Exam for Stochastic models in Discrete time 3.75 ECTS

Master's program of Financial Mathematics
January 10, 2008, 9.00 – 13.00

Max number of points: 30.
Halmstad University grading bounds: 12p ⇒ grade 3, 18p⇒ grade 4, 24p ⇒ grade 5.
ECTS bounds: 12p ⇒ grade E, 15p ⇒ grade D, 18p ⇒ grade C, 21p ⇒ grade B, 24p ⇒ grade A.
Allowed aids: Summary of formulae attached to the exam, calculator and dictionary.
Examiner: Eric Järpe (035-16 76 53, 0702-822 844).

For each problem a *complete* solution should be given. All solutions should be thoroughly presented. Each solution should start at the top of a new sheet of paper. Only one solution a sheet.
The proper solutions will be available on the internet at `http://www.hh.se/staff/erja` → `Teaching` → `Financial Mathematics` → `Stochastic models` → `Previous exams`

1. Let $\mathbb{C}_*$ be the lower price of hedging against some non-negative $\mathcal{F}_N$-measurable function f_N. Prove that if a contract is bought for a price less than $\mathbb{C}_*$, then there exists arbitrage for the buyer. (4p)

2. Assume that $\{h_n : n \in \mathbb{Z}\}$ is an $AR(2)$ process with coefficients $a_0 = 1$, $a_1 = -\frac{1}{2}$, $a_2 = \frac{1}{4}$ and white noise variance $\sigma_\epsilon^2 = \frac{5}{16}$. Calculate
   (a) $C(h_n, h_{n+3})$. (3p)
   (b) $P(h_n - h_{n+1} < 1)$. (4p)

3. Let $\{X_n\}$ be a *simple random walk*, i.e. $X_0 = 0$ and $P(X_{n+1} = x + 1 \,|\, X_n = x) =$ $= P(X_{n+1} = x - 1 \,|\, X_n = x) = \frac{1}{2}$.
   (a) Calculate $E(X_3^4)$. (3p)
   (b) Show that $\{X_n\}$ is not stationary. (4p)

4. Assume $\{M_n\}$ is a martingale with respect to the filtration $\{\mathcal{F}_n\}$. Prove that $E(e^{M_{n+1}-M_n} \,|\, \mathcal{F}_n) \geq 1$. (4p)

5. Assume that $\{X_n : n \in \mathbb{Z}^+\}$ is a stochastic volatility model of order $p = 1$ with $|a_1| < 1$. Assume that $\Delta_0 \in N(\frac{a_0}{1-a_1}, \frac{c^2}{1-a_1^2})$.
   (a) Prove that $E(e^{c\delta_n}) = e^{c^2/2}$ for any $n \in \mathbb{Z}$. (4p)
   (b) Calculate $E(X_1^2)$. (4p)

GOOD LUCK!

Some rules of Probability and Statistics

Def P is a **probability measure** if
1. $0 \le P(A) \le 1$
2. $P(\Omega) = 1$
3. $A \cap B = \emptyset \;\Rightarrow\; P(A \cup B) = P(A) + P(B)$

for all events $A \subset \Omega$ where Ω is the sample space.

Def Suppose Ω is a sample space, $\mathcal{F}$ is some σ-algebra of subsets of Ω, and that P is a probability measure on $(\Omega, \mathcal{F})$. Then $(\Omega, \mathcal{F}, P)$ is called **probability space** and if $\mathbb{F} = \{\mathcal{F}_n\}_{n\ge 0}$ is an increasing sequence of σ-algebras (i.e. $\mathcal{F}_m \subseteq \mathcal{F}_n \subseteq \mathcal{F}$ when $m \le n$), then $\mathbb{F}$ is called a **flow** and $(\Omega, \mathcal{F}, \{\mathcal{F}_n\}, P)$ is a **stochastic basis**.

Addition theorem $P(A \cup B) = P(A) + P(B) - P(A \cap B)$.

