WordPal

Group 36

Members

Hilda Deveaux
Computer Engineering

Daniel Ortiz-Gratacos
Computer Engineering

Nala Rivera
Computer Engineering

Review Committee

Dr. Sonali Das, ECE Department
Dr. John Aedo, CS Department
Dr. Mark Maddox, ECE Department

Advisor

Sreeram Sundaresh

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1 Executive Summary

The WordPal project aims to bring one of today's most popular online games, Wordle, into a physical handheld device that people can play anywhere. The main goal is to design and develop a self-contained, portable system that recreates the familiar Wordle experience without needing a phone or computer. By combining elements of embedded systems, user interface design, and electronics, our team hopes to create a fun yet technically meaningful product that demonstrates how digital entertainment can be translated into interactive hardware.

The planned device will feature a compact rectangular layout with a built-in keyboard, small screen, and colored lighting to display player feedback. When a user enters a guess, the screen will update to show the results while the keys illuminate to indicate which letters are correct, misplaced, or incorrect. This design mirrors the original Wordle interface while adding the satisfaction of a real-world interaction through buttons and responsive lighting. Together, these components form the foundation of a simple, intuitive system that emphasizes both usability and visual clarity.

At the center of WordPal's design is a microcontroller that manages user input, lighting control, display updates, and overall system coordination. The chosen microcontroller provides reliable performance and built-in connectivity features that will allow optional offline play. Through this connection, the device will eventually be able to download the official daily Wordle from The New York Times, so users can play the same puzzle as others worldwide. For offline play, WordPal will include a stored word library to generate random games. Programming is being developed using an accessible embedded platform that supports rapid testing and integration across hardware components.

The power system is being planned to make the device fully portable and easy to recharge. A rechargeable battery will supply energy to all major subsystems, with charging provided through a standard USB-C port. The system will be optimized for efficient operation, balancing performance and battery life to ensure convenient everyday use. The current design approach focuses on safety, compactness, and reliability for long-term use.

The project also takes into account important industrial standards and design constraints to ensure the final product operates safely and reliably. This includes adherence to USB charging specifications, wireless communication standards, and established PCB layout practices. Practical constraints such as cost, portability, and usability have also guided the team's design decisions, helping balance functionality with realistic production goals.

Overall, WordPal serves as a creative demonstration of how engineering principles can be applied to transform a simple online game into a standalone device. The report that follows details the research, design methodology, component selection, and planning that have gone into developing the WordPal system. Once complete, the prototype will showcase the integration of hardware, software, and design to create an interactive handheld experience that bridges entertainment and engineering.

2.1 Project Background and Motivation

Wordle is a game played daily by millions of people in all walks of life. It is simple enough to be completed in under 5 minutes, yet complex enough that it never gets boring. The game of Wordle is heavily inspired by the game of Mastermind (or “Bulls and Cows”), where the objective is to guess a sequence of 4 colored pegs in a limited number of opportunities. The key to the game is the feedback system; with each guess, the player is told the number of pegs they have in the correct position (communicated with smaller red pegs) and the number of pegs that are the same color as one present in the correct sequence but are in the incorrect position (smaller white pegs). Wordle expands on this concept by replacing the sequence of colors with real 5-letter English words. As opposed to Mastermind, where the player is not told which specific pegs are correct or present (only the count), Wordle tells the player which letters are in the right or wrong position by displaying a green or yellow background behind them respectively (absent letters are marked with dark gray).

Our project idea aims to bring Wordle to life in a unique way by turning the keyboard keys themselves into the feedback system. The native Wordle application uses its own on-screen keyboard (notably doing so regardless of whether you have a different physical or on-screen keyboard handy), which it uses as an auxiliary way of communicating feedback to the player, by changing the background of each key to reflect the status of each letter. In our project, we plan to implement a physical keyboard, a la the Blackberry or other mid-late 2000s mobile phone keyboards. However, we will make our product stand out by using semi-translucent keys to color in the background of each letter analogously to the Wordle app as presented by The New York Times and Josh Wardle.

Additionally, a major aspect of Wordle is that it is only playable once per day; at midnight local time, the Wordle resets and everyone in the world is given the same new word to guess. We plan to implement a system that will randomly pick a 5-letter English word so that our device is usable more than one time per day, but we will also take advantage of the ESP-32's Wi-Fi capability to fetch the daily word from The New York Times to maintain the critical social element of the game.

2.2 Goals and Objectives

Basic Goals

- Generation/selection of 5-letter words on device
- LCD display to show game progress and interface with user
- User input via on-device physical QWERTY keyboard
- Feedback via RGB LEDs diffused behind keyboard
- Powered by a lithium-ion battery
- Battery charged via USB-C port
- Wi-Fi capability via ESP32 (built in), for obtaining daily word

Advanced Goals

- Implement a buzzer speaker for auditory feedback (and personality?)

- Allow exporting game results as serial text data via USB-C

Stretch Goals

- Create wired local multiplayer through USB-C
- Touch screen
- Additional word games
- Multiple word lengths

Basic Objectives

- Create a Network API to obtain the daily word if necessary
- Create an algorithm that pseudo randomly generates words
- Create an algorithm that keeps track of the rounds
- Create code that allows the player to guess and for the guess to be checked for correctness
- Display colors that give hints to the player on the LCD
- Display the game playing interface on the LCD
- Light up relevant LEDs with the relevant colors that also give hints to the player (implement an LED multiplexer)
- Implement a keyboard of 26 letters in the QWERTY format, a backspace, and an enter key
- Create code that allows a button to interrupt and do a new game
- Implement a 5V regulator circuit
- Implement a 5W charger
- Implement a USB-C port/breakout
- Implement a power switch
- Create Wi-Fi configuration code

Advanced Objectives

- Create the relevant code which allows exporting (potentially take advantage of UART)

Stretch Objectives

- Implement LEDs that light up relative to who wins or loses, and this be accomplished through the USB-C cable
- Create code that can have smaller or bigger word sizes for the word that needs to be guessed, and rounds adjusted accordingly
- Implement capacitive touchscreen

2.3 Description of Features and Functionalities

The WordPal is a rectangular device with a keyboard of 26 letters arranged in the QWERTY format as well as a backspace key and enter key. It also has a button on right side on the top side that starts a new game whenever it is pressed. The WordPal can play a word guessing game (a clone of Wordle or Wordle inspired). In the game, the word is either

pseudo randomly generated or the obtained daily word, and the player has to guess it, while WordPal gives out relevant hints, in a limited amount (6) of rounds. The device has an LCD on the front side above the keyboard. The hint system of WordPal includes color changing LEDs which can be green for the correct input in the correct place, yellow for the correct input in a misplaced place, and red for an incorrect input. The LEDs are located above the keys. There is also a hint system on the LCD of WordPal in relation to the player's guesses. The same colors of the LEDs apply for background of the letters of the guesses. The enter key allows the player to submit guesses, and the backspace allows the player to delete letters. A battery component will be a rechargeable lithium-ion battery, and it can be charged via USB-C (its USB-C port is on the top as well as a power switch next to it on the right). WordPal also has the capability of exporting game results as serial text data via USB-C. It will have Wi-Fi capability where it can access the daily word from New York Times; it will also have a buzzer speaker for auditory feedback.

For the hardware of WordPal, its MCU is the ESP32. Data flows from it to other components like the Keyboard, LED Multiplexer, LCD Display, and USB-C/Breakout, and data flows back from the Keyboard. The other places of data flow are from the power switch to the lithium-ion battery and from the LED multiplexer to the RGB Key LEDs. For the power, it flows like this: from the 5W Charger it goes the USB-C/Breakout, from there it goes to the lithium-ion battery, from there it goes to the 5V regulator circuit, and from there it goes to multiple components which are the LCD Display, the Keyboard, the MCU, the LED Multiplexer, and the RGB Key LEDs. The buzzer's incorporation is something that may not be fully decided upon yet.

For the software of Wordpal, it might go a bit like this. We first start off with the power on/initial state. From there it checks to see if the daily word was solved. Then it goes to different places depending on whether the answer is yes or no. If yes, it can either send the results over USB or it can generate a word. After the results are sent, it also goes to generate a word. Before we continue from there, let's go back to what happens if the answer is no for if the daily word was solved. It will go to check if the Wi-Fi is configured. If it is then it will get the daily word. If it is not, then it will go the Wi-Fi configuration and after that has been done successfully would it to get the daily word. Once the daily word has been obtained, it will go to the same place as where it goes after the word has been generated which is maybe where the game happens and where the player guesses the word. It will check for a correct guess. If it does then it will send the results over USB, and if not then it will give feedback via LEDs and then go back where the player can guess a word. There will also be an interrupt that can come from a button on the right side where it will go generate a word and go from there. There will also be a round checker which ends the game once six rounds have completed. In relation to the sending the results over USB-C, there may be some figuring out to do but UART could potentially be taken advantage of. The programming environment that will be used with WordPal is the Arduino Core for the ESP32, and the programming language might be the Arduino programming language (based on C/C++).

In relation to the stretch goals/objectives of WordPal, it could have wired local multiplayer through USB-C implemented, perhaps reminiscent of the wired multiplayer of the Game Boys via the Game Link Cable. Through a USB-C to USB-C cable that connects between

them, it could light up the relevant LEDs between the two of them (either a red one for the loser and a green one for the winner), and it could also be implemented where the same word they are trying to guess is shared between them (though perhaps the words could also be different). For the touchscreen, it will be capacitive maybe also capable of multi-touch. There can also be additional word games. How they look like is maybe not decided currently. There is also the option that could be included of Wordle of multiple word lengths. Instead of 5 letters, it could be less or more, and the number of rounds could be changed relative to the number of letters. It might be that the round number will be one greater than the number of letters that will be guessed.

2.4 Existing Product/Past Project/Prior Related Work

We found two projects that stood out when looking at other handheld versions of Wordle. The first was a build by Michael Lacock, who made a Wordle clone on the Adafruit CLUE board using CircuitPython [2]. The CLUE already has a small color screen and two buttons, so it was an easy way to get the game working on hardware. Lacock made two versions of his build, one that relied on the A and B buttons to scroll through letters and confirm guesses, and another that connected to an external keyboard for a quicker input. Both versions displayed results on the screen just like the online game. These projects showed us that Wordle can be run on a small portable device, but it also showed the limits of using a dev board that already has everything built in. Since the CLUE handled the display, buttons, and power on its own, there wasn't much custom designing or wiring involved. Overall, the device worked as a demo but skipped the hardware challenges that we would encounter in this course.

The second project we looked at was Richard Falcema's Wordle handheld device, called "Wordle Term" [3]. This device was more about looks and design than electronics. It had a 25 square display grid and five wheels that players turned to pick letters, with the game giving feedback in orange, gray, and green. What stood out was the style of the device, the circuit board was exposed, the battery was visible, and it had bright colors and even a lanyard. However, this project didn't go into how the electronics work, so it came across more like a design concept.

Seeing both examples gave a clearer sense about what has already been done and where our project fits. Lacock's handheld device showed that Wordle logic can run on hardware, while Falcema's design gave an example of how a handheld device could look. For our project, it will expand on these two ideas. We are planning to design our own PCB and add buttons and LED indicators and connect an LCD display to run the game. Instead of just showing that Wordle can run on hardware or focusing only on how the device looks, our goal is to put the whole system together and build a working prototype.

These prior projects highlighted how important feedback and usability are in a handheld game. The Adafruit CLUE project worked, but the input method was limited to just two buttons on one of the versions, which slowed down gameplay. Our inclusion of a keypad in contrast that players can quickly select letters (which is also applicable to the other version that connects to an external keyboard), as well as LEDs to provide immediate visual feedback. Adding both features will make our design closer to the way the game is normally

played and create a smoother user experience overall. Also, having multiple feedback channels, like an LCD for displaying guesses and LEDs for color cues makes the system easier to follow. To meet course expectations, we cannot rely solely on an existing dev board. Our project is going to focus on making the game easier to play while also tackling the real hardware challenges. The keypad and LEDs give us better input and feedback.

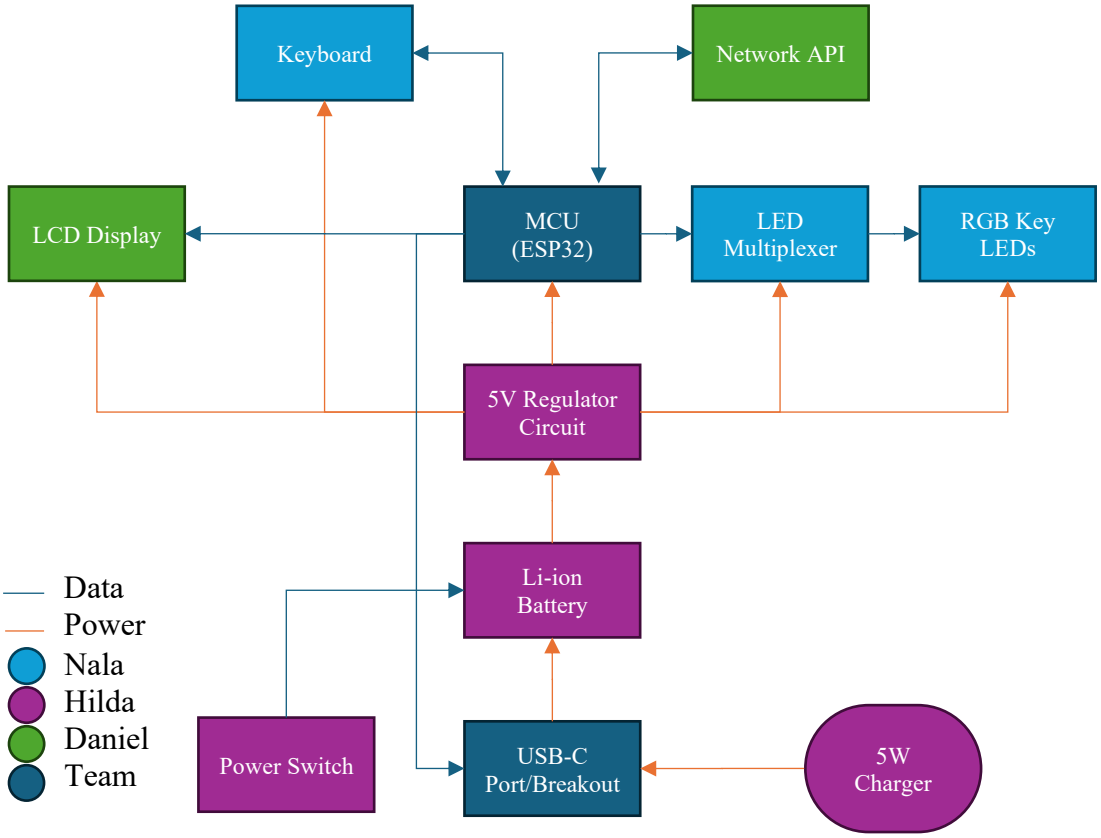
2.5 Engineering Specifications Table

Table 2.5: Engineering Specifications

General	
Dimensions	< 8 in x 5 in, < 1 in thick
Battery Capacity	> 1000 mAh
Battery Life	> 2 hours
Cost of Materials	< $350
Charging	>= 5V1A, USB-C
Weight	< 250g
Keyboard	
Response Time	Less than 100 ms
RGB LEDs	Addressable, <= 5V, >2 bpc
Display	
Response Time	Less than 100 ms
Brightness	> 250 nits

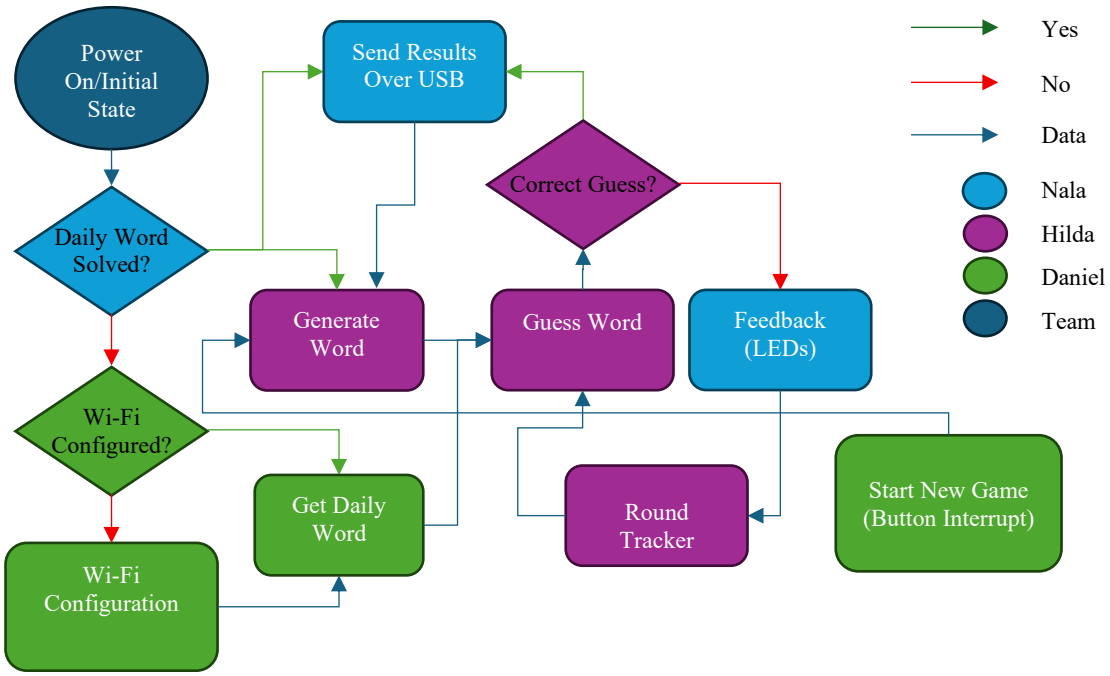
2.6 Hardware Diagram

For the following diagram, the status of all of the blocks may be currently to be acquired (sentence maybe not up to date).



