

PROJECT-BASED LEARNING APPROACH FOR LOW COST ECG CONSTRUCTION AND CARDIOVASCULAR HEALTH OUTREACH

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ABSTRACT

Project-Based Learning (PBL) is a student-centered active learning methodology in which students acquire knowledge by addressing authentic, meaningful, real-world problems through projects. This approach fosters critical thinking, collaboration, and autonomy, as opposed to passive information reception. By investigating, researching, and creating solutions or final products, students engage in practical, motivating learning that effectively bridges the gap between theory and practice. Cardiovascular diseases represent nearly one-third of deaths in Brazil, highlighting the importance of the electrocardiogram (ECG) in assessing health. Our PBL approach encouraged students to build low-cost ECGs using an easy-to-read manual at classroom workstations. Results confirmed that students were able to engage with the social and biomedical engineering aspects of our project by gathering information about cardiology and generating the expected cardiac signals. Furthermore, the manual fulfilled its purpose by facilitating the comprehension and replication of the project by students and teachers. While initial technical challenges occurred due to low signal amplitude, they were overcome with the help of specialized amplifiers. In conclusion, the project was successfully completed through this PBL approach, significantly contributing to cardiovascular health awareness and scientific education among the students.

KEYWORDS

Medical Physics, artificial intelligence, biomedical engineering, project-based learning, CDIO Standards: 7, 8.

INTRODUCTION

A central objective of the CDIO framework is to bridge the gap between academic programs and professional practice by aligning graduate competencies with market demands (CDIO, 2025). Demonstrating the social impact of biomedical engineering through project-based learning (PBL) is essential for fostering knowledge via practical experimentation and empowering students to become lifelong learners (Fidalgo *et al.*, 2025). Integrating CDIO and PBL into engineering curricula requires changes in teaching methodologies, teacher training and workspaces (Ramírez de Dampierre, M., *et al.*, 2024). The proposed educational framework is defined as a structured three-phase "Pipeline" that operationalizes the Conceive, Design, Implement, and Operate framework within the context of biomedical instrumentation. This framework is designed for transferability, offering a replicable model where specialized hardware and software tools are used to empower students to solve authentic, real-world problems. In fact, active learning leads to significant increases in examination performance and lower failure rates compared to traditional lecturing (Freeman S., 2014). This study builds upon a pioneering initiative by the authors, which introduced a CDIO design-build experience within a university extension program for the Medical Physics course at the Federal University of Goiás, Brazil. Integrating biomedical instrumentation within Medical Physics and Biomedical Engineering allows for the effective diffusion of knowledge regarding cardiovascular health (Berwanger *et al.*, 2022). By fostering synergy with the medicine program, this project uses the CDIO framework to cultivate a mindset of continuous professional development through practical engagement. The core initiative involves building a functional electrocardiogram (ECG) using low-cost, accessible materials, ensuring sustainability and replicability. The project achieves a low-cost profile by replacing expensive medical grade equipment with accessible components like the Arduino Nano, breadboards, and standard analog resistors. This approach ensures sustainability and replicability (Vasan A., *et al.*, 2020), allowing students to visualize cardiac waveforms using free, open-source software. Success is evaluated by the students' ability to capture clear QRS waves and clinical data despite using these affordable materials. This is vital for democratizing education and fulfilling the CDIO mission of social responsibility, as it allows sophisticated biomedical technology to be deployed in resource-limited public health settings. Furthermore, the creation of a simple and ludic assembly manual facilitates the understanding of complex biological signals for a diverse audience. This project-based learning (PBL) approach develops essential technical skills while highlighting the social impact of medical technology in promoting community awareness and excellence.

BACKGROUND INFORMATION

The CDIO framework

The CDIO (Conceive, Design, Implement, and Operate) framework represents an innovative educational methodology specifically tailored to modernize engineering education worldwide. Developed initially by MIT and Swedish universities, it provides students with a holistic view of the product, process, and system lifecycle. The "Conceive" stage involves defining customer needs and considering technology and regulations. In the "Design" phase, students create plans, drawings, and algorithms that describe what will be implemented. "Implement" refers to the transformation of the design into a product, including manufacturing and testing. Finally, the "Operate" stage focuses on using the implemented product to deliver the intended value. By integrating these four stages, the framework ensures that graduates possess not

only deep technical knowledge but also the professional skills required to lead complex projects in modern industry.

