Minimum Viable IO Drivers for TrustZone

Liwei Guo
University of Virginia
lg8sp@virginia.edu

Felix Xiaozhu Lin
University of Virginia
felixlin@virginia.edu

Abstract
While TrustZone can isolate IO hardware, it lacks drivers for modern IO devices. Rather than porting drivers, we propose a novel approach to deriving minimum viable drivers: developers exercise a full driver and record the driver/device interactions; the processed recordings, dubbed driverlets, are replayed in the TEE at run time to access IO devices. Driverlets address two key challenges: correctness and expressiveness, for which they build on a key construct called interaction template. The interaction template ensures faithful reproduction of recorded IO jobs (albeit on new IO data); it accepts dynamic input values; it tolerates nondeterministic device behaviors. We demonstrate driverlets on a series of sophisticated devices, making them accessible to TrustZone for the first time to our knowledge. Our experiments show that driverlets are secure, easy to build, and incur acceptable overhead (1.4×–2.7× compared to native drivers). Driverlets fill a critical gap in the TrustZone TEE, realizing its long-promised vision of secure IO.

1 Introduction
Arm TrustZone is a trusted execution environment (TEE). It hosts small programs called trustlets, which manage sensitive data against an untrusted OS. Designed for IO-rich client devices, TrustZone features secure IO: the TEE maps an IO device’s physical resources – registers, interrupts, memory regions – to the TEE’s address space, therefore keeping them inaccessible to the OS. Trustlets can use secure IO for: (1) storing credentials, keys, and biometric data; (2) acquiring sensitive audio and video for processing; (3) rendering graphical UI with security-critical contents [43]. In these use cases, IO data moves between trustlets and IO devices, bypassing the OS; the trusted computing base (TCB) consists of only the TEE and the underlying hardware.

Secure IO, however, remains largely untapped today. Popular TrustZone runtimes such as OPTEE and Trusty have been developed for almost one decade; yet they still cannot access important IO – flash storage, camera, display controller, etc [6]. The difficulty lies in device drivers. Implementing drivers for IO devices – even to only support a small set of functions needed by trustlets – can be non-trivial. For instance, to read a block from a SD card, a multimedia card (MMC) driver issues more than 1000 register accesses: configuring the MMC controller, exchanging 5–6 command sequences with the storage hardware, and orchestrating DMA transfers. To do it correctly, developers need to reason about the bus protocols in over 200 pages of MMC standard and the device’s register interface. They also need to deal with hardware quirks or bugs [5].

How about reusing mature drivers from a commodity OS? This route, unfortunately, is difficult. Mature drivers are designed to be comprehensive. They are often large, structured as multiple abstraction layers. They depend on a variety of kernel services. For instance, the MMC driver in Linux comprises 25K–30K SLoC scattered in over 150 files; it invokes kernel APIs such as slab allocator, DMA, and scheduling. Developers may attempt to port the driver in two ways. (1) They bundle the driver and all its dependencies and port them to the TEE (i.e. “lift and shift”). This is likely to move excessive, or even most, Linux kernel code to the TEE, adding hundreds of K SLoC [47]. This defeats TrustZone’s principle of a lean TCB. (2) Alternatively, they may do surgery on the driver, stripping code unneeded by the trustlets. To do so, they reason about driver and device internals such as MMC standard. Meanwhile, they still have to port a variety of kernel APIs. Our experience in Section 6 shows high efforts on reasoning, debugging, and trial-and-error.

Approach Simple trustlets do not deserve complex device drivers. We advocate a new way for deriving drivers for them: instead of reusing a mature driver’s code, we selectively reuse its interactions with the device. The basic idea is shown in Figure 1. (1) Developers exercise a mature driver with a collection of sample invocations that would be made by the trustlets, e.g. write 10 blocks at block address 42. (2)
Our recorder logs driver/device interaction events: register accesses, device memory dumps, and interrupts. (3) At run time, as the trustlets invoke the driver interfaces, the TEE replays the recorded interactions.

Compared to driver porting, our approach requires less effort. Developers only reason about the driver/device interfaces for recording, remaining oblivious to the complex device/driver internals. We further ensure security. The record runs are done on a developer’s machine, an environment often deemed trustworthy [42]. The shipped recordings only comprise primitive interaction events but no complex code. The replayer implements selective driver functionalities at the lowest software complexity. It is as simple as a few KSLoC and enforces stringent security checks. Section 7 will present a detailed security analysis.

**Challenges** We have addressed twofold challenges. (1) Correctness. By following pre-recorded interactions, how does the replayer assure that it faithfully reproduces the recorded IO jobs, e.g. having written given data to block address 42? This is exacerbated by the device’s nondeterministic behaviors, e.g. it may return different register values or different interrupts in response to the same sequence of stimuli. (2) Expressiveness. The record runs only exercise the driver with some concrete points in the whole input space, e.g. \{BlkNum=42, Count=4\}. Can the recorded interactions be generalized to cover larger regions of the input space, e.g. \{0<BlkNum<0xffff, 0<Count<32\}?

**Driverlet** We present a system for recording and replaying driver/device interactions. For a given IO device, the recorder produces recordings from multiple record runs, dubbed a driverlet. The driverlet offers satisfactory coverage of IO functions as needed by the trustlets, e.g. to access flash storage at a variety of block granularities. Essentially, a driverlet is the device’s minimal viable driver.

A driverlet provides the same level of correctness guarantee as the full driver with the following insight: a replay run is faithful when the device makes the same state transitions as in the record run. Motivated by this insight, the recorder identifies a series of state-changing events from the recorded interactions. The state-changing events are the “waypoints” that a faithful replay must precisely reproduce. As for other interaction events not affecting the device state, the recorder emits constraints on them to tolerate their deviations from the recording in a principled manner. This approach sets us apart from many record-and-replay systems [23], where replay must reproduce the recorded executions with high precision including all the non-deterministic events.

The recorder extracts from each record run an interaction template, which, at a high level, specifies the behavior envelope for the replay run. The template prescribes input events that the replayer should expect, which may come from the program (trustlet), the device, or the TEE environment; the template also prescribes output events that the replayer should emit to the latter. By reproducing the sequence of input/output events, the replayer is guaranteed to induce the same device state transitions as in the record run, reproducing the IO job faithfully.

An interaction template is more expressive than a raw log of interactions in three ways. (1) Input events accept dynamic values that are not limited to the recorded concrete values. (2) Output events may specify parameterized values, which encode data dependency between earlier input and later output. (3) Polling loops in the driver code are lifted as meta-events, each replayed as a varying number of input/output events until the loop termination condition is met.

**Results** We implement the recorder with a suite of known techniques: taint tracking, selective symbolic execution, and static code analysis. We apply our approach to a variety of device drivers that previously were regarded too complex to TEE: MMC, USB mass storage, and CSI cameras. With light developer efforts and no knowledge of device internals, our recorder generates driverlets, each comprising of 3–10 interaction templates and 50-1500 interaction events. The replayer itself has minimal dependencies on the TEE; it is of 1000 SLoC, which are three orders of magnitude smaller than the full drivers. The driverlets incur modest overheads: on Raspberry Pi 3, a low-cost Arm platform, trustlets can execute 100 SQLite queries per second (1.4× slower than a full-fledged native driver) and capture images at 2.1 FPS from a CSI camera (2.7× slower). They provide practical performance to use cases of secure storage and surveillance.

**Contributions** This paper contributes:

- A new model called driverlet for reusing driver/device interactions via record and replay. The driverlets generalize the recordings as interaction templates, ensuring sound replay while accepting new inputs beyond those being recorded.
- A toolkit for automatically exercising a full driver and generating driverlets.
- Case studies of applying driverlets to a variety of complex device drivers. The resultant driverlets are immediately deployable to TrustZone. With them, the TrustZone TEE gains access to these devices for the first time to our knowledge.

By fixing a long missed link in TrustZone, driverlets enable holistic, end-to-end protection of the IO path.

2 Motivations

2.1 Example trustlets of secure IO

The following use cases motivate our design. In these cases, TEE protects the IO, prevents the OS from observing sensitive IO data and tampering with the data.

- Secure storage. Trustlets manage sensitive data, such as credentials, fingerprints, and user emails. The trustlets store and retrieve the data by using an in-TEE multimedia card (MMC) controller and the flash medium, such as eMMC.
• Trusted perception. Trustlets ingest sensitive data from sensor hardware protected within TEE. A particularly interesting case is video, which often contains privacy sensitive contents and requires non-trivial camera drivers.
• Trusted UI. Trustlets render to screen security-sensitive contents, such as service verification codes and bank account information; the UI reads in user inputs such as key presses and touch. Both the display controller and input devices are isolated in TEE [43, 54].

