FirmGuide: Boosting the Capability of Rehosting Embedded Linux Kernels through Model-Guided Kernel Execution

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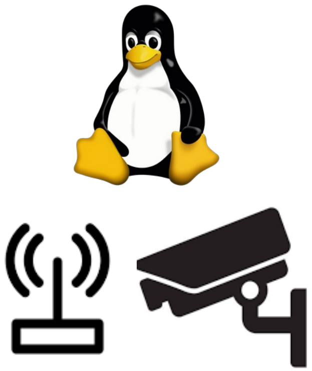
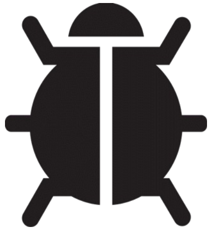
*The first two authors contributed equally to this work.

ASE2021

Motivation

Dynamic Bug or Vulnerability Understanding





Dynamic Bug or Vulnerability Mining

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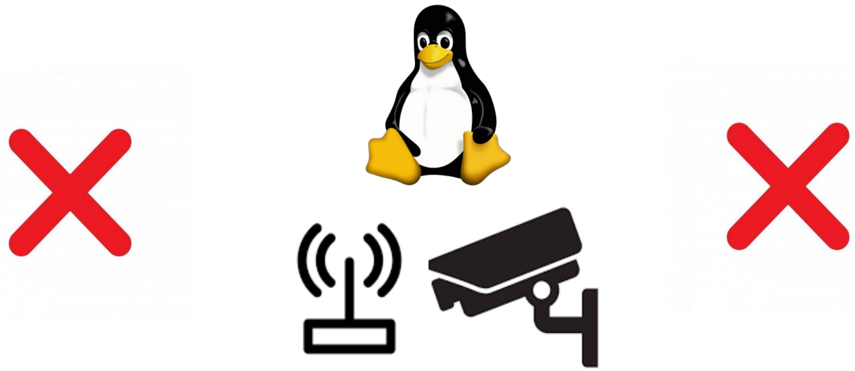

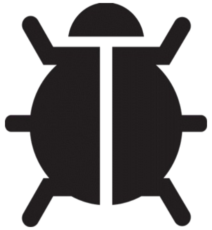

Dynamic Bug or Vulnerability Mining

- Linux kernel with drivers inside high-end embedded firmware

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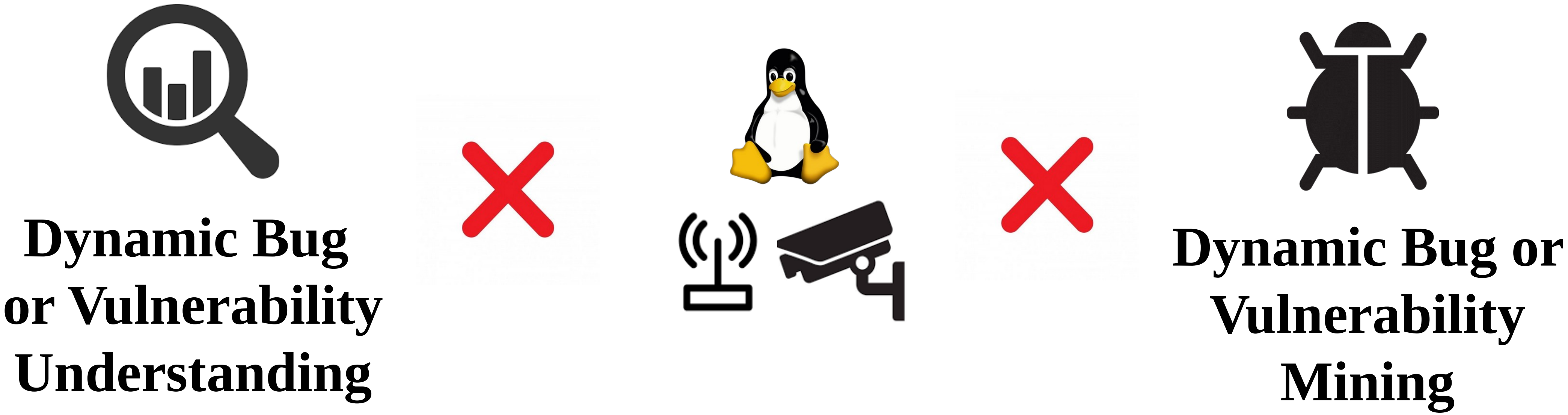

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- Understanding and testing abilities not easy and scaling due to hardware requirement

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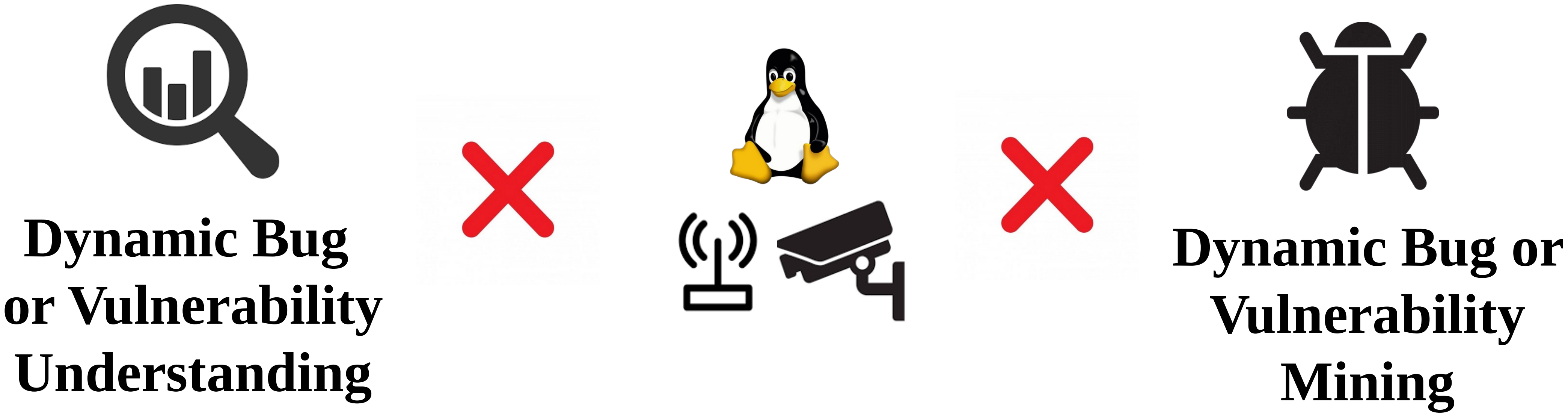

- Linux kernel with drivers inside high-end embedded firmware
- Understanding and testing abilities not easy and scaling due to hardware requirement
- **Rehosting the embedded Linux kernel with the best effort**

Challenge and Observation 1

SoC: plxtech,nas782x	
CPU	Arm11MPCore
Memory	up to 512M
Interrupt Controller	gic
Time-related	rps, oscillator, sysclk, plla, pllb, stdclk, twdclk
UART	ns16550a
Others	gmacclk, pcie, watchdog, sata, nand, ethernet, ehci, leds

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- Numerous peripherals: Type-I Type-II
- **Classifying peripherals for a minimum best effort**

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High fidelity to make the Linux kernel functional-correct

Low fidelity for successful boot

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High-fidelity Virtual Device

