ReUSB: Replay-Guided USB Driver Fuzzing

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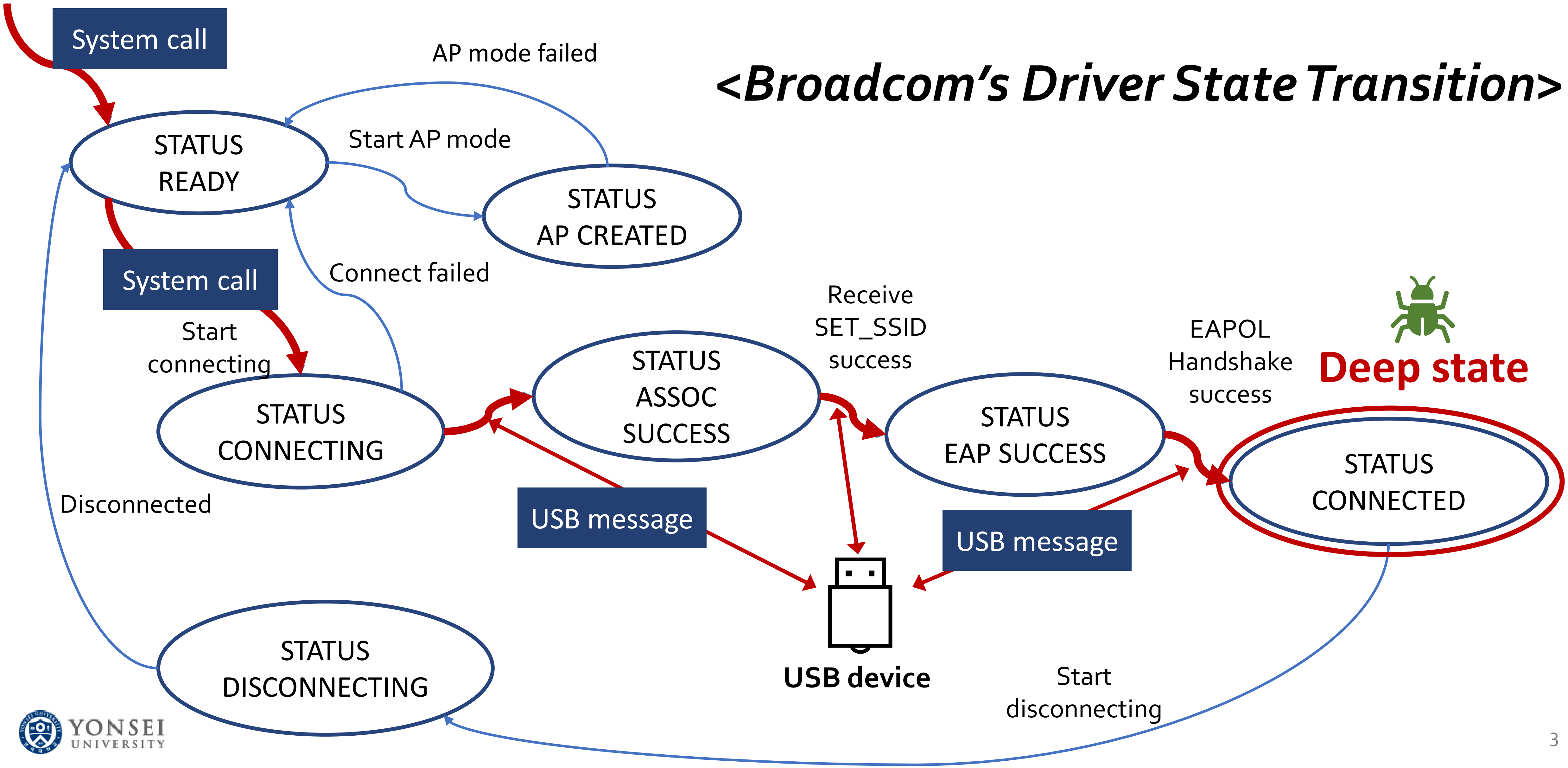
Low Code Coverage of USB Device Drivers

➤ **USB driver coverage of syzbot (as of July 2023)**

Vendor	Driver source code	Total basic block of code	Fuzzing code coverage (%)
Qualcomm	drivers/net/wireless/ath	5436	**1%**
Broadcom	drivers/net/wireless/broadcom	27881	**2%**
	drivers/bluetooth/btbcm.c	212	**0%**
Mediatek	drivers/net/wireless/mediatek	2190	**0%**
Ralink	drivers/net/wireless/ralink	4034	**0%**
Realtek	drivers/net/wireless/realtek	30250	**1%**
CSR	drivers/bluetooth/btusb.c	980	**11%**
NXP	drivers/nfc/pn533	664	**11%**

Statefulness of USB Device Drivers



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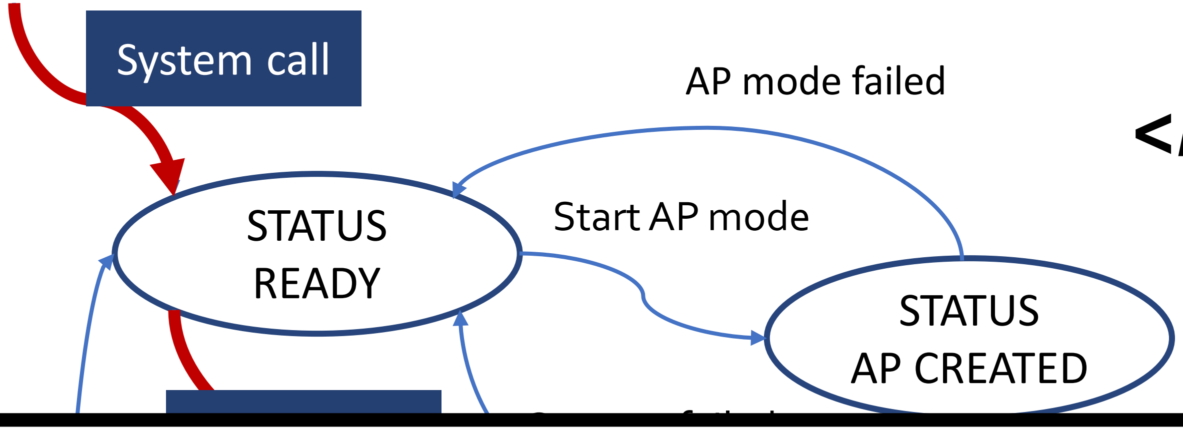
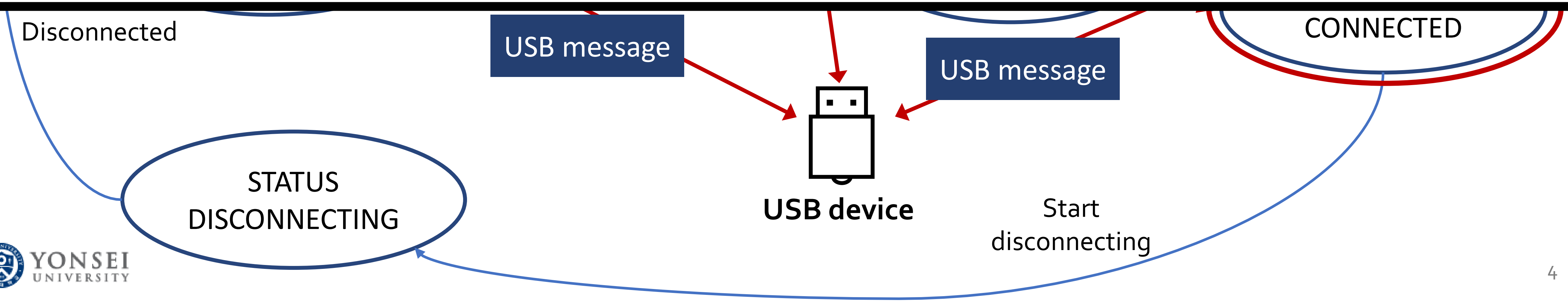
Statefulness of USB Device Drivers



<Broadcom’s Driver State Transition>

A long sequence of specific inputs are required.



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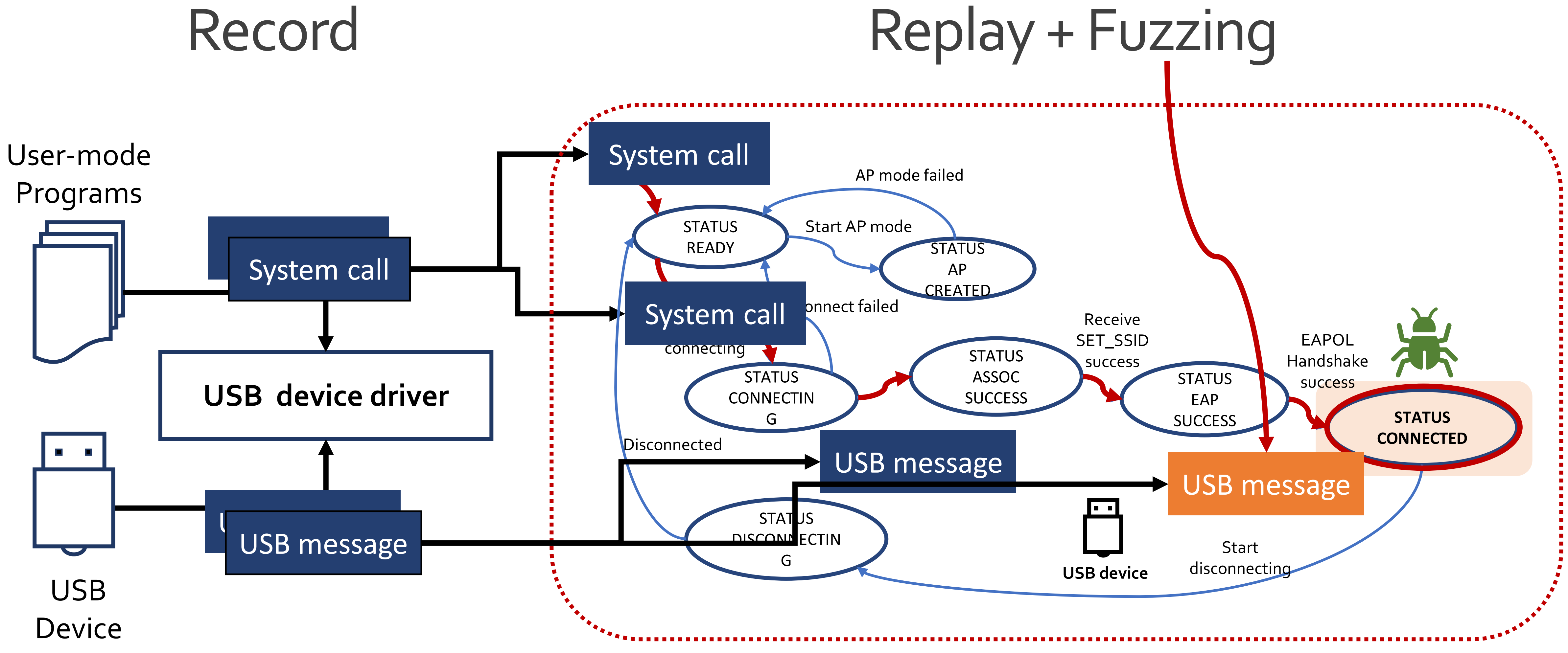
Our Approach: Combining Record-and-Replay with Fuzzing