The CDIO framework in Brazil

In Brazil, the adoption of the CDIO framework has gained significant momentum over the last two decades as universities seek to comply with the new National Curriculum Guidelines for Engineering courses (Díaz-Salazar *et al.*, 2023); Lourenço Jr. *et al.*, 2015). Pioneering institutions such as the Aeronautics Institute of Technology (ITA) and the University of São Paulo (USP) were among the first to join the international CDIO Initiative, setting a standard for others. The framework has proven particularly effective in the Brazilian context for fostering "hands-on" learning experiences that are often lacking in traditional theoretical programs. Many Federal and Private universities now utilize CDIO to promote interdisciplinary projects, university extension programs, and entrepreneurship. This approach is vital for addressing the local industry's demand for engineers who are capable of innovation and social problem-solving. Furthermore, Brazil hosts regional CDIO meetings, allowing for a robust exchange of pedagogical practices across different states.

DESIGN-IMPLEMENT ENVIRONMENT

Federal University of Goiás

The Federal University of Goiás (UFG) is the largest public university in the Central-West region of Brazil, located in Goiânia. The ECG project is offered annually by the Medical Physics course of the Institute of Physics.

Undergraduate education in Medical Physics (MP)

The Bachelor's program in MP at UFG has been offered since 2013. Every year, 25 new students enroll in undergraduate education. The first cohort concluded activities in February of 2017; by January 2026, there are five cohorts (128 undergraduate students in total) attending courses simultaneously. The undergraduate curriculum in MP is a 5-year program composed of ten semesters totalling 3,652 hours. The students undergo basic physics subjects in the first half (2.5 years), including calculus, physics, quantum mechanics, thermodynamics. The second half of the course (the remaining 2.5 years), students take specific subjects of MP, i.e., Physical Principles of Nuclear Medicine, Radiotherapy, Radiodiagnostics, Medical Image Processing, Introduction to Biomedical Instrumentation, Radiation Physics and Biological Effects of Ionizing Radiation. The ECG project is offered annually through the Medical Physics Academic League. This is, for now, the only opportunity for the students to be introduced to a design-implement experience according to the CDIO framework.

A framework for teaching Biomedical Instrumentation

In this project-based learning (PBL) module, students engage directly with the critical reality of cardiovascular health, investigating the high prevalence of heart diseases in Brazil to establish a meaningful, real-world context. Shifting from passive listeners to active protagonists, learners are tasked with the engineering challenge of assembling a functional ECG device on a breadboard (see table 1). Our approach relies on student autonomy and self-taught methodologies, where undergraduate tutors provide guidance while students

navigate technical obstacles—such as signal noise and amplifier gain—through collaboration and troubleshooting. The basis of evaluation is a multi-dimensional rubric that weights Technical Proficiency (40%), Critical Thinking (30%), and Collaboration & Communication (30%). This assessment strategy ensures that students are not only graded on the final ECG signal but also on their ability to articulate the correlation between cardiac anatomy and electronic signals, bridging the gap to professional market demands. This process demands that they rapidly synthesize theoretical concepts with hands-on practice, relying on deep collaboration and critical thinking to troubleshoot complex circuitry. By navigating these technical obstacles, students not only master the physics of biomedical instrumentation but also understand the societal impact of accessible healthcare technology. Consequently, this immersive experience bridges the gap between academia and professional expectations, cultivating the autonomy and practical problem-solving skills necessary for future scientific and engineering careers (see Figure 2). The main contribution of this work to the CDIO community is the proposal of a framework for the teaching of biomedical instrumentation for students by using hardware and software tools that are embedded in the ECG device. The proposed framework includes hardware devices such as Arduino Nano, breadboard, resistors and jumper cables, alongside the Arduino IDE software. The educational framework proposed here empowers students through the practical approach to assembling an ECG device by connecting previous knowledge of basic concepts of electronics, electromagnetism and logic. For instance, not only provides knowledge about the device itself, but also about cardiovascular health through our synergy with the undergraduate medicine course.

