

# iPhone 13 with USB-C and selective slow-charging — Design Document

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## iPhone 13 with USB-C and selective slow-charging — Design Document

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# Introduction

- Problem & Solution

- Problem

iPhones (and some other mobile Apple devices) have had the Lightning connector for almost a decade. While it has been the dream of many to have an iPhone with a USB-C connector, Apple will very likely not release iPhones with USB-C. This has multiple implications – it hinders the one-charge-for-all plan proposed by the EU to reduce e-waste, and it undermines the adoption of USB-C as a universal interface. The data transfer rate of USB-C can be significantly faster than lightning, and the power delivery of USB-C is also much more capable and universal. Moreover, phone manufacturers have been competing for faster and faster charging speeds. Indeed, fast-charging can lead to an improvement in user experience. However, fast-charging comes at an inevitable and significant cost to battery longevity. The faster we charge our phone batteries, the quicker its lithium cells wear out. To prevent premature battery failure from frequent fast-charging, some phone manufacturers have added an option to charge batteries at an intentionally slow rate (when reasonable, such as when charging your phone overnight). iPhones don't have this feature, but a USB-C iPhone can achieve selective slow-charging.

- Solution

The solution we provide is to modify an iPhone 13-series smartphone. The modification entails removing the lightning cable port inside the iPhone, and adding a lightning-to-USB-C converter with microcontroller which provides slow-charging functionality. And finally modify the iPhone chassis to accommodate all the electronics and to anchor a new USB-C receptacle inside the iPhone. For lightning to USB-C conversion logic, we will extract and use the components from the "C94" circuit on a certified Lightning to USB-C cable, and then, we will replace the lightning port inside iPhone with USB-C receptacle. For the USB-C slow-charging functionality, we are planning to design a USB-C orientation detection logic feature as the trigger of two different charging modes. And with the slow-charging mode, we will use the USB-C Power Delivery 3.0 controller to negotiate a maximum of 5V input from the charger. All these electronics will be housed on a flexible PCB in order to make use of the limited internal space in the iPhone, right below the battery.

- Visual Aid



Figure 1: A teardown view of the iPhone 13 Pro Max.