Def A and B are **independent events** if $P(A \cap B) = P(A)P(B)$

Def The **conditional probability of** A **given** B is $P(A|B) = \dfrac{P(A \cap B)}{P(B)}$

Bayes theorem If $A_1, \dots, A_n$ is a partition of Ω (i.e. $i \ne j \Rightarrow A_i \cap A_j = \emptyset$ and $\bigcup_{i=1}^n A_i = \Omega$).

then $P(A_k|B) = \dfrac{P(B|A_k)P(A_k)}{\sum_{i=1}^n P(B|A_i)P(A_i)}$ for each $k = 1, 2, \dots, n$.

Random variables

X discrete: **Probability fcn**: $p(x) = P(X = x)$
Distribution fcn: $P(X \le a) = F(a) = \sum_{x \le a} p(x)$,

X continuous: **Density fcn**: $f(x) = \frac{d}{dx} P(X \le x)$
Distribution fcn: $P(X \le a) = F(a) = \int_{-\infty}^{a} f(x)\, dx$.

Def $\{X_t\} = \{X_t : t \in T \subseteq \mathbb{R}\}$ is a **random process** if all variables $X_t, t \in T$ have the same probability distribution regardless of t. T is called **index space**.
A stochastic sequence $\{X_n, \mathcal{F}_n\}$ is a
martingale if $E(X_n \,|\, \mathcal{F}_{n-1}) \overset{P-a.s.}{=} X_{n-1}$ and $E(|X_n|) < \infty$
supermartingale if $E(X_n \,|\, \mathcal{F}_{n-1}) \overset{P-a.s.}{\le} X_{n-1}$ and $E(|X_n|) < \infty$
submartingale if $E(X_n \,|\, \mathcal{F}_{n-1}) \overset{P-a.s.}{\ge} X_{n-1}$ and $E(|X_n|) < \infty$

Expected value and variance

X discrete:

The **expected value** of X: $\mu = E(X) = \sum_{x\in\Omega} x\, p(x)$.
Variance of X: $\sigma^2 = D(X) = \sum_{x\in\Omega}(x-\mu)^2\, p(x)$.

X continuous:

Expected value of X: $\mu = E(X) = \int_{x\in\Omega} x\, f(x)\, dx$.
Variance of X: $\sigma^2 = D(X) = \int_{x\in\Omega}(x-\mu)^2\, f(x)\, dx$.

Skewness of X: $\gamma_1 = S(X) = \frac{E((X-\mu)^3)}{E((X-\mu)^2)^{3/2}}$

Kurtosis of X: $\gamma_2 = K(X) = \frac{E((X-\mu)^4)}{E((X-\mu)^2)^2} - 3$

$\gamma_2 > 0 \Rightarrow X$ is **leptokurtic** (heavy tails)
$\gamma_2 = 0 \Rightarrow X$ is **mesokurtic**
$\gamma_2 < 0 \Rightarrow X$ is **platykurtic** (light tails)

Covariance of X and Y: $C(X,Y) = E((X-\mu_x)(Y-\mu_y))$
Correlation of X and Y: $\rho = \frac{C(X,Y)}{\sqrt{D(X)D(Y)}}$

Standarddev. $\sigma = \sqrt{D(X)}$.

Linearity: $E(aX+bY) = a\,E(X) + b\,E(Y)$ for all random variables X and Y and real numbers a and b.
If X, Y indep. then $D(aX+bY) = a^2 D(X) + b^2 D(Y)$.

