The Fermiac or Fermi's Trolley

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Summary. — The *Fermiac*, known also as Fermi's trolley or Monte Carlo trolley, is an analog computer used to determine the change in time of the neutron population in a nuclear device, via the Monte Carlo method. It was invented by Enrico Fermi and constructed by Percy King at Los Alamos in 1947, and used for about two years. A replica of the *Fermiac* was built at INFN mechanical workshops of Bologna in 2015, on behalf of the *Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi"*, thanks to the original drawings made available by Los Alamos National Laboratory (LANL). This reproduction of the *Fermiac* was put in use, and a simulation was developed.

1. – Description

The *Fermiac* [1] is a little brass trolley invented by Enrico Fermi and built by Percy King in 1947. It is a 30 cm long hand-operated computer conceived to study the change in time of the neutron population in a nuclear device. The neutron population would either increase or decrease or remain constant in time, representing a supercritical, subcritical or critical system respectively. The *Fermiac* was used at the Los Alamos National Laboratory (LANL) for about two years by the Bengt Carlson's T-division group, and by scientists such as Ulam, King, Carlson and Metropolis. It was put aside in 1949 because of the general availability of new electronic computers. The *Fermiac* makes use of the Monte Carlo method to trace the histories of neutron movements in a nuclear device. This device originally had no official name, and it became also known as Fermi's trolley or Monte Carlo trolley. The original Fermiac, shown in fig. 1, is on display in the Bradbury Science Museum in Los Alamos.

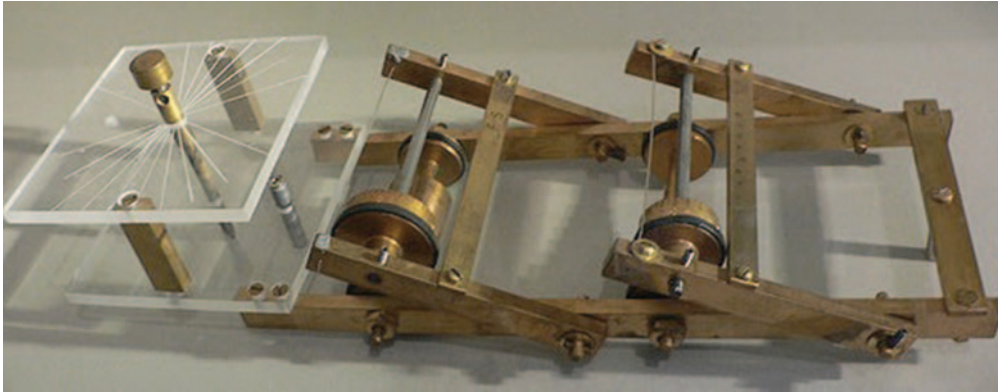(*) E-mail: fabrizio.coccetti@centrofermi.it

Fig. 1. – The *Fermiac* on display at the Bradbury Science Museum in Los Alamos. The *Fermiac* is a 30 cm long hand-operated computer conceived to study the change in time of the neutron population in a nuclear device, via the Monte Carlo method. The neutron population would either increase or decrease or remain constant in time, representing a supercritical, subcritical or critical system respectively.

2. – The Replica

Since only one *Fermiac* is known, the *Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi"*, in 2015, decided to build, with the help of Istituto Nazionale di Fisica Nucleare (INFN) - Sezione di Bologna, a replica for its own museum and for exhibitions. The Bradbury Science Museum kindly provided the drawings of the original (shown in fig. 2). In order to be able to produce the mechanical pieces of the trolley, all the measures of the drawings had to be converted from inches to metrical units. The replica, as shown in fig. 3, is identical to the original, with only one exception. In the original, the labels "F" and "S" (initials for Fast and Slow neutrons) were reversed, and this was understood only after the *Fermiac* was put in use, therefore they had to fix those labels with penciled letters on paper tape. The replica is engraved correctly. This reproduction of the *Fermiac* was on display at the exhibition: *"Enrico Fermi: a dual genius between theories and experiments"*. The exhibition, after its debut at the *"Festival della Scienza (2016)"* in Genova, was set-up in Bologna, and will soon occupy as a permanent show the rooms of the future Fermi Museum inside the institutional seat of the *Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi"*, namely the historic building of the Physics Institute of Via Panisperna in Rome.