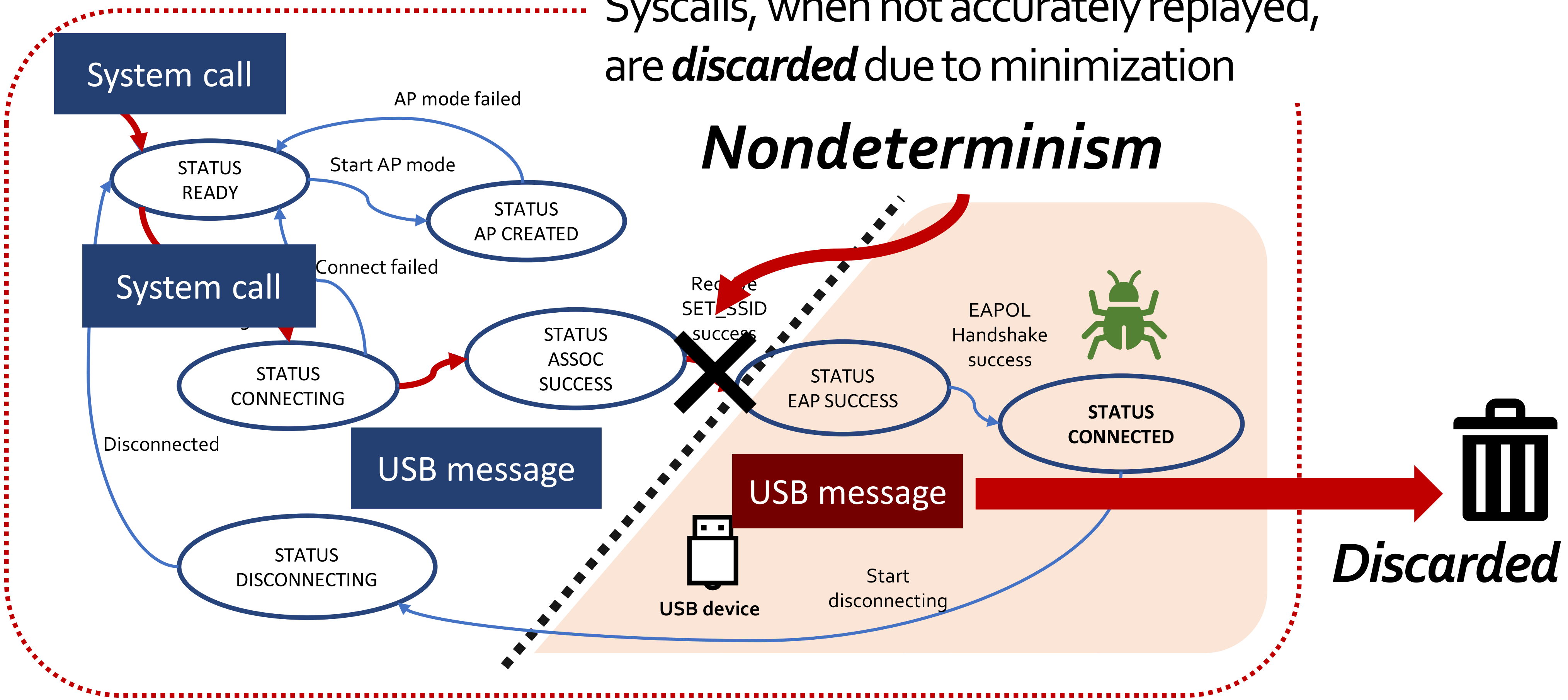
Limitations of Coverage-Guided Evolutionary Fuzzing

State-of-the-art evolves the corpus towards smaller inputs based on coverage:

- **Syzkaller's fuzzing algorithm**
- **USBFuzz (uses AFL)'s fuzzing algorithm**

1. Minimization:

Syscalls, when not accurately replayed, are ***discarded*** due to minimization



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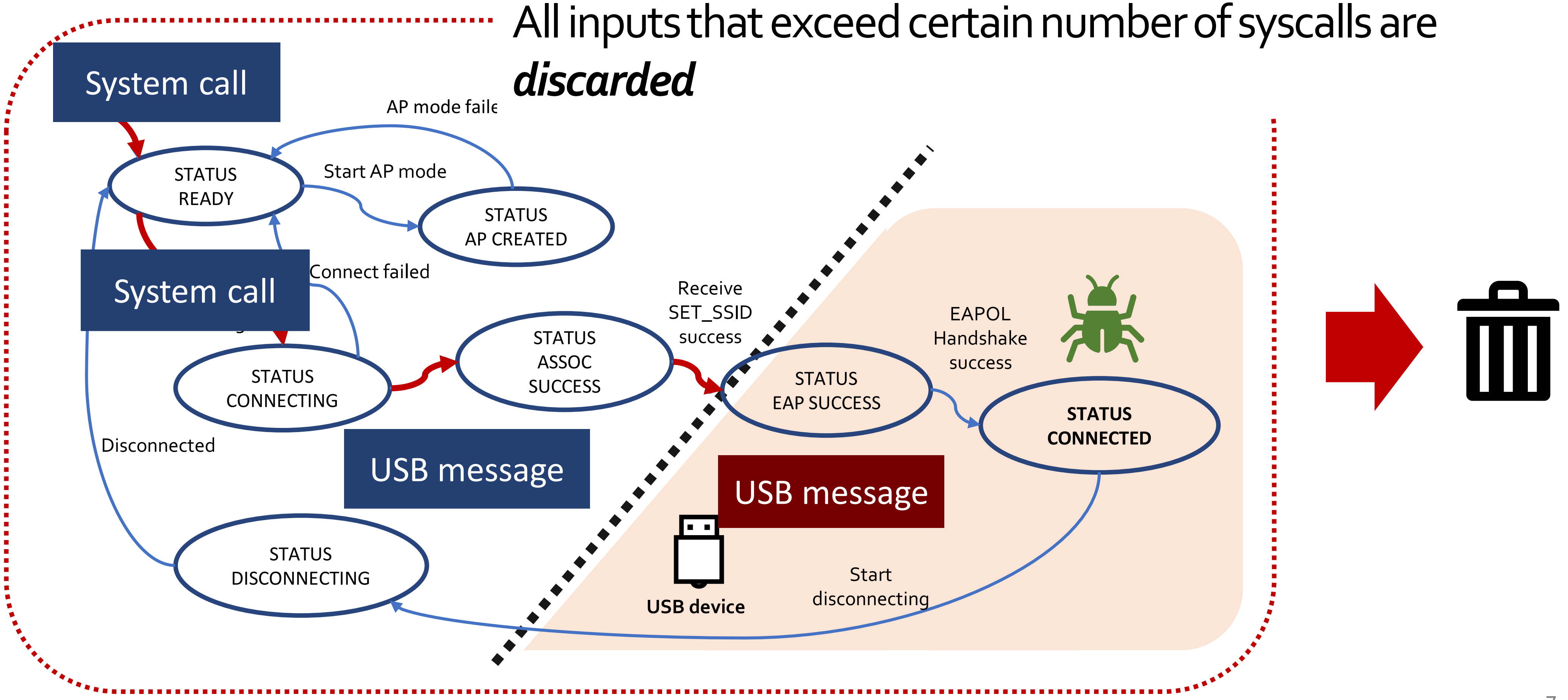
2. Hard cap on the number of syscalls:

All inputs that exceed certain number of syscalls are ***discarded***



Limitations of Coverage-Guided Evolutionary Fuzzing

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- Syzkaller's fuzzing algorithm
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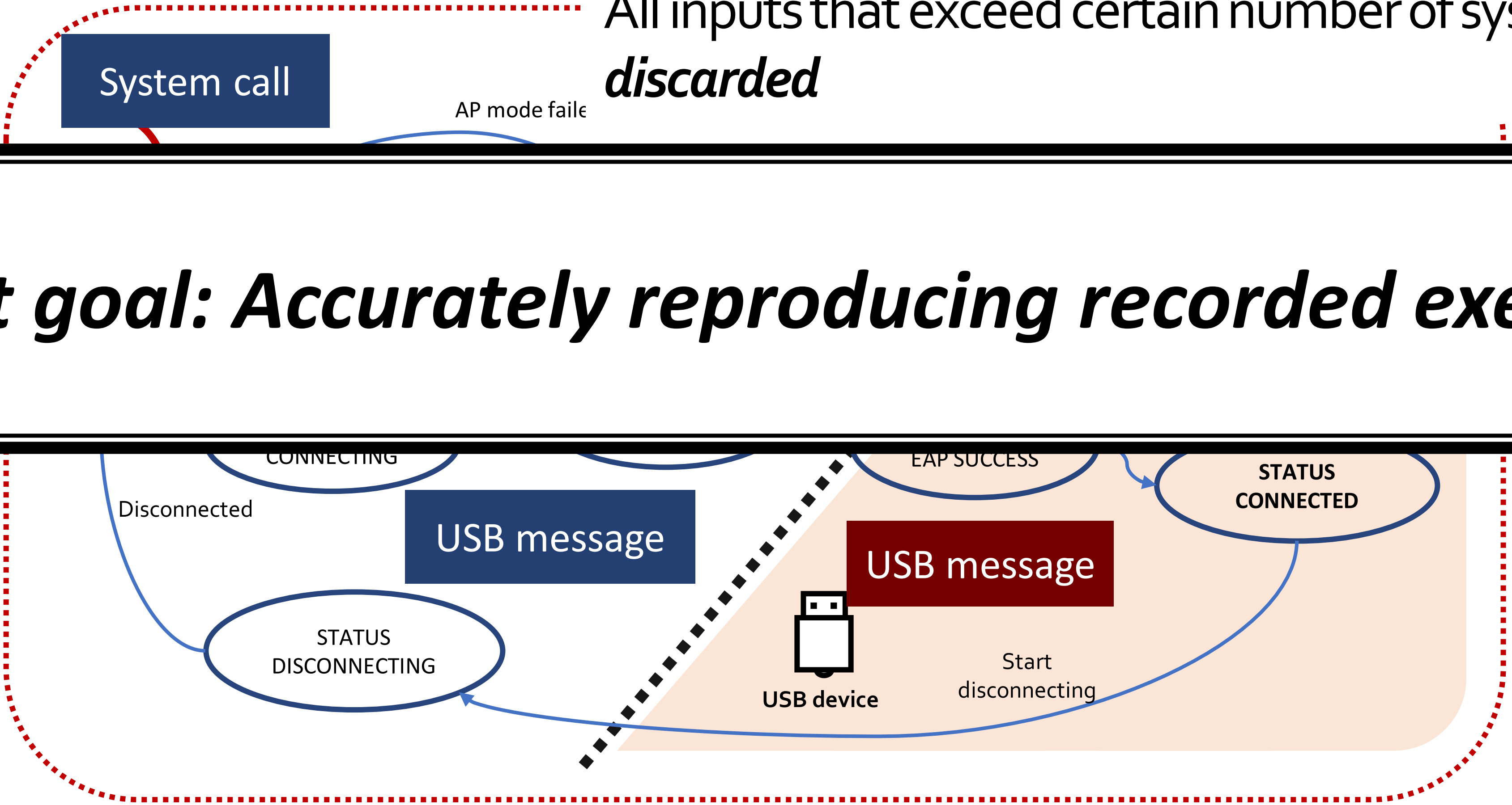
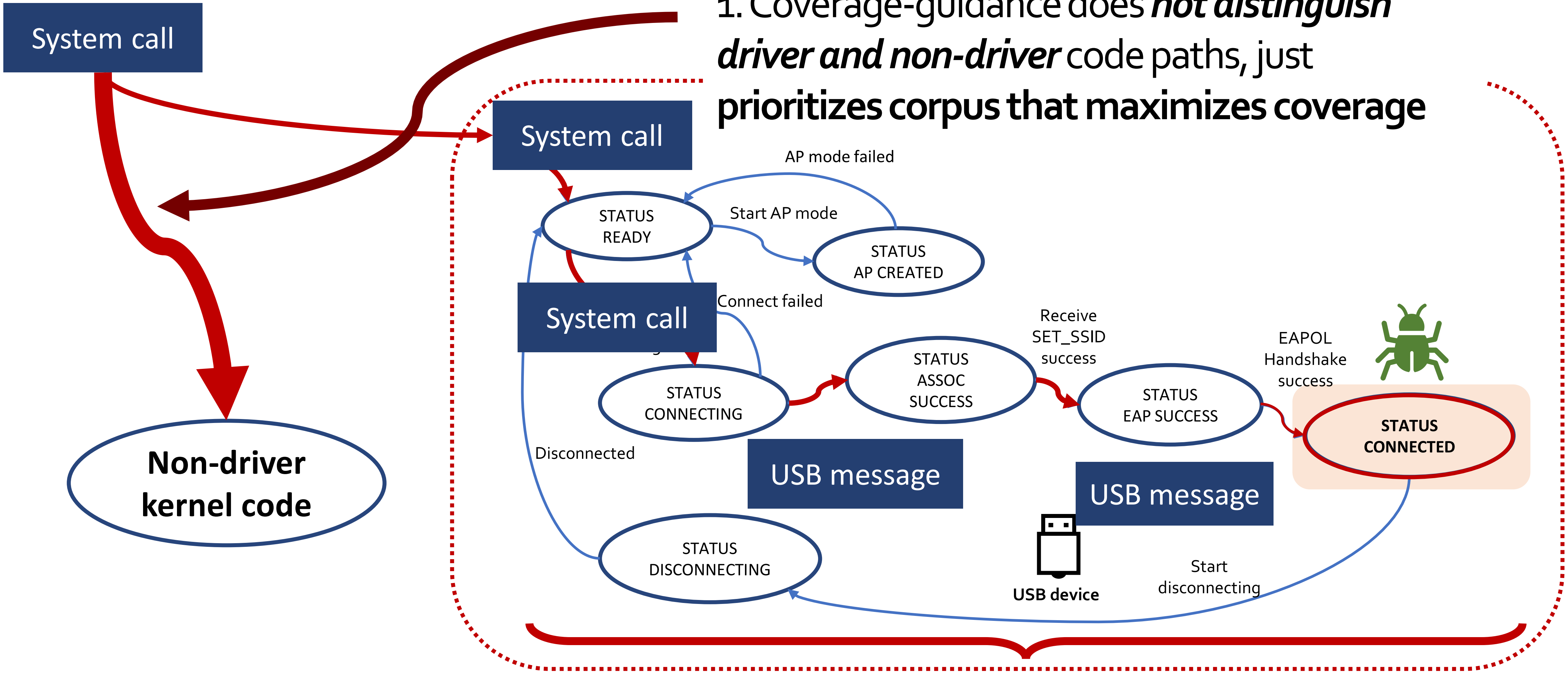
Our first goal: Accurately reproducing recorded executions



