Methodically Defeating Nintendo Switch Security

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Abstract—We explain, step by step, how we strategically circumvented the Nintendo Switch’s system security, from basic userland code execution, to undermining and exposing the secrets of the security co-processor.

To this end, we’ve identified and utilized two distinct analysis procedures. The software-based analysis suffices for reverse-engineering the userland and operating system services, and is necessary for a general architectural understanding of the software systems in the Nintendo Switch. While this method is extremely powerful and provides significant leverage over the control of the system and its software security, a hardware-based method was devised, which employs analysis of the trusted bootstrap code in ROM. This strategy was essential for the goal of defeating the hardware root of trust.

Together, these two vectors provide essential insight required to instance a chain of attacks, in order to gain code execution from the context of a high-security mode of a secure co-processor of a running system, thus allowing us to demonstrate an multifaceted approach on attacking secure, embedded devices in an unfamiliar and novel environment.

Index Terms—WebKit, ROP, Use-After-Free, Logic bug, Out of Bounds read, fuzzing, emulator, protocol reverse engineering, glitch attack, memory corruption, buffer overflow, stack overflow, TrustZone, warmboot, CMAC, cryptography, embedded device

I. INTRODUCTION

The security of home entertainment devices, such as video game consoles, has been a critical focus in consumer products engineering and development, as a prerequisite to enforcing the control and flow of media and advertisement revenue, as well as protecting end-user data, including personally identifiable and payment information, and protecting intellectual property on a consumer device. The use of Digital Rights Management (DRM) techniques, involving cryptographic signatures, depends on securing digital secrets and title content, and mitigating against attacks, both hardware and software, local and remote, in an evolving landscape of platform security challenges.

Video game consoles, in particular, pose a multi-faceted platform security engineering challenge, with many critical parts maintaining highly-demanding cryptographical systems, while not compromising the performance of the running game program. These challenges have made video game consoles a particularly interesting case study on platform security, through the lens of research.

While older consoles had minimal security, usually to prevent counterfeit and unlicensed hardware and software from entering the market, more modern consoles have begun to employ intensified system security methods, usually focused on protecting the game media from being copied. Although earlier attempts at securing these consoles have been met with trivial exploits [1] [2], newer consoles have employed more serious defenses, and researchers have had to likewise apply their creative ingenuity, and sometimes discover novel methods [3] to find security flaws in these systems.

The Switch, briefly

The Nintendo Switch is Nintendo’s take on state-of-the-art platform security for embedded devices. It does have all you would expect: a full address-space layout randomization (ASLR) scheme, hardware-enforced no-execute (NX) to facilitate a write-xor-execute (W’X) memory policy, sandboxed userland applications, and a microkernel with a modular, minimally-privileged, cryptographically-marshalled services architecture enabling strict isolation of services and enforcing a principle of least privilege. In addition to these software mechanisms, the hardware platform provides ARM TrustZone capabilities, and a somewhat useful security co-processor, which are used by a secure monitor program and secure firmware to verify that the boot path had not been tampered with, and decrypt protected boot programs, applications, and content.

In March 2017, at the time of the Nintendo Switch release, we began our research, in order to understand this new device. The first thing that we noticed right away, is that Nintendo definitely seems to have learned from its past mistakes.

II. USERLAND EXPLOITATION

A. Web of (dis)trust

An interesting point is in how Nintendo dealt with the possibility of browsers being a target, as they had been in the past, [4] [5] by removing access to the browser altogether, no longer touting it as a feature.

While this is radical, this would have been indeed a somewhat useful mitigation... if we really had no way to actually launch it. As a matter of fact the browser was still present, as an applet program for use by the system and games, to provide web- based or HTML5 content, such as software manuals or tailored online experiences. However, this browser applet could only connect, through a secure protocol such as HTTPS, to websites to whom it would have been whitelisted for access. It was also capable of accessing a limited set of local files. So, this browser seemed rather useless to our research effort. That is, until you realize that update 2.0.0, an update available at the release of the Nintendo Switch, added a notable exception to the restrictions, for authenticating to public Wi-Fi.

As a handheld console, this makes sense. Allowing the user to connect to public Wi-Fi access points when, say, waiting for a train, is a function that should be supported by a mobile device like this. The issue here, is that by only obscuring the fully-featured web browser behind the captive-portal landing page function, which is necessary to allow users to authenticate on many public Wi-Fi networks, entirely destroys and buries Nintendo’s one-pronged approach on browser security thus far. These Wi-Fi networks often depend on a web browser.

Such schemes, most of the time, do not use any kind of secure protocol for the HTTP connection and, even if it did, it would be impractical if not impossible, to actually go through
and whitelisted, one by one, all the public Wi-Fi landing pages in the world. This empowers us to perform a simple server-side redirection to a web page of choice, one hosted locally and under our control, and begin to study the system.

B. detachSecurity()

Web browsers have long been a target for security researchers, as many embedded devices use web features, and most of those use WebKit for their browser engine, a program mostly licensed under LGPL. This means that any commercial use of the WebKit engine must redistribute the source code of the software, including any modifications made to it. Not only does this allow us to reproduce an instrumentable test environment for debugging outside of the system, but by its popularity and sheer pervasiveness in the desktop world, we can easily and quickly know which existing, public and available security vulnerabilities haven’t been patched for our target version of WebKit, and adapt/reimplement them as needed for this system.