Table 1. CDIO framework in our study.

Stage	Action	Transferable Output
Conceive	Identify medical/social problem (e.g., heart disease prevalence in Brazil).	Problem Statement & Social Context.
Design	Plan circuits, derivations, and filtering strategies.	Schematic & Algorithm Design.
Implement	Assemble prototype on a breadboard and integrate with Arduino.	Functional Prototype.
Operate	Real-time signal validation and community outreach.	Validated Device & Social Impact.

METHODOLOGY

Phase 1: Contextual Foundation & Theoretical Introduction

The initial stage of this PBL framework established the medical and social context through a comprehensive, slide-based expository lecture led by an undergraduate medical student aspiring to a Clinical Cardiology residency. This session provided a deep dive into cardiac anatomy, detailing the primary muscles, heart chambers, the circulatory system, and the physiological distinctions between venous and arterial blood. Beyond the biological mechanics, the presentation addressed the critical reality of cardiovascular health by outlining the prevalence of heart diseases in Brazil, emphasizing prevention strategies and the importance of long-term heart care. During this phase, students successfully gathered essential knowledge regarding both the biological function of the heart and the broader landscape of public health policies, including an overview of the municipality's main cardiac care centers. This theoretical grounding served as the essential prerequisite for the practical

engineering challenges that followed. Aligning with CDIO Standard 4, the Design phase translates medical requirements into technical schematics, focusing on the mathematical derivation of filters and amplifier gain to capture millivolt-level cardiac signals. Students design the hardware layout on breadboards and develop software logic in the Arduino IDE to identify specific P, QRS, and T waves. This stage also includes the creation of a didactic manual, ensuring the technical design is documented for replication and social outreach.

Phase 2: Bio-instrumentation & Hardware Assembly

Following the theoretical immersion, the pipeline advanced to the technical implementation stage, bridging the gap between medical physiology and engineering. In this phase, students shifted from observing to creating. They were introduced to the essential electronic components required for bio-signal acquisition, including instrumentation amplifiers, operational amplifiers, resistors, and capacitors.

Working in collaborative teams, students took charge of the hardware assembly, mounting the analog signal conditioning circuit onto a *breadboard*. This phase demanded the direct application of physics, anatomy, and electronics principles, as students faced the challenge of configuring the circuit to amplify the faint millivolt-level electrical signals generated by the heart while designing filters to remove significant noise. This hands-on activity transformed the abstract anatomical concepts from Phase 1 into a tangible, functional prototype, requiring students to exercise critical thinking and technical troubleshooting to ensure the device was safe and effective.

Safety and Risk assessments

To ensure the device is safe and effective, students must identify connection and logic errors to prevent electrical hazards when interfacing the Arduino Nano and breadboard circuits with human subjects. While specialized amplifiers are used to manage low signal amplitudes, proper isolation and gain adjustment are critical to protecting both the user and the sensitive electronic components. This technical troubleshooting validates the prototype's reliability before it is deployed in community health outreach campaigns.

Phase 3: Digital Integration & Clinical Correlation

In the final stage of the pipeline, students interfaced their breadboard circuits with an Arduino Nano, using its analog-to-digital converter (ADC) to read the amplified heart signals, by testing them on the group members. By connecting the Arduino to personal computers, they established a real-time monitoring station. By using the Arduino IDE, the students were able to visualize the electrical activity of their own hearts as dynamic waveforms on the screen. This was the pivotal moment where theory met reality: students had to identify the specific P, QRS, and T waves they had learned about in Phase 1 within the noisy, real-world data they captured. This activity required them to apply critical analysis to distinguish between valid biological signals and motion artifacts or electrical interference. By successfully visualizing a clean ECG trace, students not only validated their engineering prototype but also solidified their understanding of cardiac physiology, effectively demonstrating how low-cost technology can be deployed to address the health challenges discussed at the start of the project.

