Unlocking the Potential of Domain Aware Binary Analysis in the Era of IoT

Zhiqiang Lin

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April 18th, 2023

History of Computing (Since 1980s)

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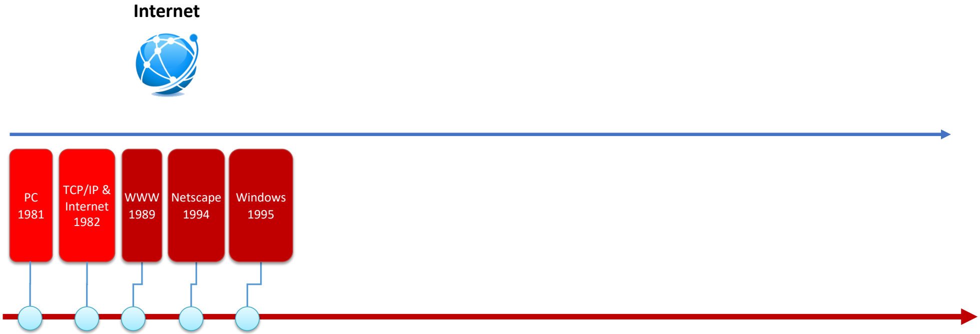

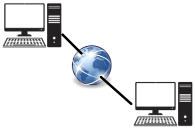

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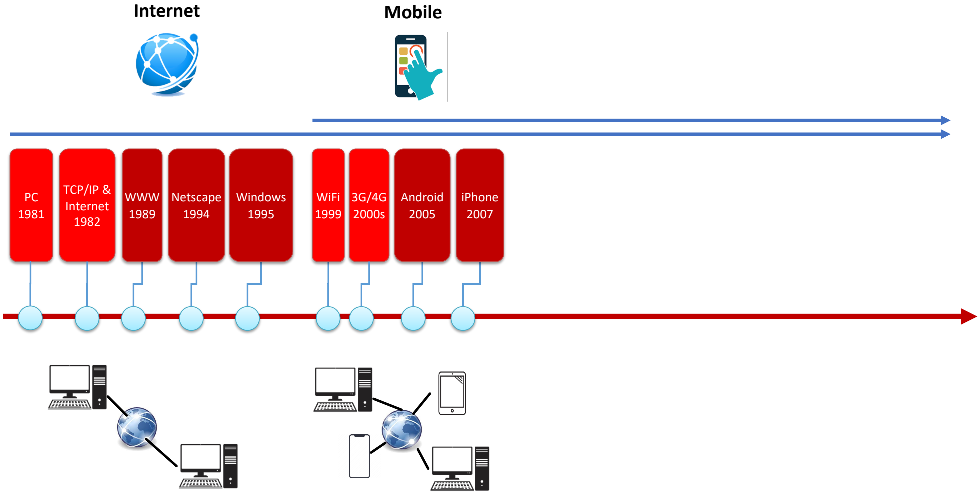

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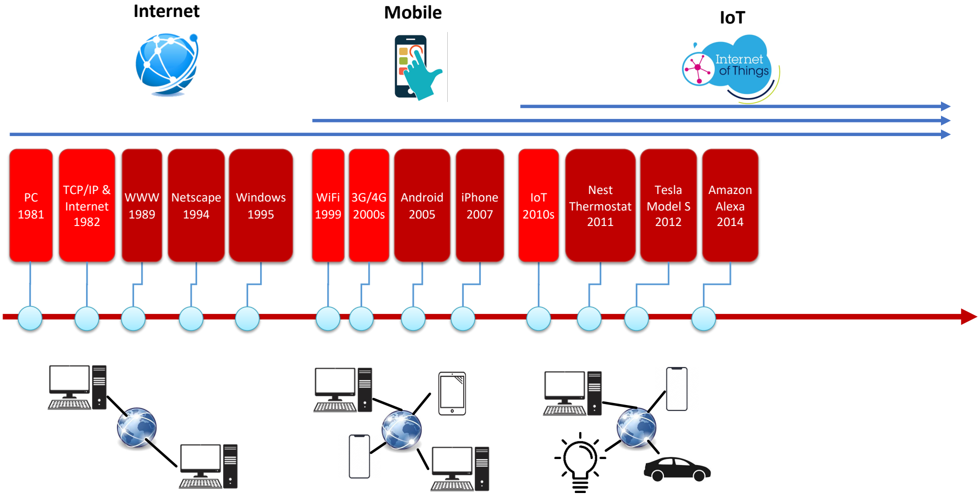

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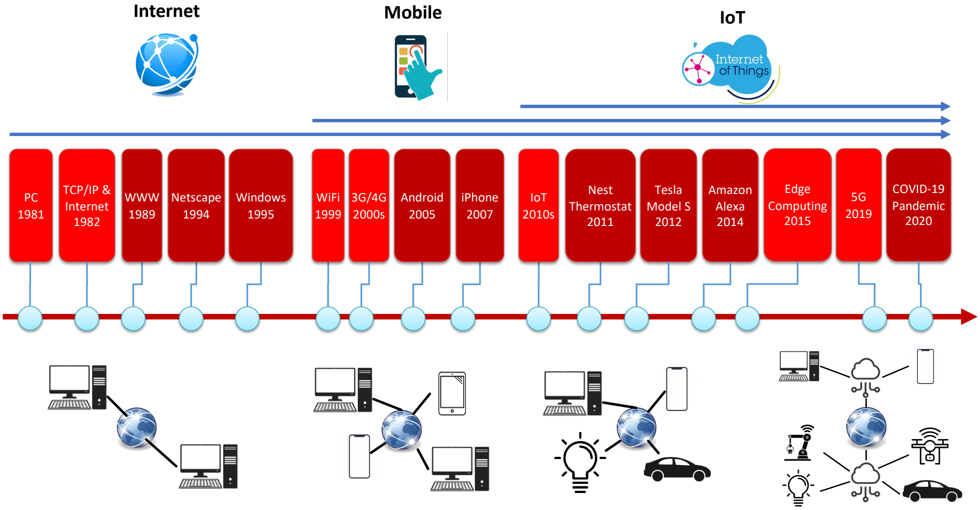

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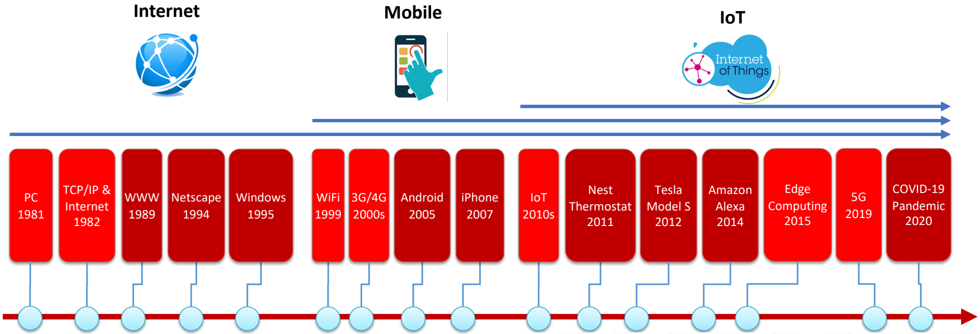

