Concept Connectivity: An educational and research framework for scientific learning in optics, photonics, and electronic education

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ABSTRACT

We present a novel framework referred to as *Concept Connectivity* that aids in educating and engaging students by presenting the topic of the Special Theory of Relativity (STR) in a coherent and unified manner. It uses different analogue implementations of the STR coming from seemingly distinct fields of study such as (i) Optics, (ii) Photonics, and (iii) Electronics to connect *not only* to the concepts of the STR but to the various concepts from these different fields. In these analogue implementations, the fundamental characteristics of the different STR phenomena can be mimicked in many different ways. *Concept Connectivity* has two major benefits. First, from an educational perspective, undergraduate students can (i) understand advanced physical phenomena (like STR) from different points of view, (ii) bridge together different learnings or concepts from Physics, Optics, Photonics, and Electronics, and (iii) learn hands-on knowledge and engineering skills from Optics and Electronic experimentations when these analogues are incorporated in undergraduate physics lectures and laboratory courses. In this way, Concept Connectivity contributes to the growing pedagogical approaches used in science education with an emphasis on Photonics, Optics and Electronics. Second, from a research perspective, *Concept Connectivity* provides undergraduate students with a rare "taste of research experience" related to the challenge of merging different concepts in STR using principles in Optics, Photonics, and Electronics.

Keywords: Concept Connectivity, analogues, photonics and optics education, Special Theory of Relativity, relativistic phenomena and concepts

1. INTRODUCTION

It is a well-known fact that the study of the Special Theory of Relativity (STR) and its corresponding relativistic effects are theoretically important but also very challenging to understand, especially for undergraduate students.[1-3] The STR is also less emphasized in schools due to limited class time and the growing list of newer and competing fields of study such as Optics, Photonics, Electronics, and others. Furthermore, for researchers, the work on STR is experimentally difficult to implement since they often necessitate outer-space environments and conditions that are costly and extremely troublesome to replicate in traditional laboratories (e.g., very fast velocity, the presence of strong gravity, cosmic radiation, extreme temperatures, and vacuum).[4] Moreover, bulky, sophisticated, and costly instruments are typically required for such endeavors.

Thus, a challenge for scientists and physics education researchers is to conceive and develop novel *analogue implementation* platforms through which STR and its relativistic effects and/or concepts can be studied easily using available and common technological platforms. In recent years, we have been researching three main relativistic effects – namely the (a) Relativistic Aberration of Light (RAL), [4,5] (b) Thomas Rotation Effect (TRE),[6-7] and (c) Einstein's Velocity Addition (EVA).[8] A unique aspect of our research approach is that we employ different implementation schemes to mimic a specific behavior or property of any of the three aforementioned relativistic effects. In particular, we have developed *relativistic analogues* based on low-cost and simple technological platforms in our previous works.[4-8] Note that a relativistic analogue is simply an analogue that is capable of mimicking a relativistic effect.

Our relativistic analogues have the potential to improve research efforts in the field of the STR and supplement the current pedagogical approaches used in STEM education – most notably in physics education. This is due to the ease at which they can be fabricated and how accurately they can mimic a specific behavior or property of a relativistic effect, which aids both students and researchers in studying the STR along with its concepts and relativistic effects. Although it is straightforward to incorporate these analogues in education and research applications, there is an ongoing challenge to

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develop a coherent framework to (a) discuss these relativistic analogues from different perspectives, and (b) demonstrate the rich linkages of the different fields (ex. Optic, Photonics, Electronics) to each other through this unique analogue approach.

Thus, our goal in this paper is to propose and present a coherent educational and research framework that we refer to as *Concept Connectivity* to accomplish the following objectives: (i) to tie together all the different concepts, (b) to couple these concepts to engineering skills needed to conceive and develop real-world platform(s), and (c) to report the different implementation approaches we described previously. We note that Concept Connectivity links the different principles in Optics, Photonics, and Electronics to explain the concepts from the STR, which aids in educating students holistically on the field of Physics, Optics, Photonics, and Electronics which are normally studied separately within a typical undergraduate Physics or Applied Physics program. It also increases students' engagement by presenting the study of Physics through the STR in a coherent and unified manner. Thus, *Concept Connectivity* has two major benefits in (a) Science, Technology, Engineering, and Mathematics (STEM) education, and (b) research. Here, we discuss what it can offer in STEM education with an emphasis on optics, photonics, and electronics education. We also outline its potential benefits in research as a conceptual scientific tool.

