

Serial: Electron, Electronics, Spin... Spintronics!

Introduction to the Serial of the 40th Volume

Dear participants, welcome to another volume—this year the milestone 40th volume—of the serial section of the physics correspondence seminar FYKOS. This year, we have decided to select a topic that is currently very timely and, moreover, in a field where Czech science has left a substantial mark. This serial will be dedicated to modern *spintronics*.

It is a multidisciplinary topic that we will examine from several perspectives. We will discuss current results and how they have aided modern electronics, present trends, possible future revolutions, as well as concepts that looked theoretically very promising but later faced technical issues that prevented their implementation.

From a physics perspective, we will address the electrical and magnetic properties of materials, as well as their ultrafast response. In the problems, you will perform simple calculations and modeling, but tasks focused purely on the symmetry of given problems also await you.

How Does a Computer Work?

The foundation of all information processing is binary logic. Complete information is rewritten into bits with possible values of 0 and 1, which can correspond to various pieces of information. For example, logical values can simply represent truth and falsehood (**True/False**). More complex information can also be stored; for example, the number 3 in integer form would be written as 0011. The calculation then proceeds using various logic gates that perform the required operations on the data. For instance, if we assigned two bits to two propositions and wanted to know from the computer whether both hold simultaneously, we would use the **AND** logic gate.

However, as we know, modern computers are significantly more complex and can perform various functions ranging from connecting people via video calls to playing movies and executing sophisticated scientific calculations. To function in this way, they operate on the basis of the von Neumann architecture. It consists of two main parts: the processor and the memory. The processor is a chip that executes instructions and calculations. At the same time, it is the central and fastest component in a computer. For example, the processor in the serial author's computer executes instructions with a frequency of 1.8 GHz. The memory is the place where data and programs are stored. Until recently, this role was fulfilled by magnetic hard drives, where a mechanically moving sensor read the magnetic field, based on which it determined the values of bits (you will learn more about this in the next part of the serial). Due to the mechanical motion of the sensor, this component was too slow (e.g., modern hard drives have around 7 200 rpm, which corresponds to approximately 120 Hz). This vast gap is bridged using random-access memory (RAM), where the currently needed data are loaded. At the same time, all data are automatically erased after powering off. Although this memory is already significantly faster, it is still not entirely sufficient for the processor. For that reason, even faster L1 to L3 cache memories are used, with L1 being the fastest (with a capacity of only a few kilobytes) and L3 being the slowest (with a capacity of tens of megabytes).

This technology worked for a very long time; however, nowadays, it is already hitting its limits...

Electronics in Trouble

The first drawback of the aforementioned approach is that the processor can process information faster than the memory can supply it (also known as *the von Neumann bottleneck*), which unnecessarily slows down the entire "ecosystem." Moreover, no further significant progress can be expected unless the entire architecture changes significantly.

Another not entirely obvious problem is energy requirements and heat dissipation. Surely we all know that feeling when, after working for a long time, we touch the bottom of a laptop and feel how warm it is. That is part of the energy that was not used to process and store information and was converted into heat. This, for example, limits higher processor clock frequencies. We will also introduce heat dissipation in a serial problem.

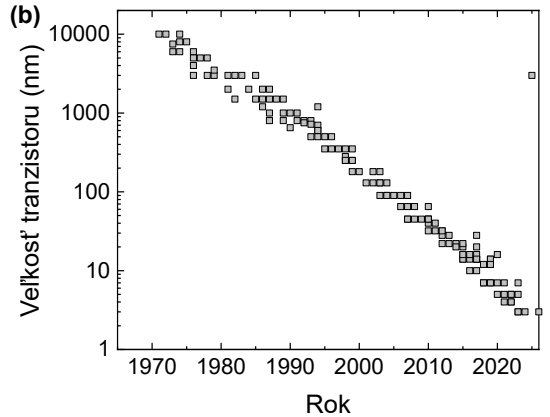
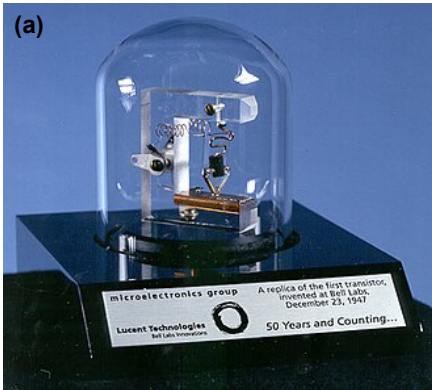


Figure 1: (a) The first transistor constructed at Bell Laboratories in 1947. (b) Transistor size by year¹. Note the logarithmic vertical axis, which clearly shows the trend of transistor miniaturization that accompanied Moore's law.

Apart from a higher clock frequency, processor performance could also be increased by a higher density of the individual units that process information. In practice, this is implemented using transistors, with current technology enabling their reduction down to 2 nm.² The path to this technology was very long, and the first transistors certainly did not have such small dimensions, as can be seen, for example, in Fig. 1(a), which shows the first point-contact transistor constructed at Bell Laboratories in New Jersey, USA. Since then, transistors have undergone significant development and gradual miniaturization, which for a long time followed

¹ Adapted from: https://en.wikipedia.org/wiki/Transistor_count#Microprocessors

² However, this is rather marketing. In reality, the size of individual transistors is in the tens of nm.

