ISSN 0915-633X

NATIONAL INSTITUTE FOR FUSION SCIENCE

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(Received – Oct. 15, 1991)

NIFS-121 Nov. 1991

RESEARCH REPORT
NIFS Series

NAGOYA, JAPAN

A Method for the High-speed Generation of Random Numbers with Arbitrary Distributions

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A new method for the high-speed generation of random numbers with arbitrary distributions is proposed. The method stores random numbers in two memories, and then picks out two random numbers and assembles them, resulting in a new random number. When the method is realized with Fortran, the method can generate random numbers with normal distribution about eleven times faster than the method relied on the central limit theorem, and those with Planck distribution about nine times faster than the acceptance-rejection method. The method is realized by hardware. The system generates 5×10^6 random numbers per second with any distribution. The statistical quality of these random numbers is similar to or better than that by the conventional methods.

Keywords : Monte Carlo, random number, high-speed generation, hardware, Planck distribution

1. Introduction

The Monte Carlo method is now the powerful and commonly used technique for analyzing statistical problems. Moreover, the method can also be used for the simulation of deterministic problems. Therefore, applications of the method have been found in many fields [1]. Since random or pseudorandom numbers with given distributions are used in the Monte Carlo method, it is worth while to search for a new method to generate them with an accelerated speed.

The following three methods are well known as procedures for generating random numbers with arbitrary distributions, that is, the inverse transform method, the composition method proposed by Butler and the acceptance-rejection method proposed by von Neumann [2]. Moreover, there are special procedures for generating random numbers with a specific distribution. For example, those with normal distribution can be generated by the well-known method relied on the central limit theorem or the method proposed by Box and Müller [2]. Although these procedures can generate random numbers with sufficient quality, it is better to accelerate the speed to generate them. For this purpose, a lot of methods for the high-speed generation of random numbers have been proposed [3-9]. However, almost all the methods were limited to the generation of random numbers with a specific distribution.

In this paper, we propose a new method for the high-speed generation of random numbers with arbitrary distributions. The method prepares two tables of random numbers and stores them in two memories of a computer, and then picks out two random numbers and assembles them, resulting in a new random number. The proposed method is realized not only by software, but also by hardware for the application to a special purpose computer, which can be as fast as or faster than general-purpose commercial super computers at modest cost [10].

2. Basic algorithm

In this paper, we consider the generation of random numbers with an arbitrary density function $f(z)$ as shown by the solid line in Fig.1. The interval $(C, AB+C)$ in which the density function $f(z)$ is defined is divided into A regions with the small interval of B, and the function $f(z)$ is approximated with a piece-wise constant function $F(z)$, the value of which in each region is equal to that of $f(z)$ at the center of the region. It is evident that $F(z)$ is a good approximation to $f(z)$ when the number of regions is large. Therefore, we try to generate random numbers z, the density function of which is equal to this $F(z)$. Random numbers z are obtained in terms of two random numbers x and y as

$$z = z_1 + z_2 \tag{1}$$

$$z_1 = Bint(Ax) + C \tag{2}$$

$$z_2 = By \tag{3}$$

where, $int(w)$ is the integer part of w, and $0 \leq x, y \leq 1$. The density function of x is chosen to be equal to that of z, therefore the density function of z_1 is represented by the distribution of the dots in Fig.1. The density function of y is chosen to be uniform.

One of our originalities can be found in the method to produce z_1 and z_2. At first, two tables are prepared for random numbers z_1 and z_2. The table is recorded in two dimensions, and the size of that is $NX_m \times NY_m$. Therefore, the number N_m of random numbers on the table is $NX_m \times NY_m$. We call the table "mother assembly" hereafter. Secondly, N_c random numbers shaded in Fig.2(a) are picked out from the mother assembly, where N_c is obviously less than N_m. We call the set of N_c random numbers "child assembly" hereafter. The mother assembly is assumed to be cyclic in two dimensions. Therefore, by setting a left-upper position (i_0, j_0) of the child assembly, we can pick out an arbitrary child assembly from the mother assembly as shown in Fig.2(b). If the number of random numbers larger than N_c is needed, another position is chosen to pick out another child assembly.

Let us introduce the method to produce two mother assemblies. The mother assembly for random numbers z_1 is produced as follows. If N_m random numbers are generated to produce the mother assembly by the well-known previous methods, for example, by the method given by Lehmer when the density function of z_1 is uniform, by the method based on the central limit theorem when the function is normal, and by the acceptance-rejection method for the other functions, it is known that the random numbers have the error $O(N_m^{-1/2})$, because the number of random numbers on mother assembly is N_m. The error approaches 0 according to the increase of N_m, that is, the number of random numbers. However, since the proposed method picks out one or more child assemblies from one mother assembly, each child assembly has the error corresponding to that of the mother assembly. Therefore, when JN_c random numbers are generated by picking out J child assemblies, the error is not $O((JN_c)^{-1/2})$ but $O(N_m^{-1/2})$. In other words, the error does not approach 0 even if the number of generated random numbers increases. In the paper, to overcome this demerit, we generate the random numbers on the mother assembly not by the previous methods, but by an alternative method. The mother assembly for random numbers z_1 is made by randomly storing N_m numbers the distribution of which is exactly equal to that of the value of F shown by the dots in Fig.1. To put it in the concrete, we prepare a number of digits whose value is C with population $F(C)$ in number and value $B+C$ with population $F(B+C)$, $\cdots$, value $AB+C$ with $F(AB+C)$. Then, we store these numbers, the total number of which is $N_m = F(C) + F(B+C) + \cdots + F(AB+C)$, randomly in the memory. In contrast, the mother assembly for random numbers z_2 can be made fast by storing sequentially the N_m random numbers produced by the previous methods, because random numbers z_2 have little influence on the statistical quality of random numbers z. It is clear that the distribution of the random numbers generated by picking out a lot of child assemblies from these two mother assemblies should approach to the profile of F(z) in Fig.1.

