March 6th, 2021

Dr. Craig Scratchley
Dr. Shervin Jannesar
School of Engineering Science
Simon Fraser University
8888 University Drive
Burnaby, BC, V5A 1S6

Re: ENSC 405W Design Specification for Boundless Graphing Calculator

Dear Dr. Scratchley and Dr. Jannesar,

The following document outlines the design specifications for the Boundless graphing calculator. The goal is to design an affordable graphing calculator that has a use after high school mathematics. BC Instrument will create a graphing calculator that can perform competitively in the current market and allow instructors to disable specific features on the calculators with an administrative remote.

The document will include the design specifications for both the wireless communications and hardware of the graphing calculator and administrative remote control for the three stages of development. There will also be a supporting test plan appendix to address testing the subsystems and components of our product, supporting design options appendix to provide design options and justifications and lastly the user interface and appearance design appendix.

Company 17, also known as BC Instrument, consists of six capable SFU engineering students. These talented team members are Dante Barr, Russell Ho, Chris Keilbart, Evan Lee, Nicholas Lee and Donald Tim Mustard. Each member is bringing their diverse experiences from both industry and education to create an exceptional graphing calculator for students.

The team at BC Instrument would like to thank you for reviewing our design specification document. If you have any questions related to our document, please contact us through comments on our GitLab or contact our Chief Communications Officer, Nicholas Lee, at nicholas_lee_3@sfu.ca.

Sincerely,

Nicholas Lee

Nicholas Lee
Chief Communications Officer
BC Instrument

Design Specification
For *Boundless* Graphing Calculator

Version 1.0

BC Instrument
Company 17

Company Members:
Dante Barr
Russell Ho
Chris Keilbart
Evan Lee
Nicholas Lee
Donald Tim Mustard

Submitted To:
Dr. Craig Scratchley, ENSC 405W
Dr. Shervin Jannesar, ENSC 405W
Dr. Andrew Rawicz, ENSC 440
School of Engineering Science
Simon Fraser University

Date Created: March 6th, 2021

Abstract

This document provides the design specification for the Boundless graphing calculator by BC Instrument. The Boundless graphing calculator project consists of two main components: the graphing calculator and the administrative remote. This document is separated into two parts to describe the design of each technical component which are the wireless communications and hardware.

The goal of the Boundless graphing calculator project is to create a novel and flexible graphing calculator that can suit the calculation needs of any test environment. This is accomplished by use of an administrative remote to control the accessible functionality of each calculator wirelessly. As such, the wireless functionality must be capable of transmitting over an appropriate range. The design must also be portable and functional while keeping costs low. The Boundless graphing calculator must also have an easy-to-use interface design that all appropriate ages can seamlessly pick up and use. With these constraints in mind, design specifications for the project are detailed in depth in the following document.

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Revision History

Version #	Implemented By	Revision Date	Approved By	Approval Date	Reason
1.0	Dante Barr, Russell Ho, Chris Keilbart, Evan Lee, Nicholas Lee, Donald Tim Mustard	03/22/21	Nicholas Lee	03/23/21	First release

Glossary

Term	Description
FPL - Free Path Loss	Power lost in transmission due to the range's effect on wave propagation
GPIO - General-Purpose Input/Output	An undedicated pin on a circuit board that could be used as input or output
I/O Pin - Input/Output Pin	Interface between a microcontroller and another circuit
RF - Radio Frequency	A frequency or band of frequencies in the range 10^4 to 10^{11} or 10^{12} Hz, suitable for use in telecommunications.
RTC - Real Time Clock	An electronic device that measures time
RAM - Random Access Memory	Computer memory used by the processor at runtime
PCB - Printed Circuit Board	The place where electrical components are connected and mounted to in electronic devices

Table 1.0: Glossary for abbreviated terms

1. Introduction

1.1 Scope

The purpose of this document is to outline the design specifications of the Boundless graphing calculator and the accompanying administrative remote control. These specifications will describe in detail the project's design decisions and corresponding justifications, as well as distinguish the design specifications for the three phases of the project: alpha phase (proof-of-concept), beta phase (engineering prototype), and production phase (final product).

This document will also include the supporting test plans appendix which will provide test plans to address testing various subsystems and components of the Boundless graphing calculator. Also included is the user interface and appearance design appendix, which provides an overview of the appearance of both the graphing calculator and the administrative remote control, in addition to some example user interface screens.

1.2 Intended Audience

The intended audience for BC Instrument's design specification document are the engineers and software developers who will be creating and designing the Boundless graphing calculator. This document will provide a detailed overview of the necessary design choices and specifications for the reader to understand each stage of development for the Boundless graphing calculator.

1.3 Design Specification Classification

The design specifications are classified according to the following format:

Des. (Section Number).(Subsection Number).(Requirement Number)-(Stage of Development)

The three stages of development for the project are as follows in Table 1.3:

Symbol Classification	Stage of Development
A	Alpha Phase (Proof-of-Concept)
B	Beta Phase (Engineering Prototype)
P	Production Phase (Final Product)

Table 1.3: Symbol classifications for the three stages of development

1.4 System Overview

The Boundless graphing calculator consists of two main units: A control transmitter that will be held by the test administrator, and the receiver graphing calculators to be used by all the students being tested. The two units will be sold separately, with the control units only being made available for purchase by school administrations, while the graphing calculator will be available for purchase in bulk by administrations and as individual units for personal use. A general overview of the system is represented in Figure 1.4 below.

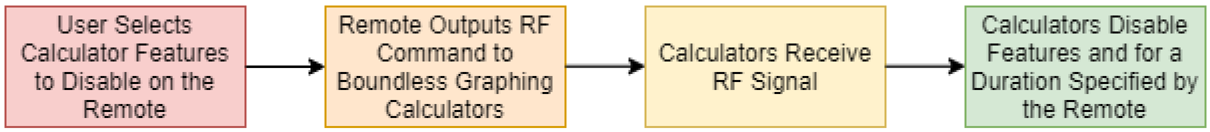

Figure 1.4: Overview block diagram

2. Wireless Communications

The wireless communications aspect of the Boundless graphing calculator is an integral part of its design and market viability. As such, the frequency and protocol chosen as well as the design and placement of the antenna were decided upon based on the key factors of range and reliability.

2.1 Wireless Communication Constraints

In order to decide upon a frequency for the constraints of the system that affect radio frequency communications must be considered.

The first crucial constraint is power. Radio frequency communication range and reliability is directly impacted by power. Many transmitters have a range of input voltages that can be used to define the system. Both devices that make up the system must be handheld and powered by batteries.

Another constraint considered was range. The range required for the system was determined based on the expected size of classrooms that the devices will be used in. Range is also determined by the position and design of the antennas. The antenna for the graphing calculators must be internal, which severely impacts its ability to receive signals. This can be mitigated by having an external antenna on the administrative remote to boost the signal in the desired direction.

Reliability is also crucial, if the Boundless calculators do not receive signals reliably then users may be able to use functions that should be restricted to cheat on tests. As reliability is tied to the strength of the signal at a given point, increasing the expected range of the transmitted signal will in turn increase the reliability.

