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A simplified approach with FFT and smartphone in high school physics

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Abstract. This paper presents a simplified approach to introducing the Fast Fourier Transform (FFT) as a graphical tool in high school physics. By combining the use of smartphones, interactive Jupyter Notebooks, and widely available applications, the module supports the study of wave phenomena in both time and frequency domains. We describe the design and implementation of the intervention, outline the learning goals, detail the module structure, and report on the data collection methods and outcomes. In addition, we discuss practical observations and challenges, and we propose future improvements. Overall, the results show that students develop both conceptual understanding and technical skills

1. Introduction

The analysis of periodic signals through the Fast Fourier Transform (FFT) [1] is an essential tool in various fields such as physics, engineering, computer science, and mathematics. The FFT decomposes complex signals into their frequency components, thus allowing the study of phenomena in both the time and frequency domains. The increasing availability of affordable technologies, such as smartphones and microcontrollers, has made these tools more accessible to high school physics education, fostering the development of numerous applications in physics teaching and learning. In this context, the Fourier Transform (FFT) has been widely applied in various domains, as extensively documented in the physics education literature. In particular, the FFT is used in mechanics for data analysis and interpretation [2, 3] and in acoustics for the study of sound phenomena [4, 5, 6, 7, 8].

Obviously, the range of applications is extensive. For example FFT has been applied to light-based experiments and AC current measurements at the high-school and undergraduate levels [9], underlining its versatility and relevance in diverse instructional contexts. We propose that the most effective and intuitive way to introduce FFT in high school physics is through the study of oscillations and mechanical waves, where its application can substantially enhance students' conceptual understanding. Guided by this approach, we designed a high school physics module incorporating FFT, which was delivered to two 12th-grade classes in Italy.The module was offered in a distance learning format, when the restrictions of the Covid-19 pandemic were still in place. To facilitate this learning process, we used interactive Jupyter notebooks and smartphone applications such as PhyPhox, which allow students to perform spectral analysis in real time. These tools, combined with programming libraries such as Python and Matlab, allow students to interact directly with the FFT and provide valuable insight into periodic phenomena through graphical representations.

The primary goal is for students to explore waves in both the frequency and time domains simultaneously, gaining complementary information that is essential for accurate modelling of physical phenomena. In this context, the FFT plot serves as an additional representational tool to enhance their conceptual understanding [10].

2. Module Overview

The module was implemented in two 12th-grade classes (N=27 students in total) in Italian high schools, following the "Scienze applicate" curriculum. The students were already familiar with sound phenomena, trigonometric functions, and basic programming skills. The starting point for introducing FFT was drawn from everyday life through the mobile application Shazam [12], which identifies songs by analyzing a short audio sample. This app operates based on FFT principles, and we presented it as a "need-to-know" example for the students [11]. The module was organized over three sessions, to gradually introduce FFT concepts and to move from simple examples to more advanced experimental applications. Prior to the lesson, students were given a simplified Jupyter notebook in Python (on Google Colab) as homework to introduce them to the basics of Python operations and data plotting. Python was chosen for its relative simplicity and extensive libraries, which make it an accessible tool for both programming and conceptual exploration, as seen in previous work [13, 14, 15]. During the sessions, the students worked together on the Jupyter Notebooks and on the assigned experiments.

Session 1: In the first session, students were introduced to FFT through another interactive Jupyter Notebook hosted on Google Colab. It contained an "enigmatic" signal consisting of three sinusoids with different frequencies (see Figure 1). Initially, the students attempted to identify these frequencies manually. However, given the challenge of distinguishing multiple components, we introduced an FFT code block - used as a 'black box' - to generate a frequency spectrum (see Figure 4). This approach allowed the students to test their hypotheses and better understand the underlying signal.