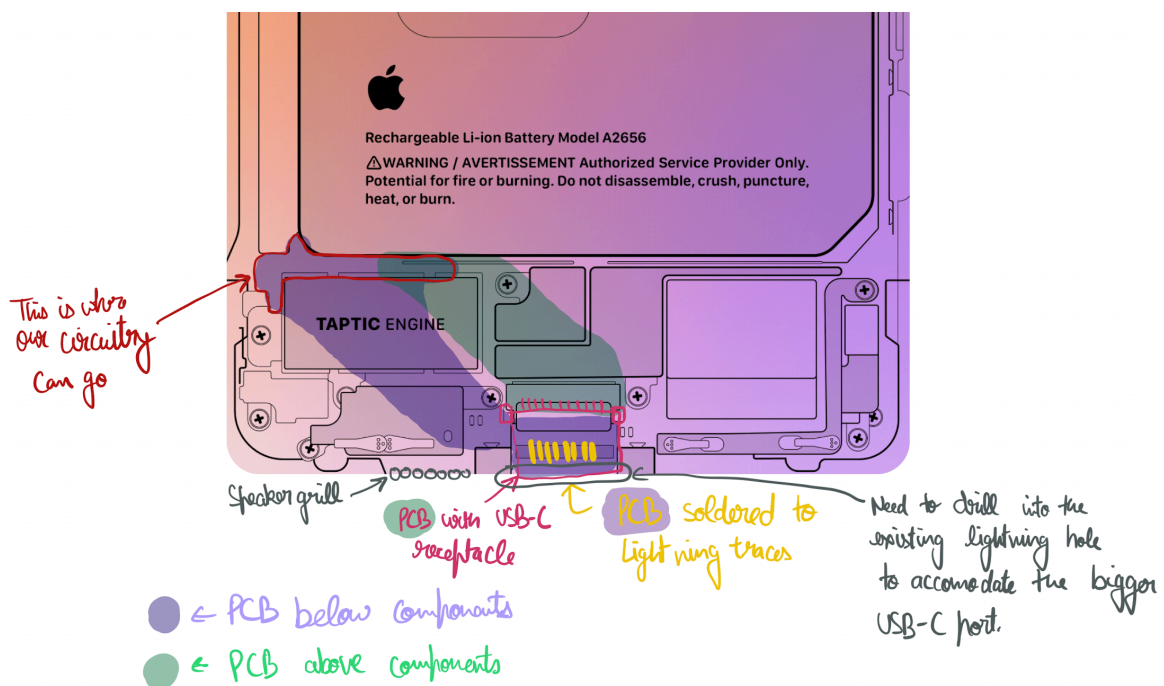


Figure 2: A summary of changes to be made to the iPhone. Source: Adapted from <sup>1</sup>.



## • High-Level Requirements

- The modified iPhone must function as intended, similar to a brand-new iPhone (except for the lack of lightning connection).
- The iPhone must be able to charge at full speed (at least 18W when discharged) and send USB 2.0 data over the USB-C connection.
- The iPhone must negotiate different charging voltages when the USB-C plug's orientation changes.

## Design

### • Block Diagram

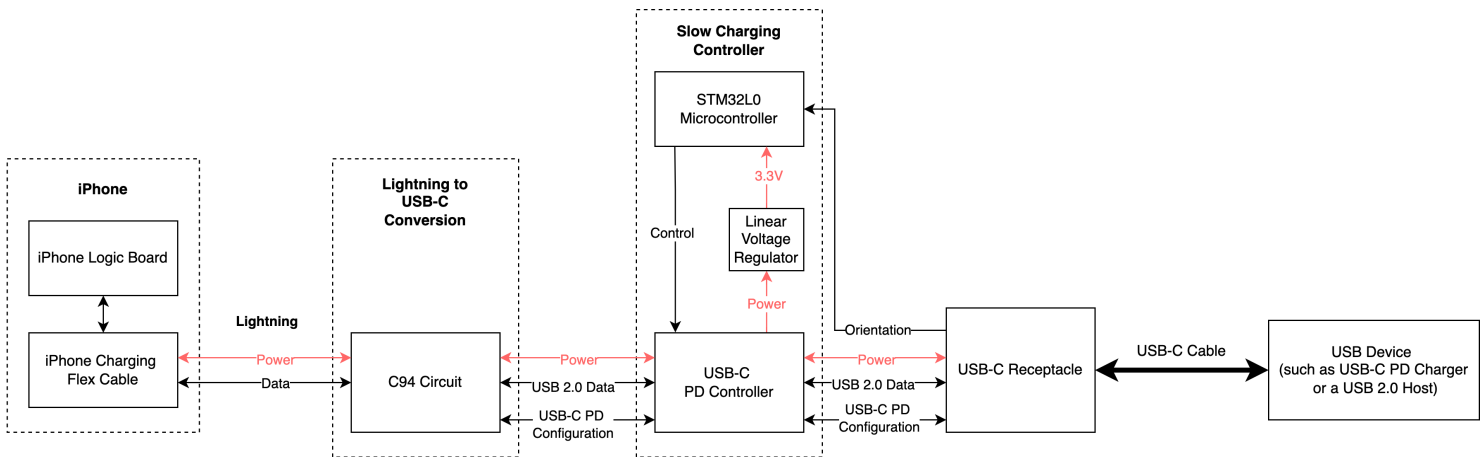


Figure 3: Block Diagram for our project

Note: the connections labelled as "Power" without a voltage specification may carry anywhere between 5V and 12V, depending on the negotiated VBus voltage as per the USB-C Power Delivery specification.

### • Subsystems

#### - Lightning to USB-C Conversion

## Subsystem Overview

This subsystem deals with converting all lightning logic to USB-C. It receives power and data from the slow charging subsystem, and passes it over to the Charging Flex Cable inside the iPhone 13, in its expected lightning protocol.