3. Realization by software

The generated random numbers can be either real numbers or integral numbers, according to the values of A, B and C in Eqs. (1),(2) and (3). For example, let

$$A = B = 2^8 = 256$$
$$C = 0$$

then the value of the random numbers is distributed from 0 to 65535($= 2^{16} - 1$). The sizes of mother assembly and child assembly are chosen as follows:

$$N_m = 2^7 \times 2^7 = 128 \times 128$$
$$N_c = 100 \times 100$$

Figs. 3, 4 and 5 show the distribution of random numbers generated by the proposed method with the following three density functions:

1) uniformly distributed random numbers.
2) normally distributed random numbers.

$$f(z) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(z-\mu)^2}{2\sigma^2}} \tag{4}$$

Here μ is the mean and σ^2 is the variance.

3) random numbers with Planck distribution [11].

$$f(z) = \frac{z^3}{e^z - 1} \tag{5}$$

The solid lines in these figures are the exact distributions. These figures also show the distribution of random numbers generated by the previous methods, that is, by the library of Pro Fortran-77 for uniformly distributed random numbers, by the method based on the central limit theorem

$$z = x_1 + x_2 + - - - - + x_{12} - 6 \tag{6}$$

for normally distributed random numbers, and by the acceptance-rejection method for the Planck distribution. Fig.3 shows that the distribution of random numbers by the proposed method is similar to or less diffusive than that by the library of Pro Fortran-77. For the normally distributed random numbers, it is well known that the distribution of random numbers generated by Eq.(6) is different from the profile of Eq.(4). It can be certified by Fig.4(d) that the top of the distribution of random numbers generated by Eq.(6) is crushed slightly. In contrast, there is no crush for that by the proposed method. For the Planck distribution, Fig.5 also shows that the proposed method can give a good statistical quality.

For a more detailed discussion, Fig.6 shows the chi-square goodness-of-fit tests. In the tests, the interval is divided into 10 nonoverlapping subintervals, and we have

$$\chi^2 = \frac{10}{N} \sum_{j=1}^{10} (N_j - \frac{N}{10})^2 \tag{7}$$

where N is the total number of random numbers, and N_j is the observed number of trial outcomes. Ten samples with different initial seed are chosen for each cases. Fig.6 shows that the χ^2 by the proposed method is smaller than that by the library on the whole, and that while one sample of random numbers by the library exceeds 5 % of significance level, no sample by the proposed method exceeds it. Fig.7 shows the relative error ε of uniformly distributed random numbers, where ε is written as

$$\varepsilon = \sum_{j=1}^{50} \left| \frac{N_j - N/50}{N/50} \right| \tag{8}$$

When these results are approximated as a linear line by least-squares methods, the slope is -0.495 for the results by the library and -0.482 by the proposed method. This demonstrates that the error of the random numbers generated by the proposed method decreases in proportion to $O(N^{-1/2})$, which is not limited by the size of the mother assembly.

Fig.8 shows the computational time required to generate the random numbers on the personal computer PC-286LS($12MHz$ 80286 + 80287). In the figure, not the library but the Lehmer method is used. The proposed method can run with the same computational time to generate random numbers being in any distributions such as uniform distribution, normal distribution and Plank distribution, as shown by the solid line in Fig.8. This computational time includes the time required for generating two mother assemblies. The figure shows that the proposed method even with the time to make mother assembly being included can generate 10^6 random numbers with normal distribution about eleven times faster than the method relied on the central limit theorem, and those with Planck distribution about nine times faster than the acceptance-rejection method.

4. Realization by hardware

In order for the proposed method to be realized by hardware, it is convenient that the following conditions are added, that is,