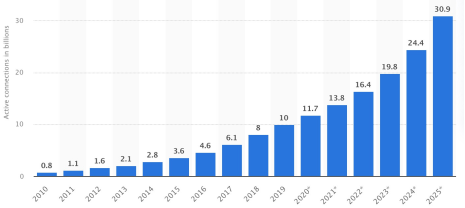

Data Source: statista

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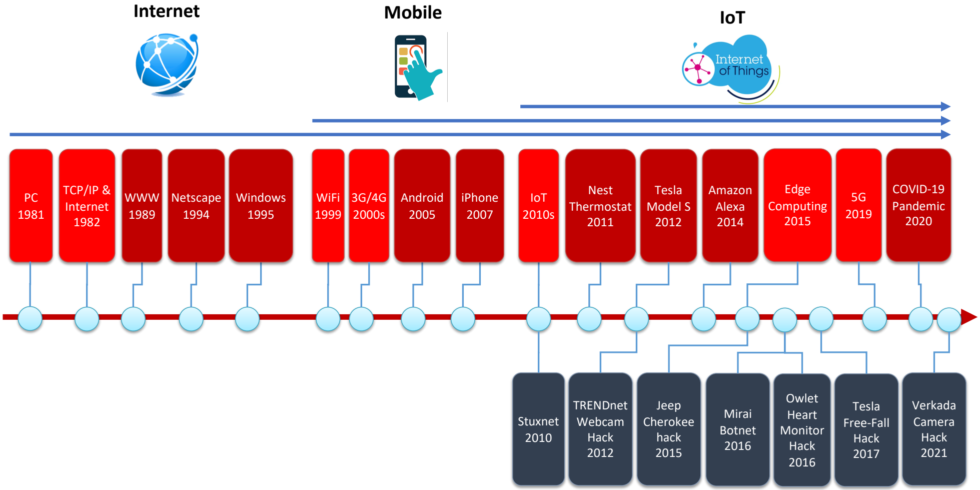
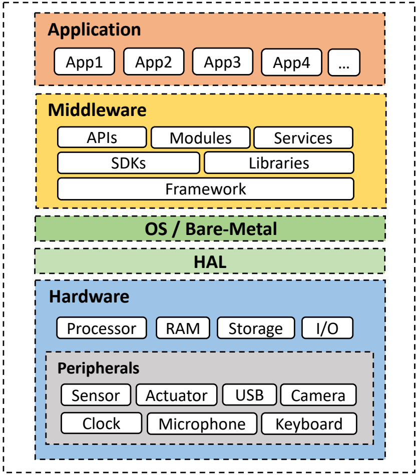
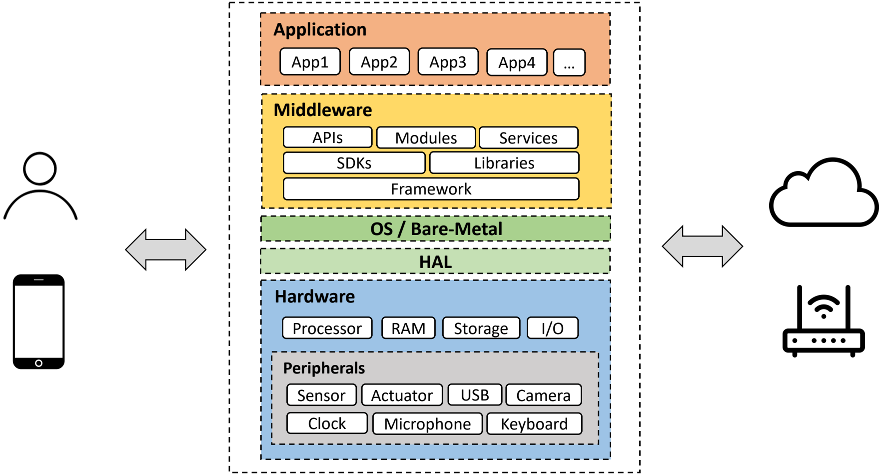


Modern IoT Architecture



An Embedded IoT Device

Modern IoT Architecture



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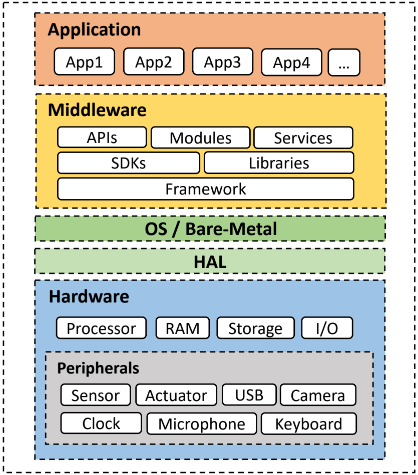


An Embedded IoT Device

Modern IoT Architecture

Application

App1 | App2 | App3 | App4 | ...

Middleware

APIs | Modules | Services

SDKs | Libraries

Framework

OS / Bare-Metal

HAL

Hardware

Processor | RAM | Storage | I/O

Peripherals

Sensor | Actuator | USB | Camera

Clock | Microphone | Keyboard

An Embedded IoT Device

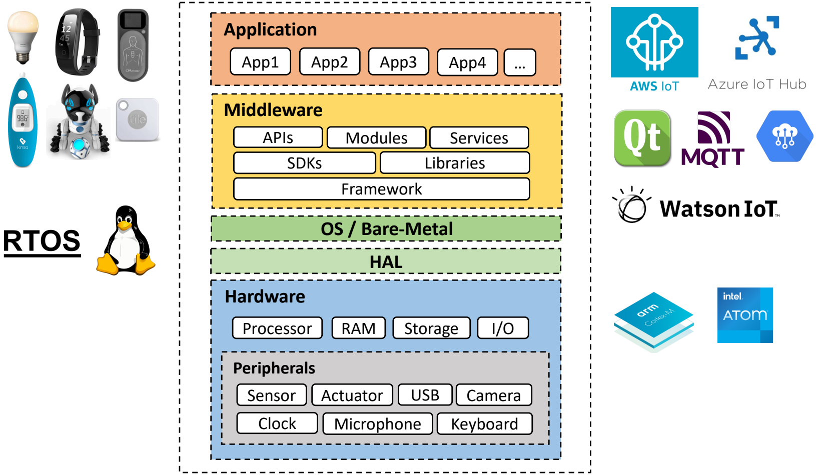
AWS IoT

Azure IoT Hub

MQTT

Watson IoT

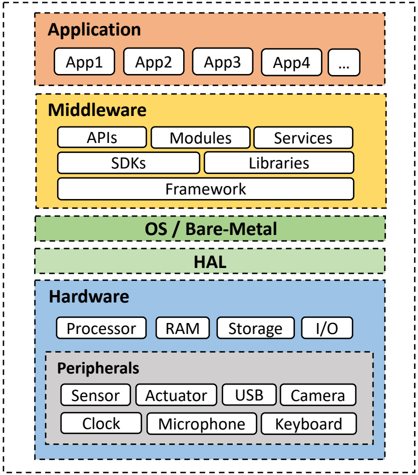
Modern IoT Architecture



An Embedded IoT Device

Modern IoT Architecture

RTOS



An Embedded IoT Device

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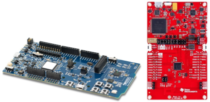

Domain-Aware Binary Analysis

Binary code analysis is *challenging*

- Control flow recovery, semantic understanding, vulnerability detection, root-cause analysis...

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Why Domain-Aware

1. *One size does not fit all*
   - Heterogeneous architecture, OS, APIs of different IoT vendors
   - Domain-specific challenges

Domain-Aware Binary Analysis

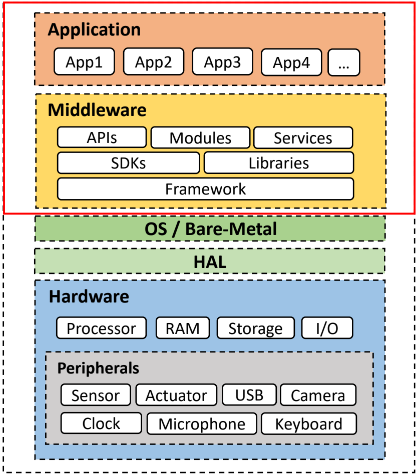
Binary code analysis is *challenging*

- Control flow recovery, semantic understanding, vulnerability detection, root-cause analysis...

