```
# basic3a.dml
#
# topology
#  client            ...            server
#             800kb  100ms
#  0(0) ---------------------------- 1(0)
#                                      |
#                                    tcpdump

_schema [ _find .schemas.Net ]

Net [

  frequency 1000000
  traffic [
    pattern [
      client 0
      servers [ port 10 nhi 1(0) ]
    ]
  ]

# ------------------------------------------------------------ LINKS

  link[attach 0(0) attach 1(0) delay 0.1]

# ------------------------------------------------------------ SERVER

  host [
   id 1
   graph [
        ProtocolSession [name server use SSF.OS.TCP.test.tcpServer port 10
                request_size 4
                show report  true
                debug        false
        ]
        ProtocolSession [name socket use SSF.OS.Socket.socketMaster]
        ProtocolSession [name tcp use SSF.OS.TCP.tcpSessionMaster
                _find .dictionary.tcpinit
                debug   true
                rttdump "basic3a.rtt"
                rexdump "basic3a.rto"
                cwnddump "basic3a.wnd"
                con_count "basic3a.con_count"
        ]
        ProtocolSession [name ip use SSF.OS.IP]
   ]
   interface [id 0 bitrate 800000 tcpdump "basic3a.tcpdump"]
   route [dest default interface 0 ]
  ]

# ------------------------------------------------------------ CLIENT

  host [
   id 0
   graph [
        ProtocolSession [
                name client use SSF.OS.TCP.test.tcpClient
                start_time 192        # earliest time to send request to server
                start_window 0        # start time jitter window size
                file size 300000      # file size
                request_size  4       # client request datagram size (bytes)
                show report true      # print client server session summary report
                debug false           # print verbose client/server diagnostics
        ]
        ProtocolSession [name socket use SSF.OS.Socket.socketMaster]
        ProtocolSession [name tcp use SSF.OS.TCP.tcpSessionMaster
               _find .dictionary.tcpinit
        ]
        ProtocolSession [name ip use SSF.OS.IP]
   ]
   interface [id 0 bitrate 800000]
   route [dest default interface 0 ]
  ]
]
```

```
dictionary [
        tcpinit[
           ISS 0                       # initial sequence number
           MSS 960                     # maximum segment size
           RcvWndSize  32              # receive buffer size
           SendWndSize 32              # maximum send window size
           SendBufferSize 32           # send buffer size
           MaxRexmitTimes 12           # maximum retransmission times before drop
           TCP_SLOW_INTERVAL 0.5 # granularity of TCP slow timer
           TCP_FAST_INTERVAL 0.2 # granularity of TCP fast(delayack) timer
           MSL 60.0                    # maximum segment lifetime
           MaxIdleTime 600.0           # maximum idle time for drop a connection
           delayed_ack false           # delayed ack option
           fast_recovery true          # implement fast recovery algorithm
           show_report true            # print terse TCP connection diagnostics
        ]
]
```

Figure 15.12 Domain Modeling Language specification of a simple network experiment.

but the methodology specifies how one does. A protocol session of a given type may include attributes specific to that type. For example, the tcpServer protocol beginning at line 32 specifies the port through which it is accessible (10). Line 37 begins the declaration of the tcpSessionMaster, a component that manages all TCP sessions. Characteristics of its version of TCP are described by including a list of attributes defined in a list held elsewhere in the DML file. The statement `_find .dictionary.tcpinit` causes the contents of the named list to essentially be inserted at the point of the statement. The string `.dictionary.tcpinit` names the list in terms of how to find it in the file: "." is the highest level list, "`dictionary`" is the name of an attribute in that list, "`tcpinit`" is the attribute associated with the sought list, an attribute of the value-list of `dictionary`. This list starts at line 82.

We quickly describe the meaning of each attribute not obvious from the comments, in order to illustrate the diversity of parameters in SSFNet's implementation of TCP. `RcvWndSize`, `SendWndSize`, and `SendBufferSize` describe units of MSS and limit buffer useage (which affects TCP behavior, as we have already seen). A missing segment will be retransmitted up to `MaxrexmitTimes` times before the TCP session is aborted. `TCP_SLOW_INTERVAL` and `TCP_FAST_INTERVAL` give timer values used to determine when enough time has gone by so that a transmitted segment has not yet been acknowledged. If a TCP session is inactive for `MaxIdleTime` seconds, it is terminated. `delay_ack` and `fast_recovery` are Boolean flags that describe whether to use particular optimizations known for TCP.

Back within the specification of the host (at lines 40–43), we find attributes whose values are files into which the system saves descriptions of how TCP variables behaved during the simulation. Following this (at line 40) is the inclusion of the IP protocol. This, in turn, is followed by declaration of the server's single interface, given id 0 for NHI coordinates and specified to have a bandwidth of 800 Kbits per second. The last attribute for the server is an "`nhi_route`", an element in IP's forwarding table, described in NHI coordinates. The server is not a router and so needs only to direct traffic from IP to one interface. Attribute–value pair `dest default` says to route *everything* through the interface to follow, 0.

Specification of the second host is similar. In this case, the uppermost ProtocolSession is that of a client that requests data, through a socket. Attributes for the client include the simulation time at which it initiates the request. (It actually specifies a window of simulation time in which this occurs, to provide some jitter when multiple clients are to start more or less simultaneously). The length of the transfer being requested is an attribute (line 60). The rest of this host's ProtocolSessions are similar to the server's, although we don't save so much information about TCP's behavior at this host.

15.7 SUMMARY

In this chapter, we touched on some important topics related to simulation of computer networks. Traffic modeling—at different levels of abstraction—is a crucial element of simulating and modeling networks. We emphasized the importance of non-Poisson arrivals models, in some cases to better match characteristics of specific applications, in others to be sure to explain and capture long-range dependence.

Next, we focused on the Data Link layer and on the Media Access Control algorithms. We examined the token-bus and ethernet protocols, discussed subleties of their simulation, and showed by example how significant an impact traffic-model assumptions can have on network performance. Following this, we mentioned issues at the Data Link layer for which simulation has been a critical tool for investigation.

Much of the traffic on the Internet is carried by using TCP. We described TCP's basic rules and used simulation to illustrate some of the consequences of these rules. Finally, we sketched how one builds network models in the SSFNet simulator.

This chapter has barely scratched the surface of how networking uses simulation. Our hope is that what we discuss leads a student to explore more deeply any one of a number of fascinating areas of networking that can be explored only with simulation. The exercises are designed to do this and to teach the student some skill in using SSF and SSFNet.

REFERENCES

BARFORD, P., AND M. CROVELLA [1998], "An Architecture for a WWW Workload Generator," *Proceedings of the 1998 SIGMETRICS Conference*, Madison, WI, pp. 151–160.

BLACK, U. [2001], "Voice Over IP," Prentice Hall, Upper Saddle River, NJ.

COMER, D. [2000], "Networking with TCP/IP Volume 1: Principles, Protocols, and Architecture, 4th ed.," Prentice Hall, Upper Saddle River, NJ.

FLOYD, S., AND V. JACOBSON [1993], "Random Early Detection Gateways for Congestion Avoidance," *IEEE/ACM Transactions on Networking*, Vol. 1, No. 4, pp. 397–413.

KARAGIANNIS T., M. FALOUTSOS, AND M. MOLLE [2003], "A User-Friendly Self-Similarity Analysis Tool," *ACM SIGCOMM Computer Communication Review*, Vol. 33, No. 3, pp. 81–93.

KUROSE, J., AND K. ROSS [2002], *Computer Networking: A Top-Down Approach Featuring the Internet*, 2d ed., Addison–Wesley, Reading, MA.

MOY, J. [1998], *OSPF: Anatomy of an Internet Routing Protocol*, Addison–Wesley, Reading, MA.

SPURGEON, C. [2000], *Ethernet: The Definitive Guide*, O'Reilly, Cambridge MA.

VAN BEIJNUM, I. [2002], *BGP: Building Reliable Networks with the Border Gateway Protocol*, O'Reilly, Cambridge, MA.

ZIMMERMAN, H. [1980], "OSI reference model—the ISO model of architecture for open system interconnection" *IEEE Transactions on Communications*, Vol. COM-28, No. 4, pp. 425–432.

ZUKEMAN, M., D. NEAME, AND R. ADDIE [2003], "Internet Traffic Modeling and Future Technology Implications," *Proceedings of the 2003 InfoCom Conference*, San Franciso, CA.

EXERCISES

1. Survey literature in models of Voice-over-IP traffic, and build a simulator that creates traffic load corresponding to one model of particular interest.

2. Create a Markov-Modulated Poisson process (see chapter 14) and a Poisson–Pareto Burst Process that yield the same average bit-rate traffic demand. Acquire the SELFIS tool for analyzing long-range dependence (it's free), and compare traces from the MMP and PPBP models.

3. Get from `www.bcnn.net` the SSF models for the Ethernet protocol experiments reported in this chapter. Design and perform a sensitivity analysis of throughput as a function of the physical distance between ethernet ports. Likewise, design and perform a sensitivity analysis of throughput as a function of maximum frame size.

4. Acquire the SSFNet simulator from `www.ssfnet.org` (free for academic use) and the TCP models described in this chapter from `www.bcnn.net`.

    - Look into how TCP behavior changes in each case by increasing the bandwidth by a factor of 10.
    - Investigate how TCP behavior changes in each case by reducing the link latency by a factor of 10.
    - Work out how TCP behavior changes in each case by increasing the buffer limits expressed in the DML file by a factor of 10.

Appendix

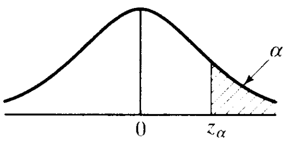
Table A.1 Random Digits

94737	08225	35614	24826	88319	05595	58701	57365	74759
87259	85982	13296	89326	74863	99986	68558	06391	50248
63856	14016	18527	11634	96908	52146	53496	51730	03500
66612	54714	46783	61934	30258	61674	07471	67566	31635
30712	58582	05704	23172	86689	94834	99057	55832	21012
69607	24145	43886	86477	05317	30445	33456	34029	09603
37792	27282	94107	41967	21425	04743	42822	28111	09757
01488	56680	73847	64930	11108	44834	45390	86043	23973
66248	97697	38244	50918	55441	51217	54786	04940	50807
51453	03462	61157	65366	61130	26204	15016	85665	97714
92168	82530	19271	86999	96499	12765	20926	25282	39119
36463	07331	54590	00546	03337	41583	46439	40173	46455
47097	78780	04210	87084	44484	75377	57753	41415	09890
80400	45972	44111	99708	45935	03694	81421	60170	58457
94554	13863	88239	91624	00022	40471	78462	96265	55360
31567	53597	08490	73544	72573	30961	12282	97033	13676
07821	24759	47266	21747	72496	77755	50391	59554	31177
09056	10709	69314	11449	40531	02917	95878	74587	60906
19922	37025	80731	26179	16039	01518	82697	73227	13160
29923	02570	80164	36108	73689	26342	35712	49137	13482
29602	29464	99219	20308	82109	03898	82072	85199	13103
94135	94661	87724	88187	62191	70607	63099	40494	49069
87926	34092	34334	55064	43152	01610	03126	47312	59578
85039	19212	59160	83537	54414	19856	90527	21756	64783
66070	38480	74636	45095	86576	79337	39578	40851	53503
78166	82521	79261	12570	10930	47564	77869	16480	43972
94672	07912	26153	10531	12715	63142	88937	94466	31388
56406	70023	27734	22254	27685	67518	63966	33203	70803
67726	57805	94264	77009	08682	18784	47554	59869	66320
07516	45979	76735	46509	17696	67177	92600	55572	17245
43070	22671	00152	81326	89428	16368	57659	79424	57604
36917	60370	80812	87225	02850	47118	23790	55043	75117
03919	82922	02312	31106	44335	05573	17470	25900	91080
46724	22558	64303	78804	05762	70650	56117	06707	90035
16108	61281	86823	20286	14025	24909	38391	12183	89393
74541	75808	89669	87680	72758	60851	55292	95663	88326
82919	31285	01850	72550	42986	57518	01159	01786	98145
31388	26809	77258	99360	92362	21979	41319	75739	98082
17190	75522	15687	07161	99745	48767	03121	20046	28013
00466	88068	68631	98745	97810	35886	14497	90230	69264