Rules:
$E(g(X)) = \int_{\mathbb{R}} g(x)\, f(x)\, dx$
$E(X|A) = E(X \cdot I(A))$
$D(X) = E(X^2) - (E(X))^2$
$C(X,Y) = \int\int_{\mathbb{R}^2} xy\, f(x,y) - E(X)E(Y)$
$C(\sum_i a_i X_i, \sum_k b_k Y_k) = \sum_i \sum_k a_i b_k C(X_i, Y_k)$

Normal distribution denoted by $N(\mu,\sigma)$ where μ is the expected value and σ is the standard deviation
$N(0,1)$ is called **standard normal distribution** with density function $\Phi(x)$
If $X \in N(\mu,\sigma)$ then $P(X \le x) = \Phi\left(\frac{x-\mu}{\sigma}\right)$
Symmetry: $\Phi(-x) = 1 - \Phi(x)$
Probabilities: $P(a \le X \le b) = \Phi\left(\frac{b-\mu}{\sigma}\right) - \Phi\left(\frac{a-\mu}{\sigma}\right)$

Def The random variables $X_1, X_2, \ldots, X_n$ are a **sample** of X if all variables, X_i, is distributed as X, $i = 1, \ldots, n$, and all variables are independent of each other at all levels.

CLT *Central Limit Theorem*

If $X_1, \ldots, X_n$ is a sample where
$E(X_i) = \mu$ and $D(X_i) = \sigma^2$, $i = 1, \ldots, n$

then $P\left(\frac{\sqrt{n}}{\sigma}(\bar{X} - \mu) \le x\right) \to \Phi(x)$ as $n \to \infty$.
This implies that $\sum_{i=1}^n X_i$ is approximately $N(n\mu, \sqrt{n}\,\sigma)$
and $\bar{X}$ is approximately $N(\mu, \sigma/\sqrt{n})$ for large n.

Thm If $\{X_t\}$ has independent, stationary increments and $X_0 = 0$
then $R_X(s,t) = \min(s,t) \cdot D(X_1)$.

Thm *Fatou lemma*
$X_n \geq 0 \;\Rightarrow\; E(\liminf X_n) \leq \liminf E(X_n)$

Thm *Dominated-convergence theorem*
If $\exists\, C < \infty : |X_n| < C$ for all n and $\exists \lim_{n\to\infty} X_n$, then $\lim_{n\to\infty} E(X_n) = E(\lim_{n\to\infty} X_n)$.

Def **White noise** in discrete time is a sequence $\{\epsilon_n\}_{n=-\infty}^{\infty}$ of independent random variables, ϵ_n, such that $E(\epsilon_n) = 0$ and $D(\epsilon_n) = \sigma_\epsilon^2$.
Let the **lag operator** L be defined by $L^k(X_n) = X_{n-k}$ and let α and β be the polynomials $\alpha(z) = 1 - \sum_{k=1}^{p} a_k z^k$ and $\beta(z) = 1 + \sum_{k=1}^{q} b_k z^k$.

Def Let $\{X_n\} = \{X_n : n \in \mathbb{Z}\}$ be a sequence of variables and let $\{\epsilon_n\}$ be white noise such that $\epsilon_m \perp X_n$ whenever $m > n$. Then $\{X_n\}$ is an

***AR(p)* process** if $\alpha(L)X_n = a_0 + \epsilon_n$

***MA(q)* process** if $X_n = \beta(L)\epsilon_n$

***ARMA(p, q)* process** if $\alpha(L)X_n = \beta(L)\epsilon_n$

***ARIMA(p, d, q)* process** if $\{(1-L)^d X_n : n \in \mathbb{Z}\}$ is an $ARMA(p,q)$ process

for all $n \in \mathbb{Z}$.

Thm *Yule Walker equations*
For an $AR(p)$ process the covariance function is

$$R(k) - \sum_{j=1}^{p} a_j R(k-j) \;=\; \begin{cases} \sigma_\epsilon^2 & \text{for } k = 0 \\ 0 & \text{for } k = 1, 2, \ldots \end{cases}$$

Thm For an $MA(q)$ process the covariance function is

$$R(k) \;=\; \begin{cases} \sigma_\epsilon^2 \sum_{i-j=k} c_i c_j & \text{for } |k| \leq q \\ 0 & \text{for } |k| > q \end{cases}$$