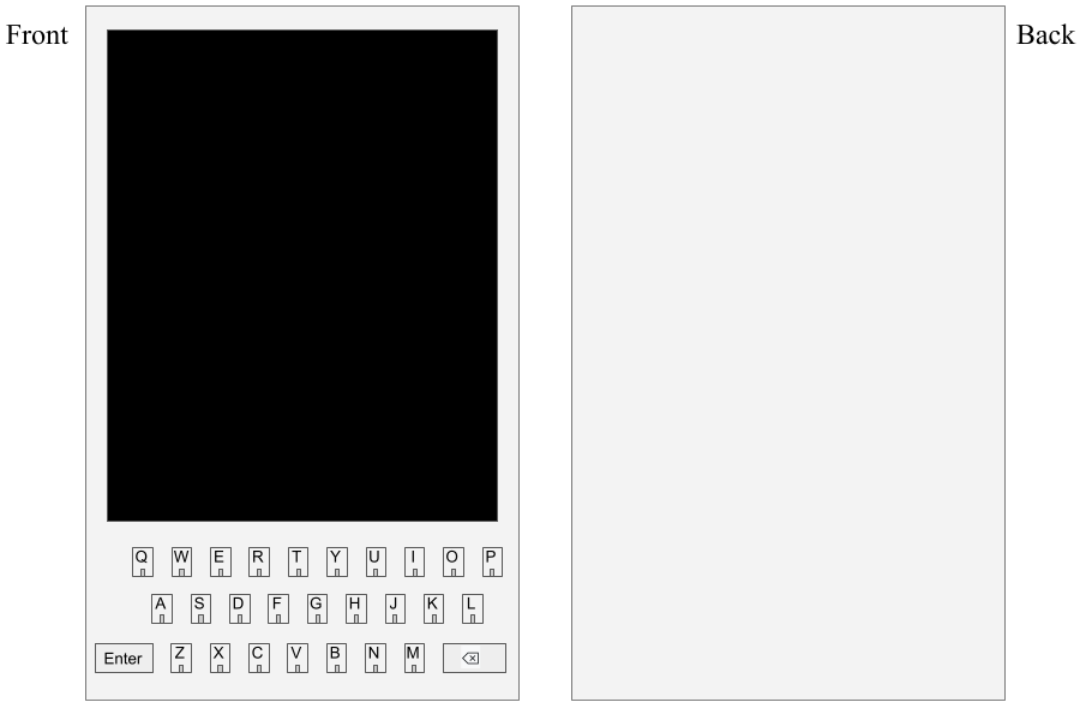
2.7 Software Flowchart

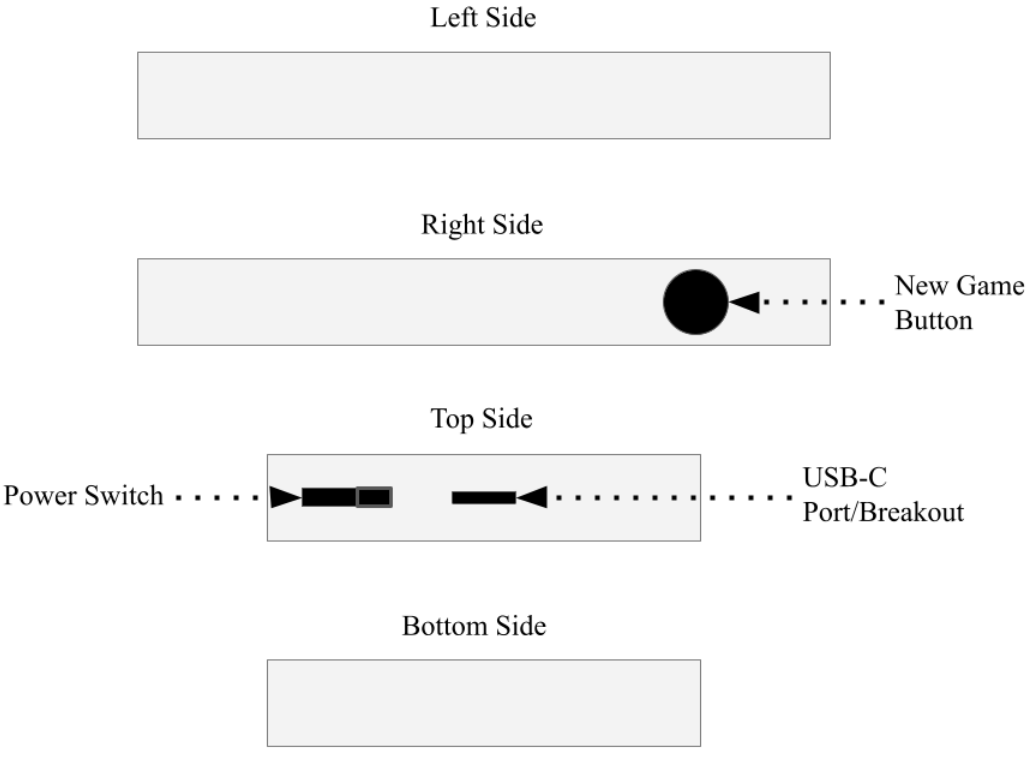
For the following diagram, the status of all of the blocks may be currently to be acquired (sentence maybe not up to date).



2.8 Prototype Illustration/Blueprint

The prototype design might still be a work in progress. The design might be similar to the BlackBerry Keyone where the screen was quite a bit bigger than the keyboard. The ratios of the design is in line with an 8 in. length by 5 in. width and a 1 in. thick type ratio though the actual device might be smaller than that. The prototype's outer casing might be built with a 3D printer, and the LEDs are above the keys.


Front
Back
Q W E R T Y U I O P
A S D F G H J K L
Enter Z X C V B N M


Left Side
Right Side
New Game Button
Top Side
Power Switch
USB-C Port/Breakout
Bottom Side

2.9 House of Quality

Table 2.9: House of Quality

			↓			
				↓		
			↓		↓	
				↓	↓	↑
	Design Requirements		Response Time	Display Brightness	Battery Capacity	Weight/Dimensions	Cost
			-	+	+	-	-
Customer Requirements	Ease of Use	+	↑	↑	↓	↓	↑
	Portability	+			↓	↑	
	Battery Life	+	↓	↓↓	↑↑	↑	↓↓
	Charge Time	-			↓		↓↓
	Cost	-	↓	↓	↓		↑↑
Targets			<100 ms	> 250 nits	>1000 mAh	<= 8x5x1in, <=250g	<$350 excluding prototyping

3 Research and Investigation

3.A Hardware

3.A.1 Processing

In the modern age, computer systems are typically defined by a central processor, and WordPad is no exception. This central processor is most often in the form of a microprocessor, which is a single integrated circuit that can handle our necessary central operations (i.e. being the central bridge between peripherals). Depending on scale and demands, this microprocessor can either be its own discrete unit relying upon external memory and other necessary components (such as in most desktop computers) or be contained in a package alongside these components. The latter approach is known as a microcontroller, which is essentially a tiny computer complete with its own processor, memory, and I/O. In mobile phones, where much more power and complexity is required for modern applications, systems-on-a-chip (SoCs) are used instead, which can often contain their own GPU and self-contained peripherals; SoCs can essentially be thought of as beefed-up microcontrollers. We will refer to microcontrollers as MCUs, for "microcontroller unit;" the microcontroller and the SoC are the first two of the three technologies we eyed for the central processor for this project.

Alongside microcontrollers and SoCs, there are FPGAs, or field-programmable gate arrays. As the name implies, these are high-density banks of logical circuitry that can be reconfigured "in the field" to fit the application and therefore are highly versatile (as any modern computer can essentially be boiled down to a large array of logic gates). However, unlike the MCU or SoC, which have access to their full "toolkit" upon installation, FPGAs are a blank canvas; they effectively require you to design the low-level logic for your processor on your own. Granted, there are many libraries and utilities that ease this process, but it is still a much lower-level task than programming a traditional MCU. The benefit to using an FPGA comes in its computing prowess; because it is programmed exactly to specifications by the user, there is little to no "waste" in its processing, and it can perform tasks in parallel with relative ease. Unfortunately, there is an additional tradeoff in that FPGAs are traditionally optimized for prototyping and not deployment and therefore have higher power usage than MCUs. In enterprise applications, this often leads to FPGAs being replaced by application-specific integrated circuits (ASICs), but these are not feasible for us to develop within a year from scratch, and are especially expensive considering they are designed to be ordered in bulk whereas we only need a single working chip in the end.

This leads us to the decision between the MCU, SoC and FPGA for WordPal. Portability is at the core of WordPal, so we want it to be power-efficient; cost efficiency and ease of use are also always pluses.

Table 3.A.1a. Processing Unit Comparison

Characteristic	**MCU**	**SoC**	**FPGA**

Cost	Affordable	Expensive	Insanely Expensive
Power Efficiency	Excellent	Fair	Poor
Performance	Fair	Good	Excellent
Flexibility	Fair	Fair	Excellent
Software Development	Moderate	Moderate	Difficult
PCB Development	Simple	Moderate	Difficult
Physical Size	Small	Medium	Large

In summary, while the FPGA and SOC are quite powerful, we believe that they do not fit our purposes nearly as well as the MCU. The MCU is cost- and power-efficient, performs well enough to meet our needs, and is relatively easy to design our PCB and software around. We all also have experience developing for an MCU from Junior Design as well as various technical courses on our path to Senior Design. For these reasons, we've decided that the microcontroller is the best technology to build WordPad upon.

Choosing an MCU

Now that we've settled on MCUs, there is a much larger subset of choices in which microcontroller to build around. We would rather choose a more commonly used unit, as with the greater popularity of a certain microcontroller comes a greater wealth of information and documentation that we can take advantage of when designing and programming.

A more classical choice would be the Texas Instruments MSP430. UCF, having a partnership with TI, typically uses MSP430-based development boards when teaching students about embedded systems, which gives the MSP430 a leg up in that we already know how to work with it. The MSP430 is cheap and highly efficient, but it is also relatively ancient, being virtually unchanged aside from spec bumps since 1992, and being a 16-bit processor. As for peripherals, serial communication is essentially the most complex one can get with the MSP430; it would be extremely taxing for both us and the MCU to try and have it run a non-segmented display. Additionally, the MSP430 has over 550 family members, and choosing a specific one to meet our needs would seem to be quite a headache.

For far more recent options, we can look to the Raspberry Pi Foundation and their RP2350 family of microcontrollers. These were released just last year, and are the successor to the RP2040, a modern microcontroller that was (and still is) an incredibly popular MCU in the hobbyist space. While the MSP430's highest-end family member can run at 25 MHz, and

has at most 66 KB of RAM, the RP2350 has 520 KB of memory and runs up to a whopping 150 MHz (whopping on the microcontroller scale; modern desktop CPUs typically run in the multi-GHz range). Plus, the RP2350 contains a hardware RNG, or random number generator, which could facilitate the "endless play" mode we have planned by selecting a random 5-letter English word. By default, the RP2350 does not have any non-volatile memory, but its RP2354 variant has 2 MB, quadrupling the MSP430's best offering. The RP2350 even has a HSTX (high-speed serial transmitter) controller for the purpose of output to a display, which fits the bill quite well.

Another popular microchip in the hobbyist world, if not the most popular, is the Espressif ESP32, which runs at up to 240 MHz. The defining feature of the ESP32 is that it has Wi-Fi and Bluetooth capabilities baked in, meaning it would be far easier to work with in terms of connectivity than the RP2350 and especially the MSP430. While the ESP32 does not come with flash memory on the chip itself, it supports up to 16 MB, easily the biggest so far; we likely won't be needing all of that, but it helps for potentially storing graphics and game data. Some variants of the ESP32 even come with their own ultra-low-power secondary processors that we could use to save battery life when inactive (granted, Wi-Fi tends to be rather power-hungry, but this is a Wi-Fi problem and not an ESP32 problem). Most ESP32 family members even have USB-OTG support out of the box, which means they can function as a host device as well as a peripheral device (something USB-C emphasizes heavily). It even has support for a sound interface!

These are the three choices we have whittled down to, and their final comparison:

Table 3.A.1b. MCU Comparison

Characteristic	**TI MSP430**	**RP2350/2354**	**ESP32**
Chip Cost	≤$5	$1-2	$2-4
Dev Board Cost	$20-30	$7-8	$10-20
Speed	Up to 25MHz	Up to 150MHz	Up to 240MHz
Volatile Memory	Up to 66KB	520KB	520KB
Flash Memory	Up to 512KB	RP2350: none RP2354: 2MB	448KB ROM Up to 16MB
Serial Connectivity	UART, SPI, I2C, USB, PWM	USB, UART, SPI, I2C, HSTX	USB, UART, SPI, I2C
Other Peripheral Interfaces	Touch, temp sensor, ADC, LCD	Touch, temp sensor, ADC,	Touch, Ethernet, IR, PWM, I2S, ADC, DAC

Other Features	AES, RTC	TRNG, crypto	Wi-Fi, Bluetooth, TRNG, crypto, RTC, USB-OTG
Physical Size (mm)	Varies wildly, commonly from 3x3-16x16	7x7 QFN, 10x10 SMD	Publicly available as ~20x20 WROOM module

With these comparisons in mind, we decided to opt for the ESP32, as its Wi-Fi capabilities, popularity, wide feature set, ease-of-use, performance, and power efficiency stood out to us. For a specific model, we chose the ESP32-S3-WROOM-1-N8R8, as it has a built-in antenna, and we were able to find a development board containing the same chip so that we can develop the prototype solderless.

Now that we have the core of our board established, we can delve into peripherals.

3.A.2 Display

Obviously, we do not have the time or budget to manufacture a custom display for this project, but we still have to choose a type of display to meet our needs. There are, of course, the simple seven-segment display, as well as the alphanumeric "rows and columns" based displays (one of which we used in Junior Design). However, while simple to use, neither of these display types really fit the needs of our project, which requires at least a 4-color display (for displaying a light color, dark color, a green, and a yellow). Instead, we are looking for something with a full matrix-based display, and thankfully, there is no shortage of resources in this regard.

The most common display technology in modern electronics is the liquid-crystal display, or LCD, which uses electronic matrices to manipulate the aforementioned liquid crystal into images, along with a backlight for brightness (as the liquid crystal does not produce light of its own). While this describes an overarching category of panels, there are important distinctions between subcategories of LCD; for instance, there exist both "passive-matrix" and "active-matrix" panels. The former will maintain the state of its pixels and therefore the entire image until it receives a signal to be refreshed (this is known as bistability, which we will circle back to shortly). The latter requires each pixel to be driven by its own transistor and capacitor to actively maintain its state, which helps for display clarity, as passive-matrix displays can sometimes experience "cross-talk" which can lead to smearing and other artifacts (think the original Game Boy). Therefore, the active-matrix LCD is considered to have superseded the passive-matrix LCD, and most LCDs available use active-matrix technology, especially those intended for use in embedded devices. (Lower pixel-density passive-matrix LCDs are still on the market, as the increased footprint minimizes cross-talk).

LCDs are so ubiquitous that they have become quite cost-effective, with LCDs at our side typically going for around $30.

The main competitor to the LCD is the OLED display, which is relatively similar but does not require a backlighting solution as the pixels illuminate themselves. This is excellent for power use, as this means any dark pixels are essentially "shut off" so as to not require power; it is also great for visual clarity in that this creates a much higher contrast between light and dark pixels. However, OLED displays are still relatively novel, meaning a higher price than the alternative LCD display.