Limitations of Coverage-Guided Evolutionary Fuzzing

1. Coverage-guidance does ***not distinguish driver and non-driver*** code paths, just **prioritizes corpus that maximizes coverage**



2.Lengthy inputs (exceeding thousands) and long execution time (5~20 seconds) make fuzzing extremely slow

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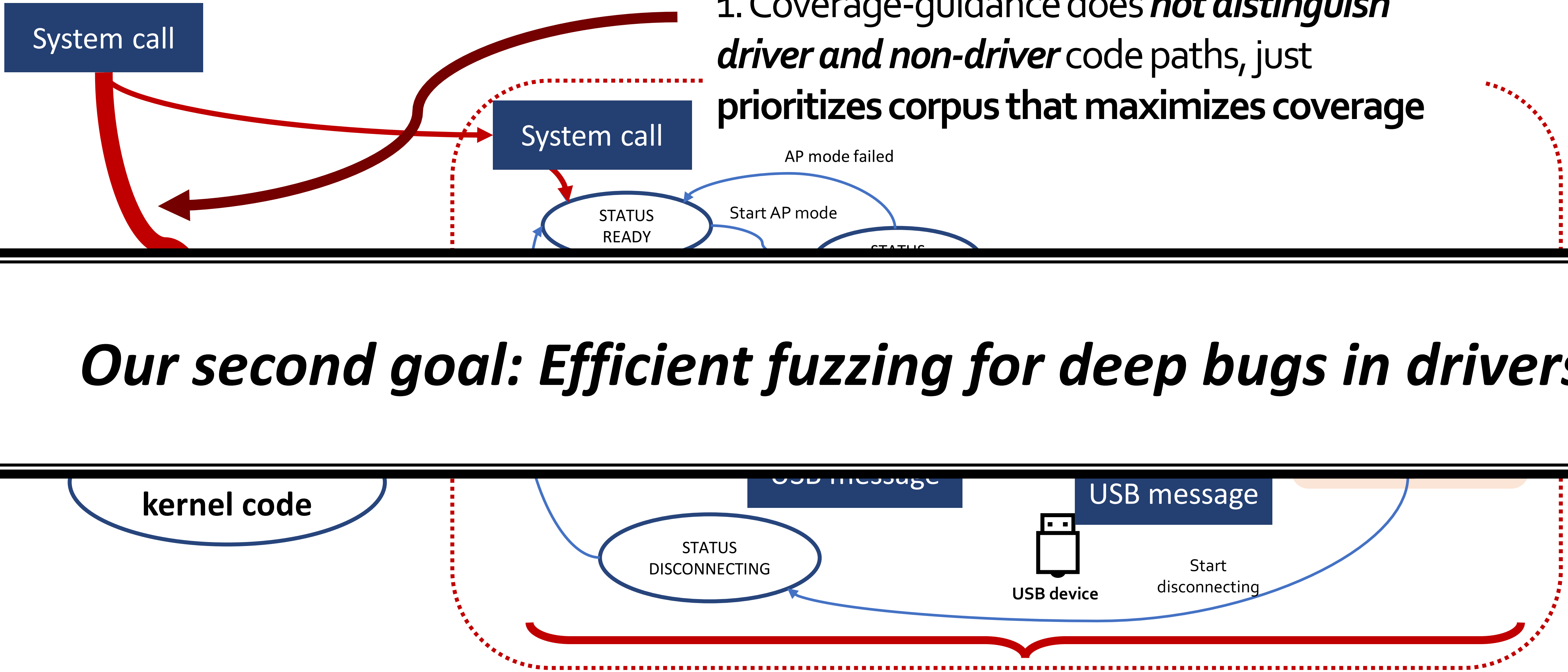

Our second goal: Efficient fuzzing for deep bugs in drivers

2.Lengthy inputs (exceeding thousands) and long execution time (5~20 seconds) make fuzzing extremely slow

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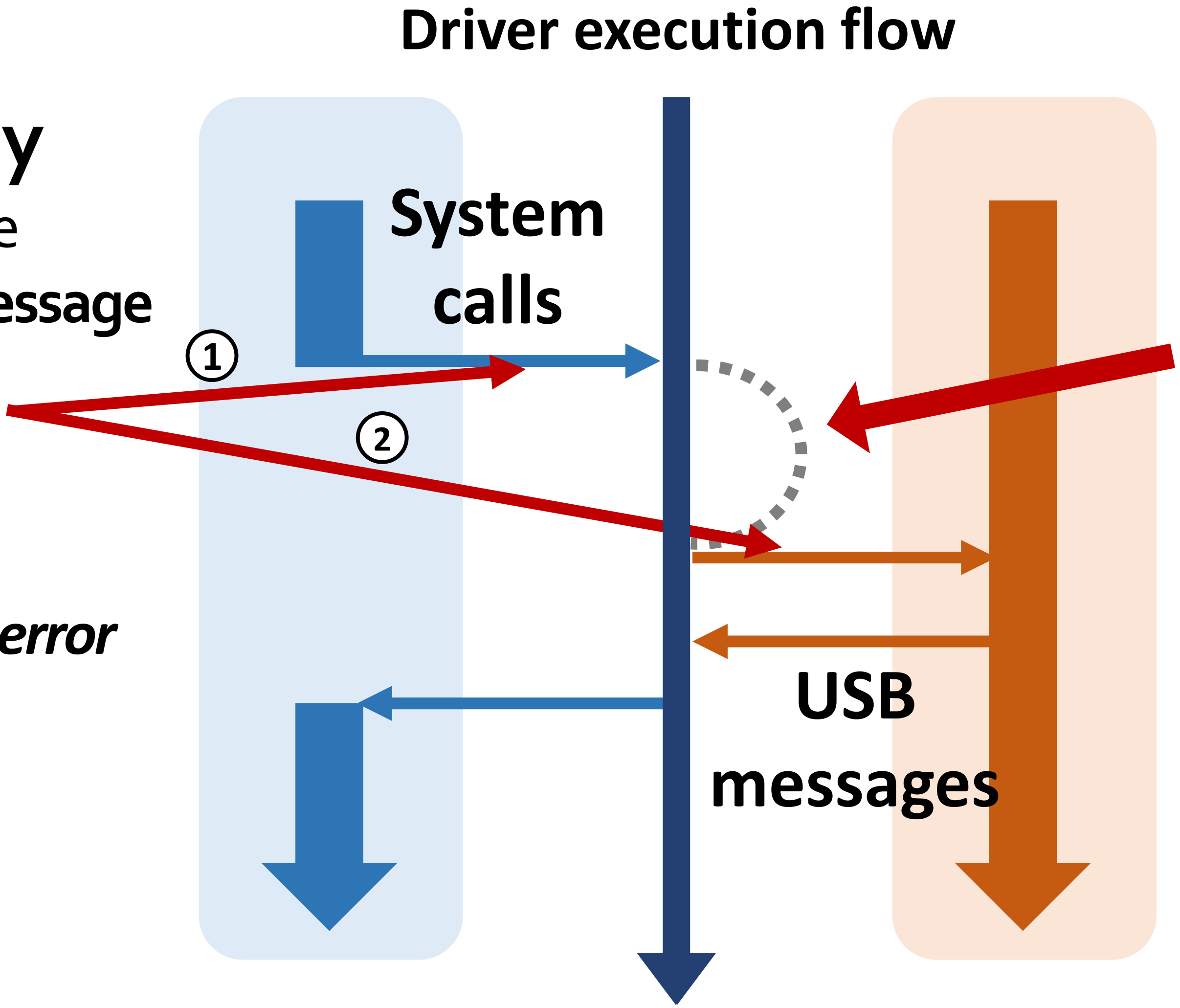
Challenges of Accurate Replay: Sensitive to Timing of Input Injection

