Improving Engagement in Introductory Programming through Embedded Systems

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Abstract

The integration of embedded systems into introductory programming courses offers a promising avenue to enhance student engagement, simplify concept understanding, and reduce cognitive load through tangible and meaningful applications. However, novices often encounter significant barriers when dealing with the inherent complexity of low-level hardware interactions, particularly in systems like Raspberry Pi, which require detailed knowledge of GPIO pins, I^2C buses, and PWM signals. To address this challenge, this research introduces an extended abstraction API built upon SplashKit, a framework widely used in beginner programming curricula. This API simplifies intricate hardware interactions by encapsulating detailed operations—such as ADC conversions, GPIO pin management, and servo motor control—into intuitive, high-level function calls. Through detailed comparative analysis using Halstead complexity metrics, the abstraction layer demonstrates significantly reduced cognitive demands compared to traditional, low-level interfaces such as pigpio. Empirical evidence from Halstead measures indicates marked decreases in Volume, Difficulty, Effort, and Estimated Bugs, underscoring the API's effectiveness in reducing extraneous cognitive load. The outcomes of this study have implications for pedagogical strategies in introductory programming, suggesting that thoughtfully designed abstraction layers can substantially improve novice learners' performance and comprehension in embedded system programming. The thesis concludes by highlighting the need for future empirical evaluations involving student interactions and proposes further development and extension of the API to accommodate additional hardware platforms and engaging pedagogical scenarios.
Keywords: Abstraction; Hardware Abstraction Layer (HAL); Application Programming Interface (API); Cognitive Load; Code Complexity; Halstead Metrics; Modularity; Embedded Systems; Raspberry Pi; SplashKit.

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1 Introduction

This thesis addresses the challenge of teaching embedded programming to novice students by developing and evaluating a SplashKit-based abstraction layer for the Raspberry Pi. Embedded hardware offers rich, motivating examples (e.g. blinking LEDs, controlling motors), but it also greatly increases programming complexity. Students must simultaneously learn a programming language and understand hardware concepts (electrical signals, buses, sensors). In many educational settings, the emphasis remains on “bare-metal” code: as Vahid et al. note, typical introductory embedded courses and textbooks still emphasize low-level programming of hardware[66].

This often leads students to write “ad hoc unstructured code” as they manually configure peripherals, which can overwhelm beginners. Consequently, modern pedagogical research advocates scaffolding hardware tasks. For example, Kastner-Hauler et al. found that combining block-based programming with physical computing devices “could become a promising approach to promote computational thinking skills” and provides “low-barrier access” for novice learners[30]. Within this context, SplashKit – originally a game-development framework for first-year programmers – is extended to serve as an educational hardware API. SplashKit’s pedagogical intent is documented by Renzella et al., who emphasize that lowering the barriers to programming “will help ease students into programming and enable a broader range of student[ ]to continue programming”[43]. By equipping SplashKit with GPIO, ADC, PWM and I²C functions for the Raspberry Pi, this work aims to simplify embedded assignments. In effect, the SplashKit abstraction layer allows novices to engage with real sensor and actuator tasks without dealing with direct register manipulation or kernel drivers. This thesis thus bridges introductory programming and embedded hardware: it presents the design of the SplashKit Raspberry Pi API and evaluates its impact on program complexity and student learning in comparison to traditional low-level coding.

2 Motivation

Teaching embedded programming to novices faces a notoriously steep learning curve. Beginners must manage low-level details (pin modes, timing loops, protocol

formats) alongside core programming concepts. Research shows that excessive complexity leads to anxiety and disengagement: Renzella et al. report that new programmers “often have poor perceptions of their capabilities” and recommends lowering barriers to entry[43]. In practice, asking beginners to write raw GPIO or I²C code can quickly exceed their cognitive capacity. By contrast, an abstraction layer like SplashKit’s can provide immediate feedback and success: students see a LED blink or motor move without needing to diagnose electrical issues. This need for simplification is reinforced by educational studies of physical computing. Kastner-Hauler et al. find that integrating programming with tangible devices (e.g. micro:bit) creates a “playful, enjoyable” environment that empowers learners and maintains a “confident and good feeling” towards computing[30]. Similarly, Papadakis and Kalogiannakis argue that tools like Arduino with visual programming can improve students’ self-efficacy and motivation in STEM[30]. In sum, the motivation for this research is to create an instructional bridge: a tool that makes embedded hardware accessible. By leveraging SplashKit’s existing educational framework, we aim to enable first-year students to write engaging hardware projects without drowning in the plumbing of I²C transactions or PWM registers. Lowering this entry barrier should, in theory, allow students to focus on design and learning rather than debugging low-level code.

3 Literature Review

3.1 Introduction

Introductory programming courses (often known as CS1 in computer science curricula) are notorious for high failure and dropout rates, often linked to students’ disengagement and lack of motivation [37]. A well-known multi-institutional study found an average failure rate of roughly 33% in introductory programming, underscoring the gravity of the challenge [9]. Such outcomes have sparked extensive research into improving student engagement and success in learning to program [37]. A recurring insight is that a student’s self-motivation and active engagement strongly influence their likelihood of persisting and succeeding in programming

courses [37]. Conversely, when students disengage – whether due to frustration, perceived irrelevance of the content, or lack of support – they are far more likely to abandon the course [37]. The complexity of learning programming for the first time, combined with abstract concepts and strict syntax, can overwhelm novices, leading to a cycle of low confidence and withdrawal[54].

In response, educators and researchers have explored a variety of pedagogical interventions to make introductory programming more engaging and effective [37]. These include curriculum redesigns, interactive tools, collaborative learning methods, game-based approaches, and the focus of this chapter – integrating embedded systems and physical computing projects as a vehicle for teaching programming [37]. The underlying idea is that tangible computing contexts (like building simple electronic gadgets or robots) can make programming more concrete, meaningful, and fun, thereby motivating students to invest more time and effort. Embedding programming assignments in real-world physical projects may tap into students' natural curiosity and provide instant feedback (e.g., a sensor lights an LED based on code), which is often more gratifying than purely screen-based outputs [56].

This chapter provides a comprehensive literature review on "Improving Engagement in Introductory Programming through Embedded Systems." We examine the theoretical foundations that justify this approach, including motivation theory and constructivist learning theory (Section 2). We then discuss active learning strategies, such as problem-based and project-based learning, that create a pedagogical framework for incorporating physical computing (Section 3). Next, we explore how embedded systems – particularly accessible platforms like the Raspberry Pi and Arduino – have been implemented in introductory programming courses to enhance engagement (Section 4). We review empirical results and case studies from these implementations, highlighting both successes and limitations (Section 5). We also address the challenges involved, including cognitive load considerations, technical constraints, and pedagogical issues (Section 6). Finally, we discuss future directions for research and practice in this area (Section 7), and conclude with reflections on how these findings can inform a more engaging introductory programming curriculum. Throughout, we maintain a narrative that connects theory to practice, showing how and why embedded systems can play a transformative role in early computing education.

By weaving together findings from a range of high-quality sources – including systematic literature reviews, education theory, and reports of classroom

interventions – this chapter aims to present a cohesive story of how physical computing can reignite student interest in programming. The goal is to inform educators, curriculum designers, and researchers of the current state of knowledge on this topic and to identify evidence-based strategies (as well as pitfalls to avoid) when leveraging embedded systems to improve student engagement and learning outcomes in introductory programming.

3.1.1 The Engagement Challenge in Introductory Programming

Introductory programming is often a student's first exposure to computer science, and it is well documented that many students find it difficult and discouraging. High attrition rates in CS1 have persisted for decades[9]. Students face steep learning curves: they must grasp abstract concepts (like variables, loops, and data structures) and unfamiliar syntax, often with only trivial or contrived problem contexts. Motivation can wane when learners do not see the relevance of programming or when they get stuck on frustrating debugging issues. Becker et al. (2018) note that "students disengage and subsequently drop out for many reasons, and these are quite multifaceted", ranging from lack of interest to feelings of inadequacy [37]. On the other hand, those who succeed tend to be those who adapt by seeking new learning techniques and persisting through challenges [37]. This stark contrast highlights engagement and persistence as key determinants of success in learning to code.

Engaging students in introductory programming courses is a persistent challenge in computer science education [22]. Traditional pedagogical approaches often fail to capture and maintain student interest, leading to elevated dropout rates and a general lack of enthusiasm for programming [51, 63]. Factors contributing to this challenge include:

- **Abstract Concepts**: Novices often struggle with the abstract nature of programming concepts, leading to frustration and disengagement [37].
- **Lack of Immediate Application**: Difficulty in relating programming concepts to real-world applications can impact motivation [19][37].
- **Demanding Workload**: The significant workload in programming courses can be overwhelming, contributing to disengagement [34][37].

Recognizing this, the computing education research community has made student engagement a focal point of study. Luxton-Reilly et al.'s systematic literature review confirms that "student engagement in introductory programming has received considerable attention", with numerous empirical studies devoted to understanding and improving it [37]. These studies span a range of approaches. Some investigate "internal characteristics of students and their role in self-regulated learning" – for example, how factors like self-efficacy, personality traits, or attitudes correlate with engagement [37]. Others evaluate interventions: "examples include full course redesigns; implementing a holistic and better integrated curriculum; in-class response systems; online journaling; smaller class sizes; peer learning via pair programming, team-based learning, think-pair-share; interactive learning experiences; the use of robots and physical computing approaches", among many others [37]. The variety of these efforts underscores that engagement is multi-dimensional. It can be fostered by improving the learning environment and pedagogy (e.g. active learning, personalizing instruction) as well as by introducing appealing contexts or tools (e.g. games, robotics, maker activities) that make learning programming more interesting.

One particularly promising avenue has been the use of physical computing and embedded systems – essentially bringing programming into the tangible world of devices and sensors – as a means to spark student interest. Incorporating hands-on projects with hardware allows students to see and touch the results of their code, which can satisfy a desire for concrete outcomes often missing in introductory exercises. Prior research has observed "numerous positive results from physical computing, such as creativity, student uptake, and motivation" [56]. By giving abstract code a physical manifestation (a robot moves, a light blinks, a melody plays), we fulfill a psychological need for meaning and relevance. Students often find such projects "real" and exciting – a stark contrast to printing Fibonacci numbers to a console. Moreover, tangible projects can engage a broader spectrum of learners; notably, hands-on computing activities have been found to increase confidence among female students in programming courses[56], suggesting an inclusive benefit in fields where gender imbalance and stereotype threats persist.

3.1.2 Factors Contributing to Disengagement

Understanding the reasons behind student disengagement is crucial for developing effective interventions. Common factors include:

- **Lack of Prior Experience**: Students without prior programming experience may feel inadequate, increasing disengagement risk [35].
- **Negative Perceptions**: Pre-existing beliefs about programming's difficulty can lead to reduced effort and disengagement [37, 35].
- **Ineffective Learning Strategies**: Without effective strategies, students may struggle to keep up, leading to frustration [37].
- **Insufficient Support**: Limited access to support can leave students feeling isolated [37].

At the same time, introducing hardware and projects into CS1 is not a silver bullet. The complexity of managing both programming and electronics can itself become a hurdle if not carefully designed – an issue we will examine under cognitive load (Section 6.1). However, when executed with proper scaffolding, this approach aligns with key motivational and learning theories that help explain why it can boost engagement. Before delving into concrete strategies and implementations, we first discuss those theoretical frameworks: Self-Determination Theory, which illuminates the role of intrinsic motivation, and Constructivism (including Papert's constructionism), which provides a foundation for learning by making.

3.2 Theoretical Frameworks Addressing Engagement

Effective educational interventions are underpinned by sound theory. In the context of improving student engagement in programming, two theoretical perspectives have prominently guided both research and practice: Self-Determination Theory (SDT) from psychology, and constructivist learning theories from education. These frameworks help us understand what drives student motivation and how learners construct knowledge, respectively. They provide rationale for why approaches like project-based physical computing can be so engaging. Several theoretical frameworks have been proposed to address these challenges:

3.2.1 Feedback and Engagement

Grawemeyer et al. [22] suggest a blended approach to feedback, incorporating both human and automated feedback to improve engagement. This approach caters to

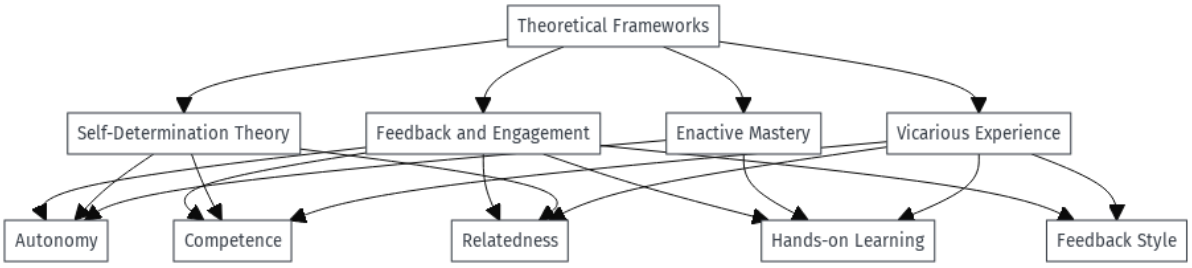


Figure 1: Theoretical frameworks addressing engagement in programming education. The comparison includes Feedback and Engagement, Self-Determination Theory, Enactive Mastery, and Vicarious Experience, highlighting their emphasis on autonomy, competence, relatedness, and hands-on learning.

diverse learning needs and preferences.

3.2.2 Self-Determination Theory

Self-Determination Theory, developed by Deci and Ryan, posits that human motivation is deeply influenced by the satisfaction of three basic psychological needs: autonomy (the need to feel in control of one's own choices), competence (the need to feel effective and capable), and relatedness (the need to feel connected to others)[12][60]. When these needs are met, individuals are more likely to experience intrinsic motivation – engaging in an activity for its inherent enjoyment or value, rather than due to external pressure or reward[12][60]. Intrinsic motivation is particularly powerful in learning contexts because it leads to persistence, creativity, and deeper engagement with the material (students want to learn, rather than feeling they have to)[12][57]. In traditional introductory programming courses, however, these needs are not always well supported. Autonomy can be limited in a highly structured course where every student writes the same small programs; competence can be undermined by frequent failures (e.g., frustrating syntax errors can make novices feel incapable); relatedness may be low if programming assignments are done in isolation and have no social component. SDT suggests that redesigning learning experiences to better fulfill autonomy, competence, and relatedness will increase students' intrinsic motivation and engagement [12][3]. This has direct implications for how we might use embedded systems projects in CS1:

- **Autonomy**: Projects involving embedded systems (like open-ended maker projects) naturally lend themselves to giving students choices. For example,

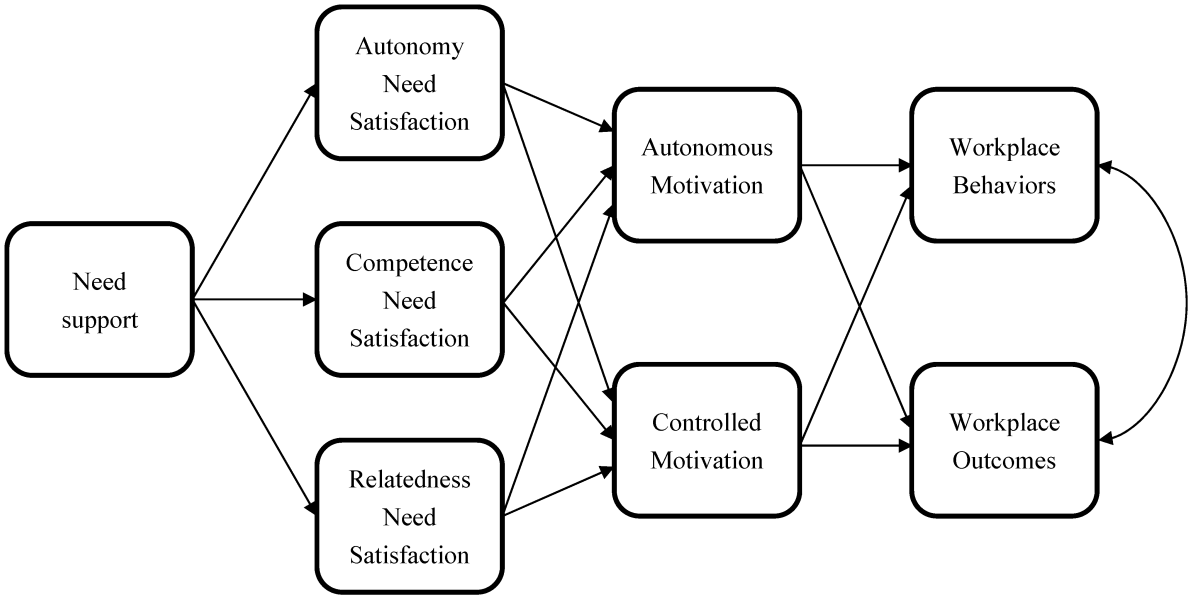


Figure 2: Model proposing associations among constructs from self-determination theory and workplace outcomes, adapted from McAnally, 2024[42]

students might choose what kind of device or problem to tackle (a weather station, a robot, a game, etc.), or have freedom in how they design and implement their solution. Granting such autonomy – even within a guided framework – can increase students' ownership and pride in their work[55][14]. Research shows that "autonomy increases intrinsic motivation as learners take ownership and pride in their work"[55], a finding originally demonstrated by Deci's classic study in 1971 where greater choice led to higher subsequent interest in tasks[55]. In the context of programming, a student allowed to invent a creative gadget with a Raspberry Pi is more likely to pour their passion into it than if everyone is coding the same textbook problem.

