Title: A Review of 70 Years of Monte Carlo Development at Los Alamos: 1953 - 2023

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A Review of 70 Years of Monte Carlo Development at Los Alamos: 1953 – 2023

Colin Josey, Avneet Sood

July 2023

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Abstract

The invention of both the Monte Carlo neutron transport methods in 1947 and deterministic discrete ordinates Sn in 1953 were all made at Los Alamos just after the Manhattan Project. The creators of these methods were Drs. Stanislaw Ulam, John von Neumann, Robert Richtmyer, and Nicholas Metropolis. Monte Carlo methods for particle transport have been driving computational developments since the beginning of modern computers; this continues today. A series of special-purpose Monte Carlo codes, including MCS, MCN, MCP, and MCG were created to transport neutrons and photons for specialized LANL applications.

This work briefly summarizes the motivation and development of early simpler and more specialized Monte Carlo codes that were specifically developed for and tightly constrained by computing hardware and programming languages available in the early days of high-performance computing in the 1950 through the 1970s.

Outline

- Origins of the Monte Carlo method
  - Development of electronic computers and the Monte Carlo method occur simultaneously
  - Ulam, Von Neumann, Richtmeyer, Metropolis, Fermi
- Early Los Alamos Monte Codes MCS, MCN, and Others
  - several special purpose codes were developed
  - codes were merged to facilitate efficient code development
- Emergence of MCNP
- MCNP’s history

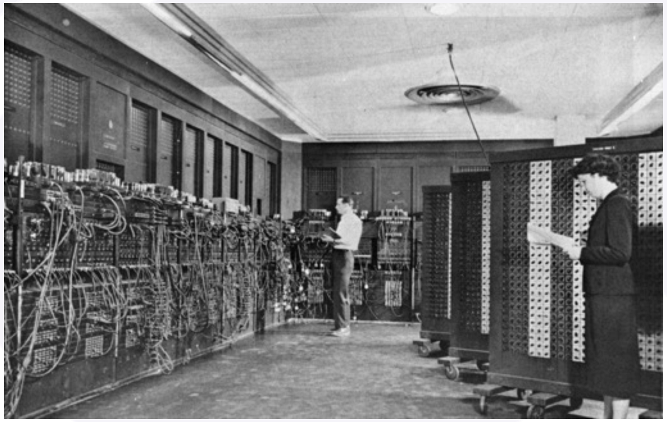
The Origins of Monte Carlo – 1946 Stanislaw Ulam

- “*The year was 1945. Two earthshaking events took place: the successful test at Alamogordo and the building of the first electronic computer*” – N. Metropolis
- The method was invented by Stanislaw Ulam in 1946 playing Solitaire while recovering from an illness.
- “*After spending a lot of time trying to estimate success by combinatorial calculations, I wondered whether a more practical method…might be to lay it out say one hundred times and simply observe and count the number of successful plays*” – S. Ulam

“Stan Ulam, John von Neumann, and the Monte Carlo Method,” R. Eckhardt, Los Alamos Science Special Issue 1987.

Stanislaw Ulam

WITH HIS WIFE, Klara, Von Neumann stood outside their Princeton home just after he was named to AEC. Dog has mathematical name, Inverse.



ENIAC– the first electronic computer, University of Pennsylvania. Solved ballistic trajectory problems for Army Ballistics Research Lab. Used electron tubes instead of mechanical counters. Minutes instead of days. Declassified in 1946.

The Origins of Monte Carlo

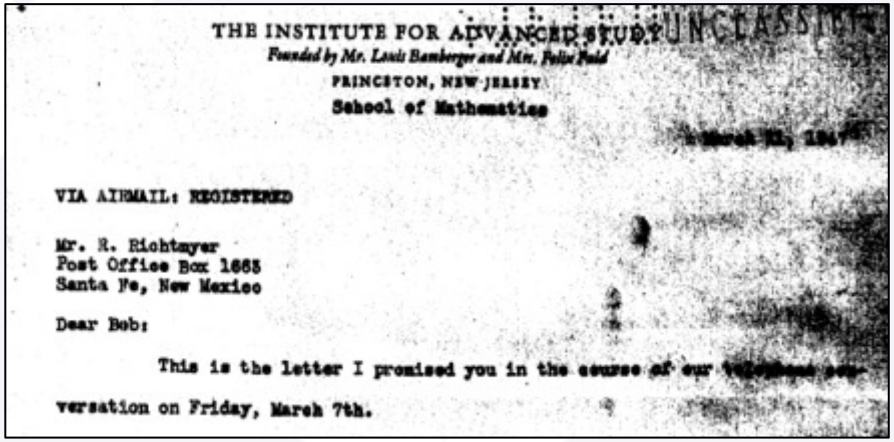
- Ulam describes this idea to John von Neumann in a conversation in 1946
- Von Neumann is intrigued
  - 1943: Electro-Mechanical computers solved non-linear diff. eq. via production line. Punch card used for every point in space/time
  - New computers could count/arithmetic and hence solve difference equations (BRL at Aberdeen, MD)
  - Statistical sampling on electronic computers
  - Especially suitable for exploring neutron chain reactions in fission – neutron multiplication rates
- R.D Richtmyer and J. von Neumann “Statistical Methods in Neutron Diffusion”, Los Alamos (LAMS-557) April 9, 1947.
  - Detailed letter from John von Neumann to Robert Richtmyer describing a conversation in March 1947
    - “I have been thinking a good deal about the possibility of using statistical methods to solve neutron diffusion and multiplication problems in accordance with the principle suggested by Stan Ulam”
    - Letter contained 81-step pseudo code for using MC for particle transport

J. Von Neumann invented scientific computing in the 1940’s
- Stored programs now called software
- Algorithms/Flowcharts
- Hardware design

Klara von Neumann ran the earliest calculations on ENIAC


John von Neumann


Klara and John von Neumann


THE INSTITUTE FOR ADVANCED STUDY UNCLASSIF
Founded by Mr. Louis Bamberger and Mrs. Felix Fuld
PRINCETON, NEW JERSEY
School of Mathematics

March 11, 1947

VIA AIRMAIL: REGISTERED

Mr. R. Richtmyer
Post Office Box 1663
Santa Fe, New Mexico

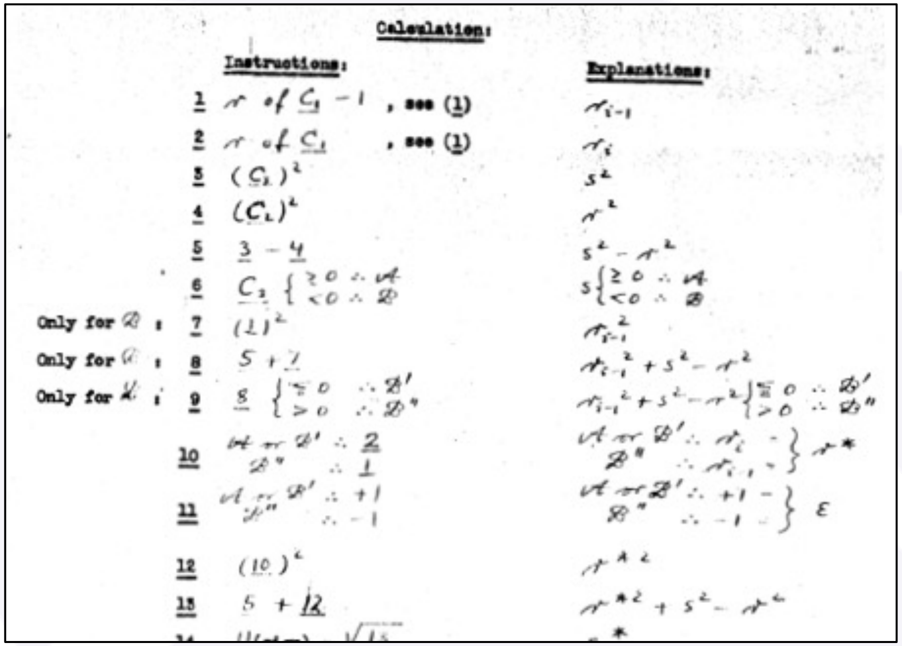
Dear Bob:

This is the letter I promised you in the course of our telephone conversation on Friday, March 7th.

The First Monte Carlo (pseudo) Code - 1947

- Von Neumann’s Assumptions:
  - Time-dependent, continuous energy, spherical but radially-varying, 1 fissionable material, isotropic scattering and fission production, fission multiplicities of 2,3, or 4
- Suggested 100 neutrons each to be run for 100 collisions
  - Thought these were too much
- Estimated time: 5 hrs on ENIAC
- Richtmyer’s response:
  - Very interested in idea and proposed suggestions
    - Allow for multiple fissionable materials, no fission spectrum energy dependence, single neutron multiplicity, run for computer time not collisions
- ENIAC: first calculations run April/May 1948
  - Code finalized in **December 1947**;
  - Continuous energy neutrons, fission spectra and XS tabulated at interval mid-points, histogram energy-dependence of XS, pseudo-RN.

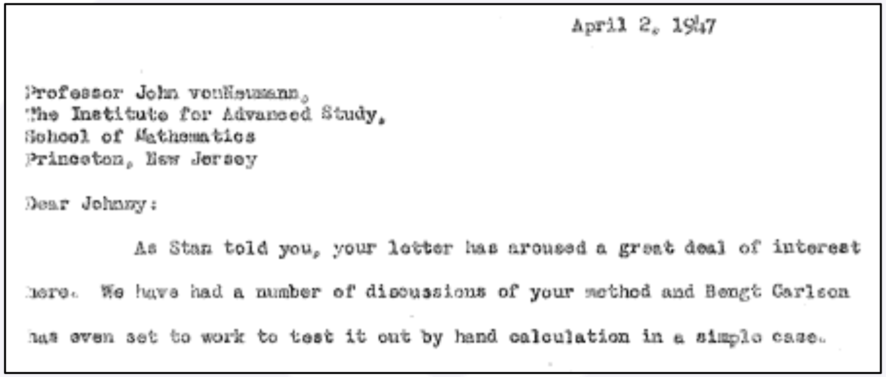
Thomas Haight, et al., “Los Alamos Bets on ENIAC: Nuclear Monte Carlo Simulations, 1947-1948, IEEE Ann. Of History of Comp July-Sept 2014



Calculation:

		Instructions:	**Explanations:**
	1	r of $C_1 - 1$, see (1)	r_{i-1}
	2	r of C_1, see (1)	r_i
	3	$(C_2)^2$	s^2
	4	$(C_1)^2$	r^2
	5	$3 - 4$	$s^2 - r^2$
	6	$C_3 \begin{cases} \geq 0 \therefore \mathcal{A} \\ < 0 \therefore \mathcal{B} \end{cases}$	$s \begin{cases} \geq 0 \therefore \mathcal{A} \\ < 0 \therefore \mathcal{B} \end{cases}$
Only for $\mathcal{B}$:	7	$(1)^2$	r_{i-1}^2
Only for $\mathcal{B}$:	8	$5 + 7$	$r_{i-1}^2 + s^2 - r^2$
Only for $\mathcal{B}$:	9	$8 \begin{cases} \leq 0 \therefore \mathcal{B}' \\ > 0 \therefore \mathcal{B}'' \end{cases}$	$r_{i-1}^2 + s^2 - r^2 \begin{cases} \leq 0 \therefore \mathcal{B}' \\ > 0 \therefore \mathcal{B}'' \end{cases}$
	10	$\mathcal{A}$ or $\mathcal{B}' \therefore 2$ $\mathcal{B}'' \therefore 1$	$\left.\begin{matrix} \mathcal{A} \text{ or } \mathcal{B}' \therefore r_i - \\ \mathcal{B}'' \therefore r_{i-1} - \end{matrix}\right\} r^*$
	11	$\mathcal{A}$ or $\mathcal{B}' \therefore +1$ $\mathcal{B}'' \therefore -1$	$\left.\begin{matrix} \mathcal{A} \text{ or } \mathcal{B}' \therefore +1 - \\ \mathcal{B}'' \therefore -1 - \end{matrix}\right\} \varepsilon$
	12	$(10)^2$	r^{*2}
	13	$5 + 12$	$r^{*2} + s^2 - r^2$

R.D Richtmyer and J. von Neumann “Statistical Methods in Neutron Diffusion”, Los Alamos (LAMS-557) April 9, 1947.