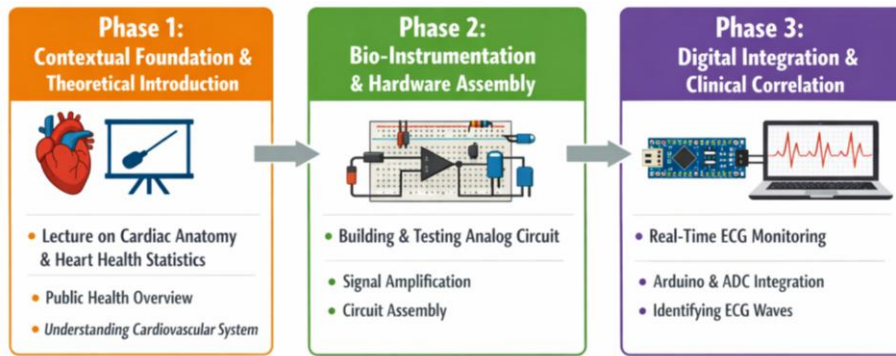


Figure 1. Diagram of the framework

Potential limitations of the framework

While highly transferable, the framework's application may be limited by the technical difficulty of acquiring low-amplitude signals without specialized instrumentation. Implementation also requires students to possess strong prerequisite knowledge in electronics and electromagnetism to succeed in the "self-taught" approach. Furthermore, its effectiveness depends on interdisciplinary synergy with medical programs to provide necessary clinical context and anatomical grounding. Finally, strict safety protocols must be maintained when testing student-built prototypes on human subjects.

Learning goals

The learning goals were to:

- Introduce how electronic devices work separately before building the ECG.
- Introduce basic concepts of how ARDUINO works on this specific task.
- Assemble the ECG device in a breadboard.
- Introduce basics of biological signals and vector derivation for signal processing.
- Introduce basics of most common cardiovascular diseases in Brazil.
- Interpret the ECG signal among peers to test the ensembled device.

Students attend an introductory session on cardiology and the most prevalent cardiovascular diseases in Brazil. During this session, they are encouraged to reflect on how their own daily routines impact their long-term health. While undergraduate tutors who have previously completed the project provide guidance, the currently enrolled students must achieve each goal through a self-taught, hands-on approach. Following the disease outreach session, students transition to the laboratory to begin the construction of the ECG.

Knowledge Dissemination and Creation of the Assembly Guide

We developed an ECG Assembly Manual using a simple, illustrative, and engaging approach, aiming to ensure accessibility for the external community (LAFISMED, 2025). This document serves as a guide for constructing the device, enabling teachers, students, and other interested parties to understand and replicate the ECG assembly; thereby it contributes to the

popularization of scientific and technological knowledge related to cardiovascular health. The manual was designed to facilitate understanding for individuals with varying levels of technical knowledge, promoting inclusive knowledge dissemination. The manual covered the following topics:

1. *Introduction*
 - 1.1. *Cardiovascular Diseases in Brazil*
 - 1.2. *Electrocardiogram (ECG)*
 - 1.3. *ECG Applications*
2. *Materials*
3. *Pin Connections*
4. *Software Setup*
5. *Conclusion*

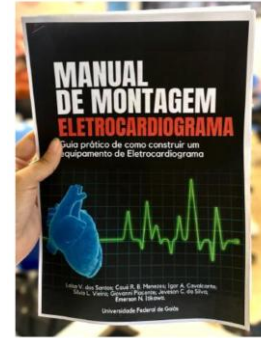


Figure 2. Assembly Guide for the students

Module conclusion & Assessment

The module concluded with a holistic review that evaluated not only the final product but also the investigative journey, reflecting the dual nature of Project-Based Learning. By integrating the medical insights from the initial lecture with the engineering challenges of the Arduino-based prototype, students demonstrated a comprehensive understanding of how biomedical instrumentation serves public health needs.