Why Domain-Aware

1. *One size does not fit all*
   - Heterogeneous architecture, OS, APIs of different IoT vendors
   - Domain-specific challenges
2. *Learn from the domain*
   - Unique domain insights for binary analysis
   - Novel techniques and methodology
   - Transition to other domains

Our Recent Works on (IoT) Binary Analysis



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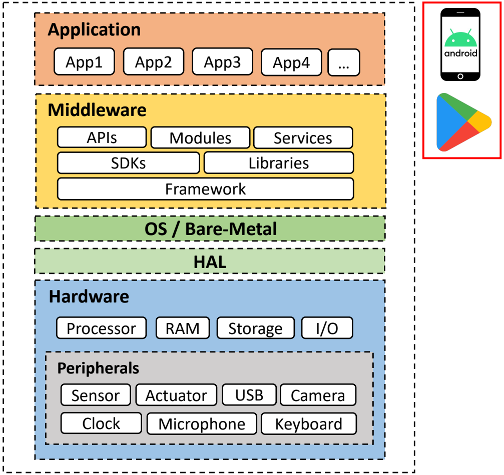

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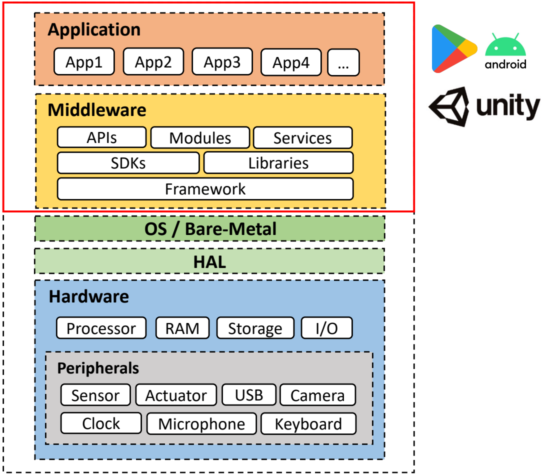

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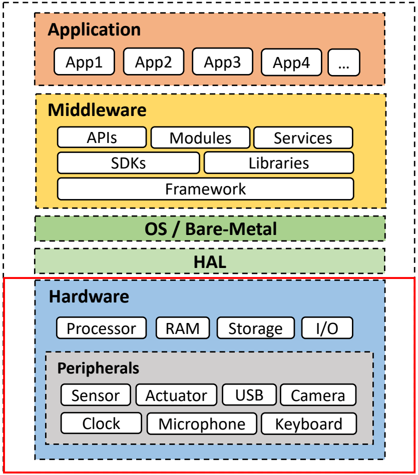

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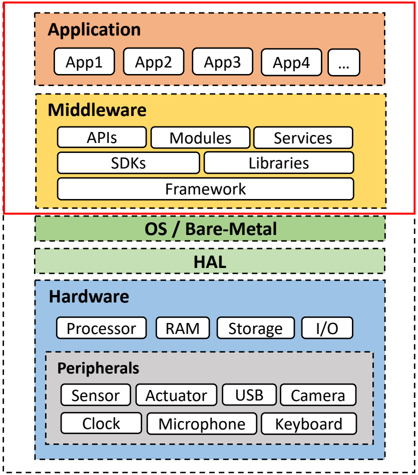

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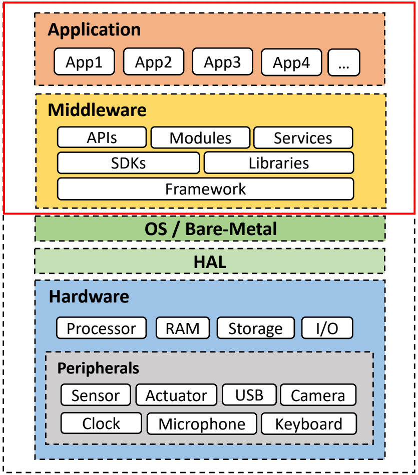

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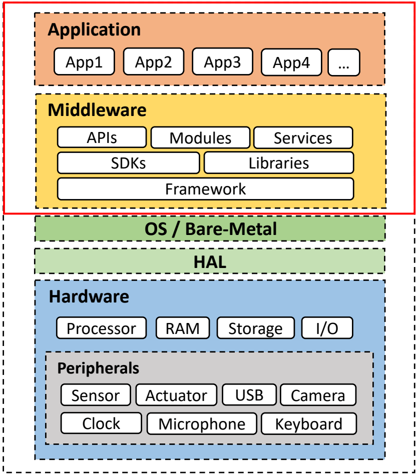

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Background

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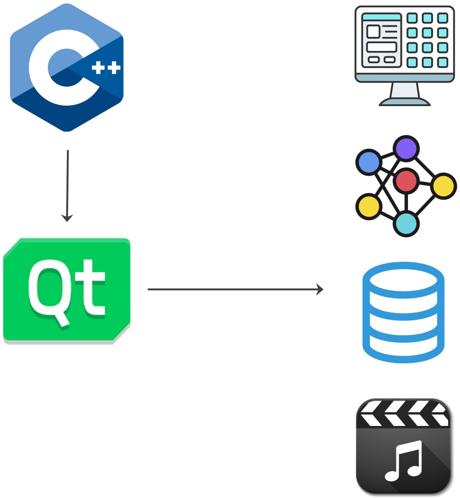

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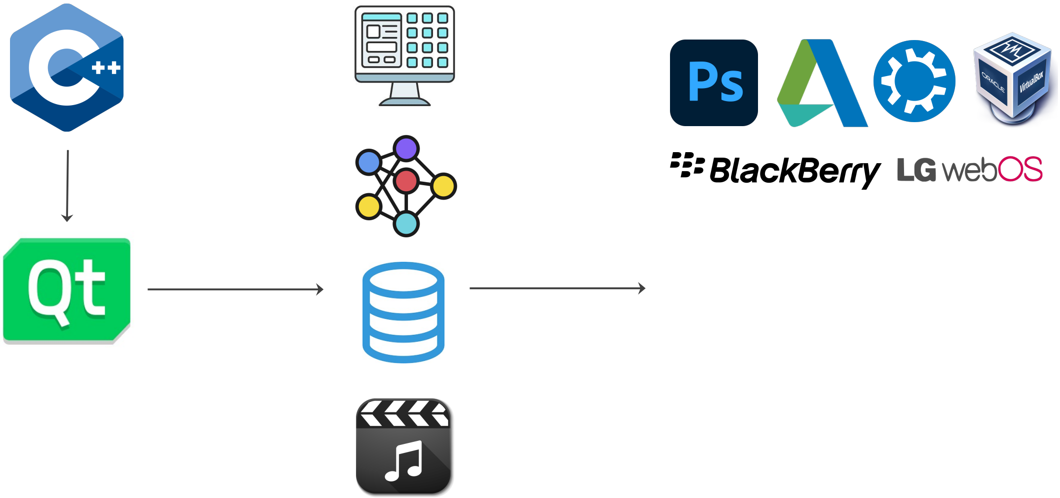