Speaking of alternatives, there also exists the humble E-ink display. E-ink displays essentially take the concept of bistability from the passive-matrix display and push it to its limit, only requiring power upon refresh. This is the type of display used in e-readers, and it is known as E-ink due to how it appears as though it were ink written on paper. However, there are two major drawbacks to E-ink tech: the color options and the refresh time. Due to how E-ink displays function, they are commonly only sold as 2-color black and white displays. There are a few four-color displays available, but yellow and red are usually the only additional colors, and we are looking for green instead of red. There are also a limited number of full-color E-ink displays, but they are preposterously expensive; just one would surpass our budget for the entire WordPal. The refresh time is also a problem in E-ink displays (at least, those that fit within our budget); hobbyist E-ink displays intended for embedded applications can often take up to 15 seconds to fully refresh, which would make the gameplay quite slow and unenjoyable. We will weigh E-ink in our comparison table, but it does not look like the advantages outweigh the stark downsides.

Table 3.A.2a. Display Technologies

Characteristic	**LCD**	**OLED**	**E-ink**
Cost	$20-50	$50+	$50+
Power Efficiency	Decent	Great	Excellent
Brightness	Backlit, decent	Good	None
Contrast	Good	Excellent	Good
Colors	8bpc	8bpc	2-4 colors total

With this in mind, we decided to go with the LCD display, as this was the most effective option for us in both cost and performance.

As for an actual display module, the main thing that we had to narrow down was the size. Our goal for WordPal is to make the final product compact and usable, so we decided to go with a 3.5-inch display module, as it was a common enough size for us to have a variety of choices. A 5-inch display would be quite big for our purposes,

3.A.3 Keyboard

For the keyboard and lighting, there is not exactly a choice of technology for us, as we are essentially forced to use the technologies that we will outline in the upcoming sections.

As for keyboard technology, we will be designing our own keyboard using pre-existing switch technology. There are a couple of options, the most prominent of which are tactile button switches. These button switches are quite power-efficient, and usually come in small packages. They are available both as through-hole and SMD devices, but in the interest of keeping things compact, we will probably go with SMDs. Our main choice is regarding the size of our switches, as we need enough room to wire in our lighting system as well. 12mm tactile switches are already too big for our purposes, as the top row of keys would not fit within our design constraints. The other most common sizes are 6mm square, and 3mm square. 6mm square switches are a good size on their own, but they do not allow us much room for lighting components. 3mm square switches seem to be just what we need, as we can design keycaps that actuate the switches as well as allow room for the lights.

3.A.4 Lighting

For the lighting, as mentioned previously, we are pretty much required to go with a specific technology, that being the RGB LED. There are two sub-categories here, though: standard individual LEDs, and addressable LEDs. Standard LEDs must be individually wired or controlled in a matrix, similar to LCD display modules. However, addressable LEDs work in the same way as SPI daisy-chaining, where each LED can be controlled through the same parent device and channel by connecting each LED's data output to the next LED's data input. This makes programming the functionality of our LEDs way more convenient.

3.A.5 Enclosure

The enclosure for WordPal is pretty much the last step, as printing or machining an enclosure without a finalized layout or PCB design would be quite wasteful. It is most likely that we use a 3D-printed case design, as it is easily accessible via the TI lab.

3.A.6 Power System and Circuitry

The power system of WordPal provides stable and efficient energy to all hardware components, ensuring reliable operation of the microcontroller unit, LCD display, keyboard, and LED system. This section focuses on the circuitry responsible for power delivery, conversion, and regulation throughout the device. The design of this subsystem is critical since it determines how long the system can operate on a single charge and how effectively it manages energy between the battery and each functional component. The following subsections begin with an analysis of the system's overall power requirements, followed by a detailed comparison and selection of the most appropriate battery technology, charging circuit, and voltage regulation design. These decisions are based on the need to balance runtime, safety, size, and cost, while maintaining compatibility with the electrical and spatial constraints of the WordPal prototype.

3.A.7 - Power Distribution and Requirements

To properly design the WordPal power system, it is necessary to determine the electrical requirements of each major component. This ensures that the selected battery, charger, and voltage regulators can reliably supply the current needed for continuous operation. Table 3.W.1 summarizes the expected voltage and current draw of each subsystem based on the components planned for the prototype. These estimates are drawn from the current design specifications and realistic performance expectations for the microcontroller, LCD screen, RGB keyboard, and other supporting hardware. Since WordPal is intended to function as a portable, battery-powered device, understanding how much power each part consumes is essential for determining the battery capacity, regulator efficiency, and overall energy management. This power breakdown serves as the foundation for all power-related design decisions discussed in the following subsections.

Table 3.A.7 Power Distribution Requirements

Component	***Supply Voltage(V)***	***Recommended Current(mA)***	***Power(W)***
ESP32 MCU	3.3V	≥ 500mA	1.65W
LCD Display TFT Logic	3.3V	50mA	0.17W
LCD Display TFT Backlight	5.0V	450mA	2.25W
QWERTY Keyboard	5.0V	16mA	0.08W
RGB Key LEDs	3.3V	60mA	0.20W
LED Multiplexer	3.3V	20mA	0.06W
Li-ion Battery	3.7V	520mA	1.92W

The numbers in Table 3.A.7 were gathered from component datasheets and technical documentation to ensure realistic estimates of voltage and current requirements. For elements that are not yet finalized, such as the specific LCD model, estimates were based on manufacturer reference designs and application notes for similar 4”-5” TFT displays. These power requirements provide a baseline for determining suitable battery capacity, regulator design, and overall energy distribution across the system. Establishing these values early helps ensure that all components receive stable power during operation and that the final design can maintain efficiency and safety. The following section discusses

how these voltage levels are generated and managed through the use of step-down and step-up converter circuits.

3.A.8 Voltage Regulation and Power Conversion

A major part of developing WordPal's circuitry involves determining how to regulate voltage for each hardware component. Since the system is powered by a single lithium-ion battery, additional regulation is required to supply both lower and higher voltages to different parts of the circuit. For this reason, it is important to research the types of voltage regulation that could be used and compare how they perform in terms of efficiency, cost, and practicality for a small portable system. Two common methods were reviewed: linear regulation and switching regulation. Linear regulators and simple and inexpensive but tend to waste energy as heat, which makes them less suitable for battery-powered designs. Switching regulators use high speed switching and feedback control to maintain a stable output with much higher efficiency.

Both methods can technically meet the voltage needs of the system, but their performance differs when size, heat generation, and power loss are considered. Linear regulators are easy to implement and provide a clean, low noise output, but they would quickly drain the battery when converting to lower voltages. Switching converters are slightly more complex but allow greater flexibility, since they can either raise or lower the battery voltage as needed. This makes them a better fit for a device like WordPal, where both 3.3V logic circuits and 5V peripherals may be required. Compact buck and boost converters are commonly used in small, embedded devices, and their high efficiency and low power loss make them strong candidates for WordPal's future design phase.

Table 3.A.8 Voltage Regulator Comparison

Characteristic	**Linear Regulator**	**Switching Regulator (Buck/Boost)**
Efficiency	40-60%	80-95%
Heat Dissipation	High	Low
Design complexity	Simple circuit	Requires inductors and feedback
Battery suitability	Moderate	Great for portable devices

The comparison in Table 3.A.8 highlights the main tradeoffs between linear and switching regulators when designing a power system for a portable device like WordPal. Linear regulators are simple and inexpensive, but they waste more energy as heat, which reduces efficiency and shortens battery life. In contrast, switching regulators are more complex but

provide much higher efficiency, which makes them better suited for battery powered applications. Because WordPal relies on a single cell lithium-ion battery to supply both voltage rails, a switching approach is more practical for maintaining stable voltages and extending runtime. The findings from this comparison provide the foundation for selecting an appropriate buck or boost converter design for the system's voltage regulation stage.

3.A.9 Battery Technology and Charging Circuit Comparison

A reliable battery is an essential part of WordPal's design since the system is meant to operate portably without constant connection to external power. The goal of this section is to evaluate different rechargeable battery options and identify which type best supports the device's power and size needs. Because the system must supply stable voltage levels for both 3.3V and 5V components, the battery should provide consistent output while maintaining a long lifespan and safe operation. A lithium-ion (Li-ion) battery and a lithium-polymer (Li-Po) battery were reviewed. Each technology offers different tradeoffs in energy, density, cost, safety, and maintenance.

Table 3.A.9 Battery Technology Comparison

Property	**Lithium-ion**	**Lithium-polymer**
Nominal voltage	3.7V	3.7V
Capacity (mAh)	2600mAh	1100 mAh
Weight (g)	46g	24g
Shape / form	Cylindrical cell	Flat pouch cell
Cost / availability	Low / widely available	Moderate / limited models

The comparison between Li-ion and Li-Po batteries shows that both technologies can meet the system's 3.7V requirement, but they differ in practicality for WordPal's design goals. The Li-ion cell offers a higher capacity and longer operating time, making it more reliable for continuous use. Although the Li-Po battery is lighter and takes up less space, its lower capacity and higher cost can make it less ideal for this application. Since WordPal's enclosure can safely support a cylindrical Li-ion cell, this option provides the best balance between energy output, affordability, and availability. The selected battery type will work with a standard constant current / constant voltage charging circuit, ensuring safe and efficient recharging through the device's USB-C port.

With the power requirements, regulation methods, and battery options analyzed, the next step is to understand how these elements work together within the overall power system. Integrating the voltage regulators, charging circuit, and energy sources is critical to ensure that each hardware component in WordPal receives stable and efficient power. The

following section discusses how these subsystems interact within the circuitry to maintain reliable operation, safety, and performance across different usage conditions.

3.A.10 Overall Power System Integration

After reviewing the battery options and voltage regulation methods, it was important to look at how these parts come together to power WordPal. The power system needs to work in a way that keeps every component running smoothly without wasting energy or damaging the battery. Each part of the circuit plays a specific role. The battery stores energy, the voltage regulators adjust it to the right levels, and the charging circuit makes sure the battery can safely recharge when connected to an external source.

In this setup, the lithium-ion battery supplies around 3.7 volts to the rest of the circuit. A buck converter lowers this voltage to 3.3 volts for parts like the ESP32 and LED controller, while a boost converter raises it to 5 volts for the LCD display and keyboard. The charging circuit works separately from the regulators to safely manage the battery charge using a constant current and constant voltage process. This setup also allows the system to keep running while the battery is charging, which helps with convenience and reliability.

Bringing all of these parts together creates a power system that is efficient, simple to manage, and safe to use. Making sure that the battery, regulators, and charger all work well together helps the device last longer and keeps performance consistent over time. This integration serves as the foundation for WordPal's electrical design, ensuring that the system can meet its power demands without compromising portability or safety.

3.B Communication Protocol

3.B.1 USB/Serial Communication

WordPal has the ability to export via USB text game results. There are three different options: Arduino Serial, TinyUSB, and ESP-IDF USB Stack.

Arduino Serial

Arduino Serial is compatible with Arduino and is simple. WordPal doesn't involve much, so this can work well.

TinyUSB

TinyUSB is more advanced, but that extra complexity isn't needed.

ESP-IDF USB Stack

ESP-IDF USB Stack allows way more control, but it is also more complex and isn't proper for this project.

3.C Software

3.C.1 Programming Environment

A programming environment can refer to some different things, but one way to think of it is the set of software things which allow for software development (it could also involve hardware). Without a programming environment, there may be a significant barrier to progressing on WordPal if there can be progress. There are different options compatible with the ESP32 MCU we are using which includes Arduino Core for the ESP32, ESP-IDF, and MicroPython. Information and analysis on these three will be below which will go over ease of use, programming language support, library support, performance, and suitability for prototype development.

Arduino Core for the ESP32

An Arduino Core would be the middleware application layer which has the low-level software needed for translation between a microcontroller's hardware capabilities and utilized Arduino IDE functions from a sketch (Arduino's name for a program) a programmer writes. There is an Arduino Core for the ESP32 which allows us to utilize the Arduino IDE (a cross platform and beginner friendly IDE). The installation process of the Arduino core can be done some ways (installing through Arduino IDE and manual installations of Windows, Linux, and macOS); the simpler ones may be the Linux and Arduino IDE ones which would likely be those two methods used for WordPal. There are 8167 Arduino libraries in a particular place (the Libraries part in the documentation). Most of these are contributed with the number going up to 8011 while the official only goes up to 140. The numbers for ESP32 specific ones are: 1097 libraries, 1088 contributed ones, and 9 official ones. However, quantity doesn't necessarily correlate to quality. Elliot Williams wrote a blog post that's while anecdotal and about 9 years ago, mentioned some experiences and made the conclusion that non-core libraries are hit and miss. For library installation, the library manager could be used, a .zip library imported, or a manual installation of one. The assumptions we will be operating with for this report in relation to library support for Arduino and the others is that official libraries are/have high quality while contributed libraries are/have mixed quality. So, given that the contributed libraries greatly outnumber the official ones, it will tend to be more mixed quality overall. Plus, while there are some requirements that a contributor must meet, it's open to anyone with a GitHub account, and the review process might be mostly automated with minimal human interaction which would mean less average overall quality.

While something like beginner friendliness is something that can't be objectively measured, it might be something that Arduino related things strive for and that at least some people agree they succeeded at. Arduino related things have been applied in different projects and applications, and the Arduino IDE and core allows for rapid prototyping which can be the difference between a successful senior design project and an unsuccessful one. The natively supported languages of the Arduino IDE are C, C++, and Arduino programming language although there are projects which allow other languages to be used. The Arduino programming language (based on C/C++) allows access to things like functions and

libraries which allows for an easier code workflow than traditional embedded programming. However, what is gained in simplicity and beginner friendliness, there would be lost some performance or stronger lower-level control. However, that is worth it in the context of WordPal. WordPal doesn't need to be the most optimized or require deeper lower-level control beyond what is necessary, and the Arduino programming language might provide enough.

ESP-IDF

ESP-IDF (stands for Espressif IoT Development Framework) is the official framework of ESP32 which is made up of a SDK (software development kit) that has APIs for networking, hardware, utilities, etc., an integrated build system, standard programming interfaces for C and C++, and comprehensive documentation and tutorials. ESP-IDF gives programmers the ability to fully leverage the capabilities of an ESP32 without being concerned about chip specific details or low-level register programming. Toolchain, Build tools (CMake and Ninja), and ESP-IDF have to be installed in order to utilize ESP-IDF on ESP32. There are some ways for installing the required software which at least are Eclipse Plugin, VSCode Extension, and manual installation (Windows, Linux, and macOS). There are 1176 components (which are libraries/modules) in a particular place. There might be around 100+ official components. Based on pure numbers, the quality of components overall is better than Arduino's since while the contributed components still outnumber the official ones, it also makes up more percentage wise. There is another reason that it could be of higher average quality which is that its code is likely more optimized and there is more of a production-grade bent. Each library is more specific for ESP32 as well. Components can be installed directly into a project from the Component Registry with relevant steps in the documentation.

For the methods we might utilize if we used ESP-IDF, we might use either the plugin or extension method or maybe the manual installations of Windows and Linux. The setup relative to Ardunio IDE might not be too bad. However, even if it might be simpler than relatively lower-level code, it is more complex than Arduino related coding. It doesn't hide as many details, and it can give us more control over the hardware. However, it wouldn't be ideal for WordPal. It is more intended for production-grade solutions which is likely not applicable for WordPal since it's intended to be more of a prototype, and the tradeoff between control and complexity is maybe not worth it for this project.

MicroPython

MicroPython is an implementation of Python 3 that is intended to work on microcontrollers, on small embedded systems, and in constrained environments. Python is considered beginner friendly similar to how the Arduino Programming language is as well. The installation process relating to MicroPython and the ESP32 requires a board with a ESP32 chip and powering it in some way first. Then the latest MicroPython firmware would be downloaded (which can be found from the MicroPython download page) and loaded on the device; the particular board's firmware would be searched for and two options can be used either a stable firmware release or a daily firmware "Preview" build. In relation to loading it on the device, the device would need to be put in bootloader mode, and the

firmware needs to be copied across. How exactly this can be done is highly board dependent, and this can be found in the relevant Micropython download page. If no errors happened, it should be installed on the board (troubleshooting is covered in the documentation). MicroPython might allow for rapid prototyping as well like with Ardunio Core.