2. CONCEPT CONNECTIVITY: NOVEL FRAMEWORK FOR EDUCATION AND RESEARCH

Concept Connectivity is concerned with *finding two or more similarities* between a concept/phenomenon from the STR with different fields of study as shown in Fig. 1(a). It shows that a particular concept in the STR can be mimicked by four different fields: Optics, Photonics, Electronics and Digital Signal Processing (DSP). We also note that these four fields can be related to one another through what we refer to as the analogue approach, which makes use of analogue implementation platforms to connect two concepts or phenomena. Thus, the more linkages that we can conceive for the same concept or effect, the richer the knowledge obtained by the researchers or students. More importantly, as a consequence, the linkages from other fields can also be related analogously to each other to obtain richer and more generic interconnections.

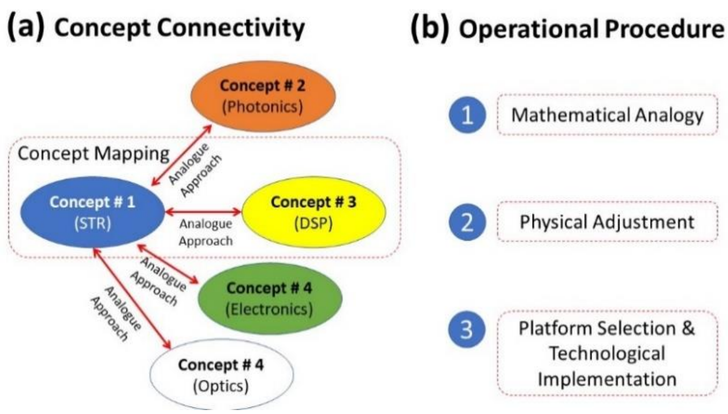

Figure 1. The principle of (a) Concept Connectivity (CC) requires that we link one STR concept with at least two or more concepts from different fields such as Optics, Photonics, Electronics, Digital Signal Processing (DSP), etc., and (b) the operational procedure of CC consisting of 3 actions.

Operationally speaking, *Concept Connectivity* consists of three main activities as outlined in Fig. 1(b):

(1) **Mathematical Analogy:** to recognize the *fundamental mathematical analogies* that tie the STR with the different fields of study such as Optics, Photonics and Electronics,
(2) **Physical Adjustment:** to make "*physical or engineering adjustments*" to suit the analogy for physical measurement which requires some creative and engineering skills from researchers and students, and
(3) **Platform Selection & Technological Implementation:** to create innovative *implementation strategies or technological platforms* to realize these analogies.

2.1 Mathematical analogy

The first activity of *Concept Connectivity* begins with the search and recognition of mathematical analogies. To elaborate, there often exists "mathematical similarities" between distinct physical concepts. These mathematical similarities are concretized in the form of analogies, which are conceptual tools that are commonly used in STEM education to help students learn unfamiliar knowledge, concepts, or phenomena by relating them to existing ones that the individuals have had prior experience with.[9] Generally speaking, analogies are well-known and effective tools for teaching science-related topics as they improve a student's comprehension and retention of abstract concepts. For this reason, analogies—specifically mathematical analogies—have played an important role in our previous works on relativistic analogues.[4-8]

As an example, we have previously reported the similarity between the equations of (i) the direction angle of *Relativistic Aberration of Light (RAL)* from the STR and (ii) *the phase response of a microring resonator (MRR)* implemented with an All-Pass Filter (APF) configuration as shown in Fig. 2(c).[5] Note that we refer to the latter as the RAL-APF for simplicity. Summarily speaking, we note that both equations shown in Fig. 2 use the expression $2 \cdot \tan^{-1}(X)$, and it is a simple matter of equating both expressions such that that $\theta = \tau_1$.

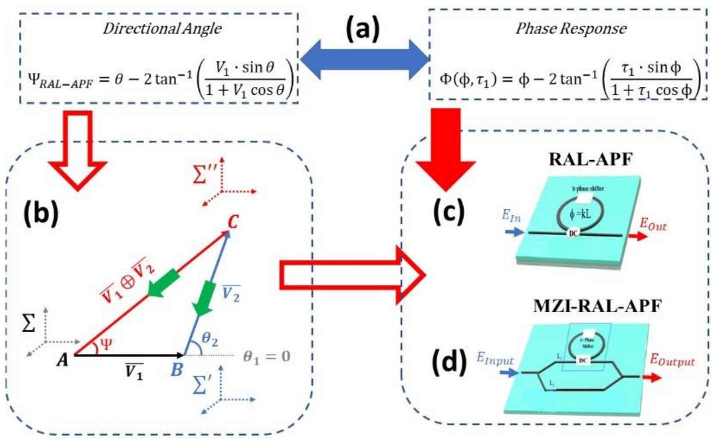

Figure 2. (a) Example of Concept Connectivity where the equations of RAL of STR and MRR-based APF are mathematically the same, (b) the physical representation of RAL, (c) the physical implementation of MRR-based APF circuit (c), and (d) the full circuit of RAL in STR is implemented with Mach-Zehnder Interferometer (MZI)-assisted RAL-APF.