IO functions needed by trustlets The above use cases all rely on trustworthy device drivers, for which we exploit the following opportunities. Compared to apps in the normal world (e.g. Linux), trustlets are less demanding on IO:
• Trustlets are less sensitive to IO performance. For instance, trustlets managing user credentials or email contents do not need high storage throughput; trustlets for surveillance can be served with median to low frame rates and resolutions (e.g. 720P at 1FPS [25, 58]).
• Trustlets can be served with simple device features for IO. In the examples above, trustlets, for their simplicity, only need write/read of flash blocks, acquisition of individual video frames, and rendering given bitmaps or vector paths to given screen coordinates. They are unlikely to need complex device features, e.g. hotplug of flash cards.
• Trustlets may share IO devices at coarse-grained time intervals. Concurrent trustlets are far fewer than normal-world apps. Even when multiple trustlets request to access the same device, their requests can be serialized without notable user experience degradation. Examples include serializing accesses to a credential storage and serializing drawing requests to a trusted display.

These observations motivate our approach of record and replay, which trades IO performance and fine-grained sharing for simplicity and security.

2.2 Prior art

Mature device drivers Drivers in commodity OSes are often overkills to trustlets because of their following design choices. (1) Optimal performance. For instance, an MMC driver tunes bus parameters periodically (by default every second). It implements a complex state machine for handling corner cases, so that the driver can recover from runtime errors with minimum loss of work. (2) Device dynamism. The drivers support full device features as permitted by hardware specifications, e.g. runtime power management [4], device hotplug [8]. (3) Fine-grained sharing. A driver maintains separate contexts for concurrent apps. The driver multiplexes requests at short time intervals. Some drivers, e.g. USB implement sophisticated channel scheduling for optimizing throughput and meeting microframe deadlines.

Existing approaches The following approaches may be used to bring drivers into TEE. (1) Lift and shift. One may bundle a full driver with all its kernel dependencies and port to the TEE [27, 47]. While easing porting, this approach often adds substantial code (tens of KSLoc) as well as inherits vulnerabilities to the TEE. (2) Trim down. Developers may manually carve out only needed driver functions from kernel, which is done to simpler drivers, e.g. UART in TEE. It however is impractical for non-trivial drivers, which have deep dependencies on numerous device configurations and kernel frameworks. Section 7 presents our own experiences on trimming three drivers. (3) Synthesis. While it is possible to synthesize some drivers from scratch – if the device FSM is fully known, this approach requires non-trivial efforts. Developers have to write specification for FSM [52], develop code templates [53], and write glue code. In case of secure IO, we deem such synthesis efforts unwarranted, because trustlets only need simple IO functions and the source code of a mature driver is already available.

3 Approach overview

3.1 System model

SoC hardware We assume an IO device instance exclusively assigned to the TrustZone TEE. This is feasible as a modern SoC often has multiple independent instances of the same device, e.g. 4–6 MMC controllers [39–41]. Through an address space controller (TZASC), the Arm SoC maps selected physical memory and device registers to the TEE.

Targeted IO devices We focus on IO devices that have strong use cases in TEE. These devices manipulate sensitive IO data while lacking end-to-end data encryption. Examples include USB storage, video/audio devices, and display controllers. We make the following assumptions.
• Device FSM. A device operates its internal finite state machine (FSM), which encodes the driver/device protocol and decides device behaviors [32, 49, 60]. The FSM is reactive to requests submitted by a driver, e.g. read/write flash blocks; it does not initiate requests autonomously. During request execution, the device state transitions are independent of IO data content, e.g. the state of a MMC controller is unaffected by the content of the block being read.
• Driver/device interactions events. The driver’s interfaces to a device include registers, shared memory, and interrupts. The interactions are a set of input and output events from the driver’s perspective. The input events include reading device registers/shared memory and receiving interrupts from a device; the output events include writes to device registers and shared memory.
• State-changing events are input/output events used by a driver to shepherd the FSM execution of the driver’s request. Figure 2 (a) shows a motivating example of them: output events prepare the buffer and kicks off the FSM execution of command 0x18; input events, i.e. interrupt and IRQ status read, reflect the device execution states; depending on the
success status (0x1), the driver de-asserts the IRQ by writing 0x0 to the status register.

Given the causality between a driver’s output to the device and the device’s state changes, we define state-changing events to include all output events, which directly change the device state, and the set of input events impacting the driver’s subsequent output, which indirectly change the device state. Our system automatically identifies them, which we present shortly in Section 4.

The gold driver. We assume that the full driver implements sufficient state-changing events, so that it can assess if the device has finished the state transitions needed by given requests. We do not rule out other bugs in the driver, of which consequence will be discussed in Section 7.

3.2 Our approach

Our idea is to selectively reuse driver/device interactions induced by device state transitions. The core mechanism is as follows.

- **Prerequisite.** To finish a given request, the device must always follow the same path of state transitions. As such, we configure the driver so that it constrains the device’s state space: disabling irq coalescing, concurrent jobs, and runtime power management.
- **To record.** The driver is invoked with a concrete request, e.g. to read 16 blocks starting from block 42. In this process, the driver/device interactions are logged, including accesses of register and DMA memory and interrupts.
- **To replay.** The raw log is generalized as an interaction template. The template strikes a balance between simplicity and flexibility. It dictates a linear sequence of input/output/meta events, which are a replayer’s minimum activities to fulfill the recorded request. It accepts dynamic inputs (from program/environment/device) that are much broader than just the logged input values.

Section 4 will present the mechanism in full.

3.3 Why driverlets work

We discuss three key questions tied to the driverlet design: how does a driverlet assure the correctness? how expressive is it? what happens if it fails?

A driverlet is as correct as a gold driver, as long as the replay is faithful. For the replay to be faithful [23], the driverlet observes the same sequence of state-changing events as the gold driver observes at record time. A proof sketch is two-step. 1) The recorded state-changing event sequence establishes an externalized device state transition path; faithful replay drives the device to undergo same path, which is equivalent to the recorded one as far as device FSM is concerned. 2) If for the same sequence there exists an alternative path undetected by a driverlet, e.g. the state-changing events of a write request are observed but data is silently lost, it is also undetected in a gold driver; this means the recorded gold driver does not implement sufficient state-changing events for inferring device states, contradicting to our assumption (§3.1). Figure 2 (b) shows an example. The replayer deems the replay run correct, because all the state-changing events match those in the record run (a), except for the generalized values in output events, which are key to driverlet’s expressiveness.

A driverlet is as expressive as a subset of full driver functionalities. The subset of functionalities is encoded in device state transition paths, externalized by sequences of state-changing events. By carefully generalizing output events of the sequences, a driverlet replaces stimuli to device FSMs while staying on the same state transition paths. It retains the capabilities to access arbitrary data but must access the data in ways specified by the recorded paths, e.g. accessing at the granularities of 1, 8, or 32 flash blocks. It leaves out other driver functionalities, such as accessing data at arbitrary granularities, optimizations for large transfers, and dynamic device management.

A driverlet deals with state divergence by device reset. Should the replayer observe any state changing event mismatching the recording, it deems a diverge in state transition and a failure in request execution. Figure 2 (c) shows an example where the IRQ status (0x2) mismatches the recording (0x1). Fundamentally, such divergences happen because the device FSM has received stimuli unexpected by driverlets. We identify three major sources. (1) Residue states left by prior requests. For example, device FIFOs are yet to be flushed; at different times the replayer may read different number of available slots. (2) Fluctuation in chip-level hardware resources such as power, clock, and memory bandwidth. (3)
Unexpected hardware failures. For example, a media accelerator losing the connection to the image sensor. To prevent divergence from happening (cause 1 above) and recover from transient failures (cause 2 and 3), the driverlet resets the device before executing each template and upon divergence. Section 7 will discuss the efficacy of recovery.

4 Record

How to use To generate a driverlet, e.g. for MMC, developers launch a record campaign, exercising the driver in multiple runs. In each run, the developers supply a different sample input (e.g. BlkCount = 1, RW = 0); from the run, a recorder produces an interaction template. Once done, the recorder signs the templates which are thereafter immutable, and reports a cumulative coverage of the input space, e.g. 0 < BlkCount < 32, RW = {0|1}. If the developers see a desirable input uncovered, they do a new record run with input v to extend the input coverage. They conclude the campaign upon satisfaction of the coverage.