3. – History

The *Fermiac* was conceived while the ENIAC (Electronic Numerical Integrator And Computer) was unavailable due to a long shut down for a refurbishment and a memory upgrade and it was also being moved from Philadelphia to its final destination in Aberdeen. In the summer of 1947, Enrico Fermi made a visit to Los Alamos Scientific Laboratory and devised a solution for the computational needs of the scientists who had the Monte Carlo method available thanks to Ulam and Metropolis [2] but could not use it on a computer. Fermi, talking with King, suggested to build an inexpensive mechanical device designed to follow hypothetical neutron tracks as they progressed through various
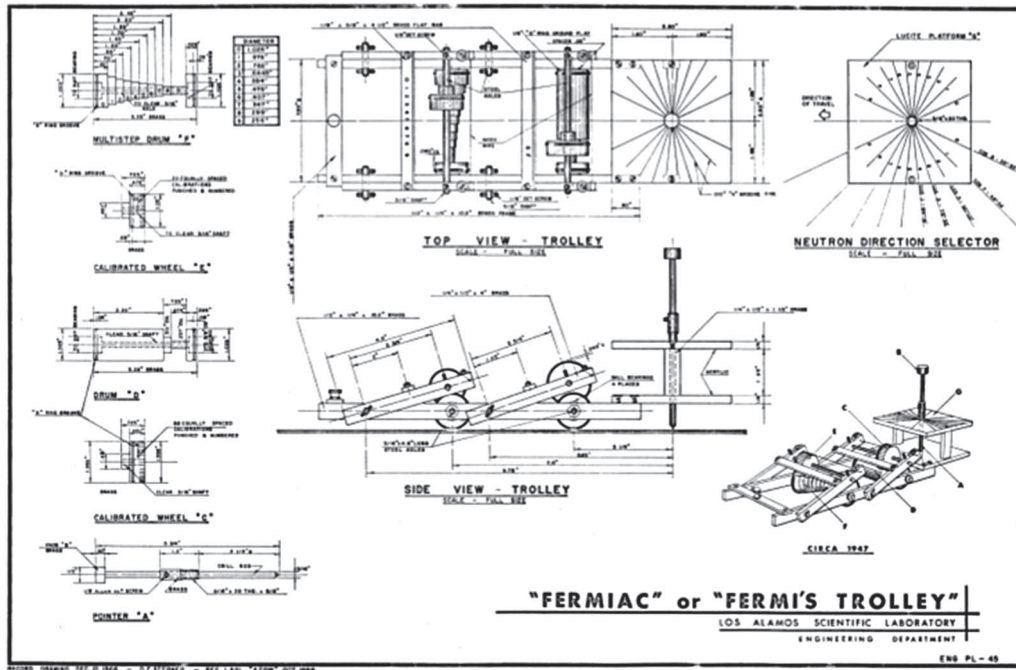
Fig. 2. – Drawings of the Fermiac, made available by the Bradbury Science Museum of Los Alamos.
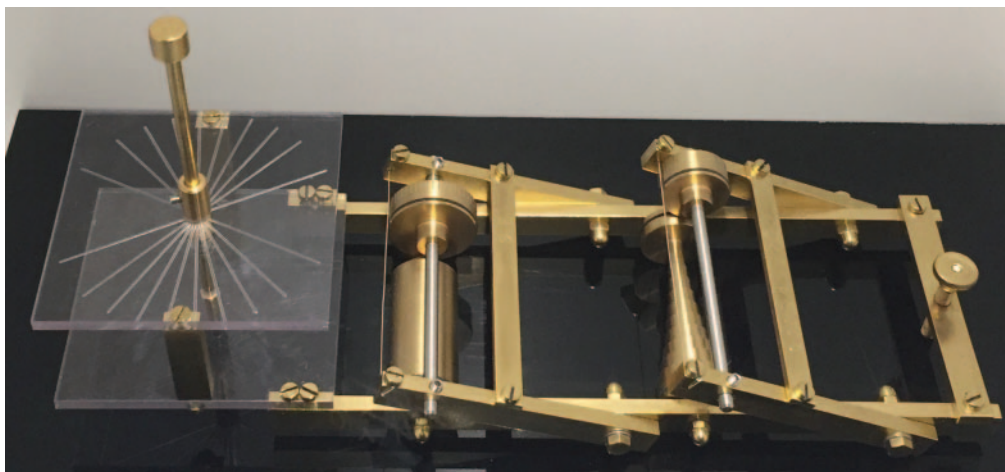