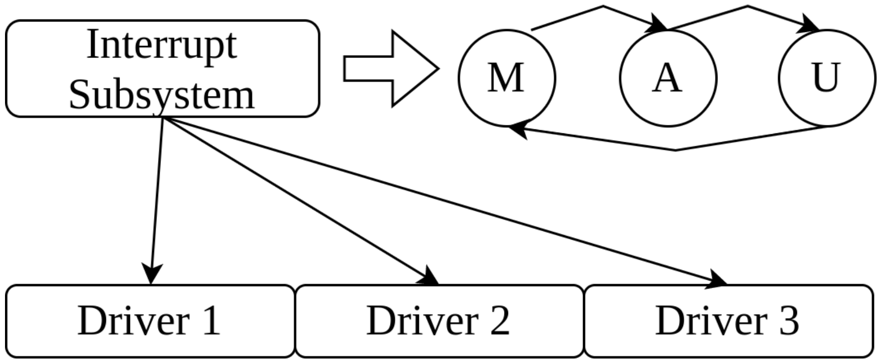
Dummy Virtual Device

Challenge and Observation 2

Challenge and Observation 2

Multiple models for interrupt controllers

- ralink-rt2880-intc
- qca,ar7240-intc
- marvell,orion-intc
- marvell,orion-bridge-intc
- arm,cortex-a9-gic
- …



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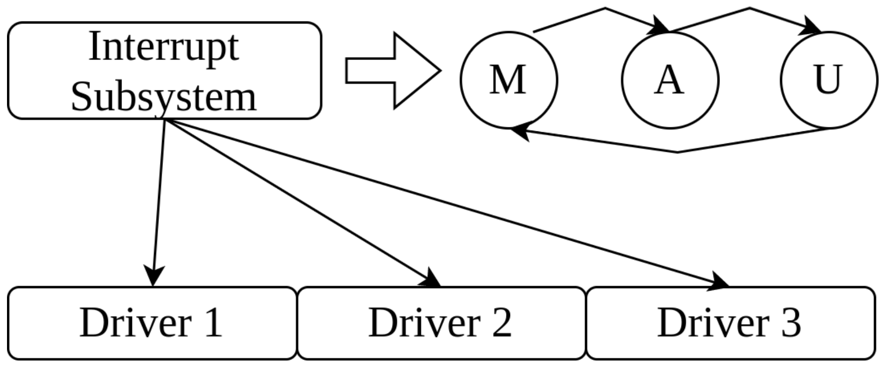

- Diverse models: Linux subsystems that hide implementation details

Challenge and Observation 2

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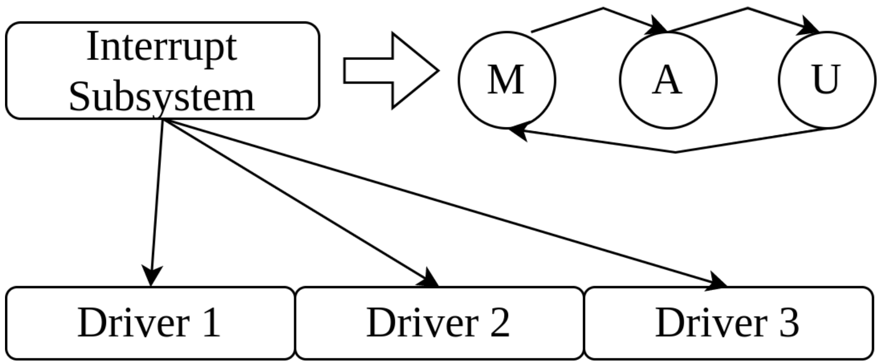

- Diverse models: Linux subsystems that hide implementation details
- **Extracting state machines from the Linux subsystems (Type-I)**

Challenge and Observation 3

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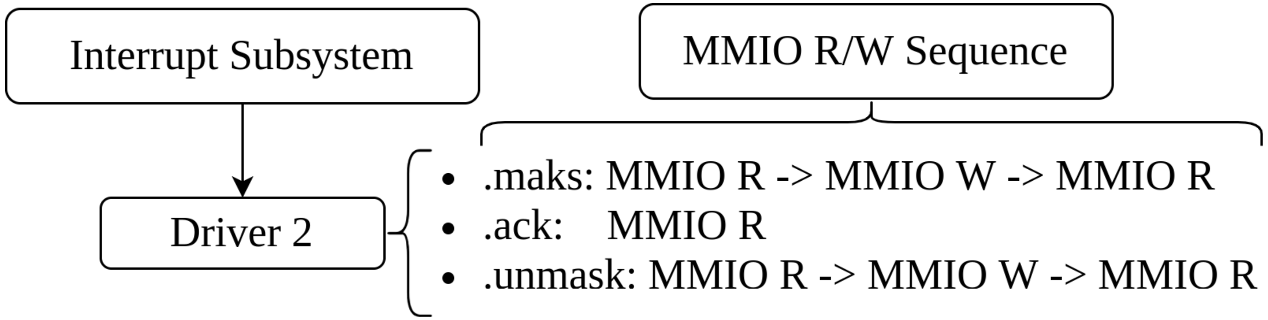
```
Mask Interrupt
    MMIO Read M -> a
    a &= flags
    MMIO Write a -> M
Load IRQ number
    MMIO Read I -> b
    switch(b)
        …
```



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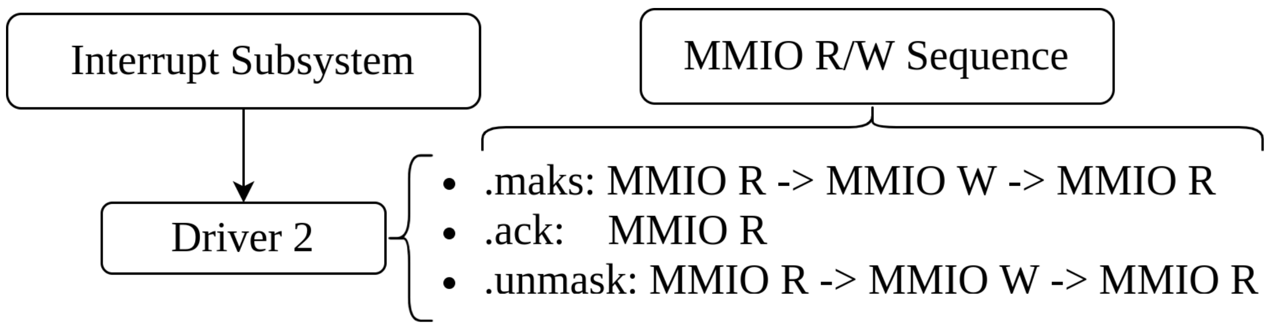

- Complex semantics: Specific driver interface callbacks that embed complex semantics