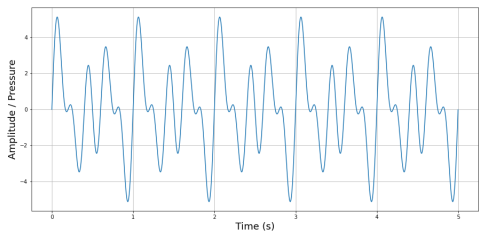


Figure 1. The unknown function: can you find the frequencies?

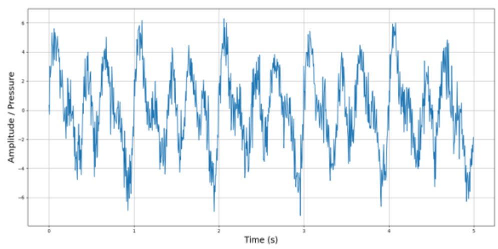
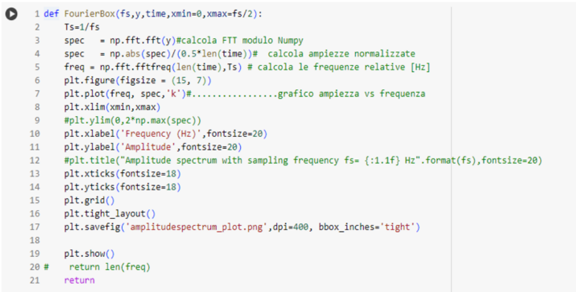


Figure 2. Function with added random noise.

The Jupyter Notebook also included the original signal with added random noise (see Figure 2) to simulate the typical interference encountered in experimental measurements, which complicates time-domain analysis and significantly affects the amplitude spectrum in the frequency domain. The notebook is available in the GitHub repository [18].

The Phyphox application was then introduced and a series of simple experiments were carried out. We started by applying a Fourier transform to the sound emitted by a cuckoo clock, then analysed the sound of a piano note, and finally performed spectrogram analysis using both Phyphox and a Chrome-based application [16].



```
def FourierBox(fs,y,time,xmin=0,xmax=fs/2):
    Ts=1/fs
    spec   = np.fft.fft(y)#calcola FTT modulo Numpy
    spec   = np.abs(spec)/(0.5*len(time))#  calcola ampiezze normalizzate
    freq = np.fft.fftfreq(len(time),Ts) # calcola le frequenze relative [Hz]
    plt.figure(figsize = (15, 7))
    plt.plot(freq, spec,'k')#................grafico ampiezza vs frequenza
    plt.xlim(xmin,xmax)
    #plt.ylim(0,2*np.max(spec))
    plt.xlabel('Frequency (Hz)',fontsize=20)
    plt.ylabel('Amplitude',fontsize=20)
    #plt.title("Amplitude spectrum with sampling frequency fs= {:1.1f} Hz".format(fs),fontsize=20)
    plt.xticks(fontsize=18)
    plt.yticks(fontsize=18)
    plt.grid()
    plt.tight_layout()
    plt.savefig('amplitudespectrum_plot.png',dpi=400, bbox_inches='tight')

    plt.show()
#    return len(freq)
    return
```

Figure 3. FFT code screenshot.

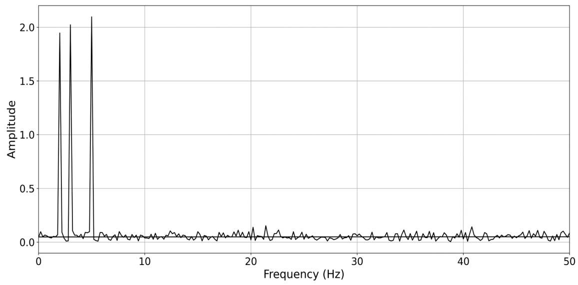


Figure 4. Amplitude spectrum revealing frequencies.