Fig. 3. – Replica of the *Fermiac*, built at INFN mechanical workshops of Bologna, in 2015, for the *Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi"*. It mainly consists of three parts. The *lucite platform* (on the left of the photo) serves as a neutron direction selector. The *rear drum* (in the centre) measures the elapsed time based on the velocity of the particular neutron in question. The *front drum* (on the right) measures the distance traveled by the neutron between subsequent collisions based on the neutron velocity and the properties of the material being traversed.
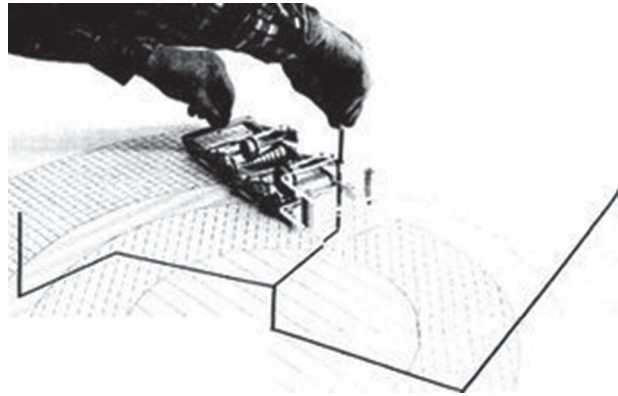
Fig. 4. – To operate the *Fermiac*, you need to make a scale drawing of the nuclear device under exam, decide an initial collection of source neutrons, establish the nature of the collision of each neutron, the distance to the next collision, and then you can move the *Fermiac* to follow the fate of each neutron (source: [2]).

materials regions. King built the device, and the T-division group successfully used it for a couple of years, learning, as Carlson stated, "invaluable things" [1]. The trolley was discontinued in 1949, when electronic computers became generally available.

4. – How the Fermiac works

The *Fermiac*, as shown in fig. 3, mainly consists of three parts:

1. The *lucite platform*, that serves as a neutron direction selector.

2. The *rear drum*, that measures the elapsed time based on the velocity of the particular neutron in question.

3. The *front drum*, that measures the distance traveled by the neutron between subsequent collisions based on the neutron velocity and the properties of the material being traversed.

Before operating the *Fermiac*, you need to make a scale drawing of the nuclear device under exam; this is obtained by projecting on a plane the concentric sections of the different materials, as shown in fig. 4. Then you need to decide an initial collection of source neutrons (at the T-Division usually 100 neutrons were taken), and for each one you need to determine the location of the first collision or possible escape. This is achieved by statistical considerations on the characteristics of the type of material being traversed. You also need to establish the nature of the collision of each neutron: elastic, inelastic scattering or fission (if the material allows), and the distance to the next collision. Then you can operate the Fermiac to follow the fate of each neutron.