4.1 Problem formulation

We next formulate the recording problem.

Record entry is one kernel function completing an IO request. A record entry may invoke multiple functions in a driver, e.g. one single kern_read() to read flash blocks or a series of ioctl() to acquire an image frame.

Recorded interfaces include the following.

- Program ↔ Driver: the interface seeds the recording. It includes kernel entry function(s) invoked with initial arguments, e.g. {BlkCount = 16, BlkId = 0}.
- Environment ↔ Driver: it includes a number of kernel APIs invoked by a driver, from which the return values may be exposed to the device. Examples include DMA memory allocation, random number generation, and timekeeping.
- Device ↔ Driver: the interface is the frontier of driver/device interaction. It includes access to device registgers, descriptors in shared memory, and interrupts.

The recorder logs raw events and their concrete values.

Record outcome: interaction templates A template exports a callable interface to the replayer. The interface has same signature as the kernel entry for recording. The template comprises a sequence of events in Table 1:

- An input event V = <I, C, A> expects an input. The input interface I can be a device register, shared memory address, or environment API. When the expected value V is specified, it must satisfy the constraint C; otherwise the replayer will reject the input event as a replay failure. The argument A specifies the input’s properties, e.g. expected input length; it can be concrete or a symbolic expression of an earlier input.
- An output event <I, V> writes a value V to an interface I. V can be concrete or a symbolic expression of an earlier input.

| Events | Description |
|--------|-------------|
| V=read(I, C, A) | Read A bytes from register/shm address I at V with constraint C |
| V=dma_alloc(C=Null, A) | DMA Allocation of A bytes at V |
| V=get_rand_bytes(C=Null, A) | Get a random bytes from env. Get A random bytes at V |
| V=get_ts(C=Null, A) | Get timestamp of A bytes at V |
| wait_for_irq(C=Null, A) | Wait for an interrupt from IRQ number A |

| Meta | delay(A) Delay for N microseconds |
| Meta | poll(I, E, Cond) Poll from register/shm address I, execute loop body E until condition Cond is met |

### Table 1. Events in interaction templates for replay

- A meta event is delay or poll < I, E, Cond >. The latter polls from an interface I until a terminating condition Cond is met. The loop body E is a series of input/output events.

For debugging, each event is accompanied by its source location in the full driver.

4.2 Key challenges & solutions

We next discuss automatic generation of interaction templates, which must handle input variation while still maintaining correctness. We have addressed three challenges.

![Figure 3. An example of our system extracting constraints, data dependencies, and polling loops into a template.](image)

**Challenge 1: How to discover causal dependencies between input/output events?** This is to identify state-changing events (§ 3.3) and discover constraints, thus to reject inputs that will compromise replay correctness, i.e. deviation from the correct device state transition path. Naively matching concrete values in raw logs does not work because variations in input values may not indicate state change, e.g. input values from a FIFO statistics register, which is time-dependent and do not correspond to a device state change.

**Solution: Concolic execution.** Our idea is to study whether variations in input values impact the driver output events, i.e. a causal dependency. The rationale is the driver, by design, always reacts to state-changing inputs and decides output events correspondingly. An example is the FIFO statistics register mentioned earlier: in MMC, finding the watermark
too high, the driver writes to a configuration register to tune the device bus bandwidth which changes the device state. To this end, the recorder uses concolic execution [14] to explore the driver’s multiple executing paths and assess if they lead to different device state transitions; to avoid path explosion, it prunes as soon as there is divergence in output event sequences. This is shown in Figure 3. As the driver executes with a concrete input BlkCnt = 6 and encounters a conditional branch pertaining BlkCnt (BlkCnt ≤ 8), the recorder forks the driver execution, explores both (one actual path with concrete BlkCnt = 6 and the other is alternative), and compares their subsequent device state transitions. It discovers the alternative path has a divergent 8K DMA memory allocation, hence concluding the path’s state transitions are different and terminates early; in the meantime due to such causality, it flags input event of BlkCnt as a state-changing event. Throughout the execution, the recorder flags state-changing events and collects path conditions of the same state transition, e.g. BlkCnt ≤ 8. These path conditions serve as the constraints input events must satisfy to stay on the same device state transition path. Section 4.3 will present implementation details.

Challenge II: How to discover data dependency between input/output events? Input values may be processed and used as an argument of another input event or as an output value by the driver, forming data dependencies. For instance, upon an incoming image frame, the driver requests a DMA memory region whose size is notified by the device, and writes aligned address of the memory region to a register to receive the image.

Solution: Dynamic taint tracking. The recorder discovers data dependencies with dynamic taint tracking: it taints all input values at all interfaces, propagating the taints in driver execution and accumulating both arithmetic and bitwise operations on the taint value until the taints reach their sinks. For each taint sink, the recorder replaces the concrete value in its raw log with a symbol for taint source and the accumulated operations. blkID in Figure 3 shows an example. The recorder tracks blkID and discovers its taint sink SDARG and a bitwise and operation (blkID& = 0x7) for alignment. It hence emits an output event with a blkID symbol plus its operations.

Sometimes, the dependency is at a higher order, e.g. input value blkcnt has dependency with the logic that decides the number of descriptors. As shown in Figure 3, the driver allocates more descriptors when blkcnt > 8. Depending on the number of descriptors, a driver, per the device protocol, often links descriptors as pointer-based structures such as lists or arrays of lists; it may further optimize the structures based on descriptor addresses, e.g. coalescing adjacent ones. Figure 4(a) shows the descriptor topology for an MMC controller (details in Table 2). For every eight sectors of a request the driver allocates a 4K page and associates a descriptor with the page; it links them via a physical pointer field in the descriptor and writes the address of the head to DMA_ADDR register.

While it may be possible to extract the logic with some device-specific heuristics, such heuristics is likely brittle; both the recorder and the replayer will be more complex in order to encode and interpret the logic. For simplicity, the recorder sets DMA allocation (an input event) as state-changing, thus mandating that a template must allocate the same number of descriptors as in a record run. The interaction template in Figure 4 (b) shows a faithful reconstruction of the descriptor topology: the template allocates a fixed number of descriptors, and chains them by writing their symbolized addresses to corresponding descriptor fields.

Challenge III: How to record polling loops? A major source of nondeterminism is polling loops. For example, a driver waits for a command to finish by polling a command status register, in which the number of register reads depends on the timing of command execution. While conceptually simple, a polling loop is known difficult to dynamic code analysis, as it may generate many or even infinite alternative executing paths [57]. To explore all paths looking for device state divergence is impractical.

Solution: Static Loop analysis. The polling loops in driver/device interfaces are often succinct, local, and have clear a code structure. For example, the Rpi3 MMC driver implements polling loops by either using standard kernel register polling function (e.g. readl_poll_timeout) or a short while loop (<10 SLoC). With static code analysis [33], we find the polling loops and lift each loop as a standalone meta event, which preserves the loop condition and the input/output events in the loop body. This allows the replayer to execute a varying number of input/output events for a loop.

4.3 Recorder implementation

We implement the recorder based on S2E v2.0 [15], a popular symbolic execution engine. We choose it because it provides in-house support for analyzing Linux kernel drivers and is
based on QEMU [11], which uses dynamic binary translation
and is easy to interpose on instruction-level execution states.
The overall idea is to exercise the driver in S2E, use S2E trace
printer to log the driver execution, and distill an interaction
template from the logs. Parsing the logs is trivial, which
is done by a Python script of 1K SLoC. The key question
is how to log the symbolic execution results as S2E exe-
cutes. Fortunately, for most logs we retrofit rich S2E plugins
and only add minor modifications to dump more informa-
tion (e.g. concrete values, callsites); e.g. ExecutionTracer
to log path conditions, MemoryTracer to log taint propagation,
LoopDetector to extract loops. To overcome the key chal-
lenge of reaching deeply (i.e. to mitigate path explosion),
we run S2E on a workstation and set up a separate target SoC,
which runs the same record campaign; the architecture is
shown in Figure 5. We record concrete input values from the
SoC during driver execution and use them to seed symbolic
execution of S2E. Specifically, they are values from actual
device registers/descriptors and invocation of kernel APIs.
We describe our experience as follows.

