VIII. CONTEMPORARY PHYSICS
RESEARCH BASED PROPOSALS TO BUILD MODERN PHYSICS WAY OF THINKING IN SECONDARY STUDENTS

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ABSTRACT

Conceptual knots in classical physics are often cited as motivation for the exclusion of modern physics from secondary school, but the physics of the last century is now part of the secondary school curricula in many EU countries and in the last 10 years appear in secondary textbooks, even if not in an organic way and with a prevalent narrative approach. Therefore, a wide discussion is now growing on goals, rationale, contents, instruments and methods for its introduction in secondary school. Modern physics in secondary school is a challenge which involves the possibility to transfer to the future generations a culture in which physics is an integrated part, not a marginal one, involving curricula innovation, teacher education and physics education research in a way that allows the students to manage them in moments of organized analysis, in everyday life, in social decisions. In the theoretical framework of the Model of Educational Reconstruction, we developed a research-based educational proposal organized in five perspective directions: 1) the analysis of some fundamental concepts in different theories, i.e. state, measure, cross section; 2) problem solving by means of a semi-classical interpretation of some physics research experimental analysis techniques; 3) the study of phenomena bridging different theories in physics interpretation, i.e. diffraction; 4) phenomenological exploration of new phenomena, i.e. superconductivity, 5) approaching the basic concepts in quantum mechanics to develop formal thinking starting from phenomena exploration of simple experiments of light polarization. Research is focused on contributions to the practice of developing coherent learning proposals in vertical perspective related to content by means of Design Based Research, to produce learning progression and to find ways to offer opportunities for understanding and experiencing what physics is, what it deals with and how it works in an operative way. Empirical data analysis of student reasoning in intervention modules supports proposed strategies.

1. THE PROBLEM OF MODERN PHYSICS IN SECONDARY SCHOOL

The upper secondary school curricula of a large part of countries of the European Union include contents of the physics of the last century, here named briefly Modern Physics (MP hereafter) [1]. The most recent texts devote chapters to MP topics, even if not in an organic way [2-5]. Although conceptual knots in classical physics are quoted often to argue the exclusion of modern physics from secondary school, the international literature shows a rich debate on how to introduce MP, concerning: goals/rationale (to create a culture of citizens? For guidance? For popularization of recent research results? For education?); contents (what is useful to treat? Fundaments, Technologies, Applications?); teaching strategy: How? (Story telling of the main results? Argumentation of crucial problems? Integrated in Classical Physics? At the end of curriculum as an additional/complementary part?) [4-6]; to whom? (All
citizens? Talented students? Lyceum/Gymnasium students?) [2-6]. MP in secondary school is a challenge which involves the possibility to transfer to the future generations the cultural value of physics, building a cultural heritage where physics is an integrated, not a marginal part, in a way that allows the students to manage themselves in moments of organized analysis, in everyday life and social decisions.

Three planes are involved: curriculum innovation, teacher education, physics education research [4, 7]. Here we present our research approach on modern physics in upper secondary school, exemplifying main contributions, presenting more extensively the path on superconductivity and some general results of research on students learning in that field.

2. OUR RESEARCH-BASED APPROACH FOR MODERN PHYSICS (MP)

Our research-based proposals on MP aim to offer a cultural perspective, focusing on the foundation of basic concepts as well as methods and applications in physics research, integrating them into the physics curriculum and not as a final appendix, offering experience of what MP is in active research. Vertical paths are identified as a learning corridor [8-10] for individual learning trajectories and step-by-step concept appropriation modalities [11-13].

Attention is paid to identify strategic angles of attack and critical details used by common knowledge to interpret phenomenology [14, 15], to study a spontaneous dynamical path of reasoning [7], to find new approaches to physics knowledge [14-18]. We avoid the reductionism in favor of offering opportunities of learning and not only understanding of information, interpreting solutions and results (to become able to manage fundamental concepts), competences of instruments and methods [7].

The Model of Educational Reconstruction (MER) is our theoretical reference for the design of research-based educational proposals [8]. According to the MER model the first step in research task is to rethink scientific content as a problematic issue and to rebuild it with an educative perspective. This task is integrated with empirical research on student reasoning and learning progress [7, 16-18], Design-Based Research (DBR) in planning intervention modules [19-22]; action–research [7] in a collaborative dialectic between school and university to contribute to classroom practice and to develop vertical T/L path proposals experimented by means of different interventions in classes [10]. The approaches in our work are therefore not purely based upon disciplinary content [23] in order to identify strategies for conceptual change [24].

The research approach on learning processes focuses on the obstacles that must be overcome to reach a scientific level of understanding and the construction of formal thinking, rather than to find general results or catalogues of difficulties. We are interested in the internal logic of reasoning, spontaneous mental models, their dynamic evolution following problematic stimuli (inquiry learning) in proposed paths, the ways for building formal thinking.

Empirical data analysis is carried out in four main research directions:

1) individual common sense perspective with which different phenomena are viewed and idea organization, in order to activate modeling perspective in the interpretation of phenomena;

2) the exploration of spontaneous reasoning and its evolution in relationship with a series of problematic stimuli in specific situations, in order to formulate activity proposals;

3) finding the modalities to overcome conceptual knots in the learning environment;

4) learning progression from defined low anchor to specific learning outcomes by means of detailed paths.
To monitor the learning progress, data collection is carried out by means of pre/post test, to obtain an overview on the student conceptions and the learning impact of the proposal experienced, IBL tutorials monitoring the students’ learning process, often integrated with Interviews carried out according semi-structured protocol and the mirroring Rogersian method and usually also Audio/Video-recording of small or large group discussions and interactions.

The different proposals for MP cover mutually inclusive perspectives, for a global vision on MR: 1) Phenomena bridging theories, as for instance diffraction and specifically light diffraction; 2) The physics in modern research analysis technics, as for instance the Rutherford Backscattering (RBS), Time Resolved Reflectivity (TRR), electrical transport properties of material analysis with resistivity versus temperature and Hall coefficient measurements (R&H) [25]; 3) Explorative phenomenological approach to superconductivity (a coherent path) [26]; 4) Discussion of some crucial / transversal concepts both in CP and MP, for instance the concept of state, the cross section concept [27], mass and energy [28]; 5) Foundation of theoretical thinking in an educational path on the fundamental concepts of quantum mechanics and is basic formalism [29-30].

3. EXAMPLES OF MODEL OF EDUCATIONAL RECONSTRUCTION (MER) PROPOSALS

3.1 Phenomena bridging theories: optical diffraction

Optical diffraction is an important context in many perspectives: it is a common phenomenon around us; it has a large use in research analysis, as well as in technological applications useful in everyday life; its interpretation bridges geometric and physical optics, classical physics and quantum physics.

The proposal on optical diffraction is based on the educational opportunities offered by the new technologies. It was designed, set up and experimented parallel to a research and development project aimed to realize the LUCEGRAFO system [31], a patented device connected to the computer USB-port in a R&D research [19-21], which is an evolution of a previous prototype [32]. Through this system, students acquire in real time and then analyse qualitatively and quantitatively the light diffraction pattern produced by a laser beam crossing a single slit, a single hair, a double slit, a grating (Fig. 1). The features of light diffraction pattern cannot be framed in the rectilinear behaviour model and motivate students to look for an interpretative hypothesis on the wave nature of light, activated by recognition of similarities that characterize the different diffraction phenomena (the sea waves rather than sound waves). In our approach, students construct a model based on the Huygens-Fresnel principle reproducing the experimental light distribution and fitting the experimental data. A software environment of modelling, now realized also on an electronic worksheet, permits students to implement that model (Fig.1.C), focusing on the physical meaning of the model rather than on the mathematical calculations to obtain an analytical expression for this model [33]. The theoretical model based on the Huygens-Fresnel principle could be interpreted in a classical physics frame as well in a quantum mechanical one, analysing the consequence of the interference of point sources on the wave front.

3.2 The physics in modern research analysis techniques

We developed three proposals concerning the research techniques involved in the analysis and characterization of materials in modern physics and regarding: the optical physics (here exemplified by concerning light diffraction [32]); the Rutherford Backscattering Spectroscopy (RBS) analysis technique [34]; The Time Resolved Reflectivity (TRR) [35]; Measurement of Hall coefficient and resistivity versus temperature of metals (R&H), semiconductors and superconductors to characterize electrical transport properties of solid materials [36].
3.2.1 Rutherford Backscattering Spectrometry (RBS)

The Rutherford Backscattering Spectroscopy (RBS) measurement consists of collecting the energy spectra of ions (He\(^{++}\) of 2 MeV from a linear accelerator) backscattered along a certain direction, after a collision with the atoms of a target. RBS provides information about the depth distribution of the constituent elements of the first 500 nm of the surface of a sample (Fig. 2). The principles of the measurement and semi-classical data treatment are discussed with students and real and simulated spectra are analyzed and interpreted as a problem solving activity [34].

Students construct the concepts used for the RBS spectra analysis as the cross-section and the stopping power. They are involved in simple experiments realized with poor materials studying the interaction of spherical projectiles and different shape targets to have an operative experience of the meaning of the cross section concept.

The RBS proposal offers the students the opportunity to: explore the Rutherford-Geiger-Marsden experiment; understand the role of energy and momentum conservation principles in the context of research analysis; understand how microscopic structures can be studied through indirect information and measurements; interpret RBS spectra; have a look of scientific material characterization research methodologies [37-39].
3.2.2 The Time Resolved Reflectivity (TRR)

The Time Resolved Reflectivity (TRR) technique exploits the interference produced by the light reflected by a double layer, using two visible light or microwave monochromatic sources (Fig.3.) [35]. The TRR techniques can be used to study the epitaxial growth of a sample, analysing the changes in the interference pattern of the two laser beams reflected by changes of the two interfaces, produced by changing one of the two sources. Students carry out measurements with microwaves and laser light, measuring thickness of various thin films of materials, analysing the interference fringes.

Fig.3. TRR for visible light (left) and relative fringe pattern (data from [35]); setting in the case of microwaves (right)

3.2.3 Electrical transport properties of solids

In the science of materials, the analysis of the electrical transport properties of materials is based on the measurement of the resistivity as a function of temperature, combined with that of the Hall coefficient (R&H) [36] (Fig.4.). That allows to identify sign, number, mobility and

Fig.4. Left: The USB interface developed for the resistivity versus temperature (example of R-T graph for an YBCO sample). Right: Hall coefficient measurements (example of graph for Germanium N)
energy level of the electrical carriers on the basis of microscopic models for metals, semiconductors, and materials such as silicides [25, 39]. The research on superconductors is based on measurements of resistivity as a function of temperature, without or in the presence of a magnetic field [38]. We developed an approach to the matter physics by developing a patented USB probe for the measurement of the resistivity as a function of temperature of metals, superconductors and semiconductors at four points, and one for the measurement of the Hall coefficient of metals and semiconductors (Fig.4.) [36]. That system was designed and developed for a high school didactic laboratory but the constructive characteristics and the reliability of the measurements allow its use even in an advanced laboratory [40].

4. CRUCIAL/TRANSVERSAL CONCEPTS IN CLASSICAL PHYSICS AND IN MODERN PHYSICS (MP)

Some concepts, for instance the concept of system, state, properties are quite general and not related specifically to classical physics or modern one, although the basic theories of the ‘900s gave a new look to all these concepts. In our perspective these concepts could be developed across all the physics curriculum in school offering also insights on how these concepts acquire new meanings in the MP, as presented for instance in the section devoted to MQ. In that perspective, we developed innovative approaches on mass and energy, considered starting with a re-analysis of their classical meaning and then considering the new vision of these concepts given by the theory of relativity [28]. Here we focus on the cross-section, a transverse concept quite important in physics, crucial in the actual research in many fields of physics, but completely neglected in the secondary school.

The concept of cross section is important both in classical physics and in MP, for instance in studying the interactions between elementary particles in nuclear physics at both low and high energies, in atomic collisions, in structure of matter studies (as seen in the brief description of the RBS proposal). It becomes essential in the case of quantum mechanics, because it is impossible to attribute a trajectory to a quantum system. Approaching the construction of the concept of cross-section allows us to move from classical physics to wider and more complex fields using a powerful research tool.

A reductionist approach based on a geometrical interpretation of the concept of cross section might seem to be the easiest approach, but this is not the case. In fact, this interpretation is adequate only in the case of classical rigid spheres. The general concept of cross section is characterized by a probabilistic meaning, and this is what needs to be highlighted in an educational approach.

In the educational approach, students analyze some typical although simple cases of collisions, highlighting the general aspects of the phenomena and showing how to relate measurements and interpretations in a way completely different from the traditional force/equation model of motion/trajectory scheme. The line of the conceptual development of the educational path on cross section is reported in Appendix 1.

5. QUANTUM PHYSICS (QP) IN SECONDARY SCHOOL. FOUNDATION OF THEORETICAL THINKING.

In literature, there are quite different educational proposals [41-44], and a preliminary clarification is necessary to distinguish between physics of quanta, quantum physics and quantum mechanics. In the description of the birth of the theory of quanta the narrative treatment of the discussions on the hypothesis (proposed and not innate to students’ reasoning) usually prevails in the educational approaches over aspects relating to the subject itself. The descriptive dimension if acceptable in a popularization plan does not appear to be satisfactory in an educational plan. There is the need to produce the awareness of the reference assumptions
of the new mechanics [45-47] and to offer some indications on the formalism that is adopted, the formalism, in fact, assumes a conceptual role in QM [44-45].

The formal approaches, based usually on the wave formulation of quantum mechanics, are rigorous, but demand strong competencies both in physics and in mathematics [48]. Computer simulation to ‘visualize’ quantum situations helps to overcome the formal obstacles [49-50], leaving the knots open for interpretation.

In our perspective, there is the need to produce the awareness of the reference assumptions of the quantum mechanics theory and to offer a look on the conceptual role of its formalism rather than to stress on the way to use that formalism in problems and applications. Two lines of intervention were developed. The first constitutes a contribution to the traditional approach to quantum phenomena: experiments that are critical for the classical physics interpretation, to focus on the problems (Photoelectric effect; Compton effect; Frank & Hertz experiment; Millikan experiment; normal and anomalous Zeeman effect; emission and absorption spectra; diffraction of light and particles; Ramsauer effect) [51]. The second line, constituting the core of our proposal, is for quantum mechanics (not quantum physics or physics of quanta) in secondary school following a Dirac approach. We chose to approach: the theory of quantum mechanics; the first step toward a coherent interpretation with a supporting formalism; an introduction to the ideas of the theory, through the treatment of crucial aspects, fundamental concepts, peculiar elements to QM [29-30, 52]. Our core proposal for QM may be divided into two levels: on the disciplinary level we have chosen to begin with and focus on the principle of superposition and its implications; on the educational level we have chosen an in-depth discussion of specific situations in a context that allows for the polarization as a quantum property of photons.

Three are the basic elements of the proposal: to explore light polarization on experimental, conceptual and formal levels [53-55]; to discuss ideal simple experiments involving interactions of single photons with polaroids and birefringent materials (calcite crystals) [51]; to describe in quantum terms by two-dimensional vector spaces the states of polarization of light (or spin) [30, 53-54].