This subsystem uses the C94 circuit from an Apple-certified Lightning to USB-C cable, which we have to add as a black-box. The components from an existing C94 circuit will be extracted and used on our custom PCB.

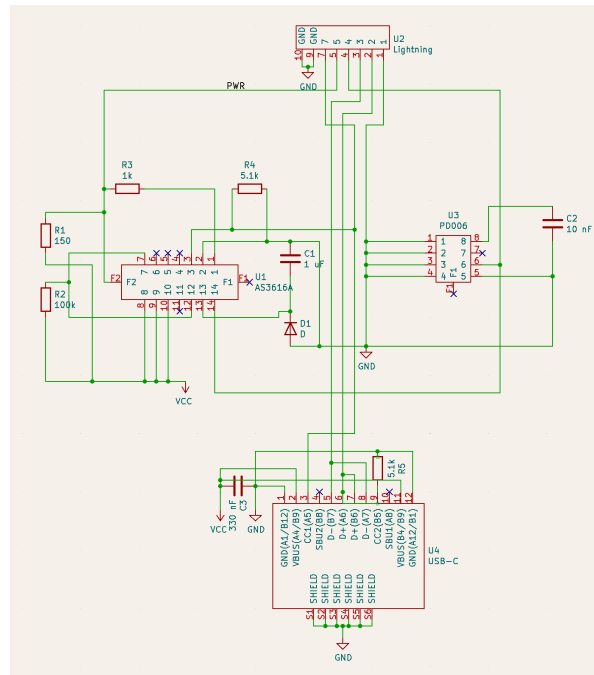


Figure 3: Schematic for the Lightning to USB-C Conversion subsystem, adapted from <sup>2</sup>.

## Subsystem Requirements & Verification

Requirements	Verification
<p>1 The subsystem is able to perform a successful USB-C PD 3.0 negotiation via the CC1 control line, providing <math>9.0V \pm 0.45V</math> to the iPhone at <math>\geq 2.0A</math>.</p>	<p>a. Connect the USB-C power meter to the charger cable on the one side and to the iPhone with another side.</p> <p>b. Measure current and voltage at every second by probing the Vbus line on the lightning connector.</p> <p>c. Terminate test if voltage reads higher than <math>9.45V</math>.</p> <p>d. Ensure all the reads are in the interval of <math>9.0V \pm 0.45V</math> to the iPhone at <math>\geq 2.0A</math>.</p>
<p>2 The subsystem is able to perform USB 2.0 data transfer over the D+ and D- lines at <math>&gt; 100</math> Mbps.</p>	<p>a. Create or download a 5GB video file on the iPhone.</p> <p>b. Send this file to a computer through a USB-C charging cable (with at least USB 2.0 data transfer specification) and measure the transfer speed from the computer.</p> <p>c. Ensure the transfer speed is faster than 100 Mbps.</p> <p>d. Redo the above steps, but this time, transfer the file from the computer to the iPhone with a USB-C charging cable. Ensure the transfer speed is faster than 100 Mbps.</p>
<p>3 The subsystem is able to meet both data and power requirements 1 and 2 simultaneously, while maintaining a temperature <math>\leq 60^{\circ}C</math> with only passive heat dissipation in a closed chassis.</p>	<p>a. Connect a laptop to the iPhone with another side in fast charging orientation, and start a file transfer for a 5GB file.</p> <p>b. Measure the temperature on all ICs at 1 minute interval using a digital thermometer.</p> <p>c. Terminate test when any temperature reads higher than <math>60^{\circ}C</math>.</p> <p>d. Ensure all the reads are under <math>60^{\circ}C</math> with a closed chassis.</p>

- Slow Charging Controller

Subsystem Overview

This subsystem contains all the required circuitry to detect the orientation of the USB-C plug, and to perform a USB-C PD negotiation if necessary. It connects to the USB-C receptacle, and upon successful power negotiation, the incoming power is routed to the Lightning to USB-C Conversion subsystem for charging the iPhone.