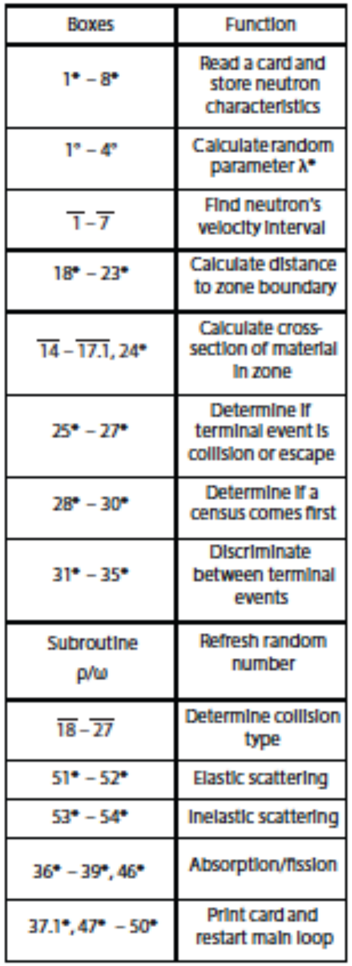
April 2, 1947

Professor John vonNeumann,
The Institute for Advanced Study,
School of Mathematics
Princeton, New Jersey

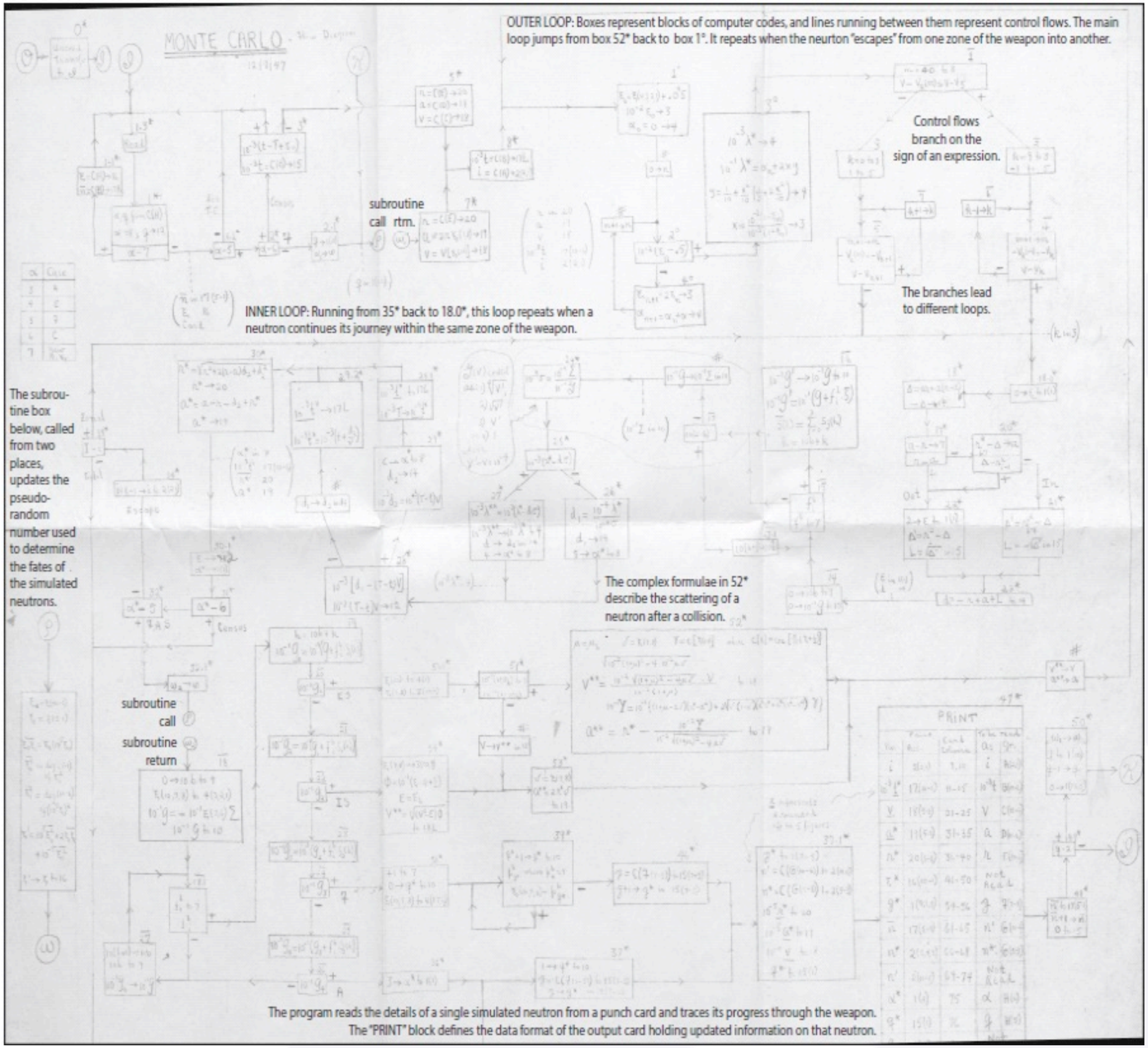
Dear Johnny:

As Stan told you, your letter has aroused a great deal of interest here. We have had a number of discussions of your method and Bengt Carlson has even set to work to test it out by hand calculation in a simple case.

ENIAC in Action: MC Program / flowchart



Boxes	Function
1* – 8*	Read a card and store neutron characteristics
1° – 4°	Calculate random parameter λ*
$\overline{1}$ – $\overline{7}$	Find neutron's velocity interval
18* – 23*	Calculate distance to zone boundary
$\overline{14}$ – $\overline{17.1}$, 24*	Calculate cross-section of material in zone
25* – 27*	Determine if terminal event is collision or escape
28* – 30*	Determine if a census comes first
31* – 35*	Discriminate between terminal events
Subroutine ρ/ω	Refresh random number
$\overline{18}$ – $\overline{27}$	Determine collision type
51* – 52*	Elastic scattering
53* – 54*	Inelastic scattering
36* – 39*, 46*	Absorption/fission
37.1*, 47* – 50*	Print card and restart main loop



OUTER LOOP: Boxes represent blocks of computer codes, and lines running between them represent control flows. The main loop jumps from box 52* back to box 1°. It repeats when the neurton "escapes" from one zone of the weapon into another.

Control flows branch on the sign of an expression.

subroutine call rtrn.

INNER LOOP: Running from 35* back to 18.0*, this loop repeats when a neutron continues its journey within the same zone of the weapon.

The branches lead to different loops.

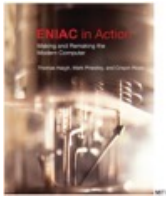
The subroutine box below, called from two places, updates the pseudo-random number used to determine the fates of the simulated neutrons.

The complex formulae in 52* describe the scattering of a neutron after a collision.

subroutine call

subroutine return

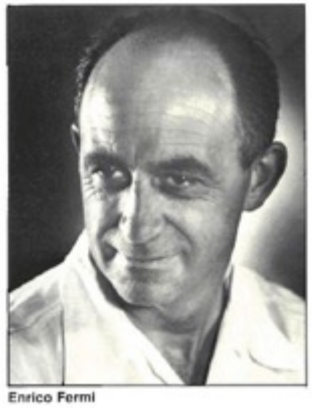
The program reads the details of a single simulated neutron from a punch card and traces its progress through the weapon. The "PRINT" block defines the data format of the output card holding updated information on that neutron.

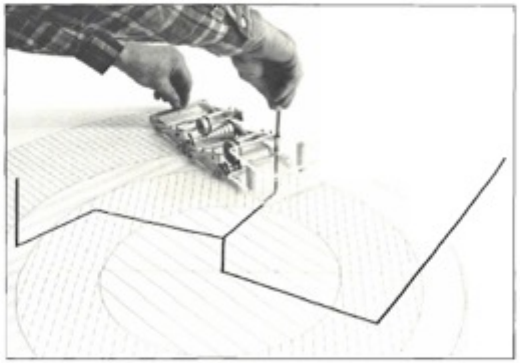


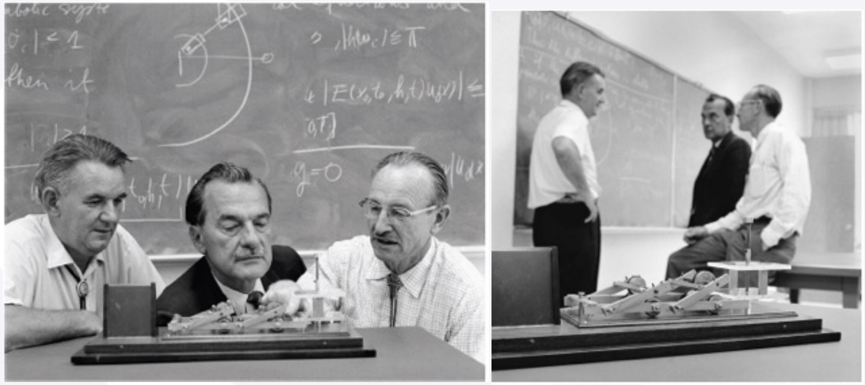
Thomas Haight, Mark Priestley, and Crispin Rope, "ENIAC in Action: Making and Remaking the Modern Computer," MIT Press 2016

Enrico Fermi: Independently developed Monte Carlo!

- Emilio Segre, Fermi's student and collaborator:
  - "*Fermi had invented, but of course not named, the present Monte Carlo method when he was studying the moderation of neutrons in Rome. He did not publish anything on the subject, but he used the method to solve many problems with whatever calculating facilities he had, chiefly a small mechanical adding machine*"
- Astonished Roman colleagues when he would predict experimental results remarkably accurately. He revealed that he used statistical sampling techniques whenever insomnia struck.
- 15 years prior to Ulam
- While in Los Alamos and awaiting ENIAC's move, he created an analog device to study neutron transport.
  - Called FERMIAC
  - Generated the site of next collision based upon characteristics of material; Another choice was made at boundary crossing; "slow" and "fast" neutron energies




FERMIAC

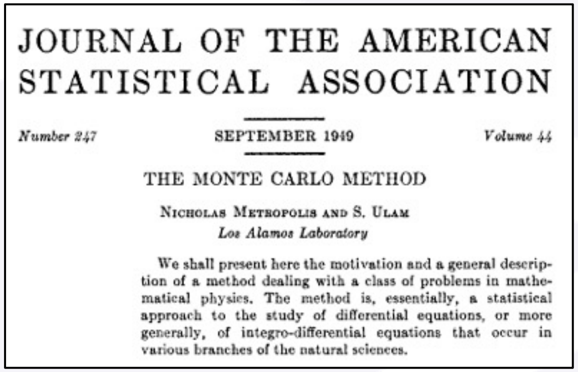

Los Alamos Scientists: Bengt Carlson, Nicholas Metropolis, LDP King with Fermiac (1966)

MANIAC – Nicholas Metropolis

- Post-war ENIAC started a revolution that continues today

- MANIAC – Mathematical and Numerical Integrator and Computer
  - Was a product of Nicholas Metropolis at LANL; borrowed concepts from von Neumann's IAS, operational in 1952;
  - MADCAP – high-level language and compiler
  - Rapid growth of computing: AVIDAC (Argonne) ORACLE (Oak Ridge), ILLIAC (U of I)
  - Special effort that helped bind Von Neumann, Fermi, Bethe, Teller, Ulam, Feynman, others in post-war efforts. MANIAC was a fascination.
  - First time "Monte Carlo" appears in publication:
    - Nicholas Metropolis and S. Ulam , "The Monte Carlo Method," *Journal of the American Statistical Association* Vol. 44, No. 247 (Sep., 1949)
  - MC on MANIAC used for multiple problems other than radiation transport:

Pion-proton phase-shift analysis (Fermi, Metropolis; 1952)
Phase-shift analysis (Bethe, deHoffman, Metropolis; 1954)
Nonlinear coupled oscillators (Fermi, Pasta, Ulam; 1953)
Genetic code (Gamow, Metropolis; 1954)
Equation of state: Importance sampling (Metropolis, Teller; 1953)
Two-dimensional hydrodynamics (Metropolis, von Neumann; 1954)
Universalities of iterative functions (Metropolis, Stein, Stein; 1973)
Nuclear cascades using Monte Carlo (Metropolis, Turkevich; 1954)
Anti-clerical chess (Wells; 1956)
The lucky numbers (Metropolis, Ulam; 1956)



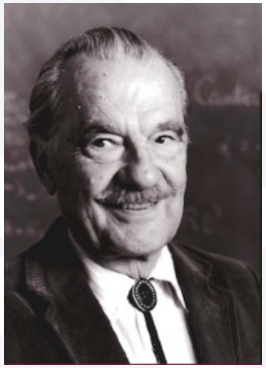
JOURNAL OF THE AMERICAN
STATISTICAL ASSOCIATION

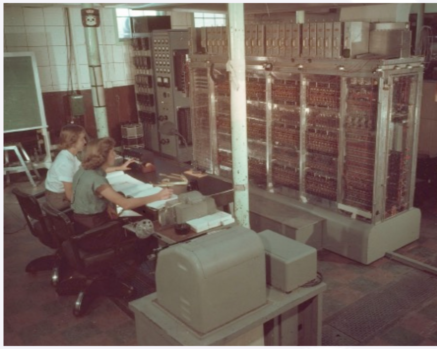
Number 247 SEPTEMBER 1949 *Volume 44*

THE MONTE CARLO METHOD

NICHOLAS METROPOLIS AND S. ULAM
Los Alamos Laboratory

We shall present here the motivation and a general description of a method dealing with a class of problems in mathematical physics. The method is, essentially, a statistical approach to the study of differential equations, or more generally, of integro-differential equations that occur in various branches of the natural sciences.