Session 2: The second session focused on Dual-Tone Multi-Frequency (DTMF) signalling [17] (see Figure 5). Students worked in pairs: one student generated DTMF tones using an online tone generator, while the other captured the resulting spectrogram with the PhyPhox application. This exercise provided a clear demonstration of how FFT can be used to identify specific frequency pairs associated with telephone key presses, as shown in Figure 6. The collaborative format encouraged discussion and peer learning, reinforcing both the technical and conceptual aspects of the activity.

1	2	3	A	**697 Hz**
4	5	6	B	**770 Hz**
7	8	9	C	**852 Hz**
*	0	#	D	**941 Hz**
1209 Hz	**1336 Hz**	**1477 Hz**	**1633 Hz**	

Figure 5. Diagram of DTMF key-frequency associations. Source: Wikipedia [17].

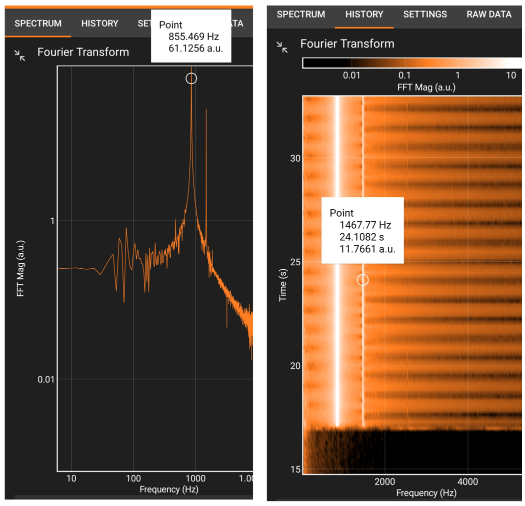


Figure 6. FFT amplitude spectrum for key '9' and corresponding spectrogram analysis.

Session 3: In the third session, an application experiment was conducted to estimate the speed of sound. Students explored the relationship between the length of a tube (using a straw as a model) and the harmonic frequencies generated when blowing through it. Data recorded via the PhyPhox app were used to perform a linear fit, which yielded an estimation of the sound velocity. Figure 7 shows the experimental setup, the collected data, and the resulting fit. This activity not only enhanced the theoretical understanding of standing waves but also provided practical experience in data analysis and error estimation.

A summary of the module activities is given in Table 1.

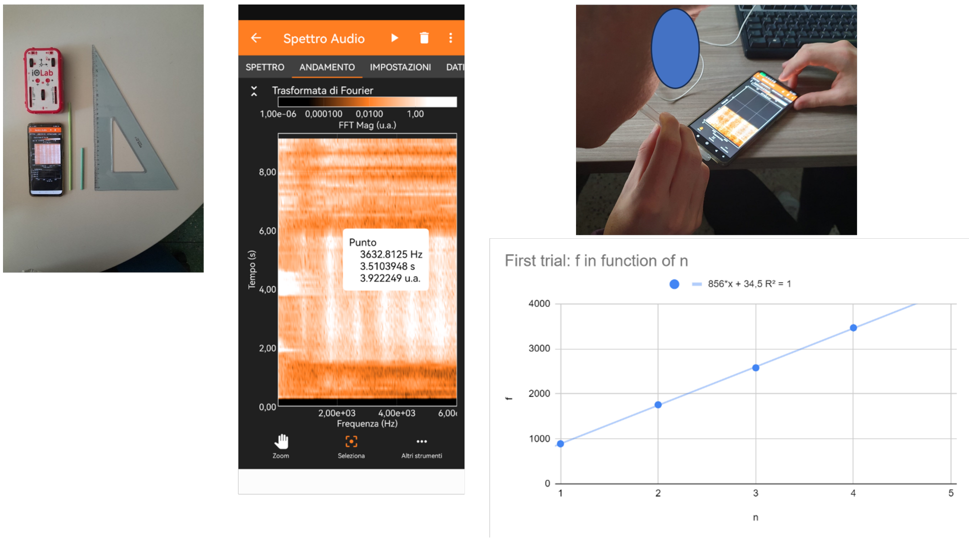


Figure 7. Spectrogram of the harmonics generated by an open-open straw, including the experimental setup and an example of a linear fit of the harmonic frequencies as a function of tube length.

