black hat EUROPE 2016

Ghost in the PLC
Designing an Undetectable Programmable Logic Controller Rootkit via Pin Control Attack

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Who we are

- Ali Abbasi, visiting researcher at chair of system security of Ruhr University Bochum and PhD student at Distributed and Embedded Systems Security Group, University of Twente, The Netherlands.

- Majid Hashemi, R&D researcher at Quarkslab, involved in this research as an independent researcher.

Plan of talk

- Background on existing attacks and defenses for embedded systems
- Applicable Defenses for PLCs
- Background on Pin Control
- The Problem
- Rootkit variant
- Non-rootkit variant
- Demo
- Discussions

What this talk is not about?

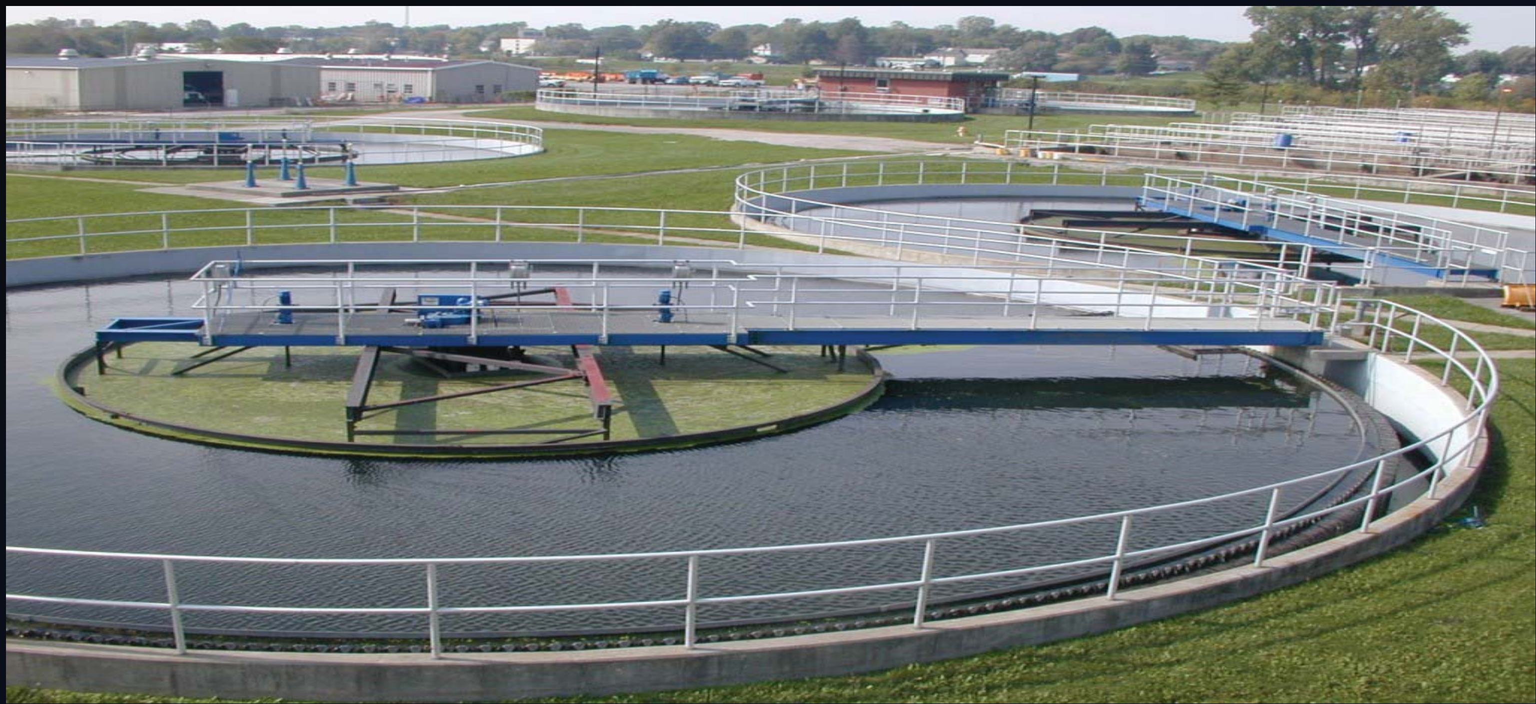
- The talk is trying to uncover existing design flaw in PLCs.
- The attack can be used in future by attackers.
- Today, there are far easier attacking techniques but it is trivial to defeat them.
- We are not unveiling fully functional rootkit for PLCs.
- NO exploitation techniques, no 0day leak
- We are not going to mention any vendor name.