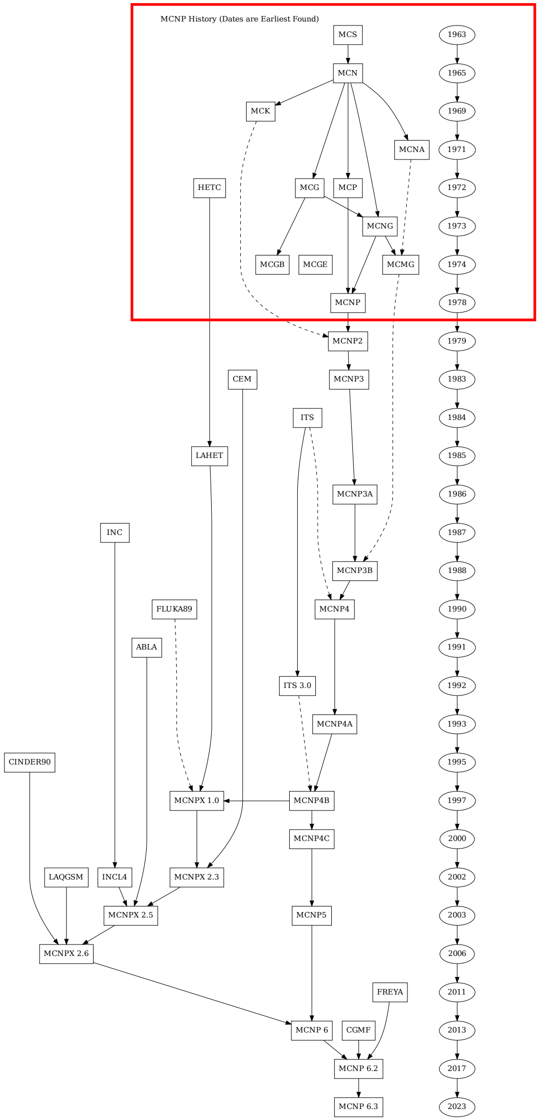


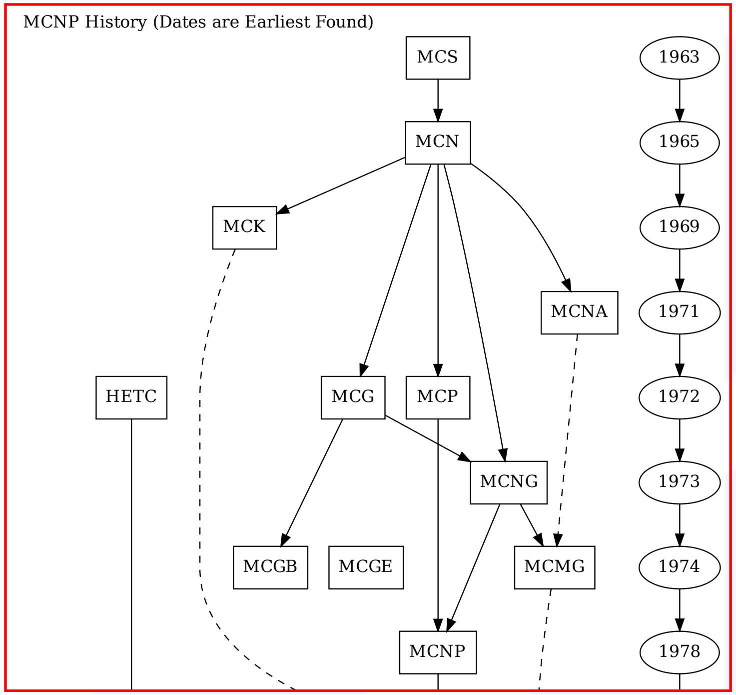
The First Practical Monte Carlo Manual

- E.D. Cashwell and C.J. Everett, “A Practical Manual on the Monte Carlo Method for Random Walk Problems,” LA-2120 (December 18, 1957)
  - Well described 228 page report specific to neutral particle transport
  - Detailed diagrams and flowcharts
    - Neutron collisions – (in)elastic scattering, fission, etc.
    - Photon collisions – Compton scattering, photoelectric, pair production
    - Particle direction after collision – direction cosines
  - Did not deal with thermal neutron collisions nor pseudo-random number generation
  - Appendix includes 20 neutron and photon problems run on the MANIAC I
    - Energy-dependent sources in various geometries and materials
    - Problems for neutrino detection and rocket motors
    - Bob Schrandt did most of the coding

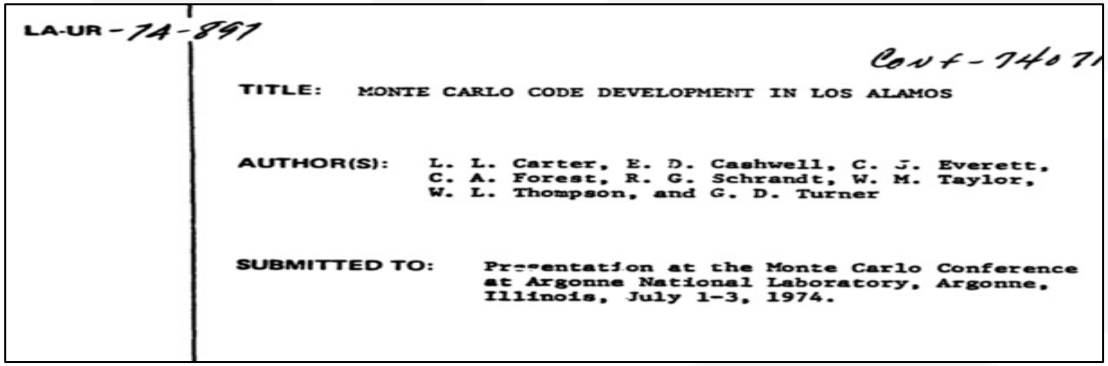
- MCNP Website contains hundreds of archival references on Monte Carlo for particle transport

Early Monte Carlo Transport Codes at Los Alamos





Code	Physics
MCN	Neutron
MCNA	Neutron Adjoint
MCG	Gamma-ray
MCP	Photon
MCNG	Neutron + Gamma-ray
MCK	Criticality
MCMG	Multigroup (MCNG based)
MCGE	Electron + Photon
MCGB	Gamma-ray + Bremsstrahlung



LA-UR-74-897

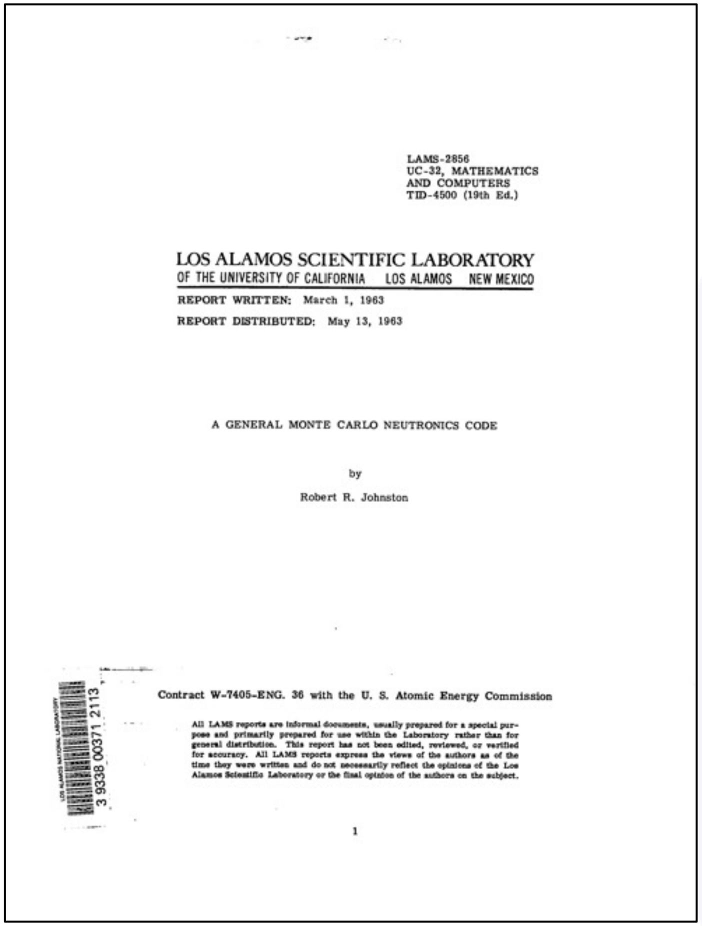
Conf-74071

TITLE: MONTE CARLO CODE DEVELOPMENT IN LOS ALAMOS

AUTHOR(S): L. L. Carter, E. D. Cashwell, C. J. Everett,
C. A. Forest, R. G. Schrandt, W. M. Taylor,
W. L. Thompson, and G. D. Turner

SUBMITTED TO: Presentation at the Monte Carlo Conference
at Argonne National Laboratory, Argonne,
Illinois, July 1-3, 1974.

MCS: A General Monte Carlo Neutronics Code (1961)



LAMS-2856
UC-32, MATHEMATICS
AND COMPUTERS
TID-4500 (19th Ed.)