The first part is focused on the superposition principle, discussing a series of experiments with polaroids and calcite crystals, and its consequences as the uncertainty principle, the non-epistemic indeterminism, the description of macro-objects and the problem of measuring, the non-local nature of quantum processes, renouncing the classical way of thinking, including trajectory [29-30]. In the second part, each of the conceptual aspects discussed in the first part is formalized with an appropriate mathematical structure, starting from the vectorial representation of the quantum state and the representation of observables with linear operators [30, 52].

The rationale of the educational path includes: the operative introduction of the phenomenology of light polarization, using polaroids on an overhead projector and organizing conceptually through the Malus law, that students can “discover” in a real lab using on-line light sensors; the recognition of the validity of the Malus law in reducing light intensity, polarization is identified as a property of a single photon; exploring the interaction of polarized photons with polaroid, they identify mutually exclusive properties, incompatible properties and the uncertainty principle; the identification of the state of the polarized photon by a vector and the superposition principle can be written as: \( \mathbf{w} = \mathbf{u} + \mathbf{v} \); distinction between state (vector) and polarization property, identified by icons living in different spaces; identification of the QM measurement as a transition of the polarized photon to a new state (the precipitation of the system in those measured and its genuine stochastic nature; interaction of polarized photons with birefringent crystals to understand entangled state, impossibility to attribute a trajectory,
non-locality of the quantum processes; introduction of basic formalism starting from the transition probability from state \( u \) to state \( w \) as a projector, expressing the probability of transition with a scalar product:

\[
P_{\text{tr}} = \frac{N_\text{tr}}{N} = \cos^2 \theta = (u \cdot w)^2.
\]

These aspects can be discussed also in a very similar way considering the more usual case of the two-slit interference, where it can also be discussed what kind of picture emerges from the quantum behaviour when a hidden variable framework is assumed.

All the steps of the proposal are implemented in stimuli worksheet tutorials, aiming to monitor the students’ learning paths and to involve them in an inquiry-based educational environment [55]. The different situations proposed in the educational path as well as allowing the pupils to explore their own hypotheses can be realized virtually in a gym of simulated ideal experiments using the applet JQM [51] (free access at: http://www.fisica.uniud.it/URDF/secif/mec_q/percorso/avv_11.htm). Fig.5. shows an example of JQM experiments and tools available.

All the proposals, discussed in a research perspective in different papers [29-30, 52], are also available on the web to be used and adapted by teachers in schools (http://www.fisica.uniud.it/URDF/secif/mec_q/percorso/teoria.htm).

Fig.5. The tools and the environments used by students to explore the phenomenology in single photon of light interaction with polaroid and birefringent crystals

Extensive research experimentation were carried out with more than 300 students [56-59]. From these it emerged that students profit from the iconographic representation and discussion in a proper way on mutually exclusive properties (80%) and incompatible properties (55%). The employment of the iconographic representation (85%) and formalism (60%) facilitate reasoning in the framework of QM. The rigorous reasoning proposed promotes the spontaneity used in new contexts (50%), the construction of a coherent framework (80%), even if in a different conceptual perspective. In fact the students’ learning paths show evolution toward quantum concepts, where some typical hidden variables assumptions often bridge them from classical to quantum way of thinking [57].

6. FROM ELECTROMAGNETISM TO SUPERCONDUCTIVITY

The explorative approach to superconductivity is integrated in a vertical path on electromagnetism [26, 60]. It uses the experimental kits developed in the European projects SUPERCOMET and MOSEM [61], including more than 100 simple low-tech experimental activities on electromagnetism and electrodynamics and 8 high-tech apparatus on superconductivity, computer modelling proposals, 20 simulations. In our approach, secondary school students explore and explain superconductivity first in classical physics and then they have a look at the quantum mechanism that can take into account the transition from normal conductor to a superconductor. The research-based path includes an inquiry-based learning (hands/minds-on) approach to SC using the theoretical framework of classical electromagnetism; ICT learning-based, integrated measurements carried out by sensors,
Modelling, simulations. The focus is on reasoning for the interpretation of the phenomena [26].

In developing vertical paths on electromagnetism and superconductivity from primary to upper secondary school, our research involved: T/L proposals development by means of DBR [19-22]; Learning process analysis by means of Empirical Research [7, 14-18] and in the perspective of Conceptual Change [24]; R&D of new ICT system [20-21]; Teachers’ professional development; Micro-steps of Conceptual Lab of Operative Exploration (CLOE) are carried out to build the formal quantities characterizing the magnetic field B [13].

In experimenting with the same explorative path in secondary school (18 schools, N=160 students, 17 years hold), magnetic field lines assume the roles of a conceptual tool: to interpret magnetic interactions (65%); to distinguish between magnetic field (direction of orientation) and force (direction of starting motion) (55%); to produce reasoning in terms of flux, individuating that it is a constant quantity in field line system (80%); with related consequences, such as that magnetic field lines are closed (68%), the non-separability of poles (50%) or div=0, interpretation electromagnetic induction (76%), identification of the related applications (56%) [60].

The rationale of the path on superconductivity and the results of the school experimentation are reported in Appendix 2 and 3.

7. CONCLUDING REMARKS

From our research in physics education we developed five different perspectives of proposals mutually inclusive for the Modern Physics to build in young people:

- physics identity
- physics as a cultural issue
- the idea of physical epistemic nature

Avoiding the reductionism our aim is to offer opportunities to:

- Experience the quantitative exploration of crucial phenomena (diffraction), individuating laws, fitting data and testing basic principal ideas and results with experimental data
- Understand the crucial role of classical physics in modern research techniques (RBS, TRR, R&H) manipulating data and interpretation like in a research laboratory
- Focusing on reasoning to conduct the exploration of a phenomenon (superconductivity) understanding the role of analogies for finding explanations
- Reflect on the physical meaning of basic concepts in different theories (state, measure, cross section) revising meanings in classical physics and understanding the different perspectives of new theories
- Approach to the new ideas of QM theory: the first step toward a coherent interpretation with a supporting formalism experiencing aspects, cardinal concepts, elements peculiar to QM

One of the main follow-ups at national level of our expertise in teaching-learning modern physics was the IDIFO Projects (2006-2016), a PER contribution for Innovation in Physics Education and Guidance. That project involves 20 Italian universities cooperating in: Master for teacher formation on modern physics (162 cts articulated in clusters of 3cts courses on the following area for (60cts) on: Modern Physics; Physics in contexts (in art, sport...); Real time Labs and modelling; OR- Formative guidance; SPER – School experimentation); Summer school for talented students; Educational Labs, co-planned with teachers, to experiment with innovation in the school [62].
APPENDIX 1. THE OUTLINE OF THE EDUCATIONAL PATH ON CROSS SECTION.

To approach the concept of cross section, students compare first the quite simple case of the collision of two spheres (or two circular disks) and the case where the target sphere is substituted by an object with an irregular shape, measuring the dependence of the scattering angle $\theta$ from the impact parameter $b$. In the first case it is simple to reconstruct the analytical relation between $b$ and $\theta$, including the radius $R1$ and $R2$ of the two spheres [$b = (R1+R2) \cos(0/2)$], in the second case the work becomes harder immediately by considering an ellipsoidal shape of the target system, both in the mathematical perspective and, much more important, in the physics perspective, because the dynamics of the collision becomes immediately strongly dependent on the initial condition: a very small variation in $b$ can cause variations of any order of magnitude in the scattering angle. A consequence of this is that by driving the two bodies against each other a number of times with a poor control of initial conditions, the individual results (final states) obtained are significantly different. Does this mean that such an experiment does not give any kind of information about the collision or the geometry of the two bodies?

Students can recognize, using both experiments and simulations when a beam of symmetrical projectiles impact on a target system of arbitrary shape, that the asymmetry in the target shape can be associated to the specific asymmetry in the distribution of the scattered projectiles [27, 37]. The relation between distribution asymmetry and asymmetrical shape shows to students that it is possible to extract information on the collision phenomenon through a statistical analysis of the distribution of scattering angle. In general, a complete characterization of the collision requires the knowledge of the probability $P_{i}$ for any given measurement outcome $S_{i}$; these probabilities can be obtained from the average $P_{i} = \langle N_{i} \rangle / N_{tot}$ , where $N_{i}$ is the number of outcomes $S_{i}$ for $N_{tot}$ observations carried out. That probability still depends on the details of the measuring procedure. For instance, increasing the width of the distribution of the impact parameter of projectiles, there will be a greater number of cases in which the projectiles will not interact with body 2 at all. In order to avoid this, it is necessary to consider more in detail a general situation like that represented in Fig.6. A uniform beam of (identical) particles colliding with a target of evenly distributed (identical) particles. So an incoming particle, wherever it crosses the panel (a), meets, on average, the same target distribution. Therefore the total number $N_{i}$ of scattering events having a certain final state $S_{i}$ will be proportional to the number of incident particles (there are no border effects due to the 'width' of the beam).

On the other hand, given the limited range of the scattering phenomenon, a certain incident particle will only interact with the particles of the target within the range of action of the force (represented in Fig.6, by the small rectangle of area $A$ on the surface of the target (panel (b)).

The probability that any incident particle of the beam interacts with a target particle within area $A$, creating a certain result $S_{i}$, will be: $P = P_{1} \cdot P_{2} \cdot P_{int}$, where $P_{1}$ is the probability that the incident particle will cross $A$, $P_{2}$ is the probability that there will be a target particle in that area and $P_{int}$ the probability for that type of interaction. With two sufficiently sparse distributions, $P_{1}$ and $P_{2}$ will be given by: $\langle N_{i} \rangle = n_{1} \cdot A$, $\langle N_{2} \rangle = n_{2} \cdot A$, where $n_{1}$ and $n_{2}$ represent the surface densities in a projection transversal to the axis of the beam. The average (total) number of interactions with outcome $S_{i}$ will be obtained by summing up all the small rectangles, of number $N_{A}$, into which the section $A_{tot}$ effectively crossed by the beam can be divided:

$$\langle N_{i} \rangle = N_{A} \cdot P_{1} \cdot P_{2} \cdot P_{int} = \left( A_{tot} / A \right) \cdot \left( n_{1} \cdot A \right) \cdot \left( n_{2} \cdot A \right) / \left( A \cdot P_{int} \right) = A_{tot} \cdot n_{1} \cdot n_{2} \cdot \left( A \cdot P_{int} \right) .$$
Modern physics way of thinking

The dotted lines represent the active volume of a beam particle (that is, the region in which it can interact with a target particle).

The factor \( s_i = (A \cdot P_{int}) \) is related to the characteristics of the observed interaction. The factor has the physical dimensions of an area and for this reason it is called cross section (for the reaction channel considered). The geometrical meaning of the cross section could be easily recognized by applying the previous results to the case of rigid spheres. The information given by \( s_i \) is on the intensity of the interaction (or, alternatively, on its range), due to its nature of integral quantity.

To obtain a similar quantity able to offer a deeper insight into the interaction phenomenon considered, it is necessary to consider explicitly each possible result \( S_i \) of the collision. If \( N_i \) is the number of the outcomes for which the scattering angle is in the interval \((\theta, \theta + \Delta\theta)\), the cross section \( \sigma \) for the collisions with a scattering angle in such an interval is:

\[
\sigma = A P_i \approx A N_i / (n_i A) = N_i / n_i
\]

where \( n_i \) is the number of incident particles per unit area.

This value depends on \( \Delta\theta \) and therefore it is better to introduce the so-called differential cross section:

\[
\frac{d\sigma}{d\theta} = \lim_{\Delta\theta \to 0} \frac{\sigma}{\Delta\theta} = \lim_{\Delta\theta \to 0} \frac{<N_i>}{n_i \Delta\theta}
\]

That concept could be easily generalized to a solid angle.

The expression of the differential cross section can be applied to the important case of the scattering of two pointlike bodies with charge \( Z e \), \( Z' e \) charge, which interact according to a repulsive Coulomb potential. The dynamics of that interaction is governed by the conservation principles of angular momentum and energy \( (E) \) and the following relation between \( b \) and \( \theta \) can be easily obtained

\[
b = \frac{Z Z' e^2}{2E} \cotg \frac{\theta}{2}.
\]

The differential cross section is immediately obtained:

\[
\frac{d\sigma}{d\Omega} = \left( \frac{Z Z' e^2}{4E} \right)^2 \sin^{-4} \left( \frac{\theta}{2} \right)
\]
That important result could be used to discuss in detail the historical study of Rutherford and the related Geiger and Marsden experiments as well as we have shown in the section of RBS, or to have a look on nuclear interactions [27].

APPENDIX 2. A COHERENT EDUCATIONAL PATH TO SUPERCONDUCTIVITY

The path on SC is structured into two parts: 1) Magnetic properties of a superconductor, Meissner effect, electromagnetic induction and eddy currents for interpretative analogy, the pinning effect [26, 38]; 2) Resistivity vs temperature using the R&H USB system (described in section 3.2.3) to find the critical temperature for a superconductor at the breakdown of resistivity [25, 36,39]. We use different perspectives: Historical, Phenomenal exploration, Applications [60, 63-64].

Let us follow the reasoning path proposed, starting from the Meissner effect, focused on understanding correctly the effect in the framework of the magnetic interactions, and focusing on how students face the main interpretative knots. The educational path [26] approaches the Meissner effect through an experimental exploration of the magnetic properties of a superconductor sample (a disc of YBCO with very weak pinning effect). Students analyse the diamagnetic nature of a superconductor constructing step by step a phenomenological interpretation based on production of persistent supercurrents produced by electromagnetic induction that are at the base of the levitation phenomenon due to the Meissner effect.

The first step of the educational path aims to individuate the change in the magnetic properties of an YBCO disc at room temperature and then at the temperature of the liquid nitrogen (LN hereafter). It could be inspired by an exploration of the magnetic properties of a set of different objects of different shapes, weights and materials (aluminium, copper, water, wood, graphite) by means of a home-made simple torsion balance, by hanging these and see if they are attracted, repelled or not affected by a “strong” magnet. A phenomenological classification of magnetic properties of material can show three main types of properties: ferromagnetic materials (that are strongly attracted, almost in any condition, by a magnet and present often that property also after the interaction with a magnet), paramagnetic materials (that are very weakly attracted by a magnet); diamagnetic materials (they show “magnetic repulsive properties” only in the presence of a magnet). Also the paramagnetic properties of the YBCO at room temperature are analysed by putting two discs of YBCO at the ends of a homemade torsion balance. At $T_{LN}$ temperature, when the YBCO is at thermal equilibrium in a bath of LN (77K), a levitation phenomenon appears due to a strongly repulsive interaction between the YBCO disc and the magnet, or, in other words, the YBCO disc shows strong diamagnetic properties.

The change in the magnetic properties of YBCO (quite evident) happens so suddenly when the temperature reaches $T_{LN}$, that is we are in the presence of a phase transition. This will be confirmed in the educational path analyzing the breakdown of resistivity.

Before proceeding, it must be emphasized here that the levitation stability of the magnet on the YBCO disc is guaranteed by a residual of pinning effect, which is always partially present in this type of superconductors. However, this does not affect decisively the conclusions that will be gradually drawn.