After installation, the REPL (Python prompt) can be accessed over UART0 or the built-in USB device of the chip (the relevant baud rate is 115200). For accessing the prompt, a terminal emulator program might be necessary. Thonny could also be used. There are around 90 libraries as could be found in the repository of micropython-lib. There are also built-in libraries as well which include 27 Python standard libraries and micro-libraries, 12 MicroPython-specific libraries with another one that provide drivers for hardware components, and 9 port-specific libraries. This comes to a total of 49 libraries though there is at least some overlap with the earlier mentioned libraries in the GitHub. MicroPython might not have a place like the Component Registry of ESP-IDF, so while there is possibly more third-party libraries relating to Arduino and ESP-IDF than has already been mentioned, MicroPython might be even more so especially since the GitHub has the future plan and/or new contributor idea of adding support for referencing remote/third-party repositories. For instance, as calculated by ChatGPT in Mike Causer's list, there are 800+ libraries (don't know how much overlap) [60]. Going back to micropython-lib, there are some requirements and things to take note of before one can contribute. The core team affiliated with MicroPython is involved with micropython-lib, and they do utilize automated tools in relation to code style issues. It might not be completely clear at the moment manual review is involved , but given they might have discussions with the contributor(s) in relation to bug fixes, reject new features in the spirit of trying to keep things "micro", not accept every port given that each port could or would require significant maintenance from the core team, and more, they might at least be more involved than in the case of Arduino. Also, you can install packages with mip and manually. In relation to performance according to a paper titled "Performance Evaluation of C/C++, MicroPython, Rust and TinyGo Programming Languages on ESP32 Microcontroller", it basically found that MicroPython is slower compared to the other programming language (it's also higher level than the others and an interpreted language). Though this is more specific to neural network edge devices, Arduino IDE was also found to be a faster platform than MicroPython which could likely apply in a general sense as well. MicroPython may work well enough for WordPal, but Arduino might have more resources dedicated to it than MicroPython which might mean the software development process will be easier and more efficient with Arduino Core compared to MicroPython.

Table 3.C.1

Criteria	**Arduino Core forESP-IDF the ESP32**		**MicroPython**
Ease of Use	Beginner Friendly	Intermediate/Advanced	Beginner Friendly

Programming Language Support	C, C++, Arduino Programming Language	C, C++	Python
Library Support	Many Libraries with Mixed Quality	Many Libraries with Better Average Quality relative to Arduino	Many Libraries with Better Average Quality relative to Arduino
Performance	Second Highest Performance Typically	Highest Performance Typically	Third Highest Performance Typically
Suitability for Prototype Development	Suitabe for Rapid Prototyping	More Suitable for Professional Grade Solutions	Suitable for Rapid Prototyping

Selection Writing

The selection will be Arduino Core for ESP32. Its beginner friendliness would make project development easier and less time-consuming. Its programming language support can strike the right balance between being easy enough while still dealing with things like performance. While libraries having more mixed quality on average can be a downside, its volume can be an upside, and for this project perhaps the mixed quality might not set us back too much. Its performance in theory is good enough; we do need good performance for one of the things we will demo as well as in maybe in general since a slow WordPal would be unideal. However, we don't need to optimize performance too much. Arduino has been used for rapid prototyping multiple times, and it could apply well here for WordPal.

3.C.2 Display Libraries

Display libraries are the bridge between graphics code and display hardware. Display libraries in relation to the LCDs are beneficial for WordPal since it avoids needless complication and work in relation to displaying things to the LCD as well as displaying things as needed which without a way to display things on the software side will take away core functionalities of the WordPal. There are three libraries to cover which are TFT_eSPI, Adafruit GFX, and LovyanGFX. Information and analysis on these three will be below which will go over ease of use, feature set/capability, and performance.

TFT_eSPI

TFT_eSPI is a graphics and fonts library that is Arduino IDE compatible (it also allows for sprites). When it comes to ease of use, some sources and how the code can look could support the idea that it's at least from a beginner to intermediate level though maybe leaning more towards the former than the latter. It is possible to have issues with the User_Setup_Select.h file (and maybe related), but this might happen more so if you're

dealing with multiple projects or types of displays. However, if we're dealing with WordPal only, it might not pose that big of a problem though we may have to be mindful of it (maybe have the related thing(s) apply locally to a project(s) rather than affect multiple projects). It might be fairly simple to deal with the file where one only needs to uncomment one of the relevant lines to have things set up (provided the relevant components are supported otherwise adding extra lines and/or files could be necessary). The installation process, at least through the library manager, is maybe not complex or hard. When it comes to graphics it supports, this includes graphics primitives, text, fonts, images, and sprites. Sprites are graphics buffers stored in RAM that allow for more efficient updating which improves performance and helps graphics be displayed in a smoother way. There's also some support for anti-aliased fonts and to some extent graphics. It supports advanced features like partial screen updates which while it could be too much for this project, it could be useful for improving performance and having faster LCD response times (though on the system-level rather than the hardware-level). According to the documentation, this is a library known for its speed which when typically compared to other libraries' rendering performance, it is 3 to 10 time faster. There is an anecdotal case where someone showed a comparison with Adafruit GFX on video, and TFT_eSPI updated quite a bit faster, and according to them with the same code Adafruit GFX's had a ~200ms update time and TFT_eSPI had a ~10 ms update time. Also, its performance has been optimized for ESP32 type processors. This might fit neatly with WordPal if we used the Arduino Core, since it should be compatible with that.

Adafruit GFX

The Adafruit GFX library can also be used with Arduino. Adafruit GFX is at most about as easy as TFT_eSPI, and possibly even easier. It shares many of the same function names and similar syntax, so code can be used between the two with possibly little changes. The setup is a bit different where there has to be another library specific to the display included with the code as well. Installing the relevant libraries can be done through the library manager if more current version(s) of Arduino IDE are used. The graphics library allows for graphics primitives, text, fonts, and images. It also has a canvas feature which is similar to the sprite feature of of TFT_eSPI albeit more limited. There are three canvas types that can be utilized: GFXcanvas1, GFXcanvas8, and GFXcanvas16; the number at the end represents the bit depth (which in this case is the number of bits used for a pixel's color). The feature set and capability is more simple, lacking support for features like anti-aliasing and partial screen updating at least natively. Performance wise, Adafruit GFX might be less optimized, and how well it performs can be processor dependent. There was already a mention earlier relating to performance in relation to Adafruit and TFT_eSPI. There was also another perhaps anecdotal case relating to tests done on STM32F401 and STM32F446 processors where it compared Adafruit GFX, TFT_eSPI Generic, and TFT_eSPI STM32 optimized. For the first processor, the results were as follows: 14.081 seconds, 10.0145 seconds, and 4.4000 seconds. For the second processor, the results were as follows: 8.3417 seconds, 6.2416 seconds, and 2.7598 seconds. This shows Adafruit GFX with the worst performance. The graphical demands of WordPal may allow Adafruit GFX to work, but its inferior overall performance may lead it to being an unideal choice.

LovyanGFX

LovyanGFX is also compatible with Arduino and ESP-IDF as well. Like the other two, it shares many of the same function names and similar syntax. The setup can at least be easier than TFT_eSPI depending on what you have since it can autodetect relevant display and board, but it is more involved if the relevant components are not supported. Its sprite system is more advanced. It supports the same graphics as TFT_eSPI as well as likely other features. It also has 18-bit color support and other color formats; it also handles sprite layering better than the other two. There are perhaps anecdotal benchmarks done which don't have the units reported on the table, but it might be microseconds (micros related things is used more frequently than millis related things in the GFXbenchmark.ino). There are four libraries compared: Adafruit_GFX, Arduino_GFX (not fully dealt with like the others), Lovyan_GFX, and TFT_eSPI. There are 15 benchmarks. Of all 15 (except for the 2 that were not applicable which were Arcs-filled and Arcs), Adafruit_GFX was the slowest in every case. For 13 benchmarks since 2 were not applicable, Lovyan_GFX was faster in every case in comparison to TFT_eSPI. There are also older test(s) of the same benchmarks which like the other test(s) have Adafruit_GFX has the slowest in the same 13 of 15, but TFT_eSPI did do better than Lovyan_GFX in 4 benchmarks. There was also a comparison in a video where the overall benchmarks time 5,570,802 µs for LovyanGFX and 5,972,744 µs for TFT_eSPI. In that same video, the LVGL test performed overall better and more smoothly with LovyanGFX compared to TFT_eSPI though this may not apply for every setup. It could potentially work for WordPal though it does have the potential of being too involved and complicated to some extent.

Table 3.C.2

Criteria	***TFT_eSPI***	**Adafruit GFX**	***LovyanGFX***
Ease of Use	Beginner to Intermediate in terms of Setup Beginner in terms of most functions Beginner to Intermediate in terms of Sprites	Beginner in terms of setup and most functions Beginner to Intermediate in terms of Canvas	Beginner to Advanced in terms of Setup Beginner in terms of most functions Beginner to Advanced in terms of Sprites
Feature Set / Capability	Graphics Primitives, Text, Fonts, Sprites, Some Anti-Aliasing, Partial Screen Updates, etc.	Graphics Primitives, Text, Fonts, Canvas, etc.	Graphics Primitives, Text, Fonts, Sprites, Color Formats, etc.

Performance	Second Highest Performance Typically	Third Highest Performance Typically	First Highest Performance Typically

Selection Writing

Adafruit_GFX however wouldn't be selected because its performance might be too much of a hinderance for WordPal. So, it might be between TFT_eSPI and LovyanGFX though due to shared functions and close syntaxes, all libraries can have a place for testing and trying things out. But the current selection may be TFT_eSPI. It's performance might be enough for Wordpal, and it's feature set/capability might also work. If we select the right components, its setup will be trivial, but with more difficult components to accommodate it still wouldn't be as bad to deal with as with LovyanGFX. Sprites would be more complicated especially dealing with memory allocation, but its complexity might not be too bad, and it is simpler than LovyanGFX. There was mention in a Medium article that users have been having great difficulty with the current ESP32 boards library as well as using newer microprocessors. It also mentioned at the time of the article's writing there are 231 'open' issues, so if we run into problems, we may have to switch to LovyanGFX.

3.C.3 LED Control

LED control is the software technologies involved that allow for control of LEDs (color, brightness, and timing are examples of properties that can be affected by LED control). Given that WordPal is dealing with RGB LEDs, LED control is necessary to get the LEDs to work as they should. There are three methods that allow for LED control on the software side which are FastLED, Adafruit NeoPixel, and pololu-led-strip-arduino. Information and analysis on these three will be below which will go over LED compatibility, ease of use, and performance.

FastLED

FastLED is a LED library which can be installed through PlatformIO, Arduino IDE, and manually. FastLED's supported LED chipsets include: WS2812B, APA102, SK6812, WS2813, and more; it also supports multiple LED protocols. Its syntax and code related things might be on an intermediate level though some of it might be simpler and easier. It does have named colors which make things easier given that WordPal uses red, yellow, and green where it isn't of the upmost necessity to have more custom colors. There were some tests done in relation to three libraries: FastLED, NeoPixelBus, and NeoPixel. For 100 LEDs and measuring time to transmission start, FastLED takes the least amount of time in 3 out of the 4 tests; NeoPixel Bus does the worst in each of them, and NeoPixel does the best in delay. For 1000 LEDs and measuring time to transmission start, NeoPixel does the best in all 4; FastLED takes a second place in 3 of 4, and NeoPixel Bus is usually last except rainbow fill where it is faster than FastLED. For complete transmission design with maybe 1000 LEDs, it's the same results as the last one. The way FastLED can be faster may be through the LED chipsets and protocols it supports, and it can maybe take advantage of some software optimizations. However, it is capped at least by how fast an

LED can update. Plus, there doesn't seem to be experimentation online that supports it being faster than NeoPixels. FastLED could maybe work with WordPal; there doesn't need to be fancy things done, and it might be reasonably doable to implement what is necessary.

Adafruit NeoPixel

Adafruit NeoPixel is a LED library which can be installed through Arduino IDE's library manager or manual installation. Adafruit NeoPixel is intended for controlling single-wire-based LED pixels and strip; its supported chipset families include: WS2812, WS2811, SK6812, and more. Its syntax and code related things might be more in a beginner level. The code WordPal will use might not be too difficult to implement in either FastLED or Adafruit NeoPixel, but the syntax might be easier to deal with at least visually. It doesn't have something similar to what FastLED has where it has named colors; with Adafruit NeoPixel you have to set the value(s) or save a variable with the relevant things. There is also another library called Adafruit_NeoMatrix which builds upon the NeoPixel library and allows one to do more. It might not be something we use for our project, but it could be useful. The ideal rate of a strip of 100 pixels is 328 updates per second; it however maybe not always reaches the ideal rate depending at least on code complexity and efficiency. Though the results mentioned above show NeoPixels being faster more often (while being slower with the 100 LEDs in 3 of the 4 tests compared to FastLED), how well NeoPixels deals with things that include code complexity and efficiency can be where FastLED gets ahead. It would maybe be easier to implement the necessary things relating to WordPal provided we have the right component(s), but there could be limits in relation to LED compatibility and theoretically performance.

pololu-led-strip-arduino

Pololu-led-strip-arduino (or Arduino library for addressable RGB LED strips from Pololu) is a LED library which can be installed through Arduino IDE's library manager or manual installation. The library can work with any of these strips: low-speed TM1804 (but one would have to use a lower version like 1.2.0), high-speed TM1804, SK6812, and WS2812B; it also supports WS2811 LEDs. There might not be too much documentation on this library, so at least the following information is more dependent on ChatGPT and the examples in the GitHub. The syntax and code related things typically would have less code relative to the other two libraries. However, while there may be less going on, the programmer would maybe have to know more low level wise and maybe related to use it effectively. So, in some sense it could be easier, but it could also be harder. It's also low level. It doesn't provide advanced features like the others, and there isn't as much abstraction. If experimental performance information in relation to the other two wasn't readily available, it might be even more so for pololu-led-strip-arduino. But, its lower level would make it more likely to reach higher performance. There is information that it takes about 1.1 ms to update 30 ms which could maybe be about 36.7 µs for an LED. If so, then when the calculations are done for finding the frames per second for 100 leds, the number becomes about 269. This is perhaps about 59 frames per second less than the ideal rate reported earlier. For its low-level status, it might not be too bad for WordPal, but that low level status could be a barrier for incorporating it with WordPal [105].

Table 3.C.3

Criteria	***FastLED***	**Adafruit NeoPixel**	***pololu-led-strip-arduino***
LED Compatibility	Supported LED Chipsets include: WS2812B, APA102, SK6812, WS2813, and more Multiple LED Protocols Supported	Supported Chipset Families Include: WS2812, WS2811, SK6812, and more	Supported Strips: low-speed TM1804 (requires a lower version like 1.2.0), high-speed TM1804, SK6812, and WS2812B WS2811 LEDs Also Supported
Ease of Use	Beginner to Intermediate in terms of setup and code	Beginner to Maybe Lower Intermediate in terms of setup Beginner in terms of code	Beginner to Maybe Lower Intermediate in terms of setup Maybe Intermediate in terms of code
Performance	Theoretically Faster than Adafruit NeoPixel Experimentally Inconclusive	Theoretically Slowest Experimentally Inconclusive	Theoretically Fastest

Selection Writing

The current selection might be for FastLED. All of them could maybe work, but one thing FastLED has is more supported LED chipsets and LED protocols which while it might be unnecessary since the LEDs we use might work with all of them, it does help deal with the case where the LEDs are not supported on the other two. Its setup may perhaps not be too bad, and for the code though it may be a bit hard to wrap your head and work with it, it's maybe doable for WordPal. The performance part is perhaps somewhat strange and not fully clear cut, but it might potentially have performance improvements that wasn't found at the moment, and if it does turn out slower it may not be too bad, but we can maybe always switch if need be.

3.C.4 Wi-Fi Software Stack and Optional Layers

The Wi-Fi stack architecture can be defined as "the layered structure of software [and hardware] components that handle the transmission and reception of data over a wireless network using the WiFi protocol" [114][133]. Though the Wi-Fi stack architecture deals with hardware and software layers, in this section we are dealing with the software layers,

specifically a subset of them that deals with APIs and libraries. The Wi-Fi software stack allows WordPal to interface with Wi-Fi. This section is different from the others because WordPal requires Arduino-esp32 WiFi.h, a full native Wi-Fi stack, to be used since another Wi-Fi stack would be wasteful and redundant. This section deals with Arduino-esp32 WiFi.h by itself and two optional layers: Wi-FiManager and AsyncTCP. Information and analysis on these three will be below which will go over ease of use, feature set and capability, and dependencies.

Arduino-esp32 WiFi.h

Arduino-esp32 WiFi.h as alluded to before is bundled in with the Arduino Core for the ESP32, so going with the relevant Arduino core means we don't have to do anything else. The syntax and code related things might be beginner. Wifi.h allows for ESP32 WiFi to run in different WiFi modes: WiFi Station, Access Point, Access Point + Station Mode, and Promiscuous mode. It also allows for scanning WiFi networks, connecting to a WiFi network, checking ESP32 WiFi connection strength, and more [117]. Wifi.h doesn't have any dependencies except what it would need in the Arduino core. ChatGPT showed some possible code that would handle getting the word from NYT. While it may be incorrect, if it's like how it is from ChatGPT, it might be doable [133].