LOS ALAMOS SCIENTIFIC LABORATORY
OF THE UNIVERSITY OF CALIFORNIA   LOS ALAMOS   NEW MEXICO

REPORT WRITTEN: March 1, 1963

REPORT DISTRIBUTED: May 13, 1963

A GENERAL MONTE CARLO NEUTRONICS CODE

by

Robert R. Johnston

Contract W-7405-ENG. 36 with the U. S. Atomic Energy Commission

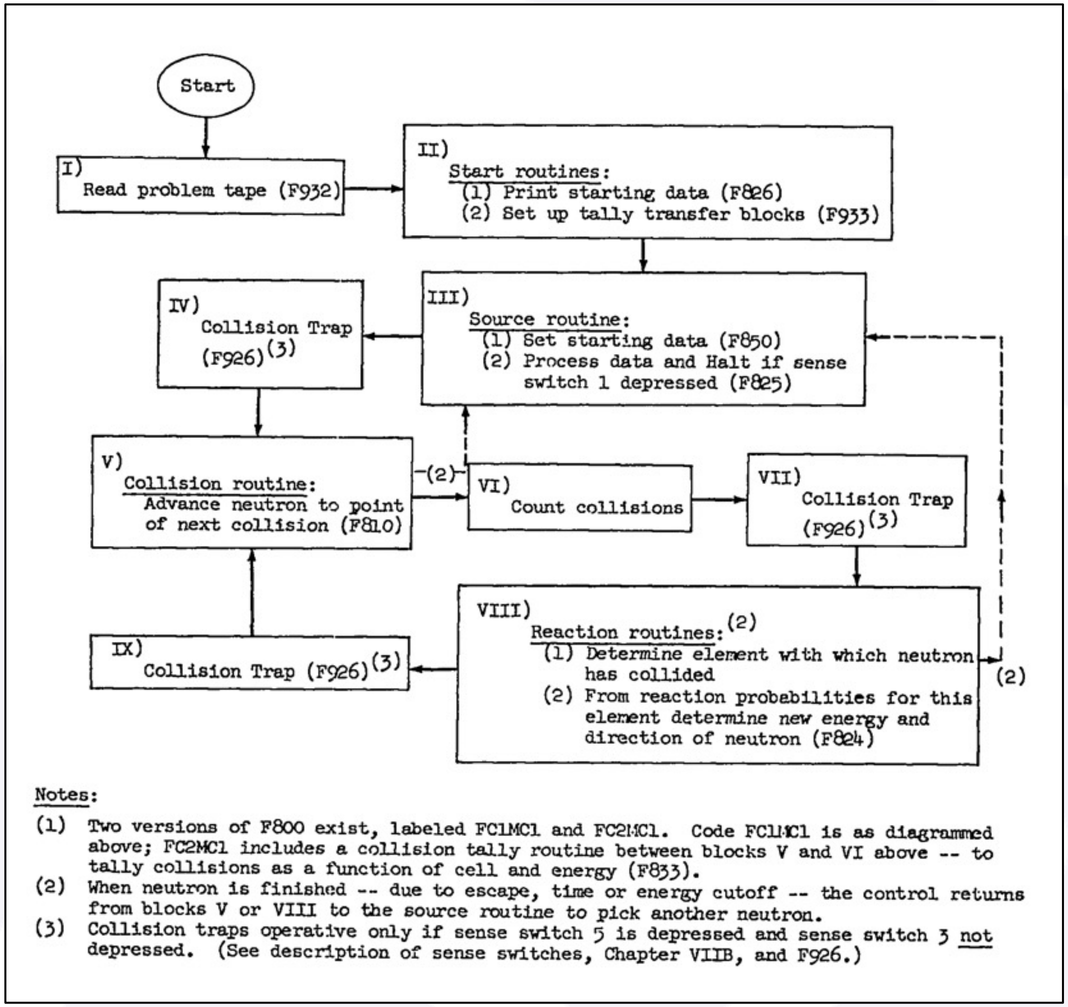
1

- R.R. Johnston, "A General Monte Carlo Neutronics Code," the MCS code, Los Alamos Scientific Laboratory report, LAMS-2856, 188 pages (1963).
  - MCS is a general Monte Carlo neutron shielding code for a time-independent geometry.
  - written in the FLOCO II coding system (described in LAMS-2339) for the IBM 7090 calculator.
- MCS Code Capabilities
  - It is capable of treating an arbitrary three-dimensional configuration of first- and second-degree surfaces.
  - basic units are cm, shakes, MeV, 10^{24} atoms/cc, and barns
  - particle weight, cell importances in the form of $I_0 + I_1E + I_2E^2$, and exponential transform
  - MCA sets up problems to be run by MCS, MCH, and MCR, max of 432 surfaces and 2048 cells
  - nuclear data from cards for different laws for inelastic and elastic scattering
  - cell and surface flux tallies with variances as a function of E and t

MCS: Flocode – controls overall flow of calculation

IBM 7090 (1958- 1969)

https://www.ibm.com/ibm/history/exhibits/mainframe/mainframe_PP7090.html



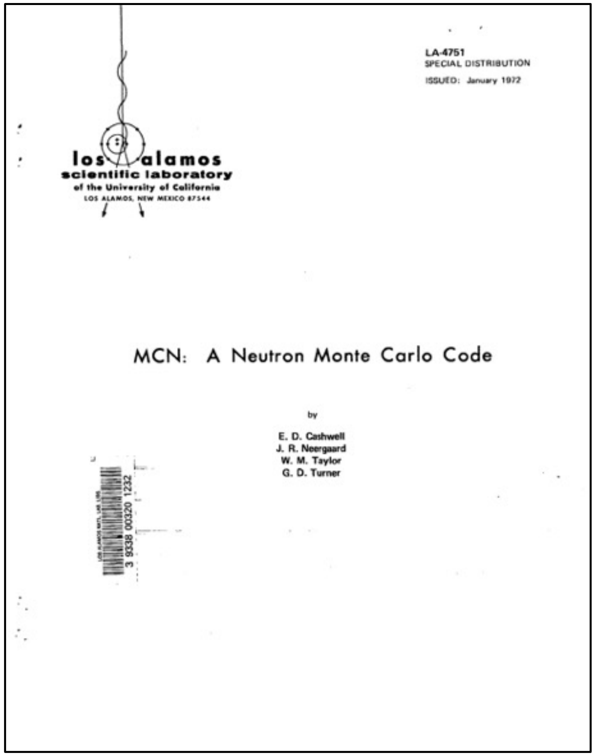
Notes:

(1) Two versions of F800 exist, labeled FC1MC1 and FC2MC1. Code FC1MC1 is as diagrammed above; FC2MC1 includes a collision tally routine between blocks V and VI above -- to tally collisions as a function of cell and energy (F833).

(2) When neutron is finished -- due to escape, time or energy cutoff -- the control returns from blocks V or VIII to the source routine to pick another neutron.

(3) Collision traps operative only if sense switch 5 is depressed and sense switch 3 not depressed. (See description of sense switches, Chapter VIIB, and F926.)

MCN: A Neutron Monte Carlo Code (1965)



LA-4751
SPECIAL DISTRIBUTION
ISSUED: January 1972

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

MCN: A Neutron Monte Carlo Code

by

E. D. Cashwell
J. R. Neergaard
W. M. Taylor
G. D. Turner

Control Data Corporation (CDC)-6600 (1964)

- MCN: A Neutron Monte Carlo Code
  - E.D. Cashwell, J.R. Neergaard, W.M. Taylor, and G.D.Turner, "MCN: A Neutron Monte Carlo Code," Los Alamos Scientific Laboratory report, LA-4751 , 32 pages (1972).
  - The general purpose Monte Carlo neutron code MCN is described in detail to help the user set up and run problems on the CDC-6600 and CDC-7600.
  - The code treats general three-dimensional geometric configurations of materials, and can use point cross-section data in either the Livermore (LLL) or the Aldermaston (AWRE) format.

- MCN Code Capabilities
  - basic units are cm, shakes, MeV, 10^{24} atoms/cc, barns
  - 5 standard sources are available and a user source subroutine
  - 24 surface types are available to build a geometry
  - an improved random number generator (Lehmer)
  - particle weight, cell importances, I, and exponential transform

MCN: A Neutron Monte Carlo Code (1965)

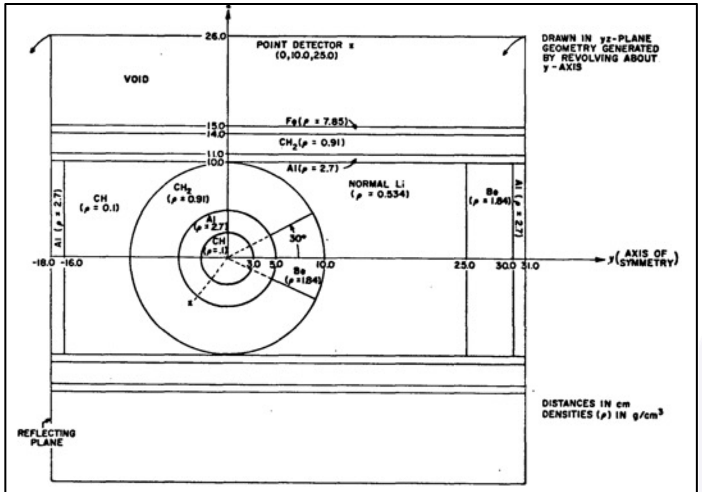


Fig. C-1.
Sample problem for the MCN code.

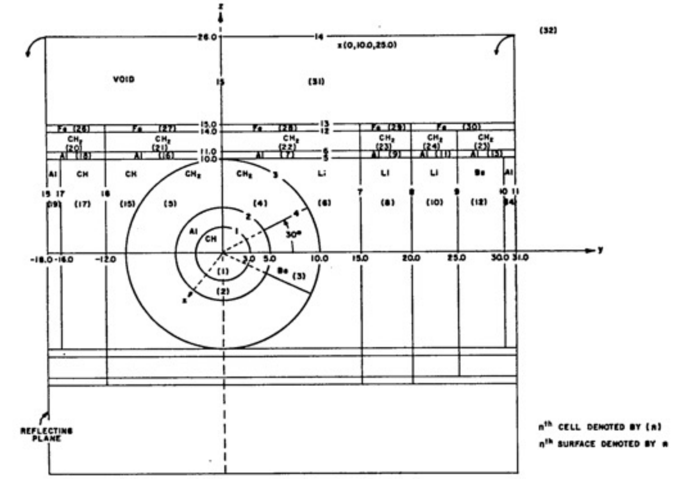


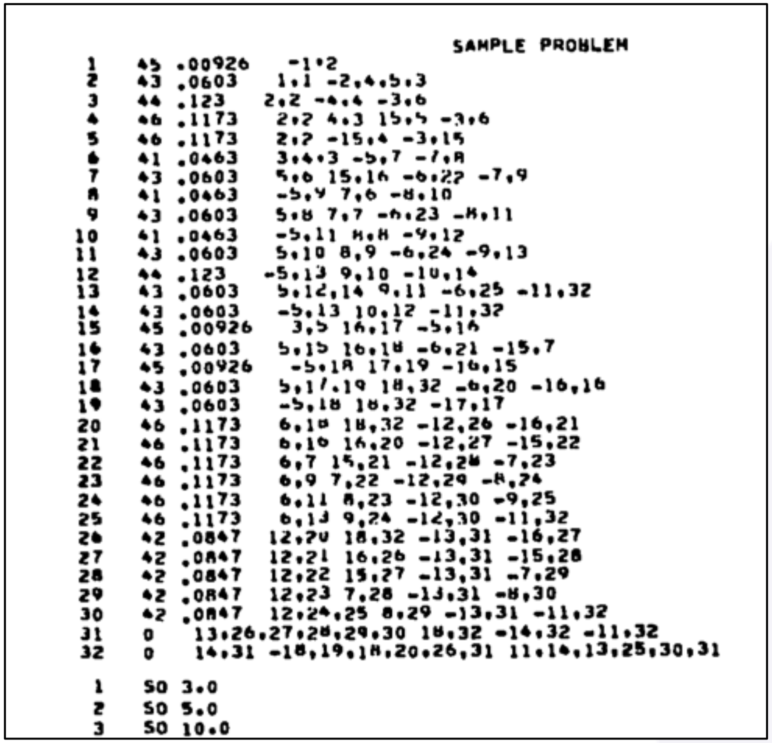
Fig. C-2.
Sample problem zoned for input to MCN.