Seeding with actual inputs from device Input values
from a device need to be symbolized for comparing state
transitions on forked paths. A device may have dozens of
symbolized input values which easily lead to path explosion.
To make it worse, QEMU cannot supply concrete values
by itself, as it only emulates device IOs via guest OS file
operations without reproducing a device FSM. We overcome
this by recording the concrete device input values from a
real device and seed S2E with them, shown in Figure 5. We
do this iteratively: as soon as the execution is curbed by
path explosion on a device input, we seed it with a concrete
value recorded from a real device. Alternatively, actual device
inputs may come from online driver execution [56], which
we forgo due to complexity.

Emulating kernel functions Input events at Env→Driver
interface are kernel API invocations. We only care about
its arguments (e.g. DMA allocation size) and return results
(e.g. DMA address); their internal invocations may cause
path explosion and pollute the log. We prevent the symbolic
execution path from digressing by emulating their APIs. We
leverage the FunctionModels plugin for the purpose: without
implementing any internal logic, it directly returns a symbol
with a seed from the actual device, e.g. a legal DMA address.

5 Replay

Overview In TEE, a trustlet statically links the replayer and
compressed package of interaction templates as a library,
which constitute “driverlets” for target devices. To use a
driverlet, the trustlet invokes the exposes callable interface
exposed by the interaction templates (§ 4.1). Under the hood,
the replayer dynamically selects a template, instantiates it,
and executes its input/output/meta events; it resets device
states between templates and upon device state divergence.

Selecting an interaction template. The replayer decom-
presses the interaction template package within the TEE.
Upon trustlet invocation, the replayer checks with constraints
of initial input values on each template. It selects one that
have all constraints satisfied by trustlet inputs. By design,
no two templates can be selected simultaneously, i.e. same
inputs satisfy initial constraints of both templates; otherwise
they should have been merged by the recorder due to same
state transition path (§ 4.3). If no template is selected, mean-
ging the desired input is not covered, it prompts the trustlet
an error and halts.

Instantiating the template. Prior to execution, the re-
player parses and instantiates the selected template with
TEE runtime. For physical device addresses, it replaces them
with newly mapped TEE virtual addresses. It preserves sym-
bolized input/output values and refers to them by unique
names. It updates callbacks of all events to point to respective
TEE APIs. Most events do not need special support from TEE
kernel. For instance, read and write which constitute over
90% events, are directly supported by memory read/write;
meta events are implemented in simple while loops and de-
lays. Only input events at Env→Driver interfaces do, e.g.
DMA allocation requires a CMA pool. Luckily, they are likely
supported by an existing TEE kernel, e.g. the default OPTEE-
OS memory allocator (malloc) already allocates contiguous
memory, it supports hardware rng.

Executing events. The replayer uses a single-threaded, se-
quential executor for events. It maintains two contexts: a nor-
mal context corresponds to the kernel context in the original
driver; an interrupt context corresponds to the IRQ handler,
where only a minimal part is handcrafted to recognize IRQ
source and the rest is for replaying. The scheduling of two
contexts is triggered by wait_for_irq input event, whose
timeout is one second. The design constrains the device state
space in the same way as a record run by limiting hardware
concurrency (§ 3.2), hence preventing many potential state
divergences.

The executor is transactional. On a happy path, all input
events constraints must be satisfied, including timely inter-
rupts; it returns to trustlet with success and requested data,
if any. Otherwise, it soft resets the device and re-executes
the template, which we next discuss.
Resetting device states. The replayer soft resets the device under two circumstances: 1) between interaction template executions, 2) upon device state divergence. The soft reset brings the device back to a clean-slate state – as if the device just finishes initialization in the boot up process. The soft reset recovers from transient device errors, e.g. data bus CRC error. In case of persistent divergence, the executor aborts and dump the call stack; it does so by rewriring all previous events, reporting their recording sites (source file and line number). Section 7 will evaluate the efficacy of device reset and its performance overhead.

Self security hardening. The replayer hardens itself by implementing following list of stringent security measures: it verifies recording integrity by developers’ signatures prior to use; it only takes inputs from trustlet and the interaction template and does pervasive boundary checks (e.g. device physical address) on both to mitigate attacks exploiting memory bugs; it eliminate concurrency to avoid dangerous race conditions. Section 7.2 will present an security analysis.

6 Experiences
We applied our system to a variety of devices, namely MMC, USB, and Camera. We select them because they have important use cases of secure IO and their drivers are complex and known difficult for TEE.

| SoC       | Raspberry Pi Model 3B+, 1GB Normal OS Linux 4.14 |
|-----------|-----------------------------------------------|
| CPU       | 4x Cortex-A53@1.4 GHz Secure OS OP-TEE 3.9     |
| MMC       | Transcend 16GB microSDHC Class10 UHS-1 Memory Card |
| USB       | Intenso GmbG Micro Line (8GB) VID:0x8644 PID:0x8003 |
| CSI Cam   | Arducam 5MP Camera with OV5647 sensor          |

Table 2. The test platform and peripherals used.

Our test platform is RPi3; Table 2 shows board the details of the board and peripherals. We choose RPi3 because of its popularity and good support for open-source TEE software. As we will show, despite an active community and high attention for RPi3 (far more than most other SoC hardware), building TEE drivers is nevertheless difficult.

For each driver, we report our findings and answer the following questions:

- How complex is the driver and why is it complex?
- With hindsight, what are discovered and recorded (i.e. do recordings what were they asked to?)

6.1 MMC

6.1.1 Driver overview. MMC is a common interface to off-chip flash, e.g. SD cards and eMMC. The Linux MMC framework supports more than 20 MMC controller models with diverse interfaces and poor documents. The framework abstracts the common driver logic as a “core” with 15K SLoC in 40 files; a driver for a concrete MMC controller plugs in the MMC core via a wide interface, including 44 callbacks implemented in four structs. The driver itself often has a few K SLoC. All combined, the MMC framework implements a FSM with thirteen states and hundreds of transitions among them. The FSM supports rich features, including streaming access of blocks and medium hotplug.

| Events    | RW_1 | RW_8 | RW_32 | RW_128 | RW_256 |
|-----------|------|------|-------|--------|--------|
| Input     | 24/27| 24/27| 27/30 | 39/42  | 55/58  |
| Output    | 17/14| 17/14| 32/29 | 76/73  | 150/147|
| Meta      | 3/3  | 3/3  | 3/3   | 3/3    | 3/3    |

Table 3. Breakdown of 10 interaction templates of MMC given the replay entry replay_mmc. RD/WR templates of same blkcnt merged in one column (e.g. RW_1), separated by ”/” (e.g. 24, 27 input events for RD_1, WR_1).

6.1.2 Recording outcome. We choose to implement a record campaign of 10 requests: read/write of 1, 8, 32, 128, 256 blocks. We reserve the 15-th DMA channel for recording. The replay entry, ten automatically generated templates (e.g. RW_1) and their event breakdown are listed in Table 3. Each template covers the full range of 31M sectors available. We have found templates are similar with each other, e.g. RW_8 and RW_32 only differ by 2 DMA allocations, due to additional descriptors.

6.1.3 Post analysis. Our system has observed two distinct state transition paths w.r.t different flags. (1) if O_DIRECT is specified, the full driver shifts individual words of data blocks from/to SDDBATA. (2) otherwise the driver uses DMA transactions to move the data. Notably, even when using the DMA transaction, the driver moves the last 3 words via SDDBATA on read path. This seems to work around an undocumented bug in the SoC’s DMA engine, which cannot move the last few words of a transfer.

Each interaction template involves 15 different registers out of 24 total registers of MMC controller and a system-wide DMA engine, in three groups: 8 for configuring the controllers, 5 for sending MMC commands, and 2 for controlling DMA engine. Key symbolized inputs values are encoded into 32-bit word written to 4 different registers, as shown in Table 4. Notably, including read/write, five different SD commands (CMD17, 18, 23, 24, 25) are sent to SDCMD; CMD23 (set block count) is used on the read path but not write path. Our system has also gathered taints on blkid by Linux block layer for 8-block alignment. We tried manually feeding misaligned blkid and caused state transition divergence.

| Input     | Constraints                     | Taint sink & operations |
|-----------|--------------------------------|-------------------------|
| rw        | =0x1(RD)||0x10(WR)              | SDCMD = ((0x8000) | (rw) <= 6) |
| blkcnt    | ≥0 & ≤0x8 & ≤0x400              | SDHBLC = blkcnt         |
| bid       | ≥0 & ≤0x1d17/18                | SDARG = bid & (~0x7)    |

Table 4. Key constraints and operations of RW_1 template.