A thing to note, however, is that the WebKit maintainers (Apple) don’t just hand us a neat, preformatted list of security bugs for us to study, as security issues are considered protected reports. They are removed from public view by the bug tracker, as necessary to allow for mitigations to develop internally. These reports permanently remain obscured by the bug tracker. Although, as those bug reports are mentioned in the commits which fix them, we can simply use the old trick of making a list of all commits linking to bug reports which we do not have access to, as those are presumably security-related issues of particular interest to us.

On our side, we settled for a use-after-free vulnerability in the FrameTree unload handlers [6] which we named detachSecurity(), as we could simply have a frame DOM object, "attached" to a detached tree. We then worked on getting some instrumentation in place, by setting up an RPC server. This let us interact with our exploit remotely to, say, dump current memory. Soon after, we realized one important thing: the Switch does not have JIT in its browser.

Since the user is not intended to be able to use a web browser at all, the lack of JIT surprisingly makes sense here. Traditionally, to exploit WebKit, the typical procedure involved creating some dummy function or functions, running it enough times so that it is selected to be optimized, wait for it to be compiled and transferred into the JIT memory, and then, since JIT memory is writable and executable by design, use a vulnerability that gives you a write in program memory, in order to overwrite said function with our own code, and execute it. The lack of JIT, and the subsequent lack of executable-and-writeable memory, completely prevented us from using this technique to gain arbitrary code execution. We had to resort to the use of Return Oriented Programming (ROP), by way of overwriting function pointers. While ROP is very powerful in its own right, by letting us redirect program control flow, it does not let us redirect it to our own code. This primitive level of control, however, is enough for further research that could lead to privilege escalation, so we went and began to implement some ROP gadgets — essentially groups of pointers to functions and existing executable code fragments, based on our memory dumps, which we can use to effect changes on the state of the system and test for more powerful vulnerabilities.

C. PegaSwitch

That period of research was, unfortunately for us, short-lived. Almost at the same time, an entire toolkit for browser-based exploitation on the Nintendo Switch was released by another independent team of researchers. The toolkit was called "PegaSwitch". [7]

While this was frustrating, as most of our effort up to this point had now seemed worthless, this was also an invaluable research tool for us, as it implemented all the core ROP functions we cared about. Whereas we had planned on discovering an applicable WebKit browser vulnerability, with the expectation that we would have to engineer an exploit stack (including ROP, privilege escalation, arbitrary code execution, sandbox escape, and shellcode to launch outside the browser sandbox), PegaSwitch used an already available exploit, namely CVE-2016-4657 [8], commonly known as "Pegasus", with the added twist that this exploit stack was already implemented for iOS systems on devices with the AArch64 architecture [9], explaining why they were able to get to ROP so quickly and reverse engineer so many things in so little time, as the Nintendo Switch is also an AArch64 machine.

Now that we have remote userland ROP code execution, our next goal was then to reverse-engineer the inner workings of the operating system, to identify potential targets for further escalation. Horizon is the name of the Nintendo Switch’s operating system, the kernel, and its system services. Horizon is also the OS on the Nintendo 3DS; the Switch version is a further development of this OS, with refinements and further progress towards being a full-fledged operating system framework. The 3DS had been thoroughly researched and documented by the time of our research, and understanding that platform was a great help in understanding the rational of its successor, as will be explained later.

To the effort of reverse-engineering the OS, we scanned the addressable memory for executable formats in order to gain useful insight on the fundamental details of the software systems. One of the first things we realized, apart from the executables being in an apparently new, custom format — not uncommon for Nintendo [10] — is that due to dynamic library linking and loading, we were able to retrieve a bunch of symbols which identified available services.

D. Services, explained

What follows is in-depth information about the system service architecture of Nintendo’s Horizon operating system. This section in particular is informative; it contains information that we had to figure out after-the-fact, but is essential to understand the rationale behind our method, moving forward.

The userland API of the Nintendo Switch is comprised of services, provided by system service processes, or servers. These are processes which run in the background, and provide controlled-access, higher-privileged system functions to
userland applications as well as other servers, by way of an IPC interface.

Most of these services are limited as to what they can affect, and their servers load as a userland program would, and thus have restricted access to other services and hardware, as any application.

Some of these services are especially privileged, and their servers load very early in the boot sequence. Because they are loaded so early, before the mechanisms are in place to securely load and verify executable content from storage, the first six of these servers are contained within the kernel binary, and load into memory along with the kernel. These kernel-initiated processes, or KIPs, are compressed and packaged with a unique executable container format, and unpacked by the kernel once it is loaded and running. Once spawned, these six servers are sufficient for continuing the secure boot process.

Access to services from userland applications, is coordinated by a service manager (sm), which is itself a server, with service endpoints. The sm reads the list of allowed services for the application, registered to sm at launch. This list is in the executable’s metadata on storage, which is signed by Nintendo during their production-signing step, the same for all applications, games, game cartridges, and system programs for the Switch. That list’s signature is verified by the filesystem server (fs), along with the executable code, to ensure that it has not been tampered with after installation.

**E. IPC and services API, explained**

Nintendo had chosen to use a marshalled, limited code surface in the serving of IPC in the kernel, and to segregate software risk and performance domains into separate services. Access to each service endpoint, both by applications and lesser-privileged services, requires different privilege and access flags, enforced cryptographically by a code-signing trust root.

This is done to further limit the attack surface of kernel-level and privileged code, while not compromising on the performance of the game program at the forefront. Its kernel is a microkernel, as stated previously. Through discovery of symbol tables in a dump of early firmware, we found that the kernel and servers are linked against the same internal library, possibly to minimize code variances in common security-critical functions, but mostly so that they could follow one known-good implementation of the rather wild IPC handler code, which we’ll explain in detail further on.