$$A = 2^a$$
$$B = 2^b$$
$$C = 0$$

and Eq.(3) is changed to be

$$z_2 = int(By) \tag{9}$$

Then, random numbers z are expressed as integer numbers of $(a + b)$ bits. However, we can regard the random numbers as real numbers with fixed point. The a upper bits correspond to random numbers z_1, and the b lower bits correspond to z_2. Therefore, random numbers z of $(a + b)$ bits can be generated by connecting random numbers z_1 of a bits and random numbers z_2 of b bits in series. Fig.9 shows the block diagram of the system for generating random numbers. ROMX is the read only memory (ROM) in which the mother assembly of random numbers z_1 is stored, and ROMY is the ROM in which that of random numbers z_2 is stored. Counters i_x, j_x, i_y and j_y count one hundred from i_0 and j_0, respectively, to specify the address of child assembly. Header ROMs H_x and H_y, in which the values from 0 to 127 are randomly stored, give the left-upper position (i_0, j_0) of child assembly, and the position (i_0, j_0) is read out from two header ROMs H_x, H_y by counting counter h up. As ROMs 27256 with 32kbytes are used as header ROMs, the left-upper position (i_0, j_0) can be set $32 \times 10^3/2$ times. Control circuits give the control signals ϕ, E_h, E_i, E_j, L_i and L_j to operate these ROMs and counters sequentially, where ϕ is a clock signal, L_i and L_j are load signals for counters, and E_i, E_j and E_h are enable signals for counters. The basic time charts are shown in Fig.10. Four bits Johnson counter is used to generate the clock signal ϕ and the strobe signal $\overline{stb}$, and four states from (1) to (4) shown in this figure correspond to one clock. In the state (1), the clock signal is made, and then counters i_x, j_x, i_y and j_y are operated by using this clock signal. The outputs of ROMX and ROMY become valid at T_{acc} after the settlement of the output of counters i_x, j_x, i_y and j_y. At this time, Johnson counter is in the state (3). Johnson counter does not become the state (4) until the request signal $\overline{req}$ arrives. In the state (4), the control circuits generate the strobe signal $\overline{stb}$ to inform that a random number has been set. A computer connected outside reads the random number after getting the strobe signal $\overline{stb}$. A random number can be generated in the cycle. If the computer connected outside can read fast, the time of the cycle is $200ns$. Moreover, this control circuits make E_i valid every cycle, L_i and E_j valid every 100 cycles, and L_j and E_h valid every 100×100 cycles.

Let us investigate the statistical quality of random numbers generated by the above system, whose top and bottom views are given in Fig.11. We can say that good pseudorandom numbers should satisfy the following requirements,

1) A lot of random numbers can be generated fast.
2) Generated random numbers have good statistical quality.
3) A period is long enough.
4) There is a reproducibility.

On term 1), as the time of one cycle is $200ns$, this system can generate 5×10^6 random numbers per second. On term 2), the statistic quality of random numbers generated by this system is equal to that by software in section 3. Therefore, the quality by this system is equal to or better than that by the conventional methods. On term

3), as this system can generate 16×10^3 pairs of (i_0, j_0), the period of random numbers is 1.6×10^8. On term 4), this system can reproduce the random numbers by initializing the counter h.

5. Conclusions

A new method for the high-speed generation of random numbers with arbitrary distributions has been proposed. When the method is realized with Fortran, the method can generate random numbers with normal distribution about eleven times faster than the method relied on the central limit theorem, and those with Planck distribution about nine times faster than the acceptance-rejection method. When the method is realized by hardware, the system can generate 5×10^6 random numbers per second with arbitrary distributions. The statistic quality of these random numbers is similar to or better than that by the conventional methods.

A special purpose computer for the Monte Carlo simulation using the proposed system will be built in future.

Acknowledgment

This work was carried out under the collaborating research program at the National Institute for Fusion Science. Part of this work was supported by the Grant-in-Aid for Encouragement of Young Scientists from The Ministry of Education, Science and Culture.

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Figure Captions

Fig.1. An arbitrary density function $f(z)$ and the approximated piece-wise constant function $F(z)$.

Fig.2. Mother assembly and child assembly.
(a) A child assembly is selected as a shaded block from a mother assembly. (b) A mother assembly is assumed to be cyclic.

Fig.3. The distributions of uniformly distributed random numbers.

Fig.4. The distributions of normally distributed random numbers.

Fig.5. The distributions of random numbers with Planck distribution.

Fig.6. Chi-square goodness-of-fit tests for uniformly distributed random numbers.

Fig.7. Relative errors of uniformly distributed random numbers.

Fig.8. Computational time to generate random numbers.

Fig.9. The block diagram of the system for generating random numbers with arbitrary distributions.

Fig.10. The basic time charts of the system for generating random numbers.

Fig.11. The photographs of the system for generating random numbers.