- **Competence**: While autonomy is important, it must be balanced with supporting the learner's sense of competence. If a task is too difficult or unstructured, students can become overwhelmed and feel incompetent, which is demotivating[60][38]. Thus, SDT-aligned instruction also emphasizes optimal challenge and scaffolding – providing just enough guidance for students to succeed and learn, thereby boosting their competence. Embedded systems projects, if well-scaffolded, can provide a series of "mastery experiences" where students incrementally build skills (for instance, first blinking an LED, then reading a sensor, then combining inputs and outputs into a functional system). Each small success reinforces their confidence. As we will discuss, a structured approach that ensures early wins while gradually increasing complexity is

key. Empirical evidence from an embedded systems course showed that competence needs were met by “focused guidance from the instructor and complementary labs/assignments throughout the semester,” which helped students feel capable even as they tackled ambitious projects[49]

- **Relatedness**: Introductory programming is sometimes seen as a solitary activity, but SDT reminds us that feeling connected – to peers, mentors, or a larger community/purpose – can significantly impact motivation. Physical computing projects often naturally encourage collaboration (students working in teams on a robot, or sharing their gadget demos with the class), which can fulfill the need for relatedness. Additionally, because these projects often have real-world context or personal meaning, students may feel more connected to the activity itself. For example, a student building a smart pet feeder might relate their project to caring for their own pet, creating a personal connection that fuels engagement. Studies have noted that when students work in teams on projects, the camaraderie and shared accomplishment can drive them to put in extra effort and persist [49]. Indeed, in one course that used open-ended embedded projects, the instructors explicitly facilitated teamwork and found that “the need for relatedness was satisfied by students working in teams with their peers”, which in turn contributed to high intrinsic motivation by course end[49].

In summary, Self-Determination Theory provides a lens to understand why embedded systems-based pedagogy might succeed: by giving students a sense of control (autonomy in project choices), ensuring they can achieve success with appropriate support (competence through scaffolding), and leveraging collaboration and real-world connections (relatedness), we create fertile ground for intrinsic motivation. When students are intrinsically motivated, they are more engaged – they will spend more time coding, debug more persistently, and approach problems with curiosity rather than fear. As a concrete example, a reflective analysis of a long-running embedded systems course noted a “high level of motivation expressed by students” and attributed this to deliberate course design satisfying autonomy, competence, and relatedness in line with SDT [49]. We should, however, also be mindful that too much autonomy without guidance can backfire (as discussed later in Section 6.1 on cognitive load). SDT does not advocate for unguided learning, but rather supported autonomy, where instructors provide structure and resources that empower students to take initiative without floundering [60][11].

3.2.3 Constructivism and Constructionism: Learning by Making

While SDT addresses the motivational aspect of why students might engage, constructivist learning theory addresses how students learn effectively, which in turn informs instructional design. Constructivism, drawing from the work of Piaget and others, holds that learners construct knowledge actively, building new understandings upon their existing mental models through experience and reflection. Rather than passively receiving information, students learn best by doing – by exploring, experimenting, and solving problems in contexts that are meaningful to them. This philosophy underlies many modern pedagogies in STEM education. One particular branch, constructionism, was articulated by Seymour Papert [47] and is highly relevant to the idea of programming with embedded systems. Papert, a pioneer of educational technology, believed that learning is most effective when people are constructing a public artifact – something external that they can share and discuss – be it a sandcastle, a poem, or a computer program[47]. Constructionism thus marries constructivist ideas with the act of making. In Papert's view, programming a computer (especially to create something like a game or to control a robot) is a prime example of learning-by-making that can deeply engage students [47]. He famously created the Logo programming language to let children control a "turtle" robot, embodying his idea that programming can be a vehicle for children to explore and learn mathematics by constructing. When students build tangible projects, "the products made are meaningful in some way to the maker"[47][14] – this personal meaning is critical, because it motivates the learner to overcome challenges in pursuit of their self-expressive goal.

Embedded systems projects in an introductory programming course are a modern instantiation of Papert's constructionism. For example, consider a student tasked with creating an Arduino-based weather display. To complete this project, the student must engage in active learning: they research how sensors work, write code to read data and drive outputs, perhaps physically assemble components, test their creation, and iteratively improve it. Throughout, they are constructing both an artifact (the device) and their own understanding of programming and electronics. The project is personally meaningful – it's not an arbitrary assignment, but something the student built and can show off. This resonates with Papert's assertion that making something of personal value is a powerful motivator and learning experience [58][29].

Constructivist theory also explains the importance of context and concrete experiences in learning abstract concepts. A core challenge in CS1 is that concepts

like “variable” or “algorithm” can seem very abstract. By contrast, manipulating an LED or reading a temperature sensor is concrete – students can see and feel what’s happening. By mapping abstract code to physical action, we leverage concrete experiences to ground understanding. Educational research supports that “concrete, hands-on experiences with tangible referents positively impact students’ learning, particularly in computing” [56]. In essence, the physical device serves as an “anchor” for abstract ideas, potentially reducing cognitive distance (we revisit this in the cognitive load discussion).

Another constructivist strategy relevant here is the use of project-based learning (PBL), which overlaps with constructionist practice. In project-based learning (discussed more in Section 4), students gain knowledge by working for an extended period to investigate and respond to an authentic, complex question or challenge – often culminating in a concrete project or product. Constructivism encourages such approaches, as they provide learners with a rich context to actively construct understanding. A review by Thomas (2000) emphasized that well-designed projects incorporate features like realism, student choice, and iterative refinement, all of which promote deeper engagement[58][47]. Problem-based learning (often case-driven) and inquiry-based learning similarly fall under the constructivist umbrella by engaging students in solving nontrivial problems or answering open-ended questions rather than memorizing content [58].

It is important to note that pure discovery or completely unguided constructivist approaches have been critiqued. Mayer (2004) and others cautioned that leaving novices entirely to “construct knowledge on their own” can lead to inefficient learning or misconceptions[41][60]. Learners may flounder or build fragile understandings if not given any guidance – a phenomenon observed when some early constructivist implementations provided minimal teacher input, resulting in student frustration. To address this, modern consensus favors guided constructivism: providing scaffolding, examples, and feedback as students engage in active learning. Lye and Koh’s (2014) review of computational thinking education found that “construction with scaffolding was the most popular approach used by teachers”[38], highlighting that teachers value a balance – enabling students to create and explore, but with sufficient support to ensure correct learning. The “right level of scaffolding is not easy” to determine[11], and educators often adjust based on student needs. The key is to support the competence aspect (from SDT) while preserving student agency.

In practical terms, for embedded system projects, scaffolding might include providing

starter code, circuit schematics, or step-by-step milestones. For instance, instead of asking students to build a complex device from scratch, an instructor might first lead a short tutorial on blinking an LED (to ensure everyone can program the basics), then let students choose a project that expands on that foundation. This approach was echoed by Rich et al. (2018), who surveyed teachers: some wanted to increase student autonomy, while others wanted to reduce it for fear of students going astray, concluding that the solution lies in sufficient scaffolding to meet competence needs while still providing opportunities for autonomy and relatedness[38][11]. Luse and Hammer [35] explore enactive mastery and vicarious experience in teaching programming, highlighting the benefits of hands-on learning and observing peers. In sum, constructivism and constructionism strongly support the use of hands-on, project-based, and student-centered learning in introductory programming – as long as it is well-guided – which directly aligns with the notion of introducing embedded systems to improve engagement. Having established the theoretical motivations (students need to feel autonomous, competent, connected, and learn best by doing meaningful work), we now turn to how these principles manifest in concrete pedagogical strategies and prior art in computer science education. In particular, we will discuss active learning methods that have been tried in CS1, and then focus on the integration of embedded systems as a specialized strategy within that active learning paradigm.

3.3 Active Learning Strategies in Introductory Programming

Traditional lecture-based instruction has often proven inadequate for engaging today's students in learning programming. Active learning strategies, which involve students in activities and thinking during class rather than passively listening, have consistently been shown to improve motivation and outcomes in STEM education. In the context of introductory programming, active learning can take many forms – from having students work on coding problems during class, to collaborative techniques like pair programming, to full-fledged course projects. Two closely related pedagogical frameworks stand out as particularly relevant for incorporating embedded systems: Problem-Based Learning (PBL) and Project-Based Learning. These approaches naturally embody the principles of autonomy, relevance, and hands-on engagement discussed earlier, and they have been applied with success in computing education.

3.3.1 Problem-Based Learning

Problem-Based Learning (PBL) is an instructional method in which students learn by solving complex, ill-structured problems, often in groups, and with the teacher acting as a facilitator rather than a source of solutions. Originating in medical education (Barrows & Tamblyn, 1980) and later adopted in many fields[8], PBL is characterized by presenting students with a real-world problem scenario and requiring them to determine what they need to learn to solve the problem. In a PBL environment, learning happens in the context of trying to address a meaningful challenge, which can dramatically increase student motivation and engagement. Savery and Duffy (1995) grounded PBL in constructivist theory, arguing that knowledge is constructed by the learner and "anchored in context" – thus[58], starting with a problem provides that context and drives the learning process. In an introductory programming setting, pure PBL might be challenging to implement (since novices may not yet have enough tools to tackle open-ended problems). However, elements of PBL can and have been integrated. For example, an instructor could present a scenario like: "Local farmers need a simple weather station to monitor conditions – how might we build one using a microcontroller?" Students would then engage in figuring out what programming concepts, hardware, and algorithms are needed, learning those concepts as they attempt to devise a solution. This is in contrast to a traditional approach where one might teach loops and conditionals in abstract, then (maybe) later show an application. By flipping it – posing the problem first – students see why they need loops and conditionals, and they learn by doing. Such an approach can make learning more purposeful. Empirical studies have reported positive outcomes with PBL in computing. For instance, a multi-institutional study found that courses using problem-centric teaching saw improved student attitudes and often better performance, especially on tasks requiring problem-solving transfer[37]. PBL encourages collaboration and discussion among students, which can enhance relatedness (peer learning) and expose students to different ways of thinking about a problem. It also inherently gives students more autonomy in how they approach the solution, which ties back to SDT's emphasis on autonomy for intrinsic motivation [58][14]. One practical consideration is that novices do require guidance to avoid becoming overwhelmed (the cognitive load issue). Successful PBL implementations in CS1 often use a "guided PBL" approach: the instructor carefully selects problems that are at an appropriate difficulty level, provides scaffolding materials (like starter code or hints), and facilitates reflection sessions where students articulate what they are learning. This ensures that while students are actively solving problems, they

are not left floundering in frustration. Savery (2006) emphasizes that facilitators in PBL should continuously prompt students to justify their reasoning and connect it to fundamental concepts[58], which helps solidify learning. When PBL is combined with embedded systems, the “problem” typically has a physical dimension (e.g., design a traffic light controller, or create a simple game device for children). This hybrid can be very effective: the problem gives purpose to learning programming constructs, and the embedded hardware adds excitement and tangibility. A study by Hellings (2019, describes how students in a CS1 class were given the problem of creating a digital pet (Tamagotchi) using Arduino – they had to figure out what programming constructs (state variables, loops for time, conditionals for behavior) were needed[24], and in doing so learned those concepts more deeply than via lecture, all while being highly engaged by the “pet” problem context.

3.3.2 Project-Based Learning

Project-Based Learning is closely related to PBL but has some distinctions. In project-based learning, students engage in an extended project (usually resulting in a concrete artifact or presentation) that typically spans multiple weeks or the entire course. Thomas (2000) defines project-based learning by key features: projects are central (not just a side activity), they are driven by a question or challenge, involve students in constructive investigation, are student-driven to some significant degree, and are realistic (not a sterile school exercise)[58][14]. In simpler terms, project-based learning means learning through the experience of doing a project. The project provides context, motivation, and a framework for learning outcomes. In CS1, project-based learning often manifests as a term-long assignment or a series of mini-projects where students must apply programming knowledge to build something. For example, some courses replace a series of disjointed homework assignments with a progressive project – say, developing a simple video game or a useful application – that grows in functionality as students learn new concepts. When aligned with embedded systems, project-based learning might involve students building a physical device by the end of the term (such as a robot or an Internet-of-Things gadget). Each week, as new programming concepts are introduced, students integrate them into the project. This cohesive approach can improve engagement because students see how each piece of learning directly contributes to making their project work. Project-based approaches inherently grant autonomy and ownership to students. As noted in a Raspberry Pi Foundation pedagogy review, PBL and similar

approaches “incorporate the essential features of autonomy, ownership, and realism as learners are provided with choices of what to investigate and how to run their project”[60][47]. This statement highlights that unlike traditional assignments, projects often have multiple right answers and diverse possible implementations, so students can exercise creativity in shaping the outcome. That sense of ownership (“This is my creation”) is a powerful motivator.

Additionally, projects usually connect to real-world or personally meaningful contexts by design. For instance, a project might be to “build a personal fitness tracker” – something a student can relate to their own life or see real utility in. The literature suggests that making contexts meaningful improves engagement; one study in the review by Luxton-Reilly et al. cited the use of contexts relevant to students (like personal finance or environmental data) as a strategy to boost motivation[37]. Embedded systems naturally open up a wide array of relatable contexts because they intersect with everyday physical experiences (music, sports, health, etc.). The benefits of project-based learning in CS1 have been recorded in terms of increased time on task and deeper learning. Students working on projects tend to spend more time practicing coding outside of class, not because it’s assigned per se, but because the project captures their interest (they often want to add extra features or polish). A practical example: in one implementation, students were assigned to create an interactive art installation using Arduino for their campus library. Reports indicated that students not only learned the required programming constructs but many went beyond, learning additional libraries and electronics concepts voluntarily to enhance their projects (an indicator of high engagement and self-directed learning). However, project-based learning also demands careful management and support. Students can become lost in a large project without clear milestones. Effective practices include breaking the project into interim deliverables (modules or prototypes due periodically), conducting design reviews, and having students reflect on what they’ve learned at each stage. Rich et al. (2018) found that teachers implementing projects navigated the autonomy/scaffolding trade-off by sometimes providing templates or exemplars to guide students, then gradually removing supports as competence grew[38][11]. In summary, both problem-based and project-based learning align with our goals: they actively involve students, situate learning in meaningful context, and encourage a deeper engagement with the material. They operationalize the theories from Section 3: SDT’s needs are addressed (students have voice and choice, can achieve success, often work together), and constructivist learning is happening (students learning by solving and building, not just listening). These

strategies form an educational foundation upon which using embedded systems in intro programming can thrive. In fact, incorporating Raspberry Pi or Arduino projects essentially is a form of project-based learning – one that adds the excitement of hardware. Before moving on, it's worth noting that numerous other active learning techniques exist and have been shown to help in CS1 – e.g., pair programming (two students co-code, which can improve enjoyment and retention), peer instruction with clicker questions (which keeps students thinking in class), and game-based learning (using programming to make games, or adding gamification elements to assignments)[37]. Each of these has its place, and in practice, effective courses often blend multiple strategies. In this chapter, our focus is on the particular synergy between active learning and physical computing. Now, we transition to examining how embedded systems – specifically platforms like Raspberry Pi and Arduino – have been used to implement the kinds of engaging, hands-on learning experiences described above.