6.2 USB

6.2.1 Device overview. USB serves as a common transport between CPU and diverse peripherals, e.g. keyboards,
and flash drives. A typical USB controller exposes more than 100 registers. A device driver programs them to initiate transactions and dynamically schedule them on multiple transmission channels; the controller translates each transaction into up to 12 types of packets on the bus. Through 21K SLoC in 82 files, Linux kernel fully implements the driver FSMs, which are big in order to accommodate rich features (e.g. dynamic discovery of bus topology) and various runtime conditions (e.g. device speed mismatch, bus checksum errors).

We focus on USB mass storage for its significance to TEE’s secure storage. The driver accepts block requests, translates the requests to various SCSI commands, and further maps the commands to USB bulk transactions.

### 6.2.2 Recording outcome

We apply the same record campaign as MMC for 10 read/write requests. We reserve 1st transmission channel. We disable Start-of-Frame (SoF), which is used to schedule USB transactions proactively for isochronous USB devices and unfit for our model (§ 3.1).

For the record campaign, our system emits 200-1500 events for 10 interaction templates, each covering the whole 15M sectors of USB storage. Interestingly, the number of events are identical in a read template and the corresponding write template; it appears only some output values to certain descriptors differ.

### 6.2.3 Post analysis

Our system has captured non-trivial interactions. To write blocks smaller than one LBA (4KB), the driver reads back the entire LBA, updates in memory, and writes back. The driver also selects the best SCSI commands: there exist five multiple variants of SCSI commands, which have different lengths and can encode different ranges of LBA; the driver picks the 2nd shortest ones (i.e. read 10, write 10) just long enough to encode the requested LBA addresses.

Our system identifies 14 USB controller registers out of the 64 KB register range in three categories: 5 manage USB peripheral states (e.g. device power state); 3 manage the controller itself (e.g. interrupts); 6 manage transmission channels (e.g. DMA address & size). Unlike MMC, the USB driver communicates with the device primarily via two descriptors: one command block wrapper (CBW) for SCSI commands and the other for querying command status (CSW). The data dependencies are similar to MMC, except aligned blkid and blkcnt are written to CBW instead of registers. Our system identifies two statistic inputs which are unseen in MMC: a monotonic command serial number and HFNUM register read. As they are not state-changing, our system does not impose any constraints.

### 6.3 Camera

#### 6.3.1 Device overview

On modern SoC, CPU typically offloads video/audio processing to accelerators, which communicate with CPU primarily via messages backed by shared memory. We studied VC4, the multimedia accelerator of Rpi3.

According to limited information, VC4 implements key multimedia services, including camera input, display, audio output. It communicates with the CPU via a complex, proprietary message queue called VCHIQ. Using VCHIQ as a transport, each media service further defines its message format and protocol, e.g. MMAL (MultiMedia Abstraction Layer) for cameras. The details of VCHIQ, as well as internals of VC4, remain largely undocumented.

We focus on one media service essential to secure IO: image capture from a CSI camera (a pervasive image sensor interface used in modern mobile devices).

---

### Table 5.

Events breakdown of 3 interaction templates with the replay entry `replay_camera`

| Events     | OneShot | ShortBurst | LongBurst |
|------------|---------|------------|-----------|
| Input      | 34      | 61         | 331       |
| Output     | 36      | 54         | 234       |
| Meta       | 5       | 22         | 115       |

---

### Table 6.

Key constraints and operations of input values for Camera. `queue` and `pg_list` are from `dma_alloc`

| Input      | Constraints | Taint sink & operations |
|------------|-------------|-------------------------|
| resolution | = 720p || 1080p || 1440p | (queue+0x239c0) = resolution |
| buf_size   | >= img_size | (queue+0x24000) = buf_size |
| img_size   | >= 0 && =((queue+0x5e630) | (queue+0x5e630) = img_size, (pg_list+0x0) = img_size |
| pg_list    | != NULL (queue+0x24198) = pg_list |
| queue      | != NULL | MBOX_WRITE = queue & ~(0x3fff) |

---

### 6.3.3 Post analysis

Of the templates, our system identifies only three registers in use. Two of them are a pair of “doorbells” for inter-processor interrupts between CPU and VC4; only one MBOX_WRITE register act as a sink for `queue`, which points to base address of message queue. We summarize the discovered dependencies in Table 6. A notable constraint is for `img_size` input variable. It is assigned by VC4 and is sent back to VC4 in a message initiating bulk receive procedure; later when the procedure finishes, VC4 passes another input value indicating successful transmission size, which `img_size` must exactly match.

Catering to concurrent media services, the message queue has sophisticated structure. It is divided into many 4KB slots, each assigned either to CPU or VC4 for enqueueing messages independently. Each slot holds multiple messages, ranging from 28 bytes to 306 bytes. These messages belong to tens of types, either for configuring the device, e.g. opening a service “port” of VC4, setting frame resolution; or for moving data, e.g. bulk receive. Slot 0 is special, as it contains...
metadata that describes the whole message queue and will be updated by both CPU and VC4, e.g., number of slots, slot allocations, read/write locations in the message queue. The doorbell registers – BELL0, BELL2 signals CPU and VC4 to parse new message, respectively. Upon a new doorbell, a slot handler thread actively polls and parses the message; a sync thread synchronizes CPU-VC4 shared states in slot0; a recycle thread actively frees and recycles used slots.

7 Evaluation

In this section we answer the following research questions: 1) How does our system reduce developer efforts? (§7.1) 2) Why are developerlets correct and secure? (§7.2) 3) What is the overhead of developerlets? (§7.3) 4) How to use developerlets to build trustlets? (§7.4)

7.1 Analysis of developer efforts

We compare three approaches to implementing the same IO functionalities as described in Section 6.

| CMDs | Proto. Spec. | Dev. Spec. | Trans. Paths | Reg./Fields | Desc./Fields |
|------|--------------|------------|--------------|-------------|--------------|
| MMC  | 5            | 231        | 30           | 10          | 17/63        |
| USB  | 4            | 650        | Unavailable  | 10          | 14/100       |
| VCHIQ| 8            | Unavailable| Unavailable  | 9           | 3/3          |

Table 7. Efforts for building drivers from scratch, showing the needed device knowledge

**Build From Scratch.** Developers handpick a set of device commands to implement, for which they consult device specifications, implement the state transitions, and work around hardware quirks (§6.1). Table 7 gives a summary of the needed knowledge. We estimate each driver takes a few months to build.

| Functions | Dev. Conf. | Macros | Callbacks | SLoC |
|-----------|------------|--------|-----------|------|
| MMC       | 22         | 11     | 90        | 79   | 1K  |
| USB       | 58         | 14     | 427       | 142  | 3K  |
| VCHIQ     | 137        | 9      | 405       | 159  | 11K |

Table 8. Efforts for porting Linux drivers, showing the code the developers need to reason about and potentially modify

**Port.** Developers familiarize themselves with device specifications, and decide what driver/kernel functions to port (and what not to). They must spin off the code paths, which span 22–137 driver functions as we measure. To resolve the kernel dependencies of the select code paths, developers have to port at least 1K, 3K, 11K SLoC for each of the MMC, USB, and VCHIQ drivers; they need to port at least 5K SLoC for emulated kernel frameworks such as block, power and memory management. We estimate it takes a few months to under and port each driver and its dependencies, and several months to build the emulated kernel frameworks.

**Our approach** By comparison, we require much lower developer efforts. We build the recorder/replayer in several weeks, which is a one-time effort. To derive each driverlet, we familiarize ourselves with the full driver’s register definitions and instrument the input interfaces for code analysis. Each driverlet takes 1–3 days.

7.2 Correctness & Security analysis

We discuss correctness and security concerns separately: correctness violation is caused by software semantics bugs; security breaches are caused by active attackers who compromise the software.

7.2.1 Correctness. Driverlets’ correctness can be affected by semantics bugs in the OS and driver for recording, e.g., the driver writing to a wrong device register. Such bugs result in malformed recordings and incorrect replay outcome. Driverlets neither mitigate nor exacerbates such semantic bugs. Our recorder and replayer may introduce semantic bugs, e.g., due to implementation glitches. Yet, we expect such bugs are rare because of software simplicity: the recorder and the replayer are only 3K SLoC.

**Experimental validation** We further validate driverlets’ correctness experimentally by following the practice in prior work [13, 50]. We develop test scripts to do the following:

- **Statically vetting of templates.** Our scripts scan templates as a sanity check for the integrity of state-changing events, e.g., which SCSI command is written to what register, what MMAL message is sent. The scripts verify the templates conform to the record campaign and developer requests.