We have chosen the STM32L053R8T6 microcontroller and STUSB4500QTR USB-C PD Controller for their low power, small footprint and ease of use.

Subsystem Requirements & Verification

Requirements	Verification
<div>4</div> The orientation detection logic is able to detect the difference in orientation of a standard USB-C to USB-C cable with USB-C PD support, regardless of the cable's USB data specification.	<div>a. Connect the USB-C power meter to the charger cable with fast charging on the one side and to the iPhone with another side</div> <div>b. Measure I and V at every second by probing the Vbus line on the lightning connector.</div> <div>c. Terminate test when any Voltage reads higher than 9.45V.</div> <div>d. With fast charging orientation, ensure all the reads are in the interval of <math>9.0V \pm 0.45V</math> to the iPhone.</div> <div>e. Flipping the charging cable to the slow charging orientation</div> <div>f. Measure I and V at every second by probing the Vbus line on the lightning connector.</div> <div>g. Terminate test when any Voltage reads higher than 5.50V.</div> <div>h. When flipping the charger, ensure all the reads are in the interval of 5.0V, with +0.50V and -0.25V</div>

	tolerance, to the iPhone.
<p>5 The subsystem is able to provide 5.00V, with +0.50V and -0.25V tolerance, to the Lightning to USB-C Conversion subsystem at <math>\geq 1.0A</math>, with one of the USB-C plug orientations.</p>	<p>a. Connect the USB-C power meter to the charger cable in slow charging orientation on the one side and to the iPhone with another side</p> <p>b. Measure I and V at every second by probing the Vbus line on the lightning connector.</p> <p>c. Terminate test when any Voltage reads higher than 5.50V.</p> <p>d. Ensure all the reads are in the interval of 5.0V, with +0.50V and -0.25V tolerance, to the iPhone.</p>
<p>6 The components of this subsystem maintain a temperature under <math>60^{\circ}C</math> with only passive heat dissipation in a closed chassis.</p>	<p>a. Connect a USB-C charger to the iPhone with another side in fast charging orientation.</p> <p>b. Measure the temperature on all ICs at 1 minute interval using a digital thermometer.</p> <p>c. Terminate test when any temperature reads higher than <math>60^{\circ}C</math>.</p> <p>d. Ensure all the reads are under <math>60^{\circ}C</math> with a closed chassis.</p>

## • Tolerance Analysis

For requirement 1, we specify a 9.00V charging voltage with a  $\pm 0.45V$  tolerance. We also specify  $\geq 2.0A$  charging current. This is based on ChargerLab's experiments on the iPhone 13 Pro Max. A summary of their findings is provided below:

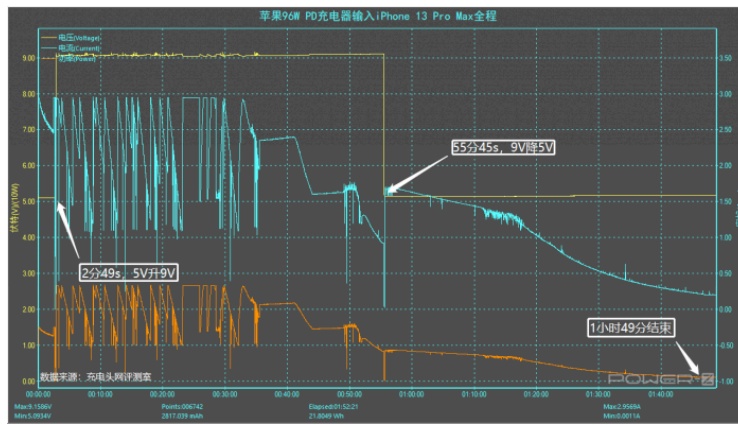


Figure 4: The charging voltage and current on an iPhone 13 Pro Max over time. Source: ChargerLab 3.