Table A.2 Random Normal Numbers

0.23	−0.17	0.43	2.18	2.13	0.49	2.72	−0.18	0.42
0.24	−1.17	0.02	0.67	−0.59	−0.13	−0.15	−0.46	1.64
−1.16	−0.17	0.36	−1.26	0.91	0.71	−1.00	−1.09	−0.02
−0.02	−0.19	−0.04	1.92	0.71	−0.90	−0.21	−1.40	−0.38
0.39	0.55	0.13	2.55	−0.33	−0.05	−0.34	−1.95	−0.44
0.64	−0.36	0.98	−0.21	−0.52	−0.02	−0.15	−0.43	0.62
−1.90	0.48	−0.54	0.60	−0.35	−1.29	−0.57	0.23	1.41
−1.04	−0.70	−1.69	1.76	0.47	−0.52	−0.73	0.94	−1.63
−.78	0.11	−0.91	−1.13	0.07	0.45	−0.94	1.42	0.75
0.68	1.77	−0.82	−1.68	−2.60	1.59	−0.72	−0.80	0.61
−0.02	0.92	1.76	−0.66	0.18	−1.32	1.26	0.61	0.83
−0.47	1.04	0.83	−2.05	1.00	−0.70	1.12	0.82	0.08
−0.40	1.40	1.20	0.00	0.21	−2.13	−0.22	1.79	0.87
−0.75	0.09	−1.50	0.14	−2.99	−0.41	−0.99	−0.70	0.51
−0.66	−1.97	0.15	−1.16	−0.60	0.50	1.36	1.94	0.11
−0.44	−0.09	−0.59	1.37	0.18	1.44	−0.80	2.11	−1.37
1.41	−2.71	−0.67	1.83	0.97	0.06	−0.28	0.04	−0.21
1.21	−0.52	−0.20	−0.88	−0.78	0.84	−1.08	−0.25	0.17
0.07	0.66	−0.51	−0.04	−0.84	0.04	1.60	−0.92	1.14
−0.08	0.79	−0.09	−1.12	−1.13	0.77	0.40	0.69	−0.12
0.53	−0.36	−2.64	0.22	−0.78	1.92	−0.26	1.04	−1.61
−1.56	1.82	−1.03	1.14	−0.12	−0.78	−0.12	1.42	−0.52
0.03	−1.29	−0.33	2.60	−0.64	1.19	−0.13	0.91	0.78
1.49	1.55	−0.79	1.37	0.97	0.17	0.58	1.43	−1.29
−1.19	1.35	0.16	1.06	−0.17	0.32	−0.28	0.68	0.54
−1.19	−1.03	−0.12	1.07	0.87	−1.40	−0.24	−0.81	0.31
0.11	−1.95	−0.44	−0.39	−0.15	−1.20	−1.98	0.32	2.91
−1.86	0.06	0.19	−1.29	0.33	1.51	−0.36	−0.80	−0.99
0.16	0.28	0.60	−0.78	0.67	0.13	−0.47	−0.18	−0.89
1.21	−1.19	−0.60	−1.22	0.07	−1.13	1.45	0.94	0.54
−0.82	0.54	−0.98	−0.13	1.52	0.77	0.95	−0.84	2.40
0.75	−0.80	−0.28	1.77	−0.16	−0.33	2.43	−1.11	1.63
0.42	0.31	1.56	0.56	0.64	−0.78	0.04	1.34	−0.01
−1.50	−1.78	−0.59	0.16	0.36	1.89	−1.19	0.53	−0.97
−0.89	0.08	0.95	−0.73	1.25	−1.04	−0.47	−0.68	−0.87
0.19	0.85	1.68	−0.57	0.37	−0.48	−0.17	2.36	−0.53
0.49	0.32	−2.08	−1.02	2.59	−0.53	0.15	0.11	0.05
−1.44	0.07	−0.22	−0.93	−1.40	0.54	−1.28	−0.15	0.67
−0.21	−0.48	1.21	0.67	−1.10	−0.75	−0.37	0.68	−0.02
−0.65	−0.12	0.94	−0.44	−1.21	−0.06	−1.28	−1.51	1.39
0.24	−0.83	1.55	0.33	−0.59	−1.24	0.70	0.01	0.15
−0.73	1.24	0.40	−0.61	0.68	0.69	0.07	−0.23	−0.66
−1.93	0.75	−0.32	0.95	1.35	1.51	−0.88	0.10	−1.19
0.08	0.16	0.38	−0.96	1.99	−0.20	0.98	0.16	0.26
−0.47	−1.25	0.32	0.51	−1.04	0.97	2.60	−0.08	1.19

Table A.3 Cumulative Normal Distribution



$$\phi(z_\alpha) = \int_{-\infty}^{z_\alpha} \frac{1}{\sqrt{2\pi}} e^{-u^2/2} du = 1-\alpha$$

z_α	0.00	0.01	0.02	0.03	0.04	z_α
0.0	0.500 00	0.503 99	0.507 98	0.511 97	0.515 95	**0.0**
0.1	0.539 83	0.543 79	0.547 76	0.551 72	0.555 67	**0.1**
0.2	0.579 26	0.583 17	0.587 06	0.590 95	0.594 83	**0.2**
0.3	0.617 91	0.621 72	0.625 51	0.629 30	0.633 07	**0.3**
0.4	0.655 42	0.659 10	0.662 76	0.666 40	0.670 03	**0.4**
0.5	0.691 46	0.694 97	0.698 47	0.701 94	0.705 40	**0.5**
0.6	0.725 75	0.729 07	0.732 37	0.735 65	0.738 91	**0.6**
0.7	0.758 03	0.761 15	0.764 24	0.767 30	0.770 35	**0.7**
0.8	0.788 14	0.791 03	0.793 89	0.796 73	0.799 54	**0.8**
0.9	0.815 94	0.818 59	0.821 21	0.823 81	0.826 39	**0.9**
1.0	0.841 34	0.843 75	0.846 13	0.848 49	0.850 83	**1.0**
1.1	0.864 33	0.866 50	0.868 64	0.870 76	0.872 85	**1.1**
1.2	0.884 93	0.886 86	0.888 77	0.890 65	0.892 51	**1.2**
1.3	0.903 20	0.904 90	0.906 58	0.908 24	0.909 88	**1.3**
1.4	0.919 24	0.920 73	0.922 19	0.923 64	0.925 06	**1.4**
1.5	0.933 19	0.934 48	0.935 74	0.936 99	0.938 22	**1.5**
1.6	0.945 20	0.946 30	0.947 38	0.948 45	0.949 50	**1.6**
1.7	0.955 43	0.956 37	0.957 28	0.958 18	0.959 07	**1.7**
1.8	0.964 07	0.964 85	0.965 62	0.966 37	0.967 11	**1.8**
1.9	0.971 28	0.971 93	0.972 57	0.973 20	0.973 81	**1.9**
2.0	0.977 25	0.977 78	0.978 31	0.978 82	0.979 32	**2.0**
2.1	0.982 14	0.982 57	0.983 00	0.983 41	0.983 82	**2.1**
2.2	0.986 10	0.986 45	0.986 79	0.987 13	0.987 45	**2.2**
2.3	0.989 28	0.989 56	0.989 83	0.990 10	0.990 36	**2.3**
2.4	0.991 80	0.992 02	0.992 24	0.992 45	0.992 66	**2.4**
2.5	0.993 79	0.993 96	0.994 13	0.994 30	0.994 46	**2.5**
2.6	0.995 34	0.995 47	0.995 60	0.995 73	0.995 85	**2.6**
2.7	0.996 53	0.996 64	0.996 74	0.996 83	0.996 93	**2.7**
2.8	0.997 44	0.997 52	0.997 60	0.997 67	0.997 74	**2.8**
2.9	0.998 13	0.998 19	0.998 25	0.998 31	0.998 36	**2.9**
3.0	0.998 65	0.998 69	0.998 74	0.998 78	0.998 82	**3.0**
3.1	0.999 03	0.999 06	0.999 10	0.999 13	0.999 16	**3.1**
3.2	0.999 31	0.999 34	0.999 36	0.999 38	0.999 40	**3.2**
3.3	0.999 52	0.999 53	0.999 55	0.999 57	0.999 58	**3.3**
3.4	0.999 66	0.999 68	0.999 69	0.999 70	0.999 71	**3.4**
3.5	0.999 77	0.999 78	0.999 78	0.999 79	0.999 80	**3.5**
3.6	0.999 84	0.999 85	0.999 85	0.999 86	0.999 86	**3.6**
3.7	0.999 89	0.999 90	0.999 90	0.999 90	0.999 91	**3.7**
3.8	0.999 93	0.999 93	0.999 93	0.999 94	0.999 94	**3.8**
3.9	0.999 95	0.999 95	0.999 96	0.999 96	0.999 96	**3.9**

(*continued overleaf*)