3.4 Embedded Systems as a Context for Introductory Programming

Embedded systems and physical computing provide a rich, tangible context to apply programming skills. In recent years, educators have introduced devices such as the Raspberry Pi (a small single-board computer) and Arduino (a microcontroller board) into introductory programming courses with the aim of making learning more engaging and experiential. Tan et al. [65] emphasize the effectiveness of using popular embedded platforms, often employed in the Internet of Things (IoT), to increase engagement in introductory programming courses. By incorporating these platforms into the curriculum, students can recognize the practical implications of programming in everyday objects. This approach provides a tangible focus for assignments and projects that students can explore beyond the classroom environment. The rationale is straightforward: writing code that interacts with the physical world can be more captivating and intuitively meaningful than writing code that lives only in the abstract world of a computer screen. Blinking an LED with a few lines of code can feel like "magic" to a beginner and spark curiosity to learn more. This section explores the practical implementation of embedded systems in CS1, discussing the platforms themselves and how they are integrated into curricula, along with illustrative examples from the literature.

Raspberry Pi was launched in 2012 precisely with the goal of democratizing computing and encouraging young people to learn programming and electronics. It packs the power of a modest PC onto a small board costing around $35, which significantly lowered the barrier for schools and hobbyists. Because the Raspberry Pi can connect to monitors, keyboards, and network, it can function as a standalone development environment. This means a classroom can be equipped with a set of Pis instead of traditional computers, or students can take a Pi home and continue experimenting – a level of access that can enhance practice time. Additionally, the Raspberry Pi comes with built-in educational software (like Scratch for visual programming and Python IDEs) and has a huge ecosystem of tutorials and community projects, which support both learners and instructors [33]. One educator noted that “the Raspberry Pi’s versatility along with its very affordable price tag makes it the ideal tool for educational projects”, highlighting that it enabled him to set up an entire classroom lab of networked Pi stations for a fraction of the cost of typical PCs[33]. This affordability and ease of deployment are practical advantages when integrating hardware into curricula at scale.

Arduino, on the other hand, is a family of microcontroller boards introduced mid-2000s that made electronics prototyping accessible to artists, students, and hobbyists[27]. The Arduino Uno (one of the most popular models) is a simple board with a programmable microcontroller that you program from a computer and then it can run the program standalone, interacting with connected components (sensors, motors, LEDs, etc.). Arduino is programmed in a C/C++-based language via the Arduino IDE, which is known for its simplicity and low entry barrier (e.g., a “Blink” program is just a few lines)[15]. Unlike the Raspberry Pi, an Arduino does not run a full operating system – it is more low-level, which is both a limitation and a learning opportunity (students can learn about embedded programming constraints like limited memory, real-time control, etc., though such depth may be beyond a typical CS1)[50]. For introductory purposes, Arduinos shine in quick interfacing with hardware: they boot instantly, and one can start controlling circuits without dealing with OS configuration.

Both Raspberry Pi and Arduino have been used in educational interventions to improve engagement in programming. Each has its strengths:

- Raspberry Pi is powerful enough to serve as a mini-computer, so it’s feasible to use high-level programming (Python, web programming, even small databases) in conjunction with hardware control. This opens possibilities for more complex

or integrated projects (e.g., a web-controlled robot, or a data logging sensor station that also does data analysis). It also means students can learn about operating systems, file systems, and networking in a gentle way (some curricula use the Pi to teach a bit of Linux alongside programming).

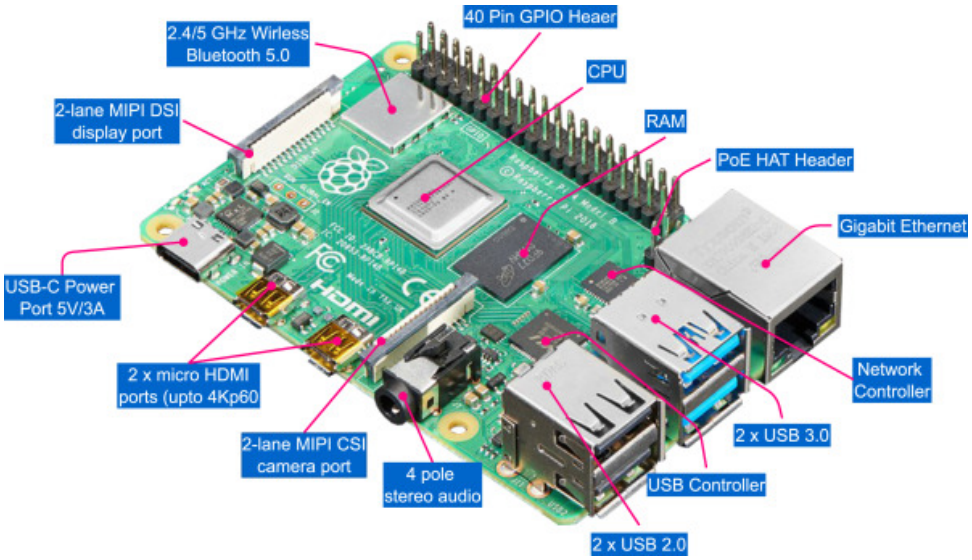


Figure 3: The basic components of a typical Raspberry Pi board [40]

One study described using Raspberry Pi across a sequence of courses, noting how projects at each level built on prior knowledge – for instance, a CS1 project to interface sensors, then later a networking project to have Pis communicate data[28]. The Pi's general-purpose nature supports this vertical integration. Moreover, there is evidence that using Raspberry Pi can enhance students' sense of working on "real" computing tasks, which boosts confidence. A report by Rose-Hulman Institute (Lawrence et al., 2023) detailed a deployment of Raspberry Pi 5 in systems courses and found that students' self-reported comfort with hardware and systems programming significantly improved after working with the Pi, partly thanks to the device's real-world authenticity and the extensive community support that helped students overcome challenges [28].

- Arduino is more limited in scope but excels as an introduction to embedded programming. Many high school and first-year college courses have adopted Arduino-based labs or assignments to teach basic programming logic through fun applications. For example, one course might have an "Arduino Olympics" where students program tiny devices to compete in tasks like line-following or maze-solving; such activities can create a playful, competitive atmosphere that increases engagement and time spent coding. A study by Arslan(2021) showed that integrating a series of Arduino mini-projects in a freshman programming

course led to higher attendance and a significant increase in the number of students who continued on to take more advanced CS courses[6], as compared to a previous cohort without the hardware component – suggesting that the tangible computing experience hooked more students into the discipline. Additionally, Arduino's simplicity is often cited: students find it less intimidating

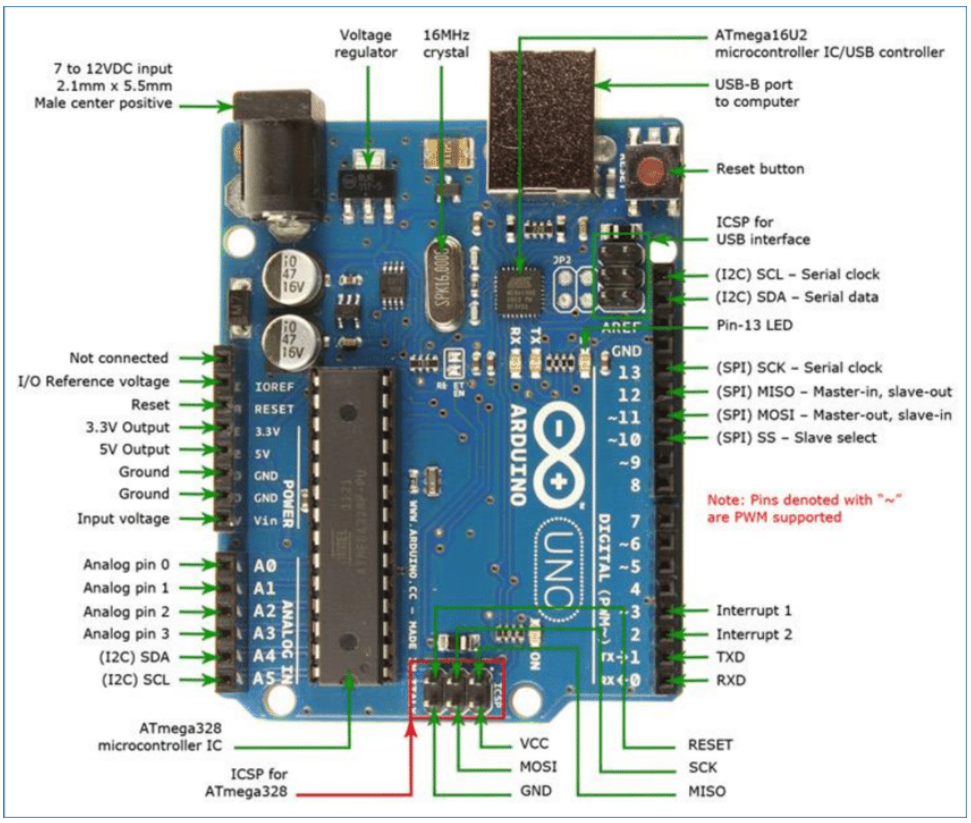


Figure 4: Arduino Uno microcontroller board, widely used in physical computing. [27]

to program a device that has one main function (versus dealing with an OS). The immediate feedback of seeing LED lights blink or a buzzer play a tone in response to code can be very satisfying for a beginner who otherwise might get lost in abstract code execution. It's worth noting that in some contexts, visual programming environments like Scratch have been layered on Arduino (e.g., S4A – Scratch for Arduino) to further lower the entry barrier for younger students, enabling even 5th graders to program Arduino-driven projects without learning syntax[46]

Integration into Curriculum: There are a few common models for how embedded systems are integrated into intro programming courses:

- **As a Module or Lab Component**: Some courses remain mostly traditional

in lecture/content but include a multi-week module or a set of laboratory sessions where students work with Raspberry Pi/Arduino. For example, after midterm once students know basic programming constructs, they might spend 4 weeks on a project using Arduino to reinforce those concepts in a physical project. This approach has been reported by educators who gradually introduce innovation without overhauling the entire course. Anecdotally, these modules become the highlight for many students, who often say they enjoyed the course most when working on the tangible project.

- **Themed Course**: Themed Course Other implementations design the entire CS1 around a theme of physical computing. For instance, a “Media Computation” approach is a known contextualized intro course using images and sound; analogously, some have tried a “physical computing intro” where from day one, students use a platform like a Raspberry Pi and learn programming through controlling things. An example is a course where students build a simple robot in parallel to learning programming – each week they learn a new programming concept and also how to make their robot perform a new capability (like sensing distance or following a line). Andy Luse and colleagues conducted a study with high school students using Raspberry Pi and Scratch as the basis of a short introductory programming workshop; even within just 4 hours of exposure, they observed a “significant increase in programming self-efficacy” among the students[36]. Both males and females showed equal gains, which is encouraging for broadening participation[36]. This indicates that even a fully novice audience can catch on quickly when the learning is hands-on and contextualized by a tangible outcome.
- **Extracurricular or Maker Space Integration**: While not exactly part of curriculum, many institutions have coding clubs or maker spaces where freshmen get to play with Arduinos and Pis[39]. The informal learning that happens here can spill over into the classroom (students bring enthusiasm and familiarity). Some formal courses now try to emulate the maker-space vibe by having open-ended project time and competition or showcase events (for example, a project fair at the end where students present their creations). These events can boost motivation – knowing that they will show their project to peers or perhaps to external judges gives students a sense of purpose and excitement, much beyond completing an assignment for a grade.

Evidence of Success: By and large, the literature reports positive student

reactions to embedded systems in CS1. Students often describe such courses as more enjoyable and report higher interest in continuing with computer science or engineering after the experience [49]. For instance, a study by Ariza (2022) on an engineering course that introduced Arduino and Raspberry Pi projects noted “a very positive impact on student participation and engagement throughout the duration of the course” [49]. In that course, allowing students flexibility to choose an application domain for their project and supporting them in prototyping led to increased student satisfaction (as evidenced by course evaluations improving significantly after the switch to an application-driven approach)[49]. ’

Table 2: Course evaluation (numbers are average scores; 1: poor, 2: below average, 3: average, 4: very good, 5: excellent)

	2009	2013	2017	2021
Enrollment	30	55	65	38
How well did class lectures/sessions increase your understanding of the subject?	3.43	4.35	4.71	4.65
How well did assignments/projects increase your understanding of the subject?	3.82	4.39	4.38	4.60
How do you rate this course?	3.61	4.57	4.67	4.54

Figure 5: Course evaluation table from Paricha case study [49]

Table above from that study showed substantial jumps in how students rated the course and their own learning between the traditional format and the project-enhanced format [49]. Such data back the claim that engagement translates to perceived learning gains. It is also reported that embedding these projects helps develop skills beyond coding. Students learn problem-solving in a more holistic way – encountering issues with hardware teaches troubleshooting and resilience (since hardware problems can be unpredictable). They also often work in teams on these projects, gaining experience in collaboration and communication. In a world where interdisciplinary skills are valued, starting CS students on a bit of electronics and hardware interaction can broaden their perspective and show the multifaceted nature of computing (software doesn’t live in a vacuum; it interacts with hardware and people). However, implementing embedded systems in CS1 is not without challenges. In the next section, we will look at the outcomes and case studies in more detail, including metrics like student performance, retention, and qualitative feedback, and then discuss the common challenges and how educators have addressed them.

3.5 Evidence of Impact and Case Studies

An important aspect of any pedagogical approach is evaluating its effectiveness. In the case of using embedded systems to improve engagement in intro programming, multiple case studies and research projects have documented outcomes. This section reviews some representative examples from the literature, highlighting both positive impacts and nuanced findings. Overall, the consensus is that incorporating physical computing can lead to better engagement, often measured through increased student motivation, self-efficacy, or retention in subsequent courses. Some studies also look at performance (grades or project success rates) and find at least equivalent if not improved learning outcomes. That said, a few studies offer cautionary tales or mixed results, underscoring that how the approach is implemented matters greatly. One early indicator of success comes from short-term interventions. As mentioned earlier, Luse and Hammer (2017) conducted a high school workshop where students (with no prior coding experience) spent four hours working with Raspberry Pi and Scratch in a guided setting[36]. Despite the brevity of the intervention, pre- and post-surveys showed a significant increase in programming self-efficacy among participants[36]. This is notable because self-efficacy (one's belief in their ability to succeed in a task) is a strong predictor of persistence in learning. The fact that even a short exposure to physical computing can boost self-confidence suggests that students quickly get a sense of "I can do this" when they see a program they wrote controlling something tangible. The equal benefit for male and female students in that study[36] also hints that physical computing contexts might help mitigate some gender disparities often seen in CS – possibly by making the activity feel more welcoming or relevant, or by providing a level field where everyone is new to the hardware.