What is Critical Infrastructure

- Electrical

What is Critical Infrastructure

- Water



What is Critical Infrastructure

- Gas

What is Critical Infrastructure

- Military

Steuerten Hacker Raketenstationen der Bundeswehr?

Hacker haben womöglich das Flugabwehrsystem Patriot geknackt: In der Türkei stationierte Raketenstationen der Bundeswehr hätten "unerklärliche" Befehle ausgeführt, berichtet eine Fachpublikation.

DIE WELT APPS

DIE WELT für Tablets
Links zum Download der Apps

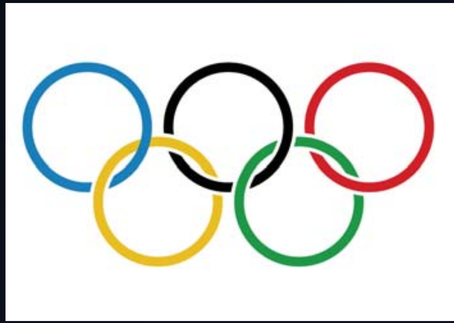
What is Critical Infrastructure

- Elements of infrastructure that, if lost, could pose a significant threat to needed supplies, services, and communication[1].

1. Church, R. L., Scaparra, M. P., & Middleton, R. S. (2004). Identifying critical infrastructure: the median and covering facility interdiction problems.

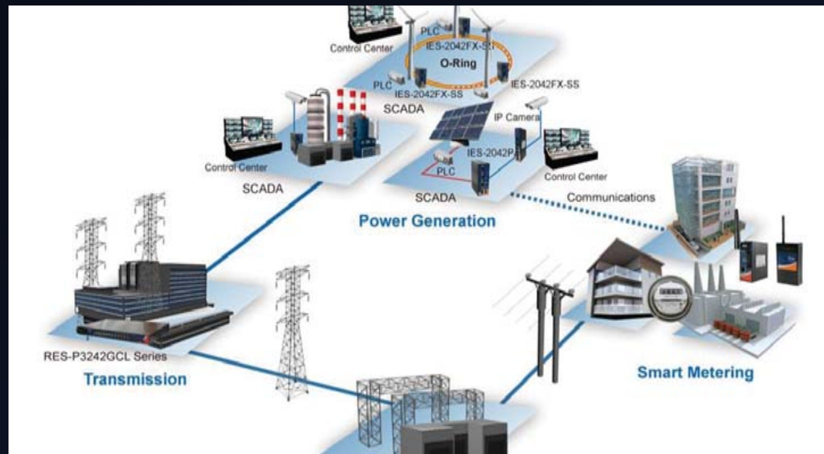
Who are the attackers

- Mostly State Sponsored
- Use 0days
- Use Sophisticated evasion techniques
- Best Example? Stux…



How to attack critical infrastructures?

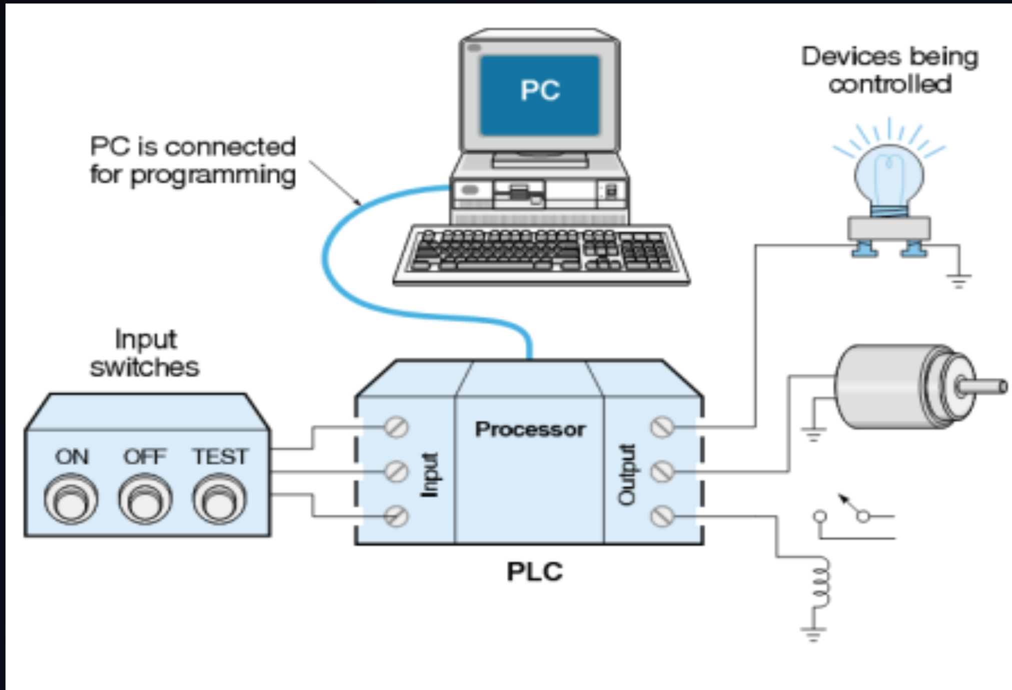
- Get into the network without being detected.
  - Defeating Emulation Based Network Intrusion Detection Systems
    - APTs Way: Evading Your EBNIDS, Black Hat Europe, 2014.
- Manipulate the PLCs
  - The PLC logic
- Manipulate the process
  - Damn vulnerable chemical processes[2]