WiFiManager

WiFiManager is an optional layer that can be installed through the Arduino IDE's Library Manager, GitHub, or through PlatformIO. The syntax and code related things might be beginner. One of the main things it tries to do is give one a way to provide Wi-Fi credentials from the outside which it simplifies doing. It also allows one to do on-demand configuration and add customer parameters. There are the potential dependencies of the DNSServer-ESP32 library and the WebServer-ESP32 library. The code(s) from ChatGPT relating to the getting the word from NYT may also be fairly doable [133]. The main problem in the fact that in order to use the WiFi configuration capabilities that WiFiManager provides, one needs a second device. So, it could be useful for testing, but since WordPal is supposed to do its own WiFi configuration by itself, WiFiManager might not be that useful.

AsyncTCP

AsyncTCP is an optional layer that has both ESP-IDF and Arduino compatibility. It can be installed through the releases page at GitHub, and it is also deployed in the Arduino Library Registry (meaning installation through the Library Manager), ESP Component Registry, and PlatformIO Registry. According to one of the older Readmes, most of AsyncTCP is made up of the classes AsyncClient and AsyncServer; the classes are low-level, and the usage of them, and by extension AsyncTCP, require more skills. Therefore, it may be concluded that syntax and code related things are from an intermediate to advanced level. AsyncTCP allows for multiple connections and makes up the base for ESPAsyncWebServer. This Wi-Fi stack is an in-between of difficulty and control. Maybe not particularly necessary for WordPal. ChatGPT might show it being more involved to get the Word from NYT using AsyncTCP [133]. Since, WordPal might not make too many

connections a day or at least multiple connections that need to happen around the same time, AsyncTCP would maybe add unnecessary complexity.

Table 3.C.4

Criteria	***Arduino-esp32 Wifi.h***	***WiFiManager***	***AsyncTCP***
Ease of Use	Beginner in terms of setup and code	Beginner to Intermediate in terms of setup Beginner in terms of code	Maybe Beginner to Intermediate in terms of setup Maybe Intermediate to Advanced in terms of code
Feature Set	ESP32 WiFi can run in different WiFi modes: WiFi Station, Access Point, Access Point + Station Mode, and Promiscuous mode. It can scan WiFi networks, connect to a WiFi network, check ESP32 WiFi connection strength, and more.	It allows one to provide Wi-Fi credentials from the outside, do on-demand configuration, and add custom parameters.	AsyncTCP allows for multiple connections and makes up the base for ESPAsyncWebServer.
Dependencies	What's necessary in the Arduino Core	DNSServer-ESP32 library, WebServer-ESP32 library, Wifi.h, and What's necessary in the Arduino Core	Wifi.h, and What's necessary in the Arduino Core

Selection Writing

While Wifi.h is a required choice, in this case it might make most sense to use it by itself. It might handle what's necessary for WordPal fine enough, and the optional layers don't add enough value. Wifi.h by itself has the simplest and/or easiest setup in the sense that once you have the Arduino core, there is nothing else one needs to do (besides including the library in the code). Its feature set is enough for the task except for the necessity of another supporting library like HTTPClient.h. The additions of WifiManager could potentially be useful at least for testing, but it's not intended for what WordPal needs to accomplish, and AsyncTCP doesn't have value even in testing. Wifi.h by itself also means we don't have to install anything else aside from potentially a supporting library as

mentioned earlier. AsyncTCP doesn't have any other dependencies, so it would be that library in addition, but WiFiManager requires other libraries which maybe isn't ideal.

4 Related Standard and Design Constraints

Every engineering project must follow established standards while staying within real-world limitations. These guidelines and constraints make sure a product can be safely designed, built, and later tested without failure. In the case of WordPal, both of these factors have a major influence on how our system is being planned, from seeing electrical components to shaping the overall layout of the device.

WordPal is a custom handheld word guessing game that combines hardware and software in a compact design. Since the project involves designing a custom PCB, connecting a display, and powering the system with a lithium-ion battery, the design must meet certain industry standards for safety, power delivery, and communication. Following these standards will help ensure that our system performs reliably, avoids electrical hazards, and remains compatible with other modern devices such as USB-C chargers and Wi-Fi networks.

Along with these standards, the project faced a series of practical design constraints that define what is realistically achievable during this course. These included limits on power consumption, physical size, total cost, and manufacturability. Because WordPal is intended to be portable and battery-powered, energy efficiency has become one of the most important design priorities. Similarly, the device must remain lightweight and affordable while still meeting functionality goals and maintaining a professional appearance for future prototyping.

The sections that follow describe the standards that are guiding our design and the constraints that are shaping how we will construct the system. The first section focuses on industrial standards, such as USB-C, Wi-Fi, and PCB design standards, which define how the device will connect and operate safely. The second section outlines practical constraints, like power, cost, and size, that we must consider as we transition into the prototyping stage. Together, these factors establish the framework for how WordPal is being engineered to be functional, efficient, and realistic to produce within the time and resources available.

4.1 Industrial Standards

The WordPal device relies on multiple electronic subsystems that must follow established engineering standards. These standards define how power is delivered, how signals are transmitted, and how the overall circuit is laid out. Designing within these guidelines helps ensure that when the device is eventually fabricated, it will operate safely, meet compatibility requirements, and follow best practices used in modern consumer electronics. The main standards considered for this project are USB Type-C specification, which defines how the device will safely receive power and charge the internal battery. Another one is the IEE 802.11 Wi-Fi standard, which outlines how wireless communication can be incorporated in later development stages. There is also the IPC-2221 printed circuit board design standard, which provides guidance on trace width, spacing, and manufacturability. Each of these standards influences a different aspect of the design and helps ensure that

WordPal is developed using reliable, industry recognized methods that will support safe operation and future scalability.

4.1.1 USB-C Standard

For this project, WordPal will use a USB Type-C connector as the main source of power and potential data communication in later stages. The USB-C standard was developed to replace older USB connectors, offering a smaller, reversible design with higher current capacity and faster data support. Compared to micro-USB or mini-USB, USB-C can deliver more power and is easier for users since it connects in either orientation. This reversible design not only improves user convenience but also helps prevent long-term wear and damage from repeated incorrect insertions. The connector housing and pins are built to withstand thousands of plug-in cycles, making it a durable choice for portable devices that will be frequently charged or connected during regular use. These features make it a reliable and modern choice for powering compact electronic devices like WordPal.

Another important consideration when using USB-C is the physical placement of the port on the printed circuit board. Because USB-C connectors are slightly wider than older micro-USB ports, spacing must be planned carefully to ensure that the cable can connect securely without pressing against nearby components. The connector is expected to be placed along the edge of the PCB, allowing the port to be easily accessible while maintaining a low profile. This positioning helps prevent mechanical stress on the board and keeps the overall device design compact and easy to handle.

The USB-C connector contains 24 pins and supports both power and data communication. Although the initial WordPal design will only use the power portion, the data pins can be reserved for future expansion, such as software updates or data transfer features. The standard allows up to 5 volts and 3 amps under typical USB power delivery conditions, which provides ample headroom for a low-powered embedded system. WordPal's power requirement is expected to stay well below that limit, with the charging circuit drawing less than one amp at 5 volts to operate safely and efficiently. Staying within this standard ensures that the charging system remains reliable, minimizes heat, and avoids potential damage to the lithium-ion battery.

Using USB-C also improves convenience for users since it eliminates the need for a specific cable orientation and keeps the system compatible with widely available chargers. This approach supports sustainability by allowing the device to use the same charging accessories as other common electronics. It also aligns with recent trends in consumer electronics, where USB-C is becoming the universal standard for both data and power delivery. By following this specification, WordPal remains up to date with modern connection practices.

Safety is another important reason for adhering to the USB-C standard. The specification defines voltage and current limits that prevent damage to connected devices and ensure safe operation across different charging adapters. For example, the default 5V power level avoids risks associated with higher-voltage fast charging systems, which can cause stress

to smaller circuits. Basic protective components will be included in the final design to guard against overcurrent and voltage spikes. These precautions reflect standard best practices for portable electronics that charge through USB-C.

Overall, the USB-C standard provides the foundation for WordPal's power and connectivity system. It offers a balance between performance, safety, and user accessibility, which makes it well suited for a handheld embedded device. Designing around this standard allows the project to follow current industry expectations while ensuring that the power interface remain efficient, durable, and ready for future enhancements.

4.1.2 Wi-Fi Standard

The ESP32 microcontroller selected for WordPal includes built-in Wi-Fi capability that follows the IEEE 802.11 standard. Understanding this standard early in the design process helps us plan for possible future features, such as multiplayer functionality. Since the ESP32 already supports this capability, it makes sense to design the circuit and PCB in a way that leaves room for future Wi-Fi use without needing major hardware changes later on.

The IEEE 802.11 standard defines how electronic devices communicate wirelessly over local area networks. It specifies details such as frequency ranges, channel bandwidth, and transmission protocols. The ESP32 operates in the 2.4GHz frequency band, which is common for Wi-Fi communication and compatible with most routers and mobile devices. This band provides good signal coverage and compatibility with typical home and mobile routers. The standard supports data rates that are far higher than anything WordPal would require, but it ensures that, if wireless features are added later, they can communicate reliably and consistently with other Wi-Fi enabled devices.

Following the IEEE 802.11 standard also affects how the hardware is physically arranged on the PCB. The ESP32 includes a small built-in antenna, and the Wi-Fi standard provides guidelines for keeping that antenna clear of obstacles and conductive materials. This means that during the PCB layout process, that corner of the board should remain open with minimal copper and no tall components nearby. Even though WordPal's prototype will not use the Wi-Fi module right away, reserving this open space ensures that the signal will remain strong and consistent if wireless communication is enabled in future versions.

In addition to signal quality, power consumption is another important factor related to the Wi-Fi standard. Wireless transmission requires more energy than other operations on the device, so the ESP32 includes low-power modes defined by the 802.11 protocol to manage energy use efficiently. These features make it possible for future updates of WordPal to support short bursts of connectivity, such as downloading a daily puzzle or sending results online, without heavily draining the battery. Understanding these aspects now helps the team balance power and performance when considering design trade-offs.

Beyond its technical details, the IEEE 802.11 standard represents a reliable and widely adopted communication method that ensures long-term compatibility across devices. By aligning WordPal's design with this standard, the team ensures that any future wireless functions will integrate smoothly with existing infrastructure rather than relying on

outdated methods. It also reinforces good engineering practice by building on a foundation of industry-accepted communication protocols.

Overall, the Wi-Fi standard plays an indirect but significant role in the WordPal project. While the initial prototype focuses on core gameplay and local operation, considering IEEE 802.11 requirements early allows the design to stay flexible for future improvements. It supports the idea of designing the product in a way that keeps it relevant and expandable tomorrow. This approach helps ensure that WordPal remains consistent with modern embedded systems standards and can continue evolving alongside new features and user expectations.

4.1.3 Printed Circuit Board Design Standard

Since WordPal will be built on a custom circuit board, it is important that the layout follows established engineering standards for safety, performance, and manufacturability. The IPC-2221 standard, known as the Generic Standard on Printed Board Design, provides the main guidelines for printed circuit board (PCB) design used across the electronics industry. This standard covers essential parameters such as trace width, spacing, hole sizes, and component placement, which all influence how well a board performs once fabricated. Following these guidelines ensures that the final PCB design can be manufactured reliably and will operate safely under normal use conditions.

The IPC-2221 standard provides recommendations that help designers balance electrical performance with physical limitations. For example, the width of a copper trace depends on how much current it must carry and how much heat it can safely dissipate. The standard provides formulas that relate current, temperature rise, and copper thickness, making it possible to choose proper trace widths for each circuit section. In WordPal's design, most signals will carry very small currents, so thinner traces can be used to save space. However, power lines connected to the voltage regulators, LED drivers, or battery charging circuits require wider traces to handle higher current without overheating. By following these current-carrying capacity charts, the design can remain compact while staying within safe electrical limits.

The IPC-2221 standard also provides guidelines for spacing between traces and pads, known as clearance and creepage distances. These rules prevent electrical arcs or interference between different circuit nodes. Even though WordPal operates at relatively low voltages (below 5V), maintaining adequate spacing still improves signal integrity and reduces noise between sensitive components such as the microcontroller and display. Keeping consistent clearances also helps reduce the risk of solder bridges or manufacturing defects during assembly, which is particularly useful when ordering boards from prototype fabrication services.

Another part of the IPC-2221 standard that applies to WordPal involves drill and via sizing. Through-holes and vias must be large enough to ensure good plating coverage and mechanical strength, especially for components that may experience small amounts of stress such as the USB-C port. Following standard recommendations for pad diameters and annular rings will make the board easier to manufacture and assemble without the need for

special fabrication steps. The standard's guidance helps maintain a balance between durability and space efficiency, which is important for a compact handheld design.

PCB layout standards also encourage organized routing and labeling. Each component should be placed logically, with short trace paths and minimal overlap between high-current and low-signal regions. This makes troubleshooting and assembly easier while minimizing interference between digital and analog signals. WordPal's circuit is relatively simple, but planning the layout according to these practices ensures it remains readable, reproducible, and scalable for future improvements. In addition, silkscreen markings for component identifiers and polarity indicators will follow IPC-2221 labeling conventions to make assembly more intuitive.

Lastly, adhering to IPC-2221 helps ensure that the PCB can be fabricated by standard manufacturers without any special requirements or design modifications. This reduces cost and turnaround time while improving consistency between design iterations. By following this widely accepted industry standard, the team ensures that WordPal's circuit board will be reliable, safe, and manufacturable using professional processes.

Overall, IPC-2221 provides the foundation for how the electrical and mechanical aspects of WordPal's PCB are planned. It defines the minimum design practices needed to produce a high-quality, dependable board while staying within realistic limits for a student project. Using these guidelines keeps the design consistent with real-world engineering methods and prepares the project for smooth transition into the prototyping phase.

4.2 Design Constraints

In addition to meeting technical standards, the WordPal design must also operate within a set of real-world limitations. These practical constraints affect how the team approaches the electrical design, physical construction, and overall cost of the device. Because this project is being developed as a portable, battery-powered system, factors such as power efficiency, size, weight, and budget play an important role in shaping the final design decisions. Understanding these constraints early allows the team to make realistic trade-offs and ensure that the prototype can be built and tested within the time and resources available. The following sections discuss the main practical constraints considered for WordPal, including power and energy, size and weight, and cost.

4.2.1 Power and Energy Constraint

Because WordPal is a battery-powered handheld device, its entire design revolves around efficient power management. The system uses a single lithium-ion cell rated around one amp-hour at 3.7 volts, which supplies only a limited amount of usable energy before recharging. Achieving at least two hours of continuous use requires strict control over how each component consumes power. The microcontroller, display, and LEDs all contribute to the overall load, so every decision in the circuit and firmware must consider its effect on battery life.

The ESP32 microcontroller supports deep sleep and low power modes, allowing the processor to remain off until the user interacts with the device. During active operation, the voltage regulators convert the battery's 3.7 volts to 3.3 volts and 5 volts with roughly ninety percent efficiency. High efficiency regulators were chosen to minimize wasted energy as heat, and the firmware coordinates power states to keep components off whenever they are not needed. The LCD backlight and keyboard LEDs are pulse width modulated so that brightness can adjust dynamically instead of running at full intensity at all times. The display controller also refreshes at a lower rate when the game is idle, which saves energy without affecting visual quality.

From a design standpoint, managing how much power turns into heat is an important part of keeping the system stable. Excess heat doesn't just waste energy; it can also shorten battery life and affect how well the components perform over time. To limit this, the layout of our custom PCB places parts that generate more heat, such as the voltage regulator and LED drivers, away from the battery and other sensitive areas. This spacing helps prevent one section of the board from running too warm. On the software side, firmware plays a big role in saving energy and keeping the system cool. Instead of constantly running tasks in the background, the program is event driven. The processor stays idle until it needs to respond to an action, like a button press, then quickly completes the task before going back to sleep. This method cuts down unnecessary activity, reduces average power use, and keeps the device operating within a comfortable temperature range during normal use.

The power constraint also influenced mechanical and component choices. A larger battery could increase runtime, but it would add weight and occupy more internal volume. Likewise, higher-brightness LEDs could make the interface more visible in bright rooms but would require more current. The solution was to balance these competing factors by maintaining moderate brightness and optimizing efficiency instead of simply increasing capacity. The resulting design offers stable performance, a comfortable temperature, and consistent operation within the intended window.

Overall, the power and energy constraint guided nearly every engineering decision in WordPal. It dictated the microcontroller selection, power conversion design, and firmware structure, ensuring that the system remains efficient without sacrificing user experience or safety. The result is a balanced power profile that supports extended battery life, controlled thermal behavior, and dependable performance for daily use.

4.2.2 Size and Weight Constraint

Because WordPal is intended to be a handheld device, the overall size and weight of the system are major considerations in the design. The device should be light enough to hold comfortably for extended periods while still housing all essential components such as the microcontroller, battery, display, and keypad. A compact design also helps with portability, making the product easy to carry in a bag or pocket, similar to other small electronic gadgets.