5. – The *Fermiac* in operation

We decided to verify how the Fermiac could be used to study the behaviour of an air-cooled neutronic reactor. A reactor of this kind is shown in fig. 5, which is taken from the Application of May 29, 1945, Serial No. 596465, then U.S. Patent No. 2836554 - Patented
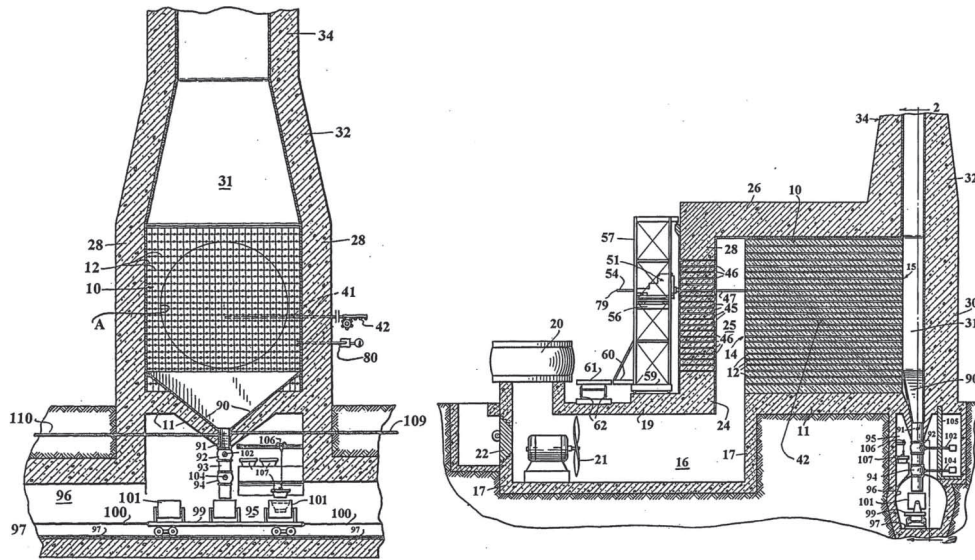
Fig. 5. – Front and side view of an air-cooled neutronic reactor. This is the picture of an uranium-graphite cooled-by-air reactor, as shown in the Application of May 29, 1945, Serial No. 596465, then U.S. Patent No. 2836554 - Patented May 27, 1958, by Enrico Fermi and Leo Szilard [3] [4].

May 27, 1958, by Enrico Fermi and Leo Szilard [3]. A graphite cube of 6 meters per side, pierced with horizontal air channels, is located at the centre of the reactor. These holes, through which the cooling air passes, are used to insert aluminum-jacketed uranium slugs that act as the fuel. The matrix of holes rises to a system that can be represented with many symmetrical longitudinal cells. Each cell can be idealised as in the drawing in fig. 6(a), where each different material is represented by a planar circle. In the middle there is the "Fuel", which in this case is an uranium slug of 2.8 cm in diameter while the aluminum jacket is thin enough to be ignored in this model. The circle around it, with the label "Gas", represents the longitudinal section of the space occupied by the cooling air with a diameter of 4.2 cm. The last circle, with the "Graphite" label, is the moderator and fills all the space up to the contiguous cells, although in the drawing it is only sketched. In this reactor, the nearest neighbour distance among the centres of each cell is 17.5 cm.