- MCN Code Capabilities (continued)
  - free-gas thermal neutron treatment with spatially and time-dependent temperatures
  - numerous input warnings and fatal errors provided
  - input, tally structure, and output similar to MCNP
  - point detector tally is now available

- Testing and Versions
  - verification test sets are routinely used
  - code was periodically updated

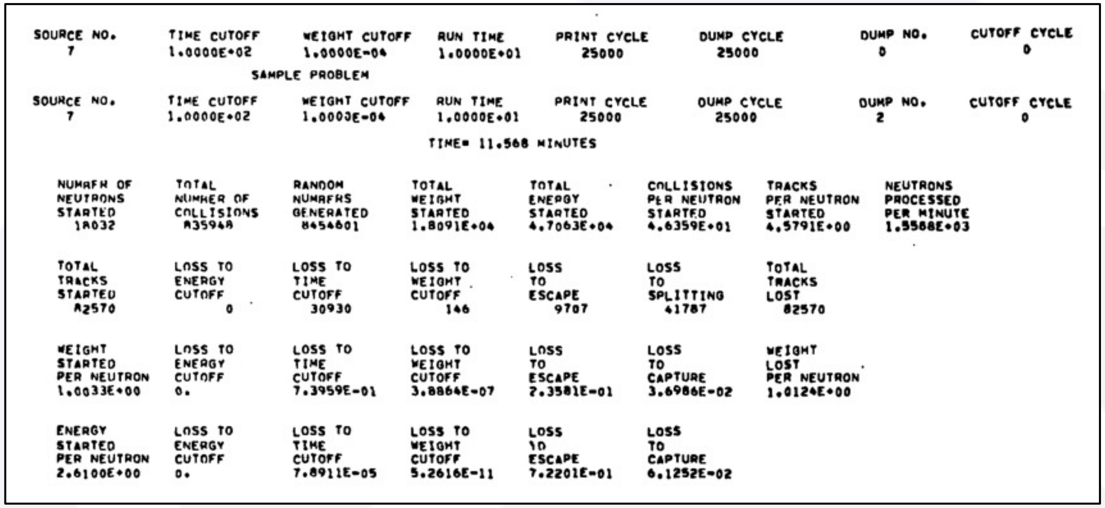
- MCN, MCG, MCP Test Problem
  - 32 cells, 18 surfaces, 6 materials
  - User-specified source subroutine: biased volume
  - Importances, and thermal temperatures f(t)
  - F1, F2, F4, F5, F6 tallies f(E,t)

MCN: Input and Output



```
                                   SAMPLE PROBLEM
  1   45 .00926   -1,2
  2   43 .0603   1,1 -2,4,5,3
  3   44 .123   2,2 -4,4 -3,6
  4   46 .1173   2,2 4,3 15,5 -3,6
  5   46 .1173   2,2 -15,4 -3,15
  6   41 .0463   3,4,3 -5,7 -7,8
  7   43 .0603   5,6 15,16 -6,22 -7,9
  8   41 .0463   -5,9 7,6 -8,10
  9   43 .0603   5,8 7,7 -6,23 -8,11
 10   41 .0463   -5,11 8,8 -9,12
 11   43 .0603   5,10 8,9 -6,24 -9,13
 12   44 .123   -5,13 9,10 -10,14
 13   43 .0603   5,12,14 9,11 -6,25 -11,32
 14   43 .0603   -5,13 10,12 -11,32
 15   45 .00926   3,5 16,17 -5,16
 16   43 .0603   5,15 16,18 -6,21 -15,7
 17   45 .00926   -5,18 17,19 -16,15
 18   43 .0603   5,17,19 18,32 -6,20 -16,16
 19   43 .0603   -5,18 18,32 -17,17
 20   46 .1173   6,18 18,32 -12,26 -16,21
 21   46 .1173   6,16 16,20 -12,27 -15,22
 22   46 .1173   6,7 15,21 -12,28 -7,23
 23   46 .1173   6,9 7,22 -12,29 -8,24
 24   46 .1173   6,11 8,23 -12,30 -9,25
 25   46 .1173   6,13 9,24 -12,30 -11,32
 26   42 .0847  12,20 18,32 -13,31 -16,27
 27   42 .0847  12,21 16,26 -13,31 -15,28
 28   42 .0847  12,22 15,27 -13,31 -7,29
 29   42 .0847  12,23 7,28 -13,31 -8,30
 30   42 .0847  12,24,25 8,29 -13,31 -11,32
 31   0    13,26,27,28,29,30 18,32 -14,32 -11,32
 32   0    14,31 -18,19,18,20,26,31 11,14,13,25,30,31

  1   SO 3.0
  2   SO 5.0
  3   SO 10.0
```



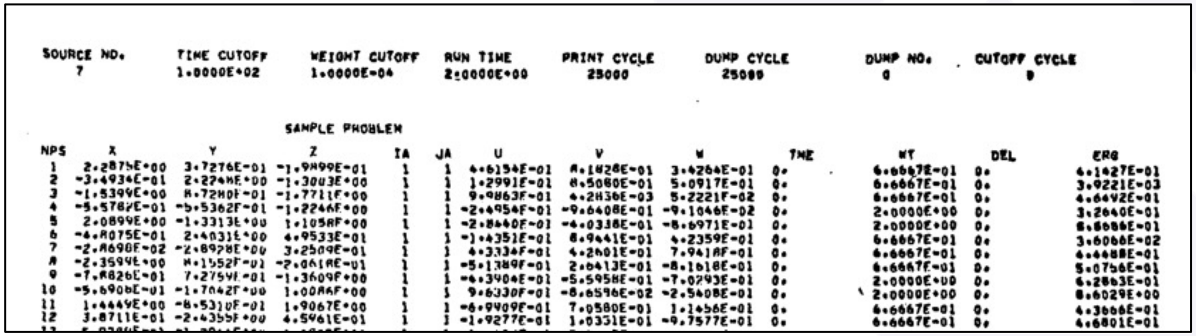
```
SOURCE NO.   TIME CUTOFF   WEIGHT CUTOFF   RUN TIME     PRINT CYCLE   DUMP CYCLE      DUMP NO.   CUTOFF CYCLE
   7         1.0000E+02    1.0000E-04      1.0000E+01     25000         25000            0            0
                          SAMPLE PROBLEM
SOURCE NO.   TIME CUTOFF   WEIGHT CUTOFF   RUN TIME     PRINT CYCLE   DUMP CYCLE      DUMP NO.   CUTOFF CYCLE
   7         1.0000E+02    1.0000E-04      1.0000E+01     25000         25000            2            0
                                         TIME= 11.568 MINUTES

  NUMBER OF    TOTAL        RANDOM       TOTAL        TOTAL        COLLISIONS   TRACKS       NEUTRONS
  NEUTRONS     NUMBER OF    NUMBERS      WEIGHT       ENERGY       PER NEUTRON  PER NEUTRON  PROCESSED
  STARTED      COLLISIONS   GENERATED    STARTED      STARTED      STARTED      STARTED      PER MINUTE
    18032       835948       8454601     1.8091E+04   4.7063E+04   4.6359E+01   4.5791E+00   1.5588E+03

  TOTAL        LOSS TO      LOSS TO      LOSS TO      LOSS         LOSS         TOTAL
  TRACKS       ENERGY       TIME         WEIGHT       TO           TO           TRACKS
  STARTED      CUTOFF       CUTOFF       CUTOFF       ESCAPE       SPLITTING    LOST
   82570             0        30930          146         9707        41787        82570

  WEIGHT       LOSS TO      LOSS TO      LOSS TO      LOSS         LOSS         WEIGHT
  STARTED      ENERGY       TIME         WEIGHT       TO           TO           LOST
  PER NEUTRON  CUTOFF       CUTOFF       CUTOFF       ESCAPE       CAPTURE      PER NEUTRON
  1.0033E+00   0.           7.3959E-01   3.8864E-07   2.3581E-01   3.6986E-02   1.0124E+00

  ENERGY       LOSS TO      LOSS TO      LOSS TO      LOSS         LOSS
  STARTED      ENERGY       TIME         WEIGHT       TO           TO
  PER NEUTRON  CUTOFF       CUTOFF       CUTOFF       ESCAPE       CAPTURE
  2.6100E+00   0.           7.8911E-05   5.2616E-11   7.2201E-01   6.1252E-02
```



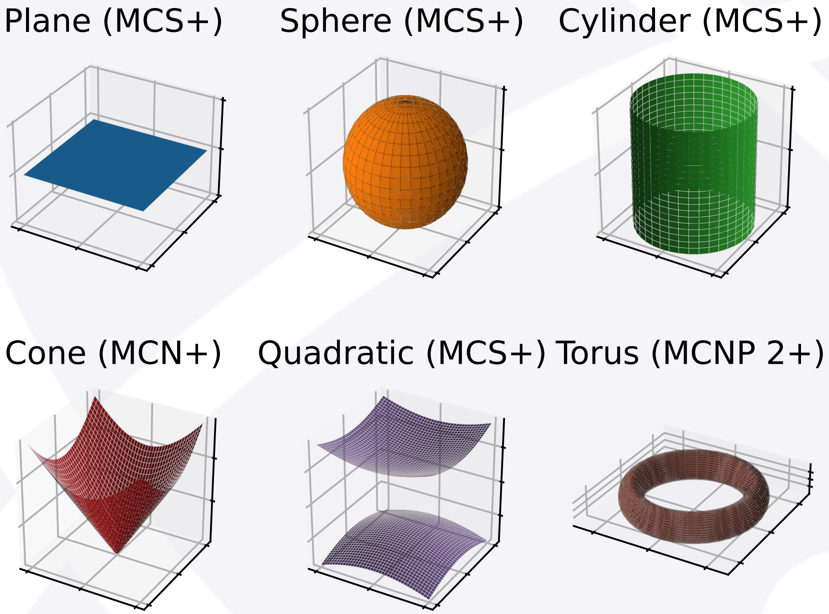
```
SOURCE NO.     TIME CUTOFF    WEIGHT CUTOFF   RUN TIME     PRINT CYCLE    DUMP CYCLE       DUMP NO.   CUTOFF CYCLE
   7           1.0000E+02     1.0000E-04      2.0000E+00     25000          25000            0            0

                                   SAMPLE PROBLEM
NPS     X            Y            Z           IA   JA     U            V            W          TME        WT          DEL         ERG
 1   2.2875E+00   3.7276E-01  -1.9899E-01    1    1   4.6154E-01   8.1828E-01   3.4264E-01   0.      6.6667E-01   0.      4.1427E-01
 2  -3.4934E-01   2.2748E+00  -1.3003E+00    1    1   1.2991E-01   8.5080E-01   5.0917E-01   0.      6.6667E-01   0.      3.9221E-03
 3  -1.5399E+00   8.7280E-01  -1.7711E+00    1    1   9.9863E-01   4.2836E-03   5.2221E-02   0.      6.6667E-01   0.      4.6492E-01
 4  -5.5782E-01  -5.5362E-01  -1.2246E+00    1    1  -2.4954E-01  -9.6408E-01  -9.1046E-02   0.      2.0000E+00   0.      3.2640E-01
 5   2.0899E+00  -1.3313E+00   1.1058E+00    1    1  -2.8440E-01  -4.0338E-01  -8.6971E-01   0.      2.0000E+00   0.      8.8686E-01
 6  -4.8075E-01   2.4031E+00   4.9533E-01    1    1  -1.4351E-01   8.9441E-01   4.2359E-01   0.      6.6667E-01   0.      3.6066E-02
 7  -2.8690E-02  -2.8978E+00   3.2509E-01    1    1   4.3334E-01   4.2601E-01   7.9418E-01   0.      6.6667E-01   0.      4.4488E-01
 8  -2.3599E+00   8.1552E-01  -2.0618E-01    1    1  -5.1389E-01   2.6413E-01  -8.1618E-01   0.      6.6667E-01   0.      5.0756E-01
 9  -7.8826E-01   7.2759E-01  -1.3609E+00    1    1  -4.3904E-01  -5.5958E-01  -7.0293E-01   0.      2.0000E+00   0.      6.2863E-01
10  -5.6906E-01  -1.7042E+00   1.0086E+00    1    1   9.6330E-01  -8.6596E-02  -2.5408E-01   0.      2.0000E+00   0.      8.6029E+00
11   1.4449E+00  -8.5310E-01   1.9067E+00    1    1  -6.9409E-01   7.0580E-01   1.1456E-01   0.      6.6667E-01   0.      4.3666E-01
12   3.8711E-01  -2.4355E+00   4.5961E-01    1    1  -1.9277E-01   1.0331E-01  -9.7577E-01   0.      6.6667E-01   0.      4.6801E-01
```

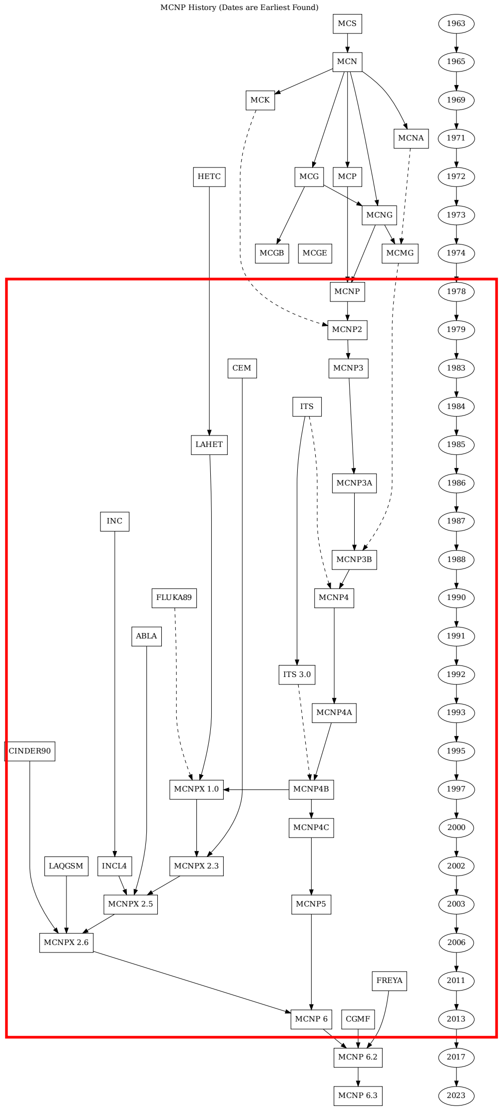
Increasing geometric modeling capabilities through LANL Monte Carlo codes