2.2 Wireless Communication Choice

Seeing as the administrative remote needs to be able to communicate with an entire class, it needs to be capable of transmitting to at least 500 devices. This should not be a problem since one-way communication is being used.

By choosing a transceiver module instead of a separate receiver and transmitter it will be easier to transition the technology to allow for two-way communication if required, for further security protocols in the future. The wireless communication design specifications are shown in Table 2.2 below.

[Des 2.2.1-A]	The system will support 1-way communication from the administrative remote to the graphing calculator
[Des 2.2.2-A]	The frequency of communication will be 400-500 MHz
[Des 2.2.3-A]	The wireless connectivity will support communication with up to 5 devices
[Des 2.2.4-F]	The wireless connectivity will support communication with up to 500 devices
[Des 2.2.5-A]	The transmitted signal will be capable of being received at a distance of 100 metres or less

Table 2.2: Wireless communication design specifications

2.3 Calculations and Unit Decision

The range of wireless communication using basic RF transmission and reception can be roughly approximated using Friis equation. The Friis equation, seen below [1], relates the power received (P_r)in Watts by the calculator models, to the transmission power(P_t)in Watts, receiver (G_r) and transmitter (G_t) antenna gains, the range of transmission (R)in metres, and the frequency/wavelength (λ)in metres of the signal.

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi R)^2} \quad [1]$$

This equation can be divided into four main parts: the antenna gains ($G_t G_r$), the sensitivity P_R, the transmitted power P_T, and the Free Path Loss (FPL).

$$FPL = (4\pi R/\boldsymbol{\lambda})^2$$

Converting the whole equation to dB, gives:

$$P_r\ (dB) = P_t\ (dB) + G_t\ (dB) + G_r\ (dB) - FPL\ (dB)$$

Using the frequency, the distance between the receiver and the transmitter given as a design specification below, and allowing an extra 20dB for reliable communication levels, and knowing the antenna gains will result in a 15dB loss, the power subtracted from the sensitivity must be -90dB. This is equivalent to the ratio of received power over transmitted power.

The frequency band has been decided to be in the 400-500MHz band, as it is a common band for transceiver operation. In addition, the wavelength is enough to decrease the FPL significantly, compared with other RF protocols such as Bluetooth. To ensure that all units can be reached in the largest of gym sizes for standardized testing, the operating distance will be 100 metres.

After careful consideration of the design requirements, the communication method that will be used is a simple transceiver unit, specifically the RFM96W/RFM98W - Low Power Long Range Transceiver Module V1.0 as shown in Figure 2.3.

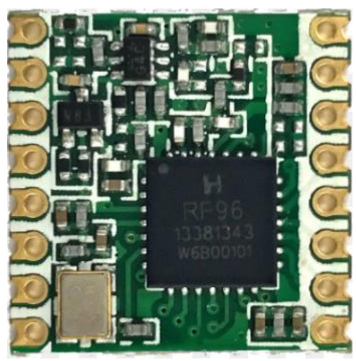

Figure 2.3: RMF96/98W RF transceiver V1.0 [2]

The design specifications that determined the wireless communication choice are outlined in Table 2.3 below.

[Des 2.3.1-A]	The 400-500 MHz frequency chosen will be able to support the desired range
[Des 2.3.2-A]	The transmitted signal will be able to support the maximum range with a mathematical buffer of 20dB in reliability losses
[Des 2.3.3-A]	The transmitter unit will contain an external antenna to increase the gain of the unit
[Des 2.3.4-A]	The ratio of received power to transmitted power in dB must be greater than -90dB

Table 2.3: Mathematical RF design specifications

2.4 Test Mode

The purpose of wireless communication is to put the calculator into a test mode, where only features that have been permitted by the remote-control module are capable of being used. To prevent calculators being disabled in nearby rooms that aren't having a test, there will first be a message on screen asking for confirmation to enter test mode. Upon confirmation, a visual cue and a unique session code will be given to the student, to confirm their calculators have entered test mode. This is outlined in Table 2.4 below.

[Des 2.4.1-A]	The calculator unit will display a message asking for confirmation to enter test mode
[Des 2.4.2-A]	The LED on the calculator will start blinking to acknowledge it has entered test mode
[Des 2.4.3-A]	The calculator will provide a unique session code to the user to confirm they have entered test mode
[Des 2.4.4-A]	The message the administrative remote sends will determine which features are disabled
[Des 2.4.5-A]	The user will be unable to access disabled features on the calculator while in test mode

Table 2.4: Test mode design specifications

3. Hardware Design

3.1 Microcontroller

3.1.1 Requirements

In the requirements document, there were three requirements associated with the processing unit of the system. These were memory (Req 4.4.1-A), computational power (Req 4.4.2-A), and sufficient I/O capabilities (Req 4.4.3-A). The memory and computational requirements are necessary to ensure that the performance of this calculator is comparable to the competition, and the IO requirement is necessary to facilitate the large quantity of inputs the calculator must support: many buttons, a screen, an RF unit, RTC, and power. These requirements have now been quantified in the following Table 3.1.

[Des 3.1.1-A]	The microcontroller will have at least 128 KB of RAM
[Des 3.1.2-B]	The microcontroller will have at least 1 MB of flash memory

[Des 3.1.3-A]	The microcontroller will have at least 20 IO ports
[Des 3.1.4-B]	The microcontroller will draw less than 50 mA of current when idle

Table 3.1: Microcontroller design specifications

The memory requirements for the Boundless graphing calculator are greater than those for the Texas Instruments 84 Plus graphing calculator, which is a primary competitor and has 480 KB of flash memory and 24 KB of RAM [3]. This surplus of memory allows for more flexibility in the implementation of features. Having at least 20 I/O ports is needed because the buttons require 14 ports (discussed later on), the RTC requires one port, the screen will require at least three ports, and the RF unit needs two ports.

3.1.2 Alpha Phase

For the alpha phase, the Raspberry Pi Zero, a powerful single board computer, has been selected. The Raspberry Pi Zero comes pre-assembled with a 1GHz single-core 32-bit ARM CPU, 512MB of RAM, and 40 IO pins. The small form factor and out-of-box ease of use makes the Raspberry Pi Zero an ideal candidate for rapid prototyping. Moreover, the Raspberry Pi Zero is more than capable of integrating with the peripheral devices and performing the basic computations as described in the requirements document. Because the Raspberry Pi Zero is a single board computer and not a microcontroller, it uses too much power for continued use after the alpha phase.

3.1.3 Beta Phase

For the beta phase, the Raspberry Pi Pico is the microcontroller of choice. It features dual-core 32-bit ARM CPU cores, running up to 133MHz, the same 40 IO pins as the Raspberry Pi Zero, 2MB of on-board flash memory, and 264 KB of RAM. This unit is a proper microcontroller, so it uses much less power with much fewer resources. The technical specifications of the Raspberry Pi Pico are sufficient for a graphing calculator. This model was chosen because of its similarity with the Raspberry Pi Zero used in the alpha phase. They have the same pinouts, which should facilitate an easy replacement. It must be noted that the Raspberry Pi Zero runs a full-fledged operating system (likely some barebones Linux distribution), but the Raspberry Pi Pico won’t. This is because of two reasons. The first reason is that an operating system is not necessary for a calculator, especially one that doesn’t allow users to write their own programs. The second reason is that the overhead of an operating system might unnecessarily strain the limited computing resources available - there might not be enough memory at runtime for the programs or memory to store the program instructions!

