APPENDIX A

PROBABILITY THEORY: OVERVIEW

In this appendix we introduce some basic concepts and notation of probability theory for use in solving stochstic linear programs.

A.1 BASIC CONCEPTS, EXPECTED VALUE, AND VARIANCE

We begin by paraphrasing some basic definitions and concepts found in W. Feller's book *Introduction to Probability Theory and Applications*.

> *Definition (Event, Sample Point, Sample Space)*: An *event* is defined to be the outcome of an experiment or an observation about the state of some system. A simple event, which is a single outcome of a single experiment or observation, is called a *sample point* and will be denoted by ω. The aggregrate of all possible sample points is referred to as the *sample space* and will be denoted by the symbol Ω.

Associated with points ω in a sample space is a function $p(\omega) \geq 0$ that is referred to as *the probability of a simple event* ω *happening*. The sum of these $p(\omega)$ is unity. For example, if we have an urn containing balls labeled with either a 0 or a 1, we might assign the probability of "randomly" choosing a 0 ball as equal to the proportion of 0 balls to the total balls in the urn. In this case, the sample space may be thought of as consisting of two points lying on a line such that one point has coordinate 0 and the other point has coordinate 1 with probabilities $p(0) = \alpha$, $p(1) = \beta$, where $\beta = 1 - \alpha$.

Definition: A *discrete* sample space is one consisting of only a finite number of points, say n.

Another example of a discrete sample space is the toss of a coin, is where the probability of observing a head is 1/2 and the probability of observing a tail is 1/2. We ignore the very remote possibility of a coin landing on its edge.

The probability of an event being observed in a subset of the sample space is assumed to be simple additions of probabilities in the subset of the sample points associated with the event.

Definition (Random Variable): A *random variable* X is not a variable but a function defined over a sample space.

In particular, a discrete random variable X is a function that takes on a discrete set of values with values $x_1, x_2, \ldots, x_n$, where x_i can be a sample point ω itself, an event, or, more generally, it can be a function of a set of sample points. The probability that a discrete random variable X can take on a value x_j is denoted by $P[X = x_j] = p_j$.

Definition (Probability Distribution): The set of these probabilities for all the outcomes of a discrete random variable X is called a *probability distribution (or density)* of the random variable. Clearly,

$$p_j \geq 0, \qquad \sum_{j=1}^{n} p_j = 1. \tag{A.1}$$

Definition (Expected Value or Mean): The *expected value* or *mean* of a discrete random variable X is

$$E[X] = \sum_{j=1}^{n} p_j x_j. \tag{A.2}$$

Often the expected value is denoted by μ_X or simply μ when the association with X is clear. In general, the expected value of a function of X, say $h(X)$, is

$$E\big[h(X)\big] = \sum_{j=1}^{n} p_j h(x_j). \tag{A.3}$$

Definition (Variance and Standard Deviation): The *variance* of a random variable X is denoted by σ_X^2 or simply σ^2 when the association with X is clear. It is defined as the expected squared deviations of an observation x_j from its expected values; i.e.,

$$\sigma_X^2 = \sum_{j=1}^{n} p_j \big(x_j - E[X]\big)^2 = E[X^2] - \big(E[X]\big)^2. \tag{A.4}$$

Its positive square root, denoted by σ_X, is called the *standard deviation*.

Definition (Independent Random Variables): If $P[X = x_i] = p_i$ and $P[Y = y_j] = q_j$, then random variables X, Y are said to be *independent* if their joint probability distribution $P\big[(X,Y) = (x_i, y_j)\big] = p_i q_j$.

Definition (Correlation Coefficient): The *correlation coefficient* between the two variables X and Y is defined to be

$$\rho_{XY} = \frac{E\big[\big(X - E[X]\big)\big(Y - E[Y]\big)\big]}{\sigma_X \sigma_Y} = \frac{E[XY] - E[X]E[Y]}{\sigma_X \sigma_Y}. \tag{A.5}$$

The correlation coefficient satisfies $-1 \leq \rho_{XY} \leq +1$. If the random variables X and Y are independent $\rho_{XY} = 0$. The *covariance* between random variables X and Y is defined to be

$$\sigma_{XY} = \sigma_X \sigma_Y \rho_{XY}. \tag{A.6}$$

In a more general setting, a random variable V can be a vector function consisting of d components $V = (V_1, V_2, \ldots, V_d)$ with outcomes $v^\omega = (v_1^\omega, v_2^\omega, \ldots, v_d^\omega)$. The probabilities associated with v^ω will be denoted by $p(v^\omega)$ or simply by $p(v)$.