Def Let $\{X_n : n \in \mathbb{Z}\}$ be a stationary random process satisfying $X_n = \sigma_n \epsilon_n$ for all n and where $\{\epsilon_n\}$ is white noise such that $\epsilon_m \perp X_n$ whenever $m > n$. Then $\{X_n\}$ is

an ***ARCH(p)* process** if $\sigma_n^2 = a_0 + \sum_{k=1}^{p} a_k X_{n-k}^2$

a ***GARCH(p, q)* process** if $\sigma_n^2 = a_0 + \sum_{k=1}^{p} a_k X_{n-k}^2 + \sum_{k=1}^{q} b_k \sigma_{n-k}^2$

a ***HARCH(p)* process** if $\sigma_n^2 = a_0 + \sum_{k=1}^{p} a_k (\sum_{j=1}^{k} X_{n-j})^2$

a **Stochastic volatility process of order *p*** if $\sigma_n^2 = e^{\Delta_n}$ and
$\Delta_n = a_0 + \sum_{k=1}^{p} a_k \Delta_{n-k} + c\delta_n$ where $\{\delta_n\}$ is white noise independent of $\{\epsilon_n\}$

for all $n \in \mathbb{Z}$. By definition all these processes are stationary.

Trigonometrics

$\cos^2\alpha + \sin^2\alpha = 1$

$\cos(\alpha+\beta) = \cos\alpha\cos\beta - \sin\alpha\sin\beta \qquad \cos\alpha = \frac{1}{2}(e^{i\alpha} + e^{-i\alpha})$

$\sin(\alpha+\beta) = \sin\alpha\cos\beta + \cos\alpha\sin\beta \qquad \sin\alpha = \frac{1}{2i}(e^{i\alpha} - e^{-i\alpha})$

Inference

Thm (Estimation of expected value)

<u>If</u> $\hat{m}_n = \frac{1}{n}\sum_{t=1}^{n} X_t$

<u>then</u> $D(\hat{m}_n) = \frac{1}{n^2}\sum_{k=-n+1}^{n-1}(n-|k|)R_X(k)$

$nD(\hat{m}_n) \approx \sum_{k=-\infty}^{\infty} R_X(k)$ for large n

Def If $\boldsymbol{X} = (X_1, \ldots, X_n)$ is a sample of the variable X distributed according to the density function $f_X(x;\theta)$, then the **likelihood function** of θ is the joint density function of $\boldsymbol{X}$, $L(\theta) = \prod_i f(x_i;\theta)$, as a function of the parameter θ. The value of θ which maximises the likelihood (or equivalently the log likelihood $\ell(\theta) = \ln L(\theta)$) is the **maximum likelihood estimator (MLE)** $\hat{\theta}$ of θ.

Def A point estimator, θ^*, of a parameter θ is **unbiased** if $E(\theta^*) = \theta$. If θ_1^* and θ_2^* are unbiased estimators of θ, then θ_1^* is **better/more efficient** than θ_2^* om $D(\theta_1^*) < D(\theta_2^*)$.

Distributions, expected values and variances

	X	$p(x), f(x)$	$E(X)$	$D(X)$
Discrete distributions	Unif(N)	$1/N$ $x = 1, 2, \ldots, N$	$(N+1)/2$	$(N^2-1)/12$
	Bin(n, p)	$\binom{n}{x} p^x(1-p)^{n-x}$ $x = 0, 1, 2, \ldots, n$	np	$np(1-p)$
	Poi(λ)	$e^{-\lambda}\lambda^x/x!$ $x = 0, 1, 2, \ldots$	λ	λ
	Geo(π)	$(1-\pi)^{x-1}\pi$ $x = 1, 2, 3, \ldots$	$1/\pi$	$(1-\pi)/\pi^2$
Cont. distributions	R(a, b)	$1/(b-a)$ $a \le x \le b$	$(a+b)/2$	$(a-b)^2/12$
	Exp(λ)	$\lambda e^{-\lambda x}$ $x > 0$	$1/\lambda$	$1/\lambda^2$
	N(μ, σ)	$(\sigma\sqrt{2\pi})^{-1}e^{-(x-\mu)^2/(2\sigma^2)}$ $x \in \mathbb{R}$	μ	σ^2