3.1.4 Production Phase

Once the production phase has been reached, the exact requirements of the software will be known - specifically the flash memory, RAM, and processing power required. This allows easy selection of the perfect microcontroller, which can match these unlikely-to-change final software requirements exactly. At that point, it will simply be a matter of balancing the cost with the power draw of all microcontrollers that have sufficient resources. Because the exact software requirements are not currently known, it is impossible to specify the microcontroller that will be used in the production phase. However, using any Raspberry Pi-based hardware platforms is not a good idea, due to the open-source nature of the hardware. That makes it harder to secure against deliberate malicious tampering by students that wish to circumvent the lock placed on features by the remote.

3.2 Screen

The display module is an integral component of both the Boundless graphing calculator and the administrative remote and is responsible for conveying information to the users. The graphing calculator screen is responsible for displaying the user input, numeric and graphical results of mathematical operations, navigation menus, and test mode related information. When considering the administrative remote, the screen must be capable of presenting the sets of calculator features to disable as well as the duration of which the features will remain disabled. Lastly, the design requirements that both screens must abide by are outlined in Table 3.2 below.

[Des 3.2.1-A]	The screen will be able to display 16 characters on a line
[Des 3.2.2-A]	The screen will possess a resolution of at least 96x64 pixels

Table 3.2: Screen design specifications

In addition to the above design requirements, the price of the screen was a major concern for BC Instrument and consequently acted as the determining factor for the module selection.

The model numbers for the calculator screen candidates that have been selected are E2271FS091 and E2287CS091. The former model has a 264 x 176 resolution and a 2.71” diagonal, while the latter has a 296 x 128 resolution and a 2.86” diagonal. Both of these models support connection via SPI interface and are RoHS compliant.

3.3 Buttons

The buttons selected for the Boundless graphing calculator are Omron’s 6x6 mm B3F-1050 tactile switch and TE Connectivity’s 12x12 mm FSM103A tactile switch as shown in Figures 3.3.1 and 3.3.3. These two types of buttons will be used with Omron’s B32-1000 and APEM Inc.’s AKTSC21I switch caps respectively as shown in Figures 3.3.2 and 3.3.4. The buttons will be wired in a 7x7 matrix to allow forty-nine physical buttons for the user but only use fourteen I/O pins on the microcontroller. The administrative remote will require six buttons and use the same FSM103A tactile switches and AKTSC21I switch caps as the Boundless graphing calculator. Also, the administrative remote will be wired in a 3x2 matrix and use five I/O pins.

Figure 3.3.1: B3F-1050 tactile switch [4]

Figure 3.3.2: B32-1000 button cap [5]

Figure 3.3.3: FSM103A tactile switch [6]

Figure 3.3.4: AKTSC21I button cap [7]

Next, the following equations represent the total number of buttons for the button matrix and the required number of I/O pins.

$$Total\ \#of\ physical\ buttons\ =\ \#of\ rows\ \cdot\ \#of\ columns$$

$$Total\ \#of\ I/O\ pins\ used\ =\ \#of\ rows\ +\ \#of\ columns$$

The 4x4 button matrix schematic shown in Figure 3.3.5 represents the matrix design that will be implemented for both the Boundless graphing calculator and remote control. The 1 kΩ resistors connected to ground and each input pin limit the current to prevent the microcontroller from short circuiting after a button has been pressed [8].

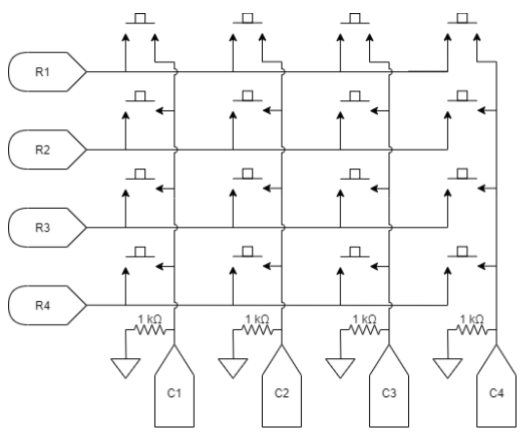

Figure 3.3.5: 4x4 button matrix schematic

The button matrix works by first separating the I/O pins into rows and columns, where the rows are outputs, and the columns are inputs. The microcontroller will iterate through each row and set the current row to output a high signal. During each iteration, it will loop through each column of the current row and check if any of the columns have received a high signal. If a high signal was received, then the microcontroller will perform an action based on that button's row and column combination. If none of the columns received a high signal, then the current row will be set to output a low signal and the microcontroller will iterate to the next row and repeat the column checks. The flow diagram in Figure 3.3.6 below represents how the button matrix method is implemented.