The diamagnetic properties of the YBCO can be explored by moving the magnet, rotating the magnet or going close to the YBCO from different directions (from lateral side for instance). It is clear that the levitation phenomena is not a suspension of two repelling magnets, constrained for instance in a tube, for two reasons: the magnet on the YBCO levitates without any constrains; by changing the pole of the magnet closer to the YBCO, the repulsion appears
anyway. Moreover, if an iron clip is put on the cooled YBCO, no interaction is observed, showing that the diamagnetic behavior is induced only by the presence of the magnet, or in other word the magnetization of the YBCO is not permanent. This aspect is similar to that of other diamagnetic materials, in the case of the superconductor the diamagnetic effects are very intense (comparable to that of ferromagnetic systems) contrary to the ordinary diamagnetic phenomena, which are usually very weak. To understand something more on the diamagnetic properties of the YBCO, it is possible to perform a simple exploration of the magnetic field inside the disc of YBCO, analysing whether the external field of the magnet penetrates the YBCO. This test can be performed using a sandwich of a YBCO putted between a magnet and an iron slab. At room temperature you can’t lift the sandwich pulling the magnet, it remains a compact structure. At \( T_{\text{LN}} \) this effect disappears, that is, the magnet is unable to lift the YBCO and the iron ring (Note: this is not completely true if there is some pinning effect). At room temperature: the YBCO is transparent for the action of the magnet on the iron, the B field of the magnet “arrives” on the iron passing through the YBCO, a magnetic field can exist in YBCO. At \( T_{\text{LN}} \), the B field of the magnet does not reach the iron clip, evidencing that it is really small or negligible through the YBCO.

To appreciate the Meissner effect, producing the repulsive effect between the magnet and YBCO and at the base of the levitation of the magnet over the YBCO disc, the levitation of the YBCO can be observed, when it is cooled in presence of a magnet. When the temperature of the YBCO goes below the critical values, the magnet lifts levitating over the YBCO.

The phenomenology described shows that the magnetic behaviour of YBCO appears to be induced by the presence of the magnet, or better by the magnetic field produced by the magnet. An analogy can give the instrument to interpret the phenomena.

A falling magnet on a copper bar decrease its velocity gradually. A magnet falling inside a copper tube falls at constant velocity. In that phenomenon, the electromagnetic induction and the eddy currents have a crucial role. The interpretation of the falling magnet in a copper tube requires as conceptual tools: the field lines (in our perspective an operative definition of that lines); the flux of B (\( \Phi(B) \)), defined operatively); The Faraday-Newman-Lenz law. To interpret how the eddy currents arise in the tube, we can ideally slice the tube in rings standing one over the other. The eddy currents arise because the change in the flux of B when the magnet passes from a ring to the ring below: in the first ring that current produces a B field in the same direction of the magnetic field of the falling magnet; in the second ring that current produces a B field in the opposite direction of the magnetic field of the falling magnet. Applying the Lorentz force law, it can be seen that a net force emerges, directed vertically opposite to the direction of the weight of the magnet and producing the braking effect on the magnet. Repeating the experiment with geometrically equal tubes of different materials (bronze, aluminium, copper…) it is possible to correlate the falling velocity and the resistivity of the material of the tube. The analogy between the “braking” of the magnet in the presence of a “real” conductor and the levitation of the magnet over the YBCO disc appear to work if the conductor is “perfect” (R=0). The currents initially induced by the magnet never stop, because the Joule effect is not present in the case of a R=0 conductor even when the electromagnetic induction ends (v=0).

Effectively a superconductor, such as the YBCO at \( T_{\text{LN}} \), shows this property. Students can explore that effectively in a lab analysing the behaviour of the resistivity as a function of the temperature, characterizing a superconductor as a system with B=0 and R=0

The interpretation of the perfect diamagnetism of a superconductor as an electromagnetic induction effect in the case of an ideal conductor (that is R=0) can be extended to also include the situation when YBCO becomes superconductor in the presence of an external field.
The explorative part of the educational path of superconductivity includes also the analysis of the pinning effect, characterizing the superconductor of type II and at the base of the functioning of the MAGLEV train. This effect manifests itself in the fact that the magnet remains anchored to the superconductor at the distance at which it was when it made the phase transition. The pinning effect is due to the penetration of the magnetic field inside the SC sample inside the vortexes created by supercurrents and at the same time the repulsive effect due to the Meissner effect (Fig.7). The analysis of the stability of the train on the magnetic track (Fig.8) offers the opportunity to discuss the conditions needed to obtain a stable levitation.

To interpret how the phase transition occurs in a superconductor it is necessary to consider a quantum approach to solid state physics. We set up a minimal treatment based on energy levels. We usually start discussing the (discrete) equilibrium energy levels of a chair, to give an analogy for the atom levels. When isolated atoms are combined to build a crystal, the energy levels of electrons change dramatically. Using simulations as that of Visual Quantum Mechanics [49] students can understand how the level of one atom splits (http://phys.educ.ksu.edu/vqm/html/eband.html) into 2….n levels close to the other forming bands when 2….n equal atoms go close to one another as it occurs in a crystal lattice.

Electrical transport properties of a solid, and in particular its nature of insulator or conductor, depend on the band structure and on electron states. These states and their occupation are determined by the Pauli exclusion principle. When the superconductive state is created a great change occurs. Due to an effective attractive interaction between electrons, mediated by the lattice vibrations (phonons), the formation of the so called Cooper pairs is favoured because of energy reasons. The Cooper pairs are particles of spin 0 and therefore they can all occupy the same state, that is, the fundamental state that is separated by an energy gap. The existence of that gap assures the stability of the superconductive state and the vanishing of the resistivity of a superconductor [26].

**APPENDIX 3. EXPERIMENTS WITH STUDENTS**

Experiments in school were performed in 44 Italian sites involving students of different age (29 K13; 6 K12-13; 1 K12; 6 K11), for a total of 1315 students of 292 classes of about 150 schools. 5/44 experiments were performed in informal educational contexts organized in the limit of university-school projects involving 275 students. From these experiments it emerged that students are strongly involved and motivated in the exploration of phenomena such as superconductivity because: it is very surprising and engaging (95%), of the great interest in the
modern physics way of thinking

technological application of the superconductors (75%), of the general interest in the construction of an explanation of that phenomenon (83%) [60]. These results were confirmed also by the other experiments done in very much different contexts and in formal setting. The majority (20/44) of these experiments were performed by service teachers and in two cases by prospective teachers involved as experimenter of the material of the European projects of the Supercomet family [63-64]. These experiments constitute positive feasibility tests of the introduction of superconductivity in different contexts and types of school, gives as outcomes that teachers individuated four different educational paths to introduce superconductivity in school: Introduction to superconductivity - approach through the magnetic properties; Approach to superconductivity through the exploration of the resistivity of materials. The energy transformations and superconductivity, Approach to superconductivity starting from the exploration of its technological applications. From that experimentation emerged also the positive evaluation of students’ learning performed in standard ways by teachers and as unresolved educational problem as treated in school the Cooper pair formation, an aspect remaining open also in their formation [60, 63]. 5/44 experiments were performed by PhD students as part of their research project with 125 students [60, 65]. From these works it emerges that prevalently (81%) students characterize the superconductive levitation as a repulsion consequence of the diamagnetic properties acquired by the YBCO, characterizing that with a magnetization vector (57%), or using a global representation using field lines (24%) explaining also in some cases (22%) that the sample becomes a superconductor or that its resistance falls down to zero. In a few cases (19%), students just describe the system of forces acting. (YBCO repels the magnet with a force that is equal to the weight force). Students were able to distinguish the features of Meissner effect from that of the pinning effect (87%), but without developing different models for the two effects [66].

Nine of these research experiments (9/44) in school were research-based activities conducted with 287 students (66 students were 17 and 261 students were 18) to understand how students learn superconductivity and to validate the didactic material prepared to monitor students’ learning paths and were performed in curricular activities, with entire school classes, or in summer schools organized at the University for selected students from all Italy [66]. The models of students are mainly centered on the concept of the magnetic field and the magnetic properties of the systems involved (68%). The static models underlying how students initially describe the superconductive levitation, was substituted at the end of the educational path in the majority of cases (84%) with models describing the condition B=0 inside the superconductor: 63% that the YBCO at T=T_{amb} was passed by field lines (was paramagnetic) and at T=T_{NL} it expels the field lines, in 1/3 of cases adding that this is due to surface currents; 25% the field lines do not cross the YBCO, the YBCO screens the field lines; 12% field lines are trapped. That models are supported by causal explanations based on an intuitive magnet image model (38%) [67] or on the induction electromagnetic role in the superconductive levitation (62%).

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Modern physics way of thinking


ALL-PERVADING LIGHT – OR HOW THE KINEMATICS OF MODERN PHYSICS IS BASED ON LIGHT

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ABSTRACT
The space-time of modern physics is tailored on light. We rigorously construct the basic entities needed by kinematics: geometry of the physical space and time, using as tool electromagnetic waves, and particularly light-rays. After such a mathematically orthodox construction, the special theory of relativity will result naturally. One will clearly understand and easily accept all those puzzling consequences that makes presently the special theory of relativity hard to digest. Such an approach is extremely rewarding in teaching the main ideas of Einstein’s relativity theory for high-school and/or university students. Interesting speculations regarding the fundaments and future of physics are made.

ON PHYSICS AND POSTULATES
Physics is undoubtedly an experimental science [1]. It’s laws are derived from experiments and it’s theories are confirmed through experiments. It is considered to be exact science, but many scientist consider it less rigorous than mathematics is. The main reason behind this fact is that mathematics is built on clear postulate systems, while in physics it is not always obvious what our postulates are. This is also the way how we teach physics: it is not straightforward for students (and sometimes also for the teacher) what we postulate and what results from these postulates. From time to time we use phrases like “it is evident”, “it is not unrealistic to assume”, or simply “let us assume”. In such cases students might get confused whether we state a new postulate or affirm something really obvious resulting logically from the already accepted postulates.

Any logically consistent theory must be based on postulates. It is not possible to prove everything, and there is thus no ultimate true [2]. Any statement or law in science is true or false in the framework of a postulate system. In physics we also have thus postulates. Postulates can change as physics progress, and our goal to reduce the number of postulates and/or to postulate more simple things is slowly, but advancing. The physical description of nature is however always bonded to a postulate framework. We might or might not realize these postulates, but they are silently there.

The less rigourous manner in which physics handles it’s postulates was however not an impediment for its development. Being non-rigorous in the pure mathematical sense has also advantages and allows for describing more easily the complexity of nature using just our intuition. This is one reason why physics became so successful and advanced quickly in describing many complex phenomena. Not realizing however the postulates on which our reasoning in physics is built and relying to much on intuition can seriously fool us and obvious facts might appear as paradoxes. There are times thus in physics when we have to stop, look back and review the postulate system on which our current understanding is built.
In this work I plan to do this, by building the basic elements of modern kinematics in a rigorous and logically consistent manner. I will argue that the tool we use nowadays to define the geometry of the physical space and time is light, or electromagnetic waves in general. After taking the effort of doing a solid grounding by postulates for our main tools: space and time, we then collect the benefits. The special theory of relativity, Lorentz transformations and all “strange” consequences of these will become crystal clear. We will be surprised how simple and logical and self-consistent this theory is. We will also realize some common misconceptions that are still surrounding us in many textbooks and science popularization books or movies.

LIGHT AND IT'S SPEED OF PROPAGATION

Light and electromagnetic waves in general are our primary source for getting information about the surrounding world [3]. Light is however a tricky entity. Light rays propagate in straight line, and it shows both wave and particle properties. In some experiments light behaves as a classical wave (diffraction, interference) and yet in other experiments exhibits particle properties (photoelectric effect, Compton scattering). There are also properties of light that can be understood both by it's particle and it's wave-like nature (refraction, reflection). Nowadays we know that light is an electromagnetic wave, which transports energy in quanta, named as photons. Electromagnetic waves and therefore the propagation of light are described by the celebrated Maxwell’s equations [4] which predicts that the propagation speed of electromagnetic waves in vaccum, and light in particular, is very big (~300 000 km/s). Experimentally it was quite a hassle to determine its value and a lot of debates were on this subject during the history of science (see Appendix 1.).

Getting the value for the speed of light is however only half way the problem done! Whenever we speak about speed we do need to specify the reference frame relative to which this is measured. Sound and acoustic waves propagate relative to a medium with mechno-elastic properties. In air for example, when we admit that the speed of sound is 340m/s this is understood as being the value measured relative to air. We are used to the fact, that each wave-like phenomenon propagate relative to some medium, and when we speak about the velocity of the wave, we usually do refer to its velocity relative to this medium. We know now that light is an electromagnetic wave, and the natural question we can pose is to find the medium in which electromagnetic waves are propagating, or the medium in which Maxwell equations are valid. The medium was hypothetically named aether and the hunt for its discovery began. The method to reveal the existence of eather was based on the detection of the eather wind. The effect of the eather wind on the propagation of light would be something similar like the effect of the wind on the propagation of sound. For sound waves in air we know that an observer that travels with a speed of 10 m/s relative to the air, would measure a speed of 350 m/s for the sound waves coming in his/her direction and a speed of 330 m/s for the sound waves travelling in the same direction as his/her motion relative to air.

Carefully designed experiments were however unable to detect such eather wind [5]. Eather proved to be either inexistent or hard to be observable due to some unknown reasons. As we will detail in the following, physics got in an unpleasant situation, which drove physicist to rethink the very basic foundation of our basic notions in physics: space and time and the postulates on which the modern apparatus of physics is build.

SPACE AND TIME IN PHYSICS

Space is the most fundamental entity of physics, the ground and background of matter, our models’ natural environment [6]. Its existence can be stated as a postulate: it is something that exists. Physical space does not have however an inbuilt, intrinsic geometry. Geometry is our attempt to describe the form of the objects and their relative positions in space, following the
idealisation we have achieved in mathematics. Physics relies on geometry, since one of our aims is to account for the relative position of objects and to describe their changes. In physics we have to distinguish clearly between the mathematically defined abstract spaces and the space we deal with, when the description of the spatiality of the matter is our focus.

The **ideal mathematical space** is defined by postulating all its *metrical* properties. Metrical, in this case means that we have a distance unit and we can construct a ‘geodesic’ line between any two points. This geodesic line is the shortest distance between two points in our ideal space. It is the generalisation of the concept of ‘straight line’ encountered in simple Euclidean geometry. Once we have the geodesic lines and postulated the distance unit, we are able to measure distances between any two points. The distance between two points will be obtained by measuring the length of the geodesic line drawn between them. We also have the possibility of defining objects with spatial extension in the space: spheres, cubes, etc. Objects placed in such a space will not alter the postulated geometry.

For example, Euclidean geometry in plane defines its metric by the five postulates we all learned in elementary or high school [7]. Euclidean space is the simplest mathematical space. Geodesic lines are the “classical straight lines” we all have imprinted in our minds since our middle school years. For any triangle we have that the sum of its interior angles is 180 degree. In the Euclidean space one can also state that for any elementary triangle built on two infinitesimally small segments perpendicular on each other: $dx$ and $dy$, the third segment ($ds$) can be calculated as: $ds^2 = dx^2 + dy^2$.