Table A.3 (*continued*)

z_α	0.05	0.06	0.07	0.08	0.09	z_α
0.0	0.519 94	0.523 92	0.527 90	0.531 88	0.535 86	**0.0**
0.1	0.559 62	0.563 56	0.567 49	0.571 42	0.575 34	**0.1**
0.2	0.598 71	0.602 57	0.606 42	0.610 26	0.614 09	**0.2**
0.3	0.636 83	0.640 58	0.644 31	0.648 03	0.651 73	**0.3**
0.4	0.673 64	0.677 24	0.680 82	0.684 38	0.687 93	**0.4**
0.5	0.708 84	0.712 26	0.715 66	0.719 04	0.722 40	**0.5**
0.6	0.742 15	0.745 37	0.748 57	0.751 75	0.754 90	**0.6**
0.7	0.773 37	0.776 37	0.779 35	0.782 30	0.785 23	**0.7**
0.8	0.802 34	0.805 10	0.807 85	0.810 57	0.813 27	**0.8**
0.9	0.824 94	0.831 47	0.833 97	0.836 46	0.838 91	**0.9**
1.0	0.853 14	0.855 43	0.857 69	0.859 93	0.862 14	**1.0**
1.1	0.874 93	0.876 97	0.879 00	0.881 00	0.882 97	**1.1**
1.2	0.894 35	0.896 16	0.897 96	0.899 73	0.901 47	**1.2**
1.3	0.911 49	0.913 08	0.914 65	0.916 21	0.917 73	**1.3**
1.4	0.926 47	0.927 85	0.929 22	0.930 56	0.931 89	**1.4**
1.5	0.939 43	0.940 62	0.941 79	0.942 95	0.944 08	**1.5**
1.6	0.950 53	0.951 54	0.952 54	0.953 52	0.954 48	**1.6**
1.7	0.959 94	0.960 80	0.961 64	0.962 46	0.963 27	**1.7**
1.8	0.967 84	0.968 56	0.969 26	0.969 95	0.970 62	**1.8**
1.9	0.974 41	0.975 00	0.975 58	0.976 15	0.976 70	**1.9**
2.0	0.979 82	0.980 30	0.980 77	0.981 24	0.981 69	**2.0**
2.1	0.984 22	0.984 61	0.985 00	0.985 37	0.985 74	**2.1**
2.2	0.987 78	0.988 09	0.988 40	0.988 70	0.988 99	**2.2**
2.3	0.990 61	0.990 86	0.991 11	0.991 34	0.991 58	**2.3**
2.4	0.992 86	0.993 05	0.993 24	0.993 43	0.993 61	**2.4**
2.5	0.994 61	0.994 77	0.994 92	0.995 06	0.995 20	**2.5**
2.6	0.995 98	0.996 09	0.996 21	0.996 32	0.996 43	**2.6**
2.7	0.997 02	0.997 11	0.997 20	0.997 28	0.997 36	**2.7**
2.8	0.997 81	0.997 88	0.997 95	0.998 01	0.998 07	**2.8**
2.9	0.998 41	0.998 46	0.998 51	0.998 56	0.998 61	**2.9**
3.0	0.998 86	0.998 89	0.998 93	0.998 97	0.999 00	**3.0**
3.1	0.999 18	0.999 21	0.999 24	0.999 26	0.999 29	**3.1**
3.2	0.999 42	0.999 44	0.999 46	0.999 48	0.999 50	**3.2**
3.3	0.999 60	0.999 61	0.999 62	0.999 64	0.999 65	**3.3**
3.4	0.999 72	0.999 73	0.999 74	0.999 75	0.999 76	**3.4**
3.5	0.999 81	0.999 81	0.999 82	0.999 83	0.999 83	**3.5**
3.6	0.999 87	0.999 87	0.999 88	0.999 88	0.999 89	**3.6**
3.7	0.999 91	0.999 92	0.999 92	0.999 92	0.999 92	**3.7**
3.8	0.999 94	0.999 94	0.999 95	0.999 95	0.999 95	**3.8**
3.9	0.999 96	0.999 96	0.999 96	0.999 97	0.999 97	**3.9**

Source: W. W. Hines and D. C. Montgomery, *Probability and Statistics in Engineering and Management Science*, 2d ed., © 1980, pp. 592–3. Reprinted by permission of John Wiley & Sons, Inc., New York.

Table A.4 Cumulative Poisson Distribution

x	α = Mean											x
	.01	.05	.1	.2	.3	.4	.5	.6	.7	.8	.9	
0	.990	.951	.905	.819	.741	.670	.607	.549	.497	.449	.407	0
1	1.000	.999	.995	.982	.963	.938	.910	.878	.844	.809	.772	1
2		1.000	1.000	.999	.996	.992	.986	.977	.966	.953	.937	2
3				1.000	1.000	.999	.998	.997	.994	.991	.987	3
4						1.000	1.000	1.000	.999	.999	.998	4
5									1.000	1.000	1.000	5

x	α = Mean											x
	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	
0	.368	.333	.301	.273	.247	.223	.202	.183	.165	.150	.135	0
1	.736	.699	.663	.627	.592	.558	.525	.493	.463	.434	.406	1
2	.920	.900	.879	.857	.833	.809	.783	.757	.731	.704	.677	2
3	.981	.974	.966	.957	.946	.934	.921	.907	.891	.875	.857	3
4	.996	.995	.992	.989	.986	.981	.976	.970	.964	.956	.947	4
5	.999	.999	.998	.998	.997	.996	.994	.992	.990	.987	.983	5
6	1.000	1.000	1.000	1.000	.999	.999	.999	.998	.997	.997	.995	6
7					1.000	1.000	1.000	1.000	.999	.999	.999	7
8									1.000	1.000	1.000	8

x	α = Mean											x
	2.2	2.4	2.6	2.8	3.0	3.5	4.0	4.5	5.0	5.5	6.0	
0	.111	.091	.074	.061	.050	.030	.018	.011	.007	.004	.002	0
1	.355	.308	.267	.231	.199	.136	.092	.061	.040	.027	.017	1
2	.623	.570	.518	.469	.423	.321	.238	.174	.125	.088	.062	2
3	.819	.779	.736	.692	.647	.537	.433	.342	.265	.202	.151	3
4	.928	.904	.877	.848	.815	.725	.629	.532	.440	.358	.285	4
5	.975	.964	.951	.935	.916	.858	.785	.703	.616	.529	.446	5
6	.993	.988	.983	.976	.966	.935	.889	.831	.762	.686	.606	6
7	.998	.997	.995	.992	.988	.973	.949	.913	.867	.809	.744	7
8	1.000	.999	.999	.998	.996	.990	.979	.960	.932	.894	.847	8
9		1.000	1.000	.999	.999	.997	.992	.983	.968	.946	.916	9
10				1.000	1.000	.999	.997	.993	.986	.975	.957	10
11						1.000	.999	.998	.995	.989	.980	11
12							1.000	.999	.998	.996	.991	12
13								1.000	.999	.998	.996	13
14									1.000	.999	.999	14
15										1.000	.999	15
16											1.000	16

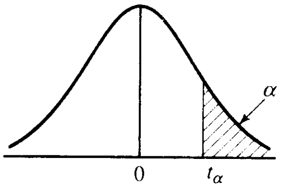
(*continued overleaf*)

Table A.4 (*continued*)

x	α = Mean											x
	6.5	7.0	7.5	8.0	9.0	10.0	12.0	14.0	16.0	18.0	20.0	
0	.002	.001	.001									0
1	.011	.007	.005	.003	.001							1
2	.043	.030	.020	.014	.006	.003	.001					2
3	.112	.082	.059	.042	.021	.010	.002					3
4	.224	.173	.132	.100	.055	.029	.008	.002				4
5	.369	.301	.241	.191	.116	.067	.020	.006	.001			5
6	.527	.450	.378	.313	.207	.130	.046	.014	.004	.001		6
7	.673	.599	.525	.453	.324	.220	.090	.032	.010	.003	.001	7
8	.792	.729	.662	.593	.456	.333	.155	.062	.022	.007	.002	8
9	.877	.830	.776	.717	.587	.458	.242	.109	.043	.015	.005	9
10	.933	.901	.862	.816	.706	.583	.347	.176	.077	.030	.011	10
11	.966	.947	.921	.888	.803	.697	.462	.260	.127	.055	.021	11
12	.984	.973	.957	.936	.876	.792	.576	.358	.193	.092	.039	12
13	.993	.987	.978	.966	.926	.864	.682	.464	.275	.143	.066	13
14	.997	.994	.990	.983	.959	.917	.772	.570	.368	.208	.105	14
15	.999	.998	.995	.992	.978	.951	.844	.669	.467	.287	.157	15
16	1.000	.999	.998	.996	.989	.973	.899	.756	.566	.375	.221	16
17		1.000	.999	.998	.995	.986	.937	.827	.659	.469	.297	17
18			1.000	.999	.998	.993	.963	.883	.742	.562	.381	18
19				1.000	.999	.997	.979	.923	.812	.651	.470	19
20					1.000	.998	.988	.952	.868	.731	.559	20
21						.999	.994	.971	.911	.799	.644	21
22						1.000	.997	.983	.942	.855	.721	22
23							.999	.991	.963	.899	.787	23
24							.999	.995	.978	.932	.843	24
25							1.000	.997	.987	.955	.888	25
26								.999	.993	.972	.922	26
27								.999	.996	.983	.948	27
28								1.000	.998	.990	.966	28
29									.999	.994	.978	29
30									.999	.997	.987	30
31									1.000	.998	.992	31
32										.999	.995	32
33										1.000	.997	33
34											.999	34
35											.999	35
36											1.000	36

Source: J. Banks and R. G. Heikes, *Handbook of Tables and Graphs for the Industrial Engineer and Manager*, © 1984, pp. 34–35. Reprinted by permission of John Wiley and Sons, Inc., New York.

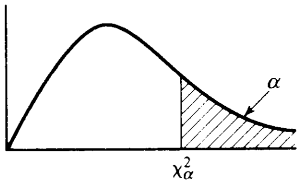
Table A.5 Percentage Points of The Student's t Distribution with v Degrees of Freedom



v	$t_{0.005}$	$t_{0.01}$	$t_{0.025}$	$t_{0.05}$	$t_{0.10}$
1	63.66	31.82	12.71	6.31	3.08
2	9.92	6.92	4.30	2.92	1.89
3	5.84	4.54	3.18	2.35	1.64
4	4.60	3.75	2.78	2.13	1.53
5	4.03	3.36	2.57	2.02	1.48
6	3.71	3.14	2.45	1.94	1.44
7	3.50	3.00	2.36	1.90	1.42
8	3.36	2.90	2.31	1.86	1.40
9	3.25	2.82	2.26	1.83	1.38
10	3.17	2.76	2.23	1.81	1.37
11	3.11	2.72	2.20	1.80	1.36
12	3.06	2.68	2.18	1.78	1.36
13	3.01	2.65	2.16	1.77	1.35
14	2.98	2.62	2.14	1.76	1.34
15	2.95	2.60	2.13	1.75	1.34
16	2.92	2.58	2.12	1.75	1.34
17	2.90	2.57	2.11	1.74	1.33
18	2.88	2.55	2.10	1.73	1.33
19	2.86	2.54	2.09	1.73	1.33
20	2.84	2.53	2.09	1.72	1.32
21	2.83	2.52	2.08	1.72	1.32
22	2.82	2.51	2.07	1.72	1.32
23	2.81	2.50	2.07	1.71	1.32
24	2.80	2.49	2.06	1.71	1.32
25	2.79	2.48	2.06	1.71	1.32
26	2.78	2.48	2.06	1.71	1.32
27	2.77	2.47	2.05	1.70	1.31
28	2.76	2.47	2.05	1.70	1.31
29	2.76	2.46	2.04	1.70	1.31
30	2.75	2.46	2.04	1.70	1.31
40	2.70	2.42	2.02	1.68	1.30
60	2.66	2.39	2.00	1.67	1.30
120	2.62	2.36	1.98	1.66	1.29
∞	2.58	2.33	1.96	1.645	1.28

Source: Robert E. Shannon, *Systems Simulation: The Art and Science*, © 1975, p. 375. Reprinted by permission of Prentice Hall, Upper Saddle River, NJ.

