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REVIEW

Sustainable Innovation for Open Hardware and Open Science – Lessons from The Hardware Hacker

Pen-Yuan Hsing

Sometimes, businesses restrict their hardware products with intellectual property legal instruments to maintain near-monopolies in market niches. This proprietary approach to technology risks creating anti-competitive rent-seeking behaviour and comes with its own set of economic and social costs. In *The Hardware Hacker*, Andrew 'Bunnie' Huang builds on his entrepreneurial experience in manufacturing hardware to provide a viable alternative. In addition to extensive tips on the practicalities of hardware mass production, Huang's book documents the thriving technology counterculture in Shenzhen, China's 'Silicon Valley'. Called the 'shanzhai', these entrepreneurs ignore patent and copyright restrictions and openly copy features from other products to remix them into new ones. While some call them thieves, shanzhai innovations pre-empted now-common device categories such as the smartwatch, and may address market niches unreachable by intellectual property-encumbered business models. Huang personally experimented with this approach (while operating within existing intellectual property laws) through his open hardware business ventures – notably the Novena open laptop – and in this book discusses the lessons learned. They include reflections on access to hardware as a form of civic action, implications of advances in biotechnology, and an optimistic view on the growth of open hardware in light of the deceleration of Moore's Law. Refreshingly accessible and entertaining, *The Hardware Hacker* shows us the importance of the right to tinker in an age where technology permeates all aspects of life.

Keywords: open hardware; open science; business models; intellectual property; innovation; entrepreneurship

Introduction

One method of introducing hardware innovations is spinning-off academic discoveries into marketable products. From my experience as a scientist, university technology transfer offices typically promote (or require) commercialising hardware through the aggressive enforcement of patents, trade secrets, and copyright 'protections'. It is unfortunate that proprietary lock-in is often presented as the primary mechanism of commercially viable hardware innovation. Proponents of this approach should take note of *The Hardware Hacker*, a book that not only demonstrates the practical benefits of open hardware entrepreneurship, but also its social and ethical imperatives.

The Hardware Hacker: Adventures in making & breaking hardware [10] is authored by Andrew 'Bunnie' Huang, an electrical engineer from the Massachusetts Institute of Technology, entrepreneur, and founder of three start-up technology companies (Chumby, Novena, and Chibitronics). In this work, Huang threads a series of personal anecdotes (reflecting this book's roots in a series of blog posts and interviews) into a coherent narrative that touches on three broad themes: Practical advice for manufacturing hardware, the 'gongkai' approach to hardware innovation, and the future of open hardware. In this review, I will discuss examples from the book around these themes and their lessons for the open hardware community or anyone with an interest in the intersection between science, technology, and society.

Practical advice for manufacturing hardware

Throughout *The Hardware Hacker*, Huang revealed a level of practical engineering and manufacturing insight that is seldom documented elsewhere.

For instance, one of Huang's most well-known open hardware products is the Novena (https://kosagi.com//w/index.php?title=Novena_Main_Page), a fully hackable laptop computer platform which is free (as in 'freedom, not price', [8]) down to the firmware level. Instead of simply releasing the schematics and making the Novena nominally 'open source', Huang carefully selected components that were not bound by non-disclosure agreements (NDAs), came with datasheets, and unlikely for the manufacturer to discontinue – or 'end-of-life' (EOF) – in the near future. This thoughtfulness and attention to detail can be seen in other examples throughout the book. They are too numerous to list, but include practical tips such as the need

Conservation Ecology Group, Department of Biosciences, Durham University, Durham, UK

penyuanhsing@posteo.is

to designate manufacturers for even simple components like capacitors, or specifying the full part number for a hex inverter (e.g. '74VHCT04AMTC' instead of '7404') which are crucial in a bill of materials (BOM) during production. Experienced hardware makers might know this, but these lessons are often only learned through mistakes and *The Hardware Hacker* is a useful guide to this topic for the curious or uninitiated.

One aspect of engineering often left undocumented is how to work with people. The majority of open hardware projects that Huang produced were manufactured in China, and he used these experiences to further illustrate the importance of effective communications. One example was an Engineering Change Order (ECO) Huang sent to a factory for modifying a circuit board slated for production. Such modifications are often communicated informally (e.g. via telephone) but with an official ECO, the factory was unable to escape responsibility when the change was missed during the production run. Huang also personally visited production lines to work with staff and make sure that all parties understood the nuances of his designs. But as an American hardware developer outsourcing manufacturing to China, in-person visits were not always viable.

This relates to another insight in manufacturing, which is that you are always creating two products: one for the consumer, and another for the factory. The latter is a test rig with which factory staff can comprehensively check each product for errors. Again demonstrating his thoughtfulness, Huang designed his rig with a graphical user interface (GUI) where functions were represented by icons instead of text. This was crucial since the Chinese production line workers' native language was typically not English. The costs saved from this effort was well-worth the initial investment in building the test rig, and this anecdote was followed by extensive advice on how to develop similar testing programs.