When choosing components, the team plans to balance functionality with physical limitations. For instance, the lithium-ion battery must provide sufficient capacity for

several hours of use, but a larger cell would also increase the weight and occupy more space inside the enclosure. Likewise, the display and LED matrix need to be large enough for readability but small enough to fit within the casing and maintain ergonomic proportions. The final design will likely involve multiple iterations to ensure that all parts fit securely without excess bulk.

PCB layout decisions are also influenced by these constraints. A smaller board means components must be placed efficiently, with attention to trace routing and connector locations. The team intends to minimize unused board area and keep the height of stacked components low to maintain a slim profile. This approach will help ensure that the enclosure can be 3D printed or machined with minimal material while still protecting internal circuitry.

Maintaining a lightweight structure not only improves comfort but also helps with durability and power efficiency. A smaller, lighter device typically requires less material and draws less power to drive components such as the display backlight. By prioritizing compactness, the team aims to create a design that feels balanced and user-friendly without compromising performance. These size and weight constraints guide mechanical and electrical design choices as the project moves toward prototyping.

4.2.3 Cost Constraint

Since WordPal is being developed as a student project, the total budget available for components and materials is limited. Every design choice must balance performance with affordability to keep the prototype realistic and within financial reach. The main expenses for this project include the microcontroller, display, lithium-ion battery, LED matrix, and PCB fabrication. Additional costs such as the enclosure, wiring, and connectors also add up, so careful part selection and comparison between suppliers are essential.

During the planning phase, the team prioritized components that provide reliable functionality at a reasonable price. For example, the ESP32 microcontroller was selected because it offers built-in Wi-Fi and Bluetooth at a low cost, reducing the need for external modules. Similarly, standard passive components and connectors will be ordered in bulk from common distributors to minimize shipping and handling costs. PCB fabrication will be outsourced to a service that offers student discounts or prototype pricing, which helps lower manufacturing expenses while maintaining professional quality.

Budget limitations also affect design decisions related to materials and mechanical construction. Instead of using custom molded parts, the enclosure will likely be 3D-printed using materials available. This allows multiple design iterations without significant added expense. The goal is to build a functional prototype that demonstrates all core features rather than producing a finished commercial product.

By understanding these cost constraints early, the team can make informed trade-offs between price and performance. Focusing on affordable, readily available components ensures that the prototype can be completed within the semester’s budget while still meeting design requirements. These financial considerations help keep WordPal practical to produce and replicate in future course offerings or student projects.

4.3 Other Constraints

In addition to the main design constraints discussed earlier, the WordPal project is also influenced by a few external and ethical factors that must be considered before prototyping begins. These include safety, environmental impact, and accessibility.

Safety is an important consideration because the device is powered by a lithium-ion battery. The design will include built-in protection features such as overcharge, over-discharge, and short-circuit protection to reduce potential hazards. Proper handling and charging procedures will also be documented to ensure the device can be safely operated by users and tested by the team.

From an environmental standpoint, the project aims to minimize electronic waste by using standardized components like USB-C and modular connectors that can be reused in future projects. The enclosure materials selected for the prototype are easily recyclable and commonly available. These decisions help lower waste and promote sustainable design practices.

Finally, accessibility plays a role in how the users interacts with WordPal. The display and input interface will be designed to be clear, simple, and easy to use for players of different ages. Button spacing and screen contrast will be adjusted to ensure the device is comfortable to operate and readable under various lighting conditions.

Considering these additional factors ensures that WordPal remains safe, environmentally responsible, and user-friendly as development progresses. These constraints will continue to guide design decisions in the next phase of the project as the team begins hardware fabrication and testing.

4.4 Summary

This chapter outlined the key standards and design constraints that shaped the planning of WordPal project. The selected standards, USB-C, IEEE 802.11 Wi-Fi, and IPC-2221, serve as the foundation for how the system will handle power delivery, future wireless communication, and PCB layout. Following these guidelines ensures the design will be safe, manufacturable, and consistent with professional engineering practices once prototyping begins.

The chapter also discussed the main practical limitations that influence the project: power and energy efficiency, physical size and weight, and total cost. Each of these constraints affects how components are chosen and arranged, guiding the team toward a realistic, portable, and affordable solution. Additional factors such as safety, environmental responsibility, and accessibility were also considered to make sure the final product is reliable and user friendly.

Overall, understanding and addressing these standards and constraints early in the design phase allows the team to create a strong foundation for the next stage of development. As the project transitions into next semester, these same considerations will continue to guide the fabrication, testing, and refinement of the WordPal prototype.

5 Application of ChatGPT and Other Similar Platforms

ChatGPT can be a useful tool for getting a good idea of how to do this project and for research. From giving answers to different questions, showing code examples, doing calculations, and finding sources, these and more were some of the ways ChatGPT helped at the moment. Parts that ChatGPT helped at the moment include Chapter 3.2, 3.3, and 7. However, there is only so far it can go. There is a speed difference between using ChatGPT on the phone and on my laptop. This may have contributed to a lot of wasted time waiting for things and having to refresh or replace the browser tab. It also repeated the same or similar responses when it couldn't find sources sometimes. There were also cases where it would give you something at one moment only through additional research and communication with ChatGPT, it turning out to be inaccurate or misleading. ChatGPT can be very confident about things, declaring something to be accurate at one moment and then telling you it's accurate in another moment. While there were parts that perhaps rely on ChatGPT more such as in saving time or when information was hard or rare to come by, there were other parts that have at least some basis in the research. ChatGPT was good for getting the meaning of things in the research. Of course, this assumes that their interpretation was good as well which may not be the case. At the moment, our AI usage varies among the group members.

5.1 Case Study 1

There was quite a bit of conversation beforehand, and there was talk relating to Chapters 3, 4, and 7 and then more focused on Chapter 3. Nevertheless, this might be a good example of something AI is good for. It can give you the basic outline or things you're supposed to look out for or research, and then you can develop it from there. It gives example sections, example tables, example conclusion writing and selections as well some references. Of course, this outline was still limited in some ways. While the conclusions and overall writing was on the right track, there was a lot of nuance and things that needed to be put. For instance, while it was somewhat correct in the idea of the display libraries in terms of the difficulty ranking, it didn't mention how a lot of the syntax and functions are shared which makes each of the display libraries more comparable than it might seem at first. For LED Control, it confidently asserts FastLED as high performance, it doesn't mention how there might not be much experimental data online to back this claim or goes more into what it means for an LED control library to have more performance than another. Also, for Wi-Fi Stack, it failed to mention that AsyncTCP is not a full Wi-Fi stack (though this section also turned out differently from how it was here to some extent). Also, the criterias were adjusted later to some degree [Prompt Example 1].

5.2 Case Study 2

For the prompts and outcomes, it extracted relevant information that connects with the ideal update time of the LEDs that was obtained earlier. It did do a calculation that might have been wrong with the time it takes to update per LED. However, the later math was more

correct based on my double checking with a calculator though this assumes the formulas were accurate (which might be the same or similar to ones used for the ideal rate and maybe related on one of Adafruit's websites). It calculated something different from what I may have wanted first (since I might have wanted 100 LEDs rather than 30). However, my prompt might have also not been specific enough for ChatGPT to assume or know that [Prompts Example 2].

5.3 Case Study 3

The prompts and outcomes were dealing with figuring out whether AsyncTCP can be installed through the library manager or related. It gave me three sources, and the one from the Espressif Component Registry documentation gave me a 404 page and the one from the Arduino Library Manager documentation didn't have the direct quote it mentioned. It later couldn't find the direct quotes which something ChatGPT does which is that it would give you a source with a direct quote only for the direct quote to not exist either in that source or maybe in any source. It doesn't mean necessarily that ChatGPT is on the wrong track. I might have found two sources (one of which it actually seen earlier in the convo though it might not necessarily connect Arduino's library registry to its Library manager) [Prompts Example 3].

6 System Hardware Design

6.1 Overview of Hardware Architecture

The hardware design of WordPal brings together all of the physical and electrical components that make the handheld game function as a fully portable device. Each subsystem in the design works together under the control of the ESP32 microcontroller, which serves as the main processor of the system. The major subsystems include the display, the keyboard, the RGB lighting network, the LED multiplexer, the lithium-ion battery, the power regulation and charging circuits, the USB-C port, and the power switch. These subsystems are integrated on a single printed circuit board that provides both power distribution and data communication.

The system follows a centralized architecture, where the microcontroller acts as the core control unit and directs all communication between input and output components. The printed circuit board layout was designed to keep high-current power lines separate from logic signals, reducing interference and allowing easier troubleshooting. The display and keyboard are positioned on the front side of the board to create an organized and compact layout that matches the intended handheld form. The power system and charging components are located near the edge of the board where the USB-C port is mounted for convenience. This structure not only simplifies assembly but also allows consistent operation when the device is used either on battery power or while charging.

6.2 Power Subsystem

The power subsystem is responsible for supplying stable voltage and current to each part of the device. It includes the 3.7-volt lithium-ion battery, a five-watt charging circuit, a set of voltage regulators, the USB-C port, and the power switch. The battery was selected for its high energy density, long lifespan, and ability to support portable operation without requiring frequent recharging. During operation, the battery's output voltage is converted to two levels: 3.3 volts for logic and LEDs, and 5 volts for the display and keyboard. Using two voltage rails allows each subsystem to function properly without overstressing any component.

The regulators use efficient switching converters to minimize power loss and extend battery life. When the system is connected to external power, the USB-C port provides a five-volt input to the charging circuit. The charger recharges the battery using a constant-current and constant-voltage process, protecting it from overheating or overcharging. The design also allows the device to continue operating while the battery is charging, which makes it easier for users to play without interruption. A physical power switch is placed between the battery and regulator input, letting the user fully disconnect power when the device is not in use. This prevents slow discharge and helps preserve battery health.

The power subsystem was designed with reliability and safety in mind. Each power line is sized to handle the expected current levels, and components are arranged to minimize voltage drop. Once the schematics are completed, this section will include circuit diagrams showing the charging and regulator paths.

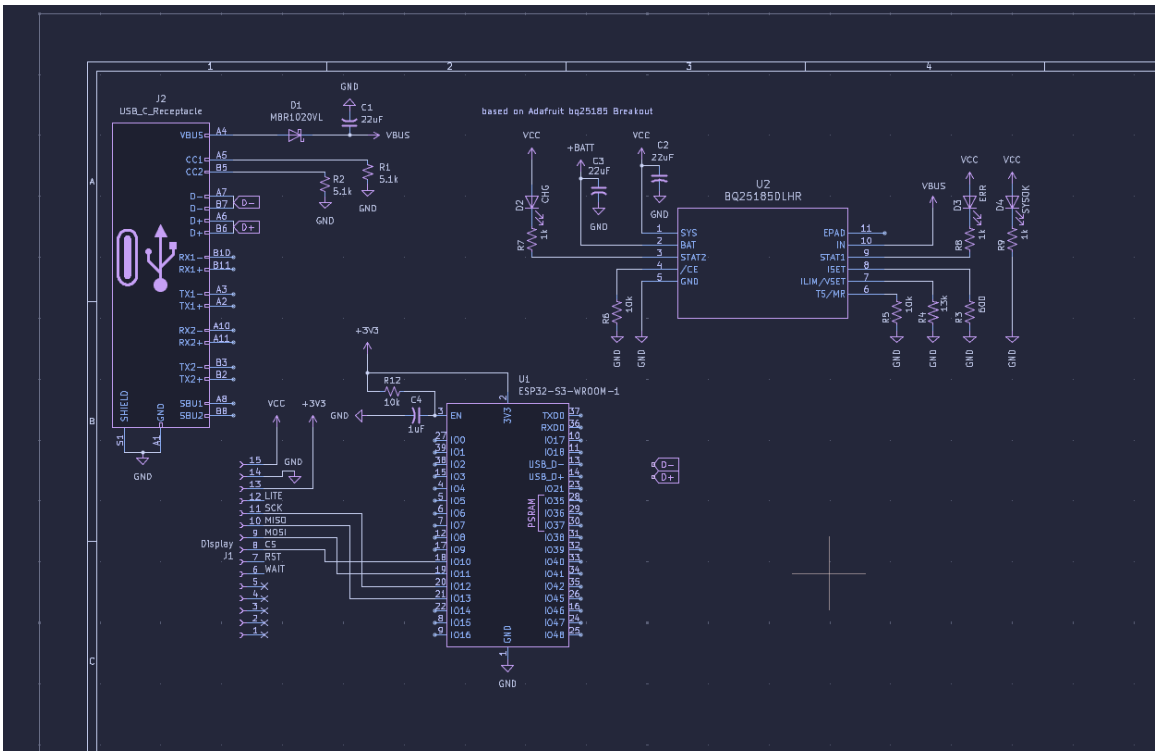
6.3 Microcontroller Subsystem

The ESP32 is the main processor of the system and serves as the brain of WordPal. It controls the logic, timing, and communication between the other parts. This microcontroller was selected because it's powerful enough to handle the game's processing needs while keeping power consumption low. It operates at 3.3 volts, which makes it compatible with most of the components in the system.

The ESP32 connects to the display using SPI communication, which allows the screen to refresh quickly without needing many pins. It also connects to the keyboard and LED multiplexer to read user input and control the RGB lighting. Since it has dual cores, one core can handle the main game logic while the other manages display updates and lighting control. This makes the system run smoother and reduces lag between the user's actions and the screen response. The ESP32 was also chosen because of its built-in flash memory and flexibility, which makes it easy to update the program later if needed.

6.4 Power Control and Safety Features

The USB-C port and power switch make the power control system complete. The USB-C port is used for charging the battery and for powering the device while plugged in. It was chosen because it's the current standard for portable electronics and works with most common chargers. When connected to a power source, the USB-C input sends five volts to the charger circuit, which safely recharges the battery. The power switch lets the user fully cut power when the device isn't being used, which protects the circuit and extends battery life.



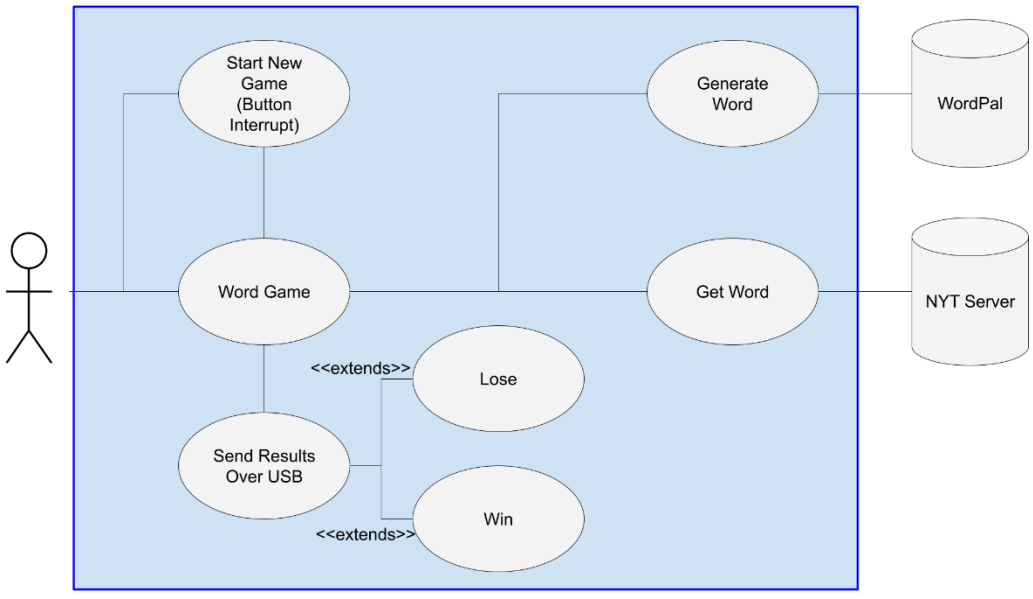
Older Version of Schematic that contains battery charging circuitry and display driver connector

7 System Software Design

In this section, there will diagrams and information surrounding the software of WordPal. This section is still in progress and maybe contain some errors and/or flaws, but there are three diagrams that deal with different aspects of WordPal. The first is the Use Case diagram which deals more with the active interactions of entities like the user or NYT server. The second is the state diagram which deals with the different states the WordPal software can be in. The third is the class diagram which goes more in depth than the other two and deals more with the classes: their attributes, methods, and relationships.