Table A.6 Percentage Points of The Chi-Square Distribution with v Degrees of Freedom



v	$\chi^2_{0.005}$	$\chi^2_{0.01}$	$\chi^2_{0.025}$	$\chi^2_{0.05}$	$\chi^2_{0.10}$
1	7.88	6.63	5.02	3.84	2.71
2	10.60	9.21	7.38	5.99	4.61
3	12.84	11.34	9.35	7.81	6.25
4	14.96	13.28	11.14	9.49	7.78
5	16.7	15.1	12.8	11.1	9.2
6	18.5	16.8	14.4	12.6	10.6
7	20.3	18.5	16.0	14.1	12.0
8	22.0	20.1	17.5	15.5	13.4
9	23.6	21.7	19.0	16.9	14.7
10	25.2	23.2	20.5	18.3	16.0
11	26.8	24.7	21.9	19.7	17.3
12	28.3	26.2	23.3	21.0	18.5
13	29.8	27.7	24.7	22.4	19.8
14	31.3	29.1	26.1	23.7	21.1
15	32.8	30.6	27.5	25.0	22.3
16	34.3	32.0	28.8	26.3	23.5
17	35.7	33.4	30.2	27.6	24.8
18	37.2	34.8	31.5	28.9	26.0
19	38.6	36.2	32.9	30.1	27.2
20	40.0	37.6	34.2	31.4	28.4
21	41.4	38.9	35.5	32.7	29.6
22	42.8	40.3	36.8	33.9	30.8
23	44.2	41.6	38.1	35.2	32.0
24	45.6	43.0	39.4	36.4	33.2
25	49.6	44.3	40.6	37.7	34.4
26	48.3	45.6	41.9	38.9	35.6
27	49.6	47.0	43.2	40.1	36.7
28	51.0	48.3	44.5	41.3	37.9
29	52.3	49.6	45.7	42.6	39.1
30	53.7	50.9	47.0	43.8	40.3
40	66.8	63.7	59.3	55.8	51.8
50	79.5	76.2	71.4	67.5	63.2
60	92.0	88.4	83.3	79.1	74.4
70	104.2	100.4	95.0	90.5	85.5
80	116.3	112.3	106.6	101.9	96.6
90	128.3	124.1	118.1	113.1	107.6
100	140.2	135.8	129.6	124.3	118.5

Source: Robert E. Shannon, *Systems Simulation: The Art and Science*, © 1975, p. 372. Reprinted by permission of Prentice Hall, Upper Saddle River, NJ.

Table A.7 Percentage Points of The F Distribution with $\alpha = 0.05$

Degrees of Freedom for Denominator (v_2)

v_1	*Degrees of Freedom for the Numerator* (v_1)																		
v_2	1	2	3	4	5	6	7	8	9	10	12	15	20	24	30	40	60	120	∞
1	161.4	199.5	215.7	224.6	230.2	234.0	236.8	238.9	240.5	241.9	243.9	245.9	248.0	249.1	250.1	251.1	252.2	253.3	254.3
2	18.51	19.00	19.16	19.25	19.30	19.33	19.35	19.37	19.38	19.40	19.41	19.43	19.45	19.45	19.46	19.47	19.48	19.49	19.50
3	10.13	9.55	9.28	9.12	9.01	8.94	8.89	8.85	8.81	8.79	8.74	8.70	8.66	8.64	8.62	8.59	8.57	8.55	8.53
4	7.71	6.94	6.59	6.39	6.26	6.16	6.09	6.04	6.00	5.96	5.91	5.86	5.80	5.77	5.75	5.72	5.69	5.66	5.63
5	6.61	5.79	5.41	5.19	5.05	4.95	4.88	4.82	4.77	4.74	4.68	4.62	4.56	4.53	4.50	4.46	4.43	4.40	4.36
6	5.99	5.14	4.76	4.53	4.39	4.28	4.21	4.15	4.10	4.06	4.00	3.94	3.87	3.84	3.81	3.77	3.74	3.70	3.67
7	5.59	4.74	4.35	4.12	3.97	3.87	3.79	3.73	3.68	3.64	3.57	3.51	3.44	3.41	3.38	3.34	3.30	3.27	3.23
8	5.32	4.46	4.07	3.84	3.69	3.58	3.50	3.44	3.39	3.35	3.28	3.22	3.15	3.12	3.08	3.04	3.01	2.97	2.93
9	5.12	4.26	3.86	3.63	3.48	3.37	3.29	3.23	3.18	3.14	3.07	3.01	2.94	2.90	2.86	2.83	2.79	2.75	2.71
10	4.96	4.10	3.71	3.48	3.33	3.22	3.14	3.07	3.02	2.98	2.91	2.85	2.77	2.74	2.70	2.66	2.62	2.58	2.54
11	4.84	3.98	3.59	3.36	3.20	3.09	3.01	2.95	2.90	2.85	2.79	2.72	2.65	2.61	2.57	2.53	2.49	2.45	2.40
12	4.75	3.89	3.49	3.26	3.11	3.00	2.91	2.85	2.80	2.75	2.69	2.62	2.54	2.51	2.47	2.43	2.38	2.34	2.30
13	4.67	3.81	3.41	3.18	3.03	2.92	2.83	2.77	2.71	2.67	2.60	2.53	2.46	2.42	2.38	2.34	2.30	2.25	2.21
14	4.60	3.74	3.34	3.11	2.96	2.85	2.76	2.70	2.65	2.60	2.53	2.46	2.39	2.35	2.31	2.27	2.22	2.18	2.13
15	4.54	3.68	3.29	3.06	2.90	2.79	2.71	2.64	2.59	2.54	2.48	2.40	2.33	2.29	2.25	2.20	2.16	2.11	2.07
16	4.49	3.63	3.24	3.01	2.85	2.74	2.66	2.59	2.54	2.49	2.42	2.35	2.28	2.24	2.19	2.15	2.11	2.06	2.01
17	4.45	3.59	3.20	2.96	2.81	2.70	2.61	2.55	2.49	2.45	2.38	2.31	2.23	2.19	2.15	2.10	2.06	2.01	1.96
18	4.41	3.55	3.16	2.93	2.77	2.66	2.58	2.51	2.46	2.41	2.34	2.27	2.19	2.15	2.11	2.06	2.02	1.97	1.92
19	4.38	3.52	3.13	2.90	2.74	2.63	2.54	2.48	2.42	2.38	2.31	2.23	2.16	2.11	2.07	2.03	1.98	1.93	1.88
20	4.35	3.49	3.10	2.87	2.71	2.60	2.51	2.45	2.39	2.35	2.28	2.20	2.12	2.08	2.04	1.99	1.95	1.90	1.84
21	4.32	3.47	3.07	2.84	2.68	2.57	2.49	2.42	2.37	2.32	2.25	2.18	2.10	2.05	2.01	1.96	1.92	1.87	1.81
22	4.30	3.44	3.05	2.82	2.66	2.55	2.46	2.40	2.34	2.30	2.23	2.15	2.07	2.03	1.98	1.94	1.89	1.84	1.78
23	4.28	3.42	3.03	2.80	2.64	2.53	2.44	2.37	2.32	2.27	2.20	2.13	2.05	2.01	1.96	1.91	1.86	1.81	1.76
24	4.26	3.40	3.01	2.78	2.62	2.51	2.42	2.36	2.30	2.25	2.18	2.11	2.03	1.98	1.94	1.89	1.84	1.79	1.73
25	4.24	3.39	2.99	2.76	2.60	2.49	2.40	2.34	2.28	2.24	2.16	2.09	2.01	1.96	1.92	1.87	1.82	1.77	1.71
26	4.23	3.37	2.98	2.74	2.59	2.47	2.39	2.32	2.27	2.22	2.15	2.07	1.99	1.95	1.90	1.85	1.80	1.75	1.69
27	4.21	3.35	2.96	2.73	2.57	2.46	2.37	2.31	2.25	2.20	2.13	2.06	1.97	1.93	1.88	1.84	1.79	1.73	1.67
28	4.20	3.34	2.95	2.71	2.56	2.45	2.36	2.29	2.24	2.19	2.12	2.04	1.96	1.91	1.87	1.82	1.77	1.71	1.65
29	4.18	3.33	2.93	2.70	2.55	2.43	2.35	2.28	2.22	2.18	2.10	2.03	1.94	1.90	1.85	1.81	1.75	1.70	1.64
30	4.17	3.32	2.92	2.69	2.53	2.42	2.33	2.27	2.21	2.16	2.09	2.01	1.93	1.89	1.84	1.79	1.74	1.68	1.62
40	4.08	3.23	2.84	2.61	2.45	2.34	2.25	2.18	2.12	2.08	2.00	1.92	1.84	1.79	1.74	1.69	1.64	1.58	1.51
60	4.00	3.15	2.76	2.53	2.37	2.25	2.17	2.10	2.04	1.99	1.92	1.84	1.75	1.70	1.65	1.59	1.53	1.47	1.39
120	3.92	3.07	2.68	2.45	2.29	2.17	2.09	2.02	1.96	1.91	1.83	1.75	1.66	1.61	1.55	1.55	1.43	1.35	1.25
∞	3.84	3.00	2.60	2.37	2.21	2.10	2.01	1.94	1.88	1.83	1.75	1.67	1.57	1.52	1.46	1.39	1.32	1.22	1.00

Source: W. W. Hines and D. C. Montgomery, *Probability and Statistics in Engineering and Management Science*, 2d ed., © 1980, p. 599. Reprinted by permission of John Wiley & Sons, Inc., New York.

Table A.8 Kolmogorov–Smirnov Critical Values

Degrees of Freedom (N)	$D_{0.10}$	$D_{0.05}$	$D_{0.01}$
1	0.950	0.975	0.995
2	0.776	0.842	0.929
3	0.642	0.708	0.828
4	0.564	0.624	0.733
5	0.510	0.565	0.669
6	0.470	0.521	0.618
7	0.438	0.486	0.577
8	0.411	0.457	0.543
9	0.388	0.432	0.514
10	0.368	0.410	0.490
11	0.352	0.391	0.468
12	0.338	0.375	0.450
13	0.325	0.361	0.433
14	0.314	0.349	0.418
15	0.304	0.338	0.404
16	0.295	0.328	0.392
17	0.286	0.318	0.381
18	0.278	0.309	0.371
19	0.272	0.301	0.363
20	0.264	0.294	0.356
25	0.24	0.27	0.32
30	0.22	0.24	0.29
35	0.21	0.23	0.27
Over 35	$\frac{1.22}{\sqrt{N}}$	$\frac{1.36}{\sqrt{N}}$	$\frac{1.63}{\sqrt{N}}$

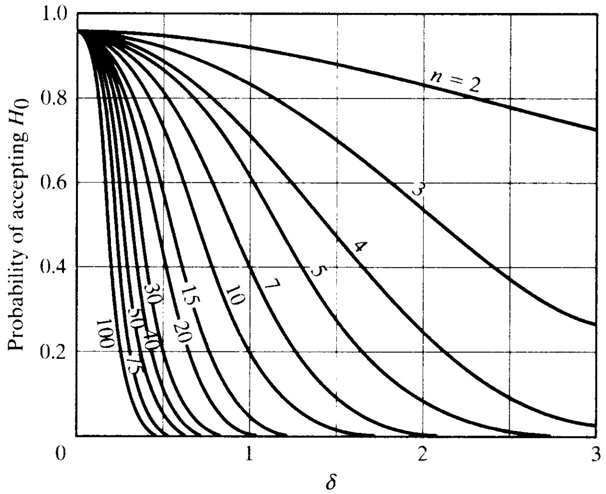
Source: F. J. Massey, "The Kolmogorov–Smirnov Test for Goodness of Fit," *The Journal of the American Statistical Association*, Vol. 46. © 1951, p. 70. Adapted with permission of the American Statistical Association.