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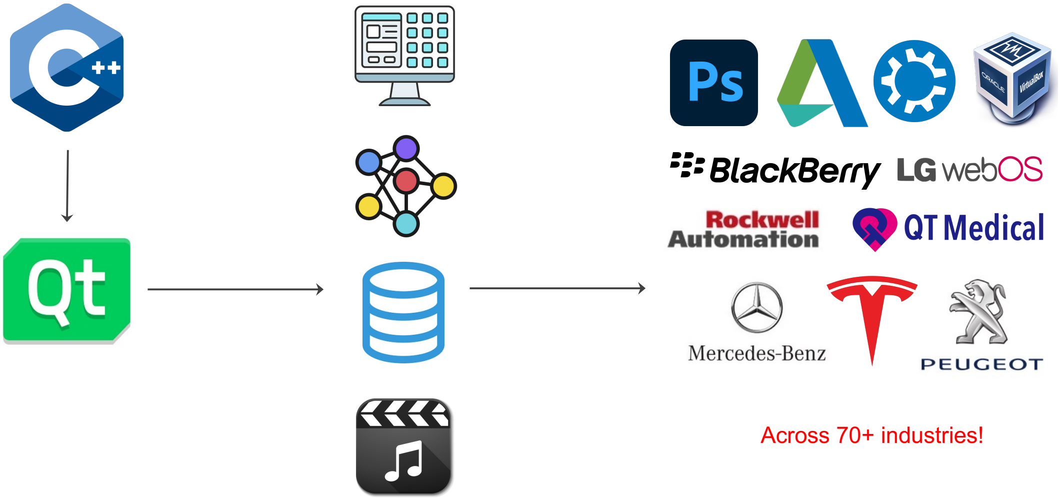
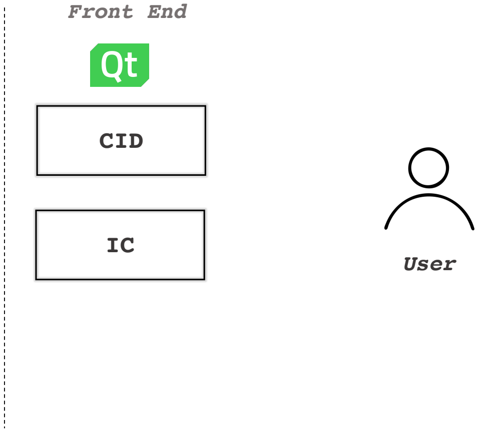


Across 70+ industries!

Tesla's Infotainment System



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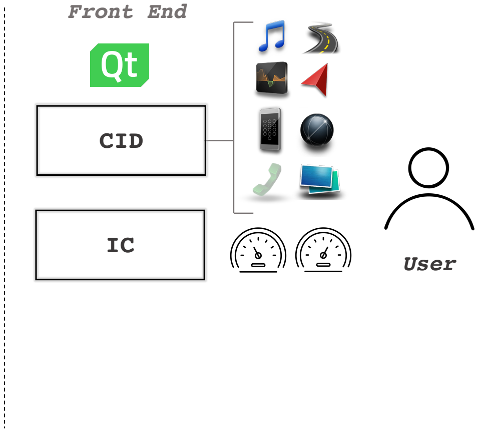

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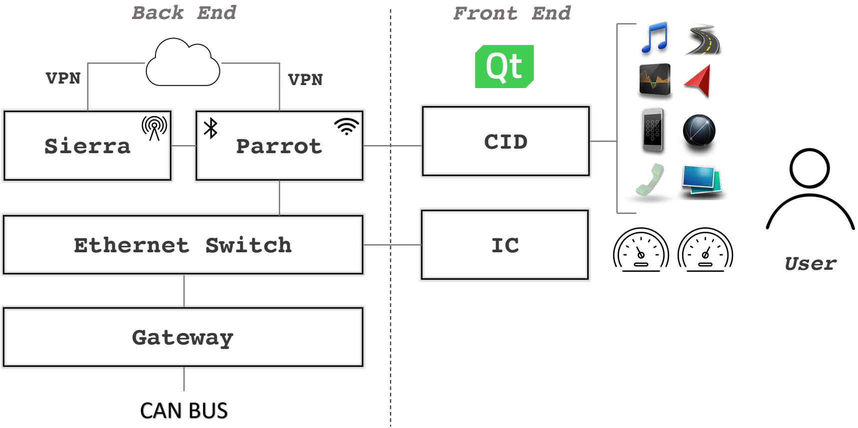

Motivation

Enabling Security Analysis of Qt Programs

- Reverse engineering (RE) is one of the keys to vet Qt binaries

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Binary RE Challenges

- **Control Flow Graph (CFG) Recovery**. Indirect control flow transfers such as callbacks and indirect calls [PCvdV+17, VDVGC+16]

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Binary RE Challenges

- **Control Flow Graph (CFG) Recovery**. Indirect control flow transfers such as callbacks and indirect calls [PCvdV+17, VDVGC+16]
- **Symbol Recovery** (e.g., names/types of functions/variables). Code stripping during binary compilation [TTN+19, SCD+18]

Key Insights

Unique Insights from Qt's Mechanisms

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   - Originally designed for run-time class member query and update
   - *We repurpose it to recover rich semantic symbols from the binary program*

Qt's Signal and Slot Mechanism

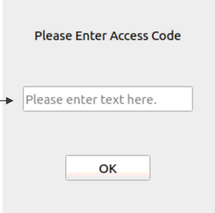
```
MainWindow::MainWindow() {
  ...
  // Create lineEdit instance
  v0 = operator.new(0x30)
  QLineEdit(v0)
  *(this + 0x30) = v0
  ...







}
```



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          , this, “1handleInput()”, 0)
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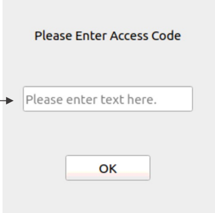

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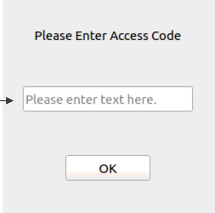
Signal

Slot



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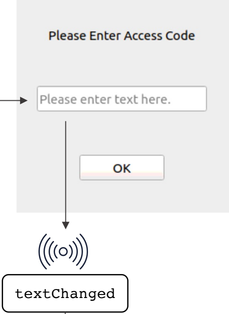
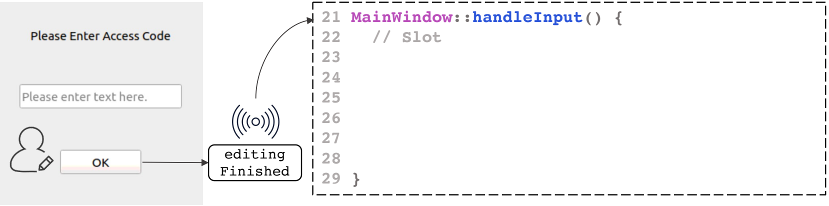


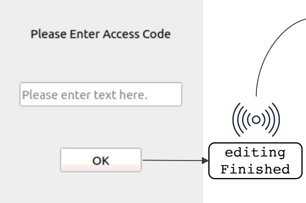

```
MainWindow::updateText(QString v1) {
  // Slot
  if (v1 != null)
      *(this + 0x48) = v1 // this->text
}
```

Qt's Dynamic Introspection



window.text = "secret"

Qt's Dynamic Introspection



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```
MainWindow::handleInput() {
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  if (v1 == "secret") {
      // Dynamic introspection


  }
}
```

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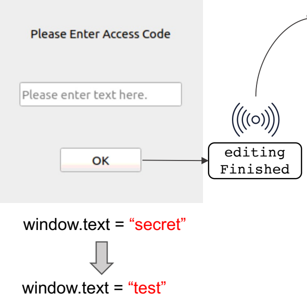


```
MainWindow::handleInput() {
  // Slot
  v1 = *(this + 0x48)    // this->text
  if (v1 == "secret") {
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      this->setProperty("text", "test")
      qDebug() << v1  // Will print out "test"
  }
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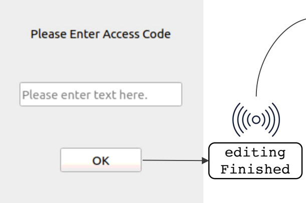
Qt's Dynamic Introspection