To summarize this a little bit better, let us imagine a process wants to use bsd sockets, which are available as a service under the ‘bsdsockets’ server process. First the process is going to connect to a port named “sm:”, short for Service Manager. It is going to use the IPC command 0, "Initialize", at this port, to bring up the service frontend for the application, inform the service of your service access, and allow sm to ensure that the service is loaded and ready to accept commands, and inform the application that it is ready. On a successful response from the service manager, the Initialize command is then followed by IPC command 1, "GetService", with the name of the service we want as an argument. Let’s assume for our example, the service is "bsd:u". We now have a handle to our service and are able to send commands via that handle, through IPC. A simpler comparison could be made that we interface with the system and its services through an address-and-port system, in comparison to TCP/IP: the service name defines where the command is to be addressed; meanwhile the handle, like a TCP port, tells us where to send a command. The IPC header defines the command format.

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![Fig. 1. The example above illustrated](image-url)

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**F. Breaking through: Privileged service access**

As the astute reader may have noticed, not only are service names segmented, e.g., “name:function”, allowing for more fine-tuned isolation, but they are managed by a central service-managing managed services server, the Service Manager server and its service manager services, which we will get back to in a moment. The first step in our research was, logically, to understand how to communicate to those services, in the hope to escalate privileges and reverse-engineer more of the system. Luckily for us, the architecture hasn’t changed much since the days of the Nintendo 3DS and, having WebKit OSS source code, we could reasonably translate the unincorporated SDK library calls to service and IPC patterns with the help of the 3DS and its webkit binaries, which include the data
necessary. Through this effort, we were able to identify and reverse engineer a bunch of service related functions. However, unfortunately, most of the services' names, functions and the IPC command structure seemed to have been changed entirely, making us do the documentation effort and tooling all over again.

Reversing the port system was trivial, as it was a simple syscall away — namely, poking at SVC 0x1f, "svcConnectToNamedPort" [11], was enough to verify that the named ports enumerated prior were correct, and to enable us to further manipulate the services behind these ports. Gaining a meaningful understanding of the IPC command structure was, to put it mildly, a fair bit more painful. By "a fair bit", of course, we regret to inform you, it had been head bangerly stupidly obfuscated, and blanketed in seemingly nonsensical optimizations. The more dedicated (read: masochistic) reader may wish to consult the additional documentation about the IPC buffer descriptors, and the bit shuffling hacks that happen behind the scenes, to completely grasp the magnitude of the topic at hand [12].

Let us assume we somehow reverse engineered this protocol and reimplemented it. As we do not have any way to dump privileged code yet, our first reflex was to fuzz the services to find any evidence of a crash thanks to an unexpected input, while documenting them... or I should say, it should have been our first option. Remember how I mentioned the Service Manager up above? If you follow the rules, you are supposed to call an Initialize function, which sets the PID of the current process to handle service permissions. It turns out, you can just skip the initialize function. Doing that, leaves the PID field uninitialized. Uninitialized fields are set to 0. PID below 8 have unrestricted service access, which we could also deduce at this point since the 3DS worked in a similar fashion [13]. It should suffice that the name given to this exploit, "sm:h", need not be further explained.

In brief:

1. Features that are able to be abused, will be abused, even if they're not "supposed" to be.
2. Completely removing such a feature may not be the easiest solution, and it may not be the best for all use-cases, but it is the most secure.
3. Sometimes compromises are necessary to meet demands, but be sure to investigate all alternatives before settling with the lesser-secure option.
4. Security through obscurity is not secure. Sometimes the very fact that something is hidden, is more than enough information to formulate a plan of action. (This goes to both the Wi-Fi browser access, and the Webkit bug reports.)
5. Just because something can’t make code executable, doesn’t mean it can’t execute code. ROP is a very powerful tool.
6. If you reuse common libraries, code and programs from other platforms, you run the risk of importing existing vulnerabilities and exploits from those platforms, too.
7. If the prior system is documented, its successor will be easier to figure out. This can be used to the benefit of both protecting, and exploiting, the system.
8. Stripping executables of their debug strings and symbols makes the adversary’s job harder.
9. A comprehensive audit strategy on privileged code’s API endpoints is crucial.

III. PRIVILEGE ESCALATION: SYSTEM SERVICES

A. Following a lead

All system service processes except for the kernel-initiated servers, are contained in "sysmodules" in storage, like the 3DS.

By this point we had a huge attack surface, nothing short of unrestricted access to all system services, which we could take advantage of to find flaws in privileged processes. However, there remained much mystery behind the workings of the system. We had not dumped the sysmodules yet, and thus could not perform out-of-system analysis on these binaries.

We began automating the process of fuzzing some services, and then kind of got disinterested from research temporarily. In the meanwhile both Switchbrew and Reswitched independently found an exploit called "plutonium". This exploit was in the first commands of the service pl:u (which handles the system shared font in shared memory), initialized by the ns server, which read from an array using the user-input arguments. That input was obviously not sanitized prior to use, allowing them to dump the entire binary of the NS sysmodule [14]. ReSwitched, on their side, created an emulator to automate the findings of vulnerabilities through fuzzing [15] [16]. Right after this, we had a surge of renewed interest into the Switch which made us investigate some of the highest privileged sysmodules, as they would be the most useful to break.

Before telling you how we decided to look at entrypoints, I would like to mention that we independently confirmed that at least one research group was able to be aware of privileged services through internal leaks they shouldn't have had access to, greatly helping their ability to document and research said modules.