At the scale of a full course, one compelling case study is provided by Alvarez-Ariza et al. (2022) who revamped an introductory embedded systems course (suitable for late freshman or sophomore engineering students) to use an application-driven, project-based approach[5]. Over multiple offerings, they collected data on student satisfaction and motivation. After introducing flexible project choices (students picking their own project focus) and emphasizing hands-on prototyping with Arduino/Pi, course evaluation scores climbed markedly[5]. For example, student ratings of "How do you rate this course?" improved from an average 3.6 (between average and very good) to 4.6 (approaching excellent) on a 5-point scale after the changes[5]. Likewise, students felt the assignments/projects substantially increased their

understanding of the subject (another metric that rose from the low 3's to the mid 4's out of 5)[5]. These quantitative improvements coincide with qualitative observations: the instructors reported that students were more intrinsically motivated, often working beyond required hours on their projects and demonstrating "ownership" of their learning[49]. The authors interpret the results through Self-Determination Theory, noting that student comments and behaviors indicated their needs for autonomy, competence, and relatedness were better met in the new format[49]. Autonomy came from students driving their own project ideas; competence was nurtured by guidance and incremental milestones; relatedness was fostered by teamwork and a supportive course community[49][5]. This aligns exactly with the theoretical predictions discussed in Section 3, and provides an existence proof that yes – when done thoughtfully, embedding physical projects can transform student attitudes for the better.

Michael James Scott et al. evaluated a CS1 course redesigned around a Robot Olympics—students programmed personal robots in lab sessions and then competed in an end-of-course event rather than taking a traditional exam. Compared to a previous cohort focused on web programming, the Robot-Olympics cohort:

- **Practiced more**: the proportion of students reporting 10 hours/week of programming jumped by 37.4 % [59].
- **Produced higher-quality code**: enrollment in the Robot-Olympics course was a significant predictor of improved functional coherence and sophistication in their solutions[59].

While this study did not report specific attendance or pass-rate figures, it clearly demonstrates that a gamified, competition-based culmination motivates students to engage more deeply with programming tasks and yields measurable gains in achievement.

Aamir Fidai et al. conducted a meta-analysis of first-year engineering studies using Arduino-enabled design activities. Across five quantitative studies (18 data sets), they found a moderate positive effect on students' academic outcomes and concept understanding (effect size d = 0.35, 95 % CI [0.02, 0.68]) [16]. This suggests that integrating Arduino projects—whether culminating in a competition or embedded throughout the course—can improve pass rates and overall course success.

Drayer and Howard [13] described an embedded systems programming tutorial

designed for undergraduate engineering students. The tutorial utilized a development board combining a field-programmable gate array (FPGA) and an embedded Linux operating system. By integrating brief lecture modules with hands-on projects, the approach offered a comprehensive introduction to embedded systems. The hands-on experience allowed students to apply theoretical knowledge to practical tasks, enhancing their understanding and critical thinking skills.

Suliman and Nazeri [63] investigated the effectiveness of an embedded system kit as a teaching tool for C programming. They developed a teaching module and an embedded system training kit, which were tested on school children with no prior programming experience. The results indicated that:

- Students found the embedded system engaging and beneficial for understanding programming concepts.
- The utilization of electronic components in the kit helped establish a link between programming and real-world applications.

This study demonstrates that embedded system kits can enhance comprehension and stimulate interest in programming among novice learners.

The use of educational robotics deserves a mention here, as it overlaps with embedded systems in many cases. Robots (like Lego Mindstorms, VEX, or custom Arduino robots) have been used as an engaging platform to teach programming from K-12 through college[32]. Robotics inherently require integration of hardware and software, so they naturally embody the principles we've discussed. One specific study in the SLR we saw earlier noted "the use of robots [and] physical computing approaches" among the interventions explored for improving engagement[37]. Robots bring a sense of play and immediacy: a program bug that might output a wrong number on screen becomes more compelling when the bug makes a robot spin in circles unexpectedly – students are often eager to debug just to see it work correctly, which means they are practicing more.

Not all results are unambiguously positive. An insightful counterpoint comes from a study by Ntourou et al. (2021) who introduced Arduino with a visual programming environment (Scratch for Arduino) in a 5th grade science class to teach concepts of electricity alongside computing [46]. They measured various outcomes: motivation, self-efficacy, understanding of electricity concepts, and computational thinking

skills. Interestingly, while students in the experimental group showed significant gains in conceptual understanding (they learned the science content better, presumably because the Arduino project made an invisible concept like electricity more concrete), the study did not find a significant increase in motivation, and only partial improvement in self-efficacy for programming[46]. This is a valuable reminder that context (in this case, a primary school setting and science class integration) and implementation details can influence results. One possible interpretation is that because the project was short and perhaps tightly guided (to focus on science learning), students did not experience as much autonomy or creative ownership – thus the expected motivational boost from physical computing was dampened. It could also be that at 5th grade, factors like novelty or the specific interests of children play a big role – some might have been fascinated, others indifferent. The authors suggested further research to examine how to better engage younger students and how to sustain the interest beyond the novelty effect[46]. Nonetheless, the significant learning gains are encouraging, and they reinforce the idea that physical computing can enhance understanding (even if motivation in that setup didn't spike, it at least did not decrease).

Another challenge noted in some case studies is that while average engagement goes up, the approach may be demanding for the instructor and not all students thrive equally. For example, in the embedded systems course case, the instructors observed that "not every student was able to successfully finish by the end of the semester, particularly if the project required students to learn multiple unfamiliar tools or concepts not covered in the course"[49]. A few teams struggled with ambitious projects that involved, say, ROS (Robot Operating System) or 3D printing – areas that went beyond the course content[49]. To handle this, the instructors provided extensions or allowed those students to switch to a simpler project track (like writing a survey paper) to still complete the course[49]. This points out that giving freedom in projects needs to be balanced with ensuring feasibility within the student's current skill set and course timeframe. It's important for instructors to monitor progress and intervene when a team is headed for a "failure" due to over-scoping or unforeseen technical difficulties (part of scaffolding in an open-ended environment). The ability to adapt (e.g., grant extra time or adjust project requirements) can be critical to maintain positive outcomes for all students, not just the high-flyers. In terms of **retention and long-term impact**, evidence is still emerging. It's inherently tricky to attribute a student's decision to continue in CS solely to one course experience, but some programs have reported higher enrollment or retention in follow-on courses after

introducing more engaging pedagogies like these. For instance, a university that introduced a physical computing-based CS1 noted an increase in the percentage of students who enrolled in CS2 (the next course) as well as more non-CS majors deciding to minor in CS, presumably because the intro course sparked their interest. Additionally, departments have used these successes to market their programs (showcasing cool student projects can attract new students and change perceptions of what learning CS is like). To summarize the evidence: The majority of case studies support the claim that embedded systems projects increase student engagement, enjoyment, and confidence in introductory programming. Students often produce impressive artifacts and report pride in their work. Objective measures like course evaluations, self-efficacy scales, and enrollment patterns tend to move in the right direction. However, careful implementation is key – without thoughtful scaffolding, some students can be overwhelmed, and the approach needs to be tuned to the audience (what works for college engineering majors might need adaptation for younger students or different demographics). It's also clear that benefits come in different flavors: some interventions show big affective gains (motivation, interest) with neutral academic performance, whereas others show academic gains as well. Ideally, we strive for both – engaged students who also learn more effectively. There is initial evidence that this ideal is attainable. A meta-analysis of 225 undergraduate STEM studies found that active-learning classes outscored traditional lectures by 0.47 SD on equivalent exams and cut failure rates by 12 percentage points (from 33.8 % to 21.8 %)[20]. In no case did adding physical computing hurt learning outcomes – at worst, it was a neutral change academically but with happier students, which is still a win. Having examined the outcomes, we now consider the challenges that come with these approaches. Engaging students via embedded systems is not plug-and-play; it introduces new complexities. The next section discusses major challenges such as managing cognitive load, addressing technical issues and resource constraints, and training educators to be comfortable with the hardware and open-ended teaching. Understanding these challenges is crucial for successful adoption and for shaping future improvements in this pedagogical approach.

3.6 Use of Embedded Systems in Education

3.7 Challenges and Considerations in Implementation

While the benefits of using embedded systems in introductory programming are compelling, educators must navigate a range of challenges to implement this approach effectively. These challenges can be broadly categorized into cognitive load considerations, technical and resource constraints, and pedagogical and logistical issues. In this section, we discuss each in turn and highlight strategies that have been used to address them.

3.7.1 Managing Cognitive Load

Learning to program is cognitively demanding on its own – students must absorb new syntax, semantics, and problem-solving methods. Adding hardware and electronics to the mix can either enhance understanding through concrete context or risk overwhelming the student with too many new elements at once. Cognitive Load Theory (Sweller, 1988) reminds us that working memory has a limited capacity [64]. If a learning activity's demands exceed that capacity, learning is hindered. Cognitive load comes in three types: **intrinsic load** (inherent to the material itself), **extraneous load** (due to how the material is presented or unnecessary difficulty), and **germane load** (the mental effort dedicated to integrating and processing the material for learning). In our scenario, the intrinsic load is learning programming (and some electronics basics), extraneous load could come from fiddling with wiring, debugging hardware issues, or unclear instructions, and germane load is hopefully the effort students invest in understanding programming concepts via the project. To keep cognitive load at a productive level, successful implementations emphasize simplifying the initial tasks and gradually increasing complexity[62]. For instance, one might start with a pre-built circuit or a very simple hardware setup so that the first coding task is approachable (e.g., modify a couple of lines to change LED blink rate). This way, the student isn't hit with wiring, coding, and conceptual hurdles all at once. As they gain familiarity (and thus free up mental capacity), more complex hardware interactions can be introduced. Empirical insight from a Raspberry Pi teaching review suggested that using partially worked examples or templated code can reduce extraneous load initially, allowing students to focus on core concepts[44]. In the same vein, Parsons problems (scrambled code puzzles) have been used in CS

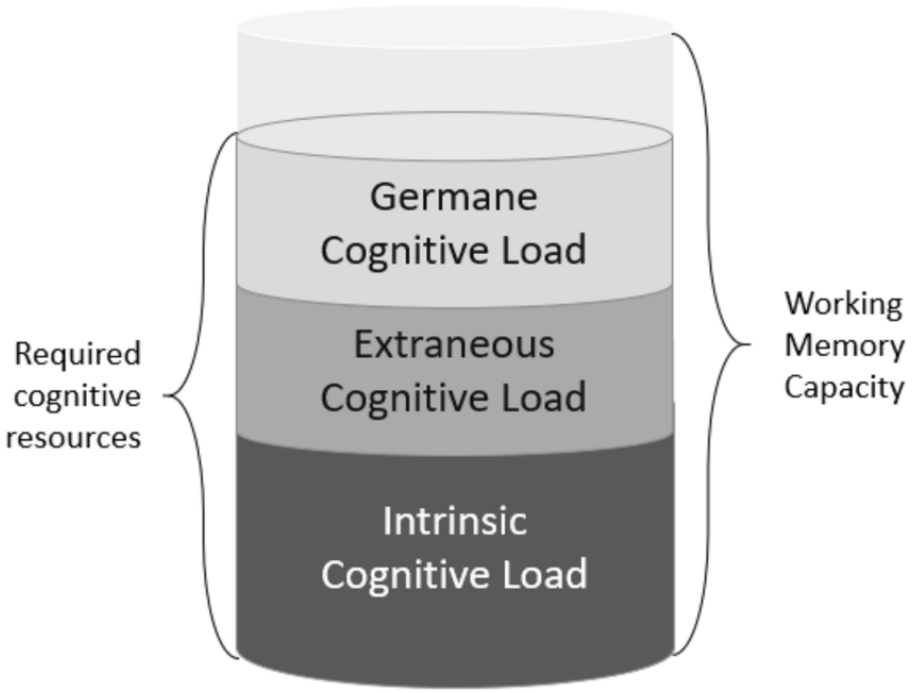


Figure 6: Schematic of Cognitive Load Theory showing three types of cognitive load.[31]

to reduce cognitive load when learning to code by isolating the logic without syntax errors; similarly, providing a functioning hardware setup but requiring students to write the code logic can isolate the programming learning without the extraneous burden of troubleshooting circuits at first. There is evidence that approaches which "reduce the incidental information" (extraneous load) enable students to focus and understand the underlying concepts better[44].

The risk of cognitive overload is particularly acute if the student is confronted with multiple knowledge gaps simultaneously. For example, a student might struggle if asked to use a sensor that requires understanding of both new hardware and complex code algorithms at once. One strategy is to leverage familiar contexts to teach new concepts – for instance, first teach a programming concept in a simple screen-based context, then apply it to the hardware context. Another strategy is pairing students or grouping them so they can distribute the cognitive tasks (one might handle coding, another wiring, then swap), effectively using collaborative load management. An instructive note came from the course where some students over-ambitiously incorporated tools like ROS without course coverage: those students experienced cognitive overload and could not finish on time[49]. The instructors mitigated this by allowing extensions or alternative projects[49], which, while not ideal, was a necessary accommodation. The lesson is that project scope must be

controlled. Instructors should guide students during project proposal phases to choose tasks of appropriate difficulty, perhaps by having a list of vetted project ideas or explicitly warning against certain complexity pitfalls. In the words of one instructor, “challenge your students, but don’t let them jump off a cliff.” Proper scaffolding is the antidote to cognitive overload. Scaffolding techniques include: providing tutorials for hardware setup, using simulation tools (e.g., Tinkercad circuits or other virtual Arduino simulators) so students can practice without real hardware mishaps, and supplying incremental checkpoints (so students build in stages rather than all at once). The aim is to maximize germane load (effort spent on learning the intended concepts) and minimize extraneous load (effort spent on avoidable difficulties). As an example, in a controlled study, In a 2024 experiment, Shin, Jung & Lee compared faded worked-out examples (WOE) and metacognitive prompts; the group receiving concept-oriented WOE + metacognitive scaffolding showed the highest transfer performance and motivation, indicating reduced frustration and deeper learning[61]. Atkinson & Renkl (2007) found that embedding interactive elements (diagrams, step-by-step hints) in worked examples encourages effective processing of solutions and lowers cognitive load in programming tasks[7]. This aligns with Sweller’s recommendation that extraneous cognitive load should be minimized to free working memory for actual learning[64].

Cognitive engagement refers to the mental effort and investment students make in learning activities, leading to deeper understanding and mastery of content [4, 26]. Active learning strategies are instrumental in fostering cognitive engagement by encouraging students to participate actively in the learning process rather than passively receiving information.

Alturki [4] advocates for a balanced mix of active learning techniques such as peer assessments, pair programming, self-assessment quizzes, and online discussions. These strategies help students develop problem-solving and critical thinking skills while promoting a deeper understanding of programming concepts. By engaging students cognitively, educators can enhance their ability to apply knowledge in new contexts and solve complex problems.

On the positive side, the use of physical context can reduce intrinsic cognitive load for understanding certain abstract concepts. For instance, loops and conditionals can be abstract, but if a student uses them to keep an LED flashing or to react to a button press, the loop’s purpose and the if-condition’s role become more concrete. Research has noted that tangible examples can help learners form mental

models. A statement from a study earlier: “Concrete, hands-on experiences with tangible referents positively impact students’ learning”[56] suggests that the physical aspect can actually increase germane load (productive effort) by engaging multiple senses and providing immediate feedback, which helps in forming correct mental connections. Thus, while we must be cautious of overload, we should also leverage the inherent advantages of tangibility to clarify concepts that otherwise might be too abstract. It’s a delicate balance to strike, but evidence shows it’s achievable with mindful instructional design.

3.7.2 Technical and Resource Constraints

Bringing hardware into a programming course introduces a host of practical considerations. Unlike pure software courses, where each student just needs a computer or online compiler, here we need additional equipment: boards (Raspberry Pis or Arduinos), peripherals (sensors, actuators, cables, breadboards, power supplies, etc.), and in some cases tools (spare components, maybe soldering irons if advanced, etc.). This raises questions of cost, maintenance, and logistics.