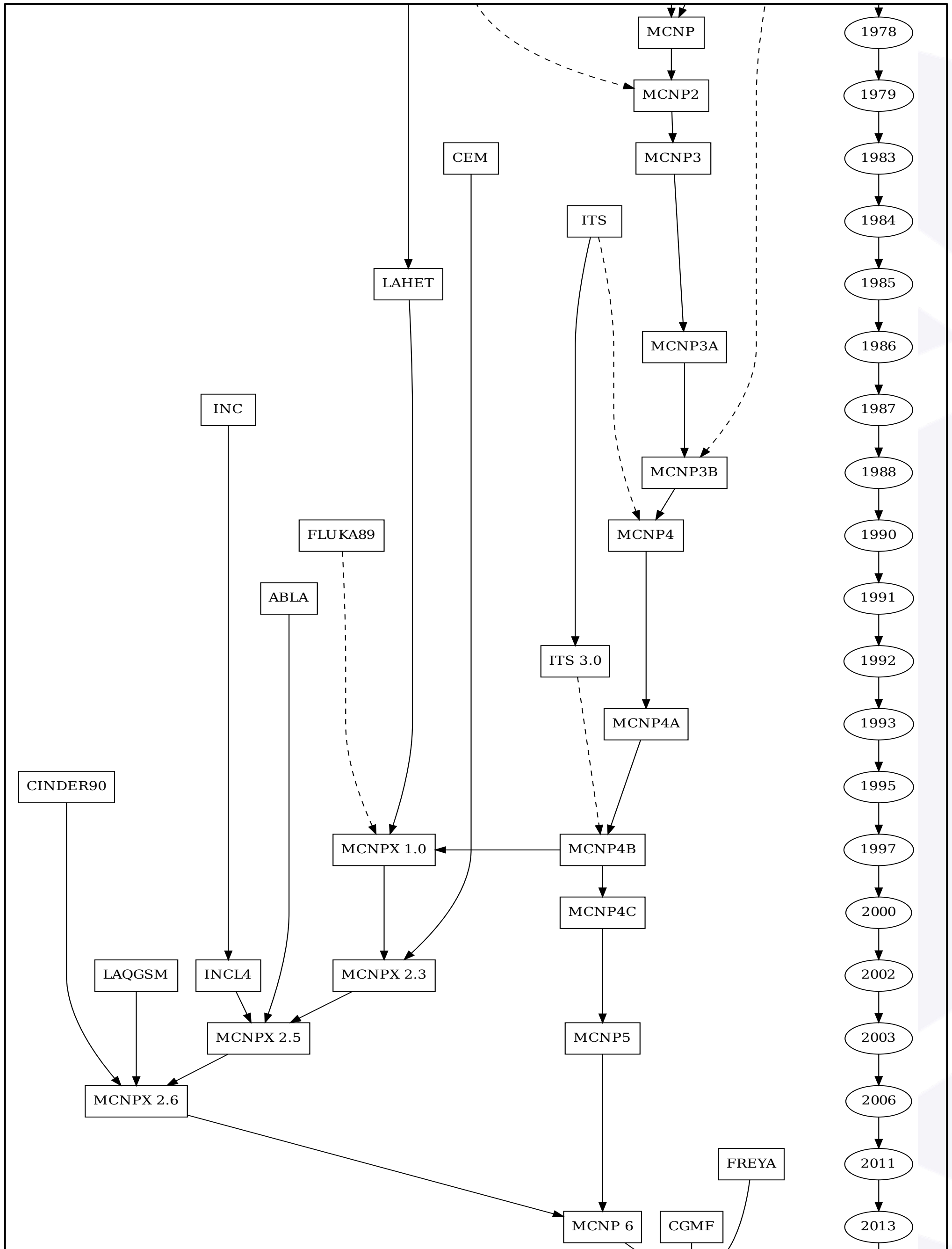
- Second order surfaces in MCS
- Fourth order surfaces in MCNP 2
- Structured and unstructured mesh in MCNP 6.1

Models from MCS are still representable in MCNP 6.3.



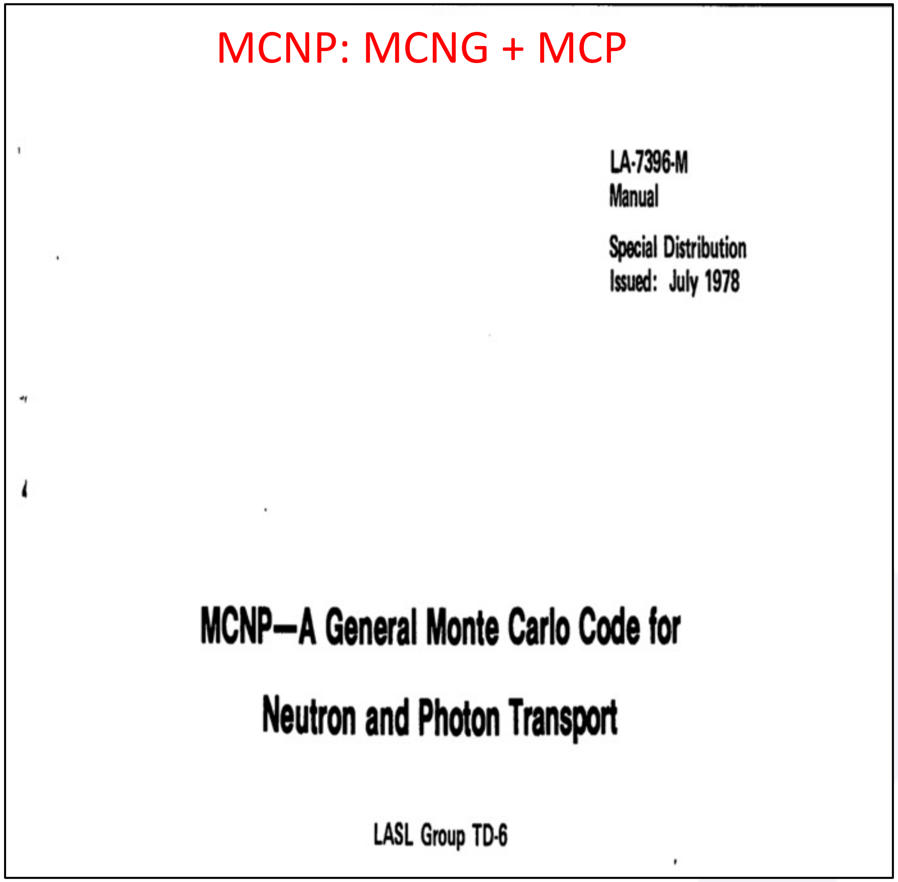
MCNP emerges in 1977 and has continued to evolve





MCNP Version 1 – 06/21/1977

MCNP: MCNG + MCP



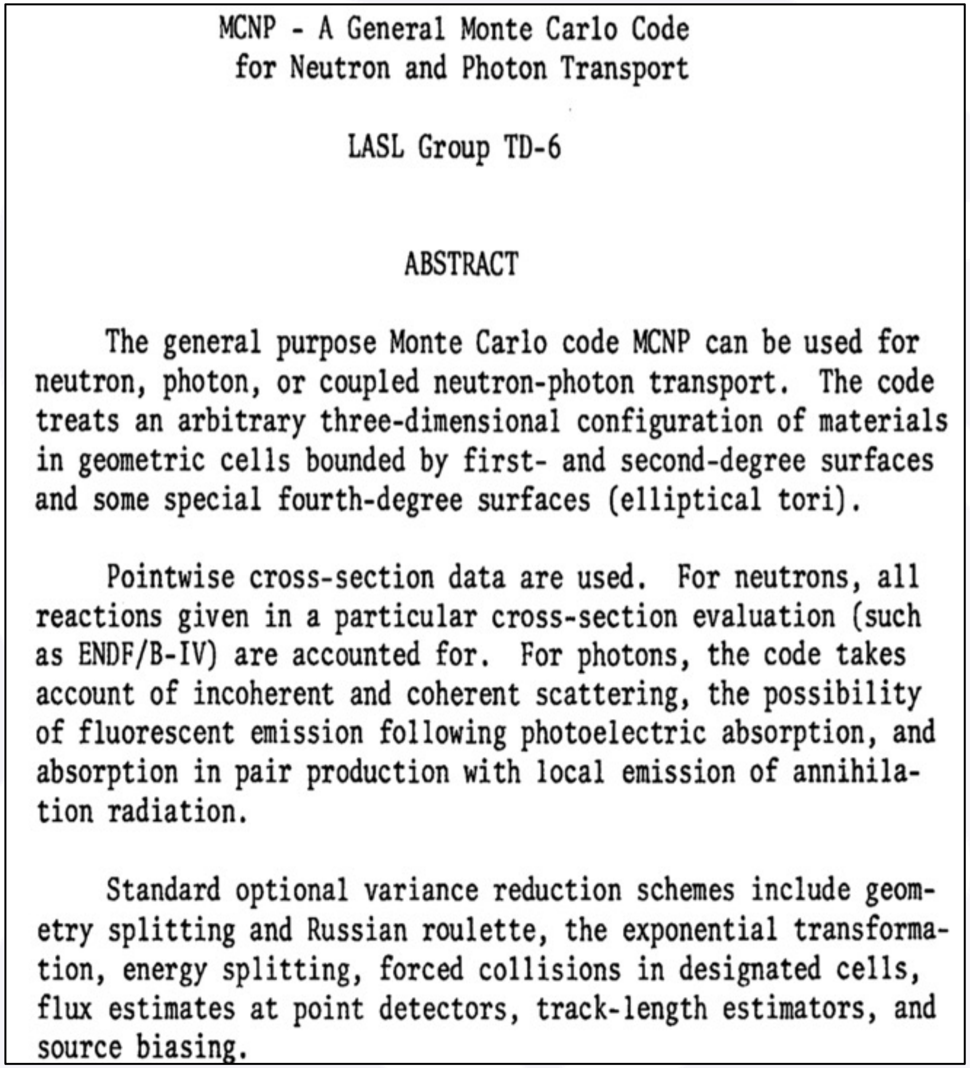
LA-7396-M
Manual

Special Distribution
Issued: July 1978

MCNP—A General Monte Carlo Code for

Neutron and Photon Transport

LASL Group TD-6



MCNP - A General Monte Carlo Code
for Neutron and Photon Transport

LASL Group TD-6

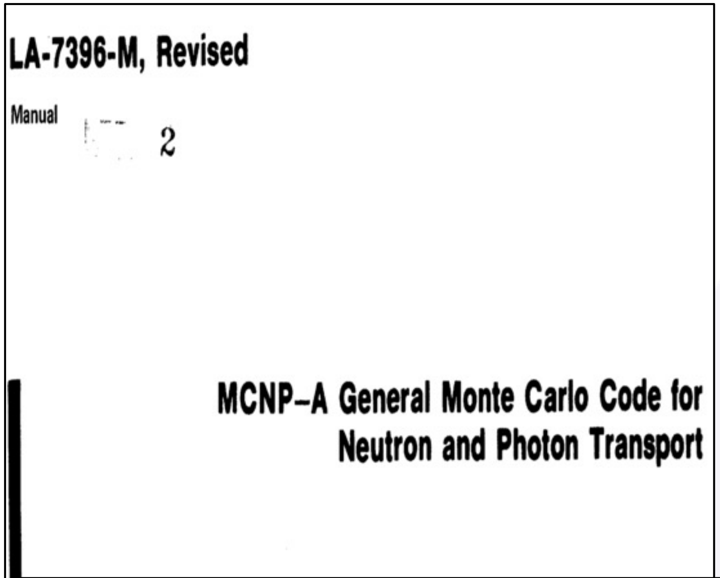
ABSTRACT

The general purpose Monte Carlo code MCNP can be used for neutron, photon, or coupled neutron-photon transport. The code treats an arbitrary three-dimensional configuration of materials in geometric cells bounded by first- and second-degree surfaces and some special fourth-degree surfaces (elliptical tori).