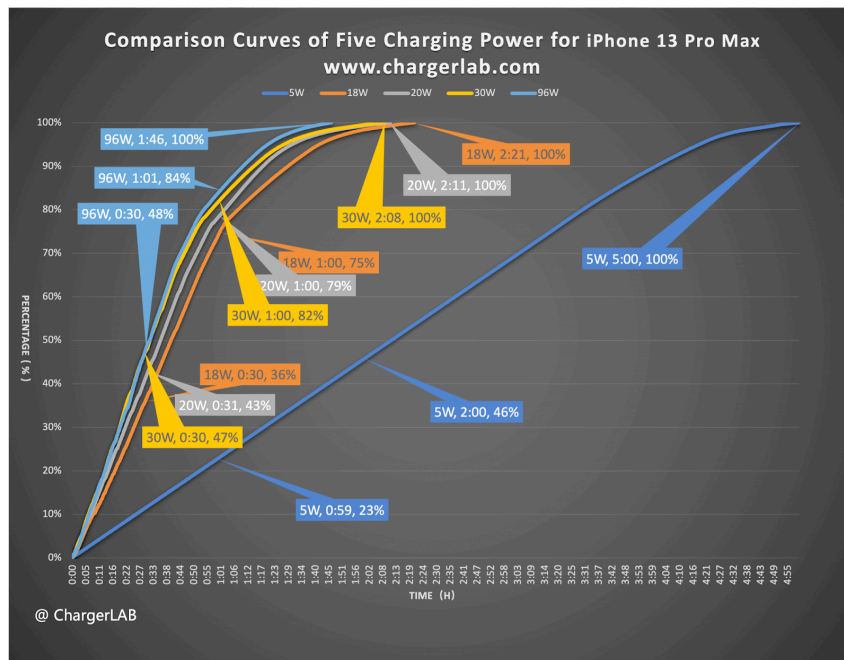


Figure 5: A comparison of charging speeds on an iPhone 13 Pro Max using different chargers. Since the charging speed is approximately the same from using any charger at or above 18W, we stick to a 9.0V, 2.0A requirement. Source: ChargerLab 3.

The  $\pm 0.45V$  is taken from 4.

For requirement 2, the  $+0.50V$  and  $-0.25V$  tolerance is taken from 4.

For requirement 3 , we expect to see full USB 2.0 ("Hi-Speed USB") speeds over the data lines. However, Hi-Speed USB only promises "upto 480Mbps" of theoretical data transfer. Taking into consideration the effects of protocol overhead and non-ideal nature of the real-world interconnects, we had to come up with a more conservative yet realistic data transfer speed requirement. Additionally, USB 2.0 does not have an easy way of measuring transfer speed at the link layer, which is why we will be using the application layer (i.e. file transfer) speeds to measure performance. Hence, we came up with the  $\geq 100$  Mbps requirement. Note that this conservative requirement is well beyond the 12 Mbps theoretical maximum speed of the USB 1.1.

## Cost and Schedule

- Cost Analysis

- Labor Costs

	Hourly Rate	Hours Worked	Labor Cost	Labor Cost $\times$ 2.5
1 member	\$30	196	\$5880	\$14700
Team (3 members)				\$44100

- Bill of Materials

Part #	Manufacturer	Quantity	Unit Cost	Total Cost
UJ31-CH-G-SMT-TR-67 USB-C Receptacle	CUI Devices	5	\$3.92	\$19.60
C94 Lightning Connector	Yitaiwei Ltd	10	\$1.35	\$13.50
STM32L053R8T6 Microcontrollers	STMicroelectronics	1	\$6.22	\$6.22
TST001 USB Tester/Meter	Pimoroni Ltd	1	\$10.40	\$10.40
STUSB4500QTR USB Controller	STMicroelectronics	5	\$2.60	\$13.00
Total				\$62.72

## - Grand Total

Section	Total
Labor	\$44100.00
Materials	\$62.72
<b>Grand Total</b>	<b>\$44162.72</b>

## Schedule

### - Week of 2/21

- Complete design document – All
- Prepare for design review – All
- Order parts from Digikey – Shreyas
- Order iPhone 13 – Shreyas

