Hardware Wallet Power Architecture SPADE

Setting

The hardware wallet we're building will need a power source in order to store funds and enable customers to access them. We've decided on wireless NFC as a communication standard intended for mobile smartphone interactions for easier use, which means we won't naturally have a tethered connection to a computer for power. We aim to target a level of functionality and consistency that prohibits relying exclusively on the power that can be harvested from the NFC field during signing, as some simpler RFID tag type devices do. In order to take advantage of the flexible, untethered experience offered by NFC, we think it is important to design out any dependence on a hard connection to another computer for the wallet hardware to work. This leaves us with a hard requirement for an on-device, self contained power source, most likely a replaceable or rechargeable battery.

We're designing the wallet using a technology called multisignature to enable a variety of use patterns, and we imagine that most people will keep our hardware in a safe place and avoid keeping it with them for the majority of its life, but it's challenging to predict the full range of use patterns in advance. With that in mind, we're trying to optimize for several different requirements all at once, including (broadly) Function, Product Experience, and Cost.

Function - The design needs to be able to meet the power requirements of the wallet hardware completely, predictably, and throughout its lifespan. This means supporting the range of features and functions of the hardware, including authentication with the wallet's owner, generating, storing, accessing, and signing with private keys, sending and receiving information with a paired smartphone, and communicating its status and activity visually to the wallet's owner.

- Reliability and Safety - While the wallet hardware might spend most of its life stored in a safe place, it also needs to reliably survive the stresses and shocks that come with its occasional use and transport. It's important to select a power solution that allows the device to be resilient to being dropped, sat on, kept in a hot car, or exposed to the grit or moisture in a pocket or a backpack.
- Current and Voltage - Power requirements of the processor and related components need to be met, including peak and continuous current at the appropriate voltage. While there is some variability here depending on complexity and feature richness, this is mostly a binary go/no-go criteria.

- Longevity - The wallet hardware is only one part of the multisig system protecting its owners money, but one that we expect to be in use for years. While the multisig system we're designing can reliably recover from hardware failures, device replacement is an inconvenience we want to minimize by ensuring a sufficient device lifespan.

Product Experience - We need the product not just to work, but to work **well**. This means being comfortable, convenient, and easy to understand, among many other variables. Some specific facets of the experience we're thinking about impacted by this decision:

- Industrial Design - The size, weight, and overall feel of the hardware is a qualitative metric, but an important one. Including external access for recharge or battery doors for battery replacement can constrain design space. A smaller, lighter power solution gives more flexibility to the design of the hardware.

- Frequency of battery replacement / recharge - Any onboard power source is going to need replenishment in the form of a swap of a dead battery or a recharge of an onboard one, and a design that allows this to happen less often will be a better one.

- Complexity (Hassle) of battery replacement / recharge - Replaceable batteries mean the wallet's owner sometimes needs to figure out what kind of battery needs replacing, keep some on hand or find out where/how to purchase it, and how to remove the old one from the device and replace it. On board rechargeable batteries mean the wallet's owner needs to make sure they have the appropriate cable or accessory handy, or find it if they don't, and find an available power plug and wait out sufficient recharge times. Any solution we implement will have tradeoffs, and so our goal should be to consider and minimize the 'hassle' of power maintenance.

Costs - To create a device that makes self custody accessible for a global audience, we need to be conscious of the all in costs for our wallet. The power architecture can impact these in a few different ways:

- Manufacturing/BOM costs - The cost of raw materials going into the device. This includes not just the power source, but all the supporting components needed to integrate it, and any in-box hardware that needs to be included for a first time setup.

- Maintenance and support costs - The costs incurred from ongoing maintenance, including replacement batteries, replacing lost accessories, or even the cost of power to recharge the device itself.

People

This decision affects most aspects of the project, from the industrial design of the hardware, the engineering requirements to incorporate, manufacture, and test, as well as the assumptions built into the accompanying software, and so requires involvement from the entire hardware wallet team. Additionally as part of our mission to design in the open we're looking to share our thought processes with the community, both to solicit feedback and to build understanding of the product we're building.