Table 1. Summary of Classroom Activities on FFT

Activity	**Short Description**
First Session	Introduction to Jupyter Notebook in Python: Examples and exercises with basic calculations and a Notebook on discovering the unknown signal with the amplitude spectrum graph. Using the audio spectrum function in Phyphox app to analyze various sounds.
Second Session	Spectrogram introduction. Musical instruments: relation between length and frequency for wind instruments. DTMF activity.
Third Session	Application experiment: Estimating the speed of sound with a straw and a smartphone.

2.1. Learning Goals

In designing this module with active learning strategies for schools, we have followed the AAPT recommendations for laboratory instruction [19] and the NGSS practices [20]. In addition, our development of learning objectives and assessment strategies has been informed by Bloom's Revised Taxonomy [21, 22], focusing on two main areas:

- **Conceptual knowledge**: Students will be able to recall and understand the fundamental physical principles related to Fourier analysis and its applications in experimental contexts. They will also develop the ability to apply this knowledge to analyze and interpret experimental data.
- **Technical skills**: Students will be able to use the Phyphox application and smartphones for data acquisition, as well as Jupyter Notebooks for data analysis and visualization. Additionally, they will develop skills in interpreting FFT amplitude spectra and understanding their significance in the context of experimental physics.

To evaluate students' performance in these two key areas, we used a descriptive rubric detailing four performance levels: *missing*, *not adequate*, *needs improvement*, and *near mastery.*

3. Methods

Throughout the module, pre- and post-intervention questionnaires were administered to capture students' prior experiences and their perceptions following the activities. These instruments were useful for evaluating the effectiveness of the teaching approach and for identifying areas that required further refinement. In addition, a test designed to assess the learning goals was conducted. This approach aligns with strategies previously adopted, for example, in ISLE-based modules [**?**].

Pre-intervention Questionnaire: Before the activities commenced, a survey was administered to assess students' familiarity with video analysis tools and electronic sensor devices. The results indicated that most students had limited exposure to these technologies, although a few reported regular use of such tools.

During the Module: Observations were recorded during the lab sessions as students engaged in hands-on activities. Data were collected both through direct observation and via the lab notebooks maintained by the students. The collaborative nature of the tasks enabled a comprehensive collection of qualitative feedback, which was later used to refine the experimental procedures.

Post-intervention Questionnaire and Final Assessment At the end of the module, a post-survey and a final individual test were administered. The test comprised both open-ended and multiple-choice questions, with assessment metrics focused on two areas: "conceptual knowledge" and "technical skills". In particular, the third question—an open-ended prompt about a piccolo and a bass—was focused exclusively on conceptual understanding. The content of both the questionnaire and the test questions can be accessed at the GitHub repository [18]. The outcomes are analyzed in the following section.

4. Results and discussion

The effectiveness of the module was evaluated by analyzing student feedback from the post-intervention questionnaire and their performance on the final assessment. The results point to positive outcomes in both students' attitudes and their achievement of the defined learning goals.

4.1. Student Attitudes and Feedback

The post-intervention questionnaire reveals a generally positive reception of the new technologies and teaching methods. Figure 8 visualizes student responses, showing that a majority found the activities "fun and interesting" and agreed that working with smartphones was easy. The hands-on, collaborative approach, making use of familiar technology, was clearly effective for student engagement.

This experience translated into increased confidence and interest. Significantly, a majority of students (approx. 60%) reported feeling more capable of using sensor devices, while a significant portion remained neutral. This interest is also reflected in future intentions: about 70% of students expressed a desire to use smartphones in future experiments. Responses regarding the future use of Python were more mixed: while about 35% of students responded positively, the largest group remained neutral (approx. 40%) reflecting the higher complexity of this new tool.