Our **physical space** is not an idealized mathematical space, and metrics is not an a priori given; rather, it is determined by the matter spread throughout the Universe. In order to construct any geometry in this space, the first task is to reveal the geodesic lines and have a well defined concept of distance. One possibility would of course be to postulate an a priori metrics for space, and the handiest would naturally be a three dimensional Euclidean space. In such an approach distances between objects would be measured using a hypothetical infinitely extensible ruler (which is postulated to be the straight line) and a postulated unit of length. This is what Newtonian physics does. Distances between the bodies around us are measured using such an ideal ruler together with a postulated unit of length, which is the International Prototype Metre kept at the International Bureau of Weights and Measures in Paris. Apart from the logical inconsistency of the a priori postulated metrics (straight line concept), the drawback of this approach is that it makes impossible to measure distances on a cosmological or micro scale. Using a ruler you cannot measure large distances on Earth, and you definitely cannot extend investigation to the cosmological or microscopic scale. A viable alternative to this approach is to use light rays to reveal the geodesic lines in the physical space. Light rays in vacuum have always been thought to move in a ‘straight line’, or at least this was considered to be true on the terrestrial scale in an optically homogeneous medium such as air or a vacuum. After the development of Euclidean geometry, measurement of large distances and methods of mapmaking, such as the classical triangulation method, employed this idea extensively. The solution seems simple. Then, why not turn the problem around, and postulate the path of light rays between any two given points as a geodesic line? The idea could work on both the cosmological, terrestrial and micro-scale and would define a usable geometry for physics.

Nowadays we need to be careful when speaking about the geometry of physical space, since we inevitably mix up two different metrics… *In our everyday life* we use the Newtonian paradigm of ideal space alongside Euclidean metrics, which we find convenient. The optically different materials around us and, as a result, the light refractions at the boundaries of different media make complicated the use of geodesic lines defined by light. This is why we
tend to say that light rays bend and we accept that sometimes they do not move in a ‘straight line’. Practical problems relating to tracking the path of light rays and handling such rays also suggest that it is easier to use a traditional ruler. But we should add here, that given the rapid advances in laser technology this picture is quickly changing; even on a small scale we nowadays use light to measure distances and trace straight lines. On a cosmological or microscopic scale, however, the concept of the straight line is inextricably linked to the path of a light ray. The metric is defined by the propagation path of light, which is influenced by the matter spread throughout the Universe. Luckily, in our everyday life the two different metrics are not at odds, since light rays do not bend in any detectable way in a homogeneous medium and the gravitational field around us is rather homogeneous over small distances. However, if light interacted more strongly with the Earth’s gravitational field and this gravitational field were not homogeneous, the situation would have been more complicated. We would immediately sense there was problem, since our ruler would no longer look ‘straight’ to us, even if the medium around us were a vacuum.

Light therefore defines the geometry of the physical space. Such geometry may not be simple, since the metrics is influenced by the interaction between matter and light. The properties of light are inevitably mapped onto the geometry of space. We might well discover that in such space the sum of the interior angle of the triangles is not 180 degree and for the diagonal ds of the elementary triangle constructed on the two perpendicular segments dx and dy we find that \( ds^2 \neq dx^2 + dy^2 \). Instead of this relation, we might find in a plane a more complicated formula of the type:

\[
\begin{align*}
\sum (dx)^2 = a(x, y) \cdot dx^2 + b(x, y) \cdot dy^2 + c(x, y) \cdot dx \cdot dy.
\end{align*}
\]

In such cases the geometry of the physical space is a non-Euclidean type. The abstract mathematics of non-Euclidean ideal spaces developed by Bolyai, Gauss, Lobachevski and Riemann therefore acquired a major application in dealing with the geometry of the physical spaces [8].

**Time in the physical space.** In order to approach the concept of time we should first think about what gives physical meaning to it. We use the concept of time, in order to describe changes [5]. In a completely static Universe, time would have no role. More precisely, we need time so that we can order the events or changes that happen in the physical space, to detect and describe their possible causality. The existence of causality is a basic postulate in science. Causality implies that the cause must always precede the effect in time, and the same causes always produce the same effects. Time is a creation of our mind and makes sense only in connection with changes and movement. It is derived from two basic quantities that do exist in the Universe: space and changes. Time is therefore not an a-priori given quantity and similarly with the geometry of the physical space, the Universe does not naturally come with time embedded in it, and it is something that we have to construct it.

Clocks are devices that are used to measure time [9]. In order to make time measurable we need an etalon clock that gives periodic signals. Once we have defined this etalon clock, the unit of time will have been properly fixed, and we will be able to time events taking place in the physical space. However, an etalon clock is just halfway in timing events. Physical events take place at different points in space and in order to describe them properly, we need synchronised ‘clones’ of this ideal etalon clock placed at each point in physical space, so that we can time events at their own spatial location. Synchronisation of clocks and thus measurement of the local time of events was—and still is—a difficult task. Let us merely scratch the surface of the problem’s complexity. In order to have reliable local clocks, ideally you first have to produce clones of the original master clock, and than from time to time you have to synchronise them with the master clock. In order to achieve synchronisation an ideal information carrier is needed. For this information carrier you need to know exactly the speed of propagation along the geodesic line between any two clocks, since only in this way can you account for the time lapse in the propagation of the information. We therefore also have to
locate the geodesic line between the clocks and calculate precisely the distance along this line. All these are of course needed if we have an information carrier that propagates at finite speed. On the other hand however, if we had an ideal information carrier that propagated at infinite speed, the problem would be much simpler, and synchronisation of local clocks using such a signal would be trivial. Alternatively, timing of events occurring at different points in space can be hypothetically achieved using only one master clock. To proceed in this way, we again need some universally available information carrier and we have to know the length of the geodesic line between the master clock and the event. When the event occurs, we transmit a signal through the information carrier to the master clock. When the master clock receives the signal, we record that time and subtract from it the time needed to travel the distance between the event and clock. This procedure requires also the knowledge of the geodesic line and the speed at which the signal is propagated along it. Timing is again simple if we use an information carrier that travels at infinite speed.

It was only natural that in the beginning physics considered the simplest alternative: definition of an ideal time. This was defined at each point in space by hypothetically similar and ideal clocks, based on the assumption that they were synchronised with an ideal information carrier that travelled at infinite speed. Alternatively, this was equivalent to time events with a master clock, assuming no time lapse between the occurrence of any event and its detection at the location of the master clock. The simplicity of Newtonian mechanics resides in the fact that we assume the existence of an ideal information carrier that moves at infinite speed. Unfortunately, however, our Universe is more complicated than that. The fastest and the only universally available information carrier we are nowadays aware of is the electromagnetic wave, and we do know that its propagation speed is finite. In such case there is a serious catch, however: we do not know the medium through which light is propagated, since we were unable to detect aether. Whether it exists and we are just unable to find it or whether it does not exist, there is still a problem. In order to be capable of timing events at different spatial locations and to have a well-defined space time in physics we have to know the propagation speed of light along the correct geodesic line in any reference frame. The aether wind would influence this propagation speed, and the timing of events would then depend upon the frame of reference where the master clock is positioned. Now imagine for a moment that we know where the aether is. Theoretically, we would then be able to make a correct timing, but in practice it would be an arduous task. However, the advantage would be that by this method we would have an absolute frame of reference related to aether, and the timing of events relative to this would preserve a time concept that would also be absolute in nature. At the beginning of the twentieth century, however, aether was undetectable, and in order to progress, physics keenly needed a properly defined concept of time in physical space, if it was to tackle cosmological and electromagnetic phenomena.

Einstein gave in 1905 the only feasible outcome from this paradoxical situation by postulating that the speed of light in vacuum is a universal constant independent of the direction of propagation or frame of reference [10]. In the context of how we constructed and introduced the logic of time, this step now seems quite obvious and it is easy to conclude that physics had no other alternative. Thitherto space-time had not been properly defined, it did not make sense to speak about speed, and so the speed of light too had no physical meaning without a properly defined time. Einstein’s postulate, as well as fixing the value of the speed of light, allowed local times to be properly defined at each point in physical space and the “catch 22” type paradox was elegantly solved. In the beginning, the value of the speed of light was set at the best available experimental data, and it was proposed that this value should be constantly revised according to new experiments.
The story of grounding the physical space-time by means of light rays does not end here, however. For a consistent definition of space-time one immediately realises that it is problematic that geodesic lines and time are defined by means of light propagation, whereas the unit of length is still defined by the traditional ruler. In addition, if we know exactly the speed of light (since in Einstein’s paradigm it is a universal constant), then the unit of length should result automatically after the time unit has been set. The time unit of the master clock has to be set in any case, both in the Newtonian and in the Einsteinian paradigm in order to have a working master clock. By setting the time unit [11], and by knowing exactly the speed of light we could measure any distance in space using light rays and an etalon clock. Instead of postulating the unit length, it is much more convenient for modern physics to postulate the value of the speed of light. It was not until 1983 that physics, accepting the proposal of the Hungarian physicist Zoltan Bay, decided to postulate this value in consensus with the best experimental results at that time [12]. Today this value is set at \( c = 299,792,458 \text{ m/s} \). This was the last crucial step in defining a logically consistent space-time for physics.

However, this last step closes the circle and makes it impossible henceforth to detect aether by the aether wind, should it exist. In our new measurement paradigm, both the physical definition of distances and the construction of space-time are linked to the fact that light travels at a constant speed in every direction through space, independently of the chosen frames of reference. Any self-consistent aether wind experiment should give thus negative results. We do have thus a usable and well-defined space-time entity, but we have lost the aether-wind in the presently postulated physical space-time.

**THE PRINCIPLE OF RELATIVITY**

In physics we may use several frames of reference for describing the same phenomenon. For example, the collision of two cars on a road can be described within the frame of reference of the road, within the frames of reference of the two colliding cars, or within the frame of reference of any other car driving past on the road. It can be even described within the frame of reference of a light ray passing at the speed of light, or infinitely many other imaginable reference frames. These frames of reference are in motion relative to each other. When describing events from different frames of reference we intend first to locate the event within the particular frame of reference (giving the spatial and time-like coordinates) and then we try to understand it in a causal way according to previous events, applying the laws of physics. Each frame of reference comes with it’s own space-time entity, so we are interested to get also the relations (transformations) that connect the spatial or time-like coordinates of any event as measured from different reference frames.

Mechanics is founded on the experimental observation, which holds that there are special frames of reference within which the law of inertia is valid. These reference frames are called *inertial frames of reference* and these are those special reference frames where the geometry is Euclidean. If one frame of reference is inertial, any other frame of reference that is moving at a constant speed relative to it is again an inertial frame of reference (according to our postulates defining the geodesic lines their geometry is also Euclidean).

For the inertial frames of reference physics accepted the *principle of relativity*. According to this principle all inertial frames of reference are equivalent when describing physical phenomena, meaning that the laws of physics are the same in all inertial frames of reference. Mathematically this implies that the basic equations describing physical phenomena should have the same form in all of them. Taking into account their Euclidean nature (similar metric properties) this seems to be a logically consistent statement. According to the principle of relativity there is also no distinguished inertial frame of reference, or in other words there is no *absolute frame of reference*. Motion is always relative, and whenever we speak about
motion we mean it only in a relative manner. On the contrary, if we had an absolute frame of reference the notion of motion and rest would also be absolute. In Newtonian space-time the absence of an absolute frame of reference is due to the fact that the information carrier travels at the same infinite speed relative to all inertial frames of reference. In Einsteinian space-time the absence of an absolute frame of reference is a direct consequence of the fact that we have postulated the constancy of speed of light independently of the frames of reference. In such a way, we postulated that there is no aether, which would have been the absolute frame of reference for physics. Our postulate about the uniform propagation speed of light, independently of the frames of reference, is thus consistent with the principle of relativity, which holds that there is no absolute frame of reference in physics.

COORDINATE TRANSFORMATIONS

Both Newton’s ideal space-time and Einstein’s tangible space-time ought to be consistent with the principle of relativity. In both cases the spatiality and temporality of events are completely measurable and we can construct a well-defined system of coordinates to characterize this. However, the principle of relativity does not affirm that the temporal or spatial coordinates of events measured from different inertial frames of reference are the same. In Newtonian space-time, all the local clocks of the inertial frame of reference are naturally synchronised and time is absolute, but spatial coordinates are not. In Einstein’s Universe the concept of the synchronisation of clocks in different inertial frames of reference is more complicated and consequently time is not absolute. In both cases, however, if we know the spatial and temporal coordinates in one inertial frame of reference, we can calculate these coordinates in any other inertial frame of reference that is in motion relative to the original one at a given velocity. We call this coordinate transformation between two frames of reference [13] (for deriving the coordinate-transformations see Appendix 2.).

For the Newtonian space-time the coordinate transformations are given by the simple Galilean transformations we all learned in high school. Within the framework of Galilean transformations time coordinates are invariable. The coordinate transformations for Einsteinian space-time are given by the more complicated Lorentz transformations. In this case, time coordinates are not invariable, and they are transformed as a whole along with spatial coordinates. This is why we say space and time forms a ‘space-time continuum’. The consistency of the space-time defined by Einstein is demonstrated by the fact that the basic equations of electrodynamics, the Maxwell’s equations [4], are fully covariant with Lorentz transformations. From this viewpoint, the electromagnetic theory of light becomes a logically consistent and closed system. Lorentz transformations were derived by assuming there is no absolute medium through which light is propagated (no aether), and the equations that describe light lead us to the same conclusion: within each reference frame light travels at the same universal speed.

THE AFTERMATH

If one uses the space-time entity tailored on the finite propagation speed of light (and implicitly the Lorentz coordinate transformations), several fascinating consequences arises. First, one can easily realize that the simultaneity of events is not an absolute concept anymore. Events that are simultaneous in one frame of reference will not necessarily be simultaneous as viewed from other reference frames. The time-length of an event, or the spatial length of an object becomes also a relative concept. An observer moving with respect of a purely time-like event (an event happening at the same spatial coordinate in a reference frame that is in rest relative to the event) will measure a longer time-length for the event than the observer in rest relative to that event, a phenomenon called time-dilation. The spatial length of an object measured by an observer in rest relative to that object is longer than the
one measured by an observer moving in the direction of the measured length. This phenomenon is known as length-contraction (Appendix 2). Composition of velocities is also more complicated than in the Galilei-Newtonian kinematics. The interested reader can learn more about these fascinating effects from many excellent textbooks (see for example Einstein’s original text [13]), here we will not elaborate more on them. All these effects that seemingly contradicts our common sense are simply the direct consequences of the method by which our actual space-time entity is tailored on light.

As we have argued in the previous chapters, the story and the logic of the construction for the physical space-time is quite complicated, and even physicists sometimes forget this. Once it has been properly understood, however, special relativity becomes crystal clear and one can also realize that the presently used space-time paradigm might not be the ultimate solution for grounding physics. In the followings I will allow myself to be less rigorous and finish with some speculative thoughts.

An important, and sometimes misunderstood issue that we have to discuss here is the existence of a signal other than electromagnetic waves for allowing information to travel on cosmological scales of length. As our detection methods improve thanks to rapid advances in technology, a channel via such a non-conventional information carrier might become more appropriate for communication and measurement. At present, nothing guarantees that such an information carrier, if it exists, would travel at a lower speed than light. Contrary with what it is falsely believed, a speed bigger than the speed of light wouldn’t be a disaster for modern physics. The problem that might arise in such a case, would be that the space-time we built in the context of the theory of special relativity would not be self-consistent and we would violate the principle of relativity. It would be inertial reference frames in which one would detect the cause preceding the effect, contradicting the principle of causality (see Appendix 3). In order to make the theory consistent, instead of light we would now use the new information transmitter signal to synchronise clocks. Postulates regarding this new signal would replace those made for light. The advantages from such a new space-time paradigm would be that we would be able to answer some of the questions we have previously labelled ‘unanswerable’. Detection of the aether wind, the universal nature of the speed of light, and straight-line propagation of light rays would become questions that once more made sense.