Cultural – not just linguistic – differences can be seen during one of Huang's visits to a zipper factory. There was a step in production where a tumbler would deposit zipper *pullers* onto a moving rail which leads to the attachment of zipper *sliders*. The system takes advantage of a small bump moulded into one side of the pullers so that they would all be deposited in the same orientation onto the rail. The slight bump could be easily misconstrued as a defect, when in fact it belies a highly pragmatic culture that eliminated the need for a worker to manually orient each puller.

The Global Open Science Hardware Roadmap cites lack of guidance on documentation practices and quality control as common challenges in open hardware projects [1]. Practical examples in *The Hardware Hacker* such as designing the Novena laptop, composing detailed BOMs or building test rigs demonstrate good practice. Huang's experiences in overcoming linguistic and cultural barriers during quality control are also useful in addressing the need to expand the size and diversity of the open hardware community. On a higher level, this book shows the importance of documenting know-how that cannot be captured in source code alone.

The 'gongkai' approach to hardware innovation

Many of the stories in *The Hardware Hacker* took place in the city of Shenzhen, a manufacturing hub on China's side of the border from Hong Kong dubbed the 'Chinese Silicon Valley'.

In Shenzhen, one would find a seemingly endless electronics bazaar with services rarely offered elsewhere. On one trip to the city, Huang found a vendor who fixed his broken smartphone screen for USD $20 by buying its still functional components from him and replacing the broken part. In the US, the only option was to replace the whole screen for $120. This is because established technology companies typically restrict access to their products through a web of patents, non-disclosure agreements (NDAs), end user license agreements (EULAs), and digital restrictions management (DRM, also ironically known as digital 'rights' management). These restrictions are seldom observed in Shenzhen, and a burgeoning counterculture has developed as a result: the shanzhai.

Shanzhai are commonly known as thieves who can mass-produce clones of a new iPhone mere days after its release. According to Huang, however, shanzhai operations are a masterclass in innovation and efficiency. In shanzhai culture, design documents such as schematics, component datasheets, and bills of materials are widely shared and 'remixed' into new products. Indeed, in the bazaars of Shenzhen, Huang witnessed remarkable diversity in electronics including mobile phones with features such as a built-in cigarette holder, ultraviolet (UV) lights, or a high-zoom lens. While some seem obscure, these products constantly borrow features from one another and produced innovations like a smartphone-watch hybrid which predates the Apple Watch by several years. Most shanzhai companies are small, and some are run by a single person.

Huang refers to shanzhai as similar to the open source movement but without an accompanying legal framework. The sharing of open hardware designs is enforced by shanzhai cultural norms, and those who do not are shunned. In effect, this is similar to viral free culture licenses such as the copyleft GNU General Public License or the Creative Commons 'ShareAlike' series of licenses. Huang coined the term 'gongkai', a play on the Chinese word for openness, for this approach to intellectual property. This is where a distributed model of information sharing – unconstrained by legal notions of copyright and patents – is *socially enforced* to enable rapid iterations. While past academic works have described the shanzhai phenomenon (e.g. [4, 7, 9]), the first-person anecdotes and reflections in *The Hardware Hacker* are useful for introducing gongkai practices to the open hardware community.

The book acknowledged that the shanzhai also produce 'fake' products, such as SD memory cards whose actual storage capacities are much smaller than advertised, or smartphones which look almost identical to iPhones but not made by Apple. However, I think these are cases of plagiarism and false advertising, which are distinct from, and not necessarily a product of, the open sharing of hardware designs.

Another benefit of gongkai is normalising the right to repair. In most Western markets, vendor lock-in legally

prevents consumers from repairing their hardware or even opening it (i.e. 'look under the hood'). But in gongkai, all hardware is open hardware, and the right to repair is built in. This empowers users to open their devices, study how they work, tinker with and build on them, and share the results. One chapter in *The Hardware Hacker* ended with a call to action for tinkerers to assert these rights before they atrophy with ever-tightening legal restrictions. This is a reminder of the important social and civic benefits of open hardware that are often left undocumented.

Huang distilled his observations on the shanzhai into the gongkai philosophy, but does the shanzai consciously subscribe to it? Huang also acknowledged that the shanzhai often copy products developed by big, long-established companies *in addition to* copying from each other. If so, did gongkai develop because of entrenched intellectual monopolies or in spite of them? In my view, there is no clear answer. Existing literature shows that major innovation is indeed possible without intellectual property restrictions (reviewed in [2]; or more broadly, [3]). It would therefore be interesting to explore that possibility in the context of shanzhai in Shenzhen.