- Responsible: Wallet Lead
- Approver: Hardware Lead
- Consulted:
  - Wallet Team: Product, Industrial Design, Product Design, Mechanical Engineering, Electrical Engineering, Embedded Software, Manufacturing Test Engineering, Engineering Program Mgmt, Software Lead
  - Hardware Team
  - Input via internal company slack and external channels including Twitter

Alternatives

Once defining our criteria for function, user experience, and cost and considering several strategies we dug deep on three of the most straightforward implementation options:

1. Coin Cell - A single coin cell battery with a battery door on the back of the enclosure. Data in the table below is based on using a CR2450, which we chose as an example for its electrical properties and relative commonality.
2. Rechargeable LiPo - A custom LiPo pack with USB-C charging port. Would possibly include a USB-C charging cable and regionalized power brick.
3. Alkaline AAA - A single AAA battery with a battery door on the back of the enclosure.

The table below compares performance to our criteria across these three concepts and highlights areas of concern or risk. No one option is perfect so we need to weigh each criteria against our goals for the overall product experience in order to make a decision.

Note: many of the values listed below come from publicly available datasheets for specific battery options. These values can vary across different manufacturers, and especially with respect to load temperature, and usage patterns. They are best understood as approximations.

		Coin Cell	Rechargeable LiPo	Alkaline AAA
Implementation Summary		Single CR2450 with battery door on back of enclosure for replacement	Custom LiPo pack with USB-C charging port. Includes possible USB-C cable and regionalized charging brick.	Single AAA battery with battery door on back of enclosure for replacement
Minimum Product Thickness		• ~8mm	• Customizable pack design possible, in general LiPo is less energy dense than coin cells by volume, but more energy dense than alkaline	• ~14.5mm
Nominal Capacity		• ~610mAh (dependent on load) @ 3.0V nominal	• Customizable pack design possible	• ~1000mAh (dependent on load) @ 1.5V nominal
Shelf Life		• 5~10 years	• 3~5 years (*see shelf life section below table)	• 5~10 years
Years between recharge or replacement (Estimated based on early power models)	Low Use (use: once per month)	• 4~5 years	• 1.5~2 years	• 4~5 years
	Medium Use (use: twice per week)	• 2~3 years	•1~1.5 years	• 2~3 years
	High Use (use: twice per day)	• 0.5~1 year	• 0.5~1 year	• 0.5~1 year
Reliability and Safety		• Low weight and many examples of reliable coin cell carrier design • Bayonet style coin cell door easily lends itself to o-ring waterproof sealing	• Connector port increases reliability risk over designs with no connector • Waterproofed port possible but more costly	• Long term storage battery corrosion risk • Increased mass adds risk in drop testing • Waterproof sealing strategy for battery door can be challenging
Replacement Availability		• Coin cells unlikely to have readily on hand and sometimes challenging to find for purchase	• Charging cable and adapter is more commonly on hand than consumable battery supply, especially for users of mobile phones with the same standard. • Can quickly charge for immediate use or use while wired (power path charger)	• AAA more likely to have on hand than Coin Cell
In-Box Considerations		• none	• Posible USB-C charging cable and regionalized charging brick	• none
System Cost		• Additional EE components to enable a workable solution, coin cell, battery carrier, waterproof battery door	• LiPo pack, USB-C connector, possible in box USB-C cable and power brick	• AAA, battery carrier, waterproof battery door
Max Continuous Current (minimum 100mA preferred)		• 3mA • Not sufficient to support EE architecture, would require a work around	• Customizable pack design possible	• Unspecified (likely 500mA+)
Max Pulse Current (1s) (minimum 100mA preferred)		• 50mA	• Customizable pack design possible	• Unspecified (likely 500mA+)
Nominal Cell Voltage (Open Circuit) (minimum 1.5V preferred)		• 3.0V	• 4.2V (may reduce to support greater battery longevity)	• 1.5V
Minimum Cell Voltage (closed circuit) (minimum 0.95V preferred)		• 2.0V	• 2.9V	• 0.8V
Nominal Cell Impedance (at		• 10Ω	• Varies (likely < 500mΩ)	• 150mΩ