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Query index

Metadata

Property Table

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0	0	QString

String Table

Index	String
0	text

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⇩

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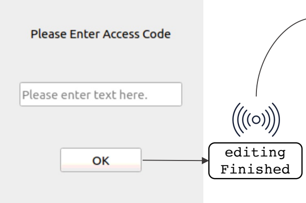
Qt's Dynamic Introspection



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Qt’s Dynamic Introspection

editing Finished

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Query index

```
MainWindow::qt_metacall(… int v1, void** v2) {
  ...
  if (v1 == 0) {
      // Set property value by index
      *(this + 0x48) = (QString) v2
  }
}
```

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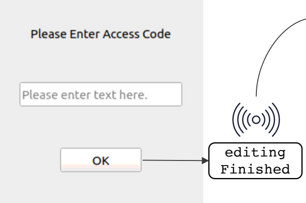


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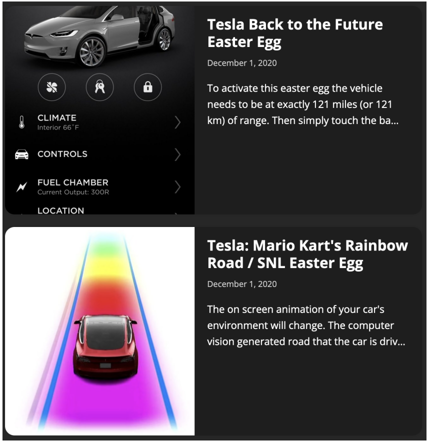
*(this + 0x48)

Type: Qstring

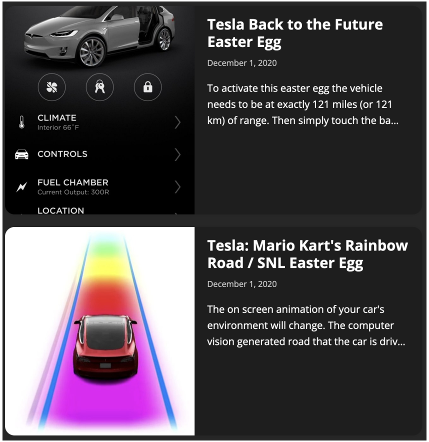
Name: text

Application: Egg Hunt in Tesla Infotainment



Easter eggs in Tesla vehicles

Application: Egg Hunt in Tesla Infotainment



Easter eggs in Tesla vehicles

- Do they raise security concerns?
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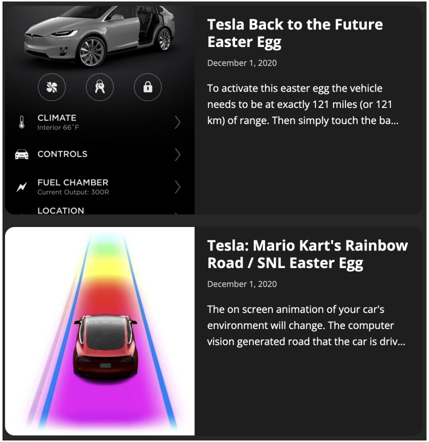

Easter eggs in Tesla vehicles

- Do they raise security concerns?
- How to systematically identify them?
  - Coverage-based fuzzing (emulation required)
  - Input validation analysis on Qt binaries

Application: Egg Hunt in Tesla Infotainment

Experiment Setup

- Use input validation analysis to extract hidden commands from Tesla firmware
- Identify user input variables from the recovered Qt symbols
- Analyze the recovered Qt control flow

Class Name	**Var./Func. Name**
QLineEdit	text()
QLineEdit	text
QAbstractSpinBox	text
QDoubleSpinBox	text
QSpinBox	text
QDateTimeEdit	text
TextField	text
PasswordTextField	text
WebEntryField	text
NavigationSearchBox	text
CompleterTextField	text
ExtEntryField	text

Table: Identified user input variables.

Application: Egg Hunt in Tesla Infotainment

Category	Content	Description
Easter Egg	"007"	Submarine Easter egg
	"modelxmas"	Show holiday lights
	"42"	Change car name
	"mars"	Turn map into Mars surface
	"transport"	Transport mode
	"performance"	Performance mode
	"showroom"	Showroom mode
Access Token	SecurityToken1	Enable diagnostic mode
	SecurityToken2	Enable diagnostic mode
	crc(token)==0x18e5a977	Enable developer mode
	crc(token)==0x73bbee22	Enable developer mode
Master Pwd	"3500"	Exit valet mode

Table: Hidden commands from Tesla firmware.

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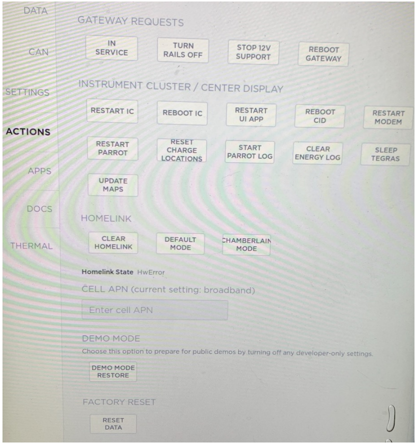

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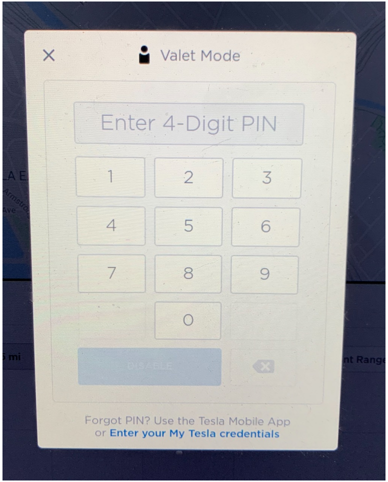

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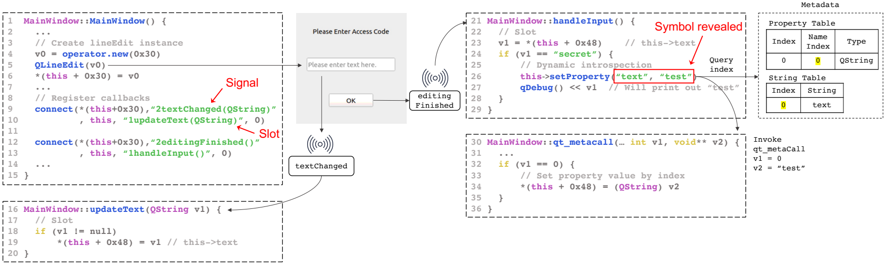
Disclosure

The Tesla security team acknowledged our findings in 2022/4 and have eliminated the feasible paths for exploiting these hidden commands in the latest firmware.