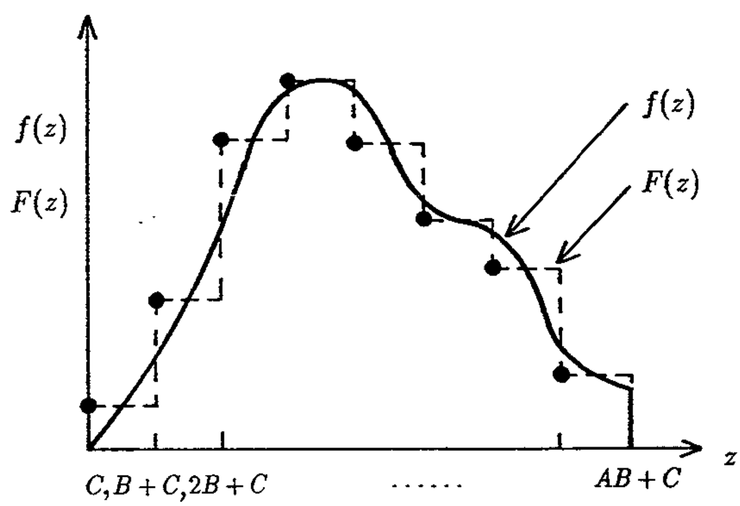


Fig.1

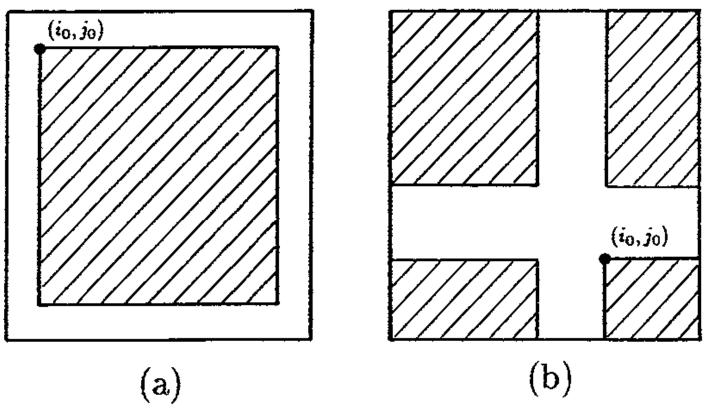
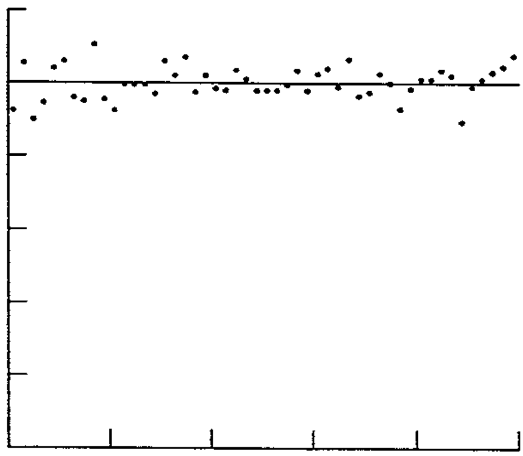
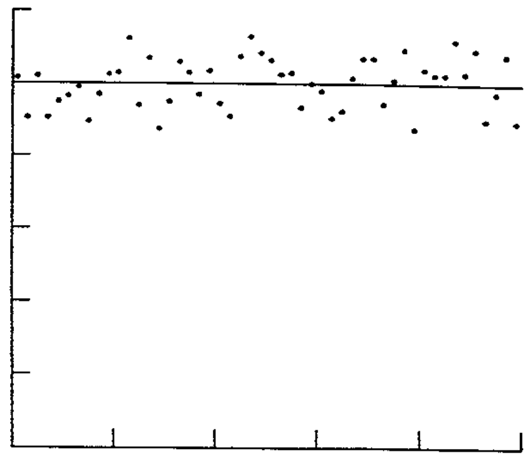


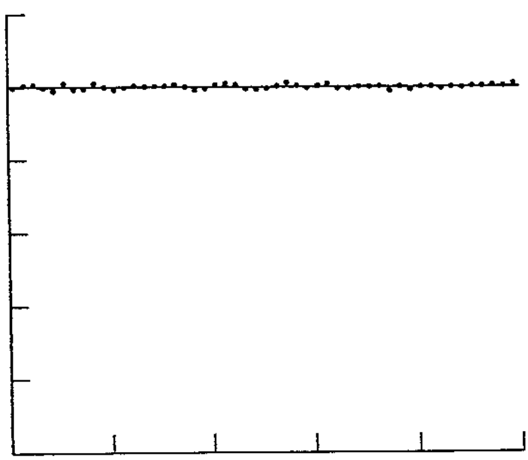
Fig.2



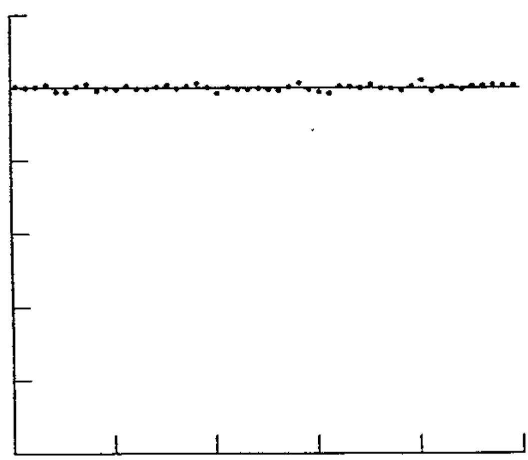
(a) the proposed method
(the number of random numbers is 1×100^2)



(c) the library of Pro Fortran-77
(1×100^2)



(b) the proposed method
(100×100^2)