25°C) (maximum 0.5Ω preferred)	• Not sufficient to support EE architecture, would require a work around		
Max Cell Impedance (at 25°C) (maximum 1Ω preferred)	• 20Ω+	• Varies (likely < 1Ω)	• 300mΩ
Evaluation Summary	Coin Cell battery enables a smaller ID and has good reliability characteristics but capabilities are challenged to support EE architecture. Additional circuitry required to avoid brownout scenarios will add to complexity and cost.	A rechargeable system with a custom pack enables a more efficient EE architecture but comes with additional cost, reliability risks, and potentially a shorter device lifespan.	Alkaline AAA implementation would likely support the EE architecture well, but comes at the cost of a thicker, larger, and heavier product with reliability risks.

L	Best / Low • Expected to meet target with no anticipated risks	MH	Good / Med-High • Potentially high risk to meet target with alternatives identified but requiring further investigation
M	Better / Medium • Unlikely or minor risks identified to meet target	H	Blocker / High • Does not meet target or is high risk without alternatives identified

Criteria and Color-Coding

Recharge / Replacement 'Hassle'

Not completely captured in the above table are some qualitative callouts worth keeping in mind when evaluating a whole solution.

- Coin cell - The pain points here come from being the least familiar power technology under consideration, as well as a battery type that comes in a wider variety of standards and specs that make the replacement process potentially confusing or frustrating. The proposed CR2450 cell type is one example, but there are many more. We expect a risk in shopping for, locating and installing may lead to purchases of the 'wrong' type of battery, replacement with battery chemistry our wallet design is not intended to support, or potentially wallet owners giving up on the use of the product in general.

- Rechargeable LiPo - The pain points with this solution stem mostly from dependence on an accessory which the wallet owner will need to have available, as well as requiring proximity to and time spent connected to a power outlet. A connector that seems relatively common today like USBc won't be common for everyone, especially as technology changes over the span of the device's lifetime. Even if it does remain prevalent as a connector standard, it still adds some mental overhead to maintaining the wallet hardware, especially if its storage location isn't in convenient range of an outlet / near other devices that regularly need recharging (like the phone used to interact with the wallet).

- Replaceable AAA - A globally common battery type, and less prone to confusion or availability challenges than a coin cell, but still one which requires a special purchase to replace, or keeping a stock of slowly aging batteries on hand for replacements. Additionally, such alkaline cells are prone to battery leaks / corrosion when kept in use or stored in a device over a number of years, leading to clean-up, possible device damage, and confusion and mistrust about continued safe operation.

Minimum Product Thickness and Industrial Design

"Minimum Product Thickness" is our most quantitative way to convey something that can be quite subjective - impact on industrial design. From the little white reader all the way to the all aluminum Square register, Block as a company has always prided itself on delivering products that are not just functional and simple to use, but also beautiful in form and something that sellers can be proud of. We're confident that the technical merits of the hardware wallet will appeal to many, and we want to give it a form that matches and accentuates its technical prowess. The components we pick have a big impact on how we can execute on the wallet's design, and the power story has the largest effect on how we can execute here. Thickness is not everything when it comes to design, but Z stack ends up mattering a lot when the engineering team gets down to trying to realize our industrial design visions. Just like our sellers appreciate the design of their Square products, we want Block's hardware wallet to be something that our future customers are proud to own and use.

Reliability and Safety

Our seller products see some of the harshest environments consumer electronics products are subjected to. Designing products that can survive those conditions for as long as possible takes a lot of upfront planning, testing, and iteration. When designing a new product like the hardware wallet, making smart decisions around reliability early pays dividends on the backend of product development. While we don't think we'd be putting ourselves at a significant disadvantage with any of our power choices, we think some options are likely to be inherently more reliable than others. For example, external connectors require a lot of consideration when it comes to reliability, as they can fail in more ways than one, and when they do, customers typically have to return their device. On the other hand, battery doors can introduce failure modes of their own, whether they be mechanical or ingress related. Since we know some choices may require more work for us to meet our high expectations for reliability, we want to make sure we factor this into our decision.