Moving on, we were aware that Plutoo was able to dump system modules [17] while excluding the possibility of a kernel hack [18]. This led us to believe that the flaw was present in some of the more privileged system servers, namely the ones built-in that Plutoo mentioned. We were also curious on why Plutoo listed both the title id and the name of the modules in the post [17] mentioning the dump, and, while this could have been a coincidence, we decided to look at what this could lead us to.

As such we looked at the list of title ids that were currently documented on switchbrew [19] and enumerated all the privileged ones: fs, ldr, ncm, pm, sm and finally, boot. As the sm server’s services have a very small attack surface with very few commands, and we had already bypassed it by way of sm:h, we decided to not look at it. The boot server being a "headless" server without any kind of service frontend, exploiting it was out of the question.
B. The FS services

After removing those two from the equation, we decided to look at everything filesystem related, because of the peculiar name listing in the post that pluto made [17]. And so we began trying to work on fs, as it was numerically the first built-in, fully-privileged module that was also related to filesystems.

We began looking at the FS documentation, and studying and exploring every possible entrypoint in the service set handled by the FS server. Coincidentally, the first service port listed was fsp-ldr, along with its first command ("OpenCode-FileSystem", though it was referred to as "MountCode" back then, due to a lack of debugging symbols for naming internal things).

Unfortunately, trying to bind to it directly, throws an error. We had somewhat anticipated this; building upon our experience with, and knowledge of, the 3DS, we figured that there was the likelihood that this service had a session limit, and that said limit was occupied at initialization time, something which happened to the FS counterpart of the 3DS [20]. As the service name was fsp-ldr (which we presume stands for "privileged filesystem service pertaining to the loader"), we figured out that if we crashed the ldr service, which, one could infer, had an exclusive handle to fsp-ldr... we could get access to the fsp-ldr handle instead!

And as a matter of fact, this is what happened: Any method of crashing, killing, stopping, unloading, or otherwise causing a denial-of-service attack to ldr (of which there are several), would cause the ldr server to release its handle on fsp-ldr, which we could hook up to, and then ask fsp-ldr nicely to dump all the code modules it had access to, since by virtue of its function, it needs access to the binaries for applications and sysmodules alike. Soon after we figured this out, a description of the vulnerability, a minimal proof-of-concept exploit, and a functional ldr DoS were released to the public by other researchers [21]. We found out that they had left out enough a functional ldr DoS were released to the public by other researchers [21].

Having a way to dump almost all of the system modules, we began to look at our options to escalate privileges in a more concrete, reproducible and persistent fashion. Having the binaries had helped a ton, and while we did get somewhere with our newfound information, we were stopped dead in our tracks by another research team, fail0verflow, who had shown off a cold-boot exploit [23], hinting at the fact that they were able to dump the bootrom.

At this point we were aware that a development kit for the Tegra X1, the System-on-Chip (SoC) used by the Nintendo Switch, was publicly available for purchase... and that it most likely had the same bootrom. Thus, the fun part began: glitching and hardware fault engineering was put into play. We will mostly skip over this part, as Yifan Lu already explained very well how glitching could be applied to embedded devices in the past [24] and an entire talk had already been given at the C4 OpenChaos event on glitching the Tegra X1, specifically [25].

Essentially, we took the path of least resistance, and voltage-glitched a Tegra X1 development kit, and a second device which we unfortunately cannot discuss here due to the aforementioned NDA. As we are unable to discuss that project, we will assume that our research is entirely unique and that fail0verflow inspired us to look into the bootrom, for the purposes of this paper. We will try to release the research currently under NDA as soon as possible. We are sorry for any mandatory omissions we do in this paper, and are hopeful that the available literature will be more than sufficient to satiate the curiosity of the dedicated reader.

B. Analyzing the boot ROM

So, we glitched our device and successfully acquired the contents of the boot IROM. At this point, since we were aware of fail0verflow’s tweet [23], we saw that they had, purposefully or not, hid the USB port of the console. Understanding that the
USB protocol — especially USB 3 and USB Type-C — has a level of implementation complexity that often stretches beyond the definition of "acceptable", and on the heels of several USB kernel flaws released a bit before this tweet [26], we surmised that it was fairly likely that the flaw was related to USB in some way. At this point we had only gained a fairly minimal understanding of the Tegra boot firmware logic, and as such, decided to write an emulator for it, and employed dynamic program analysis using that emulator, to aid the static analysis effort.

Building this emulator not only forced us to understand the boot flow of the Tegra X1, including its recovery mode (RCM) which makes use of USB, but it also made us understand way better how the boot ROM code worked. It had helped so much, that we actually found the bug in a minimal amount of time, with a minimal amount of effort, with our emulator still only operating in HLE (High Level Emulation)!

The plan we had in mind for this emulator was to, first of all, get an idea of the bootflow by implementing all the main cryptographic/USB functions in HLE, in order to develop a tool that would interface with the console’s RCM. We already knew that, besides the RCM interface, there wasn’t a way to interface to the console’s boot ROM to provide input, external to the console. Once we had a better definition of the RCM interface over USB, we would then make a basic fuzzing tool that would run in the background over a long time, while we ported our emulator to full Low Level Emulation (LLE), to allow us to more completely simulate the processor and its devices, to thoroughly fuzz out any trivial bugs we may have missed up to this point.

While we were working on the HLE part of our emulator, we decided to perform a quick audit. The USB and cryptographic functions, being prime targets, were the first items of interest to us, with some focus on cryptographic fails. Fortunately for us, the bug occurred at a point in the RCM program flow before any kind of cryptographic verification was performed. As such we discovered it naturally when trying to understand the RCM.