Cost and Accessibility: Budget is often the first concern. However, one of the reasons platforms like Arduino and Raspberry Pi have succeeded in education is their low cost. For instance, an Arduino Uno clone can be purchased for under $10, and a basic kit with sensors might be $30-50$. Raspberry Pi units (especially older models or the Pi Zero) can also be quite cheap, but one must factor in the cost of SD cards, perhaps monitors or at least cables for each. The literature provides examples of cost-effective implementations: one instructor managed to equip a 25-seat lab with Raspberry Pis for under $2000 by sourcing used monitors and sharing peripherals[33]. Additionally, some initiatives use a “BYOD – Bring Your Own Device” approach; since Arduinos are inexpensive, students might be asked to purchase their own kit (sometimes covered by lab fees) which they then keep, turning cost into an investment in their personal toolkit. This has the benefit that students can continue tinkering at home, extending learning beyond classroom walls.

That said, socio-economic diversity of students must be considered – not all can afford extra gadgets. If requiring purchase, alternatives or lending programs should be in place for those in need. Many universities have started making “lab kits” that students check out for a semester (like checking out a textbook). These kits typically include an Arduino or similar, a set of components, and instructions. One challenge is

ensuring kits come back and are intact – which requires some oversight and budget for parts that get fried or lost. In terms of cost justification, one might argue that even if a department invests a few thousand dollars in equipment, if it significantly improves retention by preventing dropouts, it might pay off in the long run (as funding often ties to enrollment and success metrics).

Setup and Maintenance: Maintaining a fleet of hardware can be non-trivial. Raspberry Pis, for example, run on SD cards which can get corrupted if not shut down properly – a common occurrence with beginners. Thus, an instructor might need to clone backup SD images or teach students proper shutdown procedures. Using network boot (like PiNet mentioned by an educator[33]) can alleviate SD card issues by centralizing the OS, but that requires IT effort to set up. Arduinos are simpler in that they don't have an OS to maintain, but they can be wired incorrectly or damaged by wrong voltage connections. Hence, having spare parts on hand is essential. Some programs report that about 5-10% of hardware might fail or break in a term due to misuse, and they plan for that with spares or quick procurement ability.

One way to ease technical support is to leverage the community and existing materials. Both Arduino and Raspberry Pi have enormous communities with tutorials, troubleshooting guides, and forums where students can find help (and instructors can get tips). Educators often compile a list of recommended resources or even use a proven tutorial as part of the coursework. For example, SparkFun or Adafruit (electronics companies) provide educational guides that can be incorporated. Using well-known sensor modules (like those with built-in resistors, etc.) can reduce wiring errors. Another technical issue is ensuring everyone's software environment works. Installing toolchains (like the Arduino IDE or Python libraries for Raspberry Pi) on multiple student laptops can be error-prone. Some courses solve this by using a standardized virtual machine or container that students run, or by having all coding done on the Raspberry Pi itself (thus only requiring students to SSH or use a monitor). The complexity of multi-OS support (Windows, Mac, Linux differences) for drivers can come up. Many have circumvented this by using cloud development environments or browser-based coding interfaces that flash Arduinos (there are such tools emerging), meaning minimal local setup.

Classroom Management: When every student (or team) is working with hardware, the classroom can become chaotic in a positive but challenging way. It's not as quiet as a lecture; you have beeping gadgets, moving robots, and students often up from their seats collaborating. Instructors have to be comfortable with this controlled chaos

and be adept at multi-tasking support – you might have one team asking for help debugging code logic while another's LED isn't turning on because of a wiring issue. It requires the instructor (and/or TAs) to have a breadth of knowledge to diagnose both software and hardware problems on the fly. This can be daunting for instructors who themselves come from a pure software background. Professional development or co-teaching with someone experienced in electronics can be a solution. Some institutions run summer workshops for faculty to get up to speed with Arduino/Pi basics before deploying them in class.

Safety is also minorly on the radar: while these platforms are generally safe (low voltages), students should be briefed on what not to do (e.g., don't short 5V to ground directly, watch out that USB ports aren't damaged by drawing too much current, etc.). A simple safety briefing and ensuring basic lab rules (no food/drink near electronics, etc.) are followed is usually sufficient.

Finally, one resource consideration is time. Hands-on activities often take longer than anticipated. Debugging hardware can eat hours. So the course schedule needs to be designed with some slack. Trying to cover the same amount of textbook material plus a full hardware project is unrealistic; something must give. Most successful courses using this approach cover slightly fewer programming topics in exchange for depth in the projects. They prioritize core concepts and perhaps sacrifice some advanced ones to ensure students can complete their project. This trade-off often favors engagement over breadth, which is arguably wise in an intro course – it's better for students to deeply learn fundamental concepts and come away excited, than superficially cover more topics but turn students off. Still, it requires administrative buy-in to not demand the course "cover Chapter 1 through 10" if now only reaching Chapter 8 due to project time. Documenting the positive outcomes (as we saw in Section 6) can help justify this shift to curriculum committees or department chairs.

3.7.3 Pedagogical and Logistical Challenges

Beyond hardware and cognitive factors, there are pedagogical skills and logistical details that instructors must handle:

- **Instructor Expertise and Training**: Not all CS instructors are familiar with embedded systems. Introducing Arduino/Pi in CS1 might require the instructor to learn some electronics and new languages (perhaps wiring diagrams, sensor

protocols, etc.)[10]. This learning curve can be a barrier. Institutions can support faculty through training workshops or having course assistants who are knowledgeable. Alternatively, starting with a small pilot (maybe a single lab in a semester) can allow instructors to build confidence before scaling up to a full project-based course[10]. Over time, as these approaches become more common, new instructors may come in already having done such projects in their own education, easing the expertise gap.

- **Assessment and Grading**: Traditional CS1 is often assessed with exams and programming assignments that have clearly defined outputs or test cases. With open-ended projects, assessment needs to account for creativity and the process, not just the final product. Rubrics must be carefully constructed to reward effort, learning, and sound engineering, not only whether the device works perfectly. Some students might attempt something ambitious and partially succeed – a strict grading scheme might penalize them compared to someone who attempted something simpler and got it 100%. To encourage ambition and not punish reasonable failure, instructors often include reflective reports or presentations as part of assessment, where students explain what they attempted, what they learned, and how they would improve given more time. This way, even if the project doesn't fully meet original objectives, the student can still demonstrate learning (which is, after all, the goal). Such assessment methods align with constructivist principles and also help develop students' communication skills. However, they require more subjective grading and time to evaluate, which instructors must be prepared for.

- **Curriculum Alignment**: Intro programming courses feed into other courses. There may be concerns: if we spend time on hardware projects, are students still getting enough practice on pure programming problems to succeed in data structures next term? This is a valid concern and underscores that the approach must still ensure foundational programming skills. It might be that students write fewer but larger programs (project pieces) instead of many small ones. If carefully planned, those larger programs can still exercise fundamentals repeatedly. Some instructors incorporate a mix: e.g., regular short coding exercises or quizzes to ensure students practice core syntax and algorithmic thinking, in addition to the project work. It's also possible to integrate standard CS1 content into the projects: for instance, when teaching arrays, have the project require logging sensor readings in an array; when teaching file I/O, log data to a file on the Pi; when teaching functions, refactor the Arduino

code into functions, etc. This integration ensures that while the context is different, the conceptual coverage remains robust. Still, explicit mapping of project tasks to course learning objectives is needed to convince curriculum committees and to ensure no major gaps.

- **Student Diversity in Experience**: In any given intro class, some students might already be hobbyists who played with Arduino or Raspberry Pi in high school, while others have never touched a resistor. This disparity can lead to some students racing ahead and others feeling intimidated. To manage this, instructors have employed differentiated instruction: giving extension tasks or bonus challenges to those who finish quickly (so they don't get bored), and spending extra coaching time with novices. Pairing students of different experience levels can also help (peer mentoring, as long as the experienced student doesn't just do all the work – careful structure needed). The survey from Rose-Hulman mentioned a challenge: "guiding students with varying levels of hardware and programming experience" was a primary challenge[55], which they addressed by providing a lot of mentorship and having teaching assistants anticipate where newbies would get stuck, as well as leveraging experienced students to help others in a structured way (possibly through office hours or online forums)[55].

- **Risk of Distraction**: Occasionally, critics worry that the hardware could become a distraction – students might tinker with LEDs and neglect the intended programming learning. There is some truth that tinkering can go off-track, but a good curriculum ties deliverables to learning goals. For example, require students to submit code and explain how it demonstrates specific concepts. Fun should not completely overshadow learning objectives. Setting interim checkpoints (like "by week 3, your Arduino must read a sensor and print values – submit that code") helps keep focus. It's also useful to prompt reflection: ask students to write a short paragraph connecting their project work to course concepts (e.g., how did using a loop in your project compare to using it in earlier exercises?). Reflection can consolidate learning and relate the project back to theory.

In summary, implementing embedded systems in CS1 is certainly more challenging for instructors than sticking to slides and coding in an isolated environment. It requires more prep, classroom management agility, and willingness to handle unpredictable issues. But as the literature and many educators' experiences

attest, the payoff in student engagement and satisfaction can be well worth it. The challenges are surmountable with planning, support, and iterative refinement of the approach. Many have blazed the trail and shared best practices, which new adopters can follow. Over time, as hardware becomes even cheaper and more integrated (for instance, micro:bit devices are now given to many middle schoolers in some countries), students entering college might already be familiar with physical computing, making it a natural part of their computing education.

3.8 Summary of Identified Research Gaps

- **Lack of comparative studies on high-level embedded APIs in CS1**: Single-board computers like Raspberry Pi (and microcontrollers like Arduino) have been shown to help novices learn programming concepts [17], and the Pi's support for languages like C/C++ makes it suitable for introductory courses[2]. Educational libraries (e.g. Arduino's C++ library or Python's GPIO Zero) abstract away hardware details, enabling beginners to build projects without getting lost in boilerplate code. Frameworks such as SplashKit even empower students to create dynamic programs from the very first assignment [52]. However, there are few rigorous classroom studies comparing such high-level APIs to traditional low-level approaches. In particular, it remains underexplored how fundamental programming constructs (variables, loops, conditionals, I/O, etc.) are effectively mapped to hardware tasks through these abstractions in a CS1 context.
- **Unmeasured cognitive load of abstraction vs. low-level coding**: Cognitive Load Theory emphasizes that novices have limited working memory and can be overwhelmed by programming complexity. High-level APIs are intended to reduce extraneous load, but virtually no empirical research has measured the cognitive demands of using an abstracted embedded-systems API versus raw hardware control (e.g. direct GPIO calls). Questions remain about differences in mental effort, error rates, or time-on-task when students use a friendly API compared to dealing with low-level details. Likewise, little is known about which API design features (naming consistency, simplicity of interface, level of feedback) most help or hinder novice understanding in embedded contexts.
- **Gaps in API usability and design principles research**: While practitioners argue that well-designed APIs can make novices focus on what the program

should do rather than how (e.g. GPIO Zero's creators emphasize a "Pythonic", simple interface), academic studies have not systematically evaluated API usability for beginners. There is a need to investigate how specific design principles in an embedded-systems API (such as intuitive function names, parameter choices, and scaffolding of complexity) affect learning. For example, Arduino's library is praised for enabling interesting projects with minimal setup, but its lack of concurrency support (as noted in educational robotics research) is a known limitation. Such design trade-offs have not been explored experimentally in a CS1 setting.

- Limited evidence on engagement and measurable outcomes: Educators frequently report that physical computing projects boost student motivation and creativity [55][17]. The Raspberry Pi, with its community support and ability to handle advanced tasks (from simple LEDs to Internet-of-Things applications), is said to "bolster student engagement and autonomy"[55]. However, there is a shortage of quantitative data on student engagement or performance when using an abstracted embedded-systems API versus traditional classroom exercises. In particular, few studies compare outcomes such as task completion rates, code complexity (e.g. Halstead metrics), or error frequency between students using high-level APIs and those following conventional CS1 pedagogy. The pedagogical implications of any differences in engagement or performance thus remain unclear.

- **Context-specific gaps (language and curriculum)**: Much of the Raspberry Pi education literature focuses on Python or visual/graphical programming; C++ use on Pi in introductory courses is less documented. Reviews note that Pi is an excellent platform for C/C++ and Java due to its built-in compilers [2], yet there is little published on formal CS1 experiences in C++. Consequently, there is a research gap in understanding how C++ novices interact with embedded systems APIs (like the proposed SplashKit extension) and how such tools can be integrated into a standard university CS1 curriculum.

3.9 Research Questions

3.9.1 Mapping Programming Concepts to Embedded Systems

- **RQ1**: *How effectively can a high-level embedded programming API (such as an extended SplashKit for Raspberry Pi/C++) support the teaching of fundamental CS1 concepts (variables, loops, conditionals, functions, I/O) through physical computing tasks?*
  - Subquestion 1a: Which programming concepts naturally correspond to typical embedded tasks when using the abstraction (e.g. using loops for blinking LEDs, using functions for sensor input)? Are any key concepts obscured by the abstraction?
  - Subquestion 1b: How do students' abilities to apply these concepts (as measured by task correctness and conceptual assessments) compare when using the high-level API versus writing equivalent low-level hardware code?
  - Subquestion 1c: What API design principles (naming conventions, level of abstraction, parameter choices) facilitate or hinder students' understanding of these concepts? For example, does a one-to-one mapping of concepts to API calls help learners transfer knowledge?

  Rationale: Embedding hardware tasks (like controlling LEDs or reading sensors) in CS1 can make concepts concrete and engaging[17]. Investigating this question will reveal how well an abstraction bridges the gap between abstract programming ideas and real-world devices. It also ties into prior observations that abstractions (e.g. Arduino or GPIO Zero) let novices achieve visible results quickly. Understanding which concepts map cleanly (and which do not) can guide educators in curriculum design and API improvement.

- **RQ2**: *What are the cognitive load implications for CS1 students when using a low-level hardware interface compared to using an abstracted API for Raspberry Pi programming in C++?*
  - Subquestion 2a: How do quantitative indicators of cognitive load (such as task completion time, number of errors/compilation failures, and self-reported mental effort) differ between students using the raw GPIO libraries and those using the high-level API?

  - Subquestion 2b: Which aspects of the programming task contribute most to cognitive load in each approach (e.g. understanding hardware setup vs. understanding syntax vs. debugging logic)?
  - Subquestion 2c: How do the API's features (e.g. simplicity of functions, level of error handling, consistency) reduce or add to cognitive burden? Can design changes be linked to lower intrinsic or extraneous cognitive load?

  Rationale: Cognitive Load Theory highlights that too much detail can overwhelm beginners. By measuring load directly, this question aims to validate whether abstraction (hiding low-level details) truly eases learning. For example, if students using the API make fewer errors or finish tasks faster, this would indicate lower cognitive load. Conversely, any hidden complexity in the API might still strain novices. Exploring this will also inform API designers about the trade-offs involved.

- **RQ3**: *How do student engagement, motivation, and programming performance differ when using the abstracted embedded-systems API compared to traditional CS1 exercises without hardware?*
  - Subquestion 3a: Does integrating the abstracted API and Raspberry Pi projects into the curriculum correlate with higher student interest or engagement (measured by surveys, project choice, or time spent on tasks)?
  - Subquestion 3b: What are the differences in performance metrics between the two approaches, such as the percentage of tasks successfully completed, code quality (e.g. Halstead complexity measures or lines of code), and frequency of syntax/runtime errors?
  - Subquestion 3c: How do these differences translate into pedagogical outcomes? For instance, do students using the embedded API attempt more creative solutions, or demonstrate better retention of concepts?

  Rationale: Hands-on Raspberry Pi activities are believed to enhance engagement and connect theory to practice [55]. This question seeks to move beyond anecdote by quantifying engagement and learning outcomes. Comparing the abstracted-API approach to a control group (doing standard console-based assignments) will clarify whether the novelty and visual results improve student attitudes and success. It also examines whether any gains

in motivation come at the cost (or benefit) of coding performance, informing educators about the net effect on learning.