Table A.9 Maximum Likelihood Estimates of the Gamma Distribution

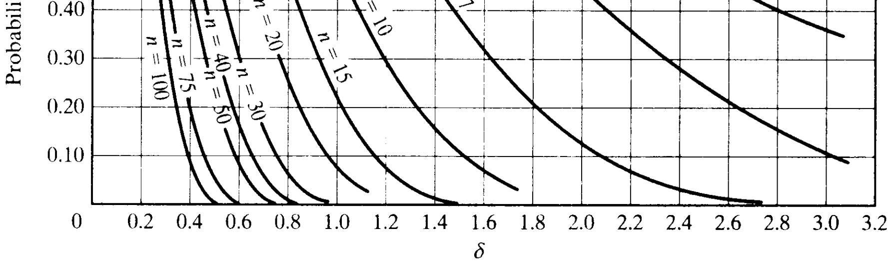
1/M	β	1/M	β	1/M	β
0.020	0.0187	2.700	1.494	10.300	5.311
0.030	0.0275	2.800	1.545	10.600	5.461
0.040	0.0360	2.900	1.596	10.900	5.611
0.050	0.0442	3.000	1.646	11.200	5.761
0.060	0.0523	3.200	1.748	11.500	5.911
0.070	0.0602	3.400	1.849	11.800	6.061
0.080	0.0679	3.600	1.950	12.100	6.211
0.090	0.0756	3.800	2.051	12.400	6.362
0.100	0.0831	4.000	2.151	12.700	6.512
0.200	0.1532	4.200	2.252	13.000	6.662
0.300	0.2178	4.400	2.353	13.300	6.812
0.400	0.2790	4.600	2.453	13.600	6.962
0.500	0.3381	4.800	2.554	13.900	7.112
0.600	0.3955	5.000	2.654	14.200	7.262
0.700	0.4517	5.200	2.755	14.500	7.412
0.800	0.5070	5.400	2.855	14.800	7.562
0.900	0.5615	5.600	2.956	15.100	7.712
1.000	0.6155	5.800	3.056	15.400	7.862
1.100	0.6690	6.000	3.156	15.700	8.013
1.200	0.7220	6.200	3.257	16.000	8.163
1.300	0.7748	6.400	3.357	16.300	8.313
1.400	0.8272	6.600	3.457	16.600	8.463
1.500	0.8794	6.800	3.558	16.900	8.613
1.600	0.9314	7.000	3.658	17.200	8.763
1.700	0.9832	7.300	3.808	17.500	8.913
1.800	1.034	7.600	3.958	17.800	9.063
1.900	1.086	7.900	4.109	18.100	9.213
2.000	1.137	8.200	4.259	18.400	9.363
2.100	1.188	8.500	4.409	18.700	9.513
2.200	1.240	8.800	4.560	19.000	9.663
2.300	1.291	9.100	4.710	19.300	9.813
2.400	1.342	9.400	4.860	19.600	9.963
2.500	1.393	9.700	5.010	20.000	10.16
2.600	1.444	10.000	5.160		

Source: S. C. Choi and R. Wette, "Maximum Likelihood Estimates of the Gamma Distribution and Their Bias," *Technometrics*, Vol. 11, No. 4, Nov. © 1969, pp. 688–9. Adapted with permission of the American Statistical Association.

Table A.10 Operating Characteristic Curves for The Two-Sided t Test for Different Values of Sample Size n



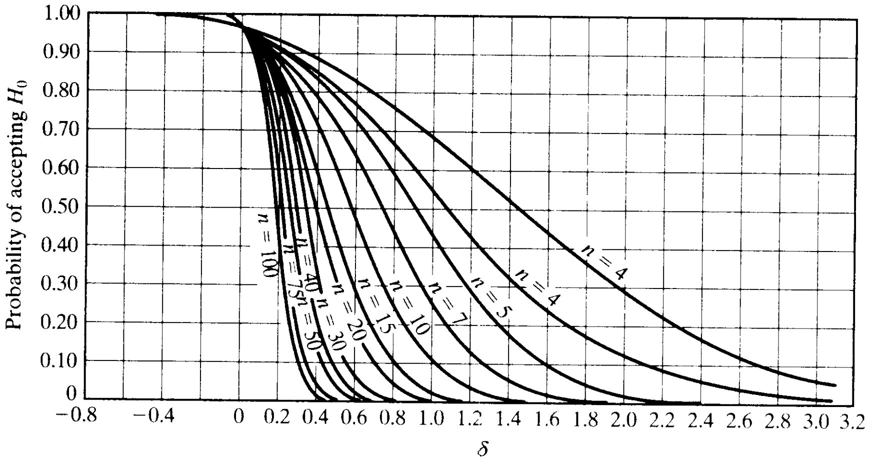
(a) $\alpha = 0.05$



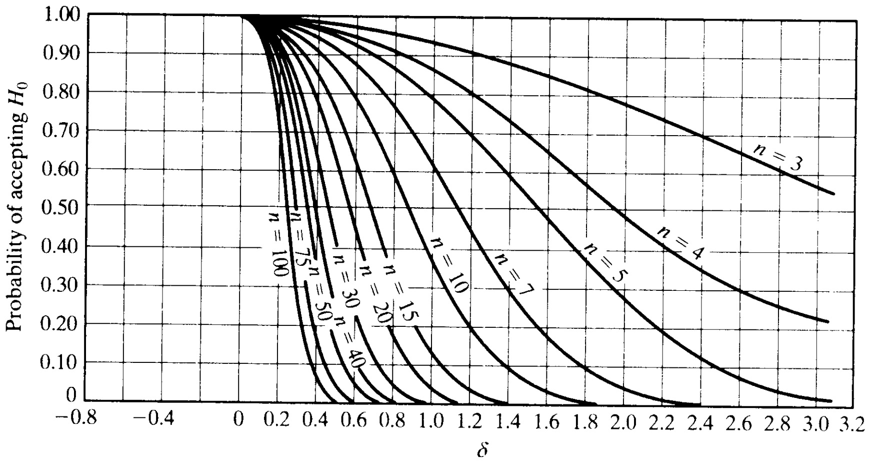
(b) $\alpha = 0.01$

Source: C. L. Ferris, F. E. Grubbs, and C. L. Weaver, "Operating Characteristics for the Common Statistical Tests of Significance," *Annals of Mathematical Statistics*, June 1946. Reproduced with permission of The Institute of Mathematical Statistics.

Table A.11 Operating Characteristic Curves for the One–Sided t Test for Different Values of Sample Size n



(a) $\alpha = 0.05$



(b) $\alpha = 0.01$

Source: A. H. Bowker and G. J. Lieberman, *Engineering Statistics*, 2d ed., © 1972, p. 203. Reprinted by permission of Prentice Hall, Upper Saddle River, NJ.

Index

A

Able-Baker call center problem, 62–63, 68, 338–339, 347–348
Abstraction, 451–452
  in computer systems, 450–452
Acceptance-rejection technique, 254–260
  gamma distribution, 259–260
  nonstationary Poisson process (NSPP), 258–259
  Poisson distribution, 255–258
Accumulating conveyor section, 428–429
Across-replication cycle-time data, 345–347
Activities, 61
  defined, 8
Activity-scanning approach, 66–68
Actual average cycle time, 344
Actual usage breakdowns, 431
AGV dispatching systems, 8
AGVs, *See* Automated guided vehicles (AGVs)
ALGOL, 87–88
Alternative system designs, 379–422
  common random numbers (CRN), 384–392
  comparison of, 393–401
    Bonferroni approach to multiple comparisons, 394–398
    Bonferroni approach to screening, 400–401
    Bonferroni approach to selecting the best, 398–400
    multiple linear regression, 409
    random-number assignment for regression, 409–410
    simple linear regression, 402–406
    testing for significance of regression, 406–408
    Two-Stage Bonferroni Procedure, 399–401
  comparison of two system designs, 380–393
  confidence intervals with specified precision, 392–393
  independent sampling:
    with equal variances, 383–384
    with unequal variances, 384
  optimization via simulation, 410–417
  systems performance, statistically and practically significant differences in, 382
American Statistical Association (ASA), 6
Ample-server system, 205
Analytical methods, 12
Anderson-Darling test, 293
Application Layer, 479
Application Program Interface (API), 106–107
Applied Research Laboratory, United States Steel Corporation, 88
Approximation for the M/G/c/∞ queue, 205
Arena, 14, 110–111
  Input Analyzer, 111

Arena (*continued*)
  Input Processor, 270
  Output and Process Analyzer, 116
  Professional Edition (PE), 110
  and SIMAN simulation language, 111
  Standard Edition (SE), 110
  website, 110
Arithmetic Logical Unit (ALU), 453
Arrays, storing records in, 79
Arrival process, queueing systems, 181–182
Arrivals class, 107–108
AS/RS (automated storage and retrieval system), 428
Assembly-line simulation, 437–443
  potential system improvements, analysis of, 441–442
  presimulation analysis, 439–440
  simulation model and analysis of the designed system, 440
  station utilization, analysis of, 440–441
  system description and model assumptions, 437–439
Association for Computing Machinery/Special Interest Group on Simulation (ACM/SIGSIM), 6
Associative memory, 473–474
@Risk's BestFit, 270
Attributes, 61
  defined, 8
Autocorrelation tests, 233–235
  for random numbers, 228–229
Automated guided vehicles (AGVs), 312, 428
Automated material handling systems (AMHS), 8
Automobile engine assembly problem, 410
AutoMod, 14, 111
  animation, 111
  AutoStat, 111
  AutoView, 111
  templates, 111
  website, 110
  worldview, 111
AutoStat, 15, 116
AutoView, 111
Average of the averages, 343
Average system time, 186–187
Awesime, 453

B

Baseline configuration, 438
Batch means, 340, 367, 370
Bernoulli distributions, 141
Bernoulli process, 141
Bernoulli trials, 141–142
Best fits, 293–294
Beta distributions, 141, 164–165
  physical basis of, 277
  suggested estimators, 281–287
BGP, 488
Bias, in point estimator, 341–342
Binomial distributions, 140–142
  physical basis of, 276
Bonferroni approach:
  to multiple comparisons, 394–398
  to screening, 400–401
  to selecting the best, 398–400
Bonferroni inequality, 394
Bootstrapping, 65
Bottom of a list, 78–79
Branch instructions, 470
Branches, 470
Breakpoints, 296
Bridge, 488
Bucket conveyors, 428
Burstiness, 458
  and traffic modeling, 482–483
Business process simulation, 7