(d) the library of Pro Fortran-77
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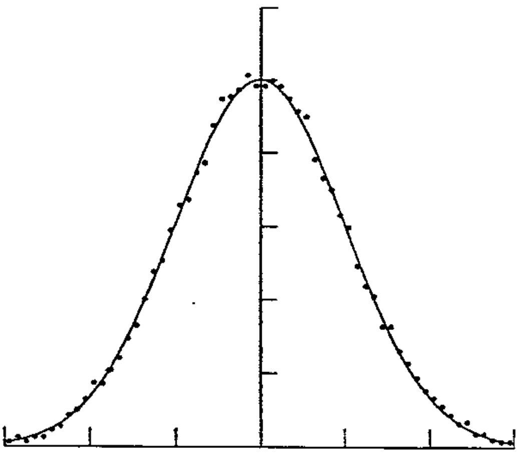
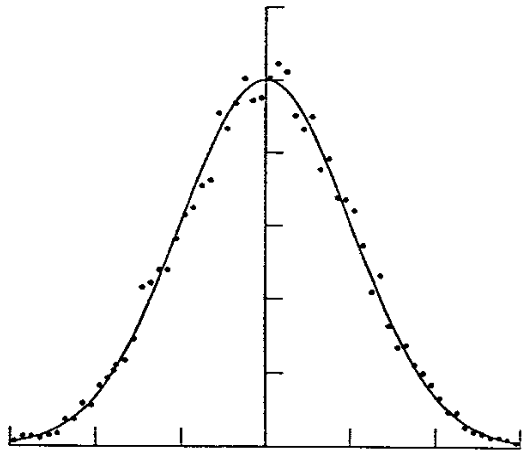
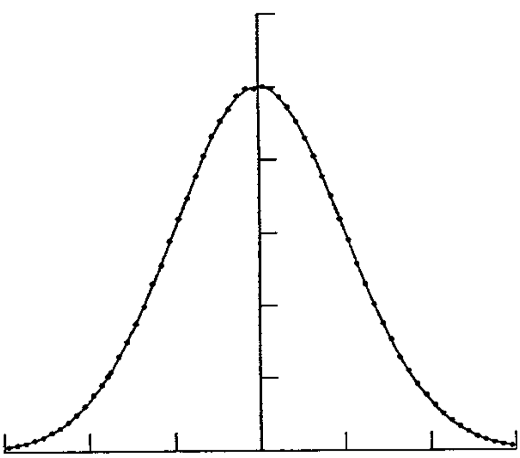
Fig.3



(a) the proposed method
(1×100^2)



(c) the central limit thorem
(1×100^2)



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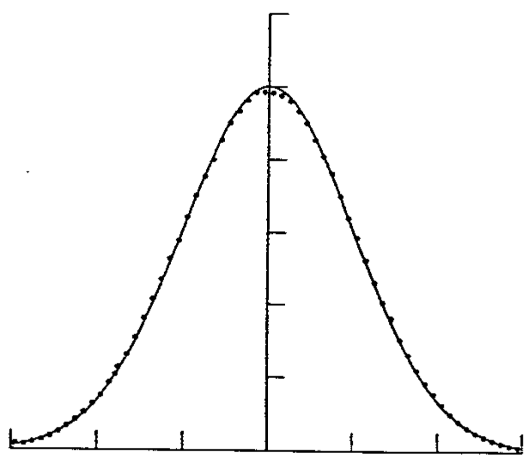

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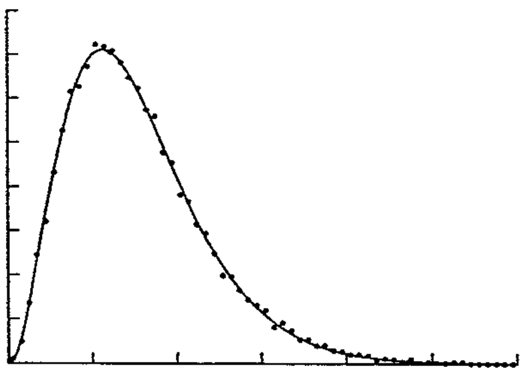
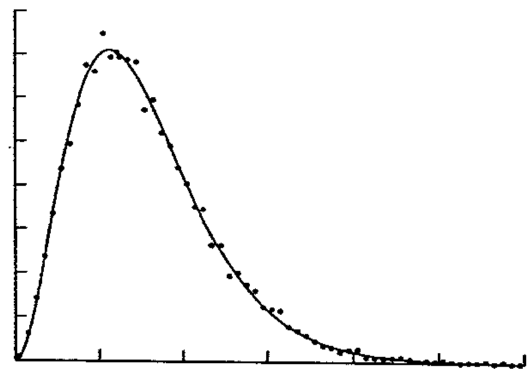
Fig.4



(a) the proposed method
(1×100^2)



(c) the acceptance-rejection method
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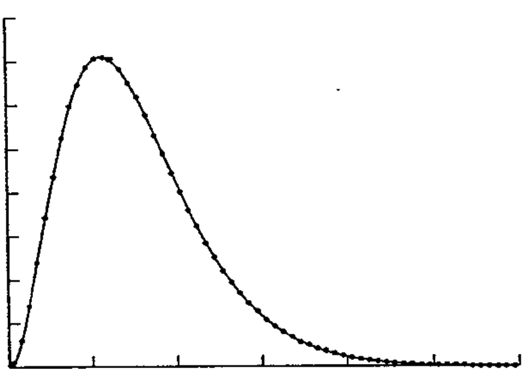