Definition (Independent Components): If the joint density probability distribution $p(v_1, v_2, \ldots, v_n)$ satisfies

$$p(v_1, v_2, \ldots, v_n) = p_1(v_1) p_2(v_2) \cdots p_n(v_n), \tag{A.7}$$

the components of the random variable V are said to be *independent*.

If the components of the random variable V are *independent*, the sample space Ω is obtained by crossing the sets of outcomes for each component of the vector entry, i.e.,

$$\Omega = \Omega_1 \times \Omega_2 \times \cdots \times \Omega_d. \tag{A.8}$$

Then the expectation of a function $h(V)$ is of the form:

$$E\big[h(V)\big] = \sum_{v_1} \sum_{v_2} \cdots \sum_{v_d} h(v) p_1(v_1) p_2(v_2) \cdots p_n(v_n). \tag{A.9}$$

A random variable that is continuous is treated in much the same way except that we now use integrals.

Definition (Probability Density Function): If X is a continuous random variable, we associate with it a *probability density function* $f(x)$ with the property that

$$f(x) \geq 0, \qquad \int_\Omega f(x)\, dx = 1. \tag{A.10}$$

We shall often use the shorter form *density function* to mean a probability density function.

In the general case of a continuous random vector V, the expectation of a function $h(V)$ is given by

$$E\big[h(V)\big] = \int_{\Omega_1}\int_{\Omega_2}\cdots\int_{\Omega_l} h(v)f(v)dv_1dv_2\cdots dv_l. \tag{A.11}$$

Sometimes an expectation is defined in terms of a Stieltjes integral; that is, the expected value of a function $g(x)$ of a random variable X, which is a combination of continuous and discrete elements, can be expressed as

$$E[X] = \int_{-\infty}^{\infty} g(x)dF(x) \tag{A.12}$$

where $F(x) = P[X \leq x]$ is the cumulative density function.

Stochastic linear programs are hard to solve, in part because of the expense and difficulty involved in evaluating multiple integrals or multiple sums. The computation of the expected value typically involves a very large number of function evaluations, and each function evaluation may require solving a very large linear program.

A.2 NORMAL DISTRIBUTION AND THE CENTRAL LIMIT THEOREM

Many techniques in statistics are based on the normal probability distribution.

Definition (Normal Distribution): A random variable X is said to be distributed *normally* if its density function $f(x)$ is a *normal distribution*, i.e., it is of the form:

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma}e^{-(x-\mu)^2/2\sigma^2}, \tag{A.13}$$

where $-\infty \leq \mu \leq \infty$ is the mean and $\sigma > 0$ is the standard deviation of the normal distribution. The normal distribution of (A.13) is often denoted by $\mathcal{N}(\mu, \sigma)$.

Definition (Standardized Normal Random Variable): A normally distributed random variable with mean $\mu = 0$ and standard deviation $\sigma = 1$, is called a *standardized* normal random variable. A standardized normal distribution is denoted by $\mathcal{N}(0, 1)$.

Normal distributions play an important role when sampling techniques are used because, according to the Central Limit Theorem, to be stated soon, the distribution of the mean of a sample of size n approaches a normal distribution as $n \to \infty$. For this purpose, we need to define what is meant by a random sample, sample mean, and sample variance.

Definition (Random Sample): The random variables $X_1, X_2, \ldots, X_n$ are defined to be a *random sample* from a population with probability density $f(x)$ if $X_1, X_2, \ldots, X_n$ are independent identically distributed random variables; i.e., if their joint probability density function satisfies

$$g(x_1, x_2, \ldots, x_n) = f(x_1)f(x_2)\cdots f(x_n), \tag{A.14}$$

where $f(x_i)$ is the density function of each of the random variables X_i.