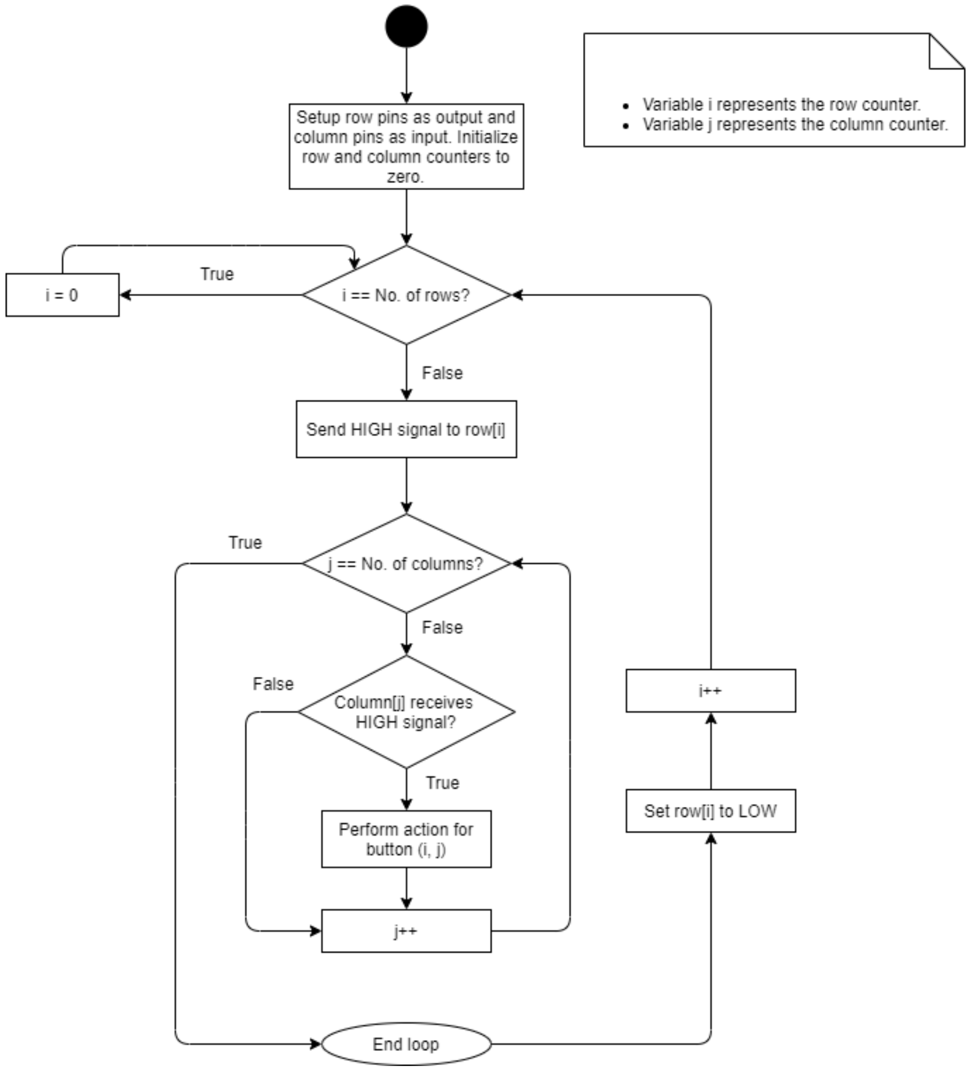

Figure 3.3.6: Button matrix flow diagram

The design specifications for the project's buttons are displayed in Table 3.3 below.

[Des 3.3.1-A]	There will be a "2nd Function" button to allow a button to perform two distinct operations
[Des. 3.3.2-B]	Buttons will be clearly labelled with its corresponding function
[Des. 3.3.3-A]	Buttons will be paired with corresponding button caps

Table 3.3: Button design specifications

3.4 Power

The main power supply for both the administrative remote and the graphing calculator must be capable of lasting a long time and supply adequate power for the system. To meet these needs, four AA batteries will be used in both devices. This will supply up to 3V and 100mA by arranging the batteries as shown below in Figure 3.4.

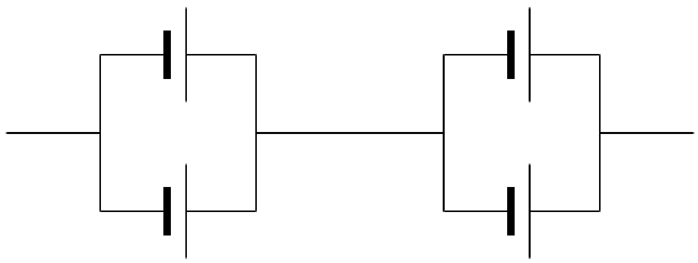

Figure 3.4: AA battery circuit diagram

The graphing calculator will also house an LIR2025 battery to power an RTC. This battery will be kept charged by the AA batteries. The RTC is required in order to retain the test mode, even if the calculator has its regular battery powered down, for the required test mode time limit. The battery design specifications can be seen in Table 3.4 below.

[Des 3.4.1-B]	The graphing calculator will be powered by 4 AA batteries.
[Des 3.4.2-B]	The administrative remote will be powered by 4 AA batteries.
[Des 3.4.3-F]	The graphing calculator will have a secondary LIR2025 battery charged by the main power supply to power an RTC

Table 3.4: Battery design specifications

4. Conclusion

This document describes the design decisions for BC Instrument's calculator and remote units as well as their respective justifications. Both the calculator and remote units include their own button interface, graphical display unit, power supply, and microcontroller. Furthermore, the two products must be capable of facilitating one-way RF communication from the administrative remote to calculator devices.

Wireless communication is an essential component of BC Instrument's Boundless system and its reliability is of utmost importance. To ensure the correct operating behavior, the design team has to consider issues involving the effective range at which signals could be transmitted and received, power consumption, signal frequency, and the size of the units. The Boundless administrative remotes must be capable of supporting communication up to 500 calculators at a 400-500MHz frequency, and at a range of 100m with a 20dB signal buffer to ensure a comfortable connection range.

The button interface serves as the primary medium for instructors and students to interface with the remote controls and graphing calculators. As the number of buttons for these types of devices often exceed the I/O capabilities of the underlying circuit, it would be wasteful to have a 1:1 button to pin dedication. This poses an interesting challenge that could be solved with a button matrix design. This would reduce the number of pins required by the calculator from 48 to 14 and from 6 to 5 for the administrative remote.

When considering potential microcontroller candidates for the Boundless system, 4 key factors had to be accounted for. These factors included RAM, flash memory, I/O capabilities, and power consumption. For the alpha phase, the main concern is to provide a device that demonstrates correct operational behavior. Due to the usability of the Raspberry Pi Zero, the single board computer was a natural choice for this stage as most of the development efforts can be focused on other aspects of the system. Developing on the Raspberry Pi Pico should be a very similar experience to the Pi Zero. As the Pico is a true microcontroller, its power consumption is much less than that of the Pi Zero. The objective of the beta phase is to produce a version of the system that is very close to the final product, hence why the Pico has been selected due to its lower power consumption characteristics and lack of operating system. Not much is known about the specific microcontroller that will be used in the production phase, as it will be tailored specifically to meet the demands of the finalized software.

The display module is in charge of visually presenting the appropriate information depending on the user-context. From the perspective of a user operating the remote controller, this information would include a collection of features to disable and the time duration that the test mode remains active. From the calculator user's perspective, this would include the user input and its respective results, navigation menus, and test mode related information.

The administrative remote will have a single power supply, while the graphing calculators will have two different power supplies. Both devices will use a series connection of two AA batteries connected in parallel as the main power supply. The secondary battery for the calculator devices would be a LIR2025 which will be used to power the RTC.

The proof-of-concept test plan has been documented and is described in detail in Appendix A. These testing procedures were designed with the intent for use against the production models but may also be applied to the earlier stages of development (i.e., alpha and beta).

This document serves as a reference to the design of BC Instrument's Boundless system and is subject to change. Throughout the course for the prototyping phase, the designs outlined here may be revised depending on potential issues that arise during the implementation.

5. Sign-off

The undersigned acknowledge that they have reviewed the product design specifications and agree with the approach they present. Any changes to these design requirements will be coordinated with and approved by the undersigned.

Signature:		Date
Print Name:	Dante Barr	23 Mar. 2021
Title:	Chief Financial Officer	
Signature:		Date
Print Name:	Evan Lee	23 Mar. 2021
Title:	Chief Software Officer	
Signature:		Date
Print Name:	Donald Tim Mustard	23 Mar. 2021
Title:	Chief Technology Officer	
Signature:		Date
Print Name:	Russell Ho	23 Mar. 2021
Title:	Chief Information Officer	
Signature:		Date
Print Name:	Nicholas Lee	23 Mar. 2021
Title:	Chief Communications Officer	

Signature:	Chris Keilbart	Date
Print Name:	Chris Keilbart	23 Mar. 2021
Title:	Chief Executive Officer	

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[15] Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment, RoHS (Directive 2002/95/EC), 2003

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A. Supporting Test Plans Appendix

Software Tests:

Date:	Test Name: Graphing Functions Test	
Description:	Enter and graph a mathematical function on the calculator, and then modify (pan and zoom) the view of the graphed function.	
Expected Outcome:	The functions are all graphed properly to the screen and the view can be manipulated.	
Actual Outcome:	Pass ⬚ Fail: ⬚	Details:

Date:	Test Name: Mathematical Functions Test
Description:	Test each of the following mathematical functions with a sample input: trigonometry, logarithms, integrals, summation, derivatives, limits, logical operations, error function.