Normal distribution values

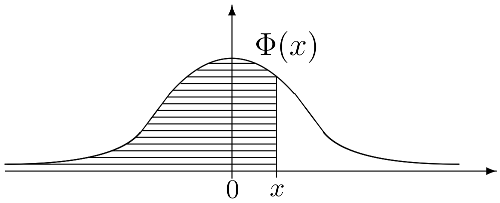

Table over values of $\Phi(x) = P(X \leq x)$ where $X \in N(0,1)$. For $x < 0$, use the relation $\Phi(x) = 1 - \Phi(-x)$.

x	+0.00	+0.01	+0.02	+0.03	+0.04	+0.05	+0.06	+0.07	+0.08	+0.09
0.0	0.5000	0.5040	0.5080	0.5120	0.5160	0.5199	0.5239	0.5279	0.5319	0.5359
0.1	0.5398	0.5438	0.5478	0.5517	0.5557	0.5596	0.5636	0.5675	0.5714	0.5753
0.2	0.5793	0.5832	0.5871	0.5910	0.5948	0.5987	0.6026	0.6064	0.6103	0.6141
0.3	0.6179	0.6217	0.6255	0.6293	0.6331	0.6368	0.6406	0.6443	0.6480	0.6517
0.4	0.6554	0.6591	0.6628	0.6664	0.6700	0.6736	0.6772	0.6808	0.6844	0.6879
0.5	0.6915	0.6950	0.6985	0.7019	0.7054	0.7088	0.7123	0.7157	0.7190	0.7224
0.6	0.7257	0.7291	0.7324	0.7357	0.7389	0.7422	0.7454	0.7486	0.7517	0.7549
0.7	0.7580	0.7611	0.7642	0.7673	0.7704	0.7734	0.7764	0.7794	0.7823	0.7852
0.8	0.7881	0.7910	0.7939	0.7967	0.7995	0.8023	0.8051	0.8078	0.8106	0.8133
0.9	0.8159	0.8186	0.8212	0.8238	0.8264	0.8289	0.8315	0.8340	0.8365	0.8389
1.0	0.8413	0.8438	0.8461	0.8485	0.8508	0.8531	0.8554	0.8577	0.8599	0.8621
1.1	0.8643	0.8665	0.8686	0.8708	0.8729	0.8749	0.8770	0.8790	0.8810	0.8830
1.2	0.8849	0.8869	0.8888	0.8907	0.8925	0.8944	0.8962	0.8980	0.8997	0.9015
1.3	0.9032	0.9049	0.9066	0.9082	0.9099	0.9115	0.9131	0.9147	0.9162	0.9177
1.4	0.9192	0.9207	0.9222	0.9236	0.9251	0.9265	0.9279	0.9292	0.9306	0.9319
1.5	0.9332	0.9345	0.9357	0.9370	0.9382	0.9394	0.9406	0.9418	0.9429	0.9441
1.6	0.9452	0.9463	0.9474	0.9484	0.9495	0.9505	0.9515	0.9525	0.9535	0.9545
1.7	0.9554	0.9564	0.9573	0.9582	0.9591	0.9599	0.9608	0.9616	0.9625	0.9633
1.8	0.9641	0.9649	0.9656	0.9664	0.9671	0.9678	0.9686	0.9693	0.9699	0.9706
1.9	0.9713	0.9719	0.9726	0.9732	0.9738	0.9744	0.9750	0.9756	0.9761	0.9767
2.0	0.9772	0.9778	0.9783	0.9788	0.9793	0.9798	0.9803	0.9808	0.9812	0.9817
2.1	0.9821	0.9826	0.9830	0.9834	0.9838	0.9842	0.9846	0.9850	0.9854	0.9857
2.2	0.9861	0.9864	0.9868	0.9871	0.9875	0.9878	0.9881	0.9884	0.9887	0.9890
2.3	0.9893	0.9896	0.9898	0.9901	0.9904	0.9906	0.9909	0.9911	0.9913	0.9916
2.4	0.9918	0.9920	0.9922	0.9925	0.9927	0.9929	0.9931	0.9932	0.9934	0.9936
2.5	0.9938	0.9940	0.9941	0.9943	0.9945	0.9946	0.9948	0.9949	0.9951	0.9952
2.6	0.9953	0.9955	0.9956	0.9957	0.9959	0.9960	0.9961	0.9962	0.9963	0.9964
2.7	0.9965	0.9966	0.9967	0.9968	0.9969	0.9970	0.9971	0.9972	0.9973	0.9974
2.8	0.9974	0.9975	0.9976	0.9977	0.9977	0.9978	0.9979	0.9979	0.9980	0.9981
2.9	0.9981	0.9982	0.9982	0.9983	0.9984	0.9984	0.9985	0.9985	0.9986	0.9986

