ satisfies the following properties:

AXIOM 1 Let $E \subseteq \Omega$. Then $0 \leq P(E) \leq 1$.

AXIOM 2 $P(\Omega) = 1$.

AXIOM 3 If $E, F \subseteq \Omega$, with $E \cap F = \emptyset$, then $P(E \cup F) = P(E) + P(F)$.

1.3.1 EXTENSIONS : ALGEBRAS AND SIGMA ALGEBRAS

Axiom 3 can be re-stated if we can consider an *algebra* $\mathcal{A}$ of subsets of Ω. A (countable) collection of subsets, $\mathcal{A}$, of sample space Ω, say $\mathcal{A} = \{A_1, A_2, ...\}$, is an *algebra* if

I $\Omega \in \mathcal{A}$

II $A_1, A_2 \in \mathcal{A} \Longrightarrow A_1 \cup A_2 \in \mathcal{A}$

III $A \in \mathcal{A} \Longrightarrow A' \in \mathcal{A}$

NOTE : An algebra is a set of sets (events) with certain properties; in particular it is *closed* under a **finite** number of union operations (II), that is if $A_1, ...A_k \in \mathcal{A}$, then

$$\bigcup_{i=1}^{k} A_i \in \mathcal{A}.$$

If $\mathcal{A}$ is an algebra of subsets of Ω, then
(i) $\emptyset \in \mathcal{A}$
(ii) If $A_1, A_2 \in \mathcal{A}$, then

$$A_1', A_2' \in \mathcal{A} \quad \Longrightarrow \quad A_1' \cup A_2' \in \mathcal{A} \quad \Longrightarrow \quad \left(A_1' \cup A_2'\right)' \in \mathcal{A} \quad \Longrightarrow \quad A_1 \cap A_2 \in \mathcal{A}$$

so $\mathcal{A}$ is also *closed under intersection*.

Extension: A *sigma-algebra* **(**$\sigma-$*algebra***)** is an algebra that is closed under *countable union*, that is, if $A_1, ...A_k, ... \in \mathcal{A}$, then

$$\bigcup_{k=1}^{\infty} A_k \in \mathcal{A}.$$

Now, if events $A_1, A_2, ...$ are disjoint elements of $\mathcal{A}$, then we can replace Axiom 3 by requiring that, for $n \geq 1$,

AXIOM 3* $\quad \mathrm{P}\left(\bigcup_{i=1}^{n} A_i\right) = \sum_{i=1}^{n} \mathrm{P}(A_i).$

Furthermore, if $\mathcal{A}$ is a σ-algebra, then Axiom 3* can be replaced by

AXIOM 3† $\quad \mathrm{P}\left(\bigcup_{i=1}^{\infty} A_i\right) = \sum_{i=1}^{\infty} \mathrm{P}(A_i).$

Thus, if $\mathcal{A}$ is a σ-algebra, then

AXIOM 3† $\Longrightarrow$ AXIOM 3* $\Longrightarrow$ AXIOM 3

COUNTABLE ADDITIVITY $\Longrightarrow$ FINITE ADDITIVITY $\Longrightarrow$ ADDITIVITY

1.3.2 COROLLARIES TO THE PROBABILITY AXIOMS

For events $E, F \subseteq \Omega$

1. $P(E') = 1 - P(E)$, and hence $P(\emptyset) = 0$.
2. If $E \subseteq F$, then $P(E) \leq P(F)$.
3. In general, $P(E \cup F) = P(E) + P(F) - P(E \cap F)$.
4. $P(E \cap F') = P(E) - P(E \cap F)$
5. $P(E \cup F) \leq P(E) + P(F)$.
6. $P(E \cap F) \geq P(E) + P(F) - 1$.