4.2. Assessment of Learning Goals

The final assessment results, summarized in Figure 9, point to student achievement of the learning goals for both technical skills and conceptual knowledge. The assessment was graded

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using a rubric with scores from 0 (missing) to 3 (near mastery). In the 'Technical Skills' domain, Figure 9 shows that a vast majority of students (approx. 80%) reached 'near mastery' (Score 3). This outcome suggests that students became proficient in using both the Phyphox application for data acquisition and Jupyter Notebooks for data analysis. Positive results were also observed for 'Conceptual Knowledge'. Here, the majority of students (approx. 77%) achieved 'near mastery' (Score 3). This finding suggests that the module's hands-on approach—connecting the abstract concept of FFT to concrete physical phenomena like sound—was effective in supporting a solid conceptual understanding. While a small minority of students scored at lower proficiency levels, the overall trend points to the effectiveness of the intervention.

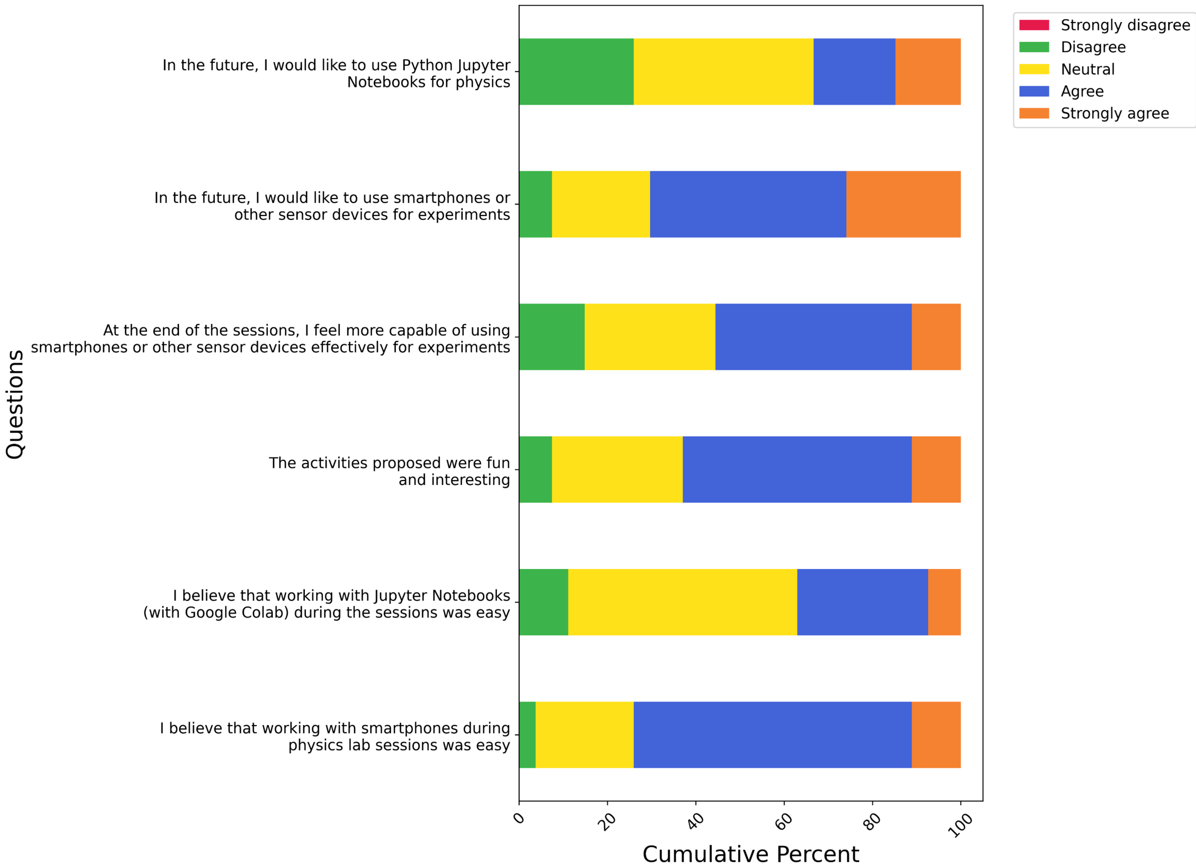

Figure 8. Stacked bar graphs showing student responses of the two classrooms (N=27) to six key questions of the post-questionnaires in the FFT module.