x	+0.0	+0.1	+0.2	+0.3	+0.4	+0.5	+0.6	+0.7	+0.8	+0.9
3	0.9987	0.9990	0.9993	0.9995	0.9997	0.9998	0.9998	0.9999	0.9999	1.0000

Percentiles:

Some values of λ_α such that $P(X > \lambda_\alpha) = \alpha$ where $X \in N(0,1)$

α	λ_α	α	λ_α
0.1	1.281552	0.005	2.575829
0.05	1.644854	0.001	3.090232
0.025	1.959964	0.0005	3.290527
0.01	2.326348	0.0001	3.719016

t percentiles

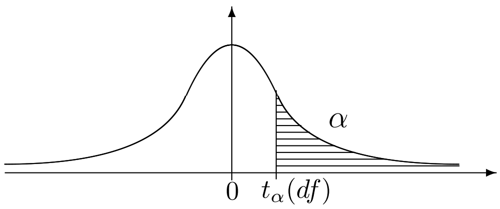

Table over values of $t_\alpha(df)$.

df \ α	0.25	0.10	0.05	0.025	0.02	0.01	0.005	0.001
1	1.0000	3.0777	6.3138	12.7062	15.8945	31.8205	63.6567	318.3088
2	0.8165	1.8856	2.9200	4.3027	4.8487	6.9646	9.9248	22.3271
3	0.7649	1.6377	2.3534	3.1824	3.4819	4.5407	5.8409	10.2145
4	0.7407	1.5332	2.1318	2.7764	2.9986	3.7470	4.6041	7.1732
5	0.7267	1.4759	2.0150	2.5706	2.7565	3.3649	4.0322	5.8934
6	0.7176	1.4398	1.9432	2.4469	2.6122	3.1427	3.7074	5.2076
7	0.7111	1.4149	1.8946	2.3646	2.5168	2.9980	3.4995	4.7853
8	0.7064	1.3968	1.8595	2.3060	2.4490	2.8965	3.3554	4.5008
9	0.7027	1.3830	1.8331	2.2622	2.3984	2.8214	3.2498	4.2968
10	0.6998	1.3722	1.8125	2.2281	2.3593	2.7638	3.1693	4.1437
12	0.6955	1.3562	1.7823	2.1788	2.3027	2.6810	3.0545	3.9296
14	0.6924	1.3450	1.7613	2.1448	2.2638	2.6245	2.9768	3.7874
17	0.6892	1.3334	1.7396	2.1098	2.2238	2.5669	2.8982	3.6458
20	0.6870	1.3253	1.7247	2.0860	2.1967	2.5280	2.8453	3.5518
25	0.6844	1.3163	1.7081	2.0595	2.1666	2.4851	2.7874	3.4502
30	0.6828	1.3104	1.6973	2.0423	2.1470	2.4573	2.7500	3.3852
50	0.6794	1.2987	1.6759	2.0086	2.1087	2.4033	2.6778	3.2614
100	0.6770	1.2901	1.6602	1.9840	2.0809	2.3642	2.6259	3.1737