Pointwise cross-section data are used. For neutrons, all reactions given in a particular cross-section evaluation (such as ENDF/B-IV) are accounted for. For photons, the code takes account of incoherent and coherent scattering, the possibility of fluorescent emission following photoelectric absorption, and absorption in pair production with local emission of annihilation radiation.

Standard optional variance reduction schemes include geometry splitting and Russian roulette, the exponential transformation, energy splitting, forced collisions in designated cells, flux estimates at point detectors, track-length estimators, and source biasing.

MCNP Version 2 - 09/26/1979, MCNP Version 3 – 1983

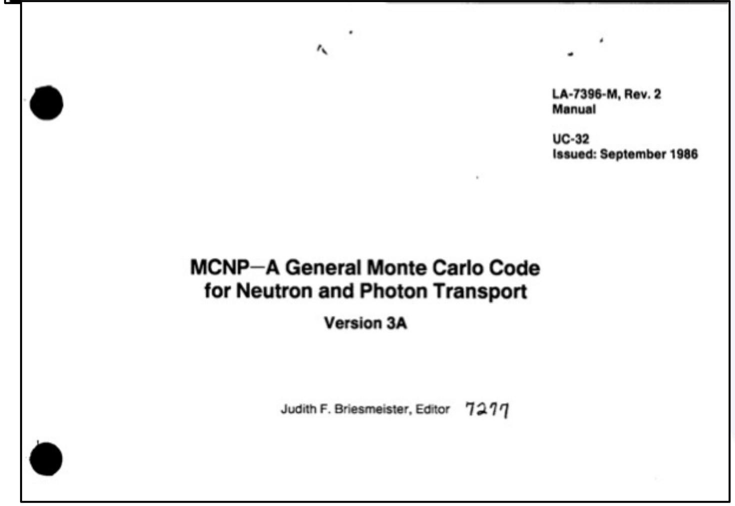


LA-7396-M, Revised

Manual

2

MCNP–A General Monte Carlo Code for Neutron and Photon Transport



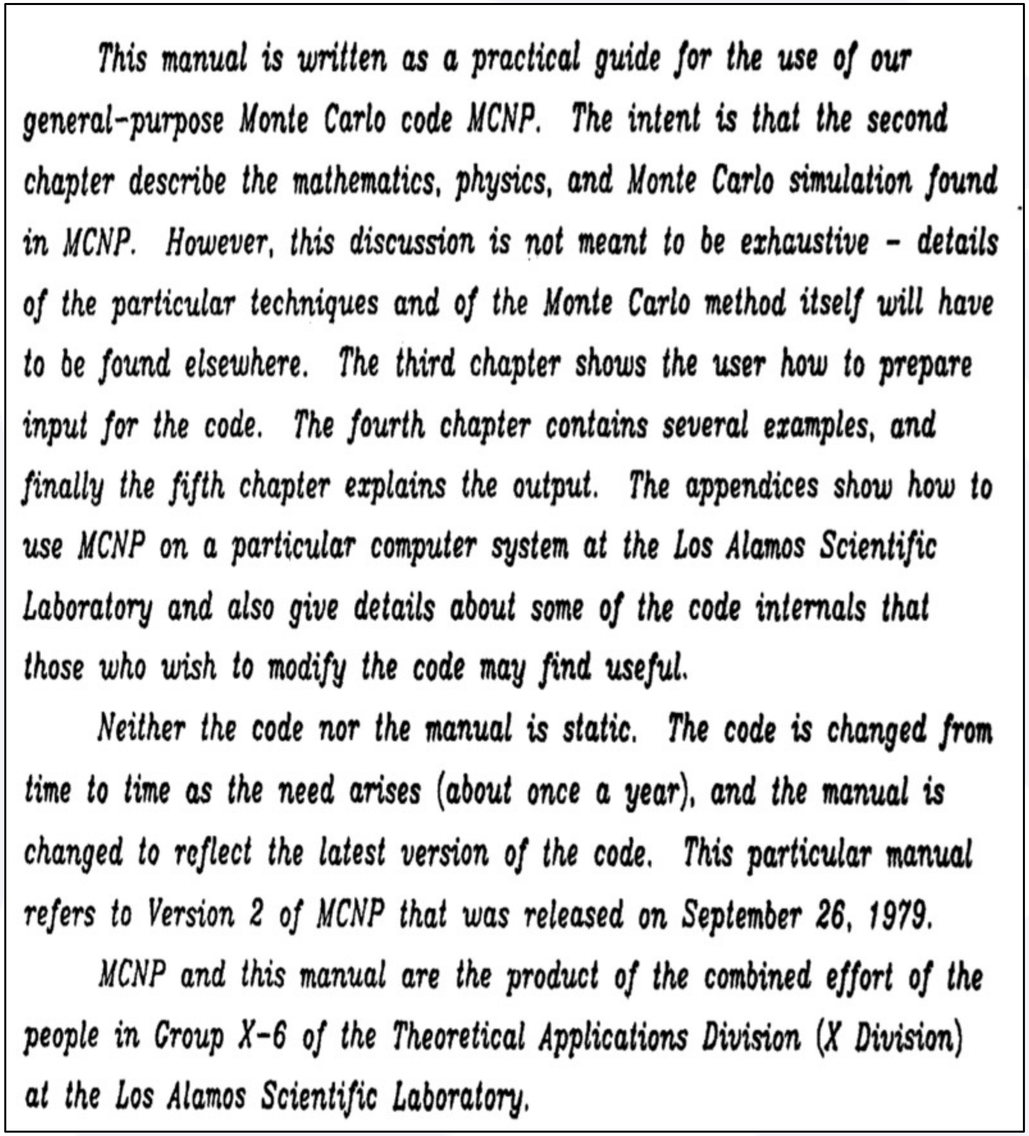
LA-7396-M, Rev. 2
Manual

UC-32
Issued: September 1986

MCNP—A General Monte Carlo Code for Neutron and Photon Transport

Version 3A

Judith F. Briesmeister, Editor 7217



This manual is written as a practical guide for the use of our general-purpose Monte Carlo code MCNP. The intent is that the second chapter describe the mathematics, physics, and Monte Carlo simulation found in MCNP. However, this discussion is not meant to be exhaustive - details of the particular techniques and of the Monte Carlo method itself will have to be found elsewhere. The third chapter shows the user how to prepare input for the code. The fourth chapter contains several examples, and finally the fifth chapter explains the output. The appendices show how to use MCNP on a particular computer system at the Los Alamos Scientific Laboratory and also give details about some of the code internals that those who wish to modify the code may find useful.

Neither the code nor the manual is static. The code is changed from time to time as the need arises (about once a year), and the manual is changed to reflect the latest version of the code. This particular manual refers to Version 2 of MCNP that was released on September 26, 1979.

MCNP and this manual are the product of the combined effort of the people in Group X-6 of the Theoretical Applications Division (X Division) at the Los Alamos Scientific Laboratory.

MCNP onwards

MCNP Version	Release Month/Year	Some Significant New Features
MCNP 3	1983	First release through RSICC. Written in Fortran 77
MCNP 3A	1986	
MCNP 3B	1988	Plotting graphics, generalized source, surface sources, repeated structures/lattice geometries
MCNP 4	1990	Parallel multitasking, electron transport
MCNP 4A	10/1993	Enhanced statistical analysis, new photon libraries, ENDF-6, color X-Windows graphics, dynamic memory allocation
MCNP 4B	4/1997	Operator perturbations, enhanced photon physics, PVM load balancing, cross-section plotting, 64-bit executables, lattice universe mapping, enhanced lifetimes
MCNPX 2.1.5	11/1999	First public release of MCNPX, based on MCNP4B with CEM INC, HTAPE3X, mesh and radiography tallies, and an improved collisional energy loss model.
MCNP 4C	4/2000	Unresolved resonance treatments, macrobodies, superimposed importance mesh, perturbation, electron transport, plotter and tally enhancements
MCNP 4C2	1/2001	Photonuclear physics, interactive plotting, plot superimposed weight-window mesh, weight-window improvements

T. Goorley, et al. “Initial MCNP6 Release Overview,” LA-UR-13-22934 (2013)

MCS can be directly traced in today’s MCNP code (1)

MCS RNG (IBM-704 + FLOCO II)

```
X00 8    902             # Function 902:
X01  LDQ C33             # RandInt = (RandInt x Multiplier) mod 2^35
X02  MPY A44
X03  STQ A44
X04  CLA A41             # RN count = RN count + 1
X05  ADD 401
X06  STA A41
X07  CLA A44             # RandFloat = (RandInt >> 9) x 2^-27
                         # Using some fancy bit manipulation.
X10  ARS  11
X11  ADD C01
X12  FAD   1
X13  TRA4  1             # Return
```

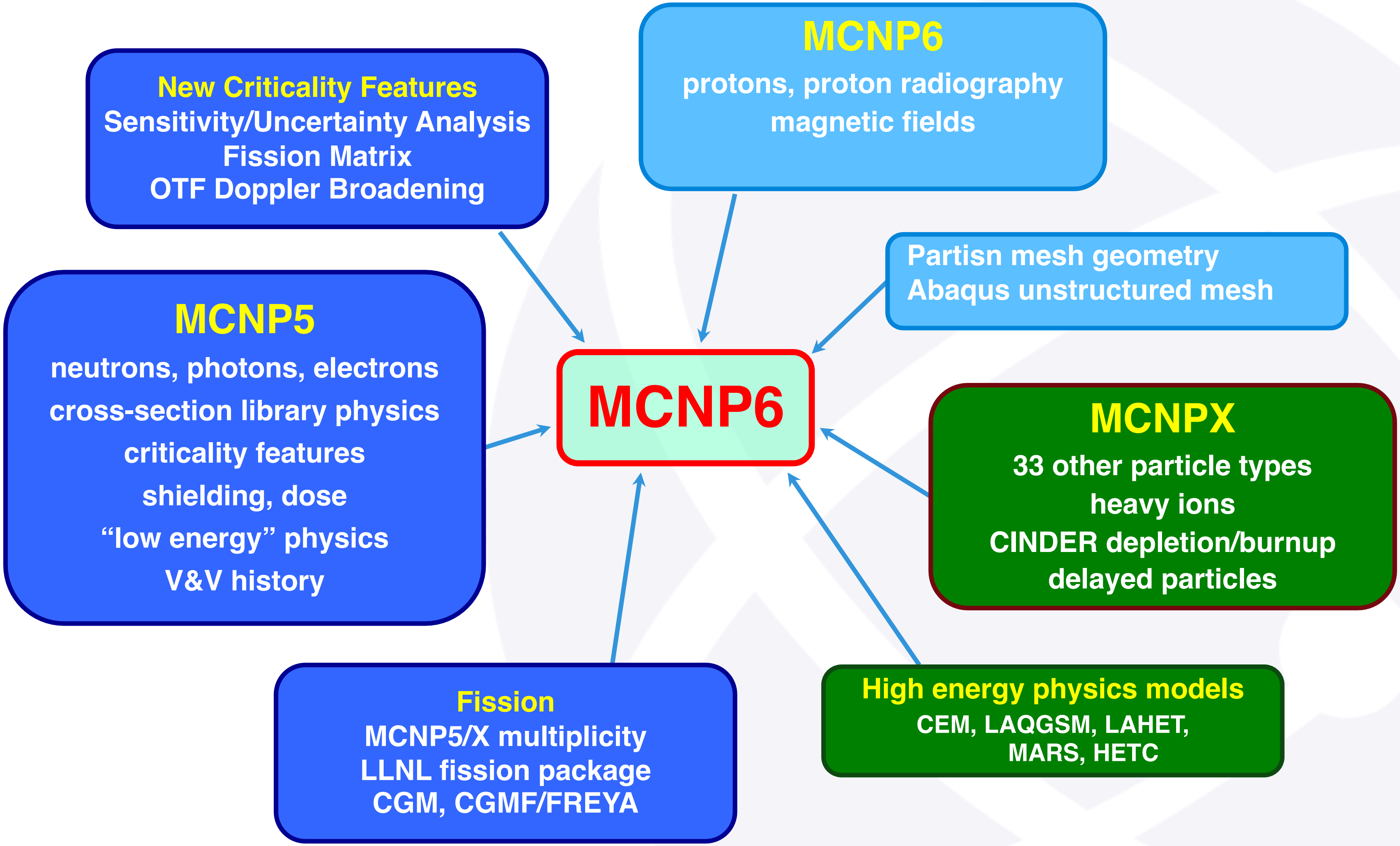
MCS can be directly traced in today’s MCNP code (2)

MCNP 6.3 RNG (C++)

```
double operator()() {
  seed_ = (multiplier_ * seed_ + increment_) & mask_;
  count_ += 1;
  return std::max((bitstream >> (bits_ - 53))*rng_norm,rng_norm);
}
```

- Uses a Linear Congruential Generator instead of Multiplicative.
- 63 bits instead of 35.
- Carefully chosen multiplier instead of user-defined.
- Guard against generating zero.
- Otherwise identical after 60+ years.