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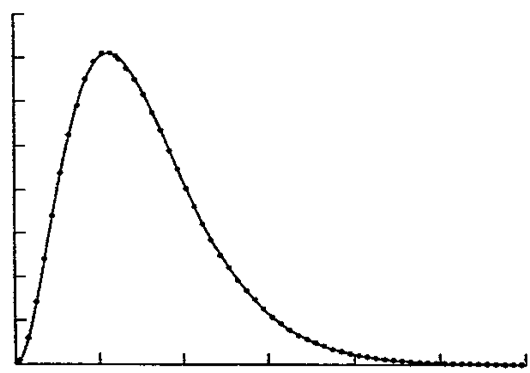
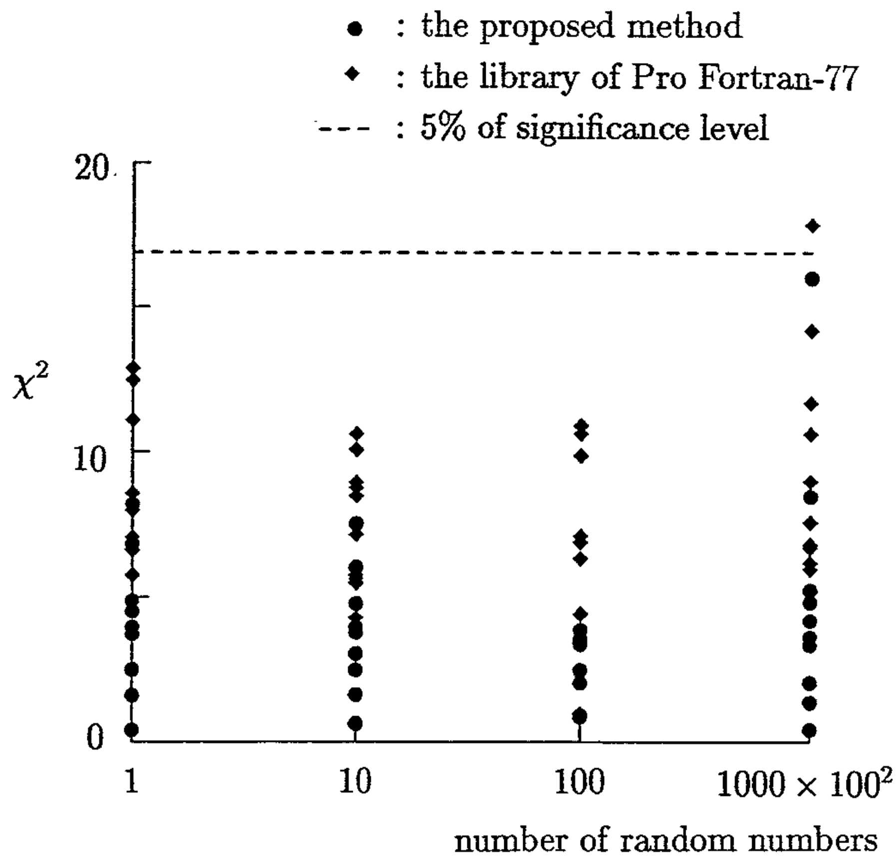


(d) the acceptance-rejection method
(100×100^2)

Fig.5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◆ : the library of Pro Fortran-77
--- : 5% of significance level
20
χ^2
10
0
1
10
100
1000 × 100²
number of random numbers