- **Validation of IO data integrity.** For MMC & USB, our scripts verify read values by developerlets match those by native drivers and writes hit the storage; for VCHIQ, the scripts analyze captured images and verify they are in valid JPEG format.

- **Stress testing templates.** Our scripts enumerate templates to stress test and validate coverage. The scripts verify a 100% coverage for MMC/USB (MMC: >31M, USB: >15M of sectors); for VCHIQ, the scripts repetitively invokes templates for 10K times and verify runs produce integral frames.

- **Fault injection.** We validate that driverlets can handle state divergences appropriately. To do so, we unplug MMC/USB storage medium amid a replay run for a large data transfer (2K blocks). the driverlet correctly detects divergence and attempts re-execution with reset. Because the injected failure is persistent, the driverlet eventually gives up. It reports unexpected values from two status register (SDEDM and GINSTS) as well as the source lines of the register reads in the driver, allow quick pinpointing of the failure causes.

7.2.2 Security. Threat model We follow the common threat model of TrustZone [22, 45]. On the target machine: we trust the SoC hardware including any firmware; we trust the TEE software; we do not trust the OS.

We assume that the OS and driver on the developer’s machine for recording are uncompromised. The rationale is that developers machines are often part of a software supplychain with strong security measures. Compromising the developer machines requires high capability and long infiltration campaigns [42].
**Security benefits** By leaving drivers out of TEE, driverlets therefore keep the TEE immune to the extensive vulnerabilities in the driver code. Examples include dirtyCoW [1] caused by racing conditions of page allocator, BadUSB [38] caused by unrestricted privilege in USB stack, and memory bugs in drivers [2, 3, 9]. They could have been exploited by adversarial peripherals (a malicious USB dongle [38]) or malformed requests sent from the OS to the TEE.

**Attacks against driverlets** (1) Fabricating interaction templates is unlikely. This is because they are signed by developers, whose recording environment is trusted. (2) Attacks against the replayer. Vulnerabilities in the replayer may be exploited by entities external to the TEE, e.g. an adversarial OS or peripherals. Successful attacks may compromise the replayer or even the whole TEE. However, such vulnerabilities are unlikely due to replayer’s low codebase (only 1K SLoC), simple logic (minimalist memory management, well-defined event semantics), and stringent security measures (§S).

### 7.3 Overhead

**7.3.1 Methodology.** The details of our test hardware are listed earlier in Table 2. Because the RP3 board does not implement TZASC, we modified ARM trusted firmware to assign devices to TEE. We isolate the whole MMC and VC4 instance. We reserve 3 MB of TEE RAM and use the stock OPTEE allocator for DMA memory.

**Table 9.** Benchmarks used from SQLite test suites and a breakdown of interaction template invocations. Template details are shown in Table 3 and in Section 6.

#### Benchmarks.

1) **SQLite-MMC:** we choose SQLite, a popular lightweight database to test MMC. We pick 6 tests from SQLite test suites to diversify read/write ratios; breakdown of their template invocations and read/write ratios are shown in Table 9. The tests issue their disk accesses in TEE and we report IOPS. 2) **SQLite-USB:** we test USB mass storage with the same SQLite test scripts. 3) **Camera** (OneShot/Short-Burst/LongBurst): we request VCHIQ to capture 1, 10, 100 still images frames at 720P, 1080P, and 1440P. We report the latency of each request.

Note that unlike many TrustZone systems [22, 24], driverlets do not incur world-switch overheads because they fully run inside the TrustZone.

**Comparisons.** We compare driverlets with drivers on Linux 4.14 which finish the same benchmarks as follows: for **SQLite**, we run a test harness invoking the full drivers with the same block accesses with default flags (**native**) and with an additional O_SYNC flag (**native-sync**); for **Camera**, we run v4l2-ctl to request the same number of frames at corresponding resolutions (**native**).

#### 7.3.2 Macrobenchmarks. **SQLite-MMC.** Figure 6a shows the results. MMC driverlet achieves a decent performance: on average, it achieves 434 IOPS, executing over 100 queries per second. As a reference, the throughput is a few orders of magnitude higher than secure storage hardware, e.g. RPMB [7]. Compared with native, driverlet’s throughput is 1.8× lower on average. The overhead grows with the write ratio, e.g. select3 (read-most) incurs 1.4× overhead while insert3 (write-most) incurs 2×. This is because driverlet mandates synchronous IO jobs: while the driver does not wait for writes to complete, the replayer must wait to match state changing events. To validate, we mandate O_SYNC flag in the driver execution (**native-sync**) and measure throughput 1.5× lower than driverlets. This is because driverlets forgo complex kernel layers such as filesystems and driver frameworks.

**SQLite-USB.** Figure 6b shows the results. The driverlet achieves 369 IOPS which is over 90 queries per second. The overhead compared with native is 1.5×. The overhead is also caused by synchronous writes, where write-most workload (insert3) incurs the highest overhead of 2×. **native-sync** is 1.7× lower than native and 1.2× lower than driverlets.

**Camera.** Figure 7 shows the results. The per-frame latencies of driverlet range from 2.1s (720p) to 3.6s (1440p) which are usable to many surveillance applications that periodically sample images [58]. The per-frame latency decreases with the number of frames in a burst, because for each burst the
driverlet pays a fixed cost to initialize the camera and the media accelerator. It replays 41 events for the initialization and 5 events to capture each subsequent frame.

Compared with Native, our latency is only 11% higher for a one-frame burst and is 2.7X higher for a 100-frame burst. This is again because the driverlet must wait for individual IRQs as mandated by the templates (§ 3.3), while the native driver processes coalesced IRQs. As requests contain more events (e.g. 75 vs. 680 to capture 1 and 100 frames, Table 5), the delays of waiting for IRQs are more pronounced.

7.3.3 Microbenchmarks. We show latency to execute a single interaction template for MMC and USB in Figure 8.

![Figure 8. Microbenchmarks](image)

In both reads/writes, driverlet’s latency is near-native or even slightly lower (12% and 13% lower for MMC, USB respectively). On larger block writes (e.g. 256), the latency of USB driverlet is even 40% lower; this is due to driverlet, unlike a native driver, does not run transfer scheduling logic for individual 4KB data pages. This confirms observations in the macrobenchmarks, where driverlet outperforms native-sync.

7.3.4 Memory overhead. After compression, the driverlets for MMC, USB, and VCHIQ are 6 KB, 26 KB, and 19 KB, respectively. For implementation ease, our current recorder emits templates as human-readable documents. Further converting them to binary format is likely to reduce their sizes.

7.4 End-to-end use case

To showcase the use of driverlets, we build an end-to-end trustlet for secure surveillance in only 50 SLoC and less than an hour. As shown in Figure 9, the trustlet periodically samples image frames and stores the frames on an SD card. Without driverlets, such a trustlet cannot enjoy secure IO path: it has to invoke the OS for the needed drivers. With driverlets, the trustlet code simply include one header file and invoke the two interfaces for camera and MMC respectively. Corresponding to the invocations, the replay器 selects two interaction templates: one for image capturing, the other for writing 256 blocks; the replayer invokes the latter multiple times for each frame in 1–2MB. We measured that storing each frame takes 3.7s, in which most is spent on initializing the camera and storing the image only takes 154ms.

8 Related Work

**Driver reuse** To reuse drivers, some “lift and shift” [19, 20, 27, 47]; some trim down simple drivers [31]; Our system shares same goal. Different from them, our system derives drivers by a novel use of record and replay.

**Record and replay** is well-known and primarily applied to bug finding [18, 23, 35, 36] and security analysis [12, 26, 59]. It also enables offloading [21, 48], emulation [37], and cheap versioning [17]. We are inspired by them to reproduce a subset of program behavior, e.g. device/driver interactions. Key difference is we generalize replay inputs such that replay completes requests beyond those recorded.

**Program analysis techniques** have been widely applied by extensive works for testing [50] and finding vulnerabilities [33] in kernel drivers and excavating data structures (e.g. in binaries [10, 55] and network protocols [16]). Inspired by them, our system is built atop well-known program analysis techniques. Differently, we use those techniques for a distinct goal: reuse device state transition paths.