Expected Outcome:	The mathematical functions compute the correct result.	
Actual Outcome:	Pass ⬚ Fail: ⬚	Details:

Date:	Test Name: User-Defined Variables and Functions	
Description:	Store and recall the results of mathematical operations using the variables. Also, create a custom function and run it.	
Expected Outcome:	The calculator should be able to correctly store and retrieve variables, and the custom function should return the correct value for the given input.	
Actual Outcome:	Pass ⬚ Fail: ⬚	Details:

Date:	Test Name: Test Mode Persistence	
Description:	Verify that the calculator remains in test mode after: ● the calculator is turned off and on ● the battery is removed and put back in	
Expected Outcome:	The calculator remains in test mode and the same features remain disabled when powered back on.	
Actual Outcome:	Pass ⬚ Fail: ⬚	Details:

Radio Frequency Tests:

Date:	Test Name: Test Mode Enabled Test	
Description:	Send a test mode signal from the administrative remote to a graphing calculator and attempt to use a restricted function throughout the duration of the test mode.	
Expected Outcome:	Graphing calculators successfully receive signals from administrative remote, and the specified features are disabled and inaccessible for the expected duration.	
Actual Outcome:	Pass ⬚ Fail: ⬚	Details:

Date:	Test Name: Test Mode Disable All Features Test	
Description:	Send a test mode signal to a graphing calculator that disables all functions. Assert the functions are not able to be used.	
Expected Outcome:	All functions are disabled and unable to be used for the test duration.	
Actual Outcome:	Pass ⬚ Fail: ⬚	Details:

Date:	Test Name: Wireless Communication Range Test	
Description:	Place several calculators at the maximum distance (100m) from an administrative remote and a signal is transmitted to them.	
Expected Outcome:	The signal is received 100% of the time on all calculators.	
Actual Outcome:	Pass: ⬚ Fail: ⬚	Details:

Date:	Test Name: Connection Time Test	
Description:	Record the time it takes between the signal being first sent from the transmitter, and 30 calculators receiving the request.	
Expected Outcome:	The last calculator will connect within 30 seconds.	
Actual Outcome:	Pass ⬚ Fail: ⬚	Details:

Hardware Tests:

Date:	Test Name: Visual Indicator for Test Mode Test
Description:	When the calculator is in test mode, does the LED blink to indicate test mode, even when the calculator is off.
Expected Outcome:	The LED continues blinking to indicate test mode, even when the calculator is off.

Actual Outcome:	Pass ⬚ Fail: ⬚	Details:

Date:	Test Name: Button Test	
Description:	Press each button on both the calculator and the remote, and all possible combinations of button presses.	
Expected Outcome:	The actions and outputs associated with the pressed buttons and combinations of button presses are correct.	
Actual Outcome:	Pass ⬚ Fail: ⬚	Details:

Date:	Test Name: Drop Test	
Description:	Drop the calculator and the administrative remote five times from a height of 2 metres onto vinyl tile.	
Expected Outcome:	The calculators should still be functional. Visible damage is permissible.	
Actual Outcome:	Pass ⬚ Fail: ⬚	Details:

Date:	Test Name: Normal Battery Life Test	
Description:	Turn on the calculator and remote and leave them running for a 48-hour period, checking on them every hour to manipulate the buttons.	
Expected Outcome:	The calculator and remote should remain on for at least 48 hours before fully draining the batteries.	
Actual Outcome:	Pass ⬚ Fail: ⬚	Details:

Date:	Test Name: Clock Battery Life Test
Description:	Connect the calculator in test mode for 3 hours. Turn off the normal calculator battery and verify the calculator’s clock can maintain its charge for the entire test period.

Expected Outcome:	The clock battery will maintain its charge until the end of the test period.	
Actual Outcome:	Pass ⬚ Fail: ⬚	Details:

B. Supporting Design Options Appendix

B.2.2 Wireless Communication Choice

There are two ways to go about implementing the wireless communications for the device. The first is to use a predefined protocol, and the other is to simply transmit signals over a chosen frequency with standard transmitters and receivers. There are several predefined radio frequency protocols such as Zigbee, Bluetooth, and Wi-Fi. Seeing as the system requires solely one-way communication, there is no need for a robust communication protocol for exchanging data. These communication protocols all use higher frequencies than necessary for the system. This results in a lower range for the given input power and cost. It is possible to compensate for the range by increasing directionality, but the communication required for this system prefers an omnidirectional range for the transmission. Therefore, standard RF modules are the best way to accomplish the needs and goals of the system.

B.2.3 Mathematics Behind Range Calculations

The power subtracted from the sensitivity eliminated most transceiver models, which left two options:

- RFM69HCW-V1.1 [9]
- RFM96/98W

The RFM96/98W is slightly more expensive but has a better range, according to the Friis equation calculation, thus making it the more desirable choice.

B.3.1 Microcontroller

Certain alternative microcontrollers were considered for the design. There are thousands (if not millions) of different microcontroller options, but most microcontrollers do not have sufficient memory for a graphing calculator such that [Des 3.1.1-A] and [Des 3.1.2-B] would be satisfied. This eliminated the wildly popular ATmega328 microcontroller (used in various Arduino boards) from consideration.

While Bluetooth was being considered for the wireless communication method, the ESP32 platform for microcontrollers were considered. These microcontrollers support both Wi-Fi and Bluetooth, and meet the previously mentioned memory requirements, but were ultimately not chosen because of the decision to use dedicated radio transmitters and receivers.

B.3.3 Buttons

The two different button sizes were selected based on the general design of similar scientific and graphing calculators. They tend to have larger buttons for the digits, and smaller buttons for everything else so the calculator remains small and handheld. As a result, two button sizes were chosen: 6x6 mm, and 12x12 mm. BC Instrument tested various 6x6 mm and 12x12 mm buttons, such as Schuter's 1301.9302 and CIT Relay and Switch's CT1103AF180 respectively. These other buttons were usable in the preliminary hardware and circuit testing stages but did not have any compatible button caps. Since the team is currently planning on using button caps in both the Boundless graphing calculator and remote-control design, compatible button caps were a requirement.

For the remote control, the 12x12 mm buttons were chosen because there are few buttons required, so there are no concerns about running out of room on the face of the device. Additionally, reusing the same buttons from the calculator results in cheaper and easier manufacturing due to bulk ordering and reusing components. The circuit design for the remote control will use the button matrix method and be wired in a 3x2 matrix to reduce the number of I/O pins needed to five versus having each button use its own I/O pin.

The button matrix method was selected to reduce the number of I/O pins needed for the buttons, without using additional hardware. This wiring method reduces the overall cost of the product because I/O expanders such as Microchip Technology's MCP23017 or MCP23S17 are not required. This method reduces the number of components on the PCB, which makes assembly and manufacturing easier for the final product.