C

C, 260, 313–314, 453
C++, 79, 260, 313–314, 453
C++SIM, 453
Calibration, 316
Call-center analysis, 8
Calling population, queueing systems, 20, 179–180
Cancellation of an event, 64
Carrier Sense Multiple Access/Collision Detection (CSMA/CD) protocol, 486
Carrying stock in inventory, 36
Central processing unit (CPU), 450, 452
Chains, *See* Lists
Chi-square distributions, 508
Chi-square test, 231–233, 270, 287–289
  computations for, 232–233
  with equal probabilities, 290–291
Classes, 79
Clock, 61
  and Java, 93
Clock-time breakdowns, 431
Combined linear congruential generators, 226–228

Commercial simulation languages, 453
Common random numbers (CRN), 379, 384–392
Component life, histograms of, 276
Computer systems:
  complexity of, 450
  levels of abstraction in, 450–451
  simulation of, 450–477
Computer-network simulations, 478–499
  data link layer, 487–488
  Media Access Control (MAC) protocol, 483–487
  Transport Control Protocol (TCP), 488–494
Computer-systems simulations, 450–477
  CPU simulation, 468–472
  event orientation, 456–457
  high-level computer simulations, 466–468
  memory simulations, 472–475
  model input, 457–466
    Modulated Poisson Process (MPP), 458–461
    virtual-memory referencing, 461–466
  process orientation, 454–456
  simulation tools, 452–457
Conceptual model, construction of, 311
Conditional event, 62
Conditional wait, 62
Confidence intervals, with specified precision, 392–393
Confidence-interval estimation, 343–344
  statistical background, 345–348
Congestion window size, 490
Conservation equation, 188–189
Construction engineering applications, simulation, 7
Continuous data, histograms for, 274–275
Continuous distributions, 146–165
  beta distribution, 164–165
  Erlang distribution, 151–153
  exponential distribution, 147–150
  gamma distribution, 150–151
  normal distribution, 153–159
  triangular distribution, 244–245
  uniform distribution, 146–147
  Weibull distribution, 159–160
Continuous model, 11–12
Continuous random variables, 132–134
Continuous system, 11
Continuous uniform distributions, physical basis of, 277
Continuous-time data, 341
Control and Simulation Language (CSL), 88
Control sampling variability, 414
Conventional limitations, as source of process information, 295
Conveyor sections, classification of, 428
Conveyors, classification of, 428–429
Convolution of distributions, 261
Correlated sampling, 379, 441
Covariance-stationary process, 297, 359
CPU simulations, 457, 468–472
Critical path, 51
CSIM, 453
Cumulative averages, 358
Cumulative distribution function (cdf), 134–136
Cumulative normal distribution, 503–504
Cumulative Poisson distribution, 505–506
Current contents and model reasonableness, 313
Cycle breakdowns or failures, 431

D

Data assumptions, 317
Data collection, guidelines for, 270–272
Data Link Layer, 478–479, 487–488
  protocols at, 479
Data-frames, 478–479
Debugger, 312
Dedicated random-number stream, 386
Delay, 61, 187
Delmia/QUEST, 114
  website, 110
Design variables, 402
Deterministic duration, 62
Deterministic simulation models, 11
Direct execution, defined, 465
Direct-execution simulation, 465–466, 473
Discrete data, histograms for, 273
Discrete distributions, 141–146, 250–254
  Bernoulli trials and the Bernoulli distribution, 141
  binomial distribution, 142–143
  discrete uniform distribution, 252–253
  empirical discrete distribution, 250–252
  geometric and negative binomial distributions, 143–144
  geometric distribution, 253–254
  physical basis of, 277
  Poisson distribution, 144–145
Discrete model, 12
Discrete random variables, 132, 141
Discrete system, 9

Discrete uniform distributions, 252–253
Discrete-event models, 60
Discrete-event simulation, 12, 60, 451
  concepts in, 61–78
  defined, 63
Discrete-time data, 341
Distribution applications, simulation, 7
Distribution of maximum ignorance, 141
Documentation, 314
Domain Modeling Language (DML) files, 495
Doubly-linked lists, 83
Dump-truck problem, 73–77, 389–392
Dynamic allocation, and linked lists, 81
Dynamic simulation models, 11

E

ECSL, 88
Ehrhardt, I., 436
Empirical distributions, 169–171, 245–249
  discrete distributions, 250–252
  physical basis of, 276
Emulation, 8
End of downtime, 66
End of runtime, 66
End-loading event (EL), 75
Endogenous events/activities, 9
Engineering data, as source of process information, 295
Ensemble averages, 354, 357–358
Entities, 3, 61, 79
  defined, 8
Ergodic chains, 458
Erlang distributions, 151–153
  and convolution method, 261–262
  physical basis of, 277
Ertek, G., 436
Ethernet, 483, 486–487
Ethernet frame, format of, 486
Event Class, 95
Event list, 61
Event methods, Java, 93
Event notices, 61, 78
Event orientation, 456–457
Events, 9, 21, 61
Event-scheduling simulation, 69–78
  checkout-counter simulation problem, 72–73
  dump-truck problem, 73–77
  single-channel queue, 69–72
Event-scheduling simulation program, overall structure of, 93–94
Event-scheduling/time-advance algorithm, 64–65
Exogenous events, 64
Expectation, 136–137
Experimentation and statistical-analysis tools, 115–116
  common features, 115
  products, 116
    Arena's Output and Process Analyzer, 116
    AutoStat, 116
    OptQuest, 117
    SimRunner, 117
Expert option, as source of process information, 295
ExpertFit, 270
Exponential backoff, 487
Exponential distributions, 168, 182, 275-276
  physical basis of, 277
  suggested estimators, 281
Extend, 14, 111
  website, 110

F

Face validity, 317
Family of distributions, selecting, 275–277
FEL, 61, 63–66
  end-loading event (EL) on, 75
Fields, 78
FIFO (first in, first out), 20
Finite population models:
  compared to infinite models, 179–180
  steady-state behavior of, 208–211
First-in-first-out (FIFO), 182
"Fixed" backoff, 487
Fixed-sample-size procedures, 393–394
Fixed-window conveyors, 429
Flexibility, in simulation tools, 456–457
Flexsim, 14
  animation, 111–112
  simulation models, 111
  website, 110
Flexsim Software Products, Inc., 112
FORTRAN, 78–79, 87–89, 93, 260, 314
Forwarding tables, 488
Frames, 483
Free-path transporters, 428
Frequency tests, 229–233
  chi-square test, 231–233
  Kolmogorov-Smirnov test, 230–233
  for random numbers, 229
Fully associative cache, 473

Functional abstraction, 452
Future event list (FEL), *See* FEL
FutureEventList, 93

G

GA, *See* Genetic algorithms (GA)
Gamma distributions, 139–141, 150–151, 181–182, 276
  acceptance-rejection technique, 259–260
  maximum likelihood estimates of, 511
  physical basis of, 314
  suggested estimators, 281
Garbage-in-garbage-out (GIGO), 270
GASP (General Activity Simulation Program), 87–88
  GASP IV, 88
gcc compiler, 462
Gebhardt, H., 436
General Simulation Program, 87–88
Generation, 413
Generator matrix, 458
Genetic algorithms (GA), 413–414
Geometric and negative binomial distributions, 143–144
Geometric distributions, 140, 150, 253–254
GIGO, 270
Goodness-of-fit tests, 287–294
  best fits, 293–294
  chi-square test, 287–288
  chi-square test with equal probabilities, 290–291
  Kolmogorov-Smirnov test, 292–293
  p-values, 293–294
Gordon, Geoffrey, 88
GPSS (General Purpose Simulation System):
  development of, 88
  simulation in, 102–106
GPSS/360, 86–87
GPSS/H, 14, 86–88, 93, 102
  single-server queue simulation in, 102–105
GPSS/NORDEN, 88
Graphical interfaces, and verification/validation, 313

H

Head of a list, 78
Head pointer, 78
Health care applications, simulation, 7
Heavy-tailed distributions, 479–483
Henriksen, James O., 88
Herper, H., 436
High-level computer simulations, 466–468
Histograms, 272–275
  of component life, 276
  for continuous data, 274–275
  for discrete data, 273
Hit ratio, 462, 473–475
Hixson, Harold, 87
Hubs, 488
Hurst parameter, 482
Hyperexponential distribution, 141

I

IBM, 88
Imagine That, Inc., 111
Imminent event, 63–64
in_service Variable, 108
inChannel classes, 107
Independent replications, 345
Independent sampling, 379
  with equal variances, 383–384
  with unequal variances, 384
Infinite population models, compared to finite models, 180
Infinite-population Markovian models, steady-state behavior of, 194–208
  single-server queues with Poisson arrivals/unlimited capacity, 195–201
Initial conditions, 336
Initialization method, 93, 97
Input modeling, 269–309
  data collection, 270–272
  defined, 269
  fitting a nonstationary Poisson process (NSPP), 294–295
  goodness-of-fit tests, 287–289
    best fits, 293–294
    chi-square test, 287–289
    chi-square test with equal probabilities, 290–291
    Kolmogorov-Smirnov test, 292–293
    p-values, 293–294
  identifying the distribution with data, 272–279
    histograms, 272–275
    quantile–quantile (q–q) plots, 277–279
    selecting the family of distributions, 275–277
  parameter estimation, 280–287
    sample mean and sample variance, 280–281
    suggested estimators, 281–287

Input modeling (*continued*)
  steps in development of a useful model of input data, 269–270
Input models:
  multivariate and time-series input models, 296–303
    covariance and correlation, 297
    multivariate input models, 298–299
    normal-to-anything transformation (NORTA), 301–303
    time-series input models, 299–301
  without data, selecting, 295–296
Input-Output (I/O) system, 452–457
Input-output transformations:
  validation process, 318–327
    using historical input data, 327–331
Institute for Operations Research and the Management Sciences: College on Simulation (INFORMS/CS), 6
Institute of Electrical and Electronics Engineers: Computer Society (IEEE/CS), 6
Institute of Electrical and Electronics Engineers: Systems, Man and Cybernetics Society (IEEE/SMCS), 6
Institute of Industrial Engineers (IIE), 6
Instruction complete, 469
Instruction decode, 469
Instruction execute, 469
Instruction fetch, 469
Instruction graduate, 469
Instruction issue, 469
Instruction level parallelism (ILP), 469
Instruction-complete stage, 470–471
Instruction-decode stage, 470
Instruction-execute stage, 470
Instruction-fetch stage, 470
Instruction-issue stage, 470
Insurance company problem, 402
Intelligent initialization, 353
Interactive Run Controller (IRC), 312
Interarrival processes, 457
Internet Protocol (IP), 479
Inventory and supply-chain systems, 140
Inventory policy, 372
Inventory systems:
  and random number synchronization, 385–386
  simulation of, 35–42
    news dealer's problem, 36–39
    order-up-to-level inventory system, 40–42
Inverse-transform technique, 240–254
  continuous distributions without a closed-form inverse, 249–250
  discrete distributions, 250–254
  empirical distributions, 245–249
  exponential distribution, 240–243
  triangular distribution, 244–245
  uniform distribution, 243–244
  Weibull distribution, 244
IP (Internet Protocol), 479