NOTE : The **general addition rule** for probabilities and Boole's Inequality extend to more than two events. Let $E_1, ..., E_n$ be events in Ω. Then

$$P\left(\bigcup_{i=1}^{n} E_i\right) = \sum_{i} P(E_i) - \sum_{i<j} P(E_i \cap E_j) + \sum_{i<j<k} P(E_i \cap E_j \cap E_k) - ... + (-1)^n P\left(\bigcap_{i=1}^{n} E_i\right)$$

and

$$P\left(\bigcup_{i=1}^{n} E_i\right) \leq \sum_{i=1}^{n} P(E_i).$$

To prove these results, construct the events $F_1 = E_1$ and

$$F_i = E_i \cap \left(\bigcup_{k=1}^{i-1} E_k \right)'$$

for $i = 2, 3, ..., n$. Then $F_1, F_2, ...F_n$ are disjoint, and $\bigcup_{i=1}^{n} E_i = \bigcup_{i=1}^{n} F_i$,so

$$P\left(\bigcup_{i=1}^{n} E_i\right) = P\left(\bigcup_{i=1}^{n} F_i\right) = \sum_{i=1}^{n} P(F_i).$$

Now, by the corollary above

$$\begin{aligned} P(F_i) &= P(E_i) - P\left(E_i \cap \left(\bigcup_{k=1}^{i-1} E_k\right)\right) \qquad i = 2, 3, ..., n. \\ &= P(E_i) - P\left(\bigcup_{k=1}^{i-1} (E_i \cap E_k)\right) \end{aligned}$$

and the result follows by recursive expansion of the second term for $i = 2, 3, ...n$.

NOTE : We will often deal with both probabilities of single events, and also probabilities for intersection events. For convenience, and to reflect connections with distribution theory, we will use the following terminology; for events E and F

$P(E)$ is the **marginal** probability of E

$P(E \cap F)$ is the **joint** probability of E and F

1.4 CONDITIONAL PROBABILITY

Definition 1.8 For events $E, F \subseteq \Omega$ the **conditional probability** that F occurs **given** that E occurs is written P$(F|E)$, and is defined by

$$P(F|E) = \frac{P(E \cap F)}{P(E)}$$

if P$(E) > 0$.

NOTE: $P(E \cap F) = P(E)P(F|E)$, and in general, for events $E_1, ..., E_k$,

$$P\left(\bigcap_{i=1}^{k} E_i\right) = P(E_1)P(E_2|E_1)P(E_2|E_1 \cap E_2)...P(E_k|E_1 \cap E_2 \cap ... \cap E_{k-1}).$$

This result is known as the CHAIN or MULTIPLICATION RULE.

Definition 1.9 Events E and F are **independent** if

$$P(E|F) = P(E) \text{ so that } P(E \cap F) = P(E)P(F)$$

Extension : Events $E_1, ..., E_k$ are independent if, for **every** subset of events of size $l \leq k$, indexed by $\{i_1, ..., i_l\}$, say,

$$P\left(\bigcap_{j=1}^{l} E_{i_j}\right) = \prod_{j=1}^{l} P(E_{i_j}).$$

1.5 THE THEOREM OF TOTAL PROBABILITY

THEOREM

Let $E_1, ..., E_k$ be a partition of Ω, and let $F \subseteq \Omega$. Then

$$P(F) = \sum_{i=1}^{k} P(F|E_i)P(E_i)$$

PROOF

$E_1, ..., E_k$ form a partition of Ω, and $F \subseteq \Omega$, so

$$\begin{aligned} F &= (F \cap E_1) \cup ... \cup (F \cap E_k) \\ \implies P(F) &= \sum_{i=1}^{k} P(F \cap E_i) = \sum_{i=1}^{k} P(F|E_i)P(E_i) \end{aligned}$$

(by AXIOM 3^*, as$E_i \cap E_j = \emptyset$).

Extension: If we assume that Axiom $3^\dagger$ holds, that is, that P is countably additive, then the theorem still holds, that is, if $E_1, E_2, ...$ are a partition of Ω, and $F \subseteq \Omega$, then

$$P(F) = \sum_{i=1}^{\infty} P(F \cap E_i) = \sum_{i=1}^{\infty} P(F|E_i)P(E_i)$$

if P$(E_i) > 0$ for all i.

1.6 BAYES THEOREM

THEOREM

Suppose $E, F \subseteq \Omega$, with P(E),P$(F) > 0$. Then

$$P(E|F) = \frac{P(F|E)P(E)}{P(F)}$$

PROOF

$$P(E|F)P(F) = P(E \cap F) = P(F|E)P(E), \text{ so } P(E|F)P(F) = P(F|E)P(E).$$

Extension: If $E_1, ..., E_k$ are disjoint, with $\mathrm{P}(E_i) > 0$ for $i = 1, ..., k$, and form a partition of $F \subseteq \Omega$, then

$$P(E_i|F) = \frac{P(F|E_i)P(E_i)}{\sum_{i=1}^{k} P(F|E_i)P(E_i)}$$

The extension to the countably additive (infinite) case also holds.