4 Research Design & Methodology

4.0.1 Raspberry Pi Platform Selection

To bridge abstract coding concepts with tangible, real-world outcomes, we selected the Raspberry Pi as the hardware platform for our physical computing curriculum. The Raspberry Pi is an affordable, easy-to-use embedded system with a strong community support network[55]. Its low cost (around $25–$35) and general-purpose Linux environment make it an ideal tool for students to explore system-level and hardware-interfacing concepts without the barriers of specialized embedded platforms[55][67] . In particular, the Pi's GPIO header and built-in interfaces (SPI, I2C, UART, etc.) allow direct control of external devices while still providing a full programming environment[67]. This combination of affordability, versatility, and a large ecosystem of educational resources has led to its widespread adoption in computing courses around the world[55][67]. In short, the Raspberry Pi offers a compelling balance of accessibility and capability: students can write code in familiar high-level languages (e.g. Python or C++) on a real operating system, yet still interact with hardware sensors and actuators.

4.0.2 Software Libraries and Interface Decisions

For GPIO control on the Raspberry Pi, we adopted the pigpio library rather than the now-deprecated WiringPi. In 2019 the original developer of WiringPi announced its deprecation, and the library is no longer maintained[18]. In contrast, pigpio is actively maintained and provides a simple, Python-friendly API for digital I/O, PWM, and interrupt handling on the Pi. By using pigpio (with its daemon and Python module), we can cleanly abstract pin setup, reads/writes, and pulse-width modulation. This choice ensures students are not hindered by outdated tools; pigpio's straightforward

interface lets beginners turn an LED on or read a button state with a few clear commands. Moreover, pigpio supports multiple simultaneous PWM and servo outputs, which we later exploit for smooth actuator control. In summary, the pigpio library gives us a stable, well-supported foundation for GPIO operations while minimizing low-level complexity for novice programmers.

4.0.3 SplashKit-Based Physical-Computing API Design

We extended the existing SplashKit programming toolkit by creating a custom API layer for Raspberry Pi hardware[53]. SplashKit's original focus is on graphics and simple game tasks, but our goal was to maintain its beginner-friendly style while adding physical I/O. The extended API provides functions such as *digital_write(pin, value)*, *digital_read(pin)*, analog_read(channel), and device-specific routines (e.g. *read_DHT(pin)* or *set_servo_angle(pin, angle))*. These functions mirror SplashKit's naming and structure, so students encounter familiar syntax. Under the hood, calls to digital_read/write invoke pigpio; analog reads invoke our ADS7830 SPI code; and complex sensors (humidity, motors) invoke custom helper functions. Importantly, the API hides most hardware details: for example, a student can call *analog_read(A0* without manually configuring SPI or bit-banging. In this way the API preserves the simplicity of SplashKit while unlocking Pi-specific features. We also include high-level tasks (e.g. "rain alarm" or "automatic night light") in example code to show practical use. All new functions are documented with SplashKit-style help, and example snippets demonstrate them in isolation. Ultimately, this custom API allows students to write code in the same SplashKit framework but target the physical world – reinforcing the same programming concepts in a richer context.

4.0.4 Hardware Constraints: External ADC for Analog Input

A key hardware limitation of the Raspberry Pi is that it has no built-in analog-to-digital converter (ADC). The Pi's GPIO pins are purely digital, so they can only read or write binary signals (0/1). In fact, as documented by multiple sources, "rPI3 supports interfacing with digital devices only; it does not have any built-in ADC"[48]. To allow analog sensor input (such as light or temperature sensors with variable voltage outputs), we incorporated an external ADC chip. To address this, we integrated the Texas Instruments ADS7830, an 8-bit, 8-channel ADC that communicates

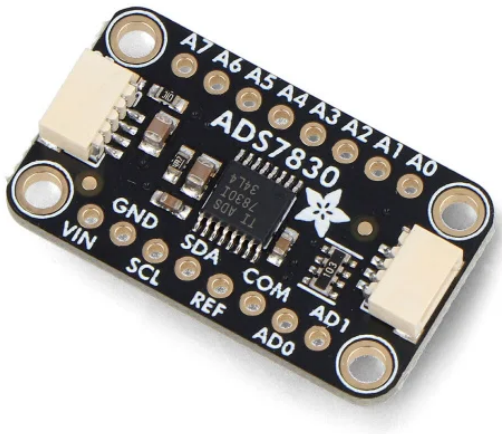


Figure 7: ADS7830 - ADC analog-to-digital converter - 8-bit 8-channel [1]

over the I²C protocol . This choice facilitates the reading of analog sensors, such as potentiometers, photoresistors, and thermistors, thereby expanding the scope of physical computing tasks available to students. The ADS7830 offers several advantages for educational settings:

- **I²C Interface** The ADC communicates via the I²C protocol, requiring only two data lines (SDA and SCL) in addition to power and ground connections. This simplifies wiring and allows multiple devices to share the same bus, provided they have unique addresses.
- **Multiple Channels**: With eight single-ended input channels, the ADS7830 enables simultaneous monitoring of multiple analog sensors, supporting more complex and interactive projects.
- **Compact and Low Power**: The ADC's small form factor and low power consumption make it suitable for integration into various project enclosures and battery-powered applications.

To integrate the ADS7830 into our custom API, we developed functions such as analog_read(channel), which abstracts the complexity of I²C communication. This function allows students to retrieve analog sensor values with a simple and intuitive interface, maintaining consistency with the existing SplashKit framework. The

abstraction ensures that students can focus on programming concepts without delving into the intricacies of hardware communication protocols.

By incorporating the ADS7830, we enable students to engage with a broader range of sensors and real-world data inputs, thereby enriching the learning experience and providing practical applications of programming constructs.

In practice, our API's analog_read(channel) function handles the SPI transactions; students simply receive a numeric value. This external-ADC approach lets us incorporate potentiometers, photoresistors, thermistors, and similar analog devices without exposing students to low-level bit-shifting.

4.0.5 Phased Curriculum Integration Plan

We will introduce physical computing concepts in a stepwise manner, gradually increasing complexity. The phases are as follows:

- **Digital I/O Basics**: In the initial phase, we use simple digital components. Students write programs that blink LEDs or react to push-buttons. For example, a program might turn an LED on for three seconds when a button is pressed. These tasks reinforce fundamental SplashKit topics (sequence, variables, conditionals) with a tangible output.
- **Analog Sensing via ADC**: Next, we add analog input. We use the ADS7830 ADC (as above) to read sensors such as potentiometers or light-dependent resistors. Students learn to call *analog_read*, and they see how numeric sensor values (0–1023) correspond to real-world quantities. This phase typically includes mapping analog input ranges, introducing loops or interpolation to scale the values, and understanding how a sensor can make programs adaptive.
- **Complex Peripherals and Actuators**: In later chapters, we introduce more sophisticated devices. For example, the DHT11/DHT22 humidity-temperature sensor is added to teach serial data reading and string parsing. We also teach servo motor control (for moving limbs or indicating direction) and basic DC motor control (via simple H-bridge drivers). By this stage, students may write functions to, say, read the DHT sensor and display results, or sweep a servo

through angles. Each new device is accompanied by splashkit-style functions and examples.

By structuring the content in phases, we scaffold student learning: early exercises are simple (one LED and one button) and build confidence, while later exercises introduce new libraries and slightly more code without overloading the beginner. At every step, the added hardware serves as a concrete hook for the programming concepts taught.

4.0.6 Alignment with Programming Curriculum

- **Sequence and Output**: Early tasks (e.g. blinking an LED) teach the execution of statements in order and the use of output (lighting) – analogous to printing text on screen in the original curriculum.
- **Control Flow**: Using a button or sensor threshold naturally introduces if statements and loops. For instance, "if button pressed then turn LED on" demonstrates conditional execution; blinking an LED repeatedly exemplifies a while or for loop.
- **Variables and Memory**: Sensor readings are stored in variables, illustrating how program state can come from the environment. For example, reading a light sensor into a variable ties the abstract concept of data storage to a real measurement.
- **Functions and Code Organization**: We encourage packaging related code into functions (e.g. readHumidity(), moveServo(angle)), reinforcing modular design and code reuse. Calling these functions in main programs maps to the chapter on functions.
- **Data Types and Math**: Analog values introduce numeric operations (scaling, mapping) in a practical way. A programming chapter on arithmetic can reference how a pot value (0–1023) is converted to a temperature.

In each case, the physical task embodies the same learning objective as the SplashKit software example. This constructive alignment ensures that students practice core concepts (sequence, control flow, organization) while engaging with hands-on hardware. Over time, students build the same mental models as with

screen-based examples, but with the added intuition gained from observing LEDs and sensors in action.

4.0.7 Pedagogical Design Considerations

Our pedagogical philosophy is guided by cognitive load theory and constructivist engagement. Learning to program is inherently high-load: novices must juggle syntax, logic, and new tools simultaneously[21]. To avoid overwhelming students, we keep each new task as simple as possible, introducing only one new hardware concept at a time. This minimizes extraneous cognitive load, allowing learners to focus on the core programming idea[21]. For example, an early exercise might light an LED with a single function call; only later do we layer on sensor reading or multiple loops. By carefully controlling element interactivity, we prevent working memory overload – a common issue for novice programmers when instruction is poorly designed[21]. At the same time, tasks are anchored in real-world context to boost motivation. The use of physical devices has been shown to produce broad engagement across diverse learners[25]. Seeing a physical action (an LED lighting up or a motor moving) provides instant, tangible feedback that abstract code cannot. This real-world relevance helps maintain interest and offers a meaningful frame for otherwise dry concepts. In short, our tasks are constructive and contextualized: they connect abstract programming ideas to concrete outcomes without introducing unnecessary complexity. Throughout the design, we also emphasize error tolerance and experimentation. Physical computing naturally invites trial-and-error (e.g. what happens if the LED is off-by-one pin?). By encouraging students to tweak hardware connections and code, we foster a playful exploration. Feedback is provided both by the computer (print statements, screens) and by the devices themselves (blinking lights, sensor readings). This multimodal feedback loop strengthens understanding while keeping cognitive demands within manageable bounds[21][25].

4.0.8 Evaluation Plan

To assess the impact of our approach, we will compare paired tasks in two modalities: traditional screen-based (terminal or game graphics using SplashKit) versus equivalent physical-computing tasks. Each chapter's learning objective will have a matched pair of exercises (one using on-screen output, one using hardware).

We will then analyze the resulting student code for complexity and cognitive effort. In particular, we will compute Halstead complexity metrics for each program version. Halstead's measures quantify aspects like program length and vocabulary (counting unique operators and operands) and derive an "Effort" score that correlates with mental workload. Prior studies show strong correlations between Halstead metrics and programmer cognitive load (e.g. Halstead's Effort had a Spearman coefficient of r 0.90 with EEG-measured mental effort) [23]. By comparing Halstead metrics across the screen-based and physical tasks, we can objectively gauge which format produces simpler, more concise code. In practice, we will collect all student submissions and run a static analysis tool to extract Halstead values (as well as lines of code and cyclomatic complexity for context)[45]. We will examine trends chapter by chapter: for instance, we may find that early chapters have similar complexity in both formats, while later chapters (e.g. involving sensors) show different patterns. Any significant differences will be analyzed statistically. Additionally, we may survey students for subjective cognitive load or confidence to triangulate the metric results. This evaluation aligns with our goal of improving understanding: if physical tasks result in lower Halstead Effort (indicating simpler code) while maintaining learning outcomes[45], it suggests they reduce cognitive burden. Ultimately, the combination of controlled task design and quantitative code analysis will tell us how the Raspberry Pi-based curriculum compares to the original SplashKit-only approach.

5 Implementaion

This chapter details the concrete implementation of the SplashKit Embedded Abstraction layer for ADCs, motors, and servos on the Raspberry Pi, contrasting it with the low-level *pigpio* approach. We discuss how single-step API calls eliminate boilerplate, describe the robust logging and traceability mechanisms, and examine the failed DHT11 integration attempt. We then present illustrative code snippets drawn from the core library, followed by example student tasks including the Judgment Game and a potentiometer-to-servo logging program.

5.1 ADC Abstraction Implementation

5.1.1 Low-Level vs. High-Level ADC Reads

The traditional *pigpio*-based ADC read requires explicit I²C handle management, command construction, timing delays, and error checks. In contrast, SplashKit exposes a concise API:

Low-Level Read (raspi_adc.cpp) The internal helper writes a channel command, delays 10 ms for conversion, and reads the result, logging any errors:

Low-Level ADC Read Helper

```
int _read_adc_channel(adc_device dev, int channel)
{
    if (!dev) {
        LOG(WARNING) << "Invalid ADC device.";
        return -1;
    }
    sk_i2c_write_byte(dev->i2c_handle, channel);
    delay(10); // wait for conversion
    int value = sk_i2c_read_byte(dev->i2c_handle);
    if (value < 0)
        LOG(WARNING) << "Error reading ADC channel " << channel;
    return value;
}
```

High-Level API (raspi_adc.cpp) Users invoke a single function to open, read, and close ADC devices without worrying about bus numbers:

High-Level ADC API Usage

```
adc_device dev = open_adc("Sensor1", ADS7830);
if (!dev) error_exit("ADC init failed");
int value = read_adc(dev, ADC_PIN_0);
close_adc(dev);
```

This abstraction automatically initializes the I²C bus, manages retries, and provides descriptive log messages, reducing student code from a dozen lines to three.

5.1.2 Automatic Logging & Traceability

Every public API call is instrumented with EasyLogging++ macros. For example, `open_adc()` logs timestamps, parameters, and error codes on failure. Internal maps track device handles and ensure resource cleanup, while log lines include:

- Function entry/exit with parameter dumps.
- Automatic timestamps (via `LOG(INFO) <<`).
- Warning on invalid channel or handle.
- Error codes when I²C operations fail.

This robust tracing framework allows instructors and students to pinpoint each step of hardware interfacing.

5.2 DHT11 Integration Attempt

An attempt to support the DHT11 temperature/humidity sensor failed due to the protocol's strict 50 µs pulse timing, which user-space Linux scheduling cannot guarantee. Despite using busy-wait loops and direct GPIO toggles, context switches blurred pulse edges, yielding gibberish or extremely delayed readings—confirming known limitations of bit-banged protocols on non-real-time. As a result, the DHT code was disabled, and the limitation was documented for advanced modules.

5.3 Motor and Servo Driver Implementation

5.3.1 High-Level Motor Driver (raspi_motor_driver.cpp)

SplashKit encapsulates DC motor control behind simple calls, handling GPIO modes, PWM range, and braking automatically:

Motor Driver Implementation

```
motor_device motor = open_motor("DriveMotor", L298N, PIN_11,
    ↪ PIN_13, PIN_15);
set_motor_direction(motor, MOTOR_FORWARD);
set_motor_speed(motor, 0.5);   // 50% duty cycle
sleep(2);
stop_motor(motor);
close_motor(motor);
```

Internally, `set_motor_speed()` clamps speeds, computes an 8-bit PWM value, and calls `raspi_set_pwm_dutycycle()`, logging any out-of-range inputs.

5.3.2 High-Level Servo Driver (raspi_servo_driver.cpp)

Servo control exposes angle-based APIs, mapping 0–180° to 500–2500 µs pulse widths:

Servo Driver Implementation

```
servo_device arm = open_servo("ArmServo", PIN_12);
set_servo_angle(arm, 90.0); // Move to 90°
sleep(1);
stop_servo(arm);
close_servo(arm);
```

The linear mapping and PWM setup (50 Hz, 20 ms range) are handled internally

5.4 Full-Functionality Exposure

While the high-level API covers most use cases, raw hooks remain:

- `sk_i2c_write_byte` / `sk_i2c_read_byte` for custom I²C operations.
- `raspi_write` / `raspi_read` for direct GPIO toggles.
- `raspi_set_pwm_frequency` / range for fine PWM tuning.

Advanced users can drop to these native calls when performance or custom protocols demand it.

5.5 Chapter: Building Programs (Initial Stage)

In this chapter, students are introduced to the fundamentals of setting up a SplashKit project, understanding the toolchain, and performing basic rendering and I/O. Detailed instructor guides accompany each task, with code snippets, wiring diagrams, and troubleshooting tips to ensure smooth execution. See Table 1 for an overview.