Escaping the bonds of Einstein’s space-time and using some other logically consistent definition of space-time is an interesting challenge even if we cannot find any new information carrier. A new method of synchronising clocks or a new procedure for measuring time, along with the traditional ruler for measuring distance, might also help to bring the aether wind to light. Such experiments would not use interference or other wave-like properties implicitly based on Lorentz covariant electrodynamics. Instead, direct time of flight measurements of the propagation of light-rays, performed on laboratory scales of length, would be the most appropriate for us. As optoelectronics is making rapid progress, this does not seem to be unrealisable in the near future.

Previously we argued that our physics is based on the presumption that we have no absolute frame of reference, and all inertial reference frames are equivalent regarding the laws of physics. This also means that there is no special frame of reference known to us, relative to which electromagnetic waves are propagated. Modern cosmology is cautious enough to teach us that this might not be true, however. Apparently, there is a special, absolute frame of reference, relative to which the Cosmic Microwave Background Radiation (CMBR) is isotropic, and this could be regarded as an absolute frame of reference for the electromagnetic waves originating from the birth of the Universe [14] (more information on CMBR is given in Appendix 4.). The special frame of reference defined by the CMBR naturally raises several
questions and thoughts about the present foundation of physics. Firstly, it would be important to know whether the CMBR’s frame of reference generally defines the aether we were looking for. Will light rays travelling through the Universe always move with constant speed only relative to this frame of reference? When investigating such questions, we have to be quite cautious, however, since our present working paradigm, built on the constancy of the speed of light, would inevitably distort the measurements and their interpretations. Nonetheless, the proven existence of a special frame of reference for the CMBR is a serious argument pointing to the need to overhaul the present foundation of our basic concepts of space and time.

Another important issue we might discuss here in connection with space-time based on light is the microcosm. At the level of elementary particles, quantum mechanics seems to work when describing the microcosm. The image currently provided by physics, which states that elementary particles are wave-like in character and at the same time behave like classic particles is merely a desperate attempt to create a visual picture. Let us make a less desperate attempt and provide an alternative understanding of elementary particles’ strange dual nature starting from the obvious fact that the tools for investigating the microcosm are also electromagnetic waves. All physical information is collected via this channel, thus the geometry of the microcosm is shaped by light. Distances are measured via electromagnetic interactions and electromagnetic waves. We do know, however, that light has an experimentally proven dual nature. Apart from being a particle, its propagation is also wave-like. On the microscopic scale (the scale of length comparable with wavelength of light) this wave-like behaviour dominates, with the result that photons (energy carriers of the light) can be propagated in a strange manner along non-deterministically defined paths between two points of the space. The straight-line concept based on light yields a fuzzy, non-deterministic trajectory. If we do extrapolate our accepted definition of geodesic lines on microscopic scales, this thinking leads us to a non-deterministic, random metrics on the microscopic scale. The movement of microscopic objects would automatically obtain a probabilistic character, something similar to what we see in quantum mechanics. From this viewpoint, geometric spaces with random metrics might be than the tool to provide the particle-wave duality with an alternative description.

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APPENDIX 1. MEASUREMENT OF THE SPEED OF LIGHT
Ancient Greek philosophers were much more interested about vision, and light was only their second concern. Empedocles for example presumed that light travels with finite speed, while Aristotle assumed an infinite propagation speed for light. The first scientifically grounded thinking about the finite light propagation speed was formulated by the Arab scientist Ibn al-Haytham in the eleven century, and the first documented attempt to measure its value was by Galileo Galilei around the year 1600. Galileo designed a very basic experiment with two lamps placed on the top of two hills sufficiently far away from each other, but still in sight. His method was the following: let in the beginning both lamps be covered. Then, he would uncover his lamp, having instructed his apprentice to uncover his lamp as soon as the light from Galileo's lamp become visible. By this experiment Galileo planned to measure the time-gap between uncovering his lamp and the receiving signal from the other lamp. Due to the extremely high propagation speed of light, this method of course couldn't work, even if the two hills are tens of kilometers apart from each other. Galileo finally concluded that if the speed of light is finite, then it is too high to be measurable in such experiments. He also concluded that the speed of light must be at least 10 times bigger than the speed of sound, and we know nowadays that this is a strongly underestimated limit. Danish astronomer Olaf Roemer gave the first scientific proof that light travels with a finite speed. He made this conclusion by studying the observed eclipse times of the Jupiter's moon: Io. Astonishingly based on his results a good estimate can be obtained on the propagation speed of light. The first successful experiment for measuring the propagation speed of light in terrestrial experiments was made by the French physicist Armand Fizau in the mid-nineteenth century, obtaining a result that differs with less than 1% from the value accepted nowadays. Many later, carefully designed experiments confirmed these estimates and improved its accuracy. Nowadays our International System of Units is built in such manner (and we will understand later why this is a natural choice!) that the propagation speed of light is postulated. Following the proposal of the Hungarian physicist Zoltan Bay, in 1983 the propagation speed of light in vacuum was postulated as: 299 792.458 km/s.

APPENDIX 2. DERIVING THE COORDINATE TRANSFORMATIONS
We consider two inertial reference frames, K and K’. The geometry in both reference frames is Euclidean and we construct the usual Ox, Oy and Oz coordinate axes in K and the O’x’,O’y’ and O’z’ axes in K’, so that the corresponding axes are parallel with each other. Let us assume that K is moving with a uniform speed u relative to K’ in the direction of the common Ox -- O’x’ axis so that at time t=0 we synchronize the etalon clocks in K and K’ (t’=0) and at this time moment the centre O is coinciding with O’. Let an event P happen on the Ox -- O’x’ axis. Assuming that the time and length units used in both reference frames are the same, we are interested in the relation between the coordinates of the event measured in K (x1,y1,z1,t1) and K’ (x’1,y’1,z’1,t’1) (see Fig. 1). In our geometry for the P event y1 = y’1 = 0 and z1 = z’1 = 0, so we are looking for the relation between x and t coordinates measured in K and K’. Assuming a general functional relationship between the (x1,t1) and (x’1,t’1) coordinates we can write:

\[ x_1' = F(x_1, t_1, u) \]
\[ t_1' = G(x_1, t_1, u) \]

Using the principle of relativity, the same functional relationship should be true inversely, if we replace \( u \) by \( -u \):
\[ x_i = F(x_i', t_i', -u) \]
\[ t_i = G(x_i', t_i', -u) \]

(2)

Fig. 1. Coordinate transformation between the inertial reference frames \( K \) and \( K' \).

One can get the inverse transformations however also from (1). In order that these should have the same functional form it is necessary that the transformations should be linear in the \( x \) and \( t \) coordinates, otherwise the functional form would change, and we would contradict equation (2) and implicitly the principle of relativity. The most general linear transformation we can write is:

\[ x_i' = a(u)x_i + b(u)t_i + d \]
\[ t_i' = g(u)x_i + f(u)t_i + k \]

Considering the initial condition \( x_i = x_i' = 0 \) at \( t_i = t_i' = 0 \) we get \( d = k = 0 \), leading to:

\[ \frac{dx_i'}{dt_i'} = v_i' = \frac{a(u)}{g(u)} \frac{dx_i}{dt_i} + \frac{b(u)}{f(u)} = \frac{a(u)v_i + b(u)}{g(u)v_i + f(u)} \]

(3)

Here \( v_i \) denotes the velocity for the movement of a body as measured in \( K \) and \( v_i' \) the same velocity measured from \( K' \). According to the principle of relativity the inverse transformations should be:

\[ x_i = a(-u)x_i' + b(-u)t_i' \]
\[ t_i = g(-u)x_i' + f(-u)t_i' \]

\[ \frac{dx_i}{dt_i} = v_i = \frac{a(-u)}{g(-u)} \frac{dx_i'}{dt_i'} + \frac{b(-u)}{f(-u)} = \frac{a(-u)v_i' + b(-u)}{g(-u)v_i' + f(-u)} \]

(4)

If we study the relative motion for the origins of the two coordinate system \( K \) and \( K' \) we get that in case \( x_i = 0 \) \( \rightarrow \frac{dx_i}{dt_i} = v_i = u \) and for \( x_i' = 0 \) \( \rightarrow \frac{dx_i}{dt_i} = v_i = -u \). These conditions in (3) yields: \( b(u) = u \cdot f(u) \) and \( a(u) = f(u) \).

**Galilei-Newton transformations.** If one assumes that the speed of light is infinite, synchronization of clocks is trivial since there is an absolute time, and in such manner for any event one should have: \( t_i' = t_i \) leading to: \( g(u) = 0 \) and \( f(u) = 1 \). The coordinate-transformations write thus as:
As an immediate consequence we have that for any event, its time-length is the same from any reference frame (\(dt_1' = dt_1\)) and the length of any object is the same from any reference frame. The length of an object from reference frame K is measured by determining its coordinates at the same time moment, so that \(dt_1 = dt_1' = 0\). As a result we get \(l_1' = dx_1' = dx_1 = l_1\). The velocity transformations result automatically from eq. (3)-(5): \(v_1' = v_1 + u\)

**Lorentz-Einstein transformations.** In case the speed of light is finite, synchronization of clocks can be made only by assuming that the speed of light is the same, from any reference frame. This means that a light beam that travels along the Ox axis in K should have the same finite value measured both from K and K'. Equation (3) and the relations established before yield thus: \(c = \frac{f(u)(c + u)}{g(u)c + f(u)} \rightarrow g(u) = f(u)\frac{u}{c^2}\)

According to this we can write:

\[
x_1' = f(u)(x_1 + u\cdot t_1)
\]

\[
t_1' = f(u)\frac{x_1}{c^2} + t_1
\]

Deriving from here the inverse transformations one gets:

\[
x_1 = \frac{x_1' + ut_1'}{f(u)\left(1 - \frac{u^2}{c^2}\right)} \quad ; \quad t_1 = \frac{x_1'\frac{u}{c^2} + t_1'}{f(u)\left(1 - \frac{u^2}{c^2}\right)}
\]

In order to satisfy the principle of relativity (and the inverse transformations should be of the form one must have: \(f(u)\cdot f(-u) = \left(1 - \frac{u^2}{c^2}\right)^{-1}\), leading in our geometry to the Lorentz transformations:

\[
x_1 = \frac{x_1 + ut_1}{\sqrt{1 - \frac{u^2}{c^2}}} \quad ; \quad t_1 = \frac{x_1\frac{u}{c^2} + t_1}{\sqrt{1 - \frac{u^2}{c^2}}}
\]

One realizes now that quite differently form the Galilei-Newton kinematics, simultaneity of events becomes a relative concept. In case of a purely time-like event taking place in K (the spatial coordinates in K are the same, \(dx_i = 0\)), we get:

\[
dt_1' = \frac{dt_1}{\sqrt{1 - \frac{u^2}{c^2}}} \geq dt_1
\]

According to this, the time-length measured by an observer who moves relative to the event that is purely time-like in K is always bigger, a phenomenon known as *time-dilation*. In the direction of the movement the lengths of the objects are measured shorter. This phenomenon is known as *length-contraction*, and can be derived immediately from equations...
(6). When measuring the length of an object from reference frame K' we need to determine the end-points coordinates in the same time moment, so \( dt_1' = 0 \). For deriving the magnitude of the length-contraction we have to use thus the inverse transformations of (6). We get:

\[
d x_i = \frac{d x_i'}{\sqrt{1 - u^2/c^2}} \rightarrow d x_i' \leq d x_i
\]

(11)

The velocity transformations result simply from equations (3),(4) and (8):

\[
v_1' = \frac{v_1 + u}{1 + \frac{v_1 u}{c^2}} \quad ; \quad v_1 = \frac{v_1' - u}{1 - \frac{v_1' u}{c^2}}
\]

(12)

APPENDIX 3. CAUSALITY PRESERVED

From the Lorentz transformations we already foresee that we have problems if we have reference frames that move relative to each other with a higher velocity than the velocity \( c \) of light, since negative numbers under the square root appear. This does not forbid however, to have a special signal that travels with a higher velocity than \( c \).

Let us now recall that our belief in the principle of causality was the main reason for which we needed time. It is imperative then that causality should be preserved by the space-time entity we have constructed. The question that makes sense from such a viewpoint is whether causality is preserved within any frame of reference. Let us assume that we have two events \( a \) and \( b \), which are causal: \( a \) causes \( b \). Let us assume that event \( a \) happens within frame of reference K at spatial location \( x_a \) and time \( t_a \), and event \( b \) happens at spatial location \( x_b \) at the time moment \( t_b \). Let us assume \( x_a < x_b \) and causality in frame of reference K means that \( t_a < t_b \). This order must be preserved in any inertial frame of reference. If we had an inertial frame of reference where this order is inverted, the principle of relativity would be violated, since the event does not make scientifically sense within this frame of reference. Causality in the frame of reference K means that there should be some signal starting from space point \( x_a \) at time moment \( t_a \) and arriving at space point \( x_b \) in time moment \( t_b \). We will consider that this signal is the one that creates a causal connection between the two events, i.e. event \( b \) is triggered through this channel. From the \( x_a < x_b \) spatial location of the events and from their time moments \( t_a < t_b \), one can calculate the propagation speed of this signal. In principle any positive velocity value \( v = (x_b - x_a)/(t_b - t_a) > 0 \) is acceptable. Let us now use a second K’ frame of reference travelling in the direction of the line from point \( x_a \) to \( x_b \) at a velocity of \( u \) (note that this is quite the opposite direction as the one sketched in Figure 1). We learn from the Lorentz transformations, (use of eq. (12) with \( u \rightarrow -u \)) that within this frame of reference:

\[
t_b' - t_a' = \frac{t_b - t_a}{\sqrt{1 - \frac{u^2}{c^2}}} \left(1 - \frac{vu}{c^2} \right)
\]

(13)

In order to preserve causality \( (t_b' > t_a') \) we need thus \( vu < c^2 \) be satisfied for any \( u < c \) value! Since the speed of reference frame K’ and the signal from \( a \) to \( b \) are not connected, their values can vary independently. We thereby arrive at the conclusion that the value of \( v \) is also bound by the value of \( c \). In other words, in order to preserve the principle of relativity (i.e. to hold causality within any frame of reference) we put forward that there is a speed limit in our Universe, and this is the speed of light! It is not allowable for any signal to be propagated
faster than the speed of light, and no frame of reference (i.e. object) can have a speed relative to the other one bigger than the speed of light. These statements must be true in order to preserve the logical consistency of the special theory of relativity.