B.3.4 Power

The power supply for both the administrative remote and the graphing calculator use AA batteries. This power source was decided upon based on the availability and ease of use associated with AA batteries. The ability to simply switch out dead batteries for new ones also makes sense with the application of our product, as it is not convenient or easy to recharge a dead calculator during an exam.

As described earlier in the document, an RTC is required to ensure the graphing calculator remains in test mode even when powered off. Any rechargeable button battery will be able to sufficiently charge the RTC component, so cost effectiveness was the main concern. In that regard the LIR2025 satisfies all the necessary requirements to power the RTC.

C. User Interface and Appearance Design Appendix

C.1 Introduction

The purpose of this appendix is to outline the user interface and appearance of the Boundless graphing calculator. The system consists of a graphing calculator used by students, and an administrative remote for instructors that is able to wirelessly disable specific features on nearby calculators. To achieve this, diagrams illustrating the user interface and appearance of several key components of the system will be presented, followed by a description explaining how the implementation considers fundamental design principles. The document concludes with a summary of the usability testing, both analytical and empirical, that BC Instrument will undertake to ensure the system is maximally appealing to users. Before any of this can happen, a thorough understanding and reflection upon the target audience is necessary, to ensure that BC Instrument is able to best suit their needs and expectations.

C.2 User Analysis

The users for the Boundless graphing calculator system are very well defined. There are two primary groups: instructors, and students. The system is targeted at a North American market, specifically the United States and Canada. By focusing on these locations, the design needs to consider a Western, primarily English-speaking market. The product consists of a graphing calculator and an administrative remote, so the physical abilities needed to use the product are minimal - basic motor dexterity is sufficient.

First, there must be an investigation into the primary (in terms of quantity) users of the graphing calculator, the students. Graphing calculators begin to replace regular calculators in mid-to-late high school, when students are around fifteen years old. Such students are by that point already familiar with scientific calculators, which contain much of the same functionality as a graphing calculator. The primary new feature introduced is graphing, so it is important that that feature be made as intuitive and easy to use as possible. Because high school students will be the primary users, the features they use frequently must be as accessible as possible. The mathematics high school students use is fairly simple, so trigonometry, logarithms, and other algebra functions should be quickly accessible.

The student users can be further subdivided by considering university and college students, in addition to the previously mentioned high school students. Graphing calculators are generally not frequently used in post-secondary education, but this depends specifically on the institution, the course, and the professor. This demographic of users is very similar to the high school demographic, the primary difference being mathematical ability and familiarity with graphing calculators. University and college students would be more likely to use the advanced features the calculator offers (such as complex numbers and matrix arithmetic), but they are also more familiar with graphing calculators. This means that these advanced functions do not require dedicated buttons, they can be accessible through menus or through the second function button. For both groups of students, their experiences with other calculators (basic, scientific, or graphing) are beneficial for their understanding of the product, but are not essential, as calculators are fairly self-explanatory (as long as the requisite math knowledge is present).

Students do not need to concern themselves with how features are disabled, it is merely something that is thrust on to them that they have little control over. The same is not true for their instructors, who use the remote to control the features their students have access to. This is the second group of users that will use the system. Instructors do not use the calculators themselves; they will use the remote to disable features accessible to students for a specified duration. As this is a new feature, instructors will have no previous experience with this product. It can be made easier for them to use by drawing parallels in the design to a television remote or a cellular phone. The knowledge required for instructors is minimal, all they will need is an idea of which functions they wish their students to have access to.

C.3 Technical Analysis

C.3.1 Discoverability

Don Norman in *The Design of Everyday Things* has outlined seven fundamental principles of design, all of which must be considered for the Boundless graphing calculator system. The first such principle is discoverability, which he defines to mean "It is possible to determine what actions are possible and the current state of the device" [10, p. 72]. This concept has been considered when creating the tentative user interface for the graphing feature of the calculator, seen below in Figure C.1.

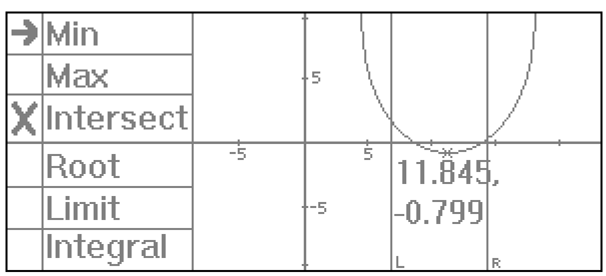

Figure C.1: Graphing screen

The graphing menu makes it very explicit to the user what mathematical functions they can perform for the given graph, and also indicates what functions are not possible for the given graph. In this example, the function intersection feature is not selectable, because only one function is present on the graph. The current state of the calculator is also made apparent: the graphing window covers the whole screen, so the user will understand that they cannot perform matrix calculations or probability analysis on the current screen.

C.3.2 Feedback

Feedback is used to inform the user of any changes or issues with the system. For the Boundless graphing calculator, the prototype model will include the following feedback mechanisms to indicate that it has entered test mode as shown in Figure C.2:

- A unique session code will appear on the UI of the calculator after the user has entered test mode
- A blinking LED to indicate that the calculator is in test mode

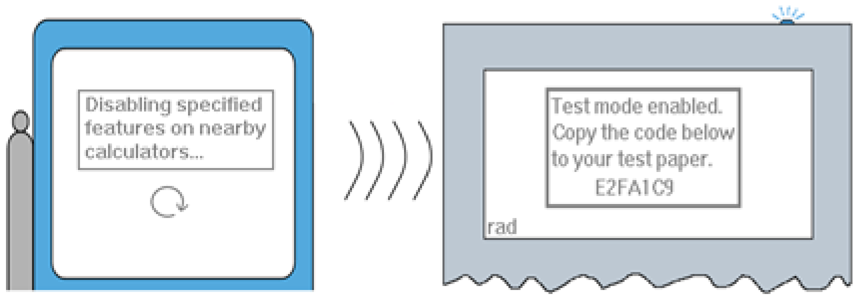

Figure C.2: Calculator in test mode

C.3.3 Conceptual models

Conceptual models are the third fundamental principle of design, because it aids users in understanding the system and gives them a feeling of control [10]. This principle has been considered in the main screen of the user interface in the calculator, where the design is a simple request-response pattern. This gives the user total command over the calculator, which merely interprets the entered request. Users will be able to easily understand this concept, as it is very prevalent when interacting with computers. This request-response pattern can be seen in web searches, computer shells, and digital assistants like Siri, Alexa, and Cortona. In Figure C.3 (the main screen of the calculator), this is emphasized by having a very minimal display. Only a few past queries and responses are shown, in addition to the current prompt. In addition, using a barebones interface makes it easier for the user to draw comparisons to calculators they may have used previously, which all function in a very similar manner.