2.2 Physical or Engineering Adjustment

In our previous example concerning the RAL-APF, we note that since the relationship between the quantities $\mathbf{\Phi}$ and $\mathbf{\Psi}_{\text{RAL-APF}}$ are exact, they can be simulated immediately. Although the direction angle $\mathbf{\Psi}_{\text{RAL-APF}}$ of the RAL can be measured physically, it must be noted that the output phase response $\mathbf{\Phi}$ of the RAL-APF cannot be measured directly. Thus, there is a need for the second procedure, which we call the "physical or engineering adjustment". This challenges researcher/students to use their engineering knowledge and skills to think of an "engineering scheme" that must be implemented to obtain the measured quantity indirectly. It must be noted that all our relativistic analogues are mostly based on the same key technology– the all-pass filter (APF) element which can be implemented in many different platforms. In bulk optical platforms, this can be generated by a Thin Film-based Gires-Tournois Interferometer (GTI). In a photonic platform, this can be implemented with microring resonator (MRR)-based photonic integrated circuits (PIC). In an electronic platform, this can be obtained using an operational amplifier (OP-Amp) based electronic integrated circuits (EIC). Despite their exact mathematical similarities, the physical or operational actions are not exact since the output phase response of the MRR and GTI cannot be measured directly. Hence, we need to perform the "Physical and engineering adjustment scheme".

2.3 Platform Selection and Technological Implementation Platforms

The next step is the selection of an appropriate implementation platform and its corresponding physical or engineering adjustment scheme to physically represent the said analogy. We refer to this implementation platform as an *analogue*, which refers to any technological device or system that can mimic the behaviors and properties of a concept or phenomenon. As mentioned previously, we have developed different relativistic analogues to study the following relativistic effects in our earlier works: the (i) RAL, (ii) TRA (or Thomas Angle), and (iii) EVA.[4-8]

The challenge to researchers/students is to use their engineering knowledge and skills to conceive of an engineering scheme for "Phase-to-Intensity conversion for the optics and photonics platform cases" that must be implemented to obtain the measured quantity indirectly. In the case of the photonic platform, the "engineering adjustment" can be accomplished by incorporating the RAL-APF circuit into one of the arms of a Mach-Zehnder Interferometer (MZI) as shown Fig. 2(d) and Fig. 3(a). We refer to this implementation as the MZI-assisted RAL-APF or MZI-RAL-APF. Thus, it is possible to experimentally verify the behavior of the RAL through the implementation of MZI-RAL-APF. In the case of bulk optics, this can be accomplished with the use of a Michelson Interferometer (MI) as shown in Fig. 3(a). The diagrams of the resultant relativistic analogues are shown in Fig. 3(a-c) for different platforms.

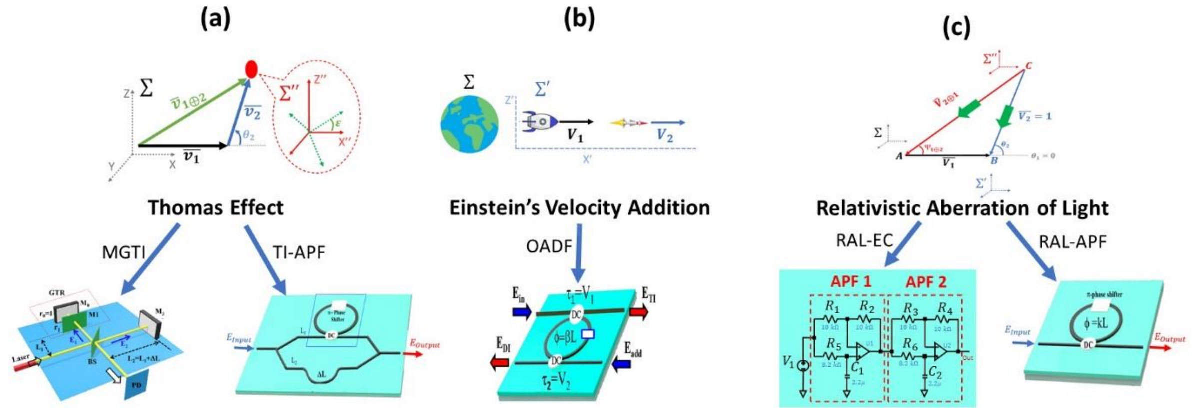

Figure 3. Relationship between the different relativistic analogues and their respective technology platforms.