APPENDIX 4. THE COSMIC MICROWAVE BACKGROUND RADIATION

The CMBR is an electromagnetic radiation detectable throughout Universe, and thus measurable on the Earth, too. Arno Penzias and Robert Wilson discovered it by accident in 1964 during radio astronomy and satellite communications experiments. In the signal captured by their specially built horn antenna, the CMBR appeared as a continuously present electromagnetic noise coming from every direction in the Universe. The spectrum of this electromagnetic radiation peaks in the microwave region, and it was found to be characteristic of very low-temperature (around 3K) thermal (or black-body) radiation. This electromagnetic radiation is assumed to be a leftover from the “Big Bang” that created our Universe. Nowadays, using modern apparatus, we are able to map this radiation with great precision at micro Kelvin resolution, and anisotropies from different directions of space are precisely measurable. It was found that apart from randomly distributed, tiny anisotropies, the CMBR measured from Earth has also a prominent “dipole-anisotropy” on milli Kelvin resolution, which results from the motion of Earth (and our group of galaxies) relative to the CMBR’s frame of reference [1]. In this way, we have a detectable, special frame of reference, relative to which the dipole anisotropy of the CMBR would vanish. Interestingly, we know this special frame of reference, and it appears to be moving at a speed of around 600 km/s relative to the Milky Way.

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SIMPLE EXPERIMENTS WITH SEMICONDUCTORS AND LEDS

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ABSTRACT
In contrast to classical chapters of physics, only a few simple experiments are available for discussing semiconductors in the schools. This paper describes some simple experiments tested several times. By examining the electrical resistance of a Ge slice, some basic properties of semiconductors are illustrated like changes in resistance under the influence of heating or illumination. The possible application of semiconductor devices in further demonstrated by experimenting with light-emitting diodes (LEDs), known from everyday practice. The focus is on the description of experiments, and explanations are given only in terms of basic physics.

INTRODUCTION
As in the science of physics, experiments play a vital role also in physics teaching. The discussion of each topic in physics should ideally start with the presentation of a related experiment. The primary task with the experiments presented here, which do not need too many devices and can be carried out quickly, is to grab the attention of pupils and to motivate them to understand the explanation of the phenomenon.

Semiconductors play an important role electronic equipment used in modern everyday life. Young people are eager to learn how the devices they use work and it should be kept in mind that almost all the main features of those devices rely on semiconductors. It is important to realise that the introduction of semiconductors in secondary schools physics is unavoidable since they have become an inevitable part of the preparation for any engineering profession. In teacher training at universities the discussion of semiconductors takes place only after thorough quantum mechanical and material science courses. This may be the reason why so many teachers don’t even think of dealing with semiconductors. In fact, students are lacking the necessary knowledge of material structure required for a deeper understanding of the related phenomena. Here we show that a different approach might be more efficient: experimental investigation of some phenomena is also a valuable, especially when experiments are carried out by the students themselves.

The topic of semiconductors is also cross-curricular, bridging the gap between different science subjects, i.e., chemistry and physics. The efficiency of learning is higher for students if they recognise that the knowledge they have acquired in chemistry can be essential for their further comprehension of physics.
EXPERIMENTAL INVESTIGATION OF THE CONDUCTIVITY OF GERMANIUM

In our first experiment we measure the resistance of a germanium slice. To this end we need a multimeter, a slice of germanium, an insulating support, and electrical wires (Fig.1). We place the germanium crystal carefully on the insulating support and fix it. (We have to be careful because a thin layer of Ge crystal is very fragile.)

The multimeter is used in the “resistance measurement” mode and is connected to two edges of the germanium slice. The multimeter contains a built-in power supply, and the circuit is closed through the germanium. The multimeter displays the resistance of the germanium at room temperature. The resistance of a thin layer of germanium, as can be seen in Fig.2, is of the order of MΩ-s. This value is very high compared to the values measured on metals of similar geometry, but it is much smaller than the resistance of electrically insulating materials.

Spray on the Ge slice some kind of freezer spray, available in medication. The instrument indicates that the electrical resistance of the cooled germanium increases dramatically. Heat the germanium slice with a hairdryer above room temperature. The electrical resistance of the material decreases with increasing temperature (Fig.3). If the germanium sheet is illuminated with a table lamp its resistance decreases again (Fig.4).
The decrease in resistance under the influence of illumination is easily measurable. This change is interesting especially in comparison with that in metals. In the case of metals the electrical resistance increases parallel to the increase in temperature, and illumination does not cause any measurable change in resistance.

For an elementary explanation of the conductivity of metals, we introduce the free electron model, the classical Drude model [1]. The structural foundation of this is already known for students from chemistry. In physics, we augment this picture with a more microscopic interpretation of currents by mentioning that the oscillating movement of the metal atoms around their equilibrium positions in the crystal hinders the free movement of electrons. This is considered to be the cause of electrical resistance of pure metals. The interpretation of conductivity of semiconducting materials is based on the knowledge of their chemical structure. In chemistry the elements of Group 4 and 5 are called metalloids, and it is noted that in these groups the metallic character increases from top to bottom. Take, e.g. diamond carbon, silicon and germanium. The crystal structure of each of these materials is tetrahedral, based on covalent bonds, a so-called diamond lattice. In the case of diamond, electrons in covalent bonding are strongly bound and there are, therefore, no free charge carriers in the crystal, diamond is thus electrically insulating. In the case of Si and Ge, that are below the carbon in the periodic table, electrons can be more easily released from the bonds (for example by heating or illumination). In Si, more energy input is needed, which demands, e.g., more intensive heating. In the case of Ge, a significant increase in the number of free electrons is experienced already at moderate temperature rise or illumination.

The electrons set free by the methods described above conduct electricity just like the free electrons in metals. The increase of current due to the electrons set free by heat or illumination is much stronger than the decrease due to the enhanced thermal oscillation around the equilibrium atomic positions.

In addition to the abovementioned electron conductivity mechanism an electron-hole mechanism gives a further contribution to electric conduction. At medium level it is sufficient to add a remark on this. At advanced level we can elaborate more on the passive movement of the holes. Our experience is that at secondary school the concept of the “energy-band structure” [2] is unnecessary since a quantum mechanical foundation is hopeless to be given at this level.

**SIMPLE EXPERIMENTS WITH LIGHT EMITTING DIODES (LEDS)**

In many appliances and instruments semiconductors are the basic components, of which the most commonly used are LEDs [3]. LEDs are well known as energy-saving light sources which directly convert electrical into light energy.

**The LED light output as a pole-dependent device**

In terms of physics, a LED is a special semiconductor diode. Simple experiments illustrate that LED conducts electricity in one direction only. If we join the anode of LED to the positive pole of a battery, and the cathode to the negative pole, the LED conducts electricity, and lights up (Fig.5). This connection is in the forward direction (Fig.6). (For protecting the LED we apply a 100-ohm resistor.) Using reverse polarity, the LED does not light up.
LED is a special semiconductor diode

The fact that LEDs conduct electricity exclusively in one direction can be illustrated with another spectacular experiment. Take an approximately half meter double-stranded electric wire and a battery. If a LED is connected between the ends of the wires, the LED lights well (for protection we apply again a 100 ohm resistor in series). When rotating the light emitting diode at the end of the connecting wires, while holding the other end of it in our hand, the LED traces out a continuous circle of light (Fig.7).

In the second experiment we use alternating current with a frequency of 50 Hz. Apparently, the LED lights well again. However, when spinning the wire with the LED, we see an interruptedly lighting circuit (Fig.8). The reason is that the LED lights up in the forward direction and goes out in the reverse direction. This alternation is so fast that without the rotation it cannot be observed by naked eye.

LED WORKS BEYOND A THRESHOLD ONLY

We can illustrate with a very impressive and interesting experiment that a LED – as any other diode – works only above a certain opening threshold voltage. We need some moderately wet earth, two electrical wires, and direct current from an electric power supply,
two electrodes made by metal plates, a voltmeter, a ruler, and a LED. The electrical circuit needed can be seen in Fig.9.

![Electrical Circuit](image)

**Fig.9.** The electrical circuit used for the illustration of the existence of a potential threshold. The white ruler marks the direction of the electric field in the system.

The distance between the two electrodes is about 10 centimetres. On the surface layer of the wet earth a nearly uniform electric field is formed. The voltmeter in Fig.9. shows about 30 Volts. We insert a LED into the wet earth. Make sure that the LED is to be inserted in forward direction. If the legs of the LED are far enough from each other, and are parallel to the ruler, the LED lights up, because the potential difference between the legs is higher than the threshold voltage. (In our experiment the distance between the legs of the LED was 2 centimetres. The maximum potential difference between the legs is thus about 6 Volts.) If we rotate the LED step by step, the potential difference between the legs decreases, the LED will provide dimmer light (Fig.10).

![LED Images](image)

**Fig.10.** When slowly rotating the LED the light become dimmer, and at a threshold angle it goes off.

Measuring the distance $x$ between the legs parallel to the ruler when the LED goes off (in our experiment $x \approx 1.4$ cm, see the second panel of Fig.10), we can determine an approximate value of the threshold voltage as:
The LED does not light up, of course, if its legs are on an equipotential line (perpendicular to the ruler). In this case the potential difference between the legs is zero. If the LED is rotated further, the potential difference between the legs becomes negative, so it does not light up because the LED conducts electricity only in one direction.

**LED as a photovoltaic cell**

A voltage can make a semiconductor light up, the reverse phenomenon is that light can generate voltage in a semiconductor. It can be shown by a simple experiment that LEDs can work as power supplies. In our experiment a LED is illuminated by another one from above (Figs.11, 12). Between the electrodes of the illuminated LED we measure voltage. By varying the intensity of illumination (e.g. by increasing and decreasing the distance between the LEDs) the measured voltage changes.

This experiment illustrates that LEDs and solar cells work in a similar way.

**CONCLUSIONS**

Based on the students’ previous knowledge on semiconductors, teachers may explain why metals conduct electricity and insulators don’t; how the conductive and semiconductive features of materials depend on the temperature and light intensity.

The experiments shown here are suitable to illustrate semiconductor properties, and the functioning of some devices made from semiconductors. To give deeper explanations was not our goal, since for these the students’ deeper previous knowledge would be necessary, such explanations could be provided e.g. in special mentor classes, if we can awake our students' interest.

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COORDINATE TRANSFORMATION IN THE DESCRIPTION OF PHYSICAL PHENOMENA

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ABSTRACT
The treatment of the collisions at secondary school level is a nice application of the general principles of mechanics, namely the conservation of the energy and the conservation of the momentum. By transforming the coordinates into a system moving with the centre of mass of the colliding bodies the use of quadratic equations can be avoided. Another interesting use of the coordinate transformations can be found in the theory of relativity. By the use of Lorentz-transformation between inertial frames it can be demonstrated that the quantum mechanical wave function is a result of the transformation of standing waves into the frame which is moving relative to the first one.

ELASTIC COLLISION
It is well known, that solving physical problems is simpler when an appropriate reference frame is used. It is suitable even in case of colliding bodies. Considering the elastic head-on collision of two discs of different masses we can use the laws of conservation of energy and momentum:

\[ m_1 v_1 + m_2 v_2 = m_1 v'_1 + m_2 v'_2, \]  
\[ \frac{1}{2} m_1 v_1^2 + \frac{1}{2} m_2 v_2^2 = \frac{1}{2} m_1 v'_1^2 + \frac{1}{2} m_2 v'_2^2. \]

In these equations the masses \( m_i \) and the velocities \( v_i \) on the left side are known, and the value of velocities \( v'_1 \) and \( v'_2 \) after the collision are to be determined. Let the mass of the first and second discs be \( m_1 = 3 \text{kg} \) and \( m_2 = 2 \text{kg} \), respectively. The first disc is moving to the right at velocity \( v_1 = 4 \text{m/s} \), while the second to the left at velocity \( v_2 = -9 \text{m/s} \) in the laboratory system which is attached to the table where the discs are moving. Substituting these values into the equations above, we get:

\[ -6 = 3v'_1 + 2v'_2, \]  
\[ 210 = 3v'_1^2 + 2v'_2^2. \]

Solving the equations, we get the velocities: \( v'_1 = -6.4 \text{m/s} \) and \( v'_2 = 6.6 \text{m/s} \) after collision. But the calculation needs the solution of a quadratic equation which is beyond the curriculum of the 9\(^{th}\) grade students.
However, the results can be obtained with simpler mathematical manipulations if the collision is described in the frame attached to the centre of mass of the system [1]. In this frame the centre of mass remains at rest during the collision and the sum of the momentums of the two bodies is zero all the time. It means that the momentum of the bodies is equal in magnitude but their direction is opposite. Since the kinetic energy of the system is also conserved, therefore only the direction of the momentums could be changed, the magnitudes of the momentums must remain the same during the collision.

The change between the frames happens on the basis of Galilean transformation, which leads to the classical addition formula of the velocities. In the laboratory frame of reference the centre of mass of the system is moving to the left with velocity \( V = -1,2 \text{m/s} \) according to the formula

\[
V = \frac{m_1v_1 + m_2v_2}{m_1 + m_2}.
\]  

(5)

Now, let us calculate the momentums in the frame of reference which is moving at this velocity. It is the reference frame of the centre of mass. In this frame the velocity and momentum of the first body are 5,2m/s and 15,6kgm/s, respectively, while those of the second body are \(-7,8\text{m/s}, \text{and } -15,6\text{kgm/s}\). As the reasoning given above shows, the direction of the momentums become opposite during the collision. From this the velocities of the first and second bodies can be calculated: \(-5,2\text{m/s} \text{ and } 7,8\text{m/s}, \text{respectively}.\) Transforming these velocities back to the laboratory system we get velocities \( v_1' = -6,4\text{m/s} \) and \( v_2' = 6,6\text{m/s}.\) The result agrees with those gained previously.

Thanks to the appropriate choice of the frame the quadratic equations could be avoided. The train of thoughts based on the coordinate transformation is not an easy one, but according to my experiences it is comprehensible for 9th grade students.

**THE DE BROGLIE WAVES**

Derivation provided in this section helps in understanding the essence of the quantum mechanical wave function. Nowadays this procedure can be used probably only at a more advanced level of physics teaching (e.g. at introductory courses of universities.) However, my previous experiences obtained in teaching the elements of the theory of relativity at secondary school level indicate that in special secondary school classes the presented train of thought can be understandable.

In 1924, one of the keynotes of de Broglie’s theses was that a frequency can be assigned to the rest energy of micro-objects according to the relation

\[
u_0 = \frac{m_0c^2}{h}
\]  

(m\(_0\) is the rest mass of a particle, c is the speed of light, h is the Planck constant) – see e.g. [2], [3]. At that time the idea was wondrous as this kind of frequency had come up before only in connection with differences of energy levels, and never in relation to the energy of a given state – see e.g. [4]. Nowadays, this relation is taken conventionally, since it is an organic part of quantum theory. In the abovementioned articles we can read about the relationship of the de Broglie waves and the theory of relativity in connection with de Broglie’s thesis. The question of de Broglie waves is also examined in [5]. Article [3] comes out from assuming that in the quantum’s rest frame a standing wave is present and the quantum is not point-like.
In the following the formula $\lambda = h/p$ will be derived from (6) with a self-constructed train of thought of the author of the present paper. It will be shown that if in the quantum’s rest frame $K$ a standing wave of infinite wavelength and rest-frequency $m_0c^2/h$ is present, then using the Lorentz transformation we get in the frame $K'$ a travelling wave with wavelength $\lambda' = h/(mV)$. This is the de Broglie wavelength. $V$ is the relative velocity of frames $K$ and $K'$, $m$ is the relativistic mass of quantum.