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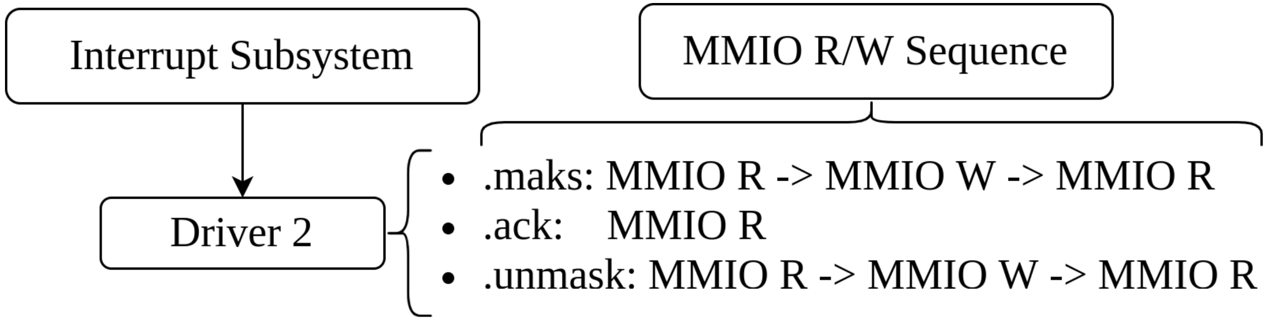
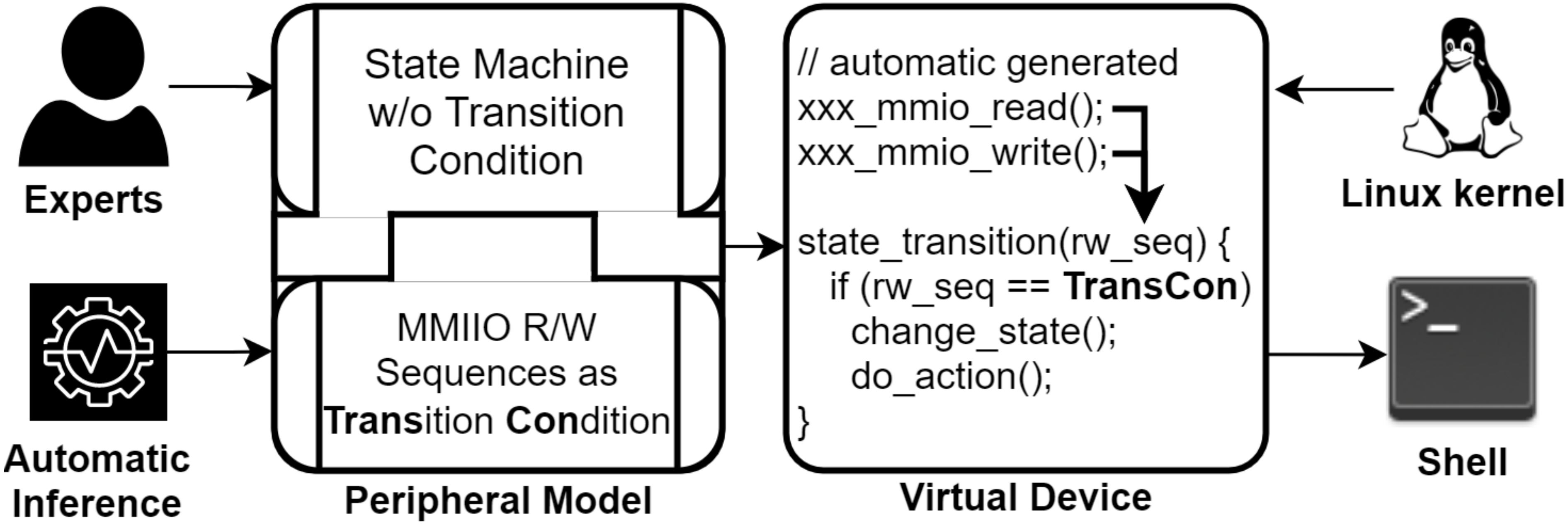


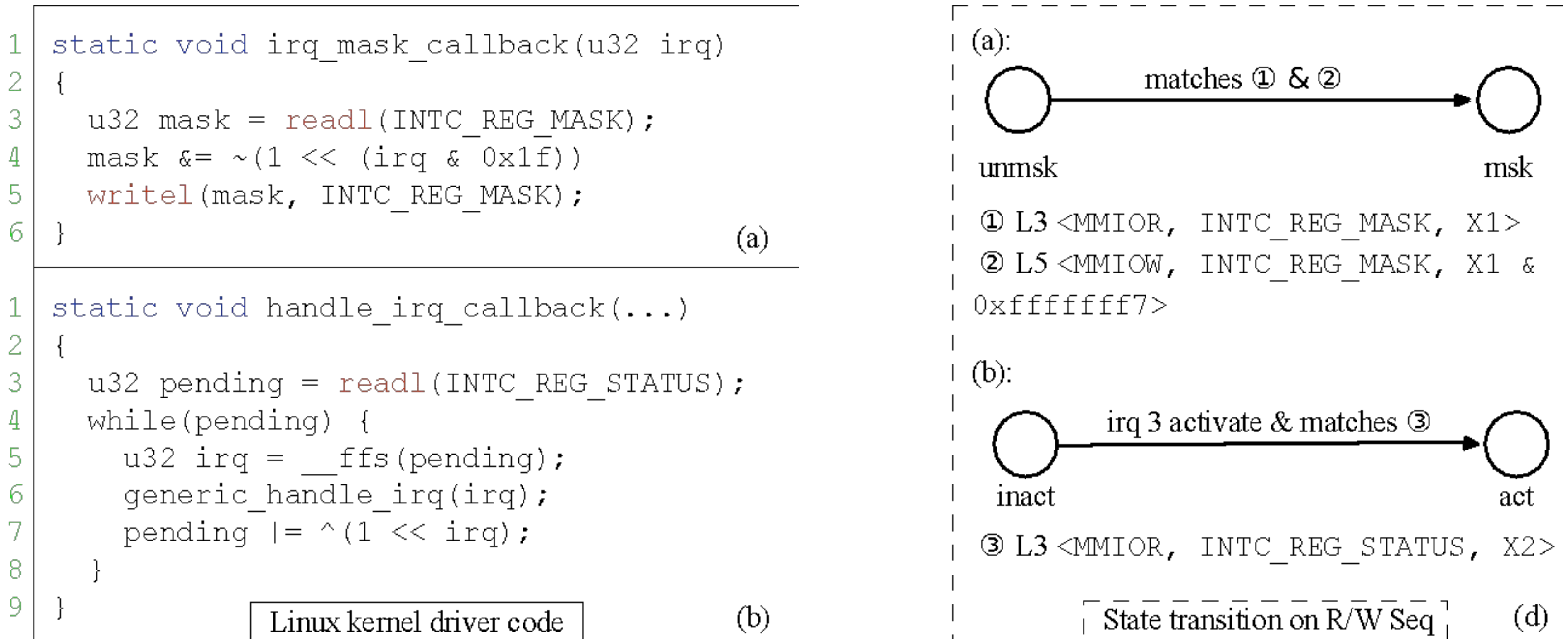
- Complex semantics: Specific driver interface callbacks that embed complex semantics
- **Extracting MMIO R/W sequences from these callbacks (Type-I)**

Core Technique: Model-guided Kernel Execution



- Peripheral model = the model template (a state machine) + the model parameters (MMIO R/W sequences as transition conditions)