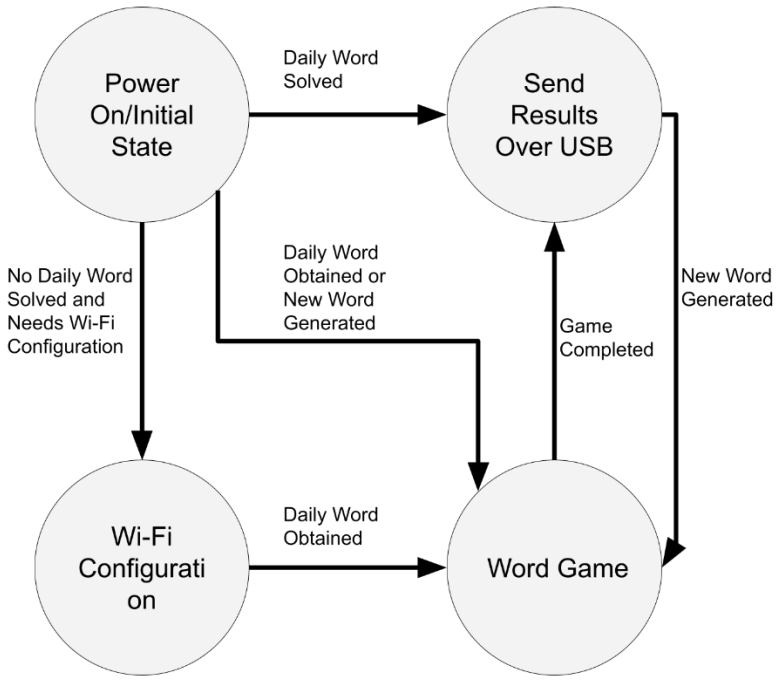
7.1 Use Case Diagram

The Use Case diagram deals with the active interactions which limits the amount of information this diagram conveys. There are automatic processes that make up the user experience but may not be conveyed so clearly here. The active interactions of the user is using a button that can start a new game whenever specifically a game with a generated word from WordPal rather than the daily word. The user can do a word game which leads to send results over USB (maybe technically an automatic thing though there may be some user interaction). The results could either be win or lose (though it would show guesses and rounds). The entity of WordPal as mentioned before can generate a word, and from the the entity of the New York Times' Server, a word can be obtained from it.



7.2 State Diagram

The state diagram deals with the states WordPal can be in which may be four. The first is the Power On/Initial State. This state is never returned to except when you restart the software. From here, there are three states it can go to (though it could maybe go to two of them at the same time). The first one is the Wi-Fi Configuration state which occurs when the daily word isn't solved, and Wi-Fi configuration is needed. From that state, it can only go to the Word Game once the Wi-Fi is configured and the daily word has been obtained. The second state the Power On/Initial State can go to is the Word Game state which can be done if the daily word is obtained or if there is a new word generated. The third state is Send Results Over USB which occurs if the daily word is solved. The states Send Results Over USB and Word Game can go in a loop. From the Word Game states, once the game is completed, and the Send Results Over USB may go to Word Game perhaps after the results have been sent and a word has been generated.



7.3 Class Diagram

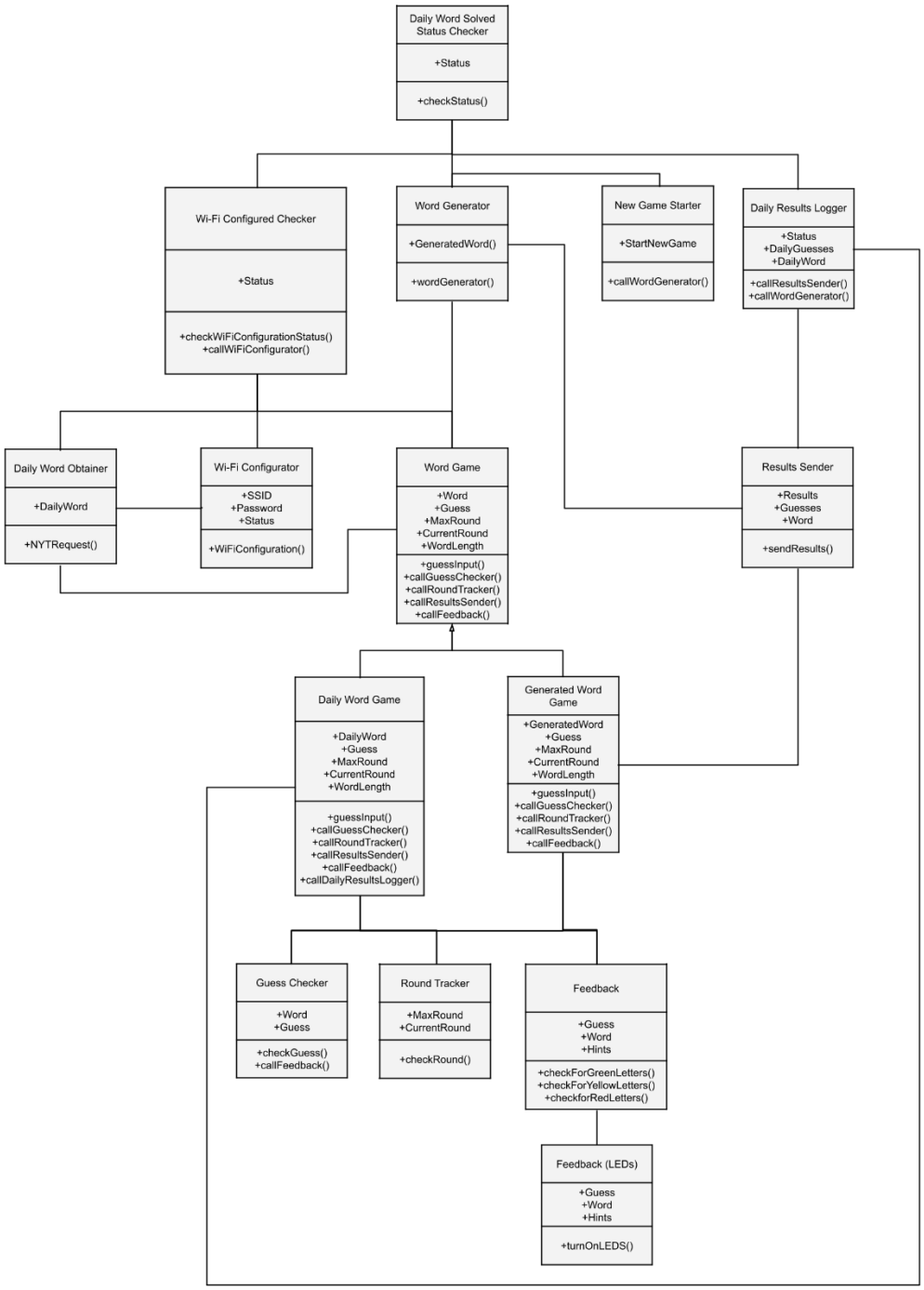
The class diagram deals with the potential classes of WordPal's software. The classes include: Daily Word Solved Status Checker, Wi-Fi Configured Checker, Word Generator, New Game Starter, Daily Results Logger, Daily Word Obtainer, Wi-Fi Configurator, Word Game, Results Sender, Daily Word Game, Generated Word Game, Guess Checker, Round Tracker, Feedback, Feedback (LEDs). All of the attributes and methods are currently public

which maybe isn't ideal in relation to object oriented programming principles, but it does maybe have the plus side of making our code easier to develop. For Daily Word Solved Status Checker, it has the Status attribute and a checkStatus() method. It would check the Status from Daily Results Logger. If the Status is solved then Daily Results Logger might use its methods of callResultsSender() and callWordGenerator(). If the Status is not solved, it would go to Wi-Fi Configured Checker which also has a Status attribute but this is for WiFi Configuration status which is has a method for checking which it checks the Status from Wi-Fi Configurator. If the Status is connected then it would go to Daily Word Obtainer otherwise it would use the method callWiFiConfigurator().

Wi-Fi Configurator has two other attributes: SSID and Password; these deal with the network name and network password. It has the method WiFiConfiguration() which it would call and which allows the user to configure the Wi-Fi on WordPal. If successful, it would go to the Daily Word Obtainer which have the DailyWord attribute and the NYTRequest() method which allows WordPal to obtain the daily word from New York Times' server. Once the daily word has been obtained, it might go to Word Game. Word might be kind of interesting since there are two other classes that inherit from it: Daily Word Game and Generated Word Game. Those two classes allow for two different types of word games which is the word game with the daily word and the word game from WordPal's generated word. For the Word Game class, it has the attributes Word, Guess, MaxRound, CurrentRound, and WordLength. It has the methods guessInput(), callGuessChecker(), callRoundTracker(), callResultsSender(), and callFeedback().

For the Daily Word Game class, which the type of word game that would follow after obtaining the daily word, it shares most of the same attributes with Word being DailyWord instead, and it has another method which is callDailyResultsLogger(). The classes it can maybe call form are Guess Checker, Round Tracker, Feedback, Results Sender, and Daily Results Logger. With guessInput(), it allows the user to input their guess bounded by certain rules. Then, it calls the Guess Checker where it can determine the accuracy of the Guess and call Feedback. Feedback has the methods checkForGreenLetters(), checkForYellowLetters(), and checkforRedLetters() which returns the relevant colors (green for correct letter and correct place, yellow for correct letter but incorrect place, and red for incorrect letter). Feedback (LEDs) depends on Feedback for allow it to know which LEDs it should turn on. The Round Tracker class checks the current round and see if it matches the maximum round.

Eventually, whether by guessing the word in the number of rounds allocated or not guessing, it calls the Daily Results Logger which saves the relevant guesses and daily word. It also changes the status, which will give the status of the daily word as solved until the daily word changes. Then it goes to the result sender which sends the results over serial communciation. From there, it goes to the Word Generator class which generates a word and then maybe goes to Word Game. For the New Game Starter which is an interrupt the user has access to at any time, it can start a new game specifically the one with a word generated from WordPal. It goes to the Word Generator also. The Generated Word Game is similar to the Daily Word Game except that it goes straight to Results Sender and it uses a generated word from WordPal.


Daily Word Solved Status Checker
+Status
+checkStatus()
Wi-Fi Configured Checker
+Status
+checkWiFiConfigurationStatus()
+callWiFiConfigurator()
Word Generator
+GeneratedWord()
+wordGenerator()
New Game Starter
+StartNewGame
+callWordGenerator()
Daily Results Logger
+Status
+DailyGuesses
+DailyWord
+callResultsSender()
+callWordGenerator()
Daily Word Obtainer
+DailyWord
+NYTRequest()
Wi-Fi Configurator
+SSID
+Password
+Status
+WiFiConfiguration()
Word Game
+Word
+Guess
+MaxRound
+CurrentRound
+WordLength
+guessInput()
+callGuessChecker()
+callRoundTracker()
+callResultsSender()
+callFeedback()
Results Sender
+Results
+Guesses
+Word
+sendResults()
Daily Word Game
+DailyWord
+Guess
+MaxRound
+CurrentRound
+WordLength
+guessInput()
+callGuessChecker()
+callRoundTracker()
+callResultsSender()
+callFeedback()
+callDailyResultsLogger()
Generated Word Game
+GeneratedWord
+Guess
+MaxRound
+CurrentRound
+WordLength
+guessInput()
+callGuessChecker()
+callRoundTracker()
+callResultsSender()
+callFeedback()
Guess Checker
+Word
+Guess
+checkGuess()
+callFeedback()
Round Tracker
+MaxRound
+CurrentRound
+checkRound()
Feedback
+Guess
+Word
+Hints
+checkForGreenLetters()
+checkForYellowLetters()
+checkforRedLetters()
Feedback (LEDs)
+Guess
+Word
+Hints
+turnOnLEDS()

10.1 Budget and Financing

Because our design is still being developed, the numbers in this budget should be seen as estimates rather than final values. The costs shown are based on online prices for the kinds of parts we plan to use, with room for adjustment once we choose exact components. The higher costs are expected from the PCB fabrication, the microcontroller, and the display. Other items such as the keypad, LEDs, power circuitry, and the enclosure are smaller line items but still important. Since prototyping often requires ordering extra boards and backup batteries, the quantities are set slightly higher in some cases. Taking everything into account, the current estimate is around $335, but the final amount will depend on part selection and any changes we make as the project moves forward.

Note: This is a self-funded project, so we there is not a strictly constrained budget at this stage. The values shown below are general estimates, and the budget can be refined once more specific details are finalized.

Table 10.1: Budget and Financing

Component	**Quantity**	**Price (Est.)**	**Total Cost (Est.)**
PCB Board	3	$35	$105
Microcontroller Unit	1	$20	$20
Rechargeable Battery (Li-ion)	2	$15	$30
LCD Display	1	$20	$20
Keypad / Buttons	1	$15	$15
RGB LEDs	1	$25	$25
USB-C Port	2	$10	$20
Voltage Regulator	2	$30	$60
Power Switch	1	$10	$10
Enclosure	1	$30	$30
Total			**$335**

10.2 Milestones

Table 10.2-1: Senior Design I - Milestones

Senior Design I – Fall 2025

Week	**Project Task**
1	Course intro, team formation, brainstorm project ideas
2	Finalize our group and decide on the project idea
3	Write and turn in the Divide & Conquer report
4	Meet with advisor about D&C and start drafting requirements
5	Create list of main components (LCD, LEDs, keypad, battery, etc.)
6	Order sample parts, draft block diagrams, initial test plans
7	Test basic LCD functionality
8	Test basic LED functionality
9	Test basic keypad functionality
10	Begin integrating simple game logic with components
11	Submit Midterm report
12	Midterm review meeting
13	Work on schematic design and component testing
14	Upload final report draft and prepare demo video
15	Submit final report and demo video
16	Reviewer evaluation period

Table 10.2-2: Senior Design II - Milestones

Senior Design II – Spring 2026

Week	**Project Task**
1	Review progress from Senior Design I
2-3	Begin PCB assembly
4-5	Test major subsystems (power, display, LEDs, etc.) to confirm basic functionality
6-7	Troubleshoot any issues and adjust code and wiring as needed
8-9	Integrate all subsystems together and refine game performance
10-11	Prepare final presentation materials
12-13	Final debugging and adjustments
14	Conduct full run throughs of the demo, report, and finalize slides
15	Submit final report and demonstrate completed project

Appendices

Appendix A – References

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Appendix E – ChatGPT prompts and outcomes

ChatGPT was used to help with chapters 3.B and 3.C as well as some of the citations in Appendix A (some were copy and pasted from their generated citations and edited)

Below are the relevant links:

[29] "Standards and Design Constraints," chatgpt.com, [Online]. Available: https://chatgpt.com/share/68f7fac1-0d20-8012-bd9b-4c9c72cbb0d0 . [Accessed: Oct. 21, 2025]

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Prompt Example 1: [29]
yeah you can

ChatGPT said:

Perfect — let's build out the **Chapter 3 (Software) comparison backbone** for WordPal. I'll give you:

- 📊 **Tables** for each major software decision (Arduino vs ESP-IDF vs MicroPython, display libraries, Wi-Fi, etc.).
- 📝 **Mini writeups** showing reasoning (short but expandable).
- 🗂️ **References** you can cite (primary = docs, secondary = tutorials/forums).

📖 Chapter 3 (Software Section Draft)

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1. Programming Environments (Arduino Core vs ESP-IDF vs MicroPython)

Environment	Ease of Use	Performance	Library Support	Community
Arduino Core	Beginner-friendly, fast prototyping	Slight overhead, but good enough for most tasks	Extensive Arduino libraries (Wi-Fi, displays, LEDs)	Very large
ESP-IDF	Steeper learning curve, CLI + CMake	Most efficient (native SDK)	Full hardware access, official support	Large but more advanced
MicroPython	Very easy (interactive REPL)	Slower, limited for real-time tasks	Decent but fewer libraries	Active, but smaller

Writeup:
Arduino Core offers the simplest development workflow, using the Arduino IDE and familiar high-level APIs. ESP-IDF is the official SDK, providing full performance and hardware access at the cost of complexity. MicroPython is ideal for prototyping but lacks the performance and efficiency for real-time LED and LCD updates, making it less suitable for WordPal's timing-sensitive game loop.

Likely choice: Arduino Core (with ESP-IDF fallback if advanced control is needed).

References:

- Arduino-ESP32 GitHub
- ESP-IDF Documentation
- MicroPython ESP32 Docs
- Random Nerd Tutorials: *ESP32 Arduino vs ESP-IDF*

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2. Display Libraries (TFT_eSPI vs Adafruit GFX vs LovyanGFX)

Library	Ease of Use	Performance	Features	Community
TFT_eSPI	Simple, Arduino-based	Optimized for ESP32, very fast	Supports fonts, sprites, graphics	Large
Adafruit GFX	Very simple, portable	Moderate performance	Basic graphics primitives	Very large
LovyanGFX	More complex	Extremely optimized for ESP32	Advanced rendering, multiple displays	Smaller

Writeup:
TFT_eSPI is the most balanced option for WordPal. It is highly optimized for ESP32 hardware and supports smooth text rendering, which is essential for the game's word display. Adafruit GFX is beginner-friendly but lacks some performance and features. LovyanGFX is powerful but overkill for this project's scope.

Likely choice: TFT_eSPI.