QtRE [USENIX Security'23]



QtRE

- A static analysis tool that leverages Qt's unique insights for function callback and symbol recovery

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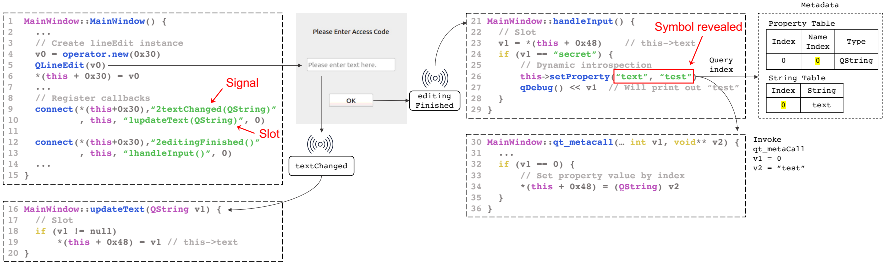

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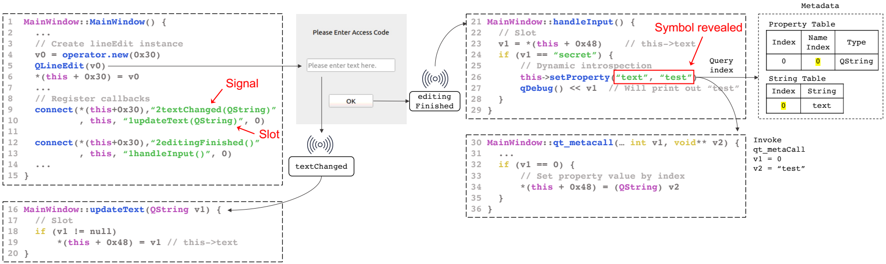


QtRE

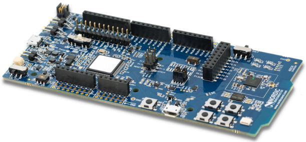
- A static analysis tool that leverages Qt's unique insights for function callback and symbol recovery
- It additionally recovered (based on GHIDRA) 10,867 callbacks and 24,973 symbols among 123 binaries
- We demonstrate an application of input validation analysis with QtRE, and extracted 12 unique hidden commands five new to the public.

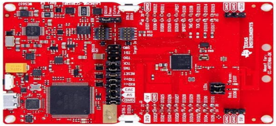
The source code will be released at https://github.com/OSUSecLab/QtRE.

Bluetooth Low Energy

Bluetooth™
4.0
Low Energy

Low Technical Barrier for IoT Development





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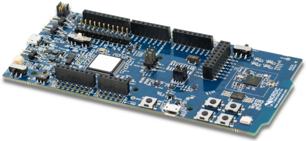

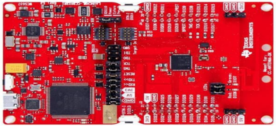

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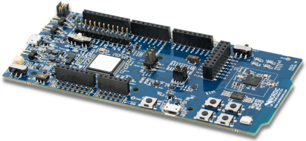

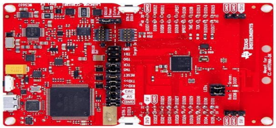

AWS IoT

Azure IoT Hub

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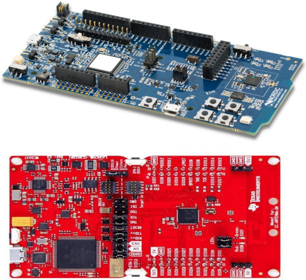

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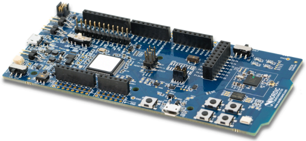

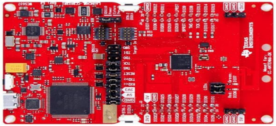

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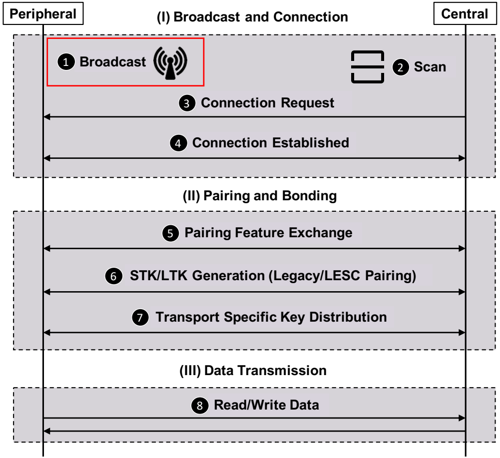
Are they secure?

BLE Link Layer Vulnerabilities



Vulnerabilities

1. **Identity Tracking**. Configure static MAC address during broadcast [DPCM16].

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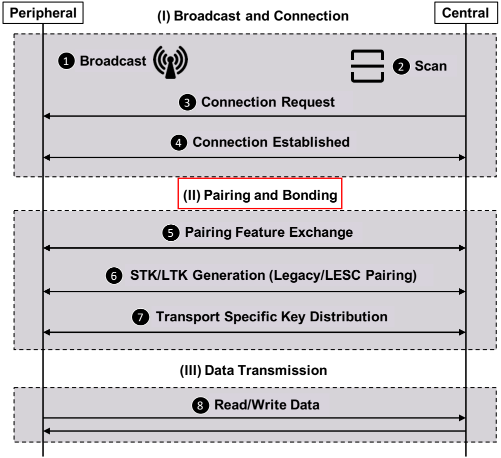

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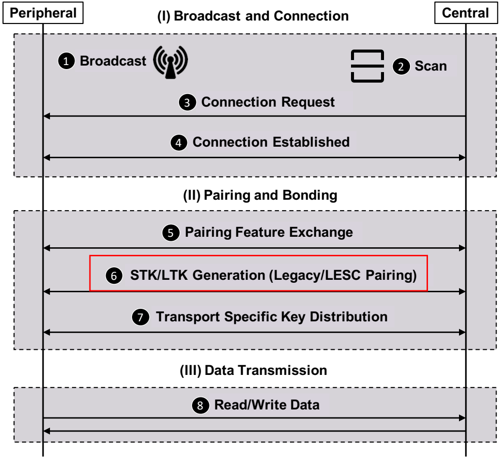

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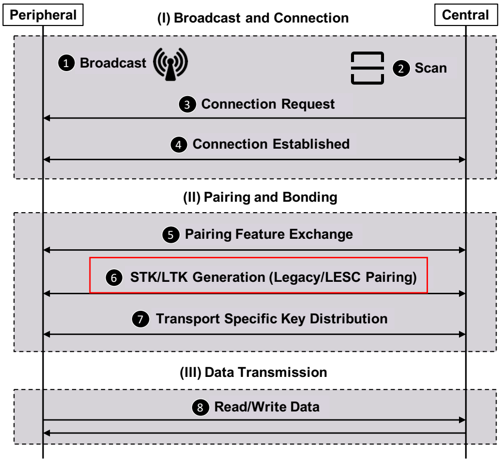

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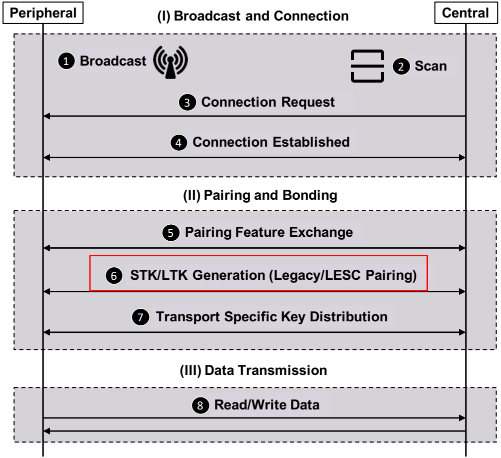

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Identification

1. Traffic analysis
2. Mobile app analysis
3. Firmware analysis

An Example of a Just Works Pairing Vulnerability

Read Only Memory

```
243a8   mov   r2, #0x0
243aa   orr   r2, #0x1
243ac   and   r2, #0xe1
243ae   add   r2, #0xc
243b0   and   r2, #0xdf
243b2   ldr   r1, [0x260c8]
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...
25f44   ldr   r2, [0x260c8]
25f46   mov   r1, #0x0
25f48   svc   0x7f
// SD_BLE_GAP_SEC_PARAMS_REPLY
...
260c8   0x20003268
        // ble_gap_sec_parms_t*
```