Model-guided Kernel Execution: Running Example



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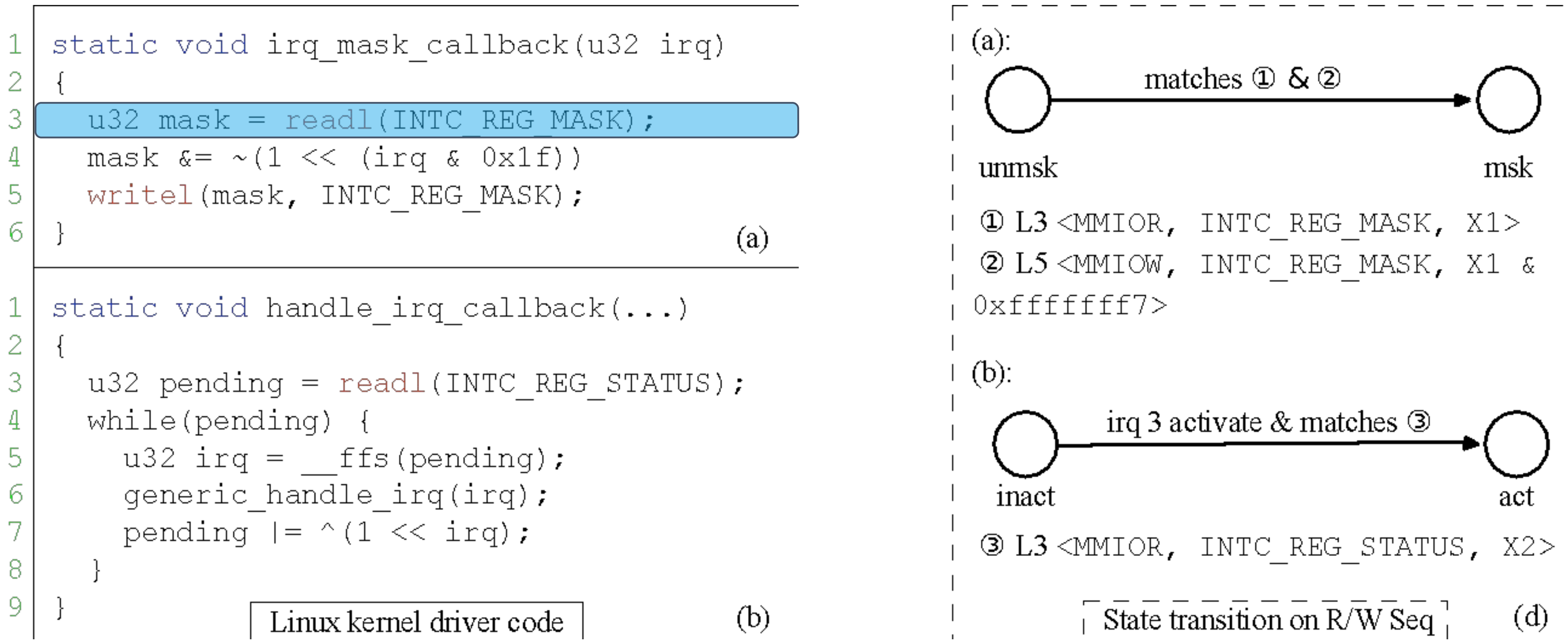

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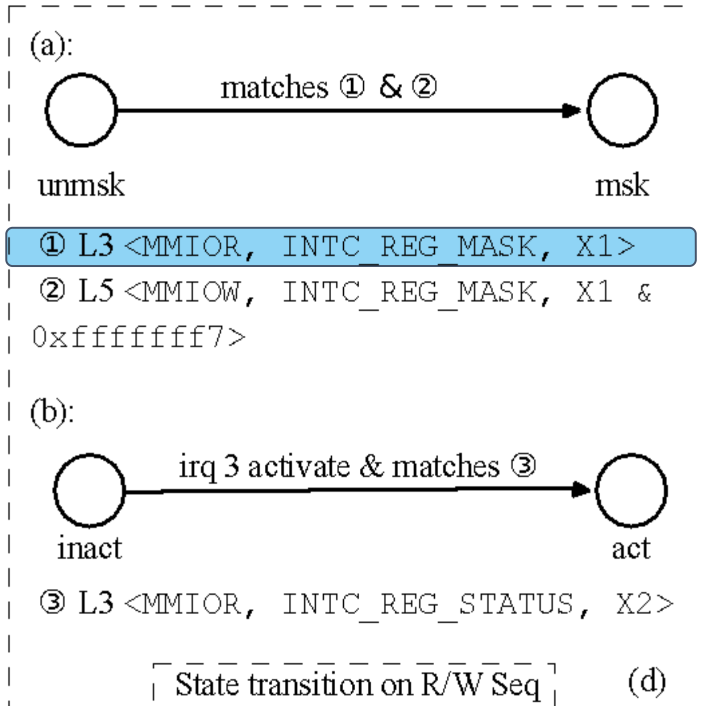
1 static void irq_mask_callback(u32 irq)
2 {
3   u32 mask = readl(INTC_REG_MASK);
4   mask &= ~(1 << (irq & 0x1f))
5   writel(mask, INTC_REG_MASK);
6 }
```

(a)