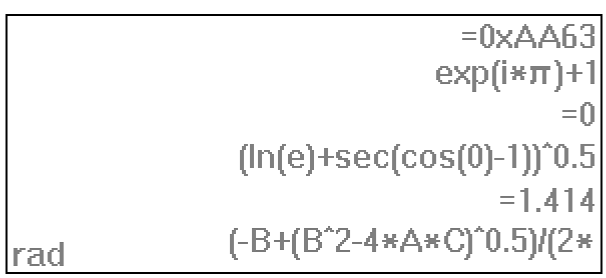

Figure C.3: Primary calculator screen

C.3.4 Affordances

Affordance of a product allows the users to clearly understand how it should be used through its qualities and properties. In BC Instrument's case, the Boundless graphing calculator has labels on all of its 48 buttons and the remote has labels for its 6 buttons to navigate/disable features and select the disable duration. Moreover, the remote controller has an antenna attached to the left to indicate that it's the transmitter to control the Boundless graphing calculator as shown in Figure C.4.

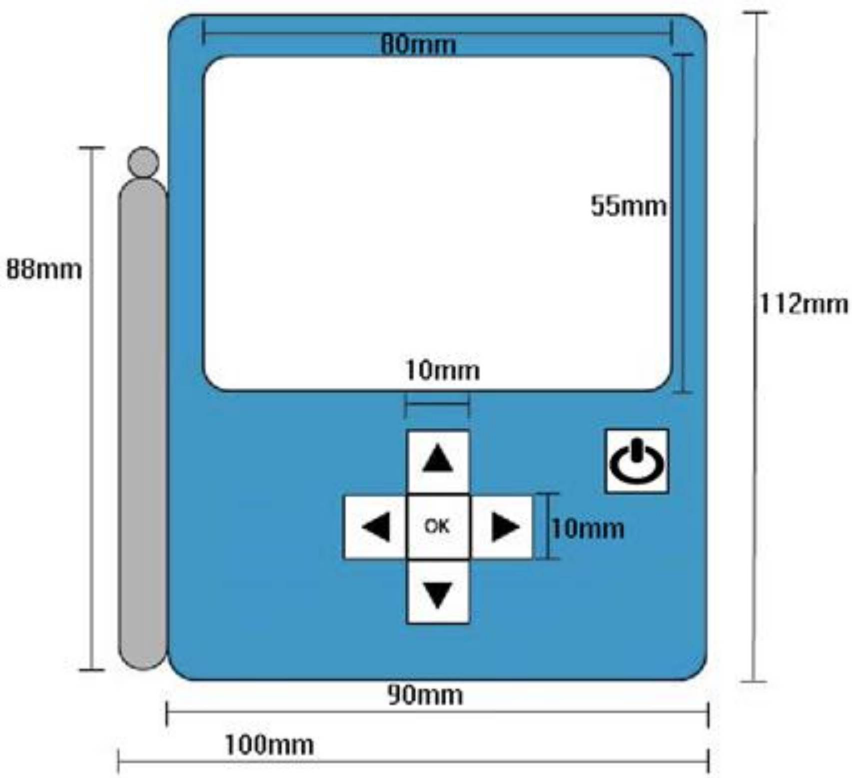

Figure C.4: Administrative remote face

C.3.5 Signifiers

Signifiers are necessary when the perception from the affordances is not enough to notify the users on how to interact with the product's main elements. Therefore, in addition to the LED and the unique code, the calculator will provide a response, "Error: <Operation> is disabled for <the remaining time in test mode>", when the users try to use disabled operations. Furthermore, the remaining time for the test mode duration will be displayed on the top left of the screen and can be chosen to be hidden in the menu. All of this can be seen below, in Figure C.5.

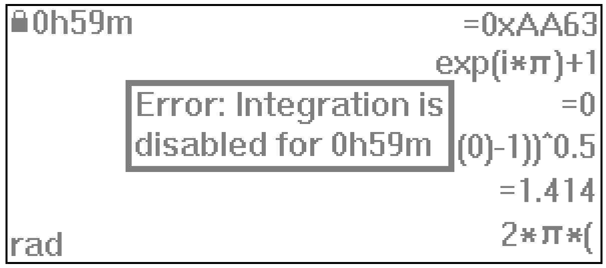

Figure C.5. Error message when accessing disabled functionality

C.3.6 Mappings

A graphing calculator has many more operations than there are buttons. This presents a challenging mapping problem that must be solved to facilitate easy usage of the calculator. The proposed calculator face is shown below, in Figure C.6, and it has several important dimensions listed.

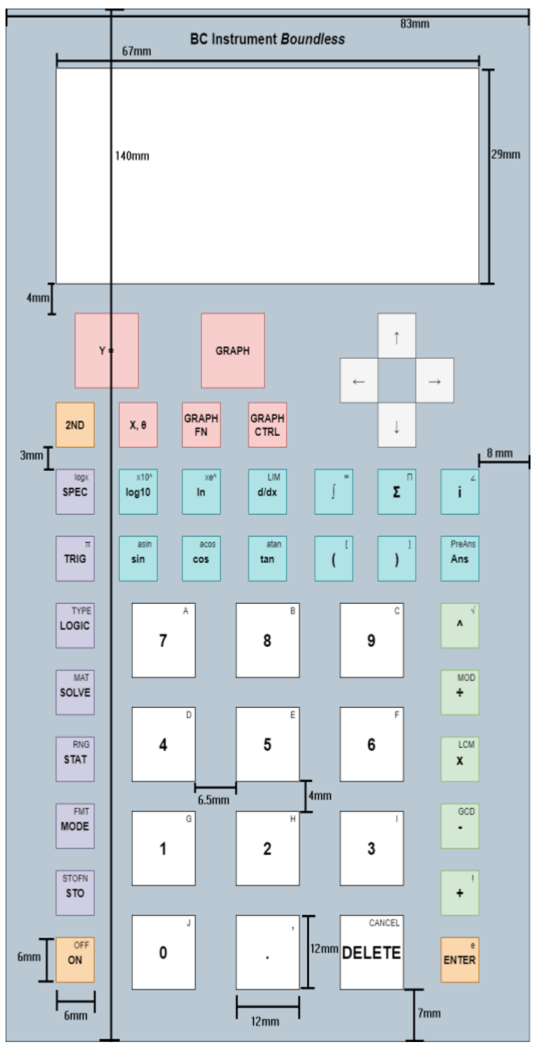

Figure C.6: Calculator face

Mapping with a focus on spatial layout has been considered in this design, with similar features grouped as much as possible. For example, there are specific clusters for the graphing buttons, the numbers, and the trigonometric functions. This concept has also been extended to the secondary functions on each button, which are attached to related buttons whenever possible. This is why division and modulus share a button, and why derivatives and limits share a button. Finally, the use of colour on groups of buttons has also been carefully chosen to show the user the expected action upon the press of a button. This can be seen in the leftmost column, which all share the same button colour. Although the buttons in this column do wildly different things, they all trigger a very similar action: when pressed, a menu opens allowing the user to further choose the operation they want to use.

C.3.7 Constraints

There are four primary types of constraints to be considered: physical, cultural, semantic, and logical [10]. The most obvious example of a physical constraint in the design is the battery slot in the calculator. Because there is only one opening to the calculator, it is obvious where the batteries are to be placed.