After a cell is drawn and a collection of source neutrons is decided, the *Fermiac* can be put in position. The tip of the pointer which is in the centre of the *lucite platform* of the *Fermiac* is placed on the location of the first source neutron. This tip ends with a pencil lead than can leave a mark while the *Fermiac* moves. If necessary, it can also be used as a pin to rotate the trolley around by an angle which is read on the lucite platform. A first calibrated wheel, placed on top of the *front drum*, measures the elapsed time based on the velocity of the neutron, and is set on a two-step drum, made of two cylinders of different diameters, that has two possible positions: one if the neutron is *"fast"*, the other if it is *"slow"*. This wheel is turned to zero each time a new source neutron is followed and the position is changed if the neutron, after a collision, changes status from *"fast"* to *"slow"*. A second wheel, placed on top of the *front drum*, measures the distance traveled by the neutron between collisions. This wheel is set on a multistep
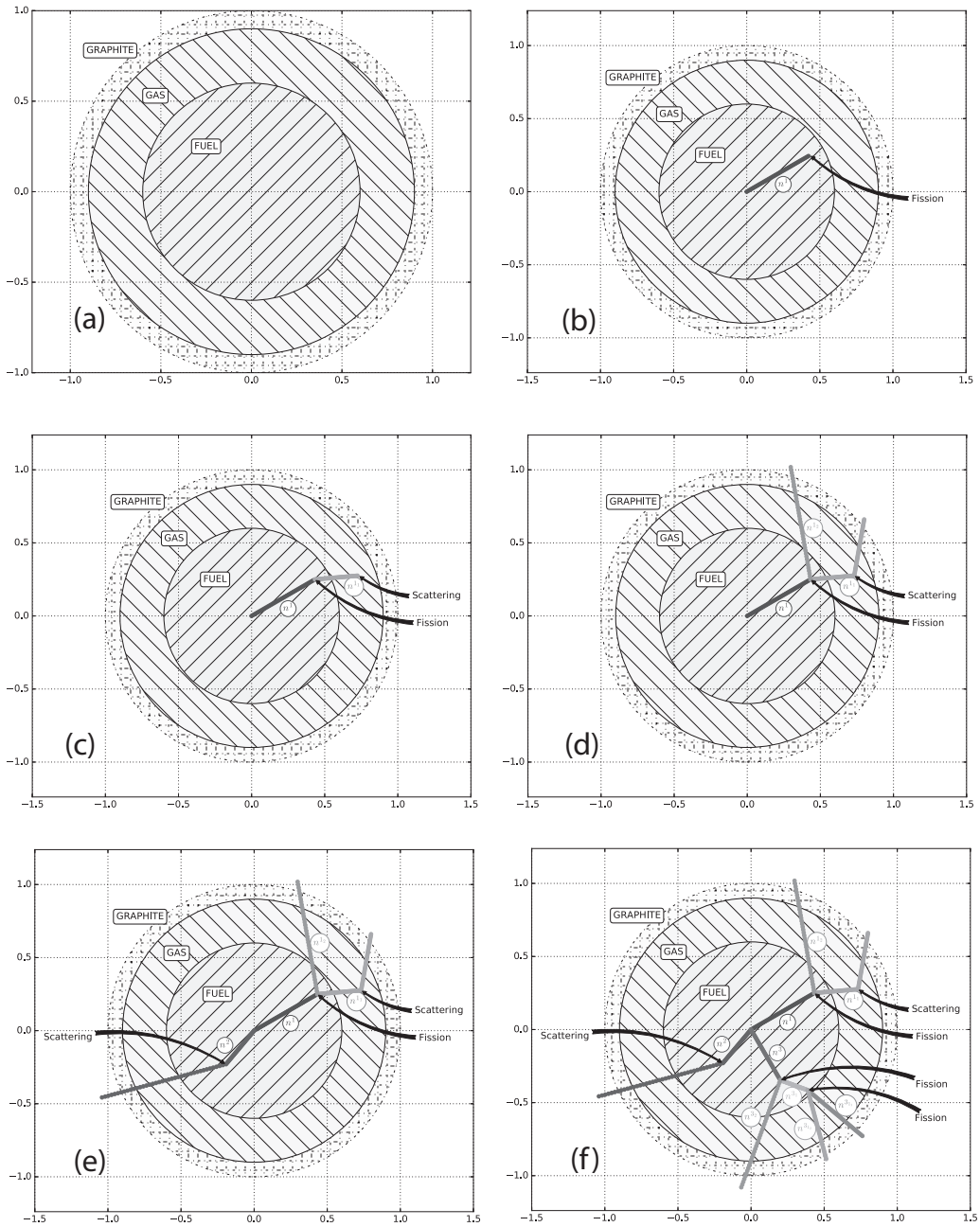
Fig. 6. – An example of the Fermiac used to follow the fate of the genealogy of source neutrons n^1, n^2, n^3 in a cell of a nuclear reactor.

drum, and the proper placement is chosen on the basis of both the neutron speed and the particular type of material at the position of the pointer. The position of this wheel is shifted depending on the change of the neutron speed and position when traversing different materials.