Moore's law³: the number of transistors on a chip doubles every two years while maintaining approximately the same manufacturing cost, which can be seen nicely in the time evolution of transistor size in Fig. 1(b). From a physics standpoint, however, this trend cannot be followed indefinitely, because at a certain point, the transistor would be composed of only a few atoms, and quantum effects would begin to manifest.

At the same time, technological development is necessary, as we are currently experiencing a huge AI boom that consumes a lot of electrical energy, and some sources even claim,⁴ that this trend may not be sustainable in the long term. One of the very promising directions of development—whether for more efficient existing components or for parts of entirely new non-von Neumann devices—is the utilization of not only the charge of an electron, but also its intrinsic angular momentum—*spin*.

Spin, Spintronics, and Spin Currents

Although most of you probably already have some experience with spin from high school, it is good to expand on this concept a bit more. The spin of an electron is its intrinsic angular momentum, thanks to which it also carries its own magnetic moment. Often, the origin of spin is explained using the rotation of an electron about its own axis, where, due to its charge, an associated magnetic field should be generated. Qualitatively, this model would indeed describe the origin of the magnetic moment of the electron; quantitatively, however, we encounter a few problems that you will be able to try out in a serial problem. Furthermore, it should be noted that particles that have no charge, such as neutrons, also possess spin and a magnetic moment.

How then should we view spin? Spin is the intrinsic quantum angular momentum of a particle. Its complete description and relationship to the magnetic moment naturally follow from relativistic quantum mechanics, which is a topic that significantly exceeds the scope of this serial, and therefore we will not address it further. We will focus on spintronics and always speak of spin as an intrinsic angular momentum, which we will denote by an arrow. At the same time, however, it is a quantum angular momentum, which in the case of electrons is half-integer. In practice, this means that we can describe it using two projections: "up" and "down"; see Fig. 2(a).

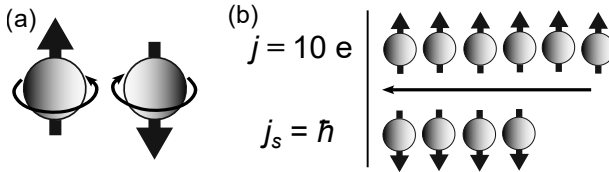


Figure 2: (a) The spin of an electron and the classical picture of its rotation. (b) Illustration of charge current and spin current according to the main text. While charge current is simply a flow of 10 electrons, spin current is the difference in the transferred spin, i.e., only "2 spins up."

³Although the name "Moore's law" is generally established, a more accurate designation would be "trend" or "prediction," as it is not a real physical law, but rather an empirical trend.

⁴A. Prieto, B. Prieto, J. J. Escobar, and T. Lampert, "Evolution of computing energy efficiency: Koomey's law revisited", Cluster Computing 28, 42 (2025).

Just as classical electric current represents the transfer of charge, we would also like to transfer our spin. How do we do that? We can help ourselves with the classical definition of current, namely that current is the magnitude of charge that flows through a given area per unit time. We do not want to transfer charge, but spin; therefore, we will be interested in how much spin flows through a given area per unit time. Within the serial, however, it will be more practical to work with current density $j = \Delta I / \Delta S$. For example, consider a charge current formed by 10 electrons (Fig. 2(b)) that flow through an area of 1 m^2 in 1 second. The current density (in the corresponding base units) will then numerically be

$$j = 10 \cdot e,$$

where e is the elementary charge of the electron. Now, however, suppose that 6 of these electrons have one spin ("up", $\uparrow$) and 4 have the opposite ("down", $\downarrow$). In that case, the spin current⁵ will be

$$j_s = \frac{\hbar}{2}(6 \uparrow, +, 4 \downarrow) = \frac{\hbar}{2}(6 \uparrow, -, 4 \uparrow) = \hbar,$$

where $\hbar/2$ is the magnitude of the spin and $\hbar$ is the reduced Planck constant.

You will be able to familiarize yourselves with spin current, its generation, and its various forms in a serial problem. You will handle it easily once you realize that you are interested in the total flux of spin through a given region. At the same time, it should be emphasized that we define spin current here as the motion of electrons, but in reality, spin current can be carried by various other channels, such as spin waves, which you will similarly try out in a serial problem.

With this (hopefully) simple introduction to the serial, we bid farewell, and in the next installment, we will talk about ferromagnets, magnetic hard drives, other spintronic components, and what makes them so efficient. Starting from the next installment, we will also begin modeling, so I would ask you to install the software **Octave Forge**⁶, in which we will do some small-scale modeling. The link leads to pages with installation files for the Windows operating system, where you should select the latest version and install it. No other non-standard packages will be required for now.

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⁵It should be emphasized that, compared to classical current, several conventions exist for spin current. Here, for simplicity, we define spin current as the flux of angular momentum. If we calculated the spin current as the difference between charge currents, it would be necessary to add a coefficient $\hbar/(2e)$, which converts the charge current into a flux of angular momentum.

⁶<http://sourceforge.net/projects/octave/files/octave/windows/binaries/> (<http://sourceforge.net/projects/octave/files/OctaveWindowsbinaries/>)