Cultural constraints relevant to the design of the system are more subtle. The multiplication operator (when explicitly present instead of implied) can be written in at least three ways: “×”, “*”, and “·”. By the time someone requires a graphing calculator for a math course, “×” is used the least of the three! Nevertheless, in English-speaking countries, “×” is the standard multiplication symbol, so it is used as the button label for multiplication (even if pressing that button draws a “*” to the screen!).

In *The Design of Everyday Things*, Don Norman says that semantic constraints “are those that rely upon the meaning of the situation to control the set of possible actions.” [10, p. 129]. An example of this is all of the functions requiring parenthesis on the calculator. For example, when “acos” is pressed on the calculator “acos(“ appears on the screen. Although someone might not know what an “acos” is, they will still get an idea of what to do: there is an unmatched bracket, so there must be a matching right bracket for it at some point

Logical constraints are the final type of constraint for this last fundamental design principle. Probably the best example of such a constraint can be found on both the remote and the calculator: the arrow keys. By having the up button on top, the bottom button on the bottom, the left button to the left, and the right button on the right, the layout logically explains what can be expected when that button is pressed.

C.4 Engineering Standards

The following engineering standards in Table C.1 are relevant standards that pertain to the proposed user interfaces and appearance of the system.

ICES-003	Limits and methods of measurement to information technology equipment [11]
CAN/CSA-ISO/IEC 9126-1:02 (R2007)	Systems and software quality requirements and evaluation [12]
IEC GUIDE 114:2005	Basics of environmentally conscious design [13]
IEC 62031:2018	Safety specifications for LED modules [14]
RoHS (Directive 2002/95/EC)	Restriction of hazardous materials [15]
IEC 62133-2:2017	Secondary cells and batteries containing alkaline or other non-acid electrolytes [16]

Table C.1: Applicable standards

C.5 Analytical Usability Testing

In the early development phase of a project, empirical usability testing with real users isn't productive, because not all of the features (both software and hardware) are fully developed. As a result, it is difficult to get a holistic evaluation about the usability of the product - the product is not whole! Because of this, analytic usability testing by the design team is useful in the early development phase, as it allows analysis on each subsystem for functionality and usability as they are created one by one.

It is straightforward to conduct analytical usability tests on the hardware of the graphing calculator and the remote, due to the minimal hardware features that are offered. A hardware test procedure (and the accompanying stage of development it is relevant for) is given below.

1. Replace the batteries in both the remote and graphing calculator without unscrewing anything. (Proof-of-concept phase)
2. Replace the RTC battery by unscrewing the unit. (Production phase)
3. Rotate the antenna for the remote. (Proof-of-concept phase)

These tests can be justified by recognizing that they are all operations that users can be expected to perform at some point. Replacing batteries is common for any electronic device, but access to the RTC battery must be restricted, as removing it can potentially allow a student to get around the feature lockout. This should all be in accordance with the relevant standard [16].

Once wireless communication between the remote and the graphing calculator is implemented, some heuristic evaluations can be performed by the developers to identify any potential issues or complaints that may arise from that feature. This can be done by emulating what users will likely do, and can be performed as early as the proof-of-concept phase once that feature is implemented:

1. Choose a variety of related features (such as root finding, integration, and derivatives) on the remote and disable them
2. Observe how long it takes for the features to be disabled
3. Examine how easy it is to confirm that features are disabled by observing the visibility of the LED.

Having functional software on the graphing calculator to facilitate student computations is not really a big selling point - it is an expectation from the users. Although this is not a selling point of the product, a poor software implementation will have a huge negative impact on user experience. First and foremost, a graphing calculator is being developed! An excellent way for the design team to test the software from a user's perspective is to use it. By using the Boundless graphing calculator as the "daily driver" calculator for various classes over a period of several months, the team will get an idea of which features are commonly used. This will allow optimization of the menu layouts.

C.6 Empirical Usability Testing

In the empirical testing stage, BC Instrument will reach out to students and instructors at both the high school and university level, to gauge the usability of the system. The users will be asked to perform a series of simple operations using the Boundless graphing calculator and its remote controller. Any feedback the users provide about their experiences and interactions with the system will be documented. Before the testing begins, a few simple entrance questions will be asked to the volunteer test users to learn about their familiarity with graphing calculators, and their level of mathematical ability. For this type of testing, it will be ideal to have users with differing levels of experience with competing calculators.

The following list summarizes the functional exercises that the user will be asked to perform. These exercises will be administered by a member of the design team, who will take a hands-off approach to these exercises, allowing the user to attempt the task without providing any assistance (unless required). This will allow the design team to observe any potential slips and errors that may happen due to how functionality has been implemented. After each test they will be asked a few specific questions about the task they just completed.

Task 1
Enter the equation tan(3.14)*ln(4+pi)+e^(4/3) and compute the result.

Questions
1. Is it difficult to find where all the mathematical functions were located on the calculator?
2. Do the buttons feel responsive when clicked?
3. Is the font size and clarity of the display sufficient?

Task 2
Find the first root of the equation cos(x)+log10(4*pi*x+10)-e^0.3x

Questions

1. Is it intuitive to navigate through the graph menu in order to compute the first root of the equation?
2. Is the graphing function easy to locate and use?
3. Does it feel responsive when navigating through certain parts of the graph?

Task 3
Use the administrative remote controller to disable all graphing on the calculators.

Questions

1. Is it simple and convenient to find all the features to disable through the remote controller interface?
2. Is it clear that the calculator is in test mode and that graphing is disabled?
3. Is it easy to verify that all the calculators are disabled?
4. Is the blinking LED distracting?

After these tasks are completed, there will be a short exit survey where the tester will be asked if they have any general feedback or suggestions to improve either the calculator or the remote. In addition, if the volunteer has sufficient mathematical ability, they may be asked to try some further tasks interacting with more niche functionality on the calculator (such as polar plotting, logical operations, statistical analysis, custom functions, integrals, derivatives, and finite series, to name a few). These tasks require sufficient and perhaps specialized mathematical knowledge to implement, which is why they are not suitable for asking all participants.

After collecting a sufficient amount of feedback from the above tasks and scenarios, BC Instrument will alter the design and then judge which features can be improved or added to enhance the user experience. The testing will then repeat in an iterative manner, to continually improve the user experience with the Boundless graphing calculator.

C.7 Conclusion

For the graphing calculator unit, the user interface is largely known, and has been developed to promote the seven fundamental principles of design. The quantity of buttons has been determined, and the mapping of features to these buttons has also been decided. However, there is still some flexibility in how some of the menus will be organized and displayed. The specifics of these menus will be developed with ongoing consultation from potential student users, to ensure that more obscure mathematical functions are still easy to locate when needed. In terms of appearance, the calculator unit itself is likely to undergo many minor modifications in terms of dimensions and styles to make it easier to manufacture and assemble, but the style should not significantly change from this point.

The remote is a similar story. The user interface (in terms of buttons) is known, but the menus themselves still need ongoing development, according to feedback from possible instructor users. The appearance and hardware for the remote are more likely to change than the calculator unit, based on trials with different prototypes and the observed range of the wireless transmission.