On the topic of safety, we test our products extensively to make sure that our products not only are reliable, but also safe for our customers to use. Out of the power choices here, lithium polymer batteries require a bit of special consideration around their design, both mechanically and electrically. It's something we're no stranger to, but we felt worth calling out for the purposes of this comparison.

Years Between Recharge / Replacement
What is a 'use'? - As we roughly define it here for estimating power use, a single instance of a wallet owner waking their device, authenticating with it, tapping to receive transaction data from a paired smartphone via NFC, signing the relevant transaction and passing it back, with a bit of idle time on either side. It's worth noting that users shouldn't require the wallet hardware for every transaction, as wallet owners may end up choosing to rely on only their Mobile Key + Backend key to make small, spontaneous transactions. Use patterns are likely to vary, but we're reasonably confident that up until we see much higher use frequency, battery drain remains relatively modest, and on order of passive discharge any battery experiences even in idle storage.

Max Current, Cell Internal Resistance, and Shelf Life
In the table above, several electrical parameters have been assigned color-coded ratings based on a preferred value. These values were obtained from early power modeling of the electrical system. The product and engineering team members first worked to define device states based on features and use cases. Typical and worst case current consumption numbers for each of the key consumers in the system (microcontroller, NFC front-end, power supplies, etc.) were then pulled from their respective datasheets and adjusted to account for voltage level and expected efficiency of the switching power supplies. While this modeling is not a substitute for measurements of real devices, it is extremely important for determining electrical requirements for batteries. In cases where the expected current consumption exceeds the max continuous discharge specs for extended periods, we have assigned a higher risk rating as extra design complexity is required to manage this scenario. Max current values are closely related to cell internal resistance, which limits the max current that can reliably be drawn from a cell without substantial voltage drop – this is important for us to consider as getting this wrong can result in 'brownouts' under certain conditions, which may manifest to customers as a reboot loop or other inscrutable failures. The power modeling also factored in expected shelf-life and self-discharge characteristics of each option, allowing the team to approximate expected battery replacement intervals.

Regarding shelf-life of rechargeable lithium batteries, self-discharge is much higher than it is for the other chemistries shown. Left untouched, a rechargeable battery will deplete on its own, and can eventually deplete to levels where it is unable to be recharged or used. This can be prevented by periodic charging, and is not representative of how long a product with such a battery would last. How long it will last is dependent on factors such as system design, peak charging voltage, cycle count, and environmental conditions (e.g. temperature). The number of battery cycles is expected to be low in most use cases, so a rechargeable battery will likely last longer than the quoted shelf-life spec, provided it is treated with care.

Why not consider multiple batteries?

Aside from the options presented above, we considered hybrid solutions containing multiple types of batteries (rechargeable and coin cell, for example), as well as multiple coin cells (series or parallel configurations). While the hybrid solutions appear to offer a way to workaround non-ideal characteristics of each battery, they cannot be guaranteed to have both batteries charged at all times, and therefore have similar constraints to the options above while adding more cost and complexity to the product. As for multiple coin cells in series or parallel configurations, there are certain benefits to each approach, but they also introduce additional complications. A parallel configuration will divide the internal resistance but is subject to back-charging if the cells are unbalanced or a short-circuit if accidentally installed with opposing polarities. Extra protection is required to mitigate this, such as an ideal 'diode-or' circuit. Additional parts add increased BOM cost and supply-chain risk, especially given the industry-wide IC shortage. A series configuration will offer a higher voltage and therefore reduced current for the system's switching supplies, but will also double the internal resistance, leading to similar voltage drop at half the current. While this drop is more tolerable at a higher voltage, transients in the system need to be carefully managed (PSRR of power supplies). Additionally, the higher nominal voltage from two cells in series exceeds the input range (5.5V max) of some of the most attractive, low-power switching supply options. These supplies are critical for managing reducing quiescent current and increasing time between replacement. In both configurations, unbalanced cells may reduce performance to that of one cell at best, and in some cases cause additional problems (such as higher internal resistance than a single cell). This increases the number of corner-cases that need to be managed and can contribute to confusion for the end customer.

Decide

After considering the above and collecting public feedback, we've decided to move forward with a design using **a built in Lithium Polymer (LiPo) rechargeable battery pack** and to depend on a **USB-C port** to supply power to recharge / use. We plan to rely on the port exclusively for power, and not to enable data transfer.

Explain

We anchored this decision on customer experience. In practice, a rechargeable battery option minimizes customer hassle and allows us to design the device to look and feel like the future of money.

The sections below detail how we narrowed down our list of options, why we believe this choice best minimizes hassle, and how we're thinking about the tradeoffs that come with including a LiPo battery and USB-C port.

First, why use a battery at all?

Part of our approach involves hardware elements that will help ensure the product is simple to use for anyone, regardless of experience. We want these elements to function even when the device isn't plugged in or positioned to draw power from the phone's NFC field, so we need a battery. We'll cover what we have in mind here and why in an upcoming newsletter.

Second, why not a Coin Cell?

We concluded that the benefits of using a coin cell are outweighed by several disadvantages.

On one hand, a single, replaceable coin cell is a compelling option from several key vantage points. Coin cells are energy dense, and thus compact. They're simple to mount in many of our preferred design concepts, and they rarely encounter problems in the field like the corrosion seen in depleted alkaline cells.

On the other hand, we worry about customer experience issues and technical risk that might arise in practice.

Replacement availability may vary significantly across regions - coin cells are not as ubiquitous as other battery types. Additionally, the replacement experience may be confusing, as customers would be forced to work with unfamiliar sizes and model numbers and could end up replacing with an inexact match that could result in poor performance or even damage the wallet's electrical system.

Moreover, the electrical system design required would add technical risk and result in degradation of customer experience. Even the largest of the coin cells we have considered (CR2450) has high internal resistance and consequently lower load bearing capabilities. While the system could be designed to compensate for this through the use of components like supercapacitors or by supplementing available power with energy harvested from the NFC field, there are pitfalls with both approaches. Even if optimized for the product as currently envisioned, there would be little room for product enhancements (e.g. through firmware update) that might come with marginally higher power consumption. Friendly features such as timeout periods for authentication would need to be whittled down. Without design margin, it would also be nearly impossible to ensure adequate performance across the range of coin cells customers purchase as replacements, thereby exposing customers to potential coin cell quality issues.

Third, why LiPo over AAA?

After narrowing to the two most plausible alternatives, our decision ultimately hinged on customer experience.

We started by asking what customers do when the hardware fails. We know that any device has failure modes, and we're building an inclusive product that lives in context of other devices people use in their lives, not designing the wallet to be operated inside of a volcano. We need to expect that some devices will fail at some point - and we'll solve for this at a system level by providing a recovery solution that keeps customer funds safe even when the wallet hardware is broken or lost (we'll detail how that works in a future post).

With this approach to recovery in mind, for this decision we focused on the customer experience during the wallet's lifespan, rather than trying to estimate the exact frequency of field failures that could lead customers to need to interact with the recovery process. That is, rather than comparing the number of expected field failures of USB-C connectors and AAA battery doors, we looked closely at how wallet owners are impacted by issues during the wallet's normal operation for these two battery options.

We think many customers will pull their wallet out of a drawer after years of non-use, because the 2-of-3 multisignature design we are using will allow customers to safely use only their phone for more frequent transfers. In this setting, with a rechargeable battery, the wallet will either work immediately, or will work when plugged in even if the battery is depleted or degraded. We believe this is a better experience than removing corroded AAA batteries, scraping the terminals, buying new batteries, and then hoping the corrosion didn't render the wallet inoperable. As mentioned earlier in the coin cell comparison, we also believe it's better than trying to power on your device and realizing the battery is depleted and having to track down a store who has the exact coin cell battery required.

