

1 Probability Theory

1.1 Some ole' Binomial

1.1.1 Expected value and variance of Binomial

Theorem 1.1. Let $X \approx \text{Bin}(n, p)$, then the expected value and variance is given by

1. $\mathbb{E}(X) = np$,
2. $\text{Var}(X) = np(1 - p)$.

1.1.2 Binomial approx to Poisson

Theorem 1.2. For $\lambda = np$,

$$\lim_{n \rightarrow \infty} \binom{n}{k} p^k (1-p)^{n-k} = \frac{\lambda^k}{k!} e^{-\lambda}$$

First, we need the following lemma

Lemma 1.1. Let $\Gamma(x) = \int_0^\infty t^{x-1} e^{-t} dt$ be the Gamma function, then the following equation holds

$$\lim_{n \rightarrow \infty} \frac{\binom{n}{k}}{n^k} = \frac{1}{k!}.$$

Proof of Lemma 1.1. Note first that

$$\Gamma(k+1) = k\Gamma(k) = \cdots = k!\Gamma(1) = k!.$$

and Stirling's Formula for Gamma function states that

$$\Gamma(x+1) = \sqrt{2\pi x} x^x e^{-x} \left(1 + \frac{1}{12x} \cdots\right).$$

Then we have

$$\begin{aligned} \lim_{n \rightarrow \infty} \frac{\binom{n}{k}}{n^k} &= \lim_{n \rightarrow \infty} \frac{n!}{n^k (n-k)! k!} \\ &= \lim_{n \rightarrow \infty} \frac{\Gamma(n+1)}{n^k \Gamma(n-k+1) \Gamma(k+1)} \\ &= \frac{1}{\Gamma(k+1)} \lim_{n \rightarrow \infty} \sqrt{\frac{n}{n-k}} \left(\frac{n}{e}\right)^n \left(\frac{e}{n-k}\right)^{n-k} \frac{1}{n^k}. \end{aligned}$$

Where we used the first order of Stirling's Formula for Gamma function in the last equality.

Next, we only need to prove the limit equals to 1:

$$\begin{aligned} \lim_{n \rightarrow \infty} \sqrt{\frac{n}{n-k}} \left(\frac{n}{e}\right)^n \left(\frac{e}{n-k}\right)^{n-k} \frac{1}{n^k} &= \lim_{n \rightarrow \infty} \sqrt{\frac{n}{n-k}} \frac{1}{e^k} \frac{(1-k/n)^k}{(1-k/n)^n} \\ &= 1, \end{aligned}$$

since

$$\begin{aligned} \sqrt{\frac{n}{n-k}} &\rightarrow 1, \\ (1-k/n)^k &\rightarrow 1, \\ (1-k/n)^n &\rightarrow e^{-k}, \end{aligned}$$

as $n \rightarrow \infty$. ■

Now we may prove the main theorem

Proof of Theorem 1.2. Let $p = \lambda/n$ and fix k , we have

$$\begin{aligned}
\lim_{n \rightarrow \infty} \frac{\binom{n}{k}}{n^k} &= \lim_{n \rightarrow \infty} \binom{n}{k} \left(\frac{\lambda}{n}\right)^k \left(1 - \frac{\lambda}{n}\right)^{n-k} \\
&= \lim_{n \rightarrow \infty} \frac{n^k}{k!} \left(\frac{\lambda}{n}\right)^k \left(1 - \frac{\lambda}{n}\right)^{n-k} \quad \text{by Lemma 1.1} \\
&= \frac{\lambda^k}{k!} \left[\lim_{n \rightarrow \infty} \left(1 - \frac{\lambda}{n}\right)^n \right] \underbrace{\left[\lim_{n \rightarrow \infty} \left(1 - \frac{\lambda}{n}\right)^{-k} \right]}_{=1} \\
&= \frac{\lambda^k}{k!} e^{-\lambda}.
\end{aligned}$$

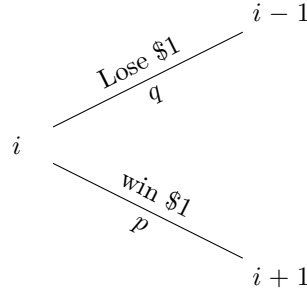
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1.2 Markov Chain