```
1 static void handle_irq_callback(...)
2 {
3   u32 pending = readl(INTC_REG_STATUS);
4   while(pending) {
5     u32 irq = __ffs(pending);
6     generic_handle_irq(irq);
7     pending |= ^(1 << irq);
8   }
9 }
```

Linux kernel driver code

(b)



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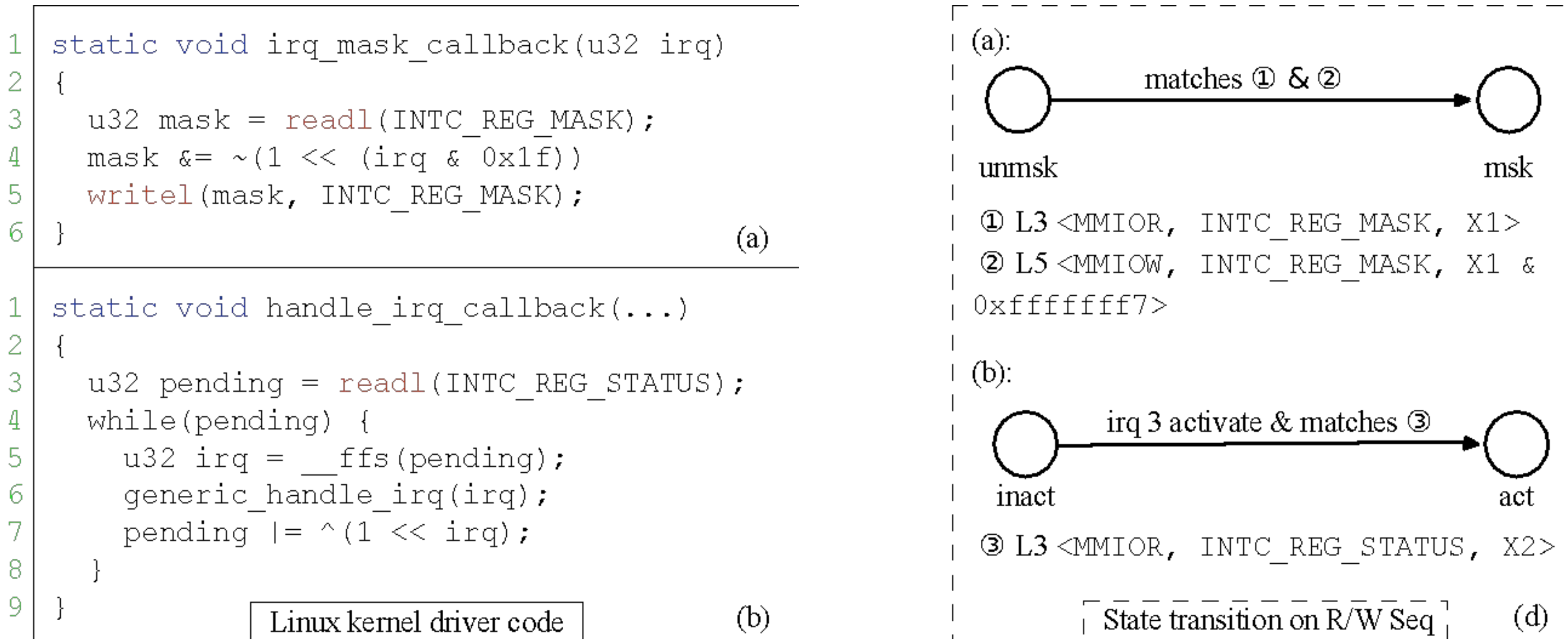

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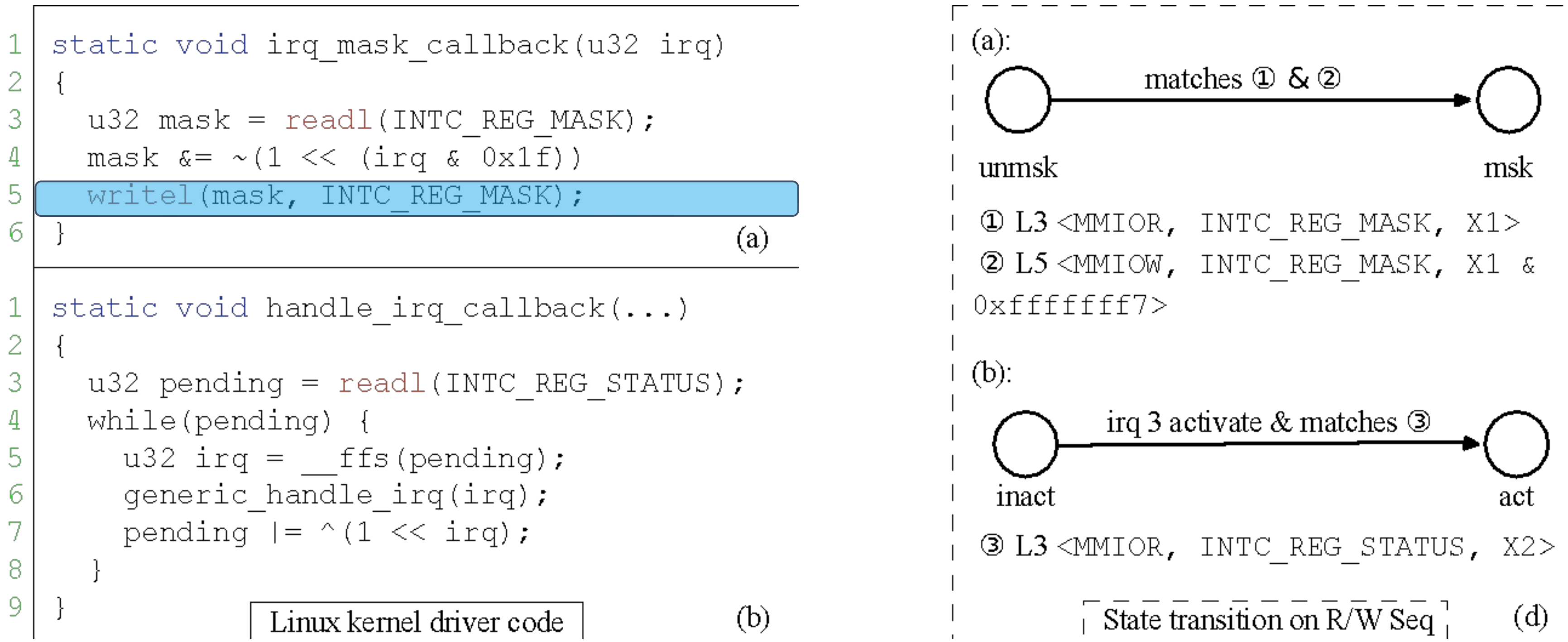

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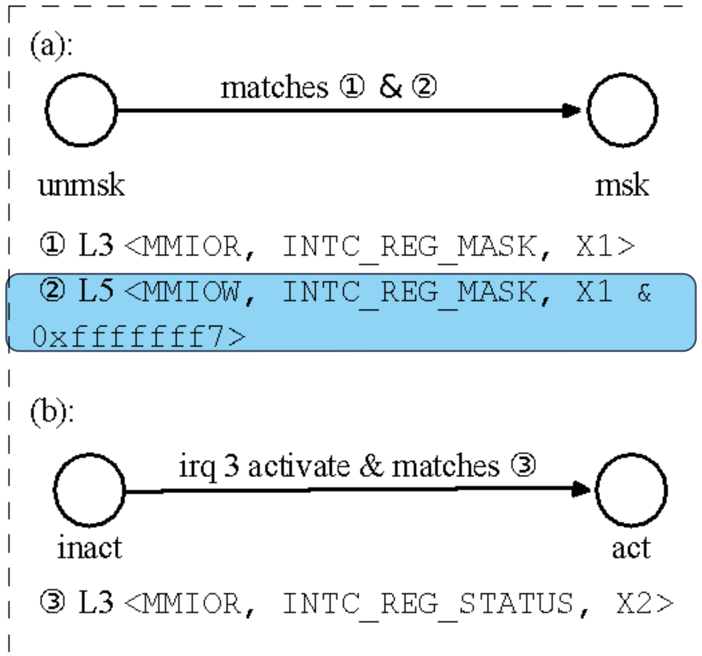

State transition on R/W Seq

(d)

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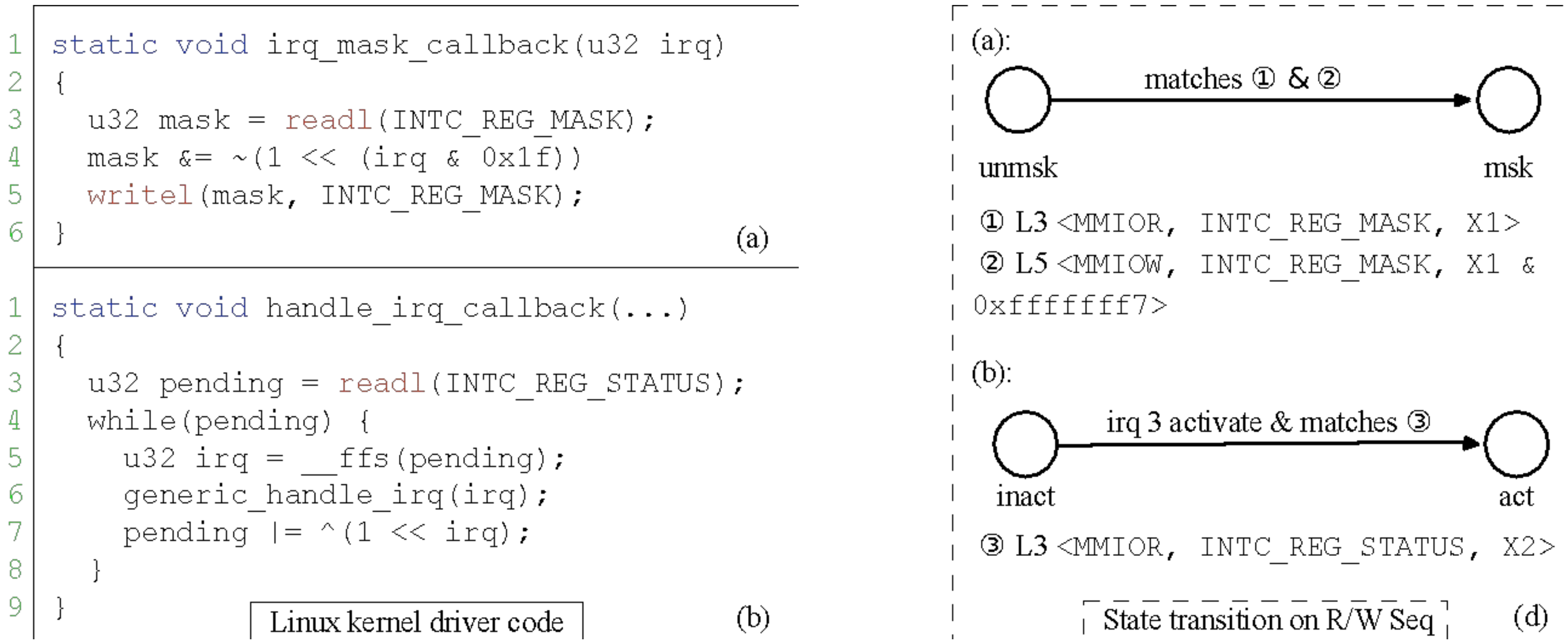

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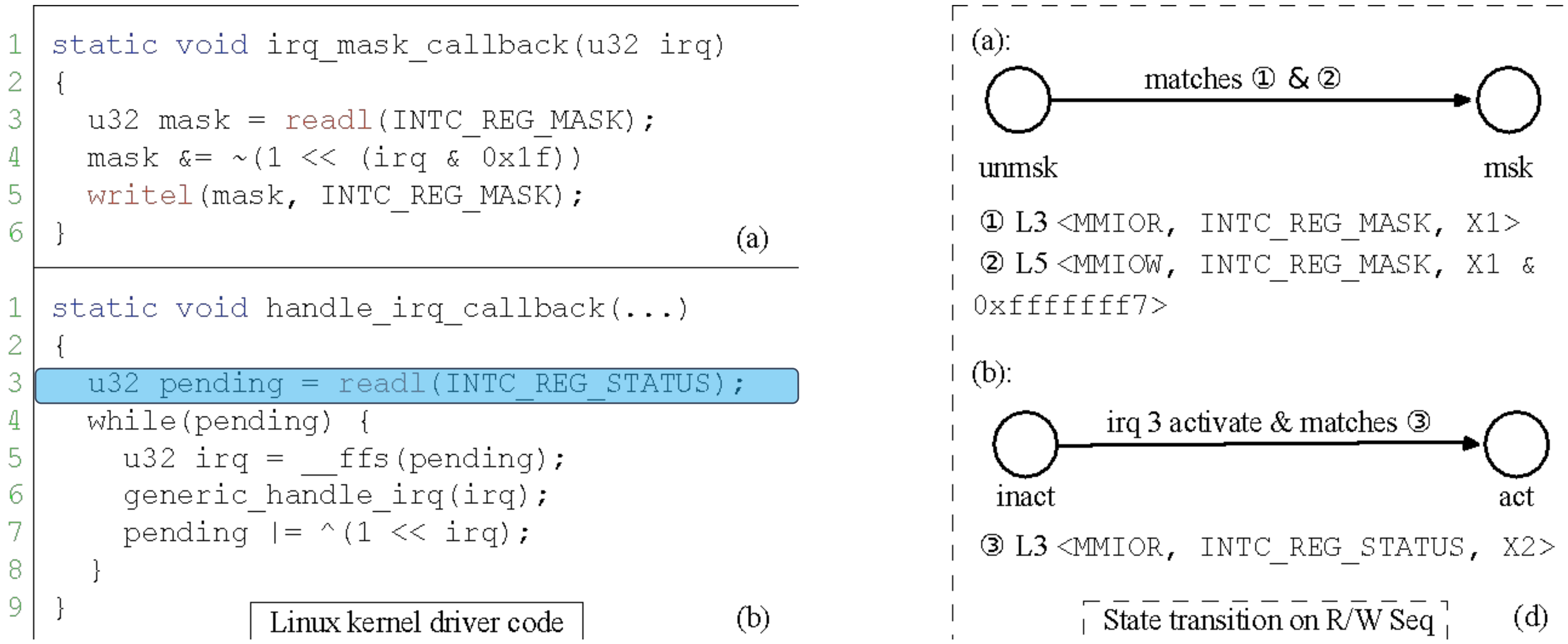

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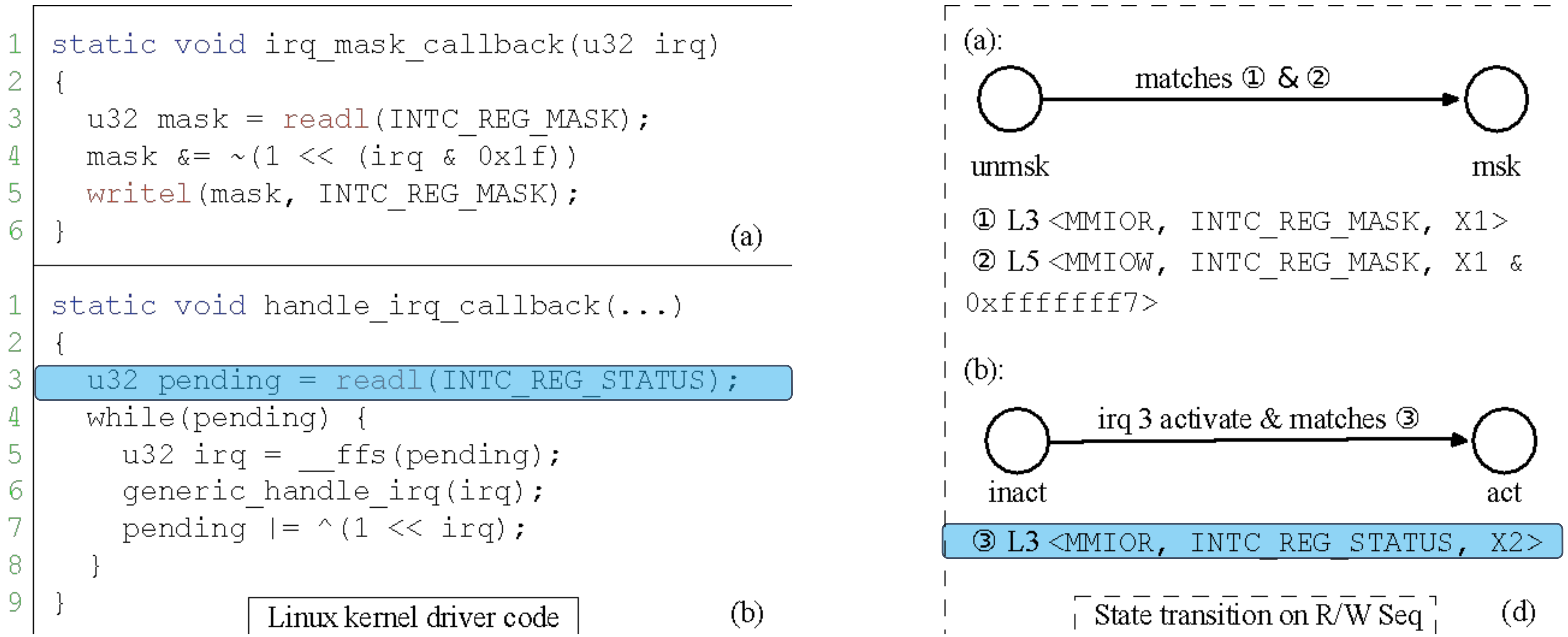

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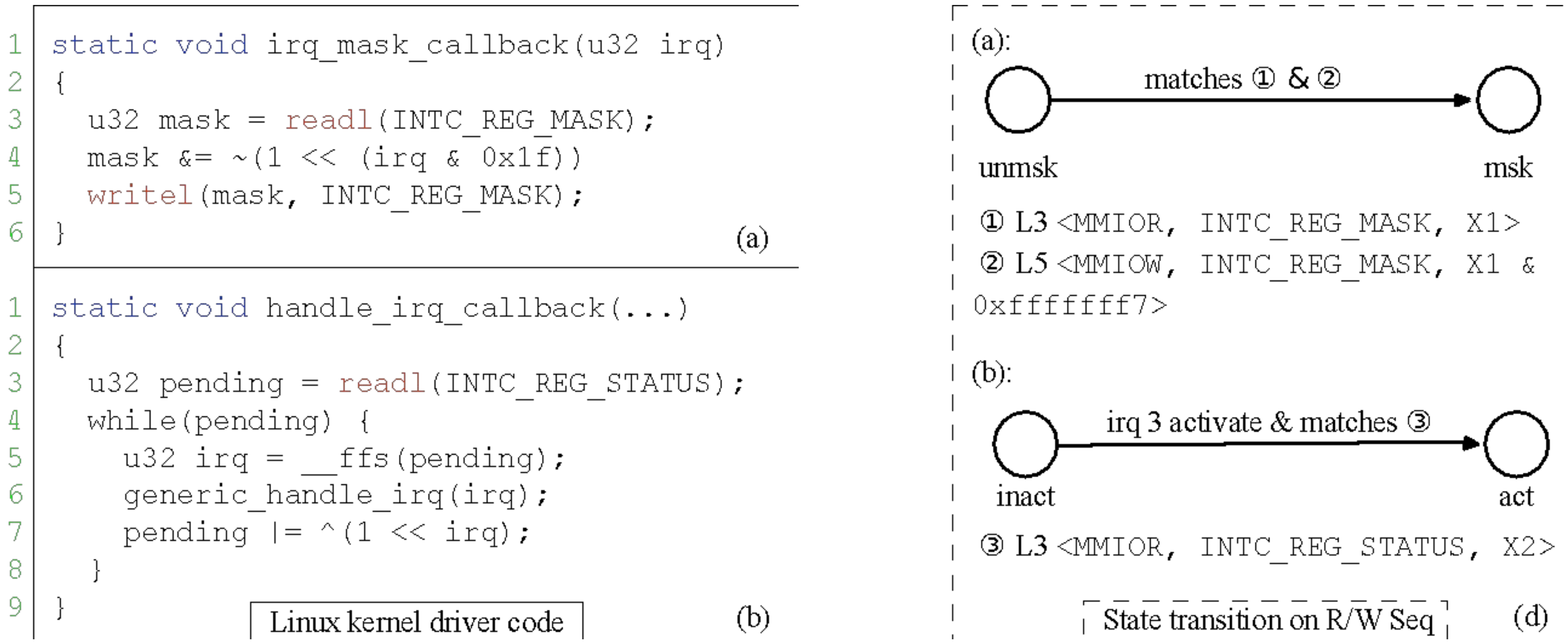

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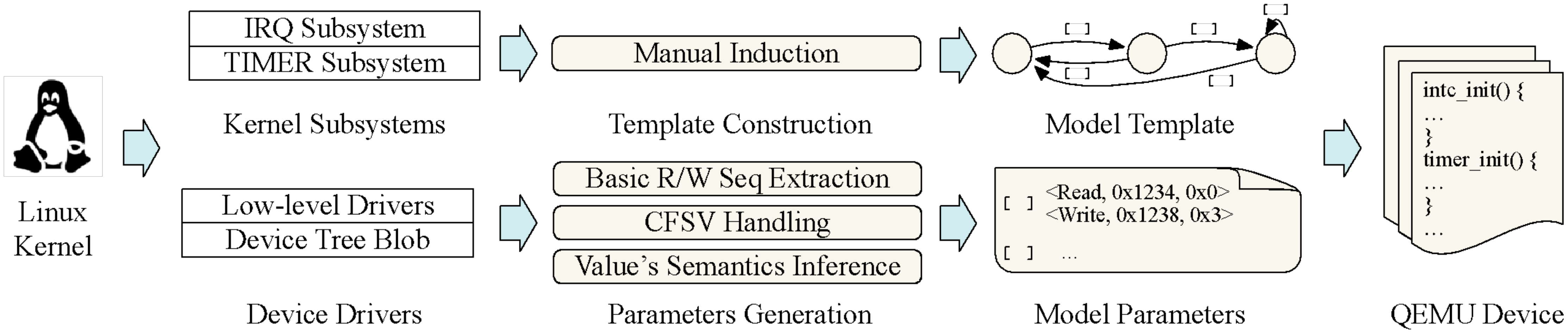
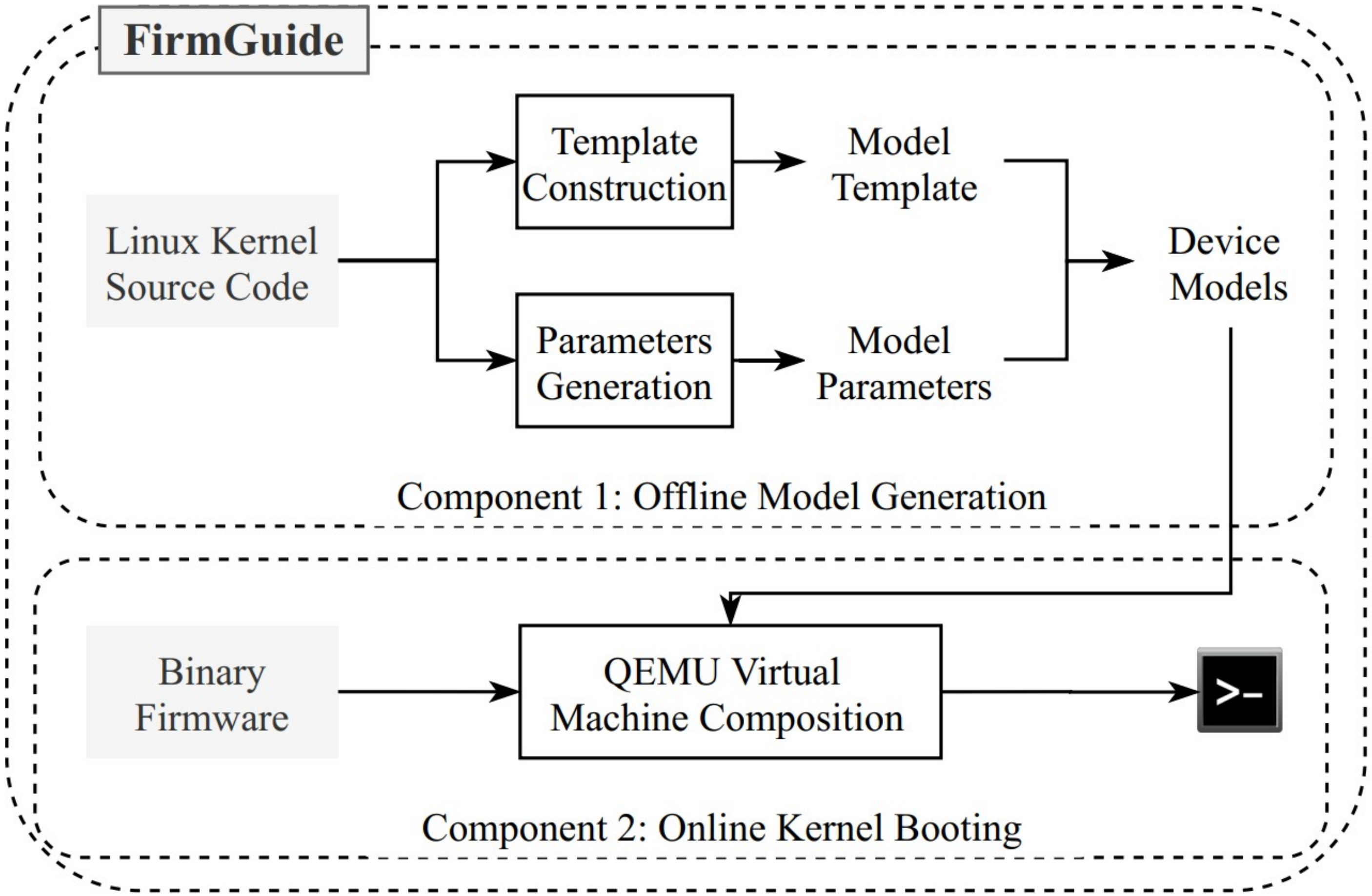
Model-guided Kernel Execution: Methodology



- **We semi-automatically build the state machine of each peripheral: a general model template (manually) plus model parameters (automatically)**

System Design and Implementation



LLVM pass for preprocess