2. Krotofil, Marina, et al. "Vulnerabilities of cyber-physical systems to stale data—Determining the optimal time to launch attacks." *International Journal of Critical Infrastructure Protection* 7.4 (2014): 213-232.

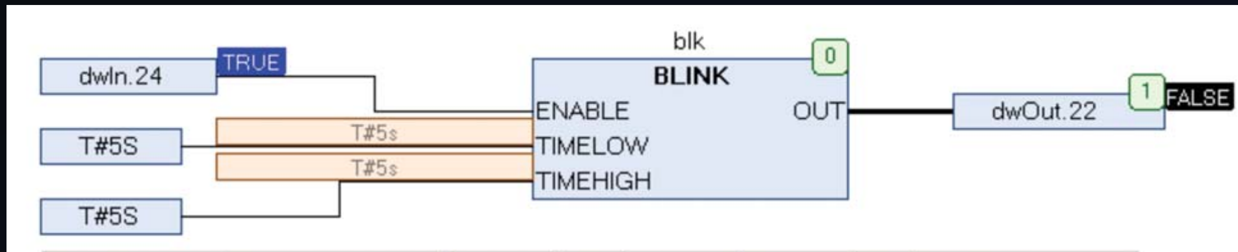
What is a PLC?

- An Embedded System with RTOS running logic.



What is Logic

- Logic is a program PLC executes



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GPIO24	Enumeration of BYTE	Input		Input	not used		configuration of GPIO24
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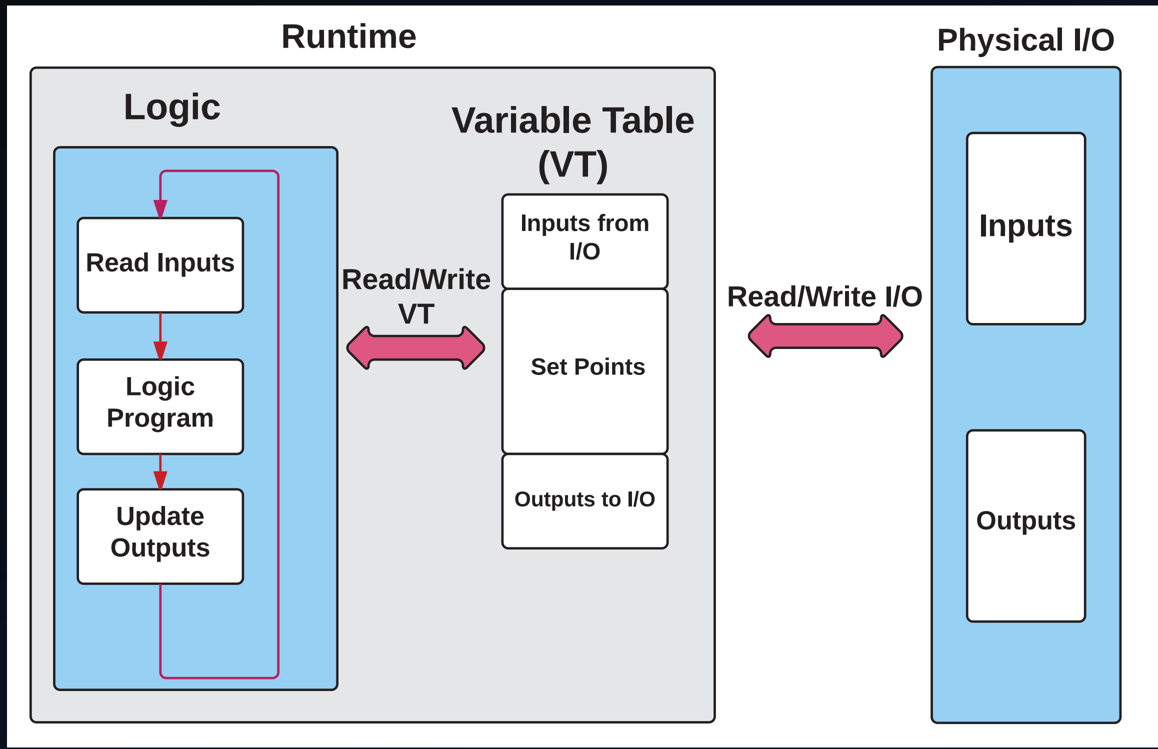
How PLC executes the Logic