Theorem 1.3 (Gambler's ruin). *Let p is the probability of winning \$1 and $q = 1 - p$ is the probability of losing \$1. Suppose that a person starts with \$ i amount of money where $0 < i < N$ and $N \in \mathbb{N}$ is the number he would want to walk away with. The probability of him winning from this starting position is given by the following equation:*

$$a_i = \begin{cases} \frac{1 - \left(\frac{q}{p}\right)^i}{1 - \left(\frac{q}{p}\right)^N} & \text{where } p \neq q, \\ \frac{i}{N} & \text{where } p = q = \frac{1}{2}. \end{cases}$$

Proof. Note that



Then, we observe

$$\begin{aligned}
a_i &= pa_{i+1} + qa_{i-1} \\
\underbrace{(p+q)}_{=1} a_i &= pa_{i+1} + qa_{i-1} \\
a_{i+1} - a_i &= \frac{q}{p}(a_i - a_{i-1}).
\end{aligned}$$

Denote $b_j := a_i - a_{i-1}$ and note that $b_1 = a_1$ since $a_0 = 0$ is the absorption edge, we deduce by recursion that

$$b_{i+1} = \left(\frac{q}{p}\right)^{i+1} a_1.$$

Moreover, note that

$$\begin{aligned}
a_{i+1} - a_1 &= \sum_{k=1}^i a_{k+1} - a_k \\
&= \sum_{k=1}^i \left(\frac{q}{p}\right)^k a_1. \\
\Rightarrow a_{i+1} &= a_1 \left(1 + \sum_{k=1}^i \left(\frac{q}{p}\right)^k\right) \\
&= a_1 \left(\sum_{k=0}^i \left(\frac{q}{p}\right)^k\right).
\end{aligned}$$

If $p \neq q$, by geometric series, we obtain

$$a_{i+1} = a_1 \frac{1 - \left(\frac{q}{p}\right)^{i+1}}{1 - \left(\frac{q}{p}\right)}.$$

If $p = q = 0.5$, then

$$a_{i+1} = a_1(i+1).$$

Now to solve for a_1 , observe that since at absorption point $a_N = 1$, then letting $i+1 = N$, we get

$$1 = a_N = \begin{cases} a_1 \frac{1 - \left(\frac{q}{p}\right)^N}{1 - \left(\frac{q}{p}\right)} & \text{where } p \neq q, \\ a_1 N & \text{where } p = q = \frac{1}{2}, \end{cases}$$

which implies

$$a_1 = \begin{cases} \frac{1 - \left(\frac{q}{p}\right)^N}{1 - \left(\frac{q}{p}\right)} & \text{where } p \neq q, \\ \frac{1}{N} & \text{where } p = q = \frac{1}{2}. \end{cases}$$

Substituting this back, we obtained the desired equation. ■

Corollary 1.1. *The expectation of stopping time with respect to Brownian motion, i.e. $\tau = \inf\{t \geq 0 : B_t \in \{-\alpha, \beta\}\}$, for any positive integer α and β is given by*

$$\mathbb{E}[\tau] = \alpha\beta.$$

Proof. From Theorem (1.3) we observe that $\Pr(B_\tau = b) = \frac{a}{a+b}$. Then, note that since $1 = \Pr(B_\tau = -\alpha) + \Pr(B_\tau = \beta)$, we have

$$\Pr(B_\tau = -\alpha) = \frac{b}{a+b}.$$

Since $(B_t^2 - t)_{t \geq 0}$ is a martingale, we by apply Optimal Stopping Theorem where

$$0 = \mathbb{E}[B_0^2 - 0] = \mathbb{E}[B_\tau^2 - \tau],$$

which implies

$$\mathbb{E}[\tau] = \mathbb{E}[B_\tau^2] = \alpha^2 \Pr(B_\tau = -\alpha) + \beta^2 \Pr(B_\tau = \beta) = \alpha\beta. \quad \blacksquare$$