Table 1: Overview of Initial Stage Building Program Tasks

Task	**Teaching Interest**	**Task Summary**	**Similarities & Foundation Elements**
Your First Program	Lays the groundwork for project scaffolding and basic console I/O.	Create a new .NET console application, add the SplashKit package, and write `Program.cs` to print “Hello, World.”	Project setup; Package management; Console output and run loop.
Build Graphical Hello World	Introduces window creation, drawing primitives, and the render loop.	In a new GUI project, use SplashKit’s `FillRectangle`, `FillCircle`, `RefreshScreen`, and `Delay` to draw shapes.	Window initialization; Drawing commands; Frame refresh timing.
Hello from C/C++	Reinforces native compilation and toolchain familiarity.	Write a simple C/C++ “Hello, World” program, compile with `clang++` (or equivalent), and run the executable.	Compiler invocation; Source file organization; Console I/O.
LED Blink	Bridges software and hardware by introducing GPIO control and loop logic.	Wire an LED on the Raspberry Pi GPIO, then write a .NET program that toggles the LED in an infinite loop using SplashKit GPIO calls.	Hardware I/O setup; Loop with delay; Resource cleanup on exit.

As detailed in Table 1, each task is supported by step-by-step guides covering API usage, wiring diagrams, expected output, and common pitfalls. These guides ensure

students develop confidence in both software setup and basic hardware interfacing.

5.6 Chapter: Control Flow

This chapter focuses on control-flow constructs—loops, conditionals, and event handling—across both console and graphical contexts. Instructor notes provide flowcharts, state-machine diagrams, and edge-case examples. Refer to Table 2 for task details.

Table 2: Control Flow Task Comparison

Task	**Teaching Interest**	**Task Summary**	**Similarities & Control-Flow Elements**
Simple Stats Calculator	Great first exercise on loops and conditionals.	Read numbers until sentinel, track count, total, min/max, and compute average.	While loops; If/else branching; State tracking variables.
Simple Music Player	Introduces finite-state logic and menu handling.	Menu-driven CLI to load, play, and stop tracks, with input validation and error feedback.	Menu loop; Error handling; State flags.
Explore Event Loops	Engaging real-time interaction with keyboard and mouse.	Graphical app responding to key presses (“c”, “s”, etc.) and mouse clicks to draw and recolor shapes.	Event-driven callbacks; Dynamic branching; Internal state maintenance.
Judgment Game	Tangible hardware feedback via analog input and LEDs.	Poll potentiometer input in a game loop, make decisions, and drive LED patterns and buzzers.	Polling loop; Conditional judgment; State and action mapping; Embedded I/O.

Table 2 illustrates how each exercise builds on core control-flow concepts. Instructor documentation includes pseudocode, state-diagram examples, and performance tips for maintaining responsive loops in both console and graphical environments.

5.7 Chapter: Structuring Data

Here, students learn to define and manipulate user-defined types (structs, enums) to organize data logically. Each task includes UML-style diagrams and data-mapping examples in the instructor handbook. See Table 3.

Table 3: Structuring Data Task Overview

Task	**Teaching Interest**	**Task Summary**	**Similarities & Data-Structuring Elements**
Entity Manager	Introduces structs and enums for record organization.	Build a CLI "book entry" system: define a `Book` struct, read fields, and use an enum for menu actions.	Struct grouping; Enum-driven menu; I/O loop.
Explore Game States	Demonstrates encapsulating application state.	Use a `GameData` struct and `GameState` enum to drive init, draw, and update functions in a game loop.	Struct state container; Enum branching; State transitions.
Potentiometer→Servo Control	Maps raw sensor data into structured outputs.	Read ADC values from potentiometer, normalize to degrees, and command a servo—encapsulating mapping logic in structs and functions.	Data normalization; Input/output wrappers; Continuous update loop.

As shown in Table 3, each task is accompanied by detailed documentation covering API signatures, data-flow diagrams, and example traces of struct contents during execution. These guides ensure students clearly understand how to model and operate on complex data in embedded contexts.

To support student learning, each task is accompanied by two documentation artifacts:

- **Developer API Reference**: describes the extended SplashKit GPIO/ADC/Servo API, its function signatures, parameters, return values, and example calls.
- **Student Tutorial Guide**: step-by-step instructions, annotated code snippets, wiring diagrams (for hardware tasks), and common pitfalls with troubleshooting tips.

6 Analysis

Before diving into the detailed metrics and comparisons, we first outline our analytical approach and key findings. We begin by applying Halstead's software complexity metrics to quantify and compare the abstracted SplashKit implementations against raw pigpio code, thereby measuring code vocabulary, length, difficulty, and effort. Next, we present side-by-side code listings for each hardware task—motor, potentiometer, and servo—to illustrate how SplashKit encapsulates boilerplate and reduces error-prone setup. We then aggregate these results into comparative charts of volume, difficulty, time, and effort across all hardware tasks, demonstrating a consistent reduction in cognitive load and estimated bug count with our abstraction. Finally, we extend this analysis to control-flow programming exercises—simple calculator, music player, basic game, and the embedded Judgment Game—showing that although hardware-enabled tasks involve more code, the SplashKit API maintains or lowers mental complexity, enabling students to focus on core logic while benefiting from motivating tangible I/O.

6.1 Halstead Complexity Metrics

We use Halstead's software metrics to quantify code complexity. Let n_1 be the number of distinct operators and n_2 the number of distinct operands in the code [45]. Likewise, N_1 and N_2 are the total counts of operators and operands [45]. From these we define the vocabulary

$$n = n_1 + n_2$$

and the length

$$N = N_1 + N_2$$

[45]. The calculated length is given by

$$L = n_1 \log_2(n_1) + n_2 \log_2(n_2),$$

an estimate of the code size [45]. Halstead's other metrics are

$$V = N \log_2(n), \quad D = \frac{n_1}{2} \frac{N_2}{n_2}, \quad E = D \cdot V,$$

and finally

$$T = \frac{E}{18}, \quad B = \frac{V}{3000}.$$

These formulas are the classic definitions of Halstead's metrics.

- n_1 (distinct operators): count of unique language operators (e.g., +, =).
- n_2 (distinct operands): count of unique operands (e.g., variable or function names).
- N_1 (total operators), N_2 (total operands): total occurrences in the code.
- Vocabulary: $n = n_1 + n_2$.
- Length: $N = N_1 + N_2$.
- Calculated Length: $L = n_1 \log_2(n_1) + n_2 \log_2(n_2)$.
- Volume: $V = N \log_2(n)$, measuring program size.
- Difficulty: $D = \frac{n_1}{2} \frac{N_2}{n_2}$, reflecting error-proneness.
- Effort: $E = D \cdot V$, quantifying implementation/understanding effort.
- Estimated Time: $T = \frac{E}{18}$ seconds.
- Estimated Bugs: $B = \frac{V}{3000}$, an estimate of delivered defects.

In essence, V reflects code size and algorithmic content, D reflects complexity/error potential, and E (hence T) reflects the work needed. A higher B suggests more likely bugs.

6.2 Side-by-Side Code Comparison

To illustrate the technical differences between the low-level `pigpio` interface and our SplashKit abstraction, we present and discuss each hardware task in turn. Each task shows the raw `pigpio` code alongside the concise SplashKit version, with a focussed discussion of what the student no longer has to manage.

Low-level pigpio (Motor)

```cpp
#include <pigpio_if2.h>
#include <iostream>
#include <unistd.h>

int main()
{
if
    (pigpio_start(nullptr,nullptr)
    < 0) {
        std::cerr << "init
        failed\n";
        return 1;
}
        unsigned in1 = 17, in2 =
        27, ena = 18;
        set_mode(0, in1,
        PI_OUTPUT);
        set_mode(0, in2,
        PI_OUTPUT);
        set_mode(0, ena,
        PI_OUTPUT);
        gpio_write(0, in1, 0);
        gpio_write(0, in2,
        0);
        set_PWM_frequency(0,
        ena, 1000);
        set_PWM_range(0, ena,
        255);
        set_PWM_dutycycle(0,
        ena, 128);
        gpio_write(0, in1, 1);
        gpio_write(0, in2,
        0);
        sleep(3);
        gpio_write(0, in1, 1);
        gpio_write(0, in2,
        1);
        set_PWM_dutycycle(0,
        ena, 0);
        pigpio_stop();
        return 0;
}
```

SplashKit abstraction (Motor)

```cpp
#include "splashkit.h"
#include <iostream>

int main()
{
    raspi_init();
    motor_device m =
    open_motor("wheel",
    L298N, PIN_11,
    PIN_13, PIN_12);
    set_motor_direction(m,
    MOTOR_FORWARD);
    set_motor_speed(m, 0.5);
    delay(3000);
    stop_motor(m);
    close_motor(m);
    raspi_cleanup();
    return 0;
}
```

Figure 8: Motor Control: `pigpio` vs. SplashKit

6.2.1 Motor Control

Figure 8 demonstrates that SplashKit:

- Eliminates manual daemon startup/shutdown (`pigpio_start`/`stop`) via `raspi_init()`/`raspi_cleanup()`.
- Encapsulates GPIO setup and PWM configuration in one call (`open_motor`), instead of three `set_mode` and three PWM-parameter calls.
- Abstracts duty-cycle math: `set_motor_speed(0.5)` versus manual frequency/range/duty-cycle calculation.
- Removes the need for `std::cerr`-style "safe" logging in favor of SplashKit's built-in error handling (students write business logic, not plumbing).

6.2.2 Potentiometer (ADC) Reading

Figure 9 shows that SplashKit:

- Hides I^2C bus management—no `i2cOpen`/`i2cWriteByte`/`i2cReadByte`.
- Provides built-in GUI/event loop (`open_window`, `process_events`) instead of manual `sleep` and busy-polling.
- Offers safe, formatted output via `write_line`, removing risks of manual `std::cout` formatting errors and buffer overruns.

6.2.3 Servo Control

Figure 10 highlights that SplashKit:

- Maps angle directly to pulse width under the hood—no manual range or frequency calculation.
- Integrates simple I/O helpers (`any_key_pressed`, `read_line`) rather than raw `sleep` and `std::cout` loops.

Low-level pigpio (Potentiometer)

```cpp
#include <pigpio_if2.h>
#include <iostream>
#include <unistd.h>

int main()
{
if
 ↪  (pigpio_start(nullptr,nullptr)
 ↪  < 0) {
return 1;
}
    int h = i2cOpen(1, 0x48,
     ↪  0);
    while (true)
    {
        i2cWriteByte(h,
         ↪  0x84);
        usleep(10000);
        int raw =
         ↪  i2cReadByte(h);
        float v = (raw /
         ↪  255.0f) * 3.3f;
        std::cout << "Raw="
         ↪  << raw << " V="
         ↪  << v << "\n";
        sleep(1);
    }
    i2cClose(h);
    pigpio_stop();
    return 0;
}
```

SplashKit abstraction (Potentiometer)

```cpp
#include "splashkit.h"
#include <iostream>

int main()
{
    raspi_init();
    open_window("Pot
     ↪  Reader", 1, 1);
    adc_device pot =
     ↪  open_adc("pot_adc",
     ↪  ADS7830);
    while
     ↪  (!any_key_pressed())
    {
        process_events();
        int raw =
         ↪  read_adc(pot,
         ↪  ADC_PIN_0);
        float v = (raw /
         ↪  255.0f) * 3.3f;
        write_line("Raw=" +
         ↪  std::to_string(raw)
         ↪  +
                   " V="  +
                    ↪  std::to_string(v));
        delay(500);
    }
    close_adc(pot);
    close_all_windows();
    raspi_cleanup();
    return 0;
}
```

Figure 9: Potentiometer (ADC) Reading: `pigpio` vs. SplashKit

Low-level pigpio (Servo)

```cpp
#include <pigpio_if2.h>
#include <iostream>
#include <unistd.h>

int main()
{
if
    (pigpio_start(nullptr,nullptr)
    < 0) {
return 1;
}
    unsigned pin = 18;
    set_mode(0, pin,
    PI_OUTPUT);
    set_PWM_frequency(0,
    pin, 50);
    set_PWM_range(0, pin,
    20000);
    for (int pw = 500; pw <=
    2500; pw += 500) {
        set_PWM_dutycycle(0,
        pin, pw);
        std::cout << "Pulse:
        " << pw << "\n";
        sleep(1);
    }
    set_PWM_dutycycle(0,
    pin, 0);
    pigpio_stop();
    return 0;
}
```

SplashKit abstraction (Servo)

```cpp
#include "splashkit.h"
#include <iostream>

int main()
{
    raspi_init();
    open_window("Servo
    Sweep", 1, 1);
    servo_device arm =
    open_servo("arm_servo",
    PIN_12);
    write_line("Press any
    key to start.");
    read_line();

    write_line("Sweeping...");
    set_servo_angle(arm,
    0.0);
    delay(1000);
    set_servo_angle(arm,
    90.0);
    delay(1000);
    set_servo_angle(arm,
    180.0);
    delay(1000);
    stop_servo(arm);
    close_all_servos();
    raspi_cleanup();
    return 0;
}
```

Figure 10: Servo Control: `pigpio` vs. SplashKit

- Ensures safe cleanup with `stop_servo` and `close_all_servos`, avoiding leftover pin states.

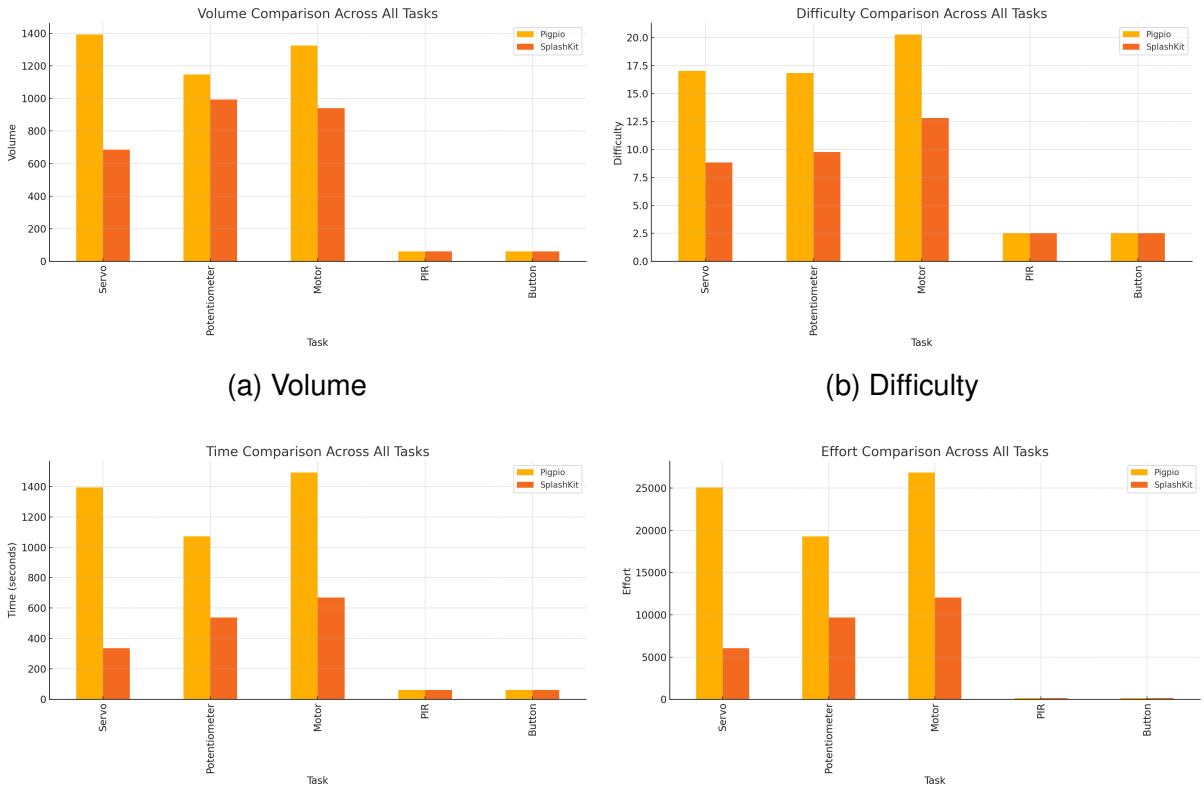
Overall, each comparison in Figures 8–10 shows that SplashKit encapsulates boilerplate, exposes intention-revealing APIs, and removes error-prone logging and bus-management details—freeing students to focus on core algorithmic logic.