![Image](image_url)

Fig. 2. The bug, courtesy of ktemkin's fusée gelée report [27]

The flaw was fairly simple actually: in some functions of the USB protocol, we could arbitrarily control the size of a memcpy, allowing us a good, simple buffer overflow, just like the 90s, with no mitigation whatsoever, no memory protection or isolation, as this is a bootrom, naturally, with no operating system or kernel to enforce it with. The memcpy occurs before the stack, so you just overwrite the stack pointer, point it to the code you copied, and since there are no stack cookies, no ASLR, and absent no-execute memory policy, you just watch it execute your code. It’s so easy, it almost feels like cheating.

### C. God’s in his TrustZone, all’s right with the world

Having access to an exploit in boot ROM, we had no real incentive to work on the switch again, but we were curious about some known but private vulnerabilities nonetheless, especially one that the ReSwitched group called "déjà vu". To put that into context: ReSwitched, early on, publicized a write-up about a flaw they found called "jamais vu", which allowed code execution on the Secure Monitor of the Nintendo Switch [28], while announcing déjà vu. As this is the type of exploit that really makes use of all the unexplored intricacies of the system, we will more thoroughly explain the overall technical architecture of the Nintendo Switch.

The Nintendo Switch is composed, first and foremost, of a SoC called the Tegra X1, created by Nvidia. While it may sound unintuitive, this SoC is actually composed of several processors with different architectures and different use-cases, out of which some are particularly notable.

The main CPU core complex, that we will henceforth call the CCPLEX, is the primary applications processor. The "Boot and Power Management Processor", referred to in this paper as BPMP or BPMP-Lite, handles system bringup, power management, and is technically the "root processor" of a Tegra system. (The Reference Manual calls it "BPMP-Lite", as it lacks some features that more advanced versions of the SoC will apparently get.) The boot ROM that we dumped before, is referred to by Nvidia as the BPMP-FW, the "firmware" for this subsystem, because it is the first program loaded and the first processor to initialize on power-up. There is also a third processor, the Tegra Security Co-Processor (TSEC), that we call the CCPLEX, is the primary applications processor. The first processor to initialize on power-up. There is also a third processor, the Tegra Security Co-Processor (TSEC), that we

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The CCPLEX is a somewhat recent ARM processor, which means it is capable of a feature that ARM calls TrustZone. For those unfamiliar with the concept, TrustZone is a hardware-enforced virtualized system-separated enclave on the processor, used to isolate security-critical parts of the operating system as much as possible (in the case of the Nintendo Switch, its internal cryptographic engine). This introduces a notion of "Secure World" and "Normal World", both running their own OS and having their own separate resources. For example, the Secure World has its own secure RAM space, "TZRAM".

In our case, the "Normal World" is the Horizon kernel, with its servers and userland applications, and the "Secure World" contains the "Secure Monitor" of the Nintendo Switch, which is just its cryptographic engine, as mentioned above, alongside some rudimentary power management services. The
normal world interacts with this secure world by using Secure Monitor Calls (SMC), roughly analogous to kernel syscalls, or “Supervisor Calls” (SVC). This is an important part of Nintendo’s security scheme, as this allows them to seal keys, even in the case of complete kernel takeover, so that:

1) We cannot replicate their cryptographic engine outside of the device, and

2) They can always patch known vulnerabilities, update the keys and we would have no way to break the DRM of newer games.

Unfortunately for them, having bootrom code execution kind of spoils the fun... but let’s just forget that for a moment. Continuing on what we mentioned above, we know that ReSwitched managed to get code execution on the Secure Monitor which they called “d’{\`e}ja vu”, on top of “jamais vu”, even in the case of complete kernel takeover, so that:

- We cannot replicate their cryptographic engine outside of the device, and
- They can always patch known vulnerabilities, update the keys and we would have no way to break the DRM of newer games.

In brief:

- Glitch attacks, fault injection, power analysis, and other hardware-level attacks, will violate your preconceptions of software/hardware validity at the lowest level, unless you proactively protect against unexpected code or register data injection.
- Complexity (such as, full implementations of bus and network stacks, RSA cryptosystems, complex implementations of storage interfaces, file systems and other device driver code) increases the potential vulnerability surface. Paradoxically, the more complex the program, the easier it becomes to exploit, in general.
- Low-level boot-time resources are a very high focus for researchers to audit. Not only the bootloader, but recovery
modes, factory modes, download modes, whatever they may be called, if it’s loading code into the system from an external source, it is going to be thoroughly studied for any possible flaws.

- Moving data between security domains (TZRAM to DRAM, for instance) is another high-focus area to audit. Anything that depends on securely saving and restoring such data should not depend on an unsecured system (PMC registers, for instance) to protect them.
- "Undocumented" features aren’t... or won’t be for long, in the context of security research.
- Further, "Deprecated" means nothing to a security researcher, until the "deprecated" feature is removed.
- Validating the state of privileged boot services goes a long way to enforcing secure boot. Payload signatures aren’t enough; further boot-time measurements of code and state are necessary.

V. BEYOND TRUST: FROM TSEC TO 0xDEAD5EC1

Having bootrom-level code execution, we thought we were pretty much done with the security challenges of this console... And yet, Nintendo still managed to surprise us.

Before we touch on how Nintendo revamped their trust chain, we’ll take a look at some background on console security.