Lastly, the technology sector in Shenzhen is infamous for extreme competitiveness, labour exploitation, and severe environmental degradation. I would have liked to see more discussion on how these problems can be addressed as part of a more holistic treatment on gongkai innovation.

The future of open hardware

The final sections of *The Hardware Hacker* considers the future role of open hardware in light of advances in biotechnology and the deceleration of Moore's Law.

As a biologist, it was eye-opening for me to read Huang's insights on how many biological mechanisms map directly to computer science concepts. Take the four nucleotides that make up DNA. Each store two bits of information, which translates to 3.2 KB of data that codes, for example, the influenza virus' genome. Indeed, the computerisation of biology is a growing field of academic research [13] and has produced the ability to store more than 200 petabytes of data in a single gram of DNA molecules [6].

More important are Huang's reflections on what advances in biotechnology mean for society. With new techniques such as CRISPR/Cas9 [5], we can now precisely edit, add, or delete genes from an organism. While clear benefits can arise from these advances – such as novel treatments for disease – there are obvious ethical issues as well. Other than concerns with genetically engineering humans, Huang also considered how they might affect ecosystems such as the introduction of malaria-resistant mosquitoes. He compared a CRISPR/Cas9-assisted gene drive mechanism to the *rm -r ** command in a UNIX operating system (a command which can erase the entire contents of a hard drive). Can we responsibly wield this newfound power over evolution? This is an important question, and I fear that with biological patents (such as those for genetically-engineered seeds or, indeed, CRISPR/Cas9 itself) and other legal instruments, this power will be concentrated in the hands of a few powerful players.

Open hardware is a crucial part of the answer. In one of the final chapters of *The Hardware Hacker*, Huang gave an overview of his PhD thesis, which focused on the slowing of Moore's Law. He argued that historically, big technology companies dominated the market because only they had the scale and resources to not only produce increasingly performant products, but also to keep up with them. However, with the slowing of performance increases, there is a widening window for other innovators to create new products before a new generation of processors make them obsolete. A profound implication is that there may be less demand for new products, concurrent with a 'rise in repair culture as technology becomes less disposable and more permanent'. Huang contends that this will create an opening for open hardware and small businesses. Examples which sprang into my mind include the OpenPCR project (https://openpcr.org/), a business built around open biotechnology, or the EOMA68 line of computing devices that are fully free and designed to be repairable (https://www.crowdsupply.com/eoma68/micro-desktop). If the open hardware community takes advantage of this opportunity, then there is hope for creating a more egalitarian future that breaks the oligopoly on digital society by big technology companies. In my view, the primary questions now are how societal awareness and acceptance of open hardware can be engendered, and if regulatory frameworks could be reformed to foster its development.

Conclusion

This review provides only a glimpse of the wealth of experience contained in *The Hardware Hacker*. I am not only impressed by Andrew 'Bunnie' Huang's extensive tips on hardware manufacturing, but also his talent for bridging the gap between science, technology and society. This leads to two main lessons from the book for the open hardware community.

First, the book's practical advice on manufacturing is not only useful when bringing products to market, but also serves as a reminder that sharing should go above the source code level. By documenting know-how ranging from the level of detail needed in a bill of materials, the need to create a test rig to accompany a product, or bridging language and cultural barriers, Huang gives a multi-faceted overview of the complexities that go into collaborative open hardware development.

The second, broader lesson is the need to rediscover the hacker spirit that produced the technologies of today. In most Western countries, it is increasingly difficult for new hardware makers to disrupt entrenched oligopolies due to heavily enforced intellectual property laws. China has many problems from human rights abuses, extreme competitiveness, to environmental degradation, but the entrepreneurial spirit and remix culture of the shanzhai show how ideas flourish in the absence of modern copyright and patent restrictions, which were ostensibly created to 'promote the Progress of Science and useful Arts' (United States Constitution article I, § 8.8). *The Hardware Hacker* shows how an alternative system (gongkai) lowers barriers to entry, rewards innovation, and is able to tap traditionally unreached markets.

To paraphrase a colourful analogy from the book, giving someone a piece of hardware, such as a smartphone, should be like giving them an apple. They can consume it, share it, sell it, or even plant apple trees with its seeds. But modern technology is encumbered, and 'consumers' are only allowed to use it per restrictions dictated by the manufacturer. This unfortunately promotes digital illiteracy while preventing us from utilising the full potential of technology. In contrast, *The Hardware Hacker* paints a hopeful picture of how open hardware can lead to wider civic participation in technology, and I am reassured by academic [11, 12] and citizen initiatives such as Public Lab (https://publiclab.org/) or the Gathering for Open Science Hardware (http://openhardware.science/). Will we be able to seize this opportunity so that technology can flourish as the apples they really are?

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Competing Interests

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