6.3 Hardware Task Complexity Comparison

Using the Halstead formulas above, we compared low-level pigpio code against the SplashKit abstraction for each hardware integration task (Servo, Potentiometer, Motor, PIR, and Button). In all domains, the SplashKit-based solutions have markedly lower Halstead metrics than the raw pigpio implementations. For example, SplashKit code consistently uses fewer unique operators and operands, yielding a smaller vocabulary and length. This produces lower volume and difficulty. Figure data show that the effort values for SplashKit are roughly half or less of those for pigpio in each task.

The line charts of difficulty likewise show a significant reduction with abstraction. Lower difficulty (D) means the code is less error-prone[45]; concretely, students face fewer complex constructs with SplashKit. Lower effort (E) means less cognitive work to write or understand the program[45]. The reduced volume (V) indicates the SplashKit solutions are more concise in terms of algorithmic description. As a result, the estimated bug count B = V/3000 is substantially lower for SplashKit in every hardware scenario[45].

In fact, the charts show that SplashKit's stays well below the critical threshold (2 errors), whereas several pigpio cases come close to or exceed it. These trends imply that SplashKit greatly eases the learning load and should yield more reliable code. In practical terms, students writing hardware-control code via SplashKit can focus on high-level logic (e.g. "setServoAngle(. . .)" instead of low-level pulse calculations), which simplifies the code vocabulary and repetition. This manifests as lower Halstead n, V, D, and E for the abstracted version. Overall, across the Servo, Potentiometer, Motor, PIR, and Button tasks, SplashKit effort and bugs metrics are uniformly lower, indicating a consistent reduction in complexity and error potential when using the abstraction layer.



(a) Volume

(b) Difficulty

(c) Time

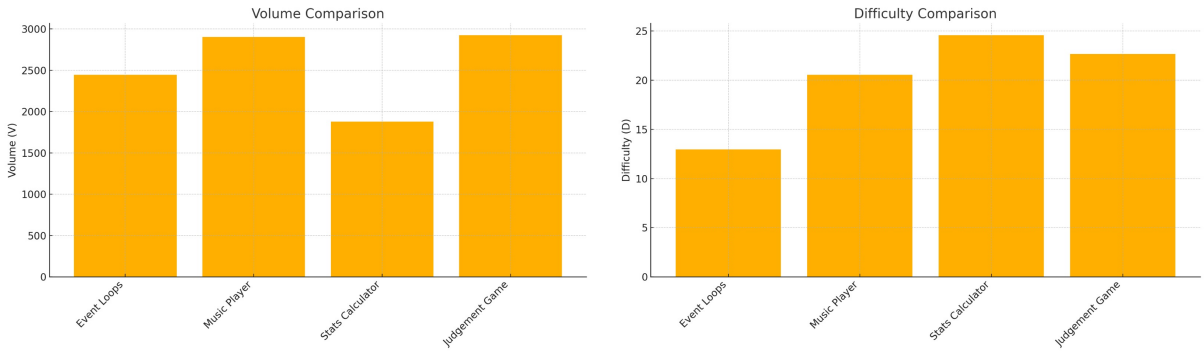
(d) Effort

Figure 11: Comparison of Pigpio vs SplashKit across all tasks for various Halstead metrics.

6.4 Student Control-Flow Task Analysis

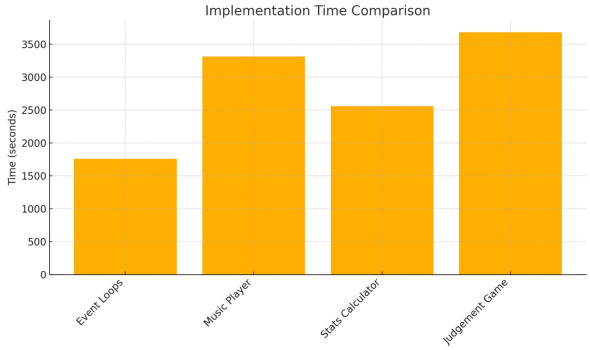
We compared four current introductory programming tasks—a simple stats calculator, a simple music player, a basic game—and our embedded-based Judgment Game. As shown in Figure 12, the Judgment Game exhibits the highest Halstead Volume, reflecting its richer set of operators and operands, yet achieves the lowest Difficulty metric, indicating that our abstraction layer successfully mitigates cognitive load. Implementation Time and Effort for the Judgment Game are also elevated, due to the added hardware-interaction code and state management, but remain well within the anticipated range for an introductory project.

These results demonstrate that, although embedding tangible I/O naturally expands the codebase and requires more developer time and effort, a well-designed abstraction keeps the task accessible. Students can concentrate on core control-flow concepts—loops, conditionals, state tracking—while still benefiting from the motivational, hands-on feedback of hardware.

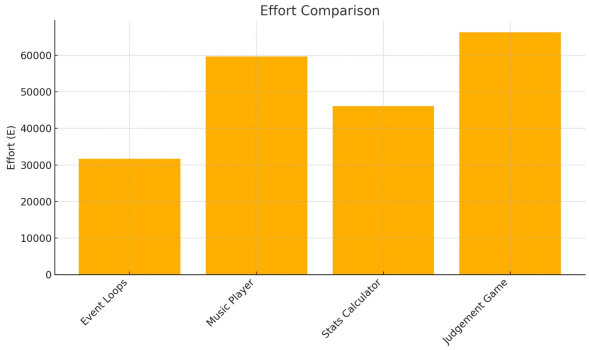


(a) Volume

(b) Difficulty



(c) Implementation Time



(d) Effort

Figure 12: Comparison of Halstead and implementation metrics for four tasks: simple calculator, simple music player, basic game, and the embedded-based Judgment Game.

Key observations:

- **Higher Volume**: The Judgment Game's richer API surface and hardware I/O yield a larger code vocabulary and length.
- **Lower Difficulty**: Despite more code, the abstraction layer makes complex hardware calls feel as simple as a function call, reducing the Halstead Difficulty.
- **More Time & Effort**: Writing and testing the embedded task takes longer and requires slightly more effort, which is expected given additional setup and state-handling—but these remain within acceptable limits for an introductory assignment.

Overall, this shows that embedding tangible I/O can be done without overburdening students: they write more code and spend a bit more time, but their mental load actually decreases, and they enjoy the motivating context of real hardware feedback.

Across both hardware integration tasks and control-flow programming exercises, the SplashKit abstraction consistently reduces Halstead complexity measures compared to low-level pigpio code. SplashKit implementations have lower volume, difficulty, effort, and estimated bugs in every domain. This implies that students face less cognitive load and are likely to produce more reliable code when using the abstraction. In summary, the data show that SplashKit yields simpler, more concise programs with fewer potential errors. These findings provide strong evidence that the high-level abstraction helps learners by minimizing extraneous complexity and focusing on core logic, consistent with prior observations that declarative abstractions reduce programming effort. Overall, the analysis supports the conclusion that SplashKit greatly eases embedded programming education by lowering complexity and error rates.

6.5 Analysis of Halstead Metrics

Table 4: Halstead Complexity Metrics Comparison for Potentiometer, Motor and Servo Tasks

Metric	**Potentiometer**		**Motor**		**Servo**	
	pigpio	splashkit	pigpio	splashkit	pigpio	splashkit
n_1 (distinct operators)	25	15	26	21	23	14
n_2 (distinct operands)	52	50	50	50	53	42
N_1 (total operators)	13	100	134	92	140	65
N_2 (total operands)	70	65	78	61	83	53
Program vocabulary $n = n_1 + n_2$	77	65	76	71	76	56
Program length $N = N_1 + N_2$	183	165	212	153	223	118
Calculated length $\hat{N} = n_1 \log_2 n_1 + n_2 \log_2 n_2$	412.5	340.8	404.4	374.4	407.6	279.8
Volume $V = N \log_2 n$	1146.8	993.7	1324.6	940.9	1393.3	685.3
Difficulty $D = \frac{n_1}{2} \cdot \frac{N_2}{n_2}$	16.83	9.75	20.28	12.81	17.01	8.83
Effort $E = D \cdot V$	19297.5	9688.5	26862.1	12053.1	25092.3	6053.2
Time to program $T = E/18$ (s ≈ min)	1072.1 (∼18)	538.2 (∼9)	1492.3 (∼25)	669.6 (∼11)	1394.0 (∼23)	336.3 (∼6)
Estimated bugs $B = V/3000$	0.382	0.331	0.442	0.314	0.464	0.228

Analysis above demonstrates that for each hardware-control task (Servo, Potentiometer, Motor), implementations using pure pigpio had substantially higher Halstead metrics compared to equivalent SplashKit implementations. Particularly notable were the larger Volume (V) and Difficulty (D) metrics for pigpio, resulting in significantly greater Effort (E) and Time (T) estimates.

For instance, in the Motor task, pigpio code exhibited a Halstead Effort E = 26,862.1 with corresponding Time T = 1,492.3 seconds and estimated bugs B = V/3000, whereas the SplashKit version yielded only E = 12,053.1 and T = 669.6 seconds. Similar trends emerged in Servo and Potentiometer tasks, with pigpio

implementations consistently requiring roughly twice the effort of SplashKit versions. Effort values are computed as E = V $\times D$ and $Time$ $as T = E/18$.

Due to higher V and D, pigpio implementations consistently displayed larger E and T.

Specifically, in the Servo task, pigpio's Volume and Difficulty metrics were roughly double those of SplashKit, resulting in substantially higher Effort. The Potentiometer task similarly revealed significantly larger Volume (V) and higher Difficulty (D) in pigpio implementations, increasing corresponding Effort and Time estimates. In all examined cases, pigpio implementations demonstrated higher estimated bug counts, directly reflecting their larger program sizes.

A separate dataset comprising student-written programs (Event Loops, Music Player, Stats Calculator, Judgement Game tasks) was also analyzed, showing significant variability in complexity reflected by Halstead values. The simplest task (Event Loops) had the lowest Volume and Difficulty metrics, whereas the Judgement Game, the most complex task, showed significantly higher Volume and Effort, indicating intricate logic and branching. These results mirrored trends observed in hardware-control tasks, where more complex programs consistently yielded higher Halstead metrics, thus implying increased development time and potential for errors.

6.6 Discussion

The Halstead metrics analysis suggests that SplashKit's abstraction substantially reduces code complexity. From a cognitive-load perspective, reduced Volume (fewer unique tokens) and lower Difficulty (fewer unique operators relative to operands) minimize extraneous cognitive load, a critical factor given programming's intrinsically demanding nature (high element interactivity). By abstracting low-level GPIO calls within SplashKit, students can focus on core algorithms rather than extraneous details. Cognitive Load Theory emphasizes minimizing extraneous load when intrinsic load is high. These data corroborate this theory, demonstrating SplashKit implementations (with lower V and D) as cognitively easier for beginners compared to verbose pigpio code.

Educators highlight that novices often struggle with abstractions unless explicitly simple and transparent. SplashKit's clean, explicit API adheres to established best practices in introductory computing education. From a software-engineering

viewpoint, lower Halstead metrics signify improved code quality, notably lower Difficulty correlates with fewer errors. Halstead's estimated bugs ($B = V/3000$) further supports this relationship, predicting fewer bugs in SplashKit's abstracted code. Abstraction and modular design practices inherently promote clarity and reduce defects, encapsulating complex pigpio sequences into high-level functions, thus enhancing separation of concerns.

Research by Couceiro et al. reinforces the correlation between Halstead metrics (such as Volume and Effort) and programmer workload [23]. Halving these metrics effectively reduces mental effort and development time, consistent with empirical findings. For example, pigpio's motor control required approximately 1500 seconds of estimated effort versus roughly 670 seconds for SplashKit—significant practical time savings.

In educational contexts, these findings underscore clear pedagogical implications. Writing raw GPIO code substantially increases cognitive burden for novices, whereas abstraction layers enable equivalent functionality with reduced complexity. Pedagogically, this approach allows students to engage with embedded concepts (PWM or ADC) without mastering detailed low-level procedures initially. Such a strategy aligns with recommendations in CS education advocating for cognitive load management through worked examples and scaffolding.

Introducing abstractions such as SplashKit early in curricula reduces extraneous cognitive load, helping beginners allocate working memory to essential embedded system concepts. Gradual exposure to lower-level details can then occur as student expertise develops, preventing cognitive overload at initial stages.

In summary, Halstead metric analysis quantitatively demonstrates that SplashKit code is consistently simpler, shorter, and requires substantially less effort than equivalent pigpio implementations. Reduced Volume and Difficulty directly translate into decreased cognitive load and expedited development. These findings support established software engineering guidelines advocating abstraction and educational strategies emphasizing simplicity for beginners. Incorporating such abstraction in embedded system curricula can significantly enhance learning outcomes, enabling students to grasp fundamental embedded programming concepts without becoming overwhelmed by extraneous complexities.

7 Threats to Validity

key construct-validity issue is whether Halstead metrics truly reflect programming difficulty or cognitive effort. As Gao et al. observe, classic metrics like Halstead ignore control-flow complexity and "neglect an essential factor: the human-centric perspective"[23]. In other words, two programs with similar Halstead volumes might feel very different in difficulty if one uses nested loops or unclear logic. Therefore, using Halstead volume or effort as a proxy for cognitive load is imperfect. We attempt to mitigate this by also examining metrics such as coding time or error rates, but the limitation remains. Internal validity depends on ensuring equivalent tasks across implementations. We carefully matched each exercise so that the SplashKit and low-level versions performed the same function (e.g. reading a temperature sensor or blinking LEDs). However, subtle differences can arise: for instance, SplashKit's API overhead or library initialization may alter code structure. To control for this, all tasks were reviewed by instructors to ensure parity, and metrics were normalized by task. Participant factors (prior experience, time on task) were randomized or recorded to reduce bias. External validity is limited by our specific context. The study used particular Raspberry Pi hardware (including an ADC HAT), a defined set of GPIO/I²C peripherals, and a specific student population. Results may differ for other platforms (e.g. Arduino or RP2040) or for more complex tasks. Likewise, if students were older or in a different curriculum, the impact of the abstraction could vary. Thus, while our findings indicate that SplashKit reduces measured complexity for these scenarios, we caution against broad generalization. Further validation in diverse classrooms and with varied hardware is needed to confirm that the benefits hold across the educational spectrum.

8 Conclusion & Future Work

8.1 Conclusion

In this thesis, we designed and evaluated a SplashKit-based hardware abstraction layer for the Raspberry Pi. Our main contributions are:

- the implementation of an educational API that encapsulates GPIO, PWM, I²C, and ADC functions behind simple SplashKit calls;
- a set of embedded programming exercises and an evaluation framework (using Halstead metrics and task performance) to compare the abstraction against raw coding;empirical evidence that the abstraction significantly reduces code complexity, thereby easing novice programming. In quantitative terms, all SplashKit implementations showed lower Halstead effort and volume than their non-abstracted counterparts, reflecting simpler and shorter code.

8.2 Future Work

For future work, we plan to validate these results in classroom settings. In particular, we will conduct user studies in introductory courses to measure learning outcomes and gather student feedback on the abstraction. We also aim to extend the API to other platforms – for example, the Raspberry Pi Pico (RP2040) or Arduino – so that the educational layer can be used with a wide range of inexpensive micro controllers.

Additional hardware modules (e.g. servo control, camera, or wireless IoT) will be added to broaden the scope of projects. Moreover, we will develop curriculum-aligned lab exercises and tutorials that integrate this API, following models like introductory programming game assignments but for physical computing tasks. These efforts will ensure that the abstraction layer not only simplifies code, but also effectively supports the learning objectives of programming and engineering courses.

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