A. How Homebrew Works

The community of developers and users making and using unlicensed homebrew software for game consoles, depends on the ability to run arbitrary, unauthorized code in a convenient way (e.g., without physically modifying the device or installing aftermarket or replacement components through high-risk hardware modifications). In order to run unauthorized code, the strict code-signature enforcement on applications needs to be relaxed, if not removed entirely. On older consoles and handheld systems, there was no code-signature enforcement; running homebrew applications depended entirely on gaining any arbitrary code execution, most commonly through specially-crafted user-generated data or savedata. On later consoles, cryptographical measures had taken place to simultaneously enable game data to be stored on removable, user-accessible memory, as well as to protect the game data from tampering, reverse-engineering, and outright replacement, and prevent unauthorized applications from being able to run on users’ systems. Needless to say, these measures are often defeated by security researchers, and made available to homebrew developers and users. In past systems with code-signature enforcement, these workarounds had been achieved through gaining code execution, and once running on the target, installing modified or patched versions of the firmware or operating system, typically called "custom firmware", or CFW. For instance, installing FlashMe on the Nintendo DS allows running unsigned code directly over the Download Play feature, through a protocol termed "Wireless Multiboot".

However, the ability to modify the system firmware or OS contents, had given rise to a handful of malware programs, often disguised as pirated games or highly anticipated homebrew applications. Trojan/DSBrick.A, one such piece of malware, simply displays a brick-wall texture on the displays of the DS system, while it overwrites the system firmware, rendering the console entirely useless (a "brick"), requiring risky or costly repairs to return the system to a usable state. As well, earlier Nintendo Wii homebrew methods involved replacing IOS packages (essentially, system drivers) with custom ones enabling homebrew to have access to more hardware that only few games had taken advantage of. These "cIOS", custom IOS packages, were high-risk modifications, and often led to bricked Wii systems, especially if modified IOSes were installed before accepting a system update from Nintendo.

Because of the risk of these and other modifications to the system potentially leading to damage, customer support headaches, and in the case of DSBrick, media attention, console manufacturers had to make a compromise to further secure against system modifications, while still allowing upgrades to firmware, system software, bundled applications, downloaded applications and content.

Because of the heightened protections on firmware modifications, homebrew methods on later consoles have given rise to live, in-memory patching, rather than modifying the necessary code in storage, either through modified bootloaders (such as Enso [31], for the PlayStation Vita) or through custom kernel modules or system programs which patch memory as well as add features (Prometheus/Pro-CFW [32], for the PlayStation Portable), or a combination of the two (Luma3DS [33], for the Nintendo 3DS). By tradition, these pre-loaders, in-memory patchers, modified or reimplemented components continue to be called "CFW", despite often being neither custom, nor firmware. These CFW environments almost universally disable or work around code-signature enforcement.

B. Switching gears

Earlier on, Nintendo Switch homebrew was rudimentary. The limited homebrew entrypoints available had placed many restrictions on the capabilities of such software, when compared to native, signed applications. The first public homebrew user and development environment, ReSwitched’s PegaSwitch, which ran on system software 3.0.0, was used to launch the Homebrew Menu, or hbmenu, an alternative launcher, loader and host for homebrew applications compiled as relocatable code objects (.nro files). This menu was intended to be bootstrapped from an existing application that had been exploited to run arbitrary code, which either had, or had escalated to obtain, the necessary permissions to read content from storage, and dynamically load executable code.

The application from which homebrew was bootstrapped, in this early environment, was the WiFiWebAuthApplet, or the captive-portal landing page web browser applet. As such, being an applet, the programs were extremely restricted with the amount of memory they could allocate, as applets ran in the foreground, while an application (such as a video game) was either running or suspended, in the background. As well, the web browser had only very minimal permissions, and while this limited environment would more than suffice for testing new toolchains and enabling homebrew development on the
platform, the Switch is a very powerful system and users were looking to develop more advanced homebrew, such as PC game engines, emulators, and even creative tools, which would take advantage of the heightened permissions and larger memory allocation a full application context can provide.

In order to run more advanced homebrew applications, a CFW environment for Horizon became a requisite, since such an environment would be able to further enable homebrew access to the system. The currently state-of-the-art implementation, Atmosphère [34], actually reimplements several system modules and servers, the secure monitor, the bootloader, and parts of the kernel-initiated processes, and plans to reimplement the entire kernel of Horizon later down the road.

The important thing is that we are within the environment of Nintendo’s firmware, and as such, we depend on their cryptosystem. As Exosphere, Atmosphère’s symmetric reimplementation, is not entirely complete. It currently patches the boot code package, Package2; and as such, needs to be able to decrypt it. Even if, by some miracle, the ongoing community effort eventually allowed us to entirely reimplement all of Horizon, we would still hit a wall when it comes to actually playing Switch games, as we would need a complete reimplementation of their cryptosystem.

Thus, we need to be able to derive keys on our own to be able to maintain the current features of this console. And this changed in the 6.2.0 update. To understand why this is important, we are going to explain the Nintendo Switch boot flow and cryptosystem in more detail below.

C. Ignition, Switch

Beginning the boot flow, the BPMP of the SoC powers up, launching its bootrom. This bootrom, depending on the state of PMC registers, either performs a warmboot and loads from existing state in DRAM, or loads and verifies package1, and jumps to package1ldr. In that case, package1ldr takes care of decrypting and verifying PK11. Package1, containing package1ldr and PK11 are stored in the first eMMC boot partition, and PK11 contains the warmboot binary, NX-Bootloader, and the secure monitor firmware. The warmboot binary is what is saved to DRAM by the secure monitor when entering the deep-sleep state.