**Trusted execution environment** is commonly used to shield trustlets from untrusted host OS [22, 29, 34, 51]. Lacking storage drivers, the trustlets delegate IO to OS [24, 28, 46] and mediate their accesses [30]. Similar with them, we leverage TEE’s strong security guarantees; differently, we provide key missing device drivers for them. Some works bring drivers to TEE, e.g. IPU [43], GPU [44]. Compared to them, which are point solutions to individual devices, we present a holistic approach to systematically derive a set of drivers.
We present driverlets, a novel approach to derive device drivers for TrustZone, fix the key missing link for secure I/O. A driverlet records driver/device interactions from a gold driver and distills interaction templates; by replaying a template with new dynamic inputs, the driverlet completes requests beyond the one being recorded while assuring correctness. We build the recorder/replayer and show driverlets have practical performance on MMC, USB, and VCHIQ.

9 Conclusions

We present driverlets, a novel approach to derive device drivers for TrustZone, fix the key missing link for secure I/O. A driverlet records driver/device interactions from a gold driver and distills interaction templates; by replaying a template with new dynamic inputs, the driverlet completes requests beyond the one being recorded while assuring correctness. We build the recorder/replayer and show driverlets have practical performance on MMC, USB, and VCHIQ.

References

[1] Cve-2016-5195: Race condition in mm/gup.c in the linux kernel 2.x through 4.x before 4.8.3 allows local users to gain privileges by leveraging incorrect handling of a copy-on-write (cow) feature to write to a read-only memory mapping, as exploited in the wild in october 2016, aka dirty cow. https://cve.mitre.org/cgi-bin/cvename.cgi?name=CVE-2016-5195. (Accessed on 09/22/2021).

[2] Cve-2016-6775: An elevation of privilege vulnerability in the nvidia gpu driver could enable a local malicious application to execute arbitrary code. https://www.cvedetails.com/cve/CVE-2016-6775/. (Accessed on 09/22/2021).

[3] Cve-2016-9120: Race condition in the ion_ioctl function in drivers/staging/android/ion.c in the linux kernel before 4.6 allows loca. https://www.cvedetails.com/cve/CVE-2016-9120/. (Accessed on 09/22/2021).

[4] Device power management basics — the linux kernel documentation. https://www.kernel.org/doc/html/v4.18/device-api/pm/devices.html. (Accessed on 10/09/2021).

[5] Lzb/broadcom bug workaround. - issue #254 - raspbianlinux. https://github.com/raspbian/raspbian/issues/254. (Accessed on 10/09/2021).

[6] optee_os/changelog.md at master · op-tee/optee_os - github. https://github.com/OP-TEE/optee_os/blob/master/CHANGELOG.md. (Accessed on 08/12/2021).

[7] Rpmb file system performance. https://cvedetails.com/cve/CVE-2016-9120/. (Accessed on 09/22/2021).

[8] Usb hotplugging — the linux kernel documentation. https://www.kernel.org/doc/html/v4.18/device-api/usb/hotplug.html. (Accessed on 10/09/2021).

[9] CVE-2016-7389. Available from MITRE, CVE-ID CVE-2016-7389., Sept. 9 2016.

[10] A. Altinay, J. Nash, T. Kroes, P. Rajasekaran, D. Zhou, A. Dabrowski, D. Gens, Y. Na, S. Volkekaert, C. Giuffrida, H. Bos, and M. Franz. Binrec: dynamic binary lifting and recomposition. In A. Bilas, K. Magoutis, E. P. Markatos, D. Kostic, and M. I. Seltzer, editors, EuroSys ’20: Fifteenth EuroSys Conference 2020, Heraklion, Crete, Greece, April 27-30, 2020, pages 36:1–36:16. ACM, 2020.

[11] F. Bellard. Qemu, a fast and portable dynamic translator. In USENIX Annual Technical Conference, FREENIX Track, pages 41–46, 2005.

[12] A. Chen, W. B. Moore, H. Xia, A. Haebeler, L. T. X. Phan, M. Sherr, and W. Zhou. Detecting covert timing channels with time-deterministic replay. In 11th USENIX Symposium on Operating Systems Design and Implementation (OSDI 14), pages 541–554, Broomfield, CO, Oct. 2014. USENIX Association.

[13] V. Chipounov and G. Candea. Reverse engineering of binary device drivers with revnic. In Proceedings of the 5th Workshop on Hot Topics in System Dependability (HotDep), number CONF, 2009.

[14] V. Chipounov, V. Kuznetsov, and G. Candea. S2E: a platform for in-vivo multi-path analysis of software systems. In R. Gupta and T. C. Mowry, editors, Proceedings of the 16th International Conference on Architectural Support for Programming Languages and Operating Systems, ASPLOS 2011, Newport Beach, CA, USA, March 5-11, 2011, pages 265–278. ACM, 2011.

[15] V. Chipounov, V. Kuznetsov, and G. Candea. S2E: a platform for in-vivo multi-path analysis of software systems. In R. Gupta and T. C. Mowry, editors, Proceedings of the 16th International Conference on Architectural Support for Programming Languages and Operating Systems, ASPLOS 2011, Newport Beach, CA, USA, March 5-11, 2011, pages 265–278. ACM, 2011.

[16] W. Cui, J. Kannan, and H. J. Wang. Discoverer: Automatic protocol reverse engineering from network traces. In N. Provos, editor, Proceedings of the 16th USENIX Security Symposium, Boston, MA, USA, August 6–10, 2007. USENIX Association, 2007.

[17] X. Dou, P. M. Chen, and J. Flinn. Knockoff: Cheap versions in the cloud. In 15th USENIX Conference on File and Storage Technologies (FAST 17), pages 73–88, Santa Clara, CA, 2017. USENIX Association.

[18] G. W. Dunlap, S. T. King, S. Cinar, M. A. Basrai, and P. M. Chen. Re-vert: Enabling intrusion analysis through virtual-machine logging and replay. SIGOPS Oper. Syst. Rev., 36(SI):211–224, Dec. 2003.

[19] V. Ganapathy, M. J. Renzelmann, A. Balakrishnan, M. M. Swift, and S. Jha. The Design and Implementation of Microdrivers. In Proc. ACM ASPLOS, ASPLOS XIII, pages 168–178, New York, NY, USA, 2008. ACM.

[20] B. Gerofi, A. Santigidis, D. Martinet, and Y. Ishikawa. Picodoor: Fast-path Device Drivers for Multi-kernel Operating Systems. HPDC ’18, pages 2–13, New York, NY, USA, 2018. ACM.

[21] L. Gomez, I. Neamtiu, T. Azim, and T. Millstein. Reran: Timing- and touch-sensitive record and replay for android. In 2013 5th International Conference on Software Engineering (ICSE), pages 72–81, 2013.

[22] L. Guan, P. Liu, X. Xing, X. Ge, S. Zhang, M. Yu, and T. Jaeger. Trust-shadow: Secure execution of unmodified applications with arm trustzone. In Proceedings of the 15th Annual International Conference on Mobile Systems, Applications, and Services, MobiSys ’17, pages 488–501, New York, NY, USA, 2017. ACM.

[23] Z. Guo, X. Wang, J. Tang, X. Liu, Z. Xu, M. Wu, M. F. Kaashoek, and Z. Zhang. R2: An application-level kernel for record and replay. In Proceedings of the 8th USENIX Conference on Operating Systems Design and Implementation, OSDI’08, pages 193–208, USA, 2008. USENIX Association.

[24] D. Hein, J. Winter, and A. Fitzek. Secure block device – secure, flexible, and efficient data storage for arm trustzone systems. In 2015 IEEE Trustcom/BigDataSE/ISP, volume 1, pages 222–229, 2015.

[25] K. Hsieh, G. Ananthanarayanan, P. Bodik, S. Venkataraman, P. Bahl, M. Philipose, P. B. Gibbons, and O. Mutlu. Focus: Querying large video datasets with low latency and low cost. In 13th USENIX Symposium on Operating Systems Design and Implementation (OSDI 16), Carlsbad, CA, 2018. USENIX Association.

[26] Y. Ji, S. Lee, M. Fazzini, J. Allen, E. Downing, T. Kim, A. Orso, and W. Lee. Enabling reliable cross-host attack investigation with efficient data flow tagging and tracking. In 27th USENIX Security Symposium (USENIX Security 18), pages 1705–1722, Baltimore, MD, Aug. 2018. USENIX Association.

[27] A. Kantee and J. Cormack. Rump Kernels No OS? No Problem! Login: USENIX Magazine, 39(5), 2014.

[28] S. Lee, H. Shi, K. Tan, Y. Liu, S. Lee, and Y. Cui. S2net: Preserving privacy in smart home routers. IEEE Trans. Dependable Secur. Comput., 18(3):1409–1424, 2021.