Fig.6

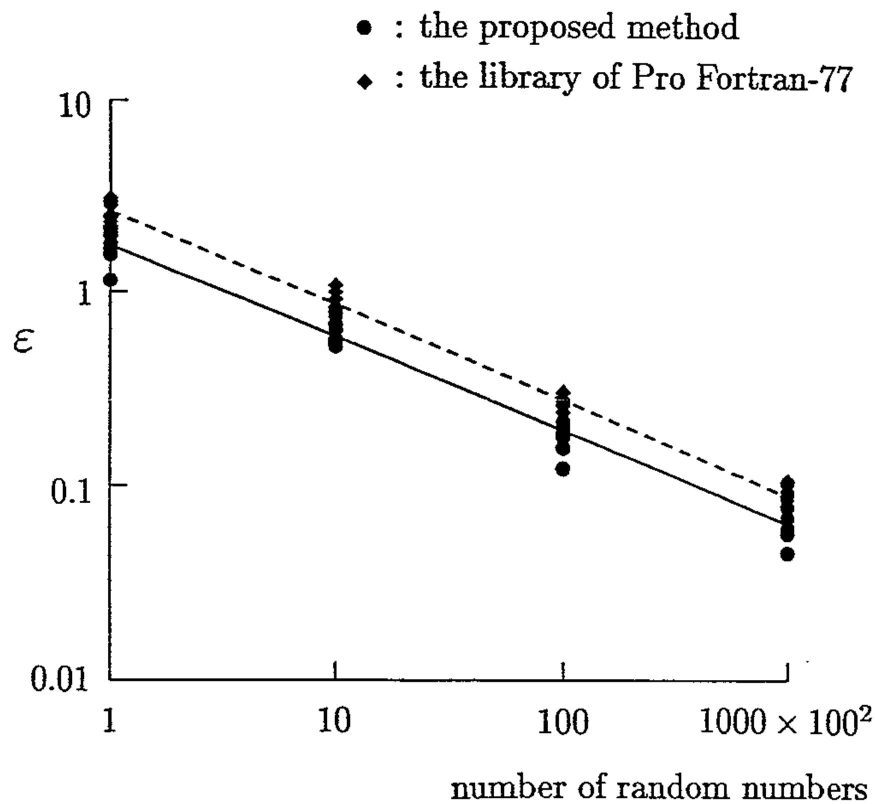
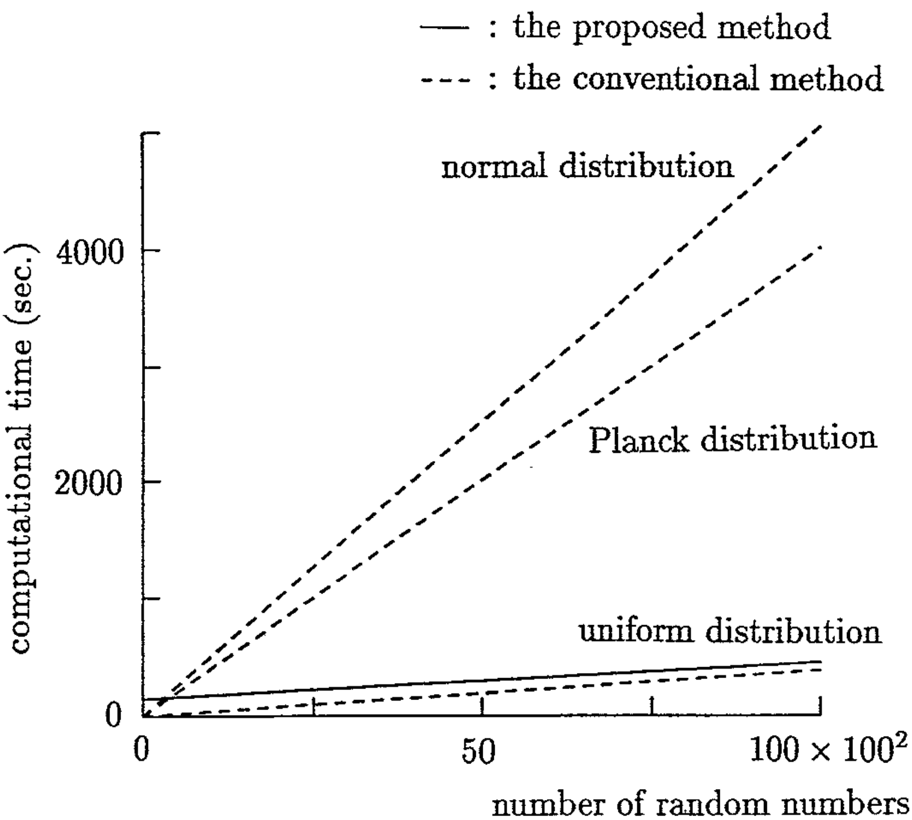

● : the proposed method
◆ : the library of Pro Fortran-77
10
1
ε
0.1
0.01
1
10
100
1000 × 100²
number of random numbers

Fig.7



— : the proposed method
--- : the conventional method
normal distribution
Planck distribution
uniform distribution
computational time (sec.)
4000
2000
0
0
50
100 × 100²
number of random numbers