2.4 Growing list of relativistic analogues

One small caveat in the previous activity on developing an analogy between two distinct concepts is that students or researchers must initially be familiar with both concepts, as the effectiveness of the resulting analogy is dependent on the depth of their knowledge of both concepts and their underlying principles. It is also worth noting that an analogy between two distinct concepts cannot always be readily translated into a corresponding analogue, especially if both concepts are theoretical in nature. Moreover, the more complex the analogy, then the greater the specifications required for the analogue or implementation platform will be. Thus, the goal of the researcher is to find an existing analogue (e.g., device, system, etc.) that can serve as the physical manifestation of an established analogy. In our previous works, we have reported various relativistic analogues for a particular relativistic effect, which are all summarized in Table 1.

Table 1. Summary of relativistic analogues using Photonics, Optics and Electronics platforms.

Relativistic Concepts	**Technological Platform and Description**	**Analogue Type**	**Established Analogy/Comments**
Thomas Rotation Effect (TRA)	All-pass filter (APF) implemented with a microring resonator (MRR) with an *unbalanced* Mach-Zehnder Interferometer (MZI) on a Photonic Integrated Circuits [4]	Photonic Analogue I (TRA-APF)	Phase response of the TRA-APF is analogous to the parameter known as the Thomas angle from the TRA. This phase response is converted to intensity for measurement using an *unbalanced* MZI.[4]
Relativistic Aberration of Light (RAL)	Modified TRA-APF circuit [5]	Photonic Analogue 2 (RAL-APF)	Phase response of the RAL-APF is analogous to the parameter known as the directional angle from the RAL of STR. This phase information is converted to intensity for measurement using a *balanced* Mach-Zehnder Interferometer (MZI).[5]
Einstein Velocity Addition (EVA)	Optical add-drop filter (OADF) implemented with an MRR on a PIC [6]	Photonic Analogue 3 (OADF- EVA)	The complex electric field of the OADF's output signal is analogous to the Lorentz boost in the EVA operation.[6]
Thomas Rotation Effect (TRA)	All-pass filter (APF) implemented with a Thin Film (TF)-based mirror with Michelson-Gires-Tournois Interferometer (MGTI) [7]	Optical Analogue I (MGTI)	Phase response of the thin film-based GT resonator is the parameter known as the Thomas angle of the TRA. This phase response is converted into intensity for measurement using an *unbalanced* Michelson Interferometer (MI).[7]
Relativistic Aberration of Light (RAL)	Two cascaded Operational amplifiers (OP-AMP)-based, first-order APF electronic circuits [8]	Electronic Analogue I (RAL-EC)	The phase shift of the RAL-EC's output signal is analogous to the directional angle of the RAL.[8]

3. PEDAGOGICAL BENEFITS OF CONCEPT CONNECTIVITY IN STEM EDUCATION

Concept Connectivity has the following benefits for STEM education: firstly, as an educational framework it promotes a structured and integrated approach to “analogous learning”, where students are encouraged to find a connection (i.e., similarities) between seemingly unrelated concepts in the form of an analogy. This fosters creative thinking among the students and allows them to see how different disciplines or fields of study such as physics and electronics are connected. Secondly, Concept Connectivity helps develop basic and practical knowledge among students through the use of implementation platforms or analogues that can manifest the established analogy between two concepts. Lastly, our proposed framework will help expose students to the myriad of applications related to analogues.

3.1 Concept Connectivity as a teaching tool for multi-disciplinary topics

As can be seen in Table 1, these analogues are implemented with any one of the three technological platforms – namely: (i) photonic integrated circuits (PICs) using microring resonator (MRR) waveguide as the primary element, (ii) free-space optic using the thin-film (TF)-based mirror as the key element, and (iii) electronics using the operational amplifier (OP-AMP)-based phase shifter as the core element. In principle, these three key elements can mimic the function of a mathematical entity called an all-pass filter (APF) as mentioned earlier. Again, it brings together the different fields of Optics, Photonics, and Electronics. More importantly, we can use their interrelationship to link these field to one another.