χ^2 percentiles

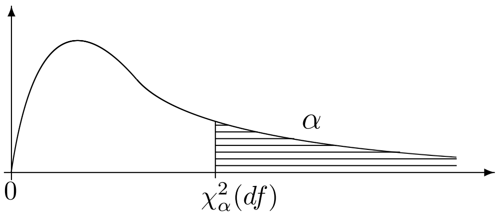

Table over values of $\chi^2_\alpha(df)$.

df \ α	0.999	0.995	0.99	0.95	0.05	0.01	0.005	0.001
1	0.0000	0.0000	0.0002	0.0039	3.8415	6.6349	7.8794	10.8276
2	0.0020	0.0100	0.0201	0.1026	5.9915	9.2103	10.5966	13.8155
3	0.0243	0.0717	0.1148	0.3518	7.8147	11.3449	12.8382	16.2662
4	0.0908	0.2070	0.2971	0.7107	9.4877	13.2767	14.8603	18.4668
5	0.2102	0.4117	0.5543	1.1455	11.0705	15.0863	16.7496	20.5150
6	0.3811	0.6757	0.8721	1.6354	12.5916	16.8119	18.5476	22.4577
7	0.5985	0.9893	1.2390	2.1673	14.0671	18.4753	20.2777	24.3219
8	0.8571	1.3444	1.6465	2.7326	15.5073	20.0902	21.9550	26.1245
9	1.1519	1.7349	2.0879	3.3251	16.9190	21.6660	23.5894	27.8772
10	1.4787	2.1559	2.5582	3.9403	18.3070	23.2093	25.1882	29.5883
12	2.2142	3.0738	3.5706	5.2260	21.0261	26.2170	28.2995	32.9095
14	3.0407	4.0747	4.6604	6.5706	23.6848	29.1412	31.3193	36.1233
17	4.4161	5.6972	6.4078	8.6718	27.5871	33.4087	35.7185	40.7902
20	5.9210	7.4338	8.2604	10.8508	31.4104	37.5662	39.9968	45.3147
25	8.6493	10.5197	11.5240	14.6114	37.6525	44.3141	46.9279	52.6197
30	11.5880	13.7867	14.9535	18.4927	43.7730	50.8922	53.6720	59.7031
50	24.6739	27.9907	29.7067	34.7643	67.5048	76.1539	79.4900	86.6608
100	61.9179	67.3276	70.0649	77.9295	124.342	135.807	140.169	149.449

Values of the Poisson distribuion

Table over values of $F(x) = P(X \leq x)$ where $X \in Po(\lambda)$.

λ	0	1	2	3	4	5	6	7	8	9	10	11	12	13
0.5	0.607	0.910	0.986	0.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1	0.368	0.736	0.920	0.981	0.996	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2	0.135	0.406	0.677	0.857	0.947	0.983	0.995	0.999	1.000	1.000	1.000	1.000	1.000	1.000
3	0.050	0.199	0.423	0.647	0.815	0.916	0.966	0.988	0.996	0.999	1.000	1.000	1.000	1.000
4	0.018	0.092	0.238	0.433	0.629	0.785	0.889	0.949	0.979	0.992	0.997	0.999	1.000	1.000
5	0.007	0.040	0.125	0.265	0.440	0.616	0.762	0.867	0.932	0.968	0.986	0.995	0.998	0.999
6	0.002	0.017	0.062	0.151	0.285	0.446	0.606	0.744	0.847	0.916	0.957	0.980	0.991	0.996

Values of the Binomial distribution

Table over values of $P(x) = P(X \leq x)$ where $X \in Bin(n, p)$.
For $p > 0.5$, use the relation $P(X \leq x) = P(Y \geq n - x)$ where $Y \in Bin(n, 1-p)$.