2 Financial Mathematics

2.1 Girsanov Theorem

Theorem 2.1. Denote

$$\eta_t := \exp\left(-\int_0^t \lambda(u) dW^{\mathbb{P}}(u) - \frac{1}{2} \int_0^t \lambda^2(u) du\right),$$

where $W^{\mathbb{P}}(t)$ is Wiener process under \mathbb{P} and $\lambda(t)$ is \mathcal{F}_t -measurable to be chosen. Then we can have the following Wiener process under arbitrage-free Wiener process $W^{\mathbb{Q}}(t)$ defined by

$$W^{\mathbb{Q}}(t) = W^{\mathbb{P}}(t) + \int_0^t \lambda(u) du.$$

The measure \mathbb{Q} is defined by

$$\mathbb{Q}[A] = \int_A \eta_t dP,$$

where $A \in \mathcal{F}_t$.

Thus, choosing $\lambda(t) = \frac{\mu-r}{\sigma}$, the discounted risk neutral process can be expressed as

$$\begin{aligned} \frac{dS_t}{B_t} &= (\mu - r) dt + \sigma dW^{\mathbb{P}} \\ &= (\mu - r) dt + \sigma [dW^{\mathbb{Q}} - \lambda(t) dt] \\ &= \sigma dW^{\mathbb{Q}}, \end{aligned}$$

which is a Martingale.

Remark 2.1. Since choice of $\lambda(t)$ is unique here to generate a Martingale process, \mathbb{Q} is known as unique equivalent martingale (EMM) which equals to say that \mathbb{Q} is a risk-neutral measure.

3 Time Series

3.1 Stationary and Autocorrelation

Definition 3.1. The *autocovariance*

$$\gamma(s, t) := \mathbb{E}[(x_s - \mu_s)(x_t - \mu_t)],$$

and *cross-covar.*

$$\rho_{x,y}(s, t) := \mathbb{E}[(x_s - \mu_{xs})(y_t - \mu_{ts})].$$

Definition 3.2. The *autocorrelation function* (ACF) is defined as

$$\rho_x(s, t) := \frac{\gamma(s, t)}{\sqrt{\gamma(s, s)\gamma(t, t)}},$$

Notation: $\rho_x(t, t + h) \equiv \rho(h)$.

Definition 3.3 (Strictly stationary). For all $k \in \mathbb{N}$, $t_k \in \mathbb{N}$ and $c_k \in \mathbb{R}$. Then the time series is strictly stationary if

$$\mathbb{P}(x_{t_1} \leq c_1, \dots, x_{t_k} \leq c_k) = \mathbb{P}(x_{t_1+h} \leq c_1, \dots, x_{t_k+h} \leq c_k),$$

for given probability measure \mathbb{P} and constant $h \in \mathbb{N}$.

Definition 3.4 (Weakly stationary). The time series is strictly stationary if

1. $\mu_t = \mathbb{E}[x_t]$ is constant, and
2. $\gamma(s, t)$ depends only on $|s - t|$.

Lemma 3.1. Assume time series is weakly stationary. Using the notation $\gamma(t, t + h) \equiv \gamma(h)$, we have

1. $|\gamma(t)| \leq \gamma(0)$,
2. $\gamma(h) = \gamma(-h)$.

Proof. 1. By Cauchy-Schwarz inequality $|\gamma(t, t + h)|^2 \leq \gamma(t, t)\gamma(t + h, t + h)$ by definition $|\gamma(h)|^2 \leq \gamma(0)\gamma(0)$.

2. From definition of covariance we have

$$\begin{aligned} \gamma(h) &= \gamma(t + h - t) \\ &= \mathbb{E}[(x_{t+h} - \mu)(x_t - \mu)] \\ &= \mathbb{E}[(x_t - \mu)(x_{t+h} - \mu)] \\ &= \gamma(t - (t + h)) = \gamma(-h) \end{aligned}$$

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Example 3.1. Suppose w_t for all $t \in \mathbb{N}$ is white noise process, i.e. iid $w_t \approx N(0, \sigma_w^2)$. Given two series

$$\begin{aligned} x_t &= w_t + w_{t-1}, \\ y_t &= w_t - w_{t-1}. \end{aligned}$$

Then for any $h \in \mathbb{N}$, we get the following for (cross-)covariance:

1.