It is known that the quantum in the rest frame has infinite de Broglie wavelength. Starting from this, the standing wave in the rest frame $K$ can be represented with a function

$$y(x, t) = A \cdot \sin(\omega t),$$

where the value of $y$ does not depend on $x$ – see Fig.1. The dependent variable $y$ can be an arbitrary scalar physical quantity. The angular frequency in the phase is $\omega = 2\pi / T$.

![Diagram of coordinate transformation](image)

Fig.1. Function $y(x, t)$ in the frame $K$ and $K'$

The function takes a maximum value simultaneously at each point of frame $K$. Let us look at what we get if we consider the values of function in a system $K'$ which moves parallel to the $x$-axis at a constant speed $V$. At this point, for describing the transformation of $x$ and $t$, we have to use the formulas

$$x' = \frac{x - V \cdot t}{\sqrt{1 - \frac{V^2}{c^2}}}$$

$$t' = \frac{t - \frac{V \cdot x}{c^2}}{\sqrt{1 - \frac{V^2}{c^2}}}$$

(8)

of the Lorentz transformation.

Because of the relativity of simultaneity, we could also expect that while the maximum values of the function occur at each point of frame $K$ at the same time, this will not be the same in frame $K'$. In a fixed moment $t'$, the value of the function is determined among others by coordinate $x'$.

In frame $K'$ we have to work with a chosen coordinate $t'$. It results from the formula of time transformation that if we want to get the same coordinate $t'$ at each point of the frame $K'$, we have to increase the $x$ coordinate along with the coordinate $t$. More precisely, the increase of coordinate $t$ with $\Delta t$ can be compensated by increasing coordinate $x$ with the suitable value of $\Delta x$. It is clear that in case of a fixed $x$, if $\Delta t$ takes the time period from zero to $T$, then with a fixed $t$, the suitable $\Delta x$ runs an interval related to a whole spatial period. Therefore, in frame $K'$, the state frozen at moment $t'$ will be a harmonic function which is equal to such a 'crease'
of the standing wave where the creases are characterized by wavelength $\lambda'$, measured along
the axis $x'$. We wish to determine this wavelength.

We transform the pair of events by data $(x, t)$ and $(x + \Delta x, t + T)$ into frame $K'$. The aim is
to have a simultaneous pair of events in frame $K'$. According to the formula for time
transformation, it is evident that the requirement $t' = \text{const}$ refers to the relation

$$t - \frac{V \cdot x}{c^2} = \text{const}.$$  \hspace{1cm} (9)

Therefore, the relation $T = V \cdot \Delta x/c^2$, otherwise $\Delta x = \frac{T \cdot c^2}{V}$ must be valid. If this
condition is valid, we will get a simultaneous pair of events in frame $K'$ from the pair of

$$\left( x, t \right) \text{ and } \left( x + \frac{T \cdot c^2}{V}, t + T \right)$$ \hspace{1cm} (10)

In frame $K'$, their distance is one period, which is equal to the sought wavelength $\lambda'$.

The event $(x, t)$ is transformed to the coordinate

$$x'_1 = \frac{x - V \cdot t}{\sqrt{1 - \frac{V^2}{c^2}}}.$$ \hspace{1cm} (11)

as the event $(x + T \cdot c^2/V, t + T)$ is transformed to the coordinate

$$x'_2 = \frac{x - V \cdot t + \frac{T \cdot c^2}{V} - V \cdot T}{\sqrt{1 - \frac{V^2}{c^2}}} = x'_1 + \Delta x'.$$ \hspace{1cm} (12)

In frame $K'$, the distance of these simultaneous events is

$$\Delta x' = \lambda' = \frac{\frac{T \cdot c^2}{V} - V \cdot T}{\sqrt{1 - \frac{V^2}{c^2}}}.$$ \hspace{1cm} (13)

Based on this, we get the result

$$\lambda' = T \cdot \sqrt{1 - \frac{V^2}{c^2} \cdot \frac{c^2}{V}}.$$ \hspace{1cm} (14)

Therefore, if we have a standing wave of infinite wavelength and angular frequency $\omega = 2\pi/T$
in frame $K$, we get a propagating wave of wavelength $\lambda'$ and phase velocity of $c^2/V$ in frame
$K'$. (As it is well known the phase velocity of a wave is the velocity of the propagation of a
given vibration-state.)

Let us consider what happens in frame $K$ if the frequency is equal to the rest frequency $m_0c^2/h$ of a quantum. In this case $T = \frac{h}{m_0c^2}$ and we get the relation

$$\lambda' = \frac{\frac{h}{m_0c^2} \cdot \sqrt{1 - \frac{V^2}{c^2} \cdot \frac{c^2}{V}}}{mV} = \frac{h}{mV}.$$ \hspace{1cm} (15)
with \( m = m_0 / \sqrt{1-V^2/c^2} \). This result is equal to the de Broglie wavelength in a general, relativistic case. Thus, the standing waves with unlimited wavelength (vibrations) are converted by Lorentz transformation into de Broglie waves.

We may apply a similar derivation when we would like to know the temporal periodicity in frame \( K' \). In this case, we make the coordinate \( x' \) be fixed instead of \( t' \) in frame \( K' \). This setting creates the condition \( \Delta x = V \Delta t \) within which we have to choose the time span \( \Delta t = T \).

Let us transform the events

\[
(x, t) \quad \text{and} \quad (x + V \cdot T, t + T).
\]

The time coordinate of event \((x, t)\) in frame \(K'\) is

\[
t_1' = \frac{t - \frac{Vx}{c^2}}{\sqrt{1 - \frac{V^2}{c^2}}} \tag{16}
\]

while the time coordinate of event \((x + V \cdot T, t+T)\) is

\[
t_2' = \frac{t + T - \frac{V(x+V\cdot T)}{c^2}}{\sqrt{1 - \frac{V^2}{c^2}}} \tag{17}
\]

The difference between the two time coordinates is

\[
T' = t_2' - t_1' = \frac{T - \frac{V^2 \cdot T}{c^2}}{\sqrt{1 - \frac{V^2}{c^2}}} = \frac{T \cdot (1 - \frac{V^2}{c^2})}{\sqrt{1 - \frac{V^2}{c^2}}} \tag{18}
\]

based on that we can come to this relation:

\[
T' = T \sqrt{1 - \frac{V^2}{c^2}}. \tag{19}
\]

The same quantity is present in the relation derived for \( \lambda' \). It refers to the fact that at the selected point, the vibrations happen with a reduced period \( T' \), thus with an increased frequency of \( \nu' = 1 / T' \) in frame \( K' \). The formula

\[
\lambda' = \frac{T' c^2}{V} \tag{20}
\]

shows that the vibrations in frame \( K' \) propagate as a wave of phase velocity

\[
V_f = \frac{c^2}{V}. \tag{21}
\]

Since \( V < c \), the phase velocity is faster than the speed of light. The phase velocity depends only on relative velocity \( V \). The velocity \( V \) of frame \( K' \), which is compared to frame \( K \), can be considered as the velocity of the quantum (in a sense, we can consider it as group velocity). According to the given relations, the product of phase velocity and group velocity is \( c^2 \). If relative velocity \( V \) approaches zero, the phase velocity will approach infinity.
The frequency of the de Broglie wave that we get in frame \( K' \) is

\[
\nu' = \frac{\nu}{\sqrt{1 - \frac{v^2}{c^2}}}. \tag{23}
\]

This frequency gives the total energy of the micro-object. If the rest mass, namely the rest frequency \( \nu \) is doubled, the frequency \( \nu' \) is duplicated too, and the equality

\[
V_f = \frac{c^2}{\nu} = \lambda' \cdot \nu'
\]

shows us that the de Broglie wavelength is also halved, since the phase velocity is constant. In frame \( K \), only the rest energy \( h \cdot \nu \) is present and it is related to the periodicity of time; on the other hand, in frame \( K' \), there is a part of the total measurable energy \( h \cdot \nu' \) which is connected with spatial periodicity (momentum \( p \)) and the periodicity of time. The disintegration of the total energy \( E \) into these two components is reflected in the formula

\[
E^2 = m_0^2 c^4 + p^2 c^2. \tag{25}
\]

The direction of momentum \( p \) is given by the direction of velocity \( V \) of frame \( K \) in frame \( K' \).

**CONCLUSIONS**

The formula (14) derived for the wavelength in the moving frame \( K' \) provides the de Broglie wavelength if the rest frequency \( m_0 c^2 / h \) is substituted into it. Therefore it can be concluded that de Broglie waves are basically the relativistic transformations of standing waves with frequency \( m_0 c^2 / h \). The relativity of simultaneity plays a crucial role in its derivation. Based on this the de Broglie wave cannot be understood outside the frame of relativity. This is not contradictory to the fact that these waves play a role in interference experiments, also in the case of small relative velocities.

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APPLICATION OF COMPUTER SIMULATIONS IN MODERN PHYSICS EDUCATION

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ABSTRACT
Teaching modern physics is an essential, yet challenging part of our curriculum. When introducing the main scientific theories and discoveries of the past century, we often find ourselves with a lack of experimental resources in it. My goal is to develop and test computer simulations which can be used in high school teaching as a virtual science lab, where students do not only passively observe, but also interactively perform measurements of modern physics phenomena. In most cases the technical conditions for real students’ experiments are not given, or the observed phenomenon runs in an uncommon (ultra-fast or ultra-slow) time scale. Thus, a simulation is able to complete the students’ experience already based on real observations.

INTRODUCTION
There are at least four essential questions that shall be answered according to modern physics education. “What shall we teach?” “Who shall we teach?” “When shall we teach it?” And finally, “how shall we teach it?” These questions are fundamental for all subdisciplines of course, but for teaching modern physics, they get a little more problematic.

In my paper, I aim to introduce the main challenges in teaching modern physics and give an idea on how to solve these problems. I will discuss the general role of computer simulations in teaching modern physics and present one of my simulations – the photoelectric effect – in detail.

TEACHING MODERN PHYSICS IN GENERAL
It is not in question that motivating our students to study or even love physics is one of the biggest challenges today. Surely there is a great amount of publications on developing teaching methods for enhanced motivation, but teaching physics – or science in general – shall always contain experiments for gathering knowledge. “Performing experiments is the basic and typical method of scientific research, learning and education. [...] Experiments in teaching is typically the base in determining laws of physics and chemistry, and also the only (exclusive) tool of validating these deduced laws, hypotheses and theories, as well as the diagnostic tool for their validity limits” [1]. This excerpt is from the Encyclopaedia of Pedagogy published in 1997. It clearly shows how important scientific experiments are in our physics teaching but it’s also a key method in keeping students motivated.

Also, the constructivist approach of teaching, particularly IBL – inquiry-based learning/teaching – moves several steps forward claiming that experiments shall always be executed by the students, letting them gather own experience, and allowing them to observe,
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measure, draw up a hypothesis and then validate it on their own. This is the ideal approach of motivating and teaching physics to our students. Chris Chiaverina and Michael Vollmer gives a statement based on results from a discussion workshop during the 2005 GIREP seminar in Ljubljana that experiments in future physics education will always play a central role, “however more will be computer based. Computer aided experiments will allow the inclusion of frictional and other effects in simple experiments” [2]. They also state that “Experiments will always be needed to motivate students.”

As for modern physics, I believe it is motivating itself, most of my student referrals in my classes state that modern physics was their favourite part of our physics curriculum and there are even ones admitting that learning about modern physics was the first time they ever wondered about studying science in the future. Therefore motivation is necessary, but manageable, though there is another challenge in teaching modern physics.

It is that it’s challenging itself, and – by a very thoughtful idea – it all comes down to the aspect of scales [3]. In classical mechanics we are working with relatively low speed and big sizes, which makes our student experiments easier to handle. The IBL approach of physics teaching works with a question-observation-hypothesis-experiment-answer system, where students are able to do their own experiments basically every lesson, not to mention the possibility of bringing these experiments home, as project works for example.

But topics in modern physics tend to happen at really high speed or/and in really small sizes. This itself makes experimenting difficult. Not to mention its theoretical challenges being far from our everyday-approach theories. (Wave-particle duality, theory of relativity, mass-energy equivalence, etc.) Students don’t observe electrons, only traces of electrons, or signs of traces of electrons, like a number on a counter. Time and number scales are also an issue, for the time of an event is often too long, too short, or it consists of too many participants.

These are the reasons why showing modern physics experiments is extremely difficult in a classroom. And even if there are really creative experimental tools, the cost of these makes it practically impossible to allow anything but a rare experimental presentation from the teacher.

Another key problem is the lack of time. Though it is part of the Hungarian physics curriculum, it is not uncommon that a student finishes high school without hearing anything about modern physics.

In the next section, I will give a brief overview on how computer simulations can help in solving the abovementioned problems.

INTRODUCING COMPUTER SIMULATIONS

For clarity we first make a clear distinction between simulations and animations. In our understanding animations can only be passively watched. In contrast, simulations are much more interactive: the students can set values of different parameters, sometimes even add new devices, or remove others, observe the results, perform measurements. They are much closer to the real world than simple animations. Whereas animations consist of a series of pre-recorded images playing in sequence, behind the simulations there is always a working mathematical model which constantly calculates the outcome.

As for the theoretical challenges, computer simulations always give us simplified images which could be visually helping in the understanding process. There are recent studies of how we can simplify even particle physics and make it understandable to even the youngest student groups [4]. It is vital to keep an eye on all these simplifications. The picture of a ball-shaped electron in a computer simulation can easily distract the students’ ideas from their
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wave function. But there is no doubt that the understanding process is enhanced when we see something leaving the cathode, not only a trace or a counter.

With the previously mentioned scales in time and numbers, we have a lot of freedom. One of the key possibilities of using a computer simulation is that we can set the time scale dynamically, allowing functions like switching between the time lapses (e.g. speed up or slow down a reaction), pause or even turn back the time. Also, we can work with a lot of particles simultaneously.

It is obvious how these simulations can make up for the lack of experimental tools in the physics departments. Surely, a simulation will never be able to fully replace the educational role of a real-life experiment. But seeing an electron beam’s trace on a fluorescent plate is visually similar to see it on a computer screen, while in the latter case students can also investigate the base principles of the phenomenon and perform their own measurements. This final potential brings us to the possibility of expanding our classrooms’ borders, creating virtual laboratories and helping students to do experiments at home, for a project work or further analysis of a problem. Through internet-assisted teaching they can help with the issue of the time frames, not only extending our teaching time, but adjusting it to the students’ needs.

“What makes a good simulation?” If we strictly keep an eye on the goals to help out high school physics education, I would take the following attributes:

1) Accessibility. A simulation shall be available to run on all the student’s current devices, including smartphones, tablets and notebooks, and on any operation systems without using separate applets. In 2015 the majority of the popular browsers dropped support for NPAPI, which impacted plugins for Java (only the applets) and Silverlight. This would require the majority of the currently available physics simulations to be rewritten to a more broad usage. With the quick spreading of smartphones and tablets, we introduce our students to teaching resources available on these platforms. Simulations written in HTML5 don’t require applets, therefore they are considered safe.

2) Diversity. Simulations applied in high school education shall offer various possible activities for the students or the teacher. This makes them easier to implement in the lessons, personalize and also allows to differentiate and extend the time of student experiment. A simulation which takes more time to prepare on a lesson than actually working with it, usually isn’t worth the time, and it always takes a few minutes just to introduce how the controls work.