In STEM education, this exercise is especially significant on three fronts. First, students can understand and establish the unlikely “concept connection” between two distinct phenomena, namely the (i) RAL—a relativistic phenomenon that is highly abstract in nature, and (ii) the RAL-APF circuit—a physical object. Second, although students mentally know that there is a link, with this proposed framework, they are also exposed to a direct example of emerging engineering fields like PICs. Clearly, students can easily recognize the clear link between the (i) science of RAL in the STR with (ii) the engineering field of PICs. Third, students can be challenged to apply their engineering skills to resolve how to demonstrate this concept (for example: how to come up with or design a phase-to-intensity conversion scheme with the use of MZI-assisted RAL-APF). In short, we formed a new bridge between the fields of photonics in engineering and the STR in physics, which opens the door to many new and exciting applications.

3.2 Pedagogical benefits of Concept Connectivity in optics and photonics education

Concept Connectivity has direct benefits for optics and photonics education. In particular, since most of our relativistic analogues are based on optical and photonic technologies, both physics and engineering students are exposed to devices such as microring resonators, all-pass filter (APF) circuits, and photonic integrated circuits. To understand their connection to their intended relativistic effect, students are tasked to first familiarize themselves with the very basics of optics and photonics (e.g., the nature and properties of light). Once this is accomplished, they are required to undergo practical training in the operation of the aforementioned devices. Thus, through Concept Connectivity, students not only learn about the STR in physics and its relativistic effects, but they also acquire knowledge and experience in optics and photonics as well, which broadens their skills and critical thinking.

3.3 Electronic Platform as Low-Cost Issue implementation platform and its impact on pedagogical teaching

In the previous sections, it must be noted that most analogies we established are implemented through optical, and photonic technologies. However, the most cost-effective platform is based on electronic circuits. In our previous work,[8] we reported an electronic analogue for the RAL (see Electronic Analogue I in Table 1) that we refer to as the RAL-EC, whose schematic design can easily be replicated using simple components as shown in Fig. 4a.

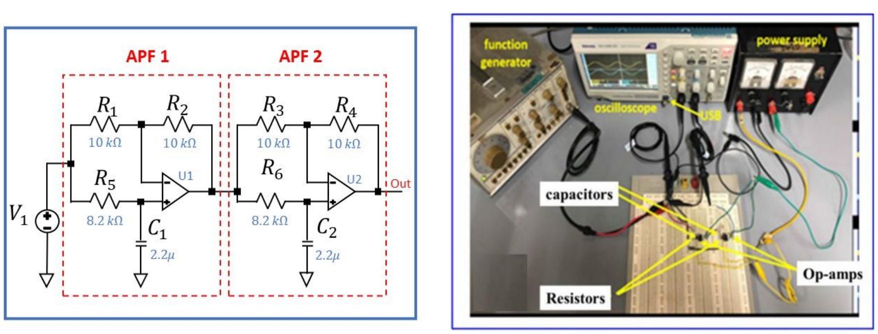

Figure 4. Schematic diagram of the RAL-EC (Left) and its experimental set-up equivalent (Right).

We emphasized in our previous work that the RAL-EC could be used as a teaching tool through which students can learn about the RAL. Specifically, the RAL-EC can be used to ground the abstract and theoretical nature of the RAL into more tangible and digestible knowledge that students can easily assimilate. This could be accomplished by first showing how the RAL-EC operates through a laboratory experiment. Once the students are familiar with this device, the instructor can then establish the mathematical analogy between it and the RAL for the students to see how they are connected. In this manner, the student's learning experience is reinforced as they are engaged through a more practical and "hands-on" approach, as opposed to the typical teaching approach of directly explaining what the RAL is.

4. CONCEPT CONNECTIVITY AND ITS IMPACT ON RESEARCH

Briefly, another benefit of Concept Connectivity is that it can be used as a conceptual tool for research. For one, as a straightforward consequence, it has the potential to pinpoint other relativistic phenomena that have not been studied yet such as (i) Relativistic Doppler Shift, (ii) Length Contraction, and (iii) Time Dilation. It challenges researchers to devise innovative analogues for these phenomena. In particular, the use of our electronic analogue for example,[8] will allow researchers to potentially study the specific behaviors and properties of the other relativistic effects aside from the RAL without complex instruments. This lowers the required costs for researchers, and it allows for ease of experimentation since our relativistic analogues are based on simple tabletop configurations that can be replicated in most laboratories at educational and research institutions.

5. CONCLUSION

In this paper, we have presented an educational and research framework that we refer to as Concept Connectivity. In addition to introducing the five main components of this framework, we have also enumerated its potential for research and educational applications in the context of our previous works on relativistic analogues. We believe that researchers and educators can make use of Concept Connectivity to improve their research methodologies and promote quality education, especially in the fields of optics and photonics.

6. ACKNOWLEDGMENTS

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