J

Java, 79, 81–82, 92, 260, 313, 453
  online resources for learning, 93–94
  simulation in, 93–102
  single-server queue simulation in, 95–102
  /Thread/ class, 454
Java simulation program, overall structure of, 95
Joshi, S. B., 435
Just-in-Time (JIT), 436

K

Kiviat, Phillip J., 88
Kolmogorov-Smirnov critical values, 510
Kolmogorov-Smirnov test, 230–233, 270
  calculations for, 233
  as goodness-of-fit test, 292–293

L

L1 cache, 473
Lack-of-fit test, 406
Lag, 234, 359
Lag-h autocorrelation, 297
Lag-h autocovariance, 297
Last-in-first-out (LIFO), 182
Lead time, 40, 140
Lead-time demand, 47–49
Least Recently Used (LRU), 474
  stack evolution, 475
Least-squares function, 403
Linear congruential method, 223–226
  or random-number generation, 223–226
Linked lists, 78
Liquified natural gas (LNG) transportation problem, 410
List processing, 64, 78–83
  basic properties/operations performed on lists, 78–79
  defined, 78

  using arrays for, 79–81
    future event list and dump-truck problem, 82–83
    list for dump trucks at weigh queue, 79–81
Lists, 61
Local area network (LAN), 483
Locality of reference, 462
Logistics applications, simulation, 7
Lognormal distributions, 141, 163–164
  pdf of, 163
  physical basis of, 276
  suggested estimators, 281–282
Long-range dependence, 481–482
Long-run average system time, 187
Long-run time-average number, 185
Lost sales case, 40

M

MAC protocol, 479, 487–488
Main program, Java, 93
"Making up backorders," 40
Manufacturing and material-handling systems, 425–449
  assembly-line simulation, 437–443
    potential system improvements, 441–442
    presimulation analysis, 439–440
    simulation model and analysis of the designed system, 440
    station utilization, 440–441
    system description and model assumptions, 437–439
  case studies of the simulation of, 435–437
  defined, 425
  goals and performance measures, 429–430
  manufacturing and material-handling simulations, trace-driven models, 433–435
  manufacturing-simulation models, major goals of, 429
  modeling issues in, 430–435
    modeling downtimes and failures, 430–433
  non-manufacturing material-handling systems, 429–430
  simulation projects, 426–429
    material-handling equipment, 428–429
    models of manufacturing systems, 426–427
    models of material handling systems, 427–428
Manufacturing applications, simulation, 6
Markov chain transitions, 452
Markovian models, 195
Markowitz, Harry, 88
Materials handling system (MHS) problem, 410
Mathur, Mahesh, 436
Maximum density, 224
Maximum period, 224
Maximum-likelihood estimators, 281
Measures of performance, 3
  confidence-interval estimation, 343–344
  point estimation, 341–343
    Media Access Control (MAC) protocol, 479, 483–487
  Ethernet, 486–487
  token-passing protocols, 483–486
Median-spectrum test, 229
Memory simulations, 457, 472–475
Memoryless property, 149, 166
Metaheuristics, 115
Metamodeling, 402
Micro Analysis and Design, Inc., 113
Micro Saint, 14, 113
  website, 110
Microsoft Windows XP, 109
Mid pointer, 83
Military applications, simulation, 7
Milling-machine-bearings-replacement-policy problem, 391
Min-time event method, Java, 93
Mixed congruential method, of random-number generation, 223
M/M/c/K/K queue, steady-state probabilities for, 208
Mode, 137
Model assumptions:
  types of, 317
  validation of, 317–318
Model building, verification and validation, 311
Model input, 457–466
  computer-systems simulations, 457
    Modulated Poisson Process (MPP), 458–461
    virtual-memory referencing, 461–466
Model input-output transformations, validation process, 318–327
  Turing test, 331
Model reasonableness, 318
  indicators of, 314
Models, 9, 61, 335–378
  defined, 3
  types of, 11

Modulated Poisson Process (MPP), 458–461
Monotonicity, 386
Monte Carlo simulation, 11
Multiple linear regression models, 409
Multiple ranking and selection procedure, 393
Multiplicative congruential method, of random-number generation, 223
Multiplier, 223
Multiserver queues, 201–204
  with Poisson arrivals and limited capacity (M/M/c/N/∞), 206–208
Multistage procedures, 393
Multivariate and time-series input models:
  covariance and correlation, 296–297
  normal-to-anything transformation (NORTA), 301–303

N

Nance, Richard, 86
Nandi, A., 437
National Institute of Standards and Technology (NIST), 6
Nature of the process, as source of process information, 295
Negative binomial distributions, 140–141, 143–144
  physical basis of, 277
Network Layer, 479, 488
Networked systems design, 478
  Application Layer, 479
  Data Link Layer, 478–479
  Network Layer, 479, 488
  Physical Layer, 478
  Presentation Layer, 479
  Session Layer, 479
  traffic modeling, 479–483
  Transport Layer, 479
Network-Host-Interface (NHI) convention, 495
Networks, 478–499
  of queues, 211–213
nextDouble Method, 100
Nonaccumulating conveyor section, 428
Non-manufacturing material-handling systems, 430
Nonstationary Poisson process (NSPP), 168–169
  acceptance-rejection technique, 258–259
  fitting, 294–295
Nonstationary simulation, 337
Nonterminating system, 337
Nonzero autocorrelation, 234
Normal distributions, 153–157, 275–276
  pdf of, 153–154
  physical basis of, 277
  special properties of, 153–154
  suggested estimators, 281
  transforming to, 155
  using the symmetry property of, 156
"Normal equations," 403
Normal-theory prediction interval, 344
Normal-to-anything transformation (NORTA), 301–303
NSPP, *See* Nonstationary Poisson process (NSPP)
*N*th moment, 136
Number of Servers is Infinite (M/G/∞/∞), 205
Numerical methods, 12

O

Offered load, 191
On-line information services problem, 410
Open System Interconnection (OSI) Stack Mode, 478
Operating characteristic curves, 512–513
Operational model, implementation of, 311–312
Optimization, 115
Optimization via simulation, 410–416
  defined, 411–412
  difficulty of, 412
  random search, 415–417
  robust heuristics, 413–414
    control sampling variability, 414
    restarting, 415
OptQuest, 15, 113, 117
Order-up-to-level inventory system, 40–42
OSPF, 488
outChannel classes, 107
Output analysis, 311
  defined, 335
  measures of performance and their estimation, 341–344
  for a single model, 335–378
  for steady-state simulations, 352–370
    batch means for interval estimation, 367–368
    error estimation, 359–362
    initialization bias, 353–358
    quantiles, 370
    replication method, 362–365

    sample size, 365–367
  stochastic nature of output data, 338–341
  for terminating simulations, 344–352
    confidence intervals with specified precision, 348–351
    estimating probabilities and quantiles from summary data, 351–352
    statistical background, 345–348
Overall error probability, 394–395
Owen, D.G., 87

P

Packet loss, 479
Page fault, 462
Page frames, 461
Pages (units), 461–462
Parallel service mechanisms, 182
Parameter estimation, 280–287
  sample mean and sample variance, 280–281
  suggested estimators, 281–287
Pareto distribution, 460
Pascal, 314
Pegden, C. Dennis, 89
Pending customer, 182
Periodic downtime, 430
Petri nets, 453
Physical Layer, 478
Physical or conventional limitations, as source of process information, 295
Picture formatting, 105
Pierce, Neal G., 435
Point estimate, 339
Point estimation, 341–342
Point estimator:
  bias in, 341–342
  unbiased, 341
Poisson arrival process, 181–182
Poisson distributions, 140–141, 143–144, 275–276
  acceptance-rejection technique, 255–258
  physical basis of, 277
  suggested estimator, 281
Poisson Pareto Burst Process, 481
Poisson probability mass function, 144
Poisson process, 165–169
  nonstationary, 168–169
  properties of, 167
Pooled process, 167
Positive autocorrelation, 341
Power of a test, 290
Presentation Layer, 479
Primary event, 62
Pritsker, Alan, 88
Probability density function (pdf), 132
Probability distribution, 132
Probability mass function (pmf), 132
Procedure, 412
ProcessArrival, 98
ProcessDeparture, 98
Process-interaction approach, 66–68
Program documentation, 15
Programmable logic controllers (PLCs), 8
Programming languages, and random-variate-generation libraries, 239
Progress reports, 15
Project management applications, simulation, 6
Project reports, 15
ProModel, 14, 113
  OptQuest Optimizer for, 113
  website, 110
Proof Animation, 102
Protocols, at the Data Link Layer, 478
ProtocolSession, 496, 498
Pseudo-random numbers, generation of, 222–223
P-values, 293–294

Q

Quantile–quantile (*q*–*q*) plots, 277–279
Quantiles, 370
Quest, 14
Queue behavior, 182
Queue discipline, 182
Queueing, 431
  effect of downtime on (problem), 432–433
Queueing Event Simulation Tool (QUEST), 114 Queueing models, 178–218
  defined, 178
Queueing networks, 453, 457
Queueing notation, 184
  for parallel server systems, 184
Queueing problems, costs in, 194
Queueing systems, 138–140
  Able-Baker call center problem, 32–35
  arrivals, 20
  calling population, 20
  characteristics, 179–184
    arrival process, 181–182
    calling population, 179–180

Queueing systems *(continued)*
      service mechanism, 182–184
      service times, 182
      system capacity, 180
   examples of, 180
   long-run measures of performance of, 185–194
      average time spent in system per customer, 186–188
      server utilization, 189–193
      time-average number in system, 185–186
   measures of performance in, 314
   services, 20
   simulation of, 20–35
   single-channel queue, 20
   single-channel queue problem, 25–30
   waiting line, 20
Queueing theory, 178, 406
Queues, *See also* Lists
   defined, 184
   networks of, 211–213

R

Ramaswamy, S. E., 435
RAND Corporation, 88
RAND() function, Excel, 22
Random digits, 501
Random Early Detection (RED), 488
Random normal numbers, 45–47, 502
Random number synchronization, 385–386
Random numbers:
   defined, 221
   distribution of, 22–23
   frequency tests for, 229
   generation of, 223
      combined linear congruential generators, 226–228
      random-number streams, 228
      techniques for, 223–228
   pdf for, 222
   properties of, 221–222
   pseudo-random numbers, generation of, 222–223
   routines, 223
   tests for, 228–235
      autocorrelation tests, 229, 233–235
      frequency tests, 229, 230–233
Random search, 415–417
   implementation problem, 416
Random splitting, 167
Random unscheduled downtime, modeling, 430–431
Random-number generation, 221–238
Random-number generators, 386
Random-search algorithm, 415
Random-spacing conveyors, 428
Random-variate generation, 239–266
   acceptance-rejection technique, 254–260
      gamma distribution, 259–260
      nonstationary Poisson process (NSPP), 258–259
      Poisson distribution, 255–257
   inverse-transform technique, 240–254
   special properties, 260–263
      convolution method, 261–262
      direct transformation for the normal and lognormal distributions, 260–261
Random-variate generators, 241
   Java, 93
Records, 78
"Register-transfer-language," 452
Regression analysis, 402, 406
Reitman, Julian, 88
Reliability function, 152
Report generator, Java, 93
ReportGeneration method, 100
Residual analysis, 406
Robust heuristics, 413–414
   control sampling variability, 414
   restarting, 415
Rogers, P., 437
Routers, 479, 488
Routines, 223
Routing algorithms, 488
Runs test, 229
Runtime, 181
RVEXPO, 102–103