[29] T. Lee, Z. Lin, S. Pushp, C. Li, Y. Liu, Y. Lee, F. Xu, C. Xu, L. Zhang, and J. Song. Occlusion: Privacy-preserving remote deep-learning inference using sycl. In The 25th Annual International Conference on Mobile Computing and Networking, MobiCom ’19, New York, NY, USA, 2019. Association for Computing Machinery.

[30] M. Lentz, R. Sen, P. Druschel, and B. Bhattacharjee. Secloak: ARM trustzone-based mobile peripheral control. In J. Ott, F. Dressler, S. Saroiu, and P. Dutta, editors, Proceedings of the 16th Annual International Conference on Mobile Systems, Applications, and Services, MobiSys 2018, Munich, Germany, June 10-15, 2018, pages 1–13. ACM, 2018.

[31] Linaro. Op-tee: Open portable trusted execution environment. https://www.op-tee.org/, 2017.

[32] Linux. USB Linux Kernel Driver: OTG-FSM. https://github.com/raspberrypi/linux/blob/rpi-5.10.y/drivers/usb/common/usb-otg-
fsm.c.

[33] A. Machiry, C. Spensky, J. Corina, N. Stephens, C. Kruegel, and G. Vigna. DR. CHECKER: A soundly analysis for linux kernel drivers. In E. Kirda and T. Ristenpart, editors, 26th USENIX Security Symposium, USENIX Security'17, Vancouver, BC, Canada, August 16-18, 2017, pages 1067–1084. USENIX Association, 2017.

[34] F. Mo, A. S. Shamshabadi, K. Katevas, S. Demetriou, I. Leonitiadis, A. Cavallaro, and H. Haddadi. Darknet: Towards model privacy at the edge using trusted execution environments. In Proceedings of the 18th International Conference on Mobile Systems, Applications, and Services, MobiSys ’20, page 161–174, New York, NY, USA, 2020. Association for Computing Machinery.

[35] J. Mohan, A. Martinez, S. Ponnapalli, P. Raju, and V. Chidambaram. Finding crash-consistency bugs with bounded black-box crash testing. In A. C. Arpaci-Dusseau and G. Voelker, editors, 13th USENIX Symposium on Operating Systems Design and Implementation, OSDI 2018, Carlsbad, CA, USA, October 8-10, 2018, pages 33–50. USENIX Association, 2018.

[36] M. Musuvathi, S. Qadeer, T. Ball, G. Basler, P. A. Nainar, and I. Nematu. Finding and reproducing heapbugs in concurrent programs. In R. Draves and R. van Renesse, editors, 8th USENIX Symposium on Operating Systems Design and Implementation, OSDI 2008, December 8-10, 2008, San Diego, California, USA, Proceedings, pages 267–280. USENIX Association, 2008.

[37] R. Netravali, A. Sivaraman, S. Das, A. Goyal, K. Winstein, J. Mickens, and H. Balakrishnan. Mahimahi: Accurate record-and-replay for HTTP. In 2015 USENIX Annual Technical Conference (USENIX ATC 15), pages 417–429, Santa Clara, CA, July 2015. USENIX Association.

[38] K. Nohl and J. Lell. Badusb - on accessories that turn evil.

[39] NVIDIA. Tegra2 Family: Technical reference manual, 2011.

[40] J. Mohan, A. Martinez, S. Ponnapalli, P. Raju, and V. Chidambaram. Finding crash-consistency bugs with bounded black-box crash testing. In A. C. Arpaci-Dusseau and G. Voelker, editors, 13th USENIX Symposium on Operating Systems Design and Implementation, OSDI 2018, Carlsbad, CA, USA, October 8-10, 2018, pages 33–50. USENIX Association, 2018.

[41] M. Musuvathi, S. Qadeer, T. Ball, G. Basler, P. A. Nainar, and I. Nematu. Finding and reproducing heapbugs in concurrent programs. In R. Draves and R. van Renesse, editors, 8th USENIX Symposium on Operating Systems Design and Implementation, OSDI 2008, December 8-10, 2008, San Diego, California, USA, Proceedings, pages 267–280. USENIX Association, 2008.

[42] R. Netravali, A. Sivaraman, S. Das, A. Goyal, K. Winstein, J. Mickens, and H. Balakrishnan. Mahimahi: Accurate record-and-replay for HTTP. In 2015 USENIX Annual Technical Conference (USENIX ATC 15), pages 417–429, Santa Clara, CA, July 2015. USENIX Association.

[43] K. Nohl and J. Lell. Badusb - on accessories that turn evil. Black Hat USA, 1(9):1–22, 2014.

[44] NVIDIA. Tegra2 Family: Technical reference manual, 2011.

[45] NXP Semiconductors. i.MX 6SoloX - fact sheet. https://www.nxp.com/docs/en/fact-sheet/IMX6SOLOXFS.pdf. (Accessed on 05/14/2019).

[46] NXP Semiconductors. i.MX 7 Series Applications Processors | Arm® Cortex®-A7, Cortex-M4 | NXP. https://www.nxp.com/products/processors-and-microcontrollers/arm-based-processors-and-mcus/i.mx-applications-processors/i-mx-7-processors/IMX7-SERIES, 2017. (Accessed on 05/14/2019).

[47] N. I. of Standards and T. (NIST). Defending against software supply chain attacks. https://www.cisa.gov/sites/default/files/publications/defending_against/software_supply_chain_attacks_508_1.pdf.

[48] C. M. Park, D. Kim, D. V. Sidhwani, A. Fuchs, A. Paul, S.-J. Lee, K. Dantu, and S. Y. Ko. Rushmore: Securely displaying static and animated images using trustzone. In Proceedings of the 19th Annual International Conference on Mobile Systems, Applications, and Services, MobiSys ’21, page 122–135, New York, NY, USA, 2021. Association for Computing Machinery.

[49] R. Ryuhyuk, P. Chubb, I. Kuz, E. Le Sueur, and G. Heiser. Automatic device driver synthesis with termite. In Proceedings of the ACM SIGOPS 22nd symposium on Operating systems principles, pages 73–86, 2009.

[50] R. Ryuhyuk, A. Walker, J. Keys, A. Legg, A. Raghunath, M. Stumm, and M. Vij. User-guided device driver synthesis. In 11th [USENIX] Symposium on Operating Systems Design and Implementation ([OSDI] 14), pages 661–676, 2014.

[51] A. A. Sani. Schrodintext: Strong protection of sensitive textual content of mobile applications. In T. Choudhury, S. Y. Ko, A. Campbell, and D. Ganesan, editors, Proceedings of the 15th Annual International Conference on Mobile Systems, Applications, and Services, MobiSys’17, Niagara Falls, NY, USA, June 19–23, 2017, pages 197–210. ACM, 2017.

[52] A. Slowinska, T. Stancescu, and H. Bos. Howard: A dynamic excavator for reverse engineering data structures. In Proceedings of the Network and Distributed System Security Symposium, NDSS 2011, San Diego, California, USA, 6th February - 9th February 2011. The Internet Society, 2011.

[53] S. M. S. Talebi, H. Tavakoli, H. Zhang, Z. Zhang, A. A. Sani, and Z. Qian. Charm: Facilitating dynamic analysis of device drivers of mobile systems. In W. Enck and A. P. Felt, editors, 27th USENIX Security Symposium, USENIX Security 2018, Baltimore, MD, USA, August 15-17, 2018, pages 291–307. USENIX Association, 2018.

[54] X. Xiao, S. Li, T. Xie, and N. Tillmann. Characteristic studies of loop problems for structural test generation via symbolic execution. In E. Denney, T. Bultan, and A. Zeller, editors, 2013 28th IEEE/ACM International Conference on Automated Software Engineering, ASE 2013, Silicon Valley, CA, USA, November 11-15, 2013, pages 246–256. IEEE, 2013.

[55] M. Xu, T. Xu, Y. Liu, X. Liu, G. Huang, and F. X. Lin. Supporting video queries on zero-streaming cameras. arXiv preprint arXiv:1904.12342, 2019.

[56] M. Yan, Y. Shalabi, and J. Torrellas. Replayconfusion: Detecting cache-based covert channel attacks using record and replay. In 2016 49th Annual IEEE/ACM International Symposium on Microarchitecture (MICRO), pages 1–14, 2016.

[57] J. Yin. White paper: Software based Finite State Machine (FSM) with general purpose processors.