NOTE: in general, $P(E|F) \neq P(F|E)$

1.7 COUNTING TECHNIQUES

Suppose that an experiment has N equally likely sample outcomes. If event E corresponds to a collection of sample outcomes of size $n(E)$, then

$$P(E) = \frac{n(E)}{N}$$

so it is necessary to be able to evaluate $n(E)$ and N in practice.

1.7.1 THE MULTIPLICATION PRINCIPLE

If operations labelled $1, ..., r$ can be carried out in $n_1, ..., n_r$ ways respectively, then there are

$$\prod_{i=1}^{r} n_i = n_1 ... n_r$$

ways of carrying out the r operations in total.

Example 1.1 If each of r trials of an experiment has N possible outcomes, then there are N^r possible sequences of outcomes in total. For example:
(i) If a multiple choice exam has 20 questions, each of which has 5 possible answers, then there are 5^{20} different ways of completing the exam.
(ii) There are 2^m subsets of m elements (as each element is either **in** the subset, or **not in** the subset, which is equivalent to m trials each with two outcomes).

1.7.2 SAMPLING FROM A FINITE POPULATION

Consider a collection of N items, and a sequence of operations labelled $1, ..., r$ such that the ith operation involves **selecting** one of the items remaining after the first $i-1$ operations have been carried out. Let n_i denote the number of ways of carrying out the ith operation, for $i = 1, ..., r$. Then there are two distinct cases;
(a) **Sampling with replacement :** an item is returned to the collection after selection. Then $n_i = N$ for all i, and there are N^r ways of carrying out the r operations.
(b) **Sampling without replacement :** an item is not returned to the collection after selected. Then $n_i = N - i + 1$, and there are $N(N-1)...(N-r+1)$ ways of carrying out the r operations.
e.g. Consider selecting 5 cards from 52. Then

(a) leads to 52^5 possible selections, whereas

(b) leads to $52.51.50.49.48$ possible selections

NOTE : The **order** in which the operations are carried out may be important
e.g. in a raffle with three prizes and 100 tickets, the draw $\{45, 19, 76\}$ is different from $\{19, 76, 45\}$.

NOTE : The items may be **distinct** (unique in the collection), or **indistinct** (of a unique type in the collection, but not unique individually).
e.g. The numbered balls in the National Lottery, or individual playing cards, are **distinct**. However balls in the lottery are regarded as "WINNING" or "NOT WINNING", or playing cards are regarded in terms of their suit only, are **indistinct**.

1.7.3 PERMUTATIONS AND COMBINATIONS

Definition 1.10 A **permutation** is an *ordered* arrangement of a set of items.
A **combination** is an *unordered* arrangement of a set of items.

RESULT 1 The number of permutations of n distinct items is $n! = n(n-1)...1$.

RESULT 2 The number of permutations of r from n distinct items is

$$P_r^n = \frac{n!}{(n-r)!} = n(n-1)...(n-r+1) \qquad \text{(by the Multiplication Principle)}.$$

If the **order** in which items are selected is not important, then

RESULT 3 The number of combinations of r from n distinct items is

$$C_r^n = \binom{n}{r} = \frac{n!}{r!(n-r)!} \qquad (\text{as} P_r^n = r!C_r^n).$$

-recall the **Binomial Theorem**, namely

$$(a+b)^n = \sum_{i=0}^{n} \binom{n}{i} a^i b^{n-i}.$$

Then the number of subsets of m items can be calculated as follows; for each $0 \leq j \leq m$, choose a subset of j items from m. Then

$$\text{Total number of subsets} = \sum_{j=0}^{m} \binom{m}{j} = (1+1)^m = 2^m.$$

If the items are **indistinct**, but each is of a unique type, say Type I, ..., Type κ say, (the so-called **Urn Model**) then

RESULT 4 The number of distinguishable permutations of n indistinct objects, comprising n_i items of type i for $i = 1, ..., \kappa$ is

$$\frac{n!}{n_1!n_2!...n_\kappa!}$$

Special Case : if $\kappa = 2$, then the number of distinguishable permutations of the n_1 objects of type I, and $n_2 = n - n_1$ objects of type II is

$$C^n_{n_2} = \frac{n!}{n_1!(n-n_1)!}$$

Also, there are C^n_r ways of partitioning n **distinct** items into two "cells", with r in one cell and $n - r$ in the other.