KLEE for MMIO R/W Seq
Python for glues

Python for main logic
Template-render pattern

Evaluation

RQ 1: What peripheral models can we generate?

Type I

Subtarget	Interrupt Controller	Timer	# of Paths	# of Solutions	First/All Solution (s)	Exists CFSV (y/n)	Timer Semantics	LoC
ramips/rt305x	ralink-rt2880-intc	`not necessary`	262	4	1/2	n	-	3,366
ath79/generic	qca,ar7240-intc	`not necessary`	110,083	1,134	5/943	n	-	4,138
kirkwood/generic	marvell,orion-intc marvell,orion-bridge-intc	marvell,orion-timer	132	2	2/3	y	$y =\sim x$	4,790
bcm53xx/generic	arm,cortex-a9-gic	arm,cortex-a9-global-timer arm,cortex-a9-twd-timer	150,336	2,592	2,027/24,070	y	$y = x_1 << 32 + x_2$	3,537
oxnas/generic	arm,arm11mp-gic	arm,arm11mp-twd-timer plxtech,nas782x-rps-timer	52,332	1,246	914/16,184	y	$y = x$	3,366

Type II

Subtarget	ramips/ rt305x	ath79/ generic	kirkwood/ generic	bcm53xx/ generic	oxnas/ generic
count	1/10	2/15	3/26	2/4	2/9

Evaluation

RQ 2: What embedded Linux kernels can we rehost?

SoC	Unpack	Kernel	Booting Validation	
			User Space	Shell
Ralink RT3050	1164	1164	1144 (98.28%)	1052 (90.38%)
Ralink RT3052	1815	1815	1815 (100.00%)	1661 (91.52%)
Ralink RT3352	173	173	173 (100.00%)	157 (90.75%)
Ralink RT5350	1632	1632	1611 (98.71%)	1475 (90.38%)
subtarget: ramips/rt305x	4784	4784	4743 (99.14%)	4345 (90.82%)
Atheros AR7161	36	36	20 (55.56%)	20 (55.56%)