From MCNP5 & MCNPX to MCNP6



New Criticality Features
Sensitivity/Uncertainty Analysis
Fission Matrix
OTF Doppler Broadening

MCNP6
protons, proton radiography
magnetic fields

Partisn mesh geometry
Abaqus unstructured mesh

MCNP5
neutrons, photons, electrons
cross-section library physics
criticality features
shielding, dose
“low energy” physics
V&V history

MCNP6

MCNPX
33 other particle types
heavy ions
CINDER depletion/burnup
delayed particles

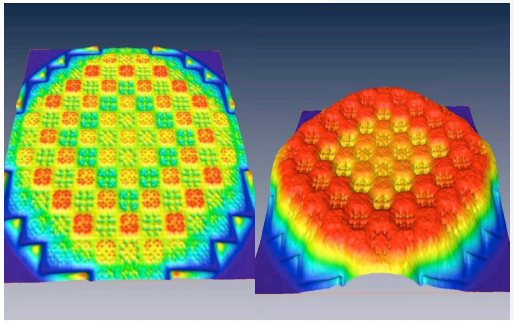
Fission
MCNP5/X multiplicity
LLNL fission package
CGM, CGMF/FREYA

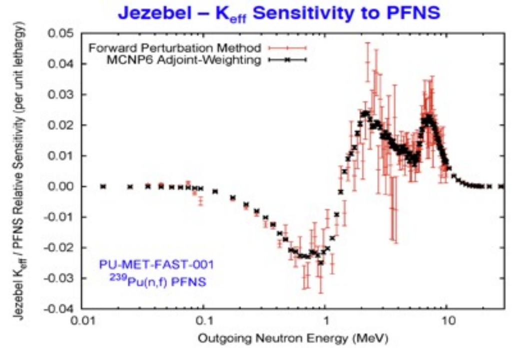
High energy physics models
CEM, LAQGSM, LAHET,
MARS, HETC

MCNP Capabilities

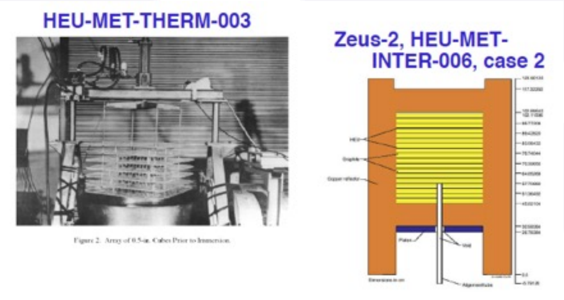
- Physics:
  - Continuous energy particle transport
  - Neutron, photon, electron, and many more particle types
- Algorithms:
  - k-eigenvalue calculations
  - Fixed source calculations
- Recently Implemented Features:
  - Unstructured mesh transport
  - Electric and magnetic field transport
  - High-energy physics models
  - 33 additional particle types
  - Reactor fuel depletion and burnup
  - Radiation source and detection capabilities
  - Sensitivity and uncertainty analysis for nuclear criticality safety
- Extensive Variance Reduction
  - Weight Windows
  - DXTRAN

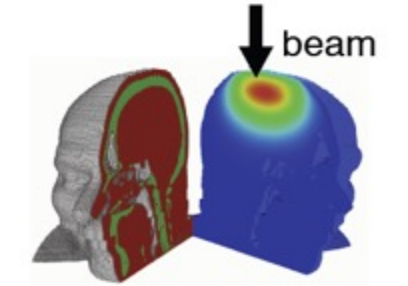
Whole-core Thermal & Total Flux

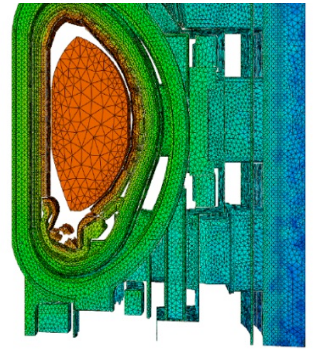




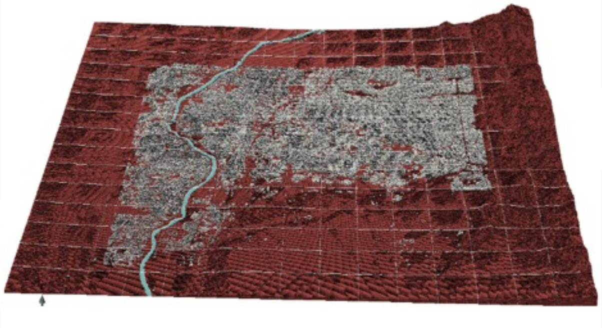
Experimental Benchmarks with Critical Assemblies







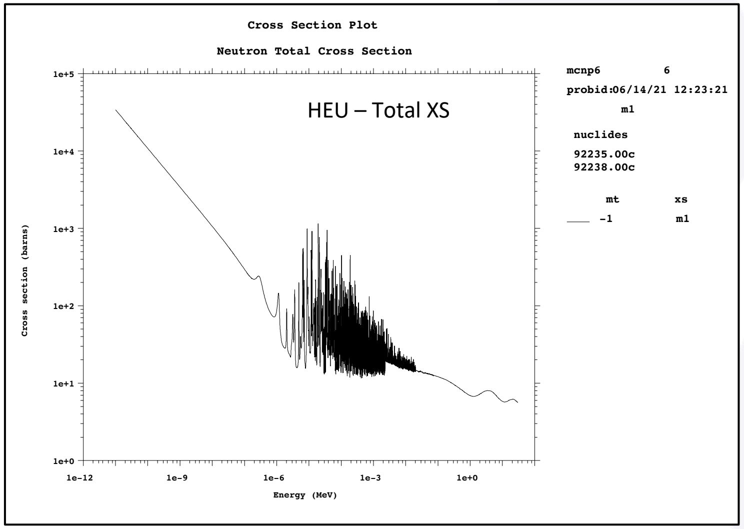
ITER Neutron Flux Calculations

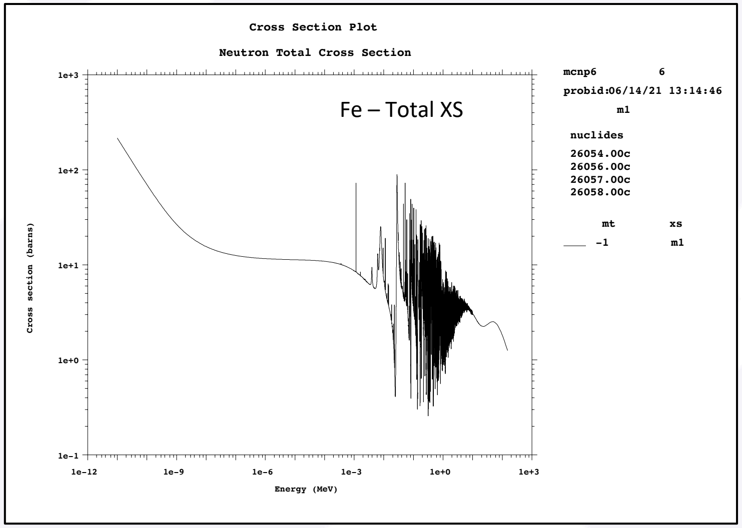


City model used to study nuclear weapon effects

History of Monte Carlo Neutron Data Libraries (1)

- Code development linked with data libraries
  - MCS: treatment of nuclear data has been designed to represent accurately the experimental data, frequently at the expense of computing time
    - particle reaction sampling laws based on data evaluations
  - MCN: LLL and AWRE data maintained on the MANIAC
  - MCN: cross sections from ENDF/B-IV files became available 1975
    - 262-group discrete reaction cross sections and elemental evaluations often used
  - Current cross section libraries are based on ENDF/B-VIII containing 556 isotopes
  - MCNP makes no gross assumptions regarding data





History of Monte Carlo Neutron Data Libraries (2)

- History of Some Major Data Improvements
  - 1968: data libraries became available
  - 1975: first data library from ENDF became available
  - 1980: first $S(\alpha,\beta)$ capability for thermal neutrons
  - 1980: continual improvements in neutron-inducted photon production
  - 1998: unresolved resonance treatment for neutrons
  - 2000: delayed neutrons
  - 2003: photonuclear data from ENDF/B-VI
  - 2015: correlated neutron multiplicity models

- ACE nuclear data libraries from LANL
  - https://nucleardata.lanl.gov/ACE/index.html

Monte Carlo & MCNP History

ENIAC – 1945

30 tons

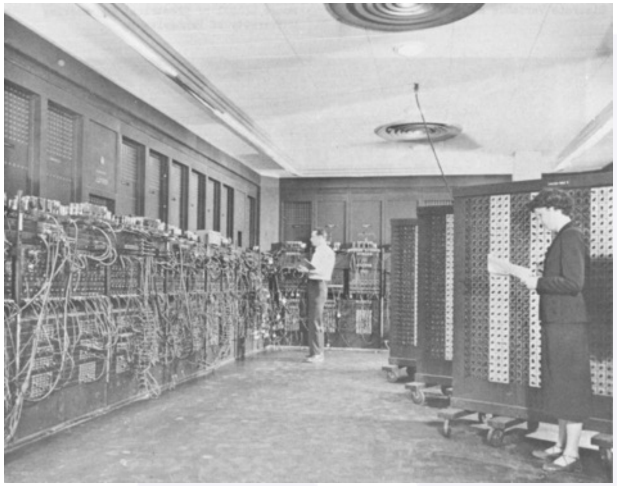
20 ft x 40 ft room

18,000 vacuum tubes

0.1 MHz

20 word memory

patchcords



Manhattan Project – 1945...

Discussions on using ENIAC

Ulam suggested using the "method of statistical trials"

Metropolis suggested the name "Monte Carlo"

Von Neumann developed the first computer code

Trinity

Cray XC40

64-bit Intel® Xeon® processor E5 family; up to 384 per cabinet, 64-256 GB per node

Total Compute Nodes: 9,408 Xeon Haswell + 9884 KNL nodes

Memory/compute node, Total Memory: 128GB HSW + 96GB KNL /2.1 PB

Peak (Tflop/s) 42,170

70 years of Monte Carlo methods development

Summary

- Modern Monte Carlo method developed at Los Alamos
  - technique of statistical sampling named Monte Carlo
  - successfully applied to problems on the ENIAC and MANIAC
  - paved the way for Monte Carlo calculations on computers
- Los Alamos Monte Carlo Theory, Physics, and Codes Have Evolved
  - particles, geometry, physics, variance reduction, computer architectures
  - cross-section libraries continually improve
  - more detailed information about calculation for user
  - MCNP was made available to users worldwide starting in 1983
- MCNP is the Monte Carlo particle transport code supported by LANL
  - rigorous verification and validation testing
  - new versions released every one to two years
  - used extensively at LANL for a variety of applications
  - used worldwide for broader range of application
  - MCNP website: https://mcnp.lanl.gov/

References

- A. Sood, “The Monte Carlo Method and MCNP – A Brief Review of Our 40 Year History,” LA-UR-17-25633.
- R. Arthur Forster, Michael Rising, Avneet Sood, “The History of Monte Carlo and MCNP at Los Alamos,” LA-UR-21-26274.
- Avneet Sood, R. Arthur Forster, B. J. Archer & R. C. Little (2021) Neutronics Calculation Advances at Los Alamos: Manhattan Project to Monte Carlo, Nuclear Technology, 207:sup1, S100-S133, DOI: 10.1080/00295450.2021.1956255

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