Often the form of the density function of a random variable is known; for example, we may know that it is normally distributed. However, the density function may have parameters such as μ and σ, which are not known. The problem is then to estimate these unknown parameters through the use of a *statistic*.

Definition: A *statistic* is a function of a random sample of size n that is used to estimate an unknown parameter of a density function. For example, $\bar{X} = (1/n)\sum_{i=1}^{n} X_j$ is a statistic used to estimate the mean of a distribution.

LEMMA A.1 (Mean and Variance of a Random Sample) *Consider a population with density function $f(x)$, which has mean μ and variance σ^2. Let $X_1, X_2, \ldots, X_n$ be a random sample from this population and let $\bar{X} = (1/n)\sum_{i=1}^{n} X_j$. Then*

$$E[\bar{X}] = \mu_{\bar{X}} = \mu \qquad \textit{and} \qquad \mathrm{Var}[\bar{X}] = \sigma^2_{\bar{X}} = \frac{1}{n}\sigma^2. \tag{A.15}$$

▷ **Exercise A.1** Prove Lemma A.1.

When sampling, we often can guess at the form of the probability density function but do not know its parameters, nor do we know its mean or variance. We can use one of several different ways to estimate the parameters; however, we typically would like the expected value of an estimator of a parameter to be equal to the true value of the parameter. Estimators that satisfy this property are called *unbiased estimators*.

Definition (Unbiased Estimator): An *unbiased estimator* γ of a function $g(\theta)$ of a parameter θ has the property $E[\gamma] = g(\theta)$. For example, the mean μ and variance σ^2 are parameters of a distribution. An unbiased estimator $\bar{X}$ of μ is the mean of a sample of size n:

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} X_i. \tag{A.16}$$

Definition (Sample Variance): The *sample variance* of a random sample of size n is by definition:

$$\frac{1}{n}\sum_{i=1}^{n}(X_i - \bar{X})^2. \tag{A.17}$$

A biased estimator of σ^2 is the sample variance because

$$E\left[\frac{1}{n}\sum_{i=1}^{n}(X_i - \bar{X})^2\right] = \frac{n-1}{n}\sigma^2 \neq \sigma^2. \tag{A.18}$$

Therefore an unbiased estimator of σ^2 is

$$\frac{1}{n-1}\sum_{i=1}^{n}(X_i - \bar{X})^2. \tag{A.19}$$

Definition (Unbiased Sample Variance): We shall refer to (A.19) as the *unbiased sample variance* for estimating σ^2.

▷ **Exercise A.2** Prove (A.18).

THEOREM A.2 (Chebyshev's Weak Law of Large Numbers) *Let $\bar{X}$ be the sample mean of a random sample of size n drawn from a probability density $f(x)$ with mean μ and variance σ^2. Then in order for*

$$P[-\epsilon < \bar{X} - \mu < \epsilon] \geq 1 - \delta \tag{A.20}$$

for some specified $0 < \delta < 1$ and $\epsilon > 0$, choose sample size $n > \sigma^2/\epsilon^2\delta$.

The *weak law of large numbers* tells us how large we must take the sample size n in order to have a probability greater than $1 - \delta$ for $\left|\bar{X} - \mu\right| < \epsilon$, where $\bar{X}$ is the sample mean.

Example A.1 (Sample Size Using Weak Law of Large Numbers) How large must the size n of the sample drawn from a population with known mean $\mu = 0$ and standard deviation $\sigma = 1000$ be in order that the probability is $\geq 1 - \delta = 0.95$ that the observed sample mean will be within $\epsilon = 10$ of the true mean 0? According to the weak law of large numbers, the sample size n should be chosen as $n = 100^2/10^2(0.5) = 200{,}000$.

THEOREM A.3 (Central Limit Theorem) *Let $X_1, X_2, \ldots, X_n$ be a random sample from a probability density function $f(x)$, which has mean μ and variance σ^2. Define the random variable Z_n as a function of the sample mean $\bar{X}$ as:*

$$Z_n = \frac{\bar{X} - E[\bar{X}]}{\sqrt{\mathrm{Var}[\bar{X}]}} = \frac{\bar{X} - \mu}{\sigma/\sqrt{n}}.$$

Then the distribution of Z_n approaches that of a standardized normal distribution as $n \to \infty$.