- Logic
- Physical I/O



Chapter One

Existing Attacks and Defenses for Embedded Systems

Applicable to the PLCs

Current attacks against embedded systems

- Firmware modification attacks
  - Attacker upload new firmware to the PLC
- Configuration manipulation attacks
  - Attacker modify the logic
- Control Flow attacks
  - Attacker find a buffer overflow or RCE in the PLC
- Authentication bypass
  - Attacker find a backdoor password in the PLC.
- Hooking functions for ICS malwares (e.g. Stuxnet)

Current defenses for embedded systems

- Attestation
  - memory attestation
- Firmware integrity verification
  - Verify the integrity of firmware before its being uploaded
- Hook detection
  - Code hooking detection
    - Detect code hooking
  - Data hooking detection
    - Detect data hooking

Applicable Defenses for PLCs

- Designed for embedded devices running modern OS.
- No hardware modifications.
- Limited CPU overhead.
- No virtualization support required.

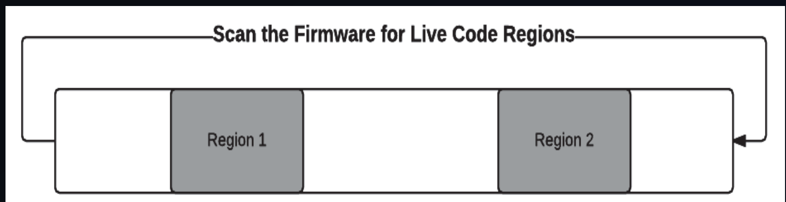
Non-trivial System-level protection for PLCs

- Trivial Defenses:
  - Logic Checksum
  - Firmware integrity verification
- Non-trivial software-based HIDS applicable to PLCs
  - Doppelganger (Symbiote Defense): an implementation for software symbiotes for embedded devices
  - Autoscopy JR: A host based intrusion detection which is designed to detect kernel rootkits for embedded control systems

How Doppelganger Works

- Scan the firmware of the device for live code regions and insert symbiotes randomly.

1



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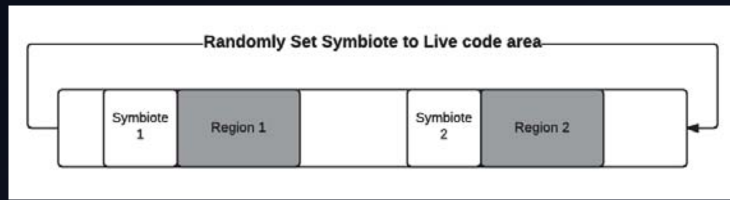
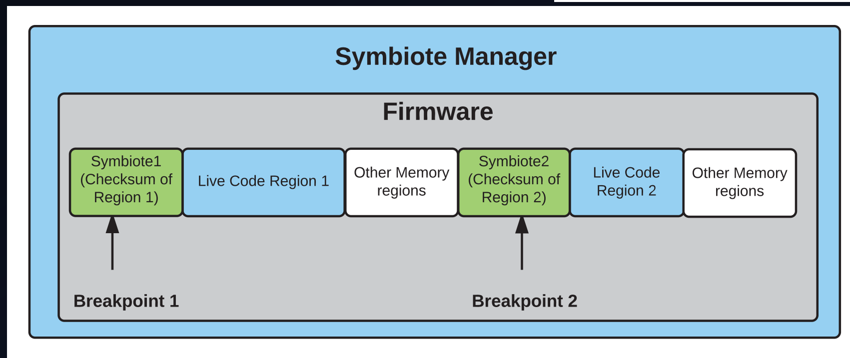
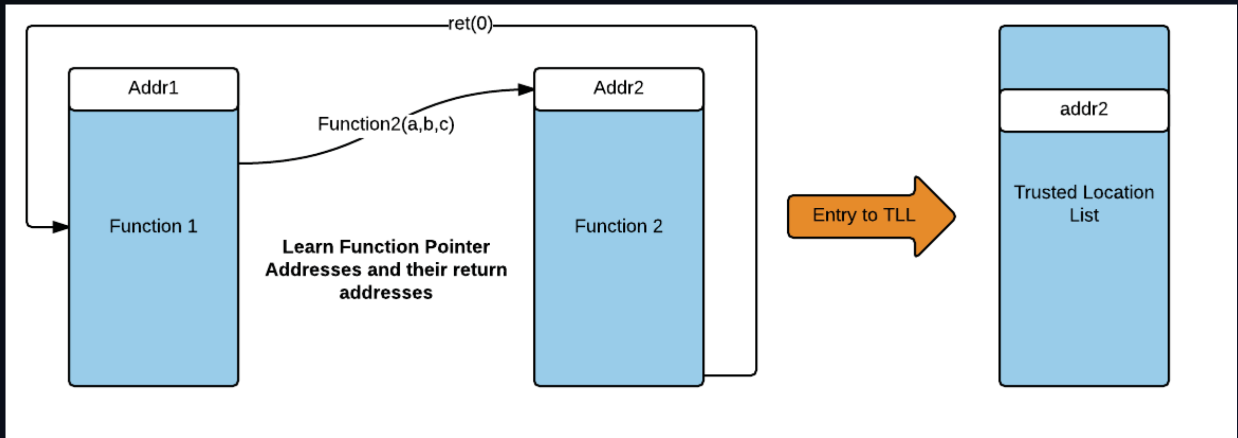