1. Concurrency

System calls trigger the **generation of USB message requests** by the driver (e.g., blocking I/O)

➡

USB response timeout error



2. Delay

Driver requires ***a certain delay*** to generate USB messages. (e.g., delay queue …)

➡

respond to USB messages ***without the corresponding USB request***

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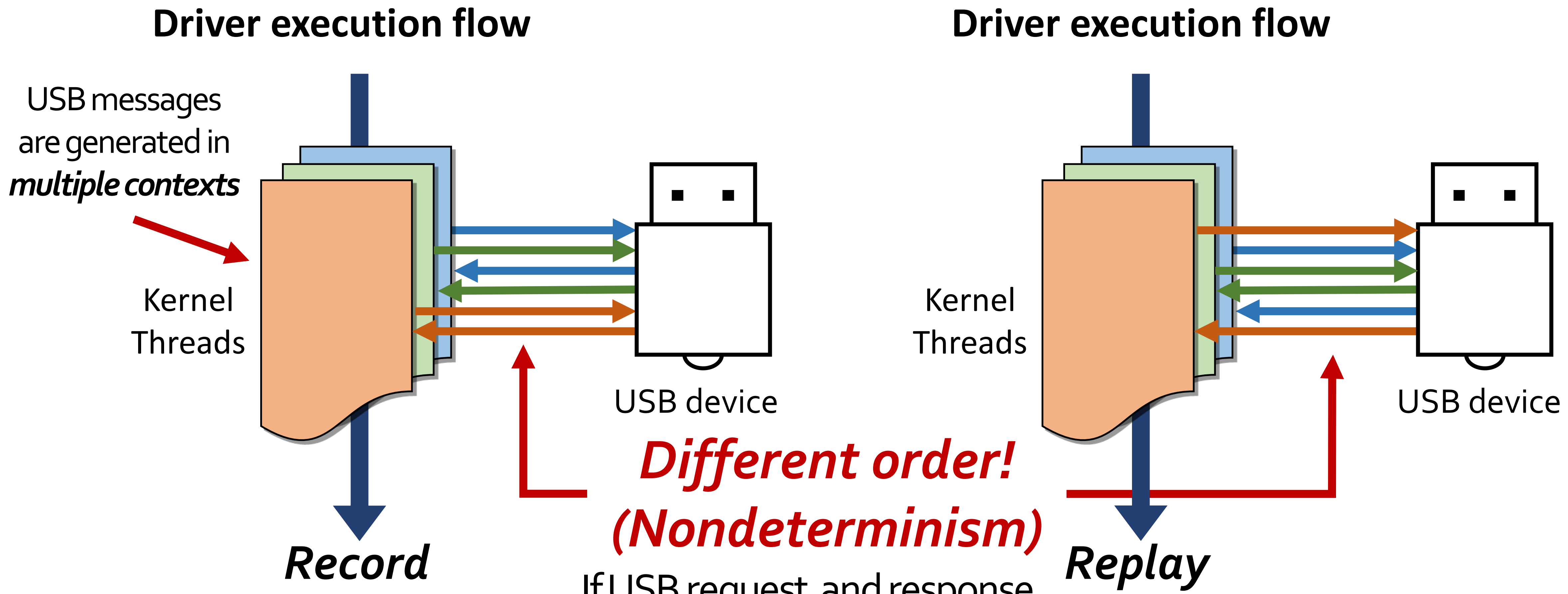
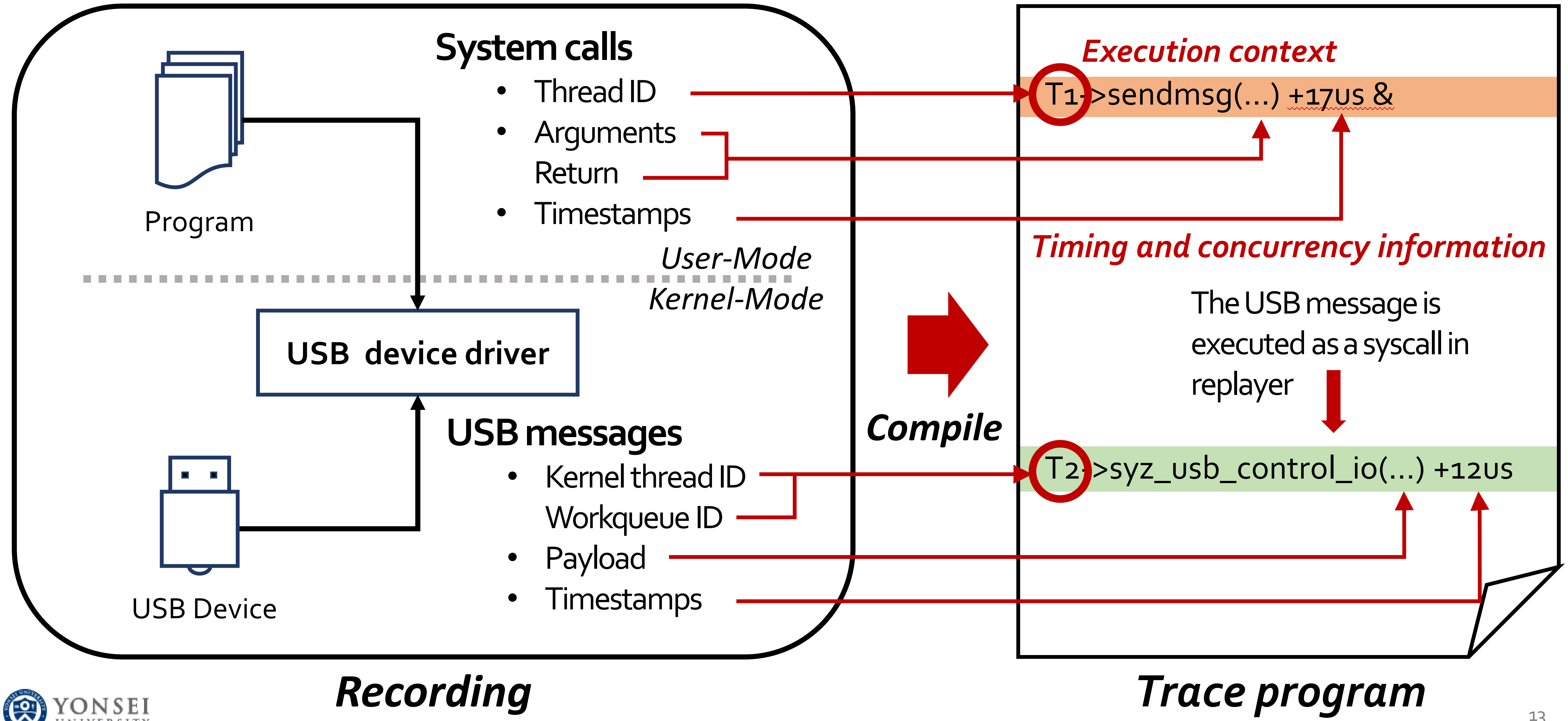
Challenges of Accurate Replay:
Unordered Concurrent USB Requests



If USB request and response are ***not matched***

➡ Driver may execute ***differently from the recording***, resulting in errors

ReUSB Design: Recording (Phase 1)



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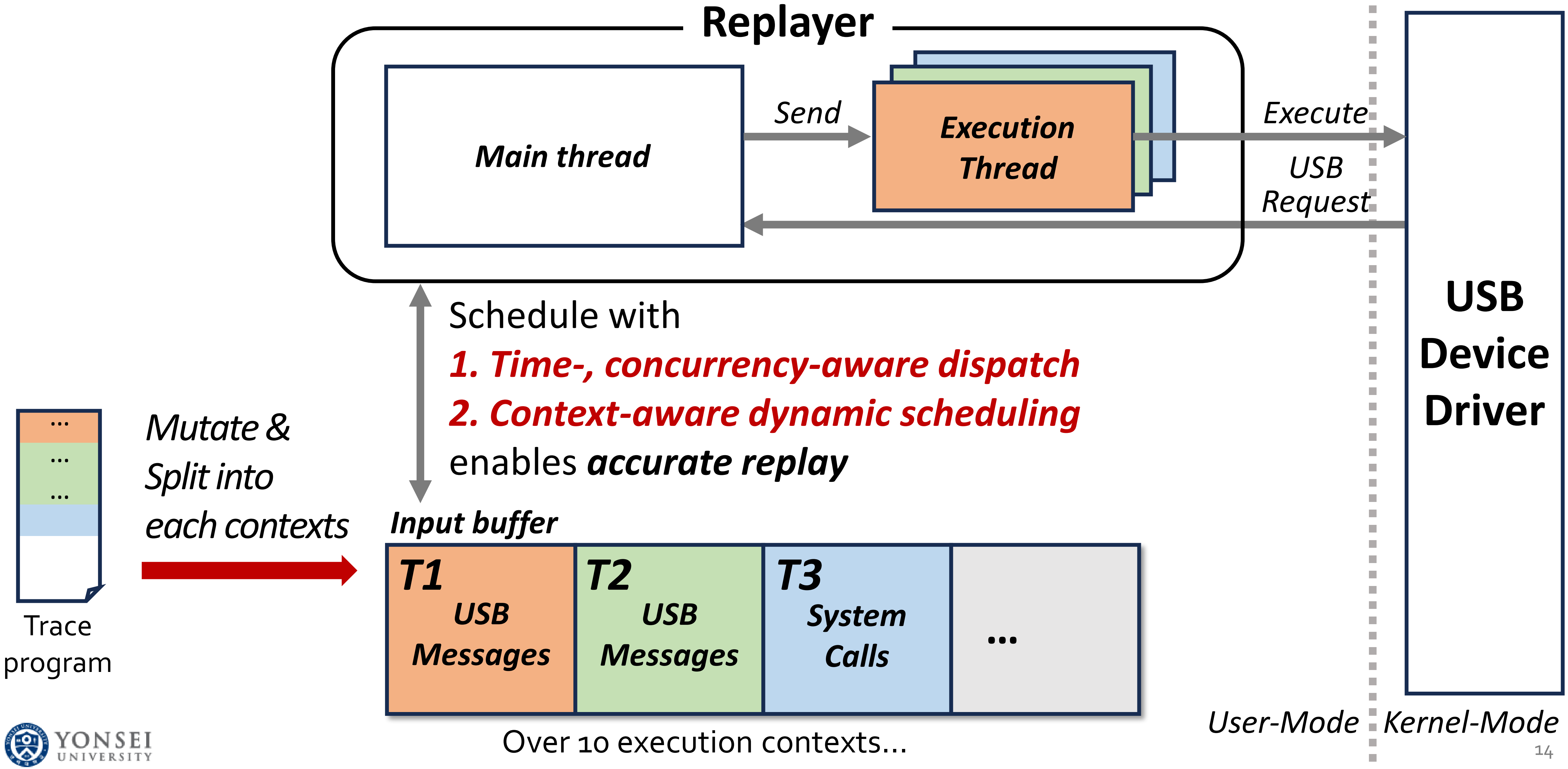
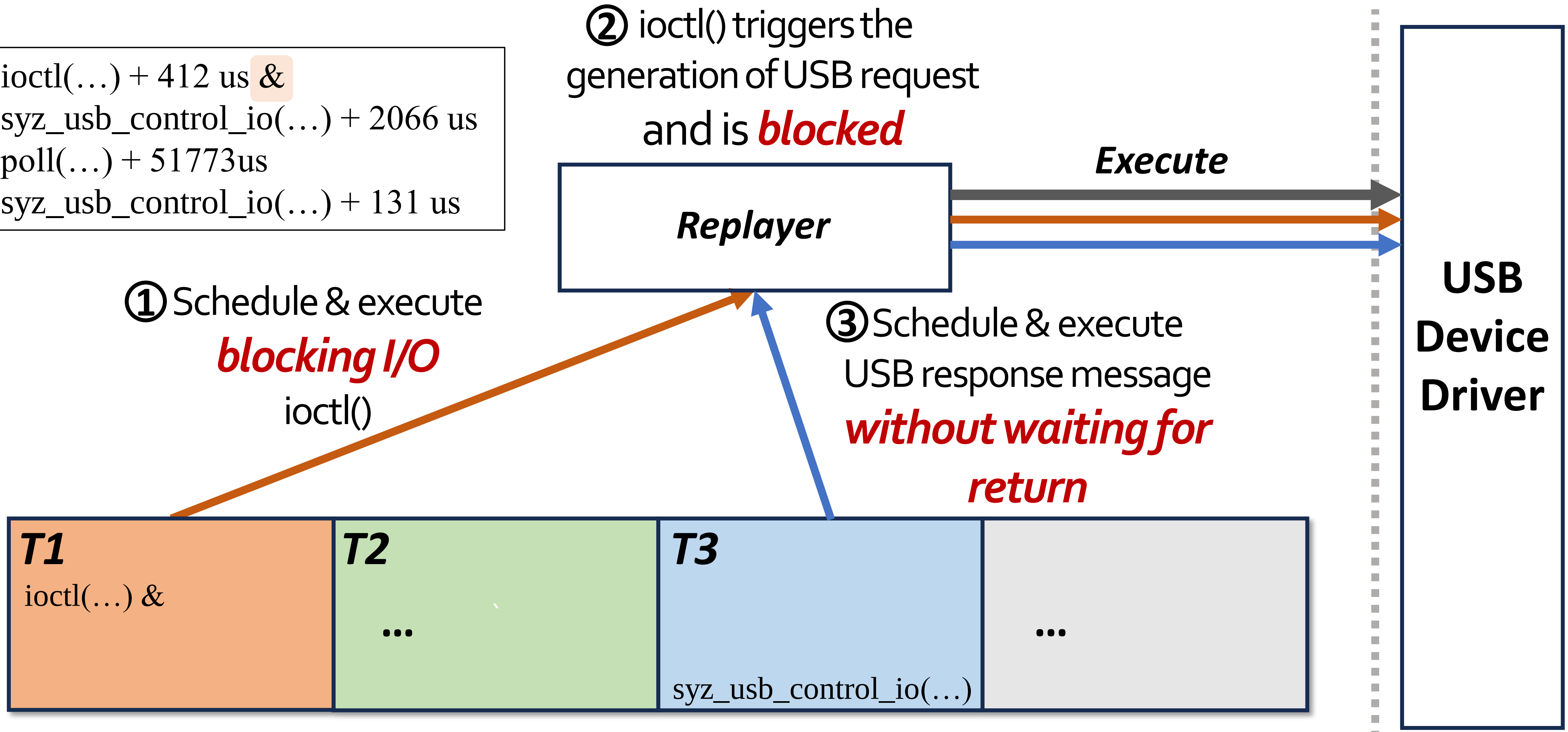
ReUSB Design: Replay & Fuzzing (Phase 2)