Example A.2 (Sample Size Using the Central Limit Theorem) If in Example A.1,

$$Z_n = \frac{\bar{X} - \mu}{\sigma\sqrt{n}} = \frac{\bar{X}}{1000/\sqrt{n}},$$

then since

$$\int_{-1.96}^{+1.96} \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}t^2} dt = 0.95,$$

we have

$$P[-10 \le \bar{X} \le 10] = P\left[\frac{-10}{1000/\sqrt{n}} \le \frac{\bar{X} - \mu}{\sigma/\sqrt{n}} \le \frac{10}{1000/\sqrt{n}}\right] \ge 0.95.$$

Then $\frac{10}{1000/\sqrt{n}} = 1.96$ or $\sqrt{n} \ge 196$ or sample size should be chosen $n \ge 196^2 = 38{,}416$. The sample size n obtained using the Central Limit Theorem is much smaller than that obtained using Chebyshev's Weak Law of Large Numbers.

The Central Limit Theorem is one of the most important theorems in probability and statistics. It basically tells us that as the sample size grows the distribution of the sample mean $\bar{X}$ approaches that of a normally distributed random variable.

A.3 CHI-SQUARE DISTRIBUTION, STUDENT'S t-DISTRIBUTION, AND CONFIDENCE INTERVALS

The "solution" of a stochastic linear program will be a decision x that is feasible. Its associated objective cost z is a random variable that depends on x and on the outcome of a random event ω. The problem is to choose $x = \hat{x}$ such that the *expected value* of $z_{\hat{x}}$ is minimum. If sample space Ω is too large, so that it is not possible to evaluate all $\omega \in \Omega$, then our goal will be given ϵ and δ to choose $x = \hat{x}$ and a sample size n such that $P\big[E[z_{\hat{x}}] < E[z_{\hat{x}}] + \epsilon\big] \ge 1 - \delta$. With this in mind we define the chi-square distribution, Student's t-distribution, and confidence intervals.

A.3.1 CHI-SQUARE DISTRIBUTION

A probability distribution, called the *chi-square distribution* plays an important role in determining the distribution of the unbiased sample variance.

Definition (Chi-Square Distribution): A random variable X is said to have a *chi-square distribution with k degrees of freedom* if its density function is of the form

$$f(x \mid k) = \frac{1}{\Gamma(k/2)} \left(\frac{1}{2}\right)^{k/2} x^{k/2-1} e^{-x/2}, \qquad 0 < x < \infty. \tag{A.21}$$

where $\Gamma(u)$ is the gamma function:

$$\Gamma(u) = \int_0^\infty x^{u-1} e^{-x} dx \quad \text{for } u > 0 \tag{A.22}$$

Integrating by parts results in the property

$$\Gamma(u+1) = u\Gamma(u).$$

Hence if u is an integer, say $u = n$, then $\Gamma(n+1) = n!$. Note that $\Gamma(u)$ is defined by (A.22) for any u, integer or noninteger, for example,

$$\Gamma(n + 1/2) = \frac{1 \cdot 3 \cdot 5 \cdots (2n-1)}{2^n} \sqrt{\pi}$$

and $\Gamma(1/2) = \sqrt{\pi}$, $\Gamma(3/2) = (1/2)\sqrt{\pi}$. A random variable with a chi-square distribution with k degrees of freedom has $E[X] = k$ and $\text{Var}[X] = 2k$.

▷ **Exercise A.3** Show that $E[X] = k$ and $\text{Var}[X] = 2k$ for a random variable X that has a chi-square distribution with k degrees of freedom.

Next we discuss some properties of random samples.