Atheros AR7241	20	20	12 (60.00%)	12 (60.00%)
Atheros AR7242	24	24	24 (100.00%)	24 (100.00%)
Atheros AR9330	4	4	4 (100.00%)	4 (100.00%)
Atheros AR9331	24	24	12 (50.00%)	12 (50.00%)
Atheros AR9341	10	10	4 (40.00%)	4 (40.00%)
Atheros AR9342	24	24	24 100.00%)	24 (100.00%)
Atheros AR9344	70	70	64 (91.43%)	64 (91.43%)
Qualcomm Atheros QCA9531	22	22	16 (72.73%)	16 (72.73%)
Qualcomm Atheros QCA9533	41	41	14 (34.15%)	14 (34.15%)
Qualcomm Atheros QCA9557	64	64	64 (100.00%)	64 (100.00%)
Qualcomm Atheros QCA9558	54	54	50 (92.59%)	50 (92.59%)
Qualcomm Atheros QCA9560	16	16	16 (100.00%)	16 (100.00%)
Qualcomm Atheros QCA9561	18	18	14 (77.78%)	14 (77.78%)
Qualcomm Atheros QCA9563	114	114	106 (92.98%)	106 (92.98%)
subtarget: ath79/generic	541	541	444 (82.07%)	444 (82.07%)
Broadcom BCM4708A0	241	241	241 (100.00%)	241 (100.00%)
Broadcom BCM4709A0	128	128	128 (100.00%)	128 (100.00%)
Broadcom BCM47189	19	19	19 (100.00%)	19 (100.00%)
subtarget: bcm53xx/generic	388	388	388 (100%)	388 (100%)
Marvell 88F6192	20	20	20 (100.00%)	20 (100.00%)
Marvell 88F6281	208	204	204 (100.00%)	144 (70.59%)
Marvell 88F6282	102	102	100 (98.04%)	80 (78.43%)
subtarget: kirkwood/generic	330	326	324 (99.39%)	244 (74.85%) †
PLX NAS7820	149	149	48 (32.21%)	48 (32.21%)
subtarget: oxnas/generic	149	149	48 (32.21%)	48 (32.21%) ✦
Overall	6,192	6,188	5947 (96.11%)	5469 (88.38%)