Schedule with
1. Time-, concurrency-aware dispatch
2. Context-aware dynamic scheduling
enables ***accurate replay***

Time-, Concurrency-Aware Dispatch: Concurrency

T1->ioctl(…) + 412 us &
T3->syz_usb_control_io(…) + 2066 us
T1->poll(…) + 51773us
T3->syz_usb_control_io(…) + 131 us



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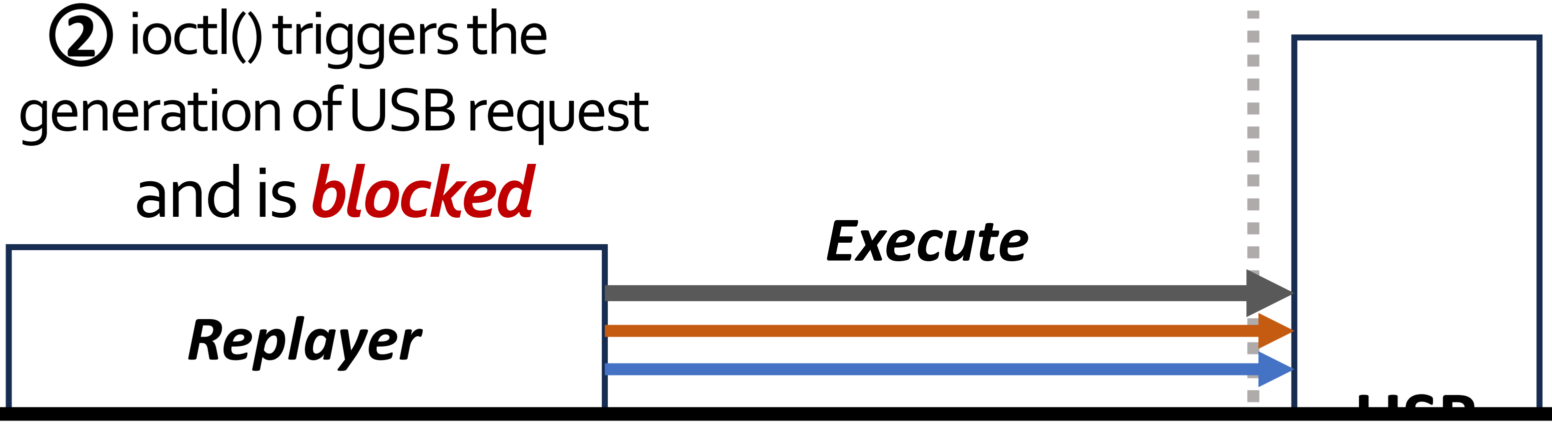
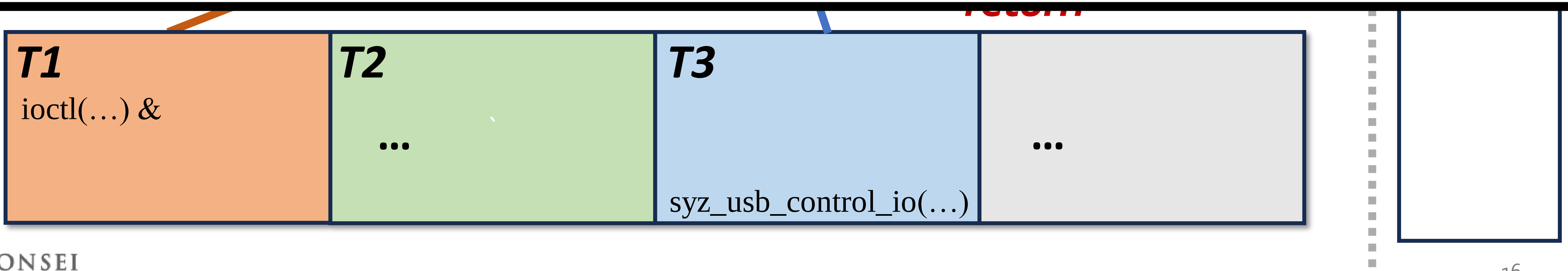


ReUSB can execute system calls in different contexts asynchronously.



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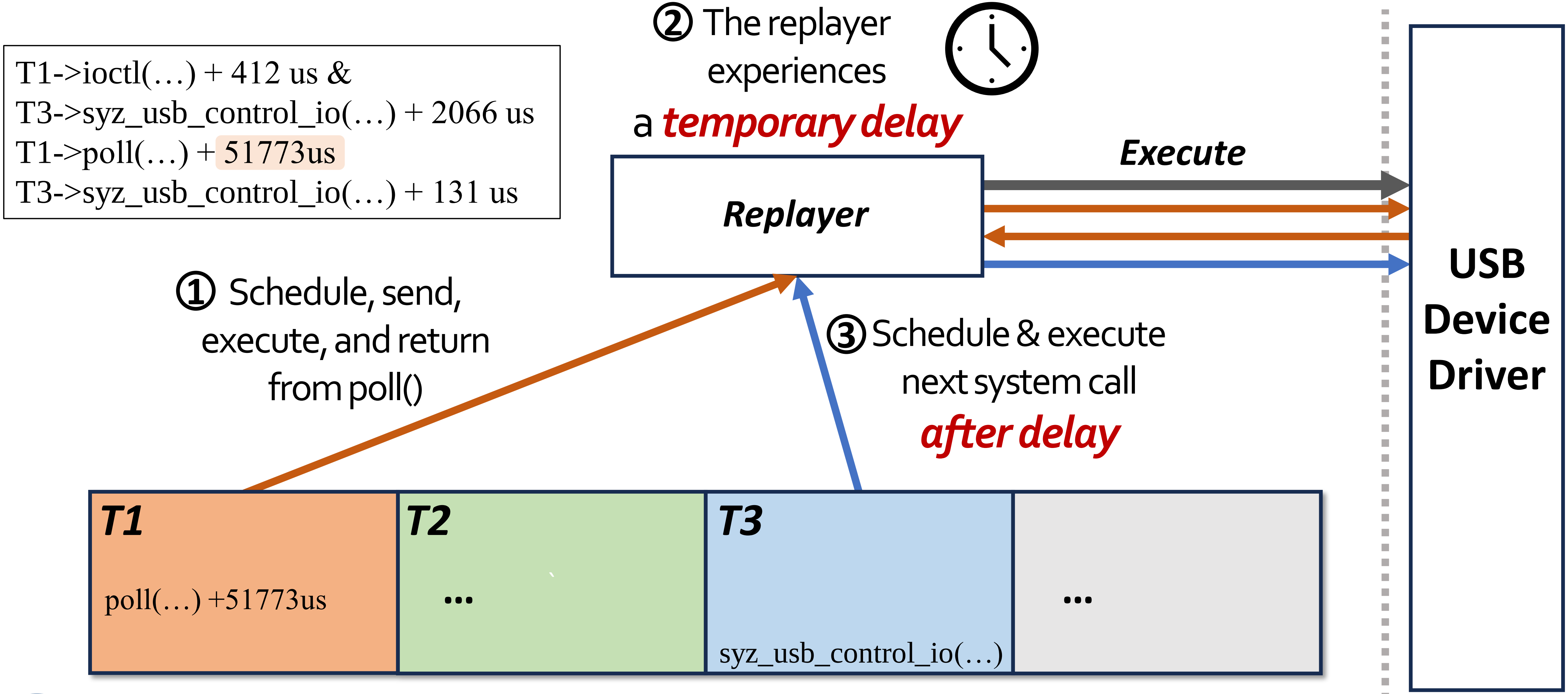