LEMMA A.4 (Sample Mean from a Normal Distribution) *Let $\bar{X}$ be the sample mean of a random sample $X_1, X_2, \ldots, X_n$ drawn from a normal distribution $\mathcal{N}(\mu, \sigma^2)$. Then $\bar{X}$ is itself normal with mean μ and variance σ^2/n.*

LEMMA A.5 (Chi-Square Distribution) *Let U be a random variable defined by:*

$$U = \sum_{i=1}^{k} \left(\frac{X_i - \mu_i}{\sigma_i} \right)^2$$

where the X_i are normally and independently distributed with means μ_i and variance σ_i^2. Then U has a chi-square distribution with k degrees of freedom.

COROLLARY A.6 *Let $S_{\bar{X}}$ be the unbiased sample variance* (A.19) *of a random sample $X_1, X_2, \ldots, X_n$ from a normal distribution with mean μ and variance σ^2. Then*

$$U = \frac{(n-1)S_{\bar{X}}^2}{\sigma^2}$$

has a chi-square distribution with $(n-1)$ degrees of freedom.

A.3.2 STUDENT'S t-DISTRIBUTION

The Student's t-distribution also plays a very important role in estimation.

Definition (Student's t-Distribution): A random variable X is said to have a *Student's t-distribution* with k degrees of freedom if its probability density function is of the form

$$stu(x \mid k) = \frac{\Gamma\big([k+1]/2\big)}{\Gamma(k/2)} \frac{1}{\sqrt{k\pi}} \frac{1}{(1+x^2/k)^{(k+1)/2}}, \tag{A.23}$$

where Γ is the gamma function defined by (A.22).

LEMMA A.7 (Student's t-Distribution) *Let Z be a random variable with a standardized normal distribution and let U be an independent random variable with a chi-square distribution with k degrees of freedom. Then the random variable*

$$X = \frac{Z}{\sqrt{U/k}} \tag{A.24}$$

has a Student's t-distribution with k degrees of freedom, $stu(x \mid k)$.

Let $X_1, X_2, \ldots, X_n$ be a random sample from a normal probability density function with mean μ and variance σ^2. Define

$$Z = \frac{(\bar{X} - \mu)}{\sigma/\sqrt{n}} \tag{A.25}$$

$$U = \left(\frac{1}{\sigma^2}\right) \sum_{i=1}^{n} (X_i - \bar{X})^2. \tag{A.26}$$

Then, from Lemma A.4, it is easy to see that Z has a standardized normal distribution and, from Corollary A.6, U has a chi-square distribution with $n-1$ degrees of freedom.

LEMMA A.8 (Independence of Z and U) *The random variables Z defined by* (A.25) *and U defined by* (A.26) *are independent.*

Because Z and U are independent by Lemma A.8, from Lemma A.7 it follows that

$$\frac{(\bar{X} - \mu)/(\sigma/\sqrt{n})}{\sqrt{(1/\sigma^2)\sum_{i=1}^{n}(X_i - \bar{X})^2/(n-1)}} = \frac{\sqrt{n(n-1)}(\bar{X} - \mu)}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2}} \tag{A.27}$$

has a Student's t-distribution with $n-1$ degrees of freedom, $stu(x \mid n-1)$.

A.3.3 CONFIDENCE INTERVALS

Before formally defining a confidence interval, we illustrate the subject of confidence intervals through an example.

Example A.3 (Illustration of Confidence Intervals) Suppose that we would like to estimate the mean μ of a normal distribution with known standard deviation $\sigma = 1$. We can sample from the distribution and construct the sample mean $\bar{X}$ as an estimate of the unknown mean μ. However, often we are more interested in constucting an interval that is guaranteed to cover the unknown mean μ with specified probability even though we do not know what the fixed value of μ is. For example, we may be interested in the interval that gives a probability of 0.9554 of covering the unknown mean μ. In order to do this, observe that, for a sample of size n, the random variable

$$Z = \frac{\bar{X} - \mu}{\sigma/\sqrt{n}} = \frac{\bar{X} - \mu}{1/\sqrt{n}} \tag{A.28}$$

has a standardized normal distribution. Now from the probability tables we know that

$$P[-2 < Z < 2] = \int_{-2}^{2} \frac{1}{\sqrt{2\pi}} e^{-x^2/2} = 0.9554 \tag{A.29}$$

to four decimal places. Substituting (A.28) into (A.29) we obtain

$$\begin{aligned} 0.9554 \;&=\; P[-2 < Z < 2] = P\left[-2 < \frac{\bar{X} - \mu}{1/\sqrt{n}} < 2\right] \\ &=\; P\left[\bar{X} - 2/\sqrt{n} < \mu < \bar{X} + 2/\sqrt{n}\right]. \end{aligned} \tag{A.30}$$