### - Week of 2/28

- Desolder all necessary components from C94 – Xinpei, Houji
- Reverse engineer C94 schematic – Xinpei, Houji
- Research and design the slow charging schematic – Shreyas

### - Week of 3/7

- Design prototype PCB – Xinpei, Houji
- Order prototype PCB – Shreyas
- Finalize the slow charging schematic – Shreyas

### - Week of 3/14

- Spring Break



## - Week of 3/21

- Test out prototype PCB – Xinpei and Houji
- Iterate on schematic to add slow charging – Shreyas
- Measure iPhone dimensions and design flexible PCB – Shreyas and Xinpei
- Try out a paper version of the flexible PCB – Houji
- Order flexible PCB – All

## - Week of 3/28

- Research about any remaining parts we need – Houji
- Second round ordering parts from Digikey – Houji
- Unit test the subsystems – All

## - Week of 4/4

- Design anchor for USB-C receptacle inside the iPhone – Shreyas and Houji
- Fabricate this anchor – Shreyas and Houji
- Redesign port on the iPhone chassis – Xinpei
- Build a chassis to hold the iPhone in the CNC machine / vice – Xinpei
- Place order with the ECE Machine Shop – Xinpei

## - Week of 4/11

- Test on individual components – All
- Assemble everything – All

## - Week of 4/18

- Mock demo – All
- Final test the product as a whole – All

## - Week of 4/25

- Ensure functionality – All
- Fix remaining issues – All
- Prepare demonstration – All
- Prepare final presentation – All

## - Week of 5/2

- Final Presentation – All
- Complete final paper – All

# Ethics and Safety

There can potentially be some electrical and heat hazards with our project since we're going to modify the charging logic inside the phone by adding our own designs. Our team will strive to ensure that we follow the IEEE Code of Ethics<sup>5</sup> throughout our project, and make sure the safety, health, and welfare of the device's user are held paramount. This, it is important for us to frequently inspect and test our device, to always be prepared to accept honest criticism of our work, and to acknowledge and correct errors, as stated in #5 of the IEEE Code of Ethics<sup>5</sup>.

Since there already exists an open source project that has demonstrated the Lightning to USB-C conversion logic on an iPhone X, we will be using it as a reference when doing similar parts in our project. We shall make sure to cite the source properly to not violate #5 of IEEE Code of Ethics<sup>5</sup> — "... to properly credit the contributions of others."

Another source of concern could be about personal privacy, since we will be modifying the USB 2.0 data channel on the iPhone. However, we can ensure that our design would not bring any new risk of privacy breaches because we will use the components from the C94 circuit on a certified Lightning to USB-C cable. Thus #1 of the IEEE Code of Ethics<sup>5</sup> is upheld.

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1. "iPhone 13 Pro Schematic Wallpapers," *Basic Apple Guy*, 19-Dec-2021. [Online]. Available: <https://basicappleguy.com/basicappleblog/iphone-13-pro-schematic>. [Accessed: 24-Feb-2022]. ↩

2. K. Pillonel, "KENP-IO/not-for-iphone-USB-C," *GitHub*. [Online]. Available: <https://github.com/kenp-io/not-for-iphone-usb-c>. [Accessed: 24-Feb-2022]. ↩

3. "Up to 27W: Charging compatibility test of apple iphone 13 pro max (20W-100W)," *Chargerlab*, 21-Oct-2021. [Online]. Available: <https://www.chargerlab.com/up-to-27w-charging-compatibility-test-of-apple-iphone-13-pro-max-20w-100w/>. [Accessed: 24-Feb-2022]. ↩ ↩

4. USB Implementers Forum, "Universal Serial Bus Power Delivery Specification." [Online]. Available: <https://www.usb.org/document-library/usb-power-delivery>. [Accessed: 24-Feb-2022]. ↩ ↩

5. "IEEE code of Ethics," *IEEE*. [Online]. Available: <https://www.ieee.org/about/corporate/governance/p7-8.html>. [Accessed: 24-Feb-2022]. ↩ ↩ ↩ ↩