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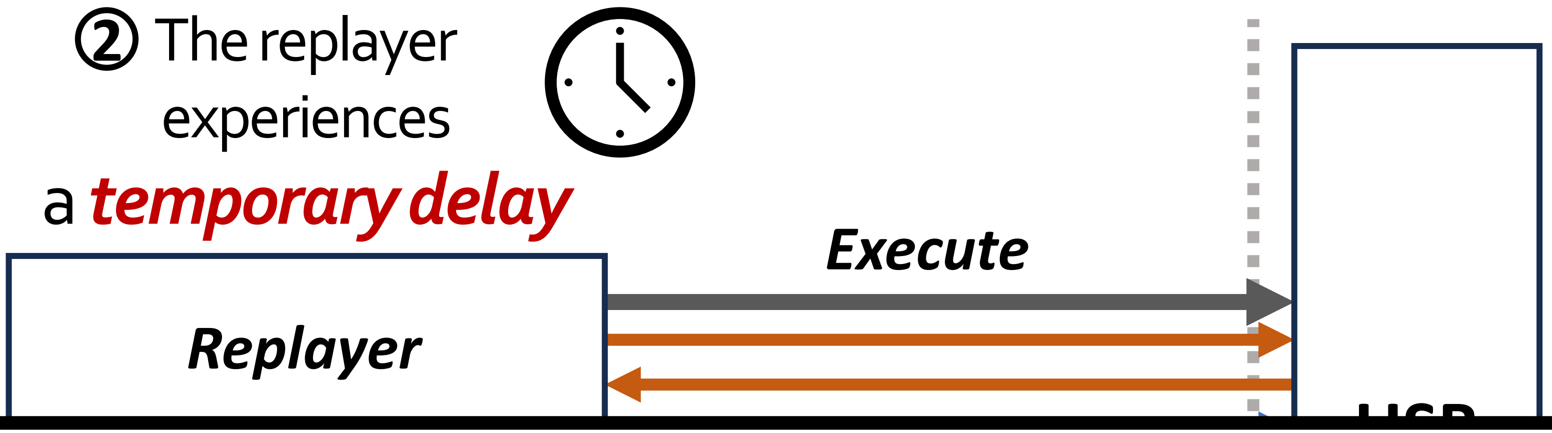
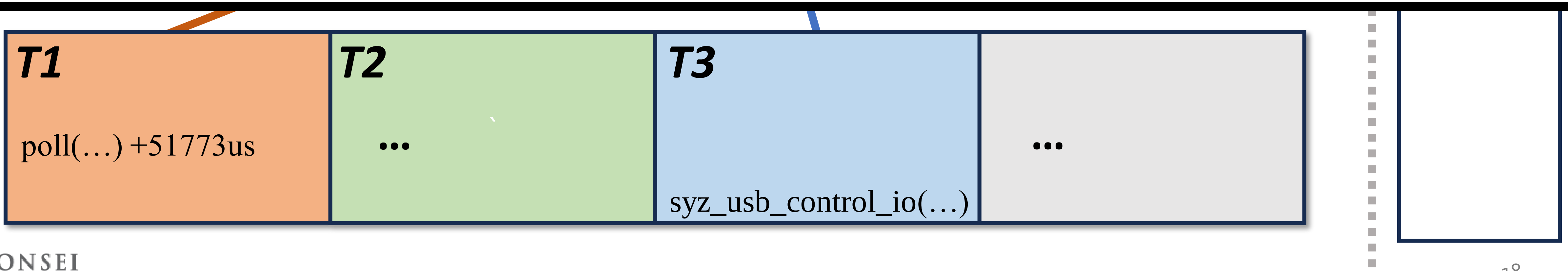
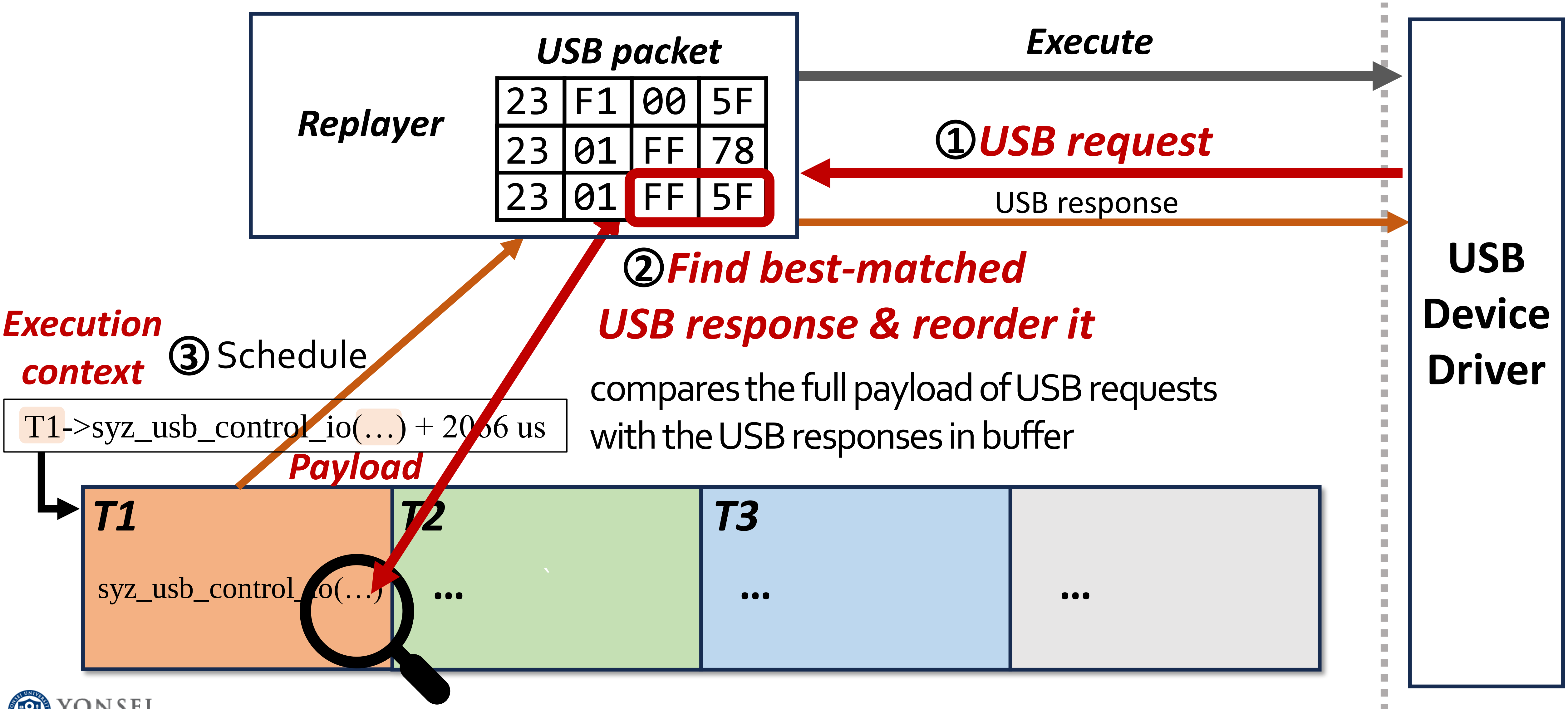


ReUSB can inject delays between system calls to account for time-dependent behavior of drivers.



Context-Aware Dynamic Scheduling



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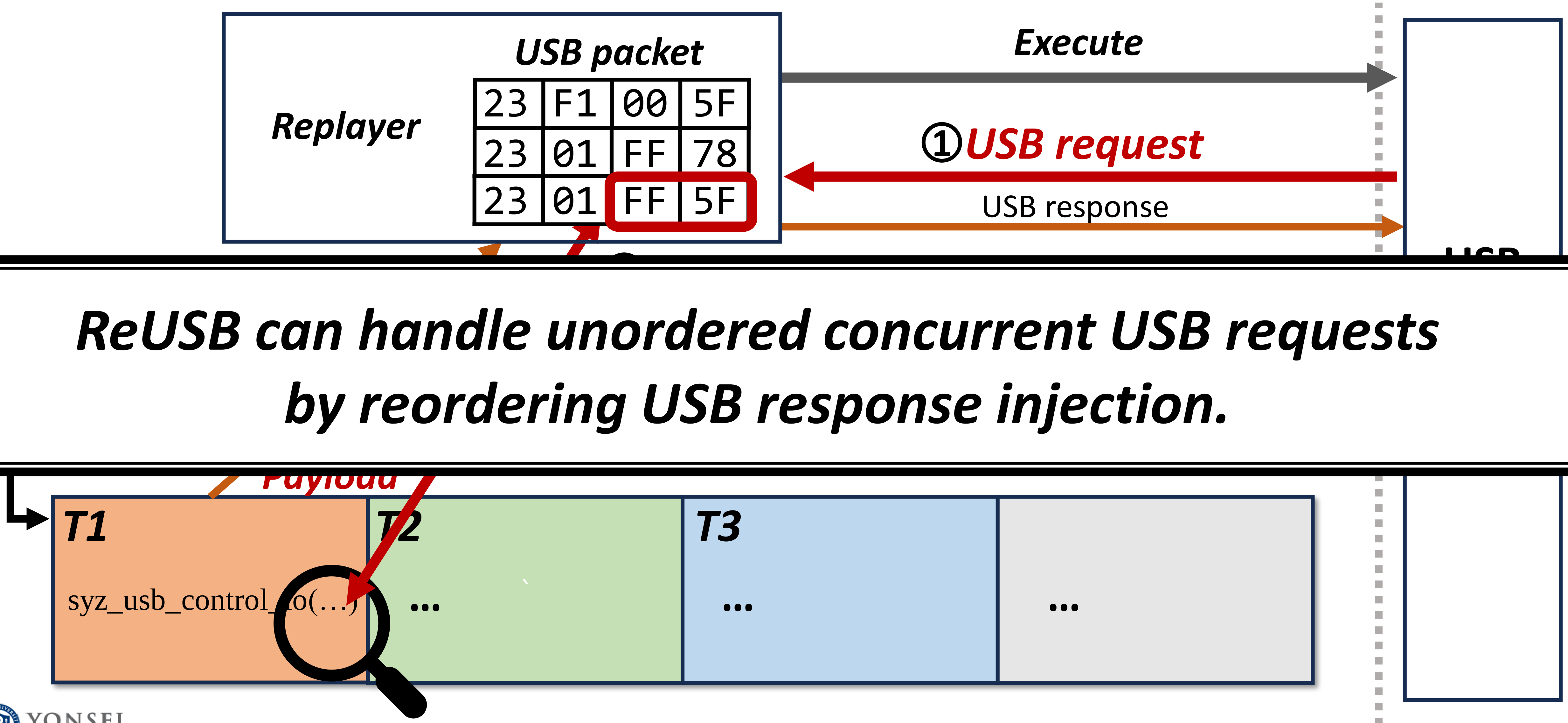

ReUSB can handle unordered concurrent USB requests by reordering USB response injection.