Given 6K+ firmware crossing 10 vendors, 3 architectures, and 22 Linux kernel versions, FirmGuide can successfully rehost more than 96% of them.

Evaluation

RQ 3: What about the functionality of the rehosted embedded Linux kernels?

Linux Test Project: Syscall Testing

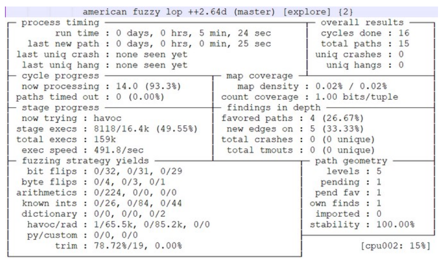
Models	Pass	Skipped	Failed	Total
Fully generated	1049	164	46	1259
Ground Truth	1049	164	46	1259

RQ 4: What are application of FirmGuide?

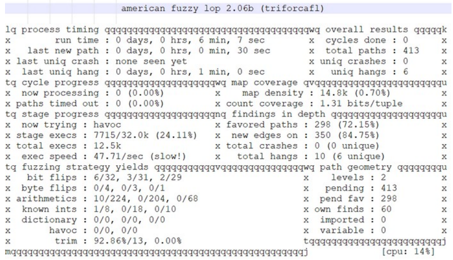
CVE Reproduction and Exploit Development

CVE ID	CVE Type	Status	Version
CVE-2016-5195	Race Condition	✗	N/A
CVE-2016-8655	Race Condition	✓ †	□
CVE-2016-9793	Integer Overflow	✓	□ ◇
CVE-2017-7038	Integer Overflow	✓ †	◇
CVE-2017-1000112	Buffer Overflow	✓ †	△
CVE-2018-5333	NULL Pointer Dereference	✓ †	□ ◇

Fuzzing



UnicoreFuzz



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Summary

Conclusion

- A novel technique “Model-Guided Kernel Execution” for peripheral modeling
- The first semi-automatic framework for embedded Linux kernel rehosting
- Feasible dynamically understanding and mining vulnerability in embedded kernels

Discussion

Limitation and future work

Manually state machine construction for more complex peripherals

High fidelity of Type-II peripherals

Q & A

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