S

Sadowski, Randall P., 436
Sample mean, 280–281
Sample variance, 280–281
Sampling numbers, 229
Saraph, P. V., 437
Scalable Simulation Framework (SSF), 106–109
Scale parameter, 150
Scatter diagram, 405

Scheduled downtime, 430
Scott, Harold A., 435
Screening procedure, 400
Secondary event, 62
Seed, 223
Selective trace, 315
SELFIS tool, 482
Semiconductor manufacturing applications, simulation, 6
Sensitivity analysis, 317
Sequential sampling scheme, 393
Server utilization, 189–193
  and service variability, 199–201
  and system performance, 192–193
Server utilization in G/G/1/∞/∞ queues, 189
Server utilization in G/G/c/∞/∞ queues, 191
Service according to priority (PR), 182
Service completion, 66
Service in random order (SIRO), 182
Service mechanism, queueing systems, 182–184
Service rate, 189
Service times, queueing systems, 182
service-time variable, 270
Service-time distributions, and data collection, 270
Session Layer, 479
Set associativity, 473
Sets, *See* Lists
Shape parameter, 150
Shortest processing time first (SPT), 182
Short-term congestion, 431
Significance of regression, testing for, 406–407
Significant differences in, 382
SIMAN (SIMulation ANalysis), 89
  and Arena, 111
SIMAN V, 86
SimPack, 453
Simple linear regression, 402–406
SimRunner, 15, 117
SIMSCRIPT, 87
SIMSCRIPT II, 88
SIMUL8, 14, 114–115
  website, 110
SIMULA, 87–88
Simulation:
  advantages of, 5–6
  applications of, 6–8
  of computer systems, 450–477
  defined, 5
  disadvantages of, 5
  examples, 19–59
  in GPSS, 102–106
  of inventory systems, 35–46
  in Java, 93–102
  of large-scale systems, 8
  lead-time demand, 47–50
  and numeric measures of performance, 429
  optimization via, 410–417
  of queueing systems, 20–35
  random normal numbers, 45–47
  reliability problem, 43–45
  in SSF, 106–109
  statistical models in, 131–177
  steps in, 19
  uses of, 4
  types of, with respect to output analysis, 336–338
  when not to use, 4–5
Simulation analysis, 178
Simulation clock, 21–22
Simulation Language for Alternative Modeling (SLAM), 89
Simulation languages, 14, 341
  and random numbers, 221
Simulation libraries, 93
Simulation models:
  calibration, 316
  compared to optimization models, 5
  conceptual model, construction of, 311
  input-output transformations, validation process, 318–327
  model building, 311–312
  observation, 295
  operational model, implementation of, 311–312
  validation of, 316–326
  verification process, 311–315
Simulation packages, 60–61
  advanced techniques, 83
  world views, 66–67
Simulation programming languages (SPLs), 86–87
Simulation software:
  history of, 87–89
    Advent (1961–65), 87
    Consolidation and Regeneration (1979–86), 89
    Expansion Period (1971–78), 88
    Formative Period (1966–70), 88
    Integrated Environments (1987-present), 89

Simulation software: (*continued*)
      Period of Search (1955–60), 87
   packages, 109–115
      animation, 109
      Arena, 110–111
      AutoMod, 111
      common characteristics, 109
      Extend, 111–123
      features, 109–110
      Flexsim, 112
      Micro Saint, 113
      process-interaction worldview, 110
      ProModel, 113
      QUEST, 114
      SIMUL8, 114–115
      and tracing, 315
      WITNESS, 115
   selection of, 89–92
      animation and layout features, 91
      checkout counter example simulation, 93
      features, 89–92
      output features, 92
      runtime environment, 91
      vendor support and product documentation, 92
Simulation study, steps in, 12–16
   data collection, 14
   documentation and reporting, 15
   experimental design, 15
   implementation, 16
   model conceptualization, 14
   model translation, 14
   problem formulation, 12
   production runs and analysis, 15
   setting of objectives/overall project plan, 12
   validation, 15
   verification, 14
Simulation trace, 314–315
Simulation-language-specific interpreter, 454
Simulation-model building process, phases of, 13, 16
Single-channel queuing simulation, interarrival times/service times, generation of, 20
Singly-linked lists, 82–83
SLAM II, 86, 89
Slot time, 485
Smith, G. D., 435
Smith, J. S., 435
Society for Computer Simulation (SCS), 6
Sockets, 489
Specialized conveyors, 429–430
Special-purpose simulation languages, 4
Speculative register state, 470
SSF, 93, 106–109
SSFNet, 492–498
   construction, 495–498
   DML models, common attributes in, 496
   DML structure, 495–496
   documentation, 494–497
   example, 495–498
SSQueue class, 93
Stack distance, 474
Stack policies, 474
Stafford, Richard, 435
Stat::Fit, 270
State, threads, 454
State of a system, 9, 21, 61
Static simulation model, 11
Stationary probability, 458
Statistical duration, 62
Statistical models, 137–141
   Bernoulli distributions, 141
   beta distributions, 141
   binomial distributions, 141–143
   gamma distributions, 150–151
   inventory and supply-chain systems, 140
   limited data, 141
   lognormal distributions, 141
   negative binomial distributions, 143–144
   Poisson distributions, 140–143
   queueing systems, 138–140
   reliability and maintainability, 140
   uniform distributions, 141
   Weibull distributions, 139–140
Statistical models in simulation, 131–177
Statistical-analysis software, 290
Steady-state behavior:
   of finite-population model, 208–211
   of infinite-population Markovian models, 194–208
Steady-state simulations, 338–339
   batch means for interval estimation, 367–369
   error estimation, 359–362
   initialization bias, 353–358
   output analysis for, 352–370
   quantiles, 349
   replication method, 362–364
   sample size, 365–367
Stochastic input models, 457
   and burstiness, 458
Stochastic nature of output data, 338–341

Stochastic simulation model, 11
Stopping time, 336
Structural assumptions, 317–318
Sturrock, D. T., 435
Subset selection procedure, 400–401
Successive times to failure, 182
Suggested estimators, 281–282
  beta distributions, 282, 287
  exponential distributions, 282, 284
  gamma distributions, 282
  lognormal distributions, 282
  normal distributions, 282
  Poisson distributions, 282
  Weibull distributions, 282, 284
Supply chain applications, simulation, 7
Surge model, 480
System capacity, queueing systems, 180
System environment, defined, 8
System state, *See* State of a system
Systems, 43, 450–472
  components of, 8–9
  continuous, 9
  defined, 8
  discrete, 9
  event orientation, 456–457
  with external arrivals, 386
  model of, 9
  process orientation, 454–456
  simulation tools, 452–457
Systems Modeling Corporation, 89
Systems performance, distinction between statistically and practically significant differences in, 382

T

Table-lookup generation scheme, 249
Tabu search (TS), 413–414
Tail of a list, 78
TCP, *See* Transport Control Protocol (TCP)
tcpdump, 491
TcpServer protocol, 498
TcpSessionMaster, 498
Terminating simulation, defined, 336
Terminating simulations, output analysis for, 344–352
Testing for the significance of regression, 406–408
  problem, 408
Thinning, 258
Threads, 454–455
Three-phase approach, 68
Tilt-tray conveyors, 428
Time average, 342
Time series, 359
  defined, 297
Time to failure, 182, 244, 431
Time to repair, modeling, 431
Time-integrated average, 186
Time-series input models, 296
Tocher, K.D., 87
Token bus protocol, 483
Token-passing protocols, 483–486
Top of a list, 78
Total count, and model reasonableness, 313
TotalCustomers, 98
Trace-driven models, 433–435
  defined, 433
  examples of, 434
Tracing, 314–315
Traffic modeling, 479–483
Traffic signal sequencing problem, 410
Transactions, 102
Transformed linear regression model, 403
Transient behavior, 77
Transient simulation, 337
Transport Control Protocol (TCP), 479, 480, 488–494
  AckN field, 489–491
  bandwidth, 490
  congestion window size, 490
  cwnd variable, 491–494
  header format, 490
  Receiver window size, 490
  round-trip time (RTT), 491–492
  segments, 489–490
  send window, 490
  SeqN field, 489–494
  slow start mode, 491
  sockets, 489
  ssthresh variable, 491–494
Transport Layer, 479
Transportation modes and traffic applications, simulation, 7
Triangular distribution, 161–163, 244–245
  density function for, 245
  mode, median, and mean for, 162
  pdf of, 161–162
Triangular distributions, 248–250
  physical basis of, 277
Truncated normal distributions, 182
Turing test, 331

Turkseven, C. H., 436
Two-Stage Bonferroni Procedure, 399–400

U

Unbiased point estimator, 341
Unconditional wait, 62
Uniform distributions, 141, 146–147
Unscheduled random downtimes, 430–433

V

Validation, 310–334
  defined, 310
Validation process, 316–327
  face validity, 317–318
  goal of, 310
  input-output transformations, 318–327
  three-step approach to, 317
  validation of model assumptions, 317–318
Variance heterogeneity test, 229
Vehicle-safety inspection system, comparison of system designs for, 387–388
Verification, defined, 310
Verification process, 311–315
  guidelines for, 312–313
VHDL language, 453–454
Virtual memory, 462
Virtual-memory referencing, 461–466
Visual Basic, 260
Visualization, and model credibility, 429
Voice over IP (VoIP), 480

W

Warehouse management systems (WMS), 8
Watson, Edward F., 436
Website server problem, 466–468
Weibull distributions, 139–141, 159–160, 182, 276
  physical basis of, 277
  suggested estimators, 281, 303
Winter Simulation Conference (WSC), 6, 86, 435
  papers:
    Behavior of an Order Release Mechanism in a Make-to-Order Manufacturing System with Selected Order Acceptance, 437
    Developing and Analyzing Flexible Cell Systems Using Simulation, 436
    Discrete Event Simulation for Shop Floor Control, 435
    Inventory Cost Model for Just-in-Time Production, 436
    Modeling Aircraft Assembly Operations, 435
    Modeling and Simulation of Material Handling System for Semiconductor Wafer Manufacturing, 435
    Modeling Strain of Manual Work in Manufacturing Systems, 436
    Shared Resource Capacity Analysis in Biotech Manufacturing, 436
    Simulation Modeling for Quality and Productivity in Steel Cord Manufacturing, 436
Within-replication cycle-time data, 345–346
WITNESS, 14, 115
  website, 110
WITNESS Optimizer, 15
Wolverine Software, 88, 102
Working set, 462
Work-in-process (WIP), 345, 427, 437
World Wide Web, and application traffic, 480
Wysk, R. A., 435

Srinivas Institute of Technology
Acc. No.:.... 17209
Call No.: