# Battery-Free Game Boy
## Sustainable Interactive Devices

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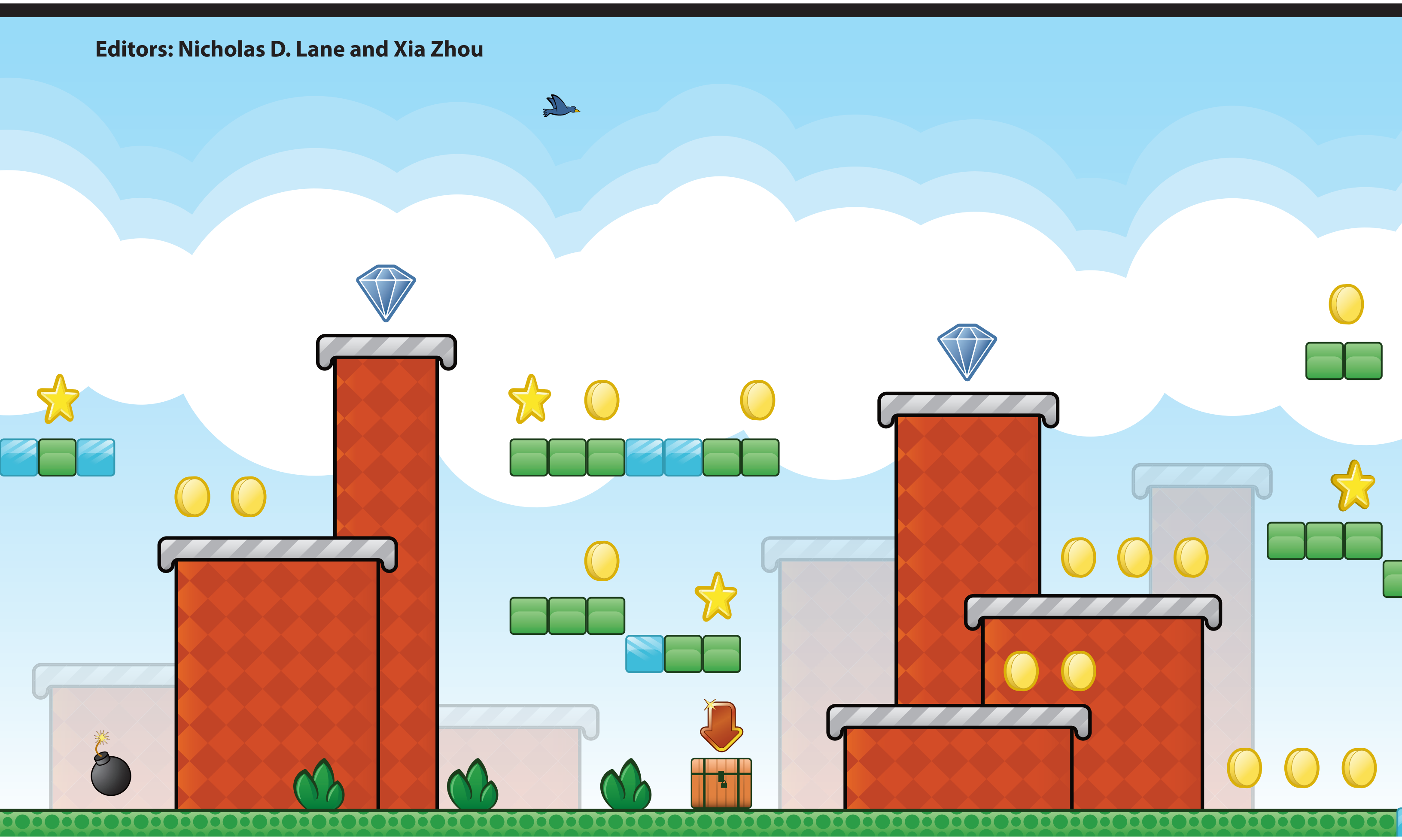

# BATTERY-FREE GAME BOY:
## Sustainable Interactive Devices

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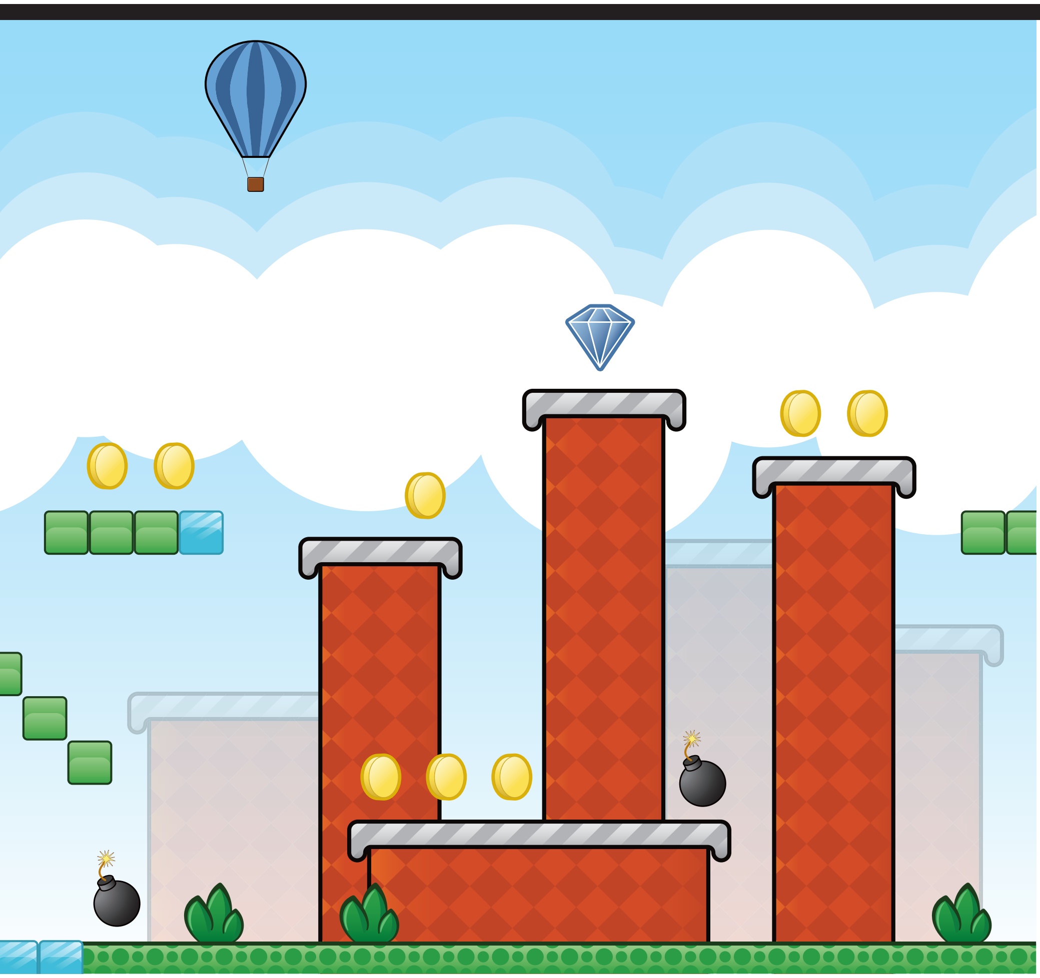
Any future mobile electronic device with which a user interacts (smartphone, hand-held game console) should not pollute our planet. Consequently, designers need to rethink how to build mobile devices with fewer components that negatively impact the environment (by replacing batteries with energy harvesting sources) while not compromising the user experience quality. This article addresses the challenges of battery-free mobile interaction and presents the first battery-free, personal mobile gaming device powered by energy harvested from gamer actions and sunlight. Our design implements a power failure resilient Nintendo Game Boy emulator that can run off-the-shelf classic Game Boy games like Tetris or Super Mario Land. Beyond a fun toy, our design represents the first battery-free system design for continuous user attention despite frequent power failures caused by intermittent energy harvesting.

Illustration, istockphoto.com



The production of consumer electronics is a significant contributor to global warming. Since the release of PlayStation 4 in 2013 [15], 8.9 billion kilograms of carbon dioxide have been produced. Significant changes need to be made to design (with less), production (by not polluting), and distribution (by carbon emissions-free means) to reduce the impact of electronic waste. However, this is a significant undertaking and will not be achieved all at once. Gradual steps need to be made by identifying the most important sources of pollution. Consumer electronics' exponential growth has made it clear that one of the major pollutants is the battery.

### Ditching the Batteries

One way to solve the problem of battery sustainability is to intensify research in battery technology (one prominent example is the EU's Horizon 2020 Program "Battery 2030+: Inventing the Sustainable Batteries of the Future"). However, a more sustainable/recyclable battery still has not yet been realized at scale. Luckily, in some cases, the battery can be replaced by a more sustainable alternative, i.e., a (super-) capacitor, which is replenished continuously by energy harvested from sources, such as solar cells or electro-mechanical switches, creating a truly self-sustainable power supply for the mobile device.

### Challenges of Battery-Free Operation

Replacement of the battery by a capacitor has its cost. Firstly, a small capacitor can store far less energy than a battery, so a fully charged capacitor can deplete very fast (in less than a second, such as in the case of computational RFID tags [https://github.com/wisp]). This causes the intermittent operation of a mobile device, where periods of activity are interleaved by random periods of non-activity (where the capacitor is charging). Secondly, energy from the ambient is also intermittent and spatiotemporally changing. Note, however that this is not a problem for low-frequency sensing tasks that do not require any guarantee of the reaction time (or computation result), a case for most battery-free intermittently powered systems [7].

### Current Research in Battery-Free Systems

To enable battery-free operation, software and hardware solutions are needed even for the most straightforward electronic sensors. On the hardware side, battery-free devices need to be protected against abrupt power supply failure (Figure 1). Hence, the state of computation needs to be regularly stored in a dedicated non-volatile memory [4]. To manage this, a dedicated software framework needs to be created that (a) regularly stores the state of computation in the aforementioned non-volatile memory and (b) guarantees that the data pushed back from this non-volatile memory back to the main memory will be consistent [10].

### Battery-Free Interaction: What Has Been Achieved So Far

While researchers have advocated for sustainable interaction for decades [3], one of the earliest screen-based and button-pressing interactive devices, a game console, was solar powered: Bandai Corporation's 1982 LCD Solarpower Handheld Electronic Games Series [https://en.wikipedia.org/wiki/Bandai_LCD_Solarpower]. This game console could play a few simple games on a LCD screen with very few pixels that can be controlled in the pixel matrix. RFID tag–based systems became the main form of interactive battery-free devices, where the relative position of the tag to the reader can report information on tag's presence, distance or velocity [8]. The obvious drawback of such interaction is that while the RFID tag is battery-free, the RFID reader (and the rest of the infrastructure) – is not. The first battery-free device that demonstrated battery-free voice interaction was the battery cell phone [13]. Unfortunately, this cell phone was also based on backscatter technology (underlying RFID) so the same limitations applied. Similar in design was a battery-free touch interface [14], where a touchpad result was backscattered to a base station. A separate class of research targets battery-free extenders to touchscreens, such as [5], enabling real button pressing or joystick-like interaction. While the extender is battery-free, the touchscreen device is obviously not. NFC-powered e-ink screens can also be treated as one of the simplest forms of user interaction [6] – user changes the content of the worn e-ink display through its own smartphone. Energy-saving components aiding in battery-free interaction are also independently developed; an example is a self-powered microphone [2]. The first system that enabled screen-based interaction that was truly battery-free was [11].

## CHALLENGES OF BATTERY-FREE INTERACTION

In general, all these platforms provide a rather limited view of interaction with a mobile device. The reason for this can be explained by the two core challenges.

### Challenge 1: Responsiveness/ Compromise of Usability

A real mobile device is composed of a screen and a touch-based user interface. For such a battery-powered device, a user expects an immediate reaction to the button/screen press. This cannot be guaranteed with a battery-free energy harvesting platform. Not only is it expected that the battery-free device will stop working during the execution (making for example, your Tetris game to restart from scratch as shown in Figure 2), but it will also have no guarantee when the battery-free device will resume its operation (as this depends on the amount of energy that is being harvested). For that reason the display – the biggest consumer of energy in any embedded platform – is severely downgraded in a battery-free system. Specifically, current battery-free interactive devices are either screen-less (inducing LED blinking [9]) or screen interaction is limited to a simple set of tasks (icon refresh [12]).

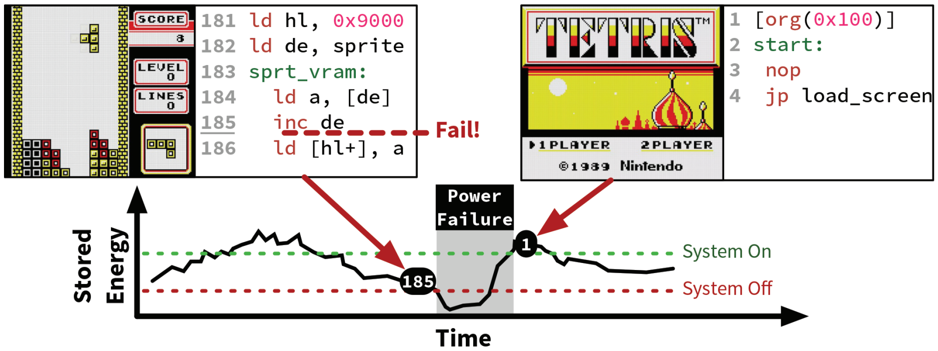



**FIGURE 1.** The impact of power failure on code that is unprotected from intermittent operation – at every power failure, the code (Nintendo Tetris in the context of this figure) starts from the first line.

*Figure, Game Boy, 2020.*

### Challenge 2: High Computational Load and Enormous Variability

No full system emulation of any complex system has been attempted on battery-free, intermittently computing devices. Games and gaming platforms, in particular, require more performant processors even when running natively. This is made worse by the enormous variability of games, both in terms of memory size, the number of sprites, actions, difficulty, and even the number of button presses per second. Each game is unique and could pose problems when creating a general-purpose battery-free solution.

## THE BATTERY-FREE GAME BOY: ENGAGE

To move beyond state of the art in battery-free interaction, we have developed *ENGAGE* – a completely battery-free system that allows one to play real Nintendo Game Boy games using emulation [1] [https://youtu.be/ErapUArQahM]. A conceptual representation of how ENGAGE works, together with its photograph, is shown in Figure 2.

Compared to earlier battery-free interactive devices, ENGAGE allows controlling operation of the device in real-time for the ultimate form of mobile interaction – handheld gaming. Moreover, ENGAGE plays real Nintendo Game Boy games, not simple toy-like examples, demonstrating that meaningful and real interaction with a battery-free device is possible.

ENGAGE is partially powered by solar energy. To reduce the unpredictability of energy harvesting, we take advantage of mechanical energy generated by "button mashing" of the console, harvesting this energy generated by playing a game on a handheld and using it, along with solar panels, to power all operations.

## DESIGN OF ENGAGE

Figure 3 presents the design of ENGAGE. We design the system hardware and software from the ground up to be energy-aware and reactive to changing energy situations to mitigate the issues caused by frequent power failures. Specifically, we design a technique to create minimal *save games* that can be quickly created, updated, and saved to non-volatile memory before a power failure, then quickly restored once power returns. Unlike save games seen in traditional gaming systems, these capture the entire state of the system so that the player can recover from the exact point of power loss; for example, mid-jump in a platform game; all this despite the device fully losing power. The actual footprint of a PCB is small and a the 3-D printed chassis, seen in Figure 2, is almost empty.

The state of ENGAGE's computation is controlled by the checkpointing mechanism that stores the state of computation in non-volatile memory. Only the difference of computation state is stored in between check-points to save memory and checkpoint time.

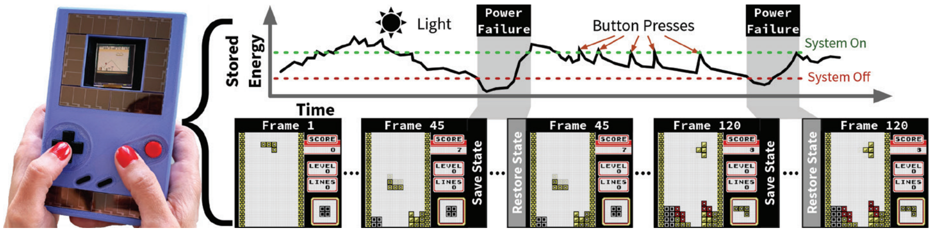



**FIGURE 2.** Battery-free handheld gaming console: ENGAGE. The system sustains gameplay despite power interruption and resumes the game from the last moment it stopped, enabling perpetual operation. ENGAGE is powered from an array of solar panels and button presses.

*Figure, Game Boy, 2020*

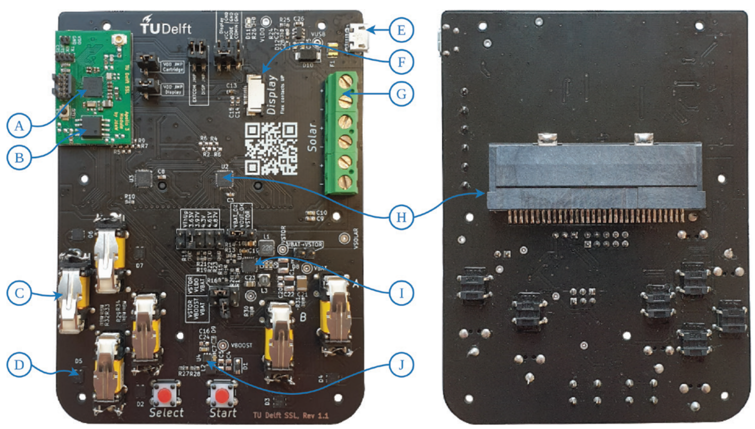



**FIGURE 3.** ENGAGE hardware, representing state-of-the-art battery-free interactive device: (A) ARM Cortex microcontroller, (B) External non-volatile memory, (C) energy harvesting switch, (D) low forward voltage diode bridge, (E) micro USB debugging port, (F) display connector, (G) solar panels connector, (H) cartridge interface, (I) harvester/power management chip, and (J) boost converter.