Register Values

```
r1 = 0x0
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Struct ble_gap_sec_params_t

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20003268   uint8  pairing_feature

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Recognize data structures

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Value computation → **Register Values**

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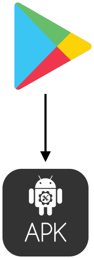
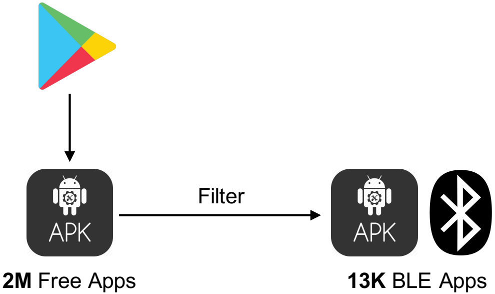
Firmware Collection

Firmware Collection



2M Free Apps

Firmware Collection



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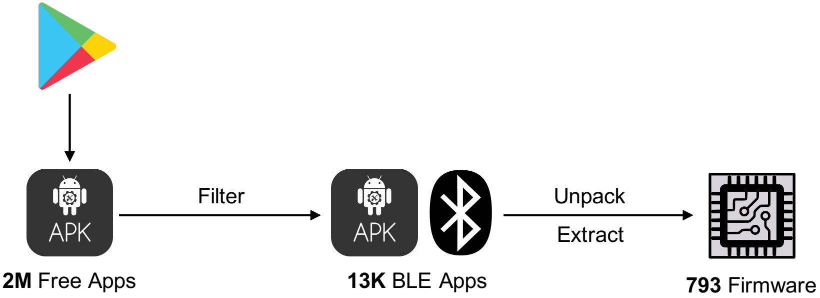

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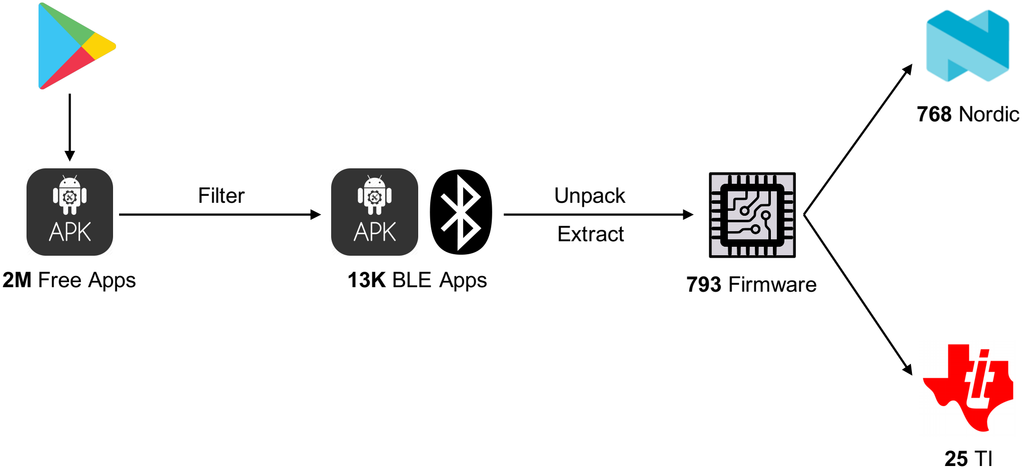

Experiment Results

Identity Tracking Vulnerability Identification

Among the 538 devices, nearly all of them (**98.1%**) have configured random static addresses that do not change periodically.

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Firmware Name	Mobile App	Category	# Device
cogobeacon	com.aegismobility.guardian	Car Accessory	4
sd_bl	fr.solem.solemwf	Agricultural Equip.	2
LRFL_nRF52	fr.solem.solemwf	Agricultural Equip.	2
orb	one.shade.app	Smart Light	1
sd_bl	com.rainbird	Agricultural Equip.	1

Table: Firmware using private MAC address.

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Active MITM Vulnerability Identification

385 (71.5%) devices use Just Works pairing, which essentially does not provide any protection against active MITM attacks at the BLE link layer.

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Item	N	T	Total	%
# Total Device	513	25	538	100
# Device w/ active MITM vulnerability	384	1	385	71.5
# Device w/ Just Works pairing only	317	1	318	59.1
# Device w/ flawed Passkey implementation	37	0	37	6.9
# Device w/ flawed OOB implementation	30	0	30	5.6
# Device w/ secure pairing	6	24	30	3.8
# Device w/ correct Passkey implementation	3	24	27	3.4
# Device w/ correct OOB implementation	3	0	3	0.4

Table: Pairing configurations of devices (N:Nordic, T:TI).

Experiment Results

Passive MITM Vulnerability Identification

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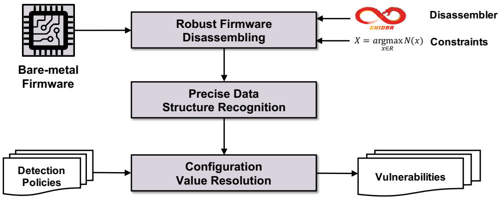
Firmware Name	Mobile App	Category	# Version
DogBodyBoard	com.wowwee.chip	Robot	16
BW_Pro	com.ecomm.smart_panel	Tag	1
Smart_Handle	com.exitec.smartlock	Smart Lock	1
Sma05	com.smalife.watch	Wearable	1
CPRmeter	com.laerdal.cprmeter2	Medical Device	4
WiJumpLE	com.wesssrl.wijumple	Sensor	1
nRF Beacon	no.nordicsemi.android.nrfbeacon	Beacon	1
Hoot Bank	com.qvivr.hoot	Debit Card	1

Table: Firmware that enforce LESC pairing.

FirmXRay [CCS'20]



FirmXRay

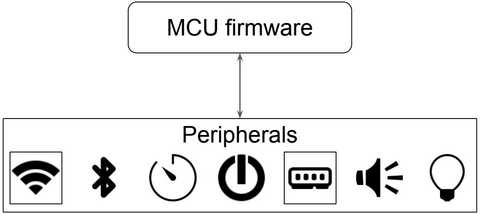
- A static analysis tool based on Ghidra for detecting BLE link layer vulnerabilities from bare-metal firmware.
- A scalable approach to efficiently collect bare-metal firmware images from only mobile apps.
- Vulnerability discovery and attack case studies.

The source code is available at https://github.com/OSUSecLab/FirmXRay.

Microcontroller Unit (MCU)

- The chip inside the board
- Ubiquitous (e.g., drone, smart light bulb)

Microcontroller Unit (MCU)



- Peripherals are inside the provided board
- Firmware controls peripherals through peripheral registers
- Peripheral executes firmware through the corresponding interrupt

Microcontroller Unit (MCU)

MCU Firmware Vulnerabilities

1. Memory corruption
2. Privacy leakage
3. Peripheral malfunctioning

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Firmware Analysis

1. **Hardware-in-the-loop**. Testing firmware with hardware
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Microcontroller Unit (MCU)

MCU Firmware Vulnerabilities

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Firmware Analysis

1. **Hardware-in-the-loop**. Testing firmware with hardware
2. **Re-hosting**. Emulating firmware without hardware

Common Challenge

Modeling Peripheral Processing

An Example of Processing a Peripheral Register

Execution just based on the firmware code

```
REG_CLOCK = 0x40023800;
*REG_CLOCK = 0x1000000; // set 24-bit
if (*REG_CLOCK & 0x2000000) == 0) { // check 25-bit
 return HAL_ERROR;
}
Freq = HAL_RCC_GetSysClockFreq();
return HAL_OK;
```

```
[REG_CLOCK] 0x40023800 = <uninitialized>
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An Example of Processing a Peripheral Register

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1:  REG_CLOCK = 0x40023800;
2:  *REG_CLOCK = 0x1000000; // set 24-bit
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An Example of Processing a Peripheral Register