We considered that with a rechargeable battery, customers will depend on a power source and a USB-C cable when the battery is depleted. However, customers will only need to charge occasionally, as a result of the battery capacity and the multisignature design that means the device will likely only be used for infrequent, larger transactions. Additionally, many customers will already have a cable from other devices or accessories that require much more frequent charging, like the mobile phone the wallet is intended to pair with.

Despite these benefits, we understand no battery decision is perfect. Including a LiPo battery and USB-C connector comes with several limitations when compared with the AAA option. However, for each of these limitations, we saw mitigating factors that ultimately meant these did not overshadow the customer experience benefits of a rechargeable option:

- Hardware failures: USB connectors can fail and LiPo batteries can degrade over time. These failure modes are typically exacerbated by frequent use, but for this wallet, many customers may only go through a handful of plug/unplug and deplete/charge cycles.
- Cost: the rechargeable option requires additional components - a USB-C connector, supporting charging components on the board, and the LiPo battery itself - all of which add cost. However, this cost comes with the flexibility to operate the wallet plugged in even when the battery is depleted. And the AAA option isn't free, either – wallet owners would be responsible for the likely recurring cost of a pack of replacement AAA's, of which only one or two end up getting used to power the wallet over time.
- Charging cables: the rechargeable option requires a plug and cable, which could lead to more items in the box we ship the wallet in, more up front cost, or both. As noted above, many customers will already have what they need, which may allow us to avoid added complexity or cost.

With all of the above in mind, we think that a rechargeable battery will ensure a seamless experience for most people most of the time.

Finally, what's next?

As we move forward with the rechargeable battery option, we'll have at least the following primary design considerations and risks in mind:

USB-C Prevalence: Even though our product will work regardless of what connectors new smartphones are built with in a few years, our decision does bet on the ubiquity of USB-C usage in devices our customers already own. We need to ensure customers are set up for success when they use our product for the first time and that they have the accessories they need to preserve the product over the long term. We have more consideration to do here as we think about the global markets we'll serve, what should be on the other end of a USB-C cable and how trends in hardware usage vary between them.

Battery Lifetime: At some point in the wallet lifetime, LiPo battery aging will result in a degraded experience. The wallet will still work when plugged in even if the LiPo battery is no longer operable, but we'd still like to ensure the longest battery lifespan we can. We'll evaluate how limiting the charging speed, limiting the percentage charge the battery gets to, and other electrical properties can help us here.

Encore: Why not an alternative power mechanism?

We received a few other interesting ideas from the community, but we eventually ruled them out after careful exploration:

- **Wireless charging** - While it would feel natural for an NFC focused device to be able to charge wirelessly, we eventually ruled this one out for cost and compatibility risks. Qi and other wireless charging technologies don't yet have wide adoption outside of the most premium phones and accessories, and so there isn't a good install base to rely on for chargers people already have, like with USB-C, nor an obvious trend towards ubiquity. We want to avoid packaging a (relatively expensive) accessory, cable, and power adapter with each unit, and dependence on one single custom charger that can be easy to misplace doesn't feel good either.

- **Solar Charging -** Even under very high indoor luminous intensities (e.g 1000 lux) a solar cell sized for our device would not be able to meet the instantaneous demands of the device. While solar-powered calculators are offered as a compelling example, the demands of a hardware wallet are much higher, due to things like ECC. While solar cells could instead be used to trickle charge a rechargeable battery, this also assumes a customer will use the product in a way that can benefit from ambient light. If a customer chose to store the wallet in a drawer or even carry it in their pocket, the product would not be able to benefit from solar charging. Requiring a customer to keep the product in a location exposed to ambient light is ultimately too restrictive.

- **Betavoltaics** - A radiation powered wallet? Interesting potential as a ‘lifetime’ battery, but too early/costly/unproven to count on for our purposes. The power available from these devices is also well below the needs of the product.
- **Kinetic charging** - Unlike a watch that can harvest daily movements from its owner, we expect our device to spend most of its life stationary. A wallet you need to shake or similar on a regular basis to use feels off-putting.