After package1ldr does its initialization, it then jumps to the bootloader within PK11, called NX-Bootloader, which in turn loads and launches the Horizon OS main kernel and modules. When the boot server process has initialized, it triggers a command in the process manager (pm), causing it to load and launch the boot2 server, which is the first non-built-in system server. For the sake of simplicity, it is shown in the figure below that boot launches boot2 directly. boot2 then takes care of launching all the system servers; one of which, Nintendo Shell (ns), launches the main front-facing user menu, qlaunch.

At the lowest level, prior to the 6.2.0 firmware update, the entire cryptosystem of the Nintendo Switch relied on 2 keys: The SecureBootKey (SBK)) and TSEC key. The first key is set by the boot ROM and is console unique, while the second one was generated from hardware secrets on the security co-processor, still console unique, which, coupled

with more console uniques keys on the eMMC boot partitions, generates static keys used for everything after this. The TSEC firmware was loaded by NX-Bootloader, and we could, at this point, simply run the firmware blob and read back our result from the SOR1 registers, which were used as a secure transfer route between the TSEC and bootloader. We could not reimplement this firmware either, as only authenticated code, and thus signed by an approved authority, would have access to the hardware secrets on the TSEC. This firmware was of course largely ignored up until the 6.2.0 update.

D. The "S" in Switch is for "Secure"

The 6.2.0 update introduced major changes to the way key generation worked, and most importantly, the TSEC firmwares. Up to this point the firmware had 3 main stages, Boot, KeygenLdr and Keygen. As mentioned earlier, TSEC firmwares can be signed, but they can also be encrypted, and as such KeygenLdr decrypted Keygen using hardware secrets we did not have access to, as KeygenLdr was signed. The update introduced two new stages to this whole chain, SecureBootLdr and SecureBoot. The entire TSEC boot chain had thus been reconstructed to the following flow: Boot → SecureBootLdr → KeygenLdr → Keygen → SecureBoot.

While KeygenLdr and Keygen haven’t been updated, SecureBoot added some interesting security concepts. Not only does it generate yet another key from hardware secrets, the TSEC root key, but this time it tries to prevent us from actually getting the contents of the SecureBoot binary through simple means, such as by halting the BPMP, rewriting its exception vectors, and dropping the BPMP instruction pointer back into code it controls (a signed and encrypted Package1). This is actually fairly interesting! We cannot replace any TSEC firmware blobs with any of our code, because we are unable to sign it, and we can’t remove it because that code would generate the new required keys from secrets we don’t have... This forces us to redirect program flow to code trusted by Nintendo, making this an adept attempt to re-secure its console, even after a critical boot firmware bug.

At least, this would be the case, if we weren’t able to simply fool TSEC into assuming everything is fine, and that we didn’t just take control from it. We can do just that, because otherwise
what good would a security co-processor be, right? We can use the BPMP’s control over the internal I/O memory management unit, the System Memory Management Unit (SMMU) as the ARM architecture calls it, to redirect all reads and writes to pages of memory we control, and fool it into thinking it effectively redirected code flow from our own control, while it just handed over the keys. That sure is a foolproof way to go about in-depth platform security.

But Nintendo was not done with TSEC, or at least not yet. As it turns out, the TSEC had a feature that was not well-documented (some would argue that it isn’t documented at all, for our usecase), that came in handy for securing the boot flow and giving us yet another new challenge. An SMMU Bypass function is available to the TSEC, which forces the TSEC to simply consider all memory as linear, and avoid the memory virtualization that SMMU can perform. That’s quite a useful feature for a security coprocessor, we must admit. This time around, in firmware update 7.0.0, they enabled it, while doing a bunch of checks to detect virtualization, updating yet again their TSEC root key so as not to let us use older ones.

E. In-”sept”-tion

Since 7.0.0 had yet again changed the security playing field, we needed to find another approach to attack TSEC. To explain our findings, we will discuss how this firmware authenticates its payloads in depth.

TSEC is based around a Falcon microcontroller. This processor has three “modes” in a security context: Non-Secure (NS), which typically restricts the microprogram from reading most registers and memory; Light Secure (LS), which is rarely used outside of debugging and development; and Heavy Secure (HS), which enables full access to the cryptographical hardware, and protected or secret registers and memory.

A small blob of unauthenticated data is present in the firmware uploaded to the TSEC. That data contains the size of each payload, and a hash of the AES CMAC (!) that should be calculated for the payload to pass boot-safety measurements.

Now, if you understand even elementary cryptographical theory, that seems counter-intuitive. Why AES-CMAC, and not an asymmetric cypher like RSA? If you get the AES key used for decryption (and the one necessary for verification), you can effectively sign your own MAC... and completely substitute the expected payload for one you have control of! Well, Nintendo has a reason. Falcon is a rather limited microcontroller environment. For one, there’s not enough memory headroom to (securely) implement RSA in software. Falcon has separate data and instruction memory, DMEM and IMEM, and together they measure in the dozens of kilobytes. For another, one would have to implement RSA from scratch to the Falcon microarchitecture, and Nintendo seems to have since learned not to roll their own crypto... However, the TSEC does include hardware AES acceleration, which is expected to be reasonably secure.

Those checks also execute in reverse order, so that KeygenLdr can ensure that Boot has not been tampered with, for example. On top of this CMAC, TSEC verifies page by page that any signed payload the payload is indeed signed, at the hardware level, before granting it the HS privileges. Those pages are then marked secret and cannot be read anymore until CPU halt, where trying to read from it would return 0xDEAD5EC1.