1.7.4 PROBABILITY CALCULATIONS

Recall that if an experiment has N equally likely sample outcomes, and event E corresponds to a collection of sample outcomes of size $n(E)$, then

$$P(E) = \frac{n(E)}{N}$$

Example 1.2 A True/False exam has 20 questions. Let E = "16 answers correct at random". Then

$$P(E) = \frac{\text{Number of ways of getting 16 out of 20 correct}}{\text{Total number of ways of answering 20 questions}} = \frac{\binom{20}{16}}{2^{20}} = 0.0046$$

Example 1.3 *Sampling without replacement*. Consider an Urn Model with 10 Type I objects and 20 Type II objects, and an experiment involving sampling five objects without replacement. Let E="precisely 2 Type I objects selected" We need to calculate N and $n(E)$ in order to calculate P(E). In this case N is the number of ways of choosing 5 from 30 items, and hence

$$N = \binom{30}{5}$$

To calculate $n(E)$, we think of E occurring by first choosing 2 Type I objects from 10, and then choosing 3 Type II objects from 20, and hence, by the multiplication rule,

$$n(E) = \binom{10}{2}\binom{20}{3}$$

Therefore

$$P(E) = \frac{\binom{10}{2}\binom{20}{3}}{\binom{30}{5}} = 0.360$$

This result can be obtained using a conditional probability argument; consider event $F \subseteq E$, where F = "sequence of objects 11222 obtained". Then

$$F = \bigcap_{i=1}^{5} F_{ij}$$

where F_{ij} = "type j object obtained on draw i" $i = 1, ..., 5, j = 1, 2$. Then

$$P(F) = P(F_{11})P(F_{21}|F_{11})...P(F_{52}|F_{11}, F_{21}, F_{32}, F_{42}) = \frac{10}{30}\frac{9}{29}\frac{20}{28}\frac{19}{27}\frac{18}{26}$$

Now consider event G where G = "sequence of objects 12122 obtained". Then

$$P(G) = \frac{10}{30}\frac{20}{29}\frac{9}{28}\frac{19}{27}\frac{18}{26}$$

i.e. $P(G) = P(F)$. In fact, **any** sequence containing two Type I and three Type II objects has this probability, and there are $\binom{5}{2}$ such sequences. Thus, as all such sequences are mutually exclusive,

$$P(E) = \binom{5}{2}\frac{10}{30}\frac{9}{29}\frac{20}{28}\frac{19}{27}\frac{18}{26} = \frac{\binom{10}{2}\binom{20}{3}}{\binom{30}{5}}$$

as before.

Example 1.4 *Sampling with replacement.* Consider an Urn Model with 10 Type I objects and 20 Type II objects, and an experiment involving sampling five objects with replacement. Let E = "precisely 2 Type I objects selected". Again, we need to calculate N and $n(E)$ in order to calculate P(E). In this case N is the number of ways of choosing 5 from 30 items with replacement, and hence

$$N = 30^5$$

To calculate $n(E)$, we think of E occurring by first choosing 2 Type I objects from 10, and 3 Type II objects from 20 in any order. Consider such sequences of selection

Sequence	Number of ways
11222	10.10.20.20.20
12122	10.20.10.20.20
.	.

etc., and thus a sequence with 2 Type I objects and 3 Type II objects can be obtained in $10^2 20^3$ ways. As before there are $\binom{5}{2}$ such sequences, and thus

$$P(E) = \frac{\binom{5}{2}10^2 20^3}{30^5} = 0.329.$$

Again, this result can be obtained using a conditional probability argument; consider event $F \subseteq E$, where F = "sequence of objects 11222 obtained". Then

$$P(F) = \left(\frac{10}{30}\right)^2 \left(\frac{20}{30}\right)^3$$

as the results of the draws are **independent**. This result is true for any sequence containing two Type I and three Type II objects, and there are $\binom{5}{2}$ such sequences that are mutually exclusive, so

$$P(E) = \binom{5}{2} \left(\frac{10}{30}\right)^2 \left(\frac{20}{30}\right)^3$$