Assessment Strategy

Evaluation was conducted using a multi-dimensional rubric designed to measure both technical competency (hard skills) and behavioral development (soft skills):

- **Technical Proficiency (40%):** Students were assessed on the functionality of their protoboard circuits and the clarity of the signal visualized on the Arduino IDE Serial Plotter. High marks were awarded to teams that successfully identified the components of the low-cost ECG, demonstrated the capacity to reveal QRS waves, and accurately explained the correlation between the electronic signal and the cardiac anatomy presented in Phase 1.
- **Critical Thinking & Problem Solving (30%):** Instructors evaluated the students' autonomy in troubleshooting, logical arguments aiming solutions, conclusions and implications (CDIO Syllabus 3.0). This included their ability to diagnose connection/logic errors, adjust amplifier gain, or reduce electromagnetic interference without immediate instructor intervention. This metric specifically measured the "protagonism" of the student in overcoming the gap between theory and practice.

- **Collaboration & Communication (30%):** Instructors evaluated the students' abilities to work in teams through the CDIO Syllabus 3.0 as well: planning, leadership, handling conflicts, clarity of language, and listening carefully to each other. Through peer reviews and a final group presentation, students were assessed on their teamwork dynamics through categorical forms of soft and hard skills, and accomplishment of the task. They were required to articulate how they divided tasks, how they synthesized the medical data with electronic assembly, and how they viewed the societal impact of their device in the context of Brazilian healthcare prevalence of cardiovascular diseases.

Ultimately, this PBL experience validated that when students are challenged to build real-world tools, they develop a durable connection between academic theory and professional application, preparing them for the complexities of modern scientific and medical careers.

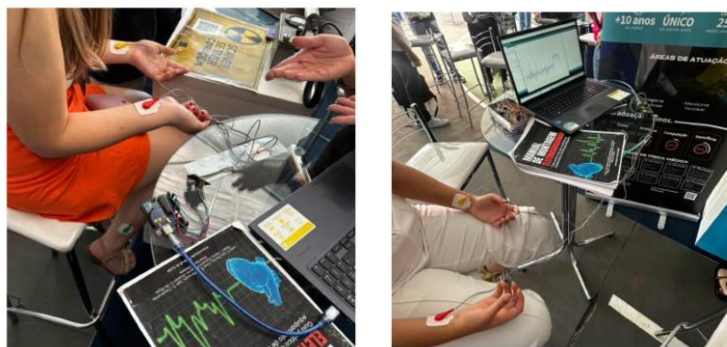


Figure 3: Testing the ECG on students.

Notably, among the positive aspects of the initiative is the social impact promoted by the Medical Physics Academic League (LAFISMED). By disseminating knowledge in a simple, accessible, and engaging manner, the group contributed significantly to fostering citizens who are aware of the importance of cardiovascular health. This initiative proved especially effective among elementary and high school students, sparking interest and awareness in the young audience, aligning with the CDIO Framework. By demystifying biomedical technology, the project fulfills the CDIO mission of developing socially responsible engineers while providing tangible public health education to the Goiânia community. Moreover, this outreach action promoted science in a practical and applied manner, enriching the students' academic training and bridging the gap to the professional market. The experience gained in constructing the ECG, developing the manual, and conducting public presentations was fundamental to developing technical and communication skills, preparing students for future challenges in their academic and professional careers.

CONCLUSIONS

The implementation of the project-based learning (PBL) framework within the undergraduate education at the Federal University of Goiás successfully bridged the gap between theoretical knowledge and professional practice. By placing students at the center of the learning process, the initiative shifted the focus from simple technical execution to active problem-solving and innovation using accessible resources. While the construction of a functional, low-cost ECG served as the vehicle for learning, the primary outcome was the development of critical

thinking and student autonomy in the face of complex challenges. Furthermore, the creation of a didactic manual and the engagement in community health campaigns transformed the project from an academic exercise into an act of social responsibility. Ultimately, this experience highlights the transformative power of PBL, equipping future professionals with the essential hard and soft skills required by the modern healthcare industry while promoting true scientific citizenship.

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BIOGRAPHICAL INFORMATION

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