References:

- TFT_eSPI GitHub
- Adafruit GFX Library
- LovyanGFX GitHub

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3. LED Control (FastLED vs NeoPixel vs Direct GPIO)

Method	Ease of Use	Performance	Flexibility	Community
FastLED	Easy, many examples	High performance, supports advanced effects	Very flexible (RGB, brightness, patterns)	Large
Adafruit NeoPixel	Very easy, official support	Good, but less optimized than FastLED	Simpler API	Large
Direct GPIO	Complex (manual handling)	Max efficiency	Full control, but error-prone	Low

Writeup:
FastLED provides the right balance of performance and flexibility for controlling the RGB LEDs behind each key. NeoPixel is simpler but less optimized for large LED arrays. Direct GPIO would offer full control but is too complex for this application.

Likely choice: FastLED.

References:

- FastLED GitHub
- Adafruit NeoPixel Library

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4. Wi-Fi Stack (Arduino WiFi.h vs ESP-IDF Wi-Fi API vs AsyncTCP)

Stack	Ease of Use	Performance	Features	Community
Arduino WiFi.h	Very easy, single function calls	Good enough for HTTP requests	Basic Wi-Fi management	Huge
ESP-IDF Wi-Fi API	Complex, event-based	High efficiency, low-level control	Advanced (mesh, WPA3, enterprise)	Large, advanced
AsyncTCP	Moderate	High performance (async)	Useful for servers, low-latency apps	Smaller

Writeup:
For WordPal, Wi-Fi is only needed to fetch the daily word from the New York Times. Arduino's WiFi.h is sufficient and keeps the implementation simple. ESP-IDF's Wi-Fi API would only be necessary if enterprise-level networking or advanced security features were required.

Likely choice: Arduino WiFi.h.

References:

- Arduino WiFi.h
- ESP-IDF Wi-Fi Programming Guide
- AsyncTCP GitHub

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5. USB/Serial Communication (Arduino Serial, TinyUSB, ESP-IDF USB stack)

Method	Ease of Use	Performance	Features	Community
Arduino Serial	Very easy (Serial.println)	Reliable for text	Simple text export	Huge
TinyUSB	Moderate setup	Flexible (HID, MIDI, etc.)	Advanced USB device support	Growing
ESP-IDF USB Stack	Complex	Full control	Full USB spec support	Smaller

Writeup:
WordPal only needs to export text game results via USB. Arduino's Serial is sufficient. TinyUSB or ESP-IDF USB stack would be better if HID devices (e.g., custom keyboard) were needed.

Likely choice: Arduino Serial.

References:

- Arduino Serial Reference
- TinyUSB GitHub
- ESP-IDF USB Host/Device Docs

🏁 Wrap-Up

So for **Chapter 3 (Software)**, your backbone looks like this:

- **Programming Environment** → Arduino Core (best balance)
- **Display Library** → TFT_eSPI (fast + simple)
- **LED Control** → FastLED (flexible)
- **Wi-Fi** → Arduino WiFi.h (simple HTTP)
- **USB/Serial** → Arduino Serial (easy text export)

This gives you **5 tables + 5 writeups** (~6–8 pages). You can expand each with screenshots of APIs, example code snippets, and block diagrams to reach your page count.

👉 Do you want me to go ahead and turn this into a **structured draft** (like a ready-to-drop-in report section with headings, tables, and writeups), or keep it in outline form for now?

Prompts Example 2: [105]

Do you have numerical performance related things for pololu-led-strip-arduino

ChatGPT said:

[There were pictures here but they might be unnecessary]

Certainly! Here's a detailed overview of the performance characteristics of the **PololuLedStrip Arduino library**, focusing on timing, efficiency, and considerations for large-scale applications:

⏱️ Timing and Efficiency

- **Update Time**: The library takes approximately **1.1 milliseconds** to update **30 LEDs** (1 meter) on a WS2812B or SK6812 strip. This translates to about **36.4 microseconds per LED**. GitHub+1
- **High-Speed Protocol**: The LED strips utilize a high-speed one-wire protocol with strict timing requirements. To ensure reliable color transmission, the library disables interrupts during updates. GitHub
- **Interrupt Handling**: Disabling interrupts can interfere with other time-dependent functions, such as serial communication and millis(), potentially affecting the timing of other operations. GitHub

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📊 Scalability

- **Large Strips**: The library can handle updates for larger strips. For instance, updating **450 LEDs** (approximately 15 meters) is feasible at a rate faster than **60 Hz**, allowing for smooth animations and effects. Pololu
- **Performance Considerations**: While the library is efficient, performance may vary depending on the microcontroller's clock speed and the number of LEDs. For extensive installations, it's advisable to test performance to ensure smooth operation.

⚠️ Considerations for Use

- **Microcontroller Compatibility**: The library is designed for use with Arduino-compatible microcontrollers. Ensure that your microcontroller's clock speed and capabilities align with the library's requirements for optimal performance.

- **Power Supply**: Adequate power supply is crucial when driving large LED strips. Ensure that your power source can supply sufficient current for the entire strip to prevent voltage drops and potential damage to the LEDs.
- **Signal Integrity**: For longer strips, signal degradation can occur. It's recommended to use a level shifter to ensure reliable data transmission over extended distances.

If you need further assistance with setup, code examples, or optimizing performance for your specific application, feel free to ask!

Sources

You said:

why 36.4 microseconds and not about 36.7 microseconds

ChatGPT said:

Ah, good catch — let's go through the calculation carefully step by step, because small differences come from rounding.

1️⃣ Given numbers

- Update time for **30 LEDs** = 1.1 milliseconds = 1100 microseconds.
- Number of LEDs = 30.

2️⃣ Compute time per LED

$$\text{Time per LED} = \frac{\text{Total time}}{\text{Number of LEDs}} = \frac{1100\ \mu s}{30}$$

Step by step:

1. 1100 ÷ 30
2. 30 × 36 = 1080 → remainder 20
3. 20 ÷ 30 ≈ 0.6667

So:

$$36 + 0.6667 \approx 36.6667\ \mu s$$

3️⃣ Round

- If you round to **one decimal place** → **36.7 µs** per LED.
- If someone rounded down slightly → **36.4 µs** is an underestimate.

☑️ So the more precise value is **≈36.7 µs per LED**.

If you want, I can recalc **theoretical maximum FPS** for PololuLedStrip based on this corrected timing, like we did for NeoPixels. It makes a nice comparison for your report. Do you want me to do that?

You said:

sure

ChatGPT said:

Great! Let's calculate the **theoretical maximum frames per second (FPS)** for a PololuLedStrip using the numbers we just worked out.

1️⃣ Given

- **Time per LED**: 36.6667 µs (≈36.7 µs)
- **Number of LEDs**: let's use 30 as an example
- **Latch time**: WS2812B typically requires **50 µs** after sending the last LED

2️⃣ Total update time for 30 LEDs

$$\text{Total time} = (\text{LEDs} \times \text{time per LED}) + \text{latch time}$$
$$\text{Total time} = (30 \times 36.6667) + 50$$

Step by step:

1. $30 \times 36.6667 \approx 1100$ µs
2. Add latch time: $1100 + 50 =$ **1150 µs**

So the **total update time per frame** ≈ 1150 µs = 0.00115 s.

3️⃣ Theoretical maximum FPS

$$\text{FPS} = \frac{1}{\text{frame time (s)}} = \frac{1}{0.00115} \approx 869.6$$

☑ So the **maximum theoretical FPS for 30 LEDs ≈ 870 FPS**.

4️⃣ **Notes**

- This assumes **no additional computation** — your microcontroller instantly calculates colors and updates the array.
- In reality, FPS will be lower depending on:
  - Animation math and loops
  - Interrupt handling
  - Microcontroller speed

If you want, I can **make a small table comparing NeoPixel, PololuLedStrip, and FastLED FPS for a few different LED counts**. This gives a clear visual for your report. Do you want me to do that?

You said:

is it possible to adjust the fps for 100 leds

ChatGPT said:

Yes — you can **estimate and "adjust" the FPS** for 100 LEDs using the same calculation method. The FPS is **limited by how long it takes to send all the data plus the latch time**, so adding more LEDs reduces the maximum FPS.

1️⃣ **Given**

- **Time per LED**: 36.6667 µs
- **Number of LEDs**: 100
- **Latch time**: 50 µs

2️⃣ **Total update time**

$$\text{Total time} = (100 \times 36.6667) + 50$$

Step by step:

1. 100 × 36.6667 ≈ 3666.7 µs
2. Add latch time: 3666.7 + 50 ≈ 3716.7 µs ≈ 0.0037167 s

3️⃣ Maximum theoretical FPS

$$\text{FPS} = \frac{1}{\text{frame time (s)}} = \frac{1}{0.0037167} \approx 269 \text{ FPS}$$

4️⃣ Adjusting FPS in practice

- You **cannot exceed this FPS** without skipping data.
- You *can* lower FPS intentionally by:
  - Adding delays between .write() calls
  - Updating only parts of the strip per frame (partial updates)
  - Reducing animation complexity
- This is useful if your microcontroller is busy with other tasks, or if you want to **throttle the refresh rate for smoother animations**.

If you want, I can make a **quick table of maximum FPS for 30, 60, 100, and 200 LEDs** for PololuLedStrip — similar to what we did for NeoPixels. It makes a nice visual for your report. Do you want me to do that?

You said:

For the 36.7 microseconds number, do you think that's accurate, like do you think the 1.1 ms number includes latch or not

ChatGPT said:

Ah, yes — that's an important subtlety. Let's reason through it carefully.

1️⃣ What the 1.1 ms figure likely represents

- The source says **"update 30 LEDs takes ~1.1 ms."**
- Usually, when libraries report update time, they are talking about **the actual time spent sending data to the LEDs**, **not including the latch time** (the extra ~50 µs the LED hardware requires to latch the data).
- So 1.1 ms ≈ 1100 µs would be **data transmission only**.

2️⃣ Time per LED

- If 1.1 ms is just data:

$$\text{Time per LED} = \frac{1100\mu s}{30} \approx 36.6667\mu s$$

- This matches our previous 36.7 µs calculation. ☑

3️⃣ Adding latch

- After sending all bits, WS2812B/SK6812 strips require a **latch period of ~50 µs**.
- So **total frame time** = 1100 + 50 ≈ **1150 µs**
- This is what you use to calculate **maximum FPS**.

4️⃣ Conclusion

- **36.7 µs per LED** is correct if you're talking about **raw transmission time**.
- To get **total frame time** for FPS calculations, **add the latch time** separately.

So yes, your original reasoning is solid — 36.7 µs is accurate for the 30-LED example **without latch**.

If you want, I can do a **recalculation of FPS for multiple LED counts including the latch time**, so you have a clean table comparing PololuLedStrip to NeoPixel and FastLED. This is perfect for your report. Do you want me to do that?

Prompts Examples 3: [133]
Also when it says it's deployed in these places what does that mean for installation, like does being deployed through Arduino's library registry necessarily mean the library manager or not really

ChatGPT said:

Excellent question — and you're thinking like an engineer writing a design justification 👍

Let's unpack what **"deployed in the Arduino Library Registry"** and **"deployed in the ESP Component Registry"** actually mean in practice — especially for installation and integration in your WordPal project.

🔧 1. Arduino Library Registry → Arduino Library Manager

If a library is **deployed in the Arduino Library Registry**, it means it is:

- Officially indexed and hosted on Arduino's GitHub-based registry of libraries,

- **Installable directly through the Arduino IDE's Library Manager** (or PlatformIO's Arduino ecosystem),
- Automatically receives updates via Arduino's infrastructure.

☑ **Implication:**
You can install AsyncTCP straight from the **Arduino IDE → Tools → Manage Libraries → search "AsyncTCP"** — no manual GitHub download needed.

🕮 **Source:**

- Arduino Library Manager documentation

"The Arduino Library Manager automatically lists libraries registered in the Arduino Library Registry. These can be installed directly from the IDE."

- AsyncTCP's registry listing confirms:

"Deployed in the Arduino Library Registry." (components.espressif.com, AsyncTCP v3.4.91)

❁ **2. ESP Component Registry → ESP-IDF integration**

If a library is **deployed in the ESP Component Registry**, it means:

- It's packaged for **ESP-IDF's "component" system**,
- Installable using the **ESP-IDF command idf.py add-dependency**,
- Includes CMake and Kconfig metadata for IDF projects.

☑ **Implication:**
When using the ESP-IDF environment (as opposed to Arduino), you can simply add:

idf.py add-dependency "esp32async/asynctcp"

and the build system pulls the correct version automatically.

🕮 **Source:**

- Espressif Component Registry documentation

"Developers can include registered components in ESP-IDF projects using idf.py add-dependency."

❁ **What this means for WordPal**

Because WordPal uses **Arduino-ESP32**, the "Arduino Library Registry" deployment is the one that matters most.

- ☑ Easy installation (via Library Manager)
- ☑ Automatic dependency resolution

- ☑ Guaranteed compatibility with Arduino-ESP32 core versions

The ESP-IDF deployment simply indicates **the same library** can also be used if you ever migrate to a more advanced ESP-IDF project.

TL;DR Summary

Registry	Environment	Installation Method	Meaning
Arduino Library Registry	Arduino-ESP32	Library Manager → Search → Install	Easiest install; integrates with Arduino build system
ESP Component Registry	ESP-IDF	idf.py add-dependency	Used for more advanced native ESP projects

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Would you like me to write a short paragraph you can plug directly into your *Compatibility* section explaining this distinction clearly for your report?

You said:

Both documentation sources you provided either the page doesn't exist or the quote doesn't exist

ChatGPT said:

Good catch — and you're absolutely right to be careful with sourcing. I found **some relevant documentation**, but I couldn't locate a **direct quote** in every case that explicitly says *"installed through Library Manager"* or *"deployed in Library Registry"* for the libraries.
Here's a more detailed breakdown of what I found, what we **can** use, and what we should avoid claiming without direct evidence:

☑ What I found that is valid

- The Arduino Library Manager documentation shows you can install third-party libraries via the Library Manager. It states:

"You can install a library into your Arduino IDE using the Library Manager." Arduino+1
This gives strong basis to say that if a library is in the Arduino Library Registry, it *will* appear in Library Manager.

- The ESP-IDF Component Manager documentation shows how components in the registry can be added via idf.py add-dependency. Espressif Systems+1
  This gives basis to use the "deployed in component registry" phrasing for ESP32/ESP-IDF libraries.

⚠ What I couldn't find or couldn't verify

- A library's **specific documentation** may not always *explicitly* say: "This library is deployed in the Arduino Library Registry."
- For some libraries (like AsyncTCP), while the registry listing exists, the readme may not highlight both Arduino and ESP-IDF support in the same wording we used earlier.
- I couldn't find a direct quote that exactly matches "Deployed in the Arduino Library Registry → Installable via Library Manager" for each library.

What this means for your report

- You *can* still make statements like:

"Because the library is listed in the Arduino Library Manager index, it is easily installed via the Library Manager interface."
And cite the Arduino Library Manager documentation.

- But avoid claiming something you can't **cite** verbatim. Instead phrase more cautiously, for example:

"The library appears in the Arduino Library Registry, which typically allows installation through the Arduino IDE Library Manager."

- For ESP-IDF components:

"The library is listed in the ESP Component Registry, suggesting it can be added via idf.py add-dependency in ESP-IDF projects."
And cite the ESP-IDF Component Manager docs.

If you like, I can dig further and try to find **the exact listing page for AsyncTCP** (or other libraries) that includes information like "*Published in Arduino Library Registry version X.X*" so you have a direct quote you can include.

Sources

You said:

Is this the library registry https://github.com/arduino/library-registry?tab=readme-ov-file#adding-a-library-to-library-manager

ChatGPT said:

Yes — that link is to the Arduino Library Manager Registry, specifically the GitHub repository for the library index: “Arduino Library Manager Registry”. GitHub

Here’s what it means and how it works in practice:

☑ What you found

- The repository includes instructions:

“If you would like to make a library available for installation via Library Manager, just submit a pull request that adds the repository URL to repositories.txt.” GitHub

- It shows this registry is **what the Arduino IDE uses** (via the Library Manager) to list installable libraries. GitHub

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🔍 What this implies for your project

- If a library (like AsyncTCP or WiFiManager) is included in that registry, it means **it can be installed via the Arduino IDE’s Library Manager** (under *Sketch → Include Library → Manage Libraries*).
- Being listed in the registry means it has undergone the submission process for being indexed.
- It provides a simpler installation experience compared to manually downloading and installing a ZIP or GitHub repo.

📌 How to use this for your report

- You can cite the registry (the link you found) as **proof** that the library installation mechanism is supported by the Arduino ecosystem.
- For example:

“The library is indexed in the Arduino Library Manager Registry, which enables installation directly from the Arduino IDE.”

- This strengthens your **Compatibility** and **Ease of Use** criteria for libraries you compare.

If you like, I can check **whether your specific libraries (AsyncTCP, WiFiManager)** are listed in that registry (and which versions) so you can cite that in your report.