*Figure and description, Game Boy, 2020.*

## Lessons Learned with ENGAGE

- **"Playing a game is really a perpetual experience."** We have shown that playing retro games perpetually is possible, even intermittently. Nothing can stop ENGAGE from playing as long as the user is able to press buttons or sufficient amount of outdoor light is available.
- **"You can play Chess, playing Super Mario is hard, Pokémon – very hard."** The quality of gaming experience is dependent, however, on what type of game is played. Checkers, Chess or even Tetris can be played with ease even with seconds of power off (these games have slow gameplay). Nonetheless, games based on precise timing of button pressing, like Super Mario, lose their charm when frequently interrupted, and menu-based games like Pokémon are incredibly frustrating.
- **"Playing in the dark is still not possible."** Just like the original Game Boy, ENGAGE does not have a backlight. Having a backlight would mean the energy would have to come completely from button presses by the user, which would be insufficient with our original design.
- **"Better user experience design is needed."** ENGAGE is a prototype, and many potential ideas that would improve the battery-free (intermittent) experience are still waiting to be explored. For example, once ENGAGE powers-off, its screen is powered off as well. But with keeping the state of the screen on (as in the case of e-ink) the user would often not notice that the system is off. Nudging mechanisms to the user ("press buttons more to continue play") of gradual reduction of features (for example, "reduce screen area of ENGAGE as the energy availability goes down to sustain gameplay") also need to be implemented.
- **"Button presses are not that great at generating energy."** The electromechanical switches we have used in ENGAGE are not generating as much power as solar panels, especially those with good solar radiation. Moreover, they are quite sturdy (simply put, they are designed for sporadic presses, not for intensive heavy use). More research is needed on better mechanical harvesters targeting human-computer interaction.
- **"Other energy harvesting sources would improve the gaming experience."** After ENGAGE was built, we realized that other forms of harvesters would fit ENGAGE well. The first one is the electromagnetic harvester hidden inside the ENGAGE chassis. Another one is the crankshaft, as present in the recent retro-revival game of Playdate [https://play.date].
- **"No sound limits the experience."** The lack of sound emulation has further limited the retro feel of ENGAGE. This is for the same reason as for other functionalities: the energy needed to power the piezoelectric generators is too high in addition to power screen and processing electronics. Additionally, playing music intermittently would be irritating. Therefore only specially designed (short) sounds can be played, or the music would have to be turned off temporarily as the intermittency rate increases above the threshold unacceptable to the user.
- **"Specially designed games for intermittent operation."** With ENGAGE we have run real Nintendo Game Boy games. These games are, however, oblivious to the intermittent nature of battery-free interaction. An idea is to create games that make use of this intermittency: giving extra points for faster button mashing or for moving ENGAGE closer to an area of stable energy.

## MOVING FORWARD

Battery-free remote control, screen-based battery-free toys, and battery-free interaction with wireless connectivity are only a handful of examples of systems that could easily be ported to the battery-free intermittently powered domain. The ultimate vision is to design a smartphone of current generation (deployed on the market in 2021) having the same level of functionality but operating completely battery-free. This is the goal we should be aiming for and we believe we will be able to see such a handheld within the coming years.

## SUMMARY

This article presented the motivation and inner workings of a battery-free gaming console, and the first full system emulation on intermittent power with ENGAGE. We demonstrate we can port existing battery-based gaming platforms – such as 8-bit Nintendo Game Boy in our case – to the battery-free domain. With this platform, we have shown that deeply interactive devices, like gaming platforms, are possible to create without batteries, and in spite of frequent power failures. ENGAGE represents a bright future of deeply interactive, maintenance- and battery-free devices.

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**Jasper de Winkel** is a Ph.D. candidate at Delft University of Technology, and received his M.Sc. (Cum Laude) in Embedded Systems from the same university. His research focuses on the intersection of batteryless devices and wireless networking, furthering the feasibility of networked batteryless devices through novel device architectures, ultra low power wireless networking and supporting software.

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