In particular, for $n = 100$,

$$P\left[\bar{X} - 0.2 < \mu < \bar{X} + 0.2\right] = 0.9554 \tag{A.31}$$

Then $P[\bar{X} - 0.2 < \mu < \bar{X} + 0.2] = 0.9554$ measures our "confidence" that the unknown true mean lies in the *open interval* $(\bar{X} - 2/\sqrt{n}, \bar{X} + 2/\sqrt{n})$, which is called the 95.54% confidence interval. Notice that the interval $(\bar{X} - 0.2, \bar{X} + 0.2)$ is a random interval that covers the unknown true mean μ with probability 0.9554. That is, if random samples of size 100 were repeatedly drawn from the population and the random intervals $(\bar{X} - 0.2, \bar{X} + 0.2)$ repeatedly computed, then the fraction of times that the interval actually covered the mean would approach 0.9554 as the number of repetitions tends toward infinity. At this point we would also like to point out that often a particular realization of an interval (i.e., for one sample size of 100) is also called a *confidence interval for estimating* μ.

We now formalize the definition of a confidence interval.

Definition (Confidence Interval, Confidence Limit, Confidence Level): Let $X_1, X_2, \ldots, X_n$ be a random sample from a probability density function $f(x; \theta)$ parameterized by a constant θ whose unknown value we wish to estimate. Let $L \leq H$, where $L = L(X_1, X_2, \ldots, X_n)$, $H = H(X_1, X_2, \ldots, X_n)$, be statistics for θ such that $P[L < \theta < H] = \gamma$ where γ does not depend on θ. Then (L, H) is defined to be a 100γ *percent confidence interval* for θ and γ is called

the *confidence level*. Furthermore, the random variable L is called the *lower confidence limit* and the random variable H is called the *upper confidence limit* for θ. A particular realization (l, h) of (L, H) is also called a 100γ *percent confidence interval* for estimating θ. In a similar manner one can define upper and lower *one-sided confidence intervals*.

In order to derive a confidence interval for estimating the unknown mean μ of a distribution whose variance is also unknown, we note that

$$\frac{(\bar{X} - \mu)/(\sigma/\sqrt{n})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2/(n-1)\sigma^2}} = \frac{\bar{X} - \mu}{S_{\bar{X}}^2/\sqrt{n}}$$

has a Student's t-distribution with $(n-1)$ degrees of freedom, $stu(x \mid n-1)$. For some choice of q_1 and q_2, typically $q_1 = q_2$, let

$$P\left[-q_1 < \frac{\bar{X} - \mu}{S_{\bar{X}}^2/\sqrt{n}} < q_2\right] = \gamma.$$

Then $\left(\bar{X} - q_2(S_{\bar{X}}^2/\sqrt{n}), \bar{X} + q_1(S_{\bar{X}}^2/\sqrt{n})\right)$ is a 100γ percent confidence interval for μ.

In a similar manner we can derive a confidence interval for estimating the unknown variance σ^2 of a distribution whose mean is also unknown. In order to do this we note that

$$\frac{\sum_{i=1}^{n}(X_i - \bar{X})^2}{\sigma^2} = \frac{(n-1)S_{\bar{X}}^2}{\sigma^2}$$

has a chi-square distribution with $n-1$ degrees of freedom, $f(x \mid n-1)$. For some choice of q_1 and q_2, let

$$P\left[q_1 < \frac{(n-1)S_{\bar{X}}^2}{\sigma^2} < q_2\right] = \gamma.$$

Then $\left((n-1)S_{\bar{X}}^2/q_2, (n-1)S_{\bar{X}}^2/q_1\right)$ is a 100γ percent confidence interval for the variance σ^2.

A.4 NOTES & SELECTED BIBLIOGRAPHY

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