Fig.8

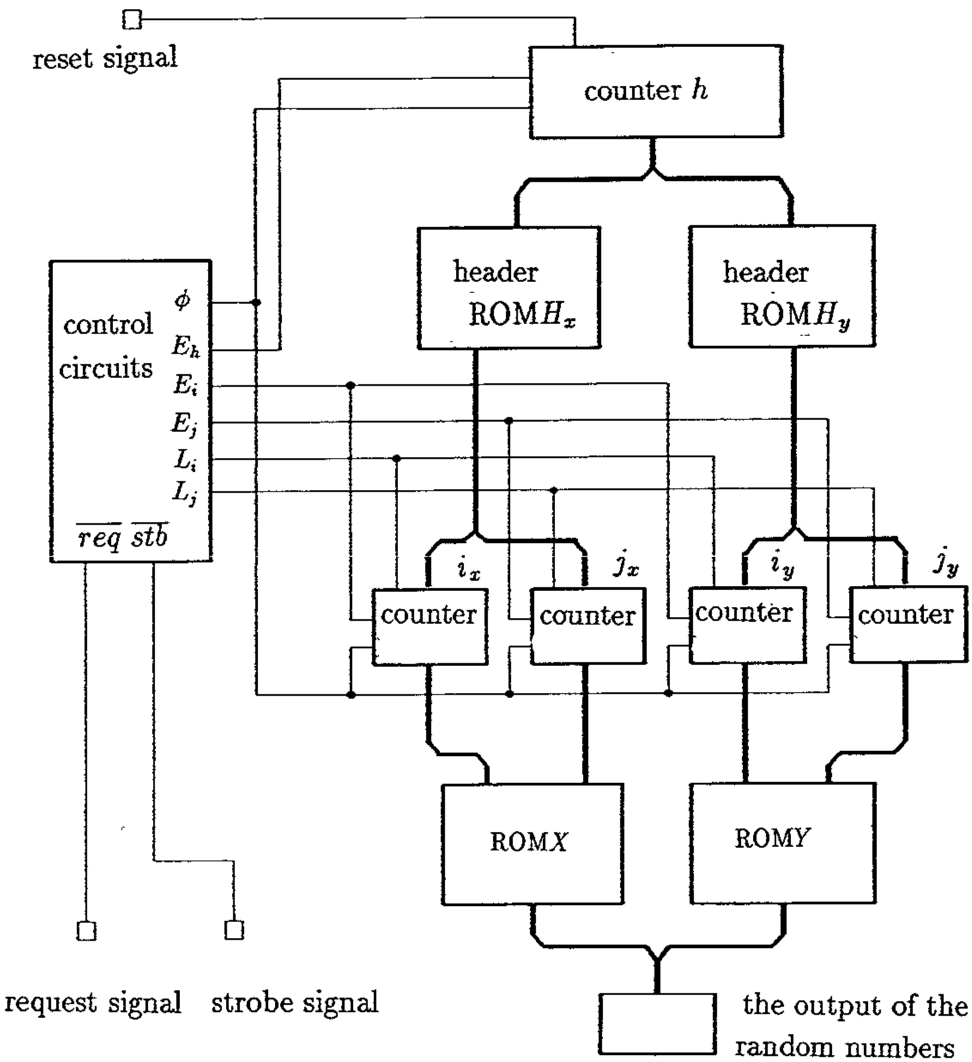

reset signal
counter h
header ROMH_x
header ROMH_y
control circuits
ϕ
E_h
E_i
E_j
L_i
L_j
$\overline{req}$ $\overline{stb}$
i_x
j_x
i_y
j_y
counter
counter
counter
counter
ROMX
ROMY
request signal
strobe signal
the output of the random numbers

Fig.9

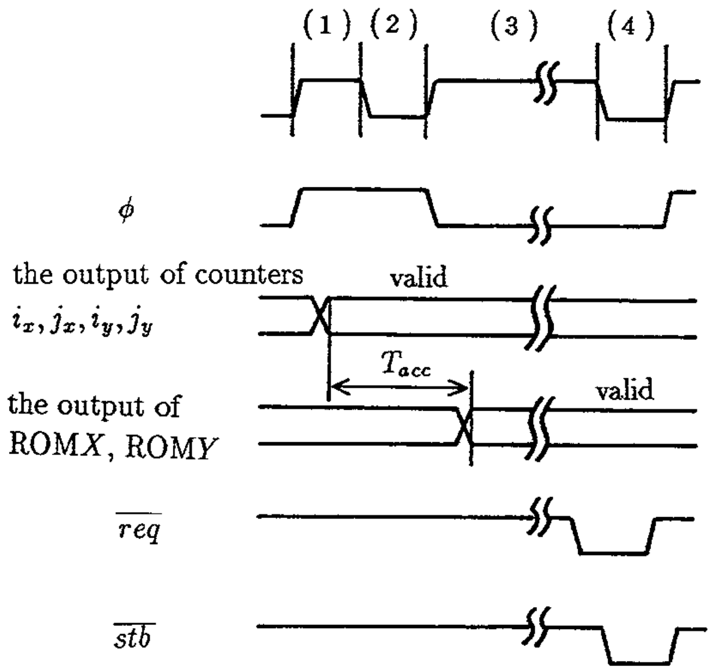
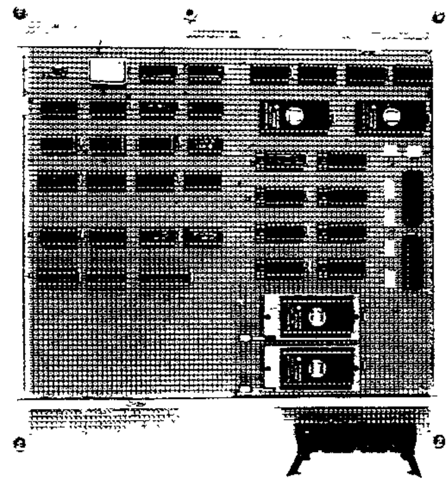

(1) (2) (3) (4)
ϕ
the output of counters
i_x, j_x, i_y, j_y
valid
T_{acc}
the output of
ROMX, ROMY
valid
$\overline{req}$
$\overline{stb}$

Fig.10



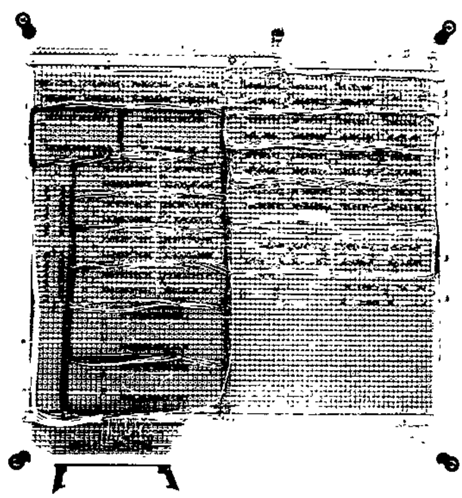


Fig.11

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