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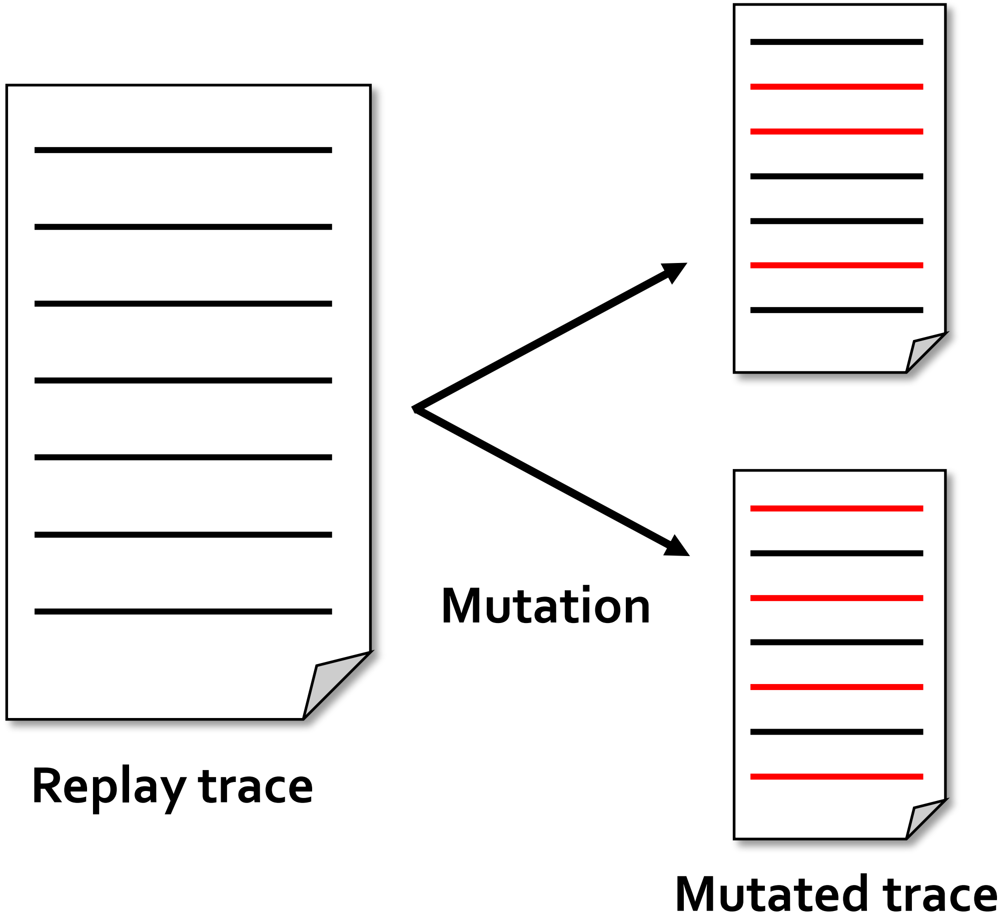
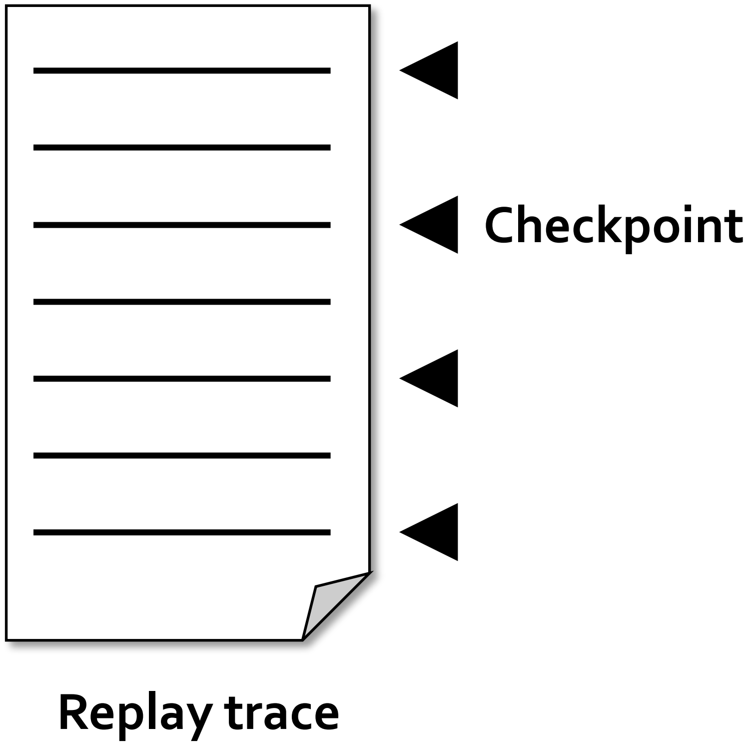
Efficient USB Driver Fuzzing





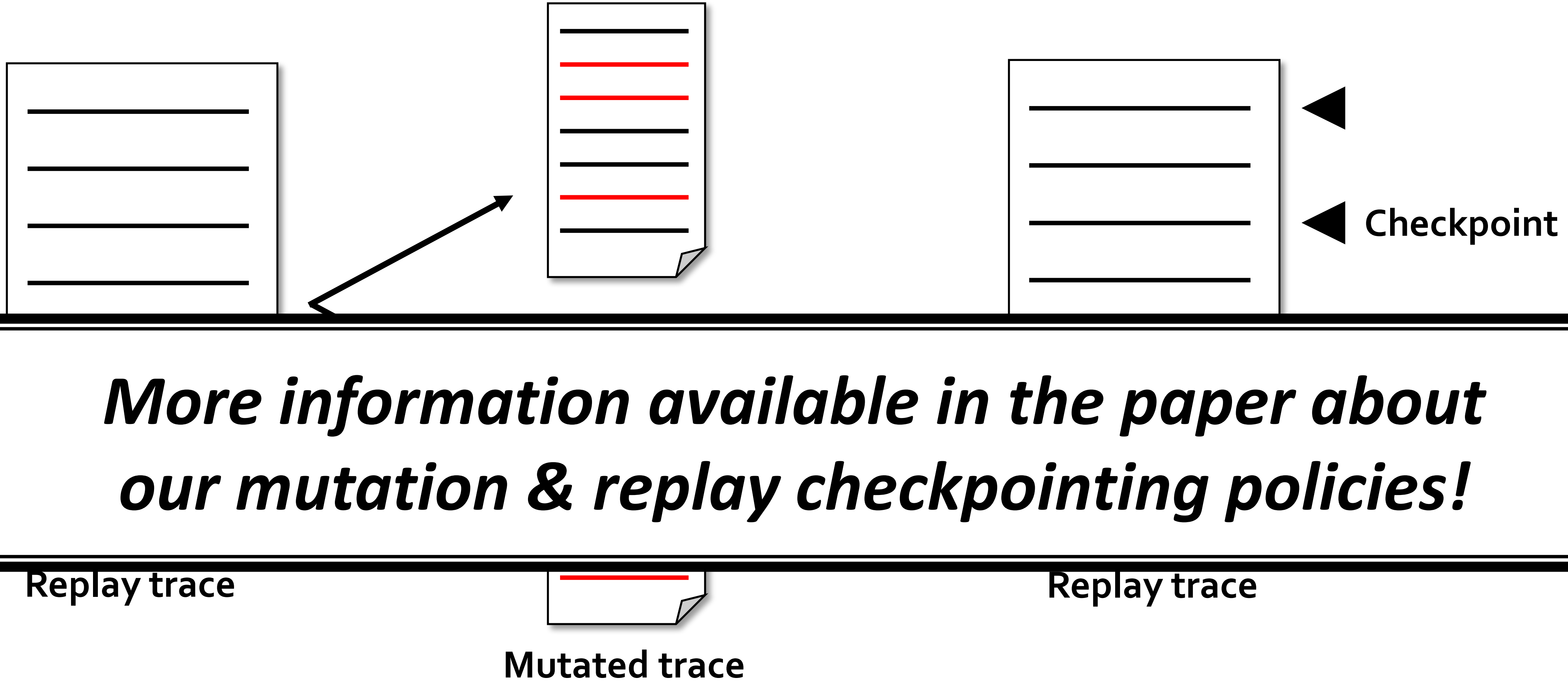
Too large mutation surface

➡ ***Replay-guided fuzzing***

Excessively slow and lengthy

➡ ***Replay checkpointing***

Efficient USB Driver Fuzzing



More information available in the paper about our mutation & replay checkpointing policies!

Too large mutation surface

➡ ***Replay-guided fuzzing***

Excessively slow and lengthy

➡ ***Replay checkpointing***

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Implementation

- Qemu 4.0, Linux KVM
- XHCI USB controller
- STRACE, Wireshark, and USBMON
- Syzkaller
- Agamotto
- Linux's raw gadget

10 Wireless USB Device Drivers

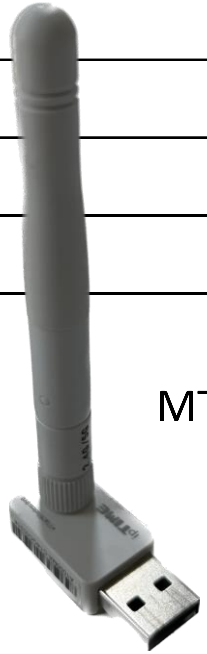
* Out-of-tree drivers whose source code is available at the shown URL

Class	Vendor	Device	Driver Source Code
Wi-Fi	Broadcom	BCM43236	drivers/net/wireless/broadcom/brcm80211
	Qualcomm	AR9271	drivers/net/wireless/ath/ath9k
	Ralink	RT5370	drivers/net/wireless/ralink/rt2x00
	Realtek	RTL8821BU RTL8821AU	github.com/morrownr/88x2bu-20210702* github.com/aircrack-ng/rtl8812au*
	Mediatek	MT7601U MT7610U	drivers/net/wireless/mediatek/mt7601u drivers/net/wireless/mediatek/mt76/mt76x0
Blue-tooth	Broadcom	BCM20702	drivers/bluetooth/btbcm.c
	CSR	CSR8510	drivers/bluetooth/btusb.c
NFC	NXP	PN533	drivers/nfc/pn533

BCM43236

CSR8510

PN533

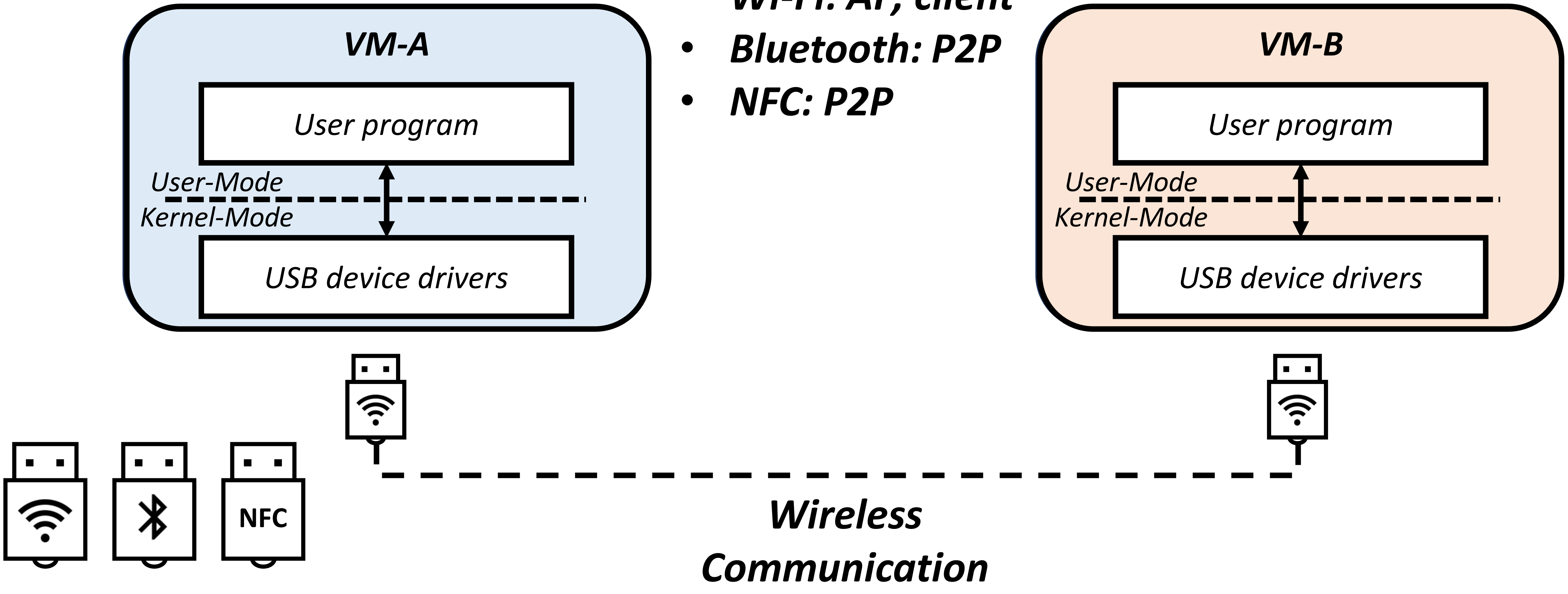


MT7601U

Dual-VM Recording Environment

Dual-VM recording of typical communication scenarios

- ***Wi-Fi: AP, client***
- ***Bluetooth: P2P***
- ***NFC: P2P***



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Result: Number of Input Injections