Now that we’ve covered that, let’s assume we are working with earlier TSEC firmwares, for brevity. Those are easier to work with, while maintaining, thanks to the nature of our exploit, the exact same level of control.

KeygenLdr, during normal operation, reads that blob of data, so that it can parse it and check the first stage size and CMAC hash, in our case Boot. This is done in order to retroactively verify that it hadn’t been tampered with. The thing is, this blob of data is not authenticated. We can control both the size and content of data being copied over, hence, we can control a rudimentary stack smash. To go about that, we can have KeygenLdr copy our modified boot payload, fail verification, and return. Fortunately for us the verified MAC has not been cleared from memory, so we can restart the process along with this MAC, pass verification and return to our crafted ROP gadgets, allowing us to get code execution in the Heavy Secure mode of the TSEC.

The exploit described above is used to get code execution after Keygen has been decrypted, but its pages have been marked secret. We could optionally get ROP after the verification has failed, but we would be unable to decrypt Keygen. We would also like to note that the same result could have been replicated thanks to design flaws of the TSEC that we shall not further discuss here.

In brief:

- The community behind developing homebrew software is pervasive; methods to gain homebrew access are often invasive, and often co-opted by software pirates.
- It is very difficult to secure a system where the boot chain of trust has been compromised.
- Adding a new cryptographically-secure system may seem like a good protection against such a compromise moving forward, but keep in mind that added complexity makes for a larger attack surface.
- Understand that using symmetric algorithms (such as AES) where asymmetric crypto would typically be employed, means that a compromise of the key or keystream will allow forging the data in question.
- If you’re depending on unauthenticated data from within a high-security domain, even if it is only accessible by highly-privileged code, exercise due diligence on ensuring that the data is valid — e.g., employ bounds-checking on structures in the data.

As a side note, we would like to warn the interested reader that, should they decide to further attempt to understand the secure boot process of the Switch by reading the publicly available Atmosphère reference code, take note that the key-generation is not done for 7.0.0 firmwares in the same way that it is done on the original bootloader.

Sept [35], is a payload they designed to bypass checks implemented in SecureBoot. It does so by loading the original 7.0.0 TSEC firmware, unmodified. The TSEC firmware is
designed to verify the AES CMAC of the PK11 binary, before returning execution to the bootloader there. Sept works because the CMAC was forged on the custom PK11, passing the code authentication routines in SecureBoot. Sept, now in PK11, derives keys in place in packageLdr and scrambles the TSEC and TSEC root key, making it impossible whatsoever to use the original Secure Monitor firmware, as it doesn’t have the keys necessary to further perform key generation.

VI. Conclusion

We completely broke the security system of one of the most secure embedded consumer devices on the market with no prior knowledge of its hardware nor software.

Unlike most of the existing literature on computer science security, we decided to focus on the inductive process of finding security flaws and fixing them, rather than explaining how they work and implementing exploits for them. This decision was motivated by having most of the security flaws we independently found already published online, some being released before or even during the writing of this paper! Our inability to talk about some potentially damaging non-public security vulnerabilities related to the Tegra X1 did not help either. We also think finding flaws in embedded devices is much more interesting to write about, as a whole.

We would also like to stress that this paper’s ultimate goal is not to expose Nintendo’s flaws, but rather to help computer security research be aware of such possible flaws, and as such would like to give our point of view on what could have been improved by Nintendo to avoid those exploits.

Firstly, exploits such as sm:h and pl:utonium seem to present a crucial lack of auditing. While we are aware that auditing the entire runtime code of the Switch firmware would be impractical, serious security audits must be done on every privileged bit of code that could be harmful and are a prime attack target, which is indeed the case of the NS and SM servers. Optionally, switching to safer languages (such as Rust [37] or formally-verified coding paradigms, would have altogether avoided both of those flaws. If some code has to be privileged and yet not trusted, such as a blob of third party code, then it is good practice to try to isolate it as much as possible. Positioning services such as pl:u separately from the main NS services is also a good idea, even though such separation should have been more pronounced in that particular case.

Moving on to any secure code attacks and secure key retrieval: it is crucial to add anti glitch measures to make glitching with low-cost, low-complexity equipment as hard as possible. Depending on your threat model, it might also be a good idea to encrypt the ROM stored inside the SoC. While a powerful attacker could, ultimately, decap the SoC, reverse engineer cryptography primitives used to decrypt the boot ROM [38], and laser glitch his way around the program, the process should be as arduous as possible if we want any cryptographically secure software boot on devices at all. Decap and laser glitching will most likely always be possible, but when this becomes part of the least effort approach then we might have some chance at protecting secrets.

Any code implementing any cryptography primitive, especially if it’s considered secure and crucial to the chain of trust in a system, should not only be audited in order to avoid basic security issues, but also be hardened against side-channel attacks, such as power analysis and fault injection [39], at the very least, to avoid any early breakage of the trust chain.

Ultimately, security is defined by failures thereof. Software Engineering should learn from traditional engineering in that point, as software and software systems CAN fail, and we should accordingly plan for even a slim margin of error in that regard. As such, mitigations against common faults in software security should be graciously applied whenever possible, and a clear list of everything a user could potentially control, must be set.

A sad thing about security, is that it is mostly decided by your budget. Even if you have a state-level intelligence threat the smaller your budget is, the less you’ll invest in security, if this isn’t one of your unique selling points. This shows in IoT devices and, in some cases, forced hackers to exploit vulnerabilities, in order to patch them. Our approach to security should change altogether.

We must focus on putting the best practices at the forefront, to the point that they are the easiest to implement, otherwise we will continue to be trapped in the conspiracy against trust.

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