n	p	0	1	2	3	4	5	6	7	8	9	10
3	0.1	0.729	0.972	0.999	1.000	–	–	–	–	–	–	–
	0.2	0.512	0.896	0.992	1.000	–	–	–	–	–	–	–
	0.3	0.343	0.784	0.973	1.000	–	–	–	–	–	–	–
	0.4	0.216	0.648	0.936	1.000	–	–	–	–	–	–	–
	0.5	0.125	0.500	0.875	1.000	–	–	–	–	–	–	–
4	0.1	0.656	0.948	0.996	1.000	1.000	–	–	–	–	–	–
	0.2	0.410	0.819	0.973	0.998	1.000	–	–	–	–	–	–
	0.3	0.240	0.652	0.916	0.992	1.000	–	–	–	–	–	–
	0.4	0.130	0.475	0.821	0.974	1.000	–	–	–	–	–	–
	0.5	0.062	0.312	0.688	0.938	1.000	–	–	–	–	–	–
5	0.1	0.590	0.919	0.991	1.000	1.000	1.000	–	–	–	–	–
	0.2	0.328	0.737	0.942	0.993	1.000	1.000	–	–	–	–	–
	0.3	0.168	0.528	0.837	0.969	0.998	1.000	–	–	–	–	–
	0.4	0.078	0.337	0.683	0.913	0.990	1.000	–	–	–	–	–
	0.5	0.031	0.188	0.500	0.812	0.969	1.000	–	–	–	–	–
6	0.1	0.531	0.886	0.984	0.999	1.000	1.000	1.000	–	–	–	–
	0.2	0.262	0.655	0.901	0.983	0.998	1.000	1.000	–	–	–	–
	0.3	0.118	0.420	0.744	0.930	0.989	0.999	1.000	–	–	–	–
	0.4	0.047	0.233	0.544	0.821	0.959	0.996	1.000	–	–	–	–
	0.5	0.016	0.109	0.344	0.656	0.891	0.984	1.000	–	–	–	–
7	0.1	0.478	0.850	0.974	0.997	1.000	1.000	1.000	1.000	–	–	–
	0.2	0.210	0.577	0.852	0.967	0.995	1.000	1.000	1.000	–	–	–
	0.3	0.082	0.329	0.647	0.874	0.971	0.996	1.000	1.000	–	–	–
	0.4	0.028	0.159	0.420	0.710	0.904	0.981	0.998	1.000	–	–	–
	0.5	0.008	0.062	0.227	0.500	0.773	0.938	0.992	1.000	–	–	–
8	0.1	0.430	0.813	0.962	0.995	1.000	1.000	1.000	1.000	1.000	–	–
	0.2	0.168	0.503	0.797	0.944	0.990	0.999	1.000	1.000	1.000	–	–
	0.3	0.058	0.255	0.552	0.806	0.942	0.989	0.999	1.000	1.000	–	–
	0.4	0.017	0.106	0.315	0.594	0.826	0.950	0.991	0.999	1.000	–	–
	0.5	0.004	0.035	0.145	0.363	0.637	0.855	0.965	0.996	1.000	–	–
9	0.1	0.387	0.775	0.947	0.992	0.999	1.000	1.000	1.000	1.000	1.000	–
	0.2	0.134	0.436	0.738	0.914	0.980	0.997	1.000	1.000	1.000	1.000	–
	0.3	0.040	0.196	0.463	0.730	0.901	0.975	0.996	1.000	1.000	1.000	–
	0.4	0.010	0.071	0.232	0.483	0.733	0.901	0.975	0.996	1.000	1.000	–
	0.5	0.002	0.020	0.090	0.254	0.500	0.746	0.910	0.980	0.998	1.000	–
10	0.1	0.349	0.736	0.930	0.987	0.998	1.000	1.000	1.000	1.000	1.000	1.000
	0.2	0.107	0.376	0.678	0.879	0.967	0.994	0.999	1.000	1.000	1.000	1.000
	0.3	0.028	0.149	0.383	0.650	0.850	0.953	0.989	0.998	1.000	1.000	1.000
	0.4	0.006	0.046	0.167	0.382	0.633	0.834	0.945	0.988	0.998	1.000	1.000
	0.5	0.001	0.011	0.055	0.172	0.377	0.623	0.828	0.945	0.989	0.999	1.000