	VM-A		VM-B		
	Device	# of action (Syscall/USB)	Device	# of action (Syscall/USB)	Duration (sec.)
Wi-FI	BCM43236	**1,894**(1,495/ 399)	MT7601U	-	20
	AR9271	**8,143**(1,577/ 6,566)	MT7601U	-	19
	RT5370	**6,311**(1,568/ 4,743)	MT7601U	-	19
	RTL8812BU	**24,529**(2,761/21,768)	MT7601U	-	23
	RTL8821AU	**9,328**(2,550/ 6,778)	MT7601U	-	23
	MT7601U	**4,099**(1,494/ 2,605)	MT7601U	**9,489**(2,047/ 7,442)	20
	MU7610U	**15,011**(2,639/12,372)	BCM43236	**1,484**(1,051/ 433)	20
	MT7601U	-	AR9271	**11,094**(2,600/ 8,494)	24
	MT7601U	-	RT5370	**11,272**(2,244/ 9,028)	21
	MT7601U	-	RTL8812BU	**12,577**(1,104/11,473)	21
	MT7601U	-	RTL8821AU	**6,728**(1,104/ 5,624)	19
Bluetooth	BCM20702	**6,108**(3,866/ 2,242)	CSR8510	**1,219**(1,037/ 182)	21
	CSR8510	**9,219**(6,423/ 2,796)	BCM20702	**2,004**(1,035/ 969)	24
NFC	PN533	475(437/ 38)	PN533	528(484/ 44)	4

The number of recorded input mostly exceeds thousand!

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Result: Coverage Increase in Replay

		Record	Replay		
			Baseline	After Time-and-concurrency -aware dispatch	After Context-aware dynamic scheduling
AR9271	Client AP	3,956 4,311	1,709 (34.5%) 1,447 (33.6%)	**2,808 (56.7%)** **2,721 (63.1%)**	2,808 (56.7%) 2,721 (63.1%)
BCM43236	Client AP	3,533 3,205	1,346 (38.1%) 1,295 (40.4%)	**2,507 (71.0%)** **1,440 (44.9%)**	**3,441 (97.4%)** **2,827 (88.2%)**
MT7610U	Client AP	4,458 3,976	1,629 (36.5%) 1,326 (33.4%)	**1,762 (39.5%)** **1,437 (36.1%)**	**2,265 (50.8%)** **2,240 (56.3%)**
RT5370	Client AP	4,232 3,724	1,269 (30.0%) 1,005 (27.0%)	**1,832 (43.3%)** **2,073 (55.7%)**	**1,933 (45.7%)** **2,831 (76.0%)**
		...	...	...	...
Geometric mean			42.0%	**62.5%**	**69.7%**

Result: Finding 15 Previously Unknown Bugs

Device	Role(s)	Error Type	Upstream patch
BCM43236	Client & AP	Slab-out-of -bounds	4920ab1
	Client & AP	Slab-out-of -bounds	4920ab1
	Client & AP	Stack-out-of –bounds	0a06cad
	Client & AP	Stack-out-of -bounds	660154d
	Client & AP	Null pointer dereference	683b972
	Client & AP	Shift-out-of-bounds	81d17f6
	Client & AP	Slab-out-of -bounds	6788ba8
	Client	Slab-out-of -bounds	0da40e0
MT7601U	Client	Null pointer dereference	803f317
MT7610U	Client & AP	Null pointer dereference	Bd5dac7
AR9271	Client & AP	Stack-out-of -bounds	8a2f35b
	Client	Use-after-free	F099c5c
PN533	Master	Slab-out-of -bounds	9f28157
	Master & Slave	Use-after-free	9dab880
	Slave	Use-after-free	4bb4db7

CVE-2022-3628

CVE-2023-1380

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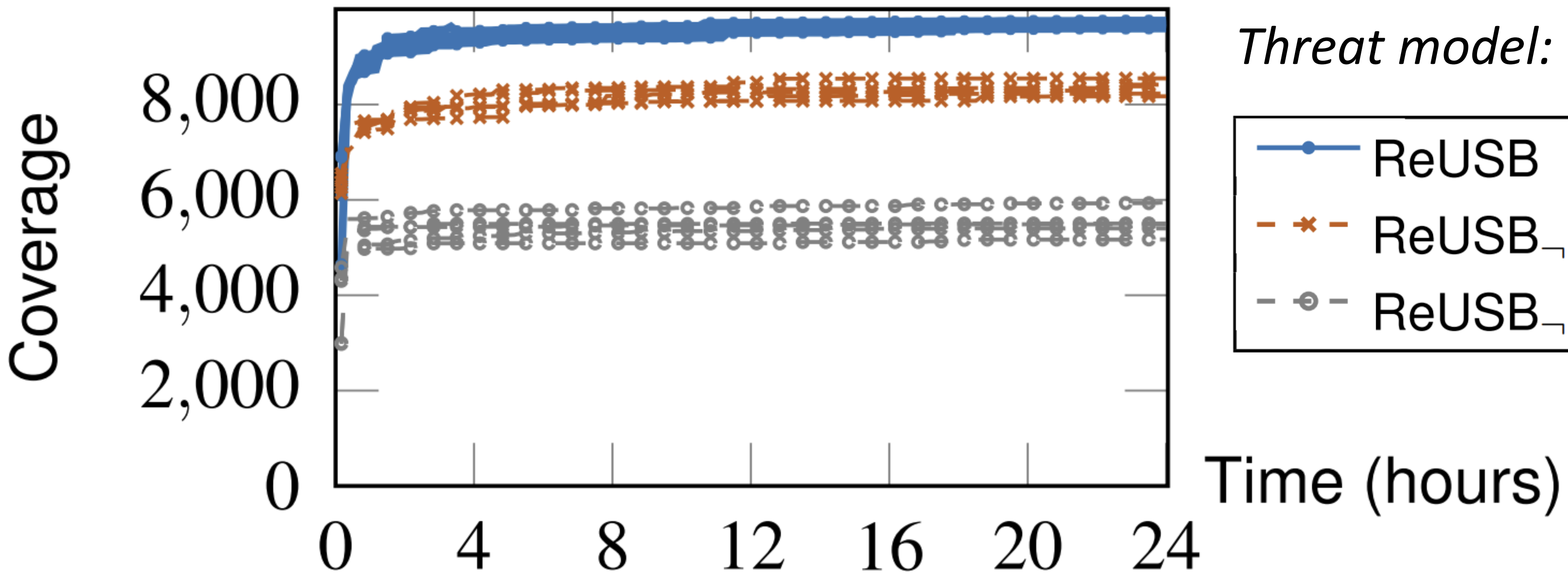
Result: Coverage Increase in Fuzzing



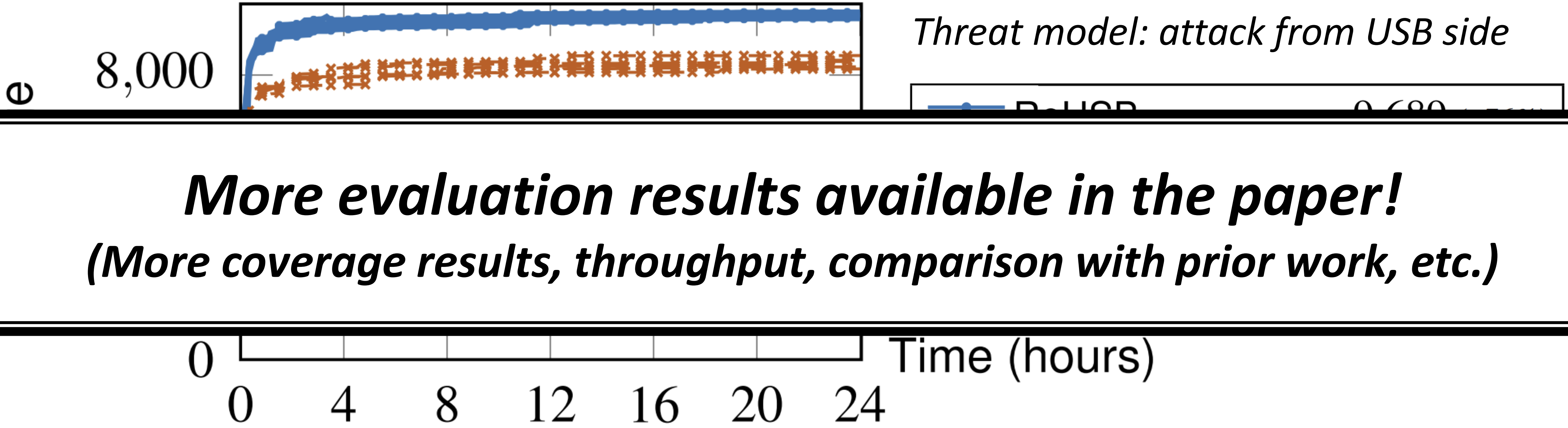
Threat model: attack from USB side

ReUSB	9,689	(+76%)
ReUSB$_{\neg Replay}$	8,349	(+52%)
ReUSB$_{\neg Replay\text{-}Guided}$	5,501	

Using all of our 19 trace programs as an initial seed corpus

Result: Coverage Increase in Fuzzing

Threat model: attack from USB side



More evaluation results available in the paper!

(More coverage results, throughput, comparison with prior work, etc.)

Using all of our 19 trace programs as an initial seed corpus

Conclusion

- We proposed a replay-guided approach to USB driver fuzzing.
  - Controlling timing, concurrency, order of input injection matters for accurate replay of USB drivers.
  - The overhead stemming from accurate replay can be compensated through replay-guided fuzzing and replay checkpointing.

- We showed that replay-guided fuzzing is effective.
  - Fuzzed 10 stateful USB drivers, increased the coverage by up to 76%.
  - Found 20 bugs, of which **15** were previously unknown.
    - Obtained 2 CVEs: **CVE-2022-3628**, **CVE-2023-1380**

Thank you!

Contact

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