3) Simplicity and challenge. Students are different, therefore simulations shall have different layers of difficulties fitting the diverse abilities and motivation, in help of teachers to differentiate. Not all students will understand a method of a measurement, and not all of them will be satisfied with only a dynamic animation. The layers should be easily separated not to confuse students.

Not many of the currently available simulations fit these conditions. I looked up working simulations on a specific phenomenon – the photoelectric effect – and I found only one HTML5-simulation out of five most popular ones [5]. The others required downloading an applet or adding the webpage to the browser’s exceptions. This requires a careful preparation for the simulation-supported lesson, and means a lot of problems with the students’ own devices.

The lack of diversity and possible student interaction was also a returning problem. It doesn’t mean that the simulations are wrong, it just means sometimes the only possible way of using them is a brief show or tryout. Only one of them offered an idea on possible
classroom differentiation, whilst the others were too simple or too difficult to understand for some students. A pleasant surprise was that three out of five offered the possibility of measurement. Trying out these in my classes I found that only one (the PhET simulation) can be used effectively, but it lacks a helping grid for recording the data, so needed real rulers for the students to make their calculations.

Out of the five, the PhET simulation was the most complex, which wasn’t a surprise, knowing how much research and effort was implemented in their works, but there were some points missing, like accessibility and some extra possibilities in students’ measuring exercises. My motivation in creating a new simulation of this phenomenon was to add these functions and to create a simulation that fulfills all requirements above that did not exist so far.

APPLICATION OF A SIMULATION ON PHOTOELECTRIC EFFECT [6]

I used the JetBrains WebStorm [7] program to develop the simulation. It works with HTML5, which means you can run this on any device including smartphones. The simulation adapts for the device we are running on, rearranging the simulation plane and the icons.

![Simulation Diagram](image)

**Fig.1. My simulation on the photoelectric effect**

The main interactions of the simulation are the following. Students can set (see Fig.1.) the desired cathode material they are experimenting with, also the wavelength of the light, the intensity, and the percentage of the photons producing an actual photoelectric effect (as the efficiency). They can also give an accelerating or decelerating voltage on the photocells, thus making the electrons stop and turn back. The simulation solves the mathematical model of the photoelectric effect on the one hand, and the motion of charged particles (electrons) in electric field on the other. The result is visualized as (non-ball-shaped) electrons moving toward the anode, and the following output parameters are calculated: the photon energy of the selected light, the kinetic energy of the electrons when they leave the cathode, and the anode current.

The strength of the simulation is the possibility to make simulated measurements with the side icons. Students can save any or every data to a chart. Every time they change any of the settings, the data will be created in a new column. After the end of the measurement, they can export it to an Excel file, and they can freely work with it. There are many possible measuring
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tasks. For instance, wavelength versus kinetic energy, or wavelength versus stopping voltage which we can use for measuring Planck’s constant.

As mentioned, we need to keep an eye on this simulation’s simplifications. The simulation relies on fundamental physical laws (such as Coulomb’s law and the photoelectric effect itself) but it does not include either the electron-electron interactions, for example, or the small fluctuations in the energy of the electrons. In my experience the simulation in its current form can be a helpful tool in classroom education, as mentioned below, although future improvements might be added for increasing the number of observable phenomena.

IMPACT ON STUDENTS’ PERFORMANCE

For observing the impact of the simulation impact on students’ performance I also give them an exercise on the topic taken from the Hungarian physics graduation exams, where they have to find the wavelength limit, the speed of emitted electrons and the stopping voltage of a given photocell. Then, without any further discussion they are introduced to the simulation with a user’s guide on its key functions. Then, after several minutes of independent work, they are asked to solve a similar exercise. The first results were recorded in two half-class sized groups with a total number of 27 students. I used the authorized correction key provided for the original graduation exam and split the total 12 points into 10 parts, as the correction key did the same. Then added up all the points of the students before and after working with the simulation. They used it for only 25 minutes though (with 10 minutes for each task). Use of a calculator and also a table containing the primal scientific functions and laws – as in the real exam – were allowed. The results can be seen in Fig.2. below:

![Fig.2. First results on solving a calculation task about the photoelectric effect](image)

As one can see, all the parts showed slight or bigger improvement. The students didn’t get any help on how to solve the problem between the two parts besides using the simulation. The three biggest differences were on the 4th, 6th and 8th parts of the task. The 4th one was the last part of the first question, about finding the wavelength limit. The 6th (and 7th) one was the last part of the second question, about finding the speed of the emitted electron. There wasn’t much difference on parts 1-3 and 5. These points were given for finding the correct physics laws and writing down the needed equations. Points 4 and 6-7 were given for using and transforming the equations to find the solution. As the equations were known (or could be looked up in the table of functions) this is hardly a surprise. It is comforting though that the simulation helps to make these equations be understood. The 8th part (containing two points) was understanding how the stopping voltage works and writing down the correct equation. This was the hardest one for the students, but many gave good explanations after using the
simulation, for instance “the energy loss of the electron in the field of the stopping voltage equals its initial kinetic energy” – even though not being able to find the correct relation between the energy and the voltage (U·e).

There are examples on giving more detailed and more correct explanations on the calculated problem after using the simulation.

The research was done on a regular physics class without previous notification of the students. This means that a vast part of the students were naturally unprepared for it, though they were all introduced to the topic and calculation examples before in the previous classes.

CONCLUSIONS

Of course, further investigation is needed for a complex view on the efficiency of using these simulations, but my first feedbacks show that even if the performance on solving the concrete task doesn’t change, the students’ answers are more complex and precise, not only writing down equations but also trying to explain the phenomenon. I believe computer simulations are not the exclusive method, but a great source as teaching materials, helping in many of the challenges we face while teaching modern physics.

ACKNOWLEDGMENTS

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Let’s build particle physics!

LET’S BUILD PARTICLE PHYSICS!

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ABSTRACT
Particle physics is one of the fastest developing areas of science in the world. High schools do not have time to deal with this topic, so the students can get to study it after the regular lessons only. The students consider this topic too difficult. There are many unknown terms, they are hard to imagine, because particles are very-very small, they are invisible and their size is below $10^{-18}$ meters. I have developed a low-cost educational material on particle physics for teachers and students. It is easy to make and students can learn with them while playing with paper cubes.

INTRODUCTION
Having taught physics for several years at secondary level I realized that one of the areas of the subject that is very difficult for students to comprehend is particle physics. The main reason for this is that the sizes of the particles are below $10^{-18}$ meters so they are very hard to imagine as they are invisible. Although particle physics is not yet part of the curriculum, I feel it is vital to deal with this topic as this is one of the fastest developing fields of science in the 21st century.

Students like doing experiments, but unfortunately, there are no good tools for explaining the particles. I have developed a tool and a method for this using paper cubes. My goal is to introduce the basics of particle physics with the help of an easily made and cheap instrument, to help to understand the structure of the small particles and their behaviour in different reactions. At the same time I want to help other teachers to deal with this topic.

THE TOOL
The basic set (Fig.1.) consists of
- 15 cubes of size 5x5 cm,
- 4 small cubes of size 2x2 cm,
- 2 large cubes of size 12x12 cm,
- 1 tetrahedron of 10 cm edge size and
- a lot of Styrofoam filling material.

The cube was chosen as it has six surfaces, and we know six kinds of quarks with antiquarks and six leptons with antileptons.

At present this programme is recommended to be implemented in extracurricular study circles as it is not part of the regular curriculum and unfortunately there is not enough time for this during regular classes. Preparing the cubes will take about two hours and understanding and effectively using it about five to six. As for the age group of the students: I have used the tool from the age of 13-14 upwards.

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PEDAGOGICAL ASPECTS
Students like playing and in my opinion we must teach them while playing, because as I see it, the motivation of the students to study natural sciences is very low. Numerous studies have shown that knowledge is best retained when students not only verbally or visually receive information but also have a chance to actively participate in the learning process. Besides it also meets the requirements of visual and kinaesthetic learners. So in this project the most important part is the „hands on, mind on” method. The teacher is not an authority figure but rather the facilitator in this process, so students feel they play an equally important role, thus become more motivated to learn. I experienced with my students that they were very open to this new method. During the work they also learn the basics of particle physics.

GETTING TO KNOW THE QUARKS
First students need to make quark and antiquark cubes. For that we need red, blue and green cardboard paper. The sides of the cubes will have the signs and charges of the quarks. While making the cubes the students will memorize the signs of the quarks and their unnatural charges. In the beginning the emphasis is on getting to know the quarks, but even at this stage we emphasize the three colours for the quarks and the complementary colours for the antiquarks (Fig.2).

For example if one of them is red, the other cubes will have blue and green colours. This expresses quantum colour dynamics. In nature there is just white colour. The colour white consists of red, blue, green, or colour-anticolour pairs. Those particles which contain quarks are called hadrons. Inside the baryons there are three quarks, their colours are red, blue and green. Inside the mesons there is one quark and one antiquark, colour-anticolour pair.
Let’s build particle physics!

The students make different hadronic particles, baryons and mesons (Fig.3.), and they write the signs and charges of quarks on the surfaces. So they can check the sum of the charges. In these examples they will learn expressions which are quite far from everyday life, and they can observe the systematics of particle physics.

THE STRUCTURE OF A PROTON

Unfortunately, in chemistry, while studying the atomic structure the students meet just the names of the electron, proton and neutron and most of the textbooks call all of them elementary particles. In order to fight this misconception I apply a very demonstrative method. In a large cube we place 3 quark cubes, a pair of quark+anti-quark cubes and many little coloured Styrofoam “worms” representing the gluons (Fig.4). This shows that the proton consists of three quarks, gluons, and sea quarks.

The electric charges of the nucleons, the protons and neutrons are generally known, but the cubes help students to understand how they are composed of the fractional charges of the quarks.
In this way it is easy to remember that the proton is a hadron, a baryon, because it contains three quarks, two up-quarks and one down-quark. The electric charge of the proton is plus one. The charges of quarks are 2/3 and minus 1/3 (Fig.5.).

**ELEMENTARY QUANTUM NUMBERS OF THE QUARKS**

The quarks are presented in the chart of Fig.6. There are the names, signs, charges and other parameters. Using that table the students can prepare their own quark cubes.

<table>
<thead>
<tr>
<th>English name</th>
<th>Sign</th>
<th>Rest mass (GeV/c²)</th>
<th>Electric charge (e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up</td>
<td>(u)</td>
<td>0.0016-0.003</td>
<td>2/3</td>
</tr>
<tr>
<td>Down</td>
<td>(d)</td>
<td>0.0045-0.0051</td>
<td>-1/3</td>
</tr>
<tr>
<td>Charm</td>
<td>(c)</td>
<td>1.25-1.3</td>
<td>2/3</td>
</tr>
<tr>
<td>Strange</td>
<td>(s)</td>
<td>0.09-0.1</td>
<td>-1/3</td>
</tr>
<tr>
<td>Top</td>
<td>(t)</td>
<td>165-180</td>
<td>2/3</td>
</tr>
<tr>
<td>Bottom</td>
<td>(b)</td>
<td>4.15-4.21</td>
<td>-1/3</td>
</tr>
</tbody>
</table>

Fig.6. The chart of quarks

**THE GLUONS**

The gluons, the bosons mediating the strong interaction, carry two colours actually, but they are painted white here. While painting the gluons the students learn the basics of quantum chromodynamics. As they are painted white they should carry a colour and an anti-colour, although not necessarily of the same kind. The fact that of the 9 possible colour+anti-colour combinations allowed only 8 gluons exist belongs the group theory, well over the high school level.

**FURTHER USES OF THE TOOL**

Having learnt the basics, it is interesting to know what else the cube set can be used for. During my research work I regularly participate with a group of high school students in the development of gas-filled detectors for the detection of cosmic muons at the laboratory of the High Energy Physics Department of the Wigner Research Centre for Physics. During this work we study the various production reactions of those particles. There are detailed explanations in the literature, but in my experience the students cannot understand them. For a demonstration I developed the following method.

**HADRONIZATION**

Using quark cubes the process of hadronization can be well demonstrated. In Fig.7, you can see how the pions are generated. A proton collides with a nucleus, say, of an oxygen atom (as depicted by the quarks, gluons and sea quarks in Fig.7). During the collision one of the quarks is separated from the others and produces a gluon string. One of the gluons splits into a quark+anti-quark pair and the anti-quark creates a meson with the distant quarks. The pion, the lightest meson, is produced in the simplest picture this way.
Let’s build particle physics!

THE PROCESS OF BETA DECAY ON QUARK LEVEL
There is another field of particle physics the processes of which can be demonstrated using the cubes: the beta decay. Here the rotation of the cubes can be used when different properties are depicted on the different sides. Teachers teach beta decay in high school and the students use the reaction formulas, but they do not understand the essence of the process. Actually, in the beta decay the type of one quark is changed, the d-quark of the neutron becomes a u-quark. The d-quark decays into a u-quark plus a \( W^- \)-boson and that in turn decays into an electron and an electron antineutrino [1-4] (Fig.8.)

DECAY OF THE NEUTRON
Using the cubes the students understand the beta decays. In this exercise every cube represents one particle with its conserving quantities on the sides; by turning the cubes the students themselves find out the kinds of beta decay. They have to apply the conservation laws. They check the conservation of charge, baryon number, lepton number etc. If they turn the cubes, they see different conservation laws. The sums standing on the left and right side of the equation are equal. In Fig.9. the neutron decay to proton, electron and electron antineutrino is presented. Under the names of the particles there are their electric charges. By comparing the sums on the two sides the students can think that the equality is fulfilled without the anti-neutrino cube. If now we rotate all cubes the same direction to see their baryon numbers (introduced by the teacher beforehand as +1 for baryons, -1 for anti-baryons and 0 for all others) which are also conserved without the anti-neutrino cube. However, with the next turn of the cubes the lepton numbers (to be also introduced) show up. As all leptons
have a lepton number \( L = +1 \), while for anti-leptons \( L = -1 \), the antineutrinos are necessary to keep the conservation of lepton number. The other conserving quantities, like energy, are more complicated to account for, so they are shown on the cubes just for completeness.

![Image of cubes with lepton numbers and decay modes]

**Fig. 9. The decay of the neutron**

The other two kinds of beta decay can also be demonstrated with the cubes, and the students will learn the essence of nuclear reactions while rotating the cubes. During this "discovery learning" with my students they also contributed to the project. It was their idea to add the Higgs boson with its decay modes to the set as the Nobel Prize was awarded for it in those days.

**CONCLUSIONS**

I experienced that students are very enthusiastic when they have to work on tools that will eventually help them discover the wonders and secrets of the micro world. While working, they get familiar with previously unknown terms and expressions, and through games understand the basic ideas of a very complex subject, particle physics. It was a great experience for me to do it together with the students as they contributed quite a few ideas to the project. I have made several presentations to fellow physics teachers with the cubes, giving methodical help to deal with modern physics in this unusual way and already in several school were similar cube sets made.

**ACKNOWLEDGMENTS**

I would like to express my special appreciation and thanks to my advisors Dr. Dezső Horváth and Dr. Dezső Varga who have been tremendous mentors for me. I would like to thank you for encouraging my research and for allowing me to grow as a research scientist.

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