$$\begin{aligned}
\gamma_x(0) &= \mathbb{E}[(w_t + w_{t-1})^2] = \mathbb{E}[w_t^2] + \mathbb{E}[w_{t-1}^2] + 2 \underbrace{\mathbb{E}[w_t w_{t-1}]}_{=0} \\
&= 2\sigma_w^2, \\
\gamma_y(0) &= \mathbb{E}[(w_t - w_{t-1})^2] = \mathbb{E}[w_t^2] + \mathbb{E}[w_{t-1}^2] - 2 \underbrace{\mathbb{E}[w_t w_{t-1}]}_{=0} \\
&= 2\sigma_w^2.
\end{aligned}$$

2.

$$\begin{aligned}
\gamma_x(1) &= \mathbb{E}[(w_t + w_{t-1})(w_{t+1} + w_t)] \\
&= \mathbb{E}[w_t w_{t+1}] + \mathbb{E}[w_t^2] + \mathbb{E}[w_{t-1} w_{t+1}] + \mathbb{E}[w_{t-1} w_t] \\
&= \sigma_w = \gamma_x(-1), \\
\gamma_y(1) &= \mathbb{E}[w_t w_{t+1}] - \mathbb{E}[w_t^2] + \mathbb{E}[w_{t-1} w_{t+1}] - \mathbb{E}[w_{t-1} w_t] \\
&= -\sigma_w = \gamma_y(-1).
\end{aligned}$$

3. $\gamma_{xy}(0) = \mathbb{E}[w_t^2] - \mathbb{E}[w_{t-1}^2] = 0$ and $\gamma_{xy}(1) = \text{cov}(x_{t+1}, y_t) = -\sigma_w^2$ and $\gamma_{xy}(-1) = \text{cov}(x_t, y_{t-1}) = -\sigma_w^2$

4. ACF

$$\rho_{xy}(h) = \begin{cases} 0 & h = 0, \\ 1/2 & h = 1, \\ -1/2 & h = -1, \\ 0 & |h| \geq 2 \end{cases} \quad (3.1)$$

Thus the joint time series is stationary.

Definition 3.5 (Linear Process). $\{x_t\}$ is linear process if

$$x_t = \mu + \sum_{j=-\infty}^{\infty} \psi_j w_{t-j}, \quad \sum_{j=-\infty}^{\infty} |\psi_j| < \infty,$$

where w_t is white noise.

Definition 3.6 (Gaussian Process). $\{x_t\}$ is Gaussian process if the vector $x := (x_{t_1}, x_{t_2}, \dots, x_{t_n})' \in \mathbb{R}^n$ has a multivariate normal distribution with density function

$$f(x) = \frac{1}{(2\pi)^{n/2}} \det(\Gamma)^{-1/2} \exp\left(-\frac{1}{2}(x - \mu)' \Gamma^{-1} (x - \mu)\right),$$

where $\mu \in \mathbb{R}^n$ and $\Gamma := \text{var}(x) = \{\gamma(t_i, t_j); i, j = 1, \dots, n\}$.

3.1.1 ARIMA

$ARMA(p, q)$:

$$x_t - \phi_1 x_{t-1} - \dots - \phi_p x_{t-p} = w_t + \theta_1 w_{t-1} + \dots + \theta_q w_{t-q}.$$

3.2 Autoregressive Model

Definition 3.7 ($AR(p)$). Let w_t be white noise, $AR(p)$ is defined as

$$x_t - \phi_1 x_{t-1} - \cdots - \phi_p x_{t-p} = w_t.$$

Definition 3.8 (Autoregressive Operator). Let B be time-lagged operator, i.e. $Bx_t = x_{t-1}$, the autoregressive operator is defined as

$$\phi(B) = 1 - \phi_1 B - \phi_2 B^2 - \cdots - \phi_p B^p.$$

Example 3.2. Assuming $\phi_j = \phi$ for all $j \in \mathbb{N}$, from $AR(1)$

$$\begin{aligned} x_t &= \phi x_{t-1} + w_t = \phi(\phi x_{t-2} + w_{t-1}) + w_t \\ &= \phi^2 x_{t-2} + \phi w_{t-1} + w_t \\ &\vdots \\ &= \phi^k x_{t-k} + \sum_{j=0}^{k-1} \phi^j w_{t-j}. \end{aligned}$$