Execution on real MCU hardware

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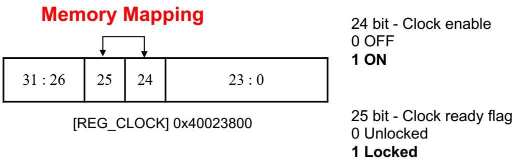
Hidden Memory Mapping

Peripheral register bits get simultaneously updated by the MCU hardware
As some bits are semantically relevant (e.g., clock status)



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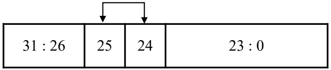

[REG_CLOCK] 0x40023800

24 bit - Clock enable
0 OFF
1 ON

25 bit - Clock ready flag
0 Unlocked
1 Locked

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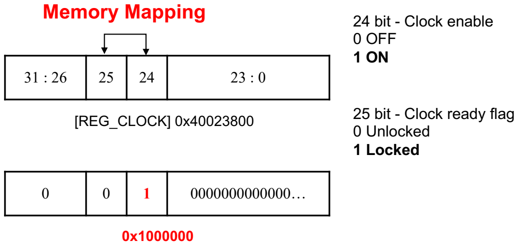

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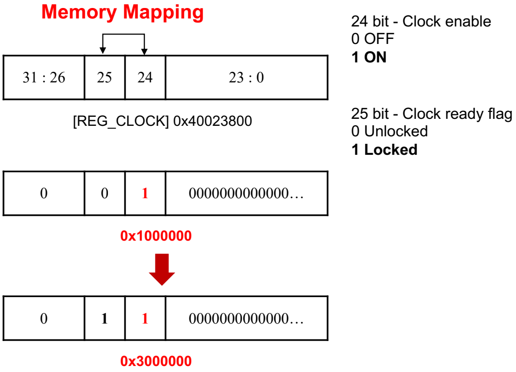
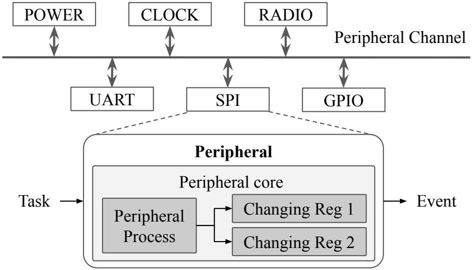


Hidden Memory Mapping

Root cause: Autonomous Peripheral Operation

Hardware feature in microcontroller architectures. The peripheral performs its operation without CPU intervention to save energy.



Hidden Memory Mapping

Root cause: Autonomous Peripheral Operation

Hardware feature in microcontroller architectures. The peripheral performs its operation without CPU intervention to save energy.

Bit 24 PLLRDY: Main PLL (PLL) clock ready flag

Set by hardware to indicate that PLL is locked.
0: PLL unlocked
1: PLL locked

Bit 1 SBF: Standby flag

This bit is set by hardware and cleared only by a POR/PDR (power-on reset/power-down reset) or by setting the CSBF bit in the PWR_CR register
0: Device has not been in Standby mode
1: Device has been in Standby mode

AutoMap Overview

Challenges

1. Nearly infinite number of possible writes to peripheral registers
2. Cannot infer memory mappings from code-level
3. Dependency of peripheral register writes

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Solutions

1. On-demand memory mapping inference
2. Differential memory introspection through hardware-in-the-loop
3. Memory context preparation by executing previous peripheral registers write intrusions

Experiment Setup

- Three MCUs
  - Nordic NRF52832
    - 41 example firmware included in SDK
  - STMicroelectronics STM32F103
    - 5 real-world firmware from μEMU [ZGLZ21]
  - STMicroelectronics STM32F429
    - 4 real-world firmware from μEMU [ZGLZ21]

Experiment Results

Identity Memory Mapping in Example Firmware

At least one memory mapping is discovered in every firmware. Even single register write can affect multiple other registers.

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MCU	Firmware	# of Writes Causing M.M	Max # of M.M by single write
NRF52832	bk_freertos	21	7
	bk	9	3
	bk_rtc	21	7
	bk_systick	9	3
	bsp	35	11

Table: Memory mapping result on example firmware of NRF52832

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Integrating AutoMap with μEMU

AutoMap with μEMU can cover at most 15.59% more basic blocks than μEMU.

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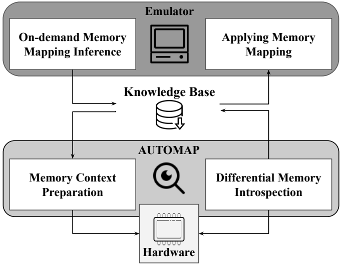
Firmware	# executed BBs		BBs portion of AutoMap not in μEMU	
	AutoMap	μEMU	#	%
Drone	1,413	1,410	5	0.35%
Gateway	1,385	1,248	216	15.59%
Steering_Iron	1,402	1,289	116	8.27%
Reflow_Oven	845	830	17	2.01%
Robot	1,035	964	77	7.43%

Table: Fuzzing result comparison between μEMU and both AutoMap and μEMU.

AutoMap [RAID'22]



AutoMap

- Discover memory mapping in peripheral registers.
- Propose AutoMap to discover memory mappings systematically.
- Emulate firmware properly with memory mappings and execute more basic blocks when AutoMap integrates with μEMU.

The source code is available at https://github.com/OSUSecLab/AutoMap.

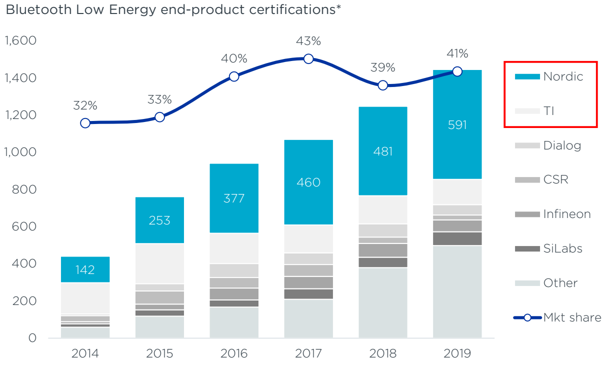
Takeaways

- The need to analyze new domains for heterogeneous IoT binary analysis
- New domains (mechanisms, architecture, API...) lead to new *insights* and *techniques*

The Potentials of Domain-Aware Analysis

Name	Category	# Repository	%
Qt	Framework	45,635	35.70%
ROS	Robotics	16,796	13.14%
Boost	Framework	6,205	4.85%
MFC	Framework	4,409	3.45%
Cocos2d	Game Engine	3,587	2.81%
OpenFrameworks	Framework	3,264	2.55%
JUCE	Framework	2,204	1.72%
PCL	Robotics	1,719	1.34%
imgui	GUI	1,557	1.22%
wxWidgets	GUI	1,076	0.84%
Cinder	Framework	1,042	0.82%
Allegro	Game Engine	958	0.75%
Godot	Game Engine	682	0.53%
GamePlay	Game Engine	561	0.44%
dlib	Framework	547	0.43%
FLTK	GUI	518	0.41%
GTK++	GUI	436	0.34%
LibU	Framework	425	0.33%
raylib	Game Engine	376	0.29%
gtkmm	GUI	349	0.27%

Top C++ frameworks for software development.



Data Source: Nordic Quarterly Presentation Q4 2019

The Potentials of Domain-Aware Analysis

1. Systematically vetting domain-specific applications

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2. Extension to other IoT domains, architectures, frameworks...

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2. Extension to other IoT domains, architectures, frameworks...
3. Support various security applications (e.g., Qt-Fuzz, Automap-Fuzz)
4. Generalize methodology and insights to other similar domains

Thank You

Unlocking the Potential of Domain Aware Binary Analysis in the Era of IoT

Zhiqiang Lin

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April 18th, 2023

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