4.3. Students' Qualitative Feedback

To enrich our analysis with qualitative perspectives, we analyzed student responses to two open-ended questions regarding the module's strengths and weaknesses. The analysis reveals a clear picture of the student experience.

Among the most valued aspects, students frequently highlighted the connection to real-world phenomena, with one student appreciating the ability "to apply it to reality". The use of personal devices was seen as a significant strength, particularly "using the smartphone with a didactic purpose". A central theme was the role of data visualization in fostering understanding; many students noted that "the graphs were very useful in better understanding the topic".

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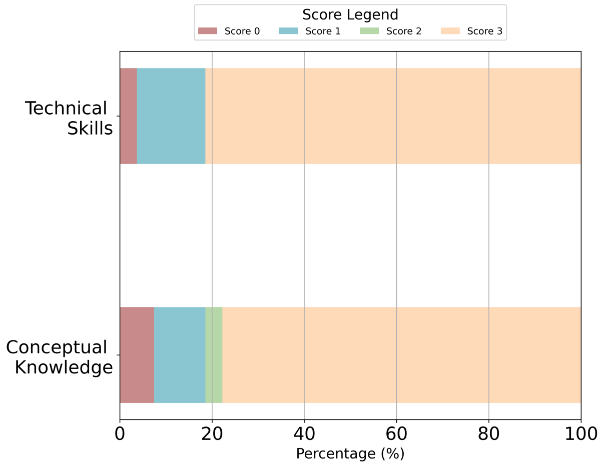

Figure 9. Distribution of student proficiency levels in 'Conceptual Knowledge' and 'Technical Skills' (N=27).

Regarding weaknesses and areas for improvement, students primarily pointed to logistical and contextual challenges. The most frequent comments concerned the limitations of the remote/online format and the insufficient time available. Some students also reported practical issues during the experiments, such as sound interference in the classroom, and requested a clearer framing of the learning objectives.

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5. Conclusions

Preliminary results suggest that the integration of FFT as a graphical tool in high school physics education can be both feasible and effective, facilitating the connection between theoretical principles and practical experiments. This approach seems to allow students to visualise and analyse complex signals in real time. The use of well-known applications, such as Shazam, together with musical examples, has proven to be an immediate entry point, increasing motivation and supporting the achievement of educational objectives.

Assessment data showed good levels of both conceptual knowledge and technical skills, with the collaborative, hands-on nature of the activities reinforcing these improvements. Although there were challenges - particularly with the limitations of distance learning - the results suggest that this method could be integrated into curricula.

Although this study focused primarily on two high school classes in Italy, the approaches described here can be adapted to different educational contexts and student populations. Further research in different settings and with different resource constraints—such as limited technological equipment, reduced laboratory time, or inadequate support for professional development— will help to determine the wider applicability and refine the methodology. In addition, ongoing improvements to the experimental setups and data collection procedures will address current limitations - particularly those observed in distance learning - and ensure a more robust and scalable implementation of this FFT-based approach. Finally, it is also possible to extend the use of the Fourier transform to other units of the physics curriculum, as demonstrated for example with AC signals and light signals.

Overall, this simplified introduction to FFT not only deepens students' understanding of wave phenomena but also provides them with practical competencies essential in modern scientific and technological contexts. The positive outcomes documented here contribute to the wider field of physics education, facilitating further instructional innovations.

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