Thus, if $|\phi| < 1$ and x_t is stationary then for large $k \rightarrow \infty$, we have

$$x_t = \sum_{j=0}^{\infty} \phi^j w_{t-j}.$$

Taking expectation value,

$$\mathbb{E}[x_t] = \sum_{j=0}^{\infty} \phi^j \mathbb{E}[w_t] = 0.$$

Moreover, for $h \geq 0$ the autocovariance function is

$$\begin{aligned} \gamma(h) &= \mathbb{E} \left[\left(\sum_{j=0}^{\infty} \phi^j w_{t+h-j} \right) \left(\sum_{k=0}^{\infty} \phi^k w_{t-k} \right) \right] \\ &= \mathbb{E} [(w_{t+h-1} + \phi w_{t+h-2} + \cdots + \phi^h w_t + \phi^{h+1} w_{t-1} + \cdots)(w_t + \phi w_{t-1} + \cdots)] \\ &= \sigma_w^2 \sum_{j=0}^{\infty} \phi^{h+j} \phi^j = \sigma_w^2 \phi^h \sum_{j=0}^{\infty} \phi^{2j} \\ &= \frac{\sigma_w^2 \phi^h}{1 - \phi^2}. \end{aligned}$$

And ACF is

$$\rho(h) = \frac{\gamma(h)}{\gamma(0)} = \phi^h.$$

As well as

$$\rho(h) = \phi \rho(h-1).$$

Definition 3.9. The *moving average operator* is defined as

$$\theta(B) := 1 + \theta_1 B + \theta_2 B^2 + \cdots + \theta_q B^q.$$

4 Operational Research

4.1 Safety Stock

Theorem 4.1. *Let the lead-time T be normally distributed, i.e. $T \sim N(\mu_\ell, \sigma_\ell^2)$ and denote the set of demand of period i as $\{D_i\}_{i=1}^T$ where $D_i \sim N(\mu_d, \sigma_d^2)$ for each $1 \leq i \leq T$. Then the safety stock level, SS satisfies the following equation*

$$SS = z_\alpha \sqrt{\sigma_d^2 \mu_\ell + \mu_d^2 \sigma_\ell^2},$$

where z_α is the Z-value of a desired α which is chosen.

Proof. Denote the demand between within lead-time as $D(T) := \sum_{i=1}^T D_i$. The safety stock level is then set at

$$SS = z_\alpha \sqrt{\text{Var}(D(T))}.$$

Thus we need only to prove $\text{Var}(D(T))$.

From Towering-property, note that

$$\begin{aligned} \mathbb{E}[D(T)] &= \mathbb{E}[\mathbb{E}[D(T)|T]] \\ &= \mathbb{E}[T\mu_d] = \mu_d \mathbb{E}[T] = \mu_d \mu_\ell. \end{aligned}$$

Furthemore, again with Towering-property, we have

$$\begin{aligned} \mathbb{E}[D^2(T)] &= \mathbb{E}[\mathbb{E}[D^2(T)|T]] \\ &= \mathbb{E}[\text{Var}[D(T)|T] + (\mathbb{E}[D(T)|T])^2] \\ &= \mathbb{E}[T\sigma_d^2 + (T\mu_d)^2] \\ &= \sigma_d^2 \mathbb{E}[T] + \mu_d^2 \mathbb{E}[T^2] \\ &= \sigma_d^2 \mu_\ell + \mu_d^2 (\text{Var}(T) + (\mathbb{E}[T])^2) \\ &= \sigma_d^2 \mu_\ell + \mu_d^2 (\sigma_\ell^2 + \mu_\ell^2). \end{aligned}$$

Finally,

$$\begin{aligned} \text{Var}(D(T)) &= \mathbb{E}[D^2(T)] - (\mathbb{E}[D(T)])^2 \\ &= \sigma_d^2 \mu_\ell + \mu_d^2 (\sigma_\ell^2 + \mu_\ell^2) - (\mu_d \mu_\ell)^2 \\ &= \sigma_d^2 \mu_\ell + \mu_d^2 \sigma_\ell^2. \end{aligned}$$

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