We can try to follow a sample of three source neutrons, to better understand how the Fermiac operates. When we decided the initial collection of the neutrons, we determined that the first three neutrons are all slow and they start at the centre of the cell in fig. 6(a). We begin with the first neutron n^1.

The *Fermiac* is placed with the tip of the pointer in the centre of the cell, and we move the first wheel on the position of the slow neutron on the two-step drum. Then we place the second wheel on the position of the multistep drum made for slow neutron while traversing uranium material. Next, a pseudo-random digit is selected from an isotropic distribution, representing a rotation angle, and the trolley is rotated about the pointer of the relative amount. Another pseudo-random number is then selected, accordingly to the distribution of free paths (the mean in this case is $\sim$2.5 cm), to represent the distance to the next collision. The *Fermiac* is moved forward, marking a line on the cell, as shown in fig. 6(b), until the reading on the second wheel corresponds to the number selected. Then the nature of the collision is determined by picking another appropriately selected pseudo-random number. In this example a fission is drawn, with the production of two child neutrons. Therefore the neutron n^1 history is terminated, and the time is read on the first wheel. Now we follow its genealogy: neutrons n^{1_1} and n^{1_2}, starting from the time just read. For each of these child neutrons, which are fast (so we have to shift the position of the first wheel), we determine the angular direction, and the length of the path. When we start to trace the trajectory of n^{1_1}, we have to keep in mind, as shown in fig. 6(c), that this neutron crosses the boundary between fuel and gas. Therefore we have to stop momentarily the trolley to shift the second wheel to a new position in the multistep drum, for the new material. After the *Fermiac* reaches the position where n^{1_1} has a collision, again a pseudo-random number is selected to determine its kind, which eventually is an elastic scattering. A new angle and a new length of the path is chosen, and the trolley is moved forward. These steps are repeated until each neutron reaches the border of the cell, then it is considered escaped from the system and it is not followed any longer. In fig. 6(d) we see that both n^{1_1} and n^{1_2} enter the moderator layer; we should follow them for other steps till the boundary of the cell. After we have finished to follow the genealogy of the first neutron, we can start with the second source neutron n^2. We put back the trolley in the center of the cell, we set the time wheel to zero, and we start following the fate of the second neutron as in fig. 6(e). The neutron n^2 turns out not to have any children. Again, after n^2 reaches the end of the cell, we can start dealing with the third neutron n^3. In this case, the genealogy turns out to be a bit more articulated, due to the major number of fissions in this example. The child neutron n^{3_1} undergoes a fission which produces its own child neutrons $n^{3_{1_1}}$ and $n^{3_{1_2}}$. At each step of the simulation, the time can be read on the first wheel. And we can see how, in this example, starting with three neutrons, we end up with a population of six neutrons that move to other cells. Therefore, thanks to the *Fermiac*, it is possible to understand if the system will be supercritical or not, depending on the geometry of the reactor and the materials of each cell.

6. – Conclusions

The Monte Carlo method is now widely used in fields such as physics, engineering, economics, biology, and many more, thanks to the increasing computational power and availability of computing resources. The *Fermiac*, an inexpensive hand-operated small brass trolley, can be considered one of the first computers in history used to implement the Monte Carlo method. It is another example, yet not well known, of the genius of Enrico Fermi.

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REFERENCES

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[2] METROPOLIS N., *Los Alamos Sci.*, **15** (1987) 125.
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[4] FERMI E. and SZILARD L., *Air Cooled Neutronic Reactor*, Application May 29, 1945, Serial No. 596465 U.S. Patent No. 2836554 - Patented May 27, 1958.