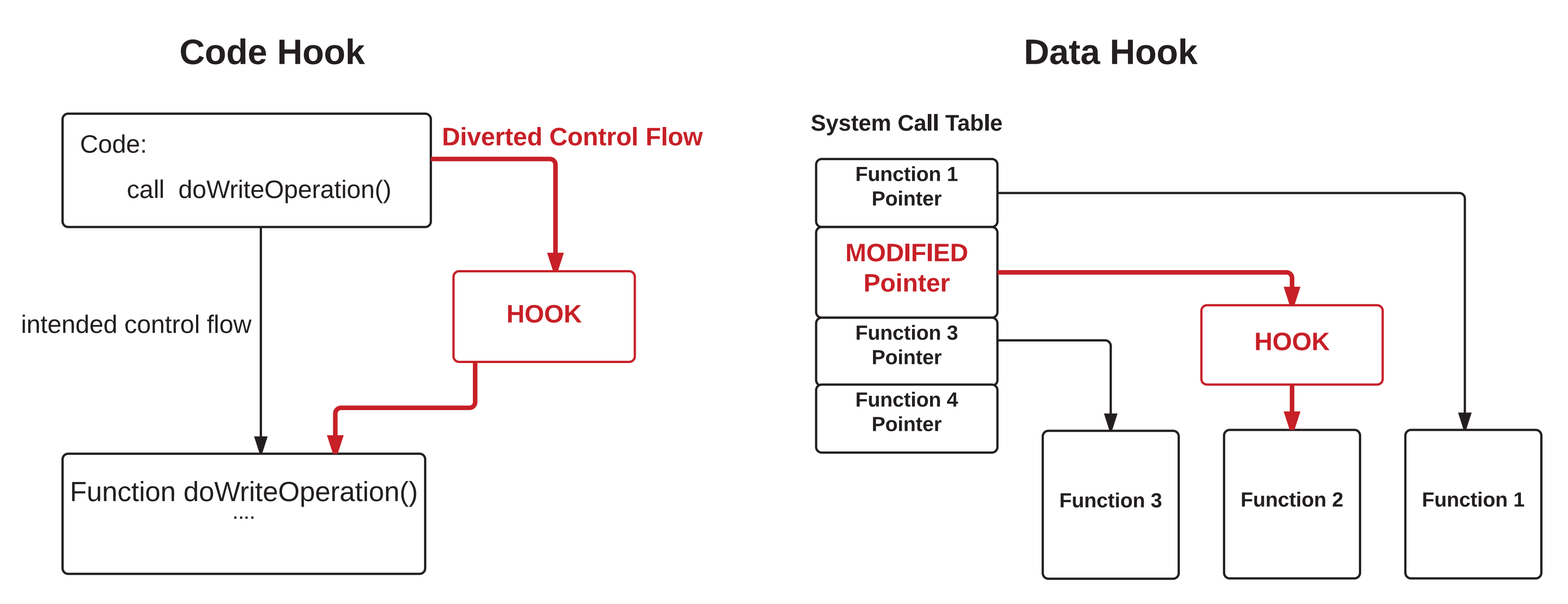


How Autoscopy Jr works

- Tries to Detects function hooking by learning
- Verifies the destination function address and returns with the values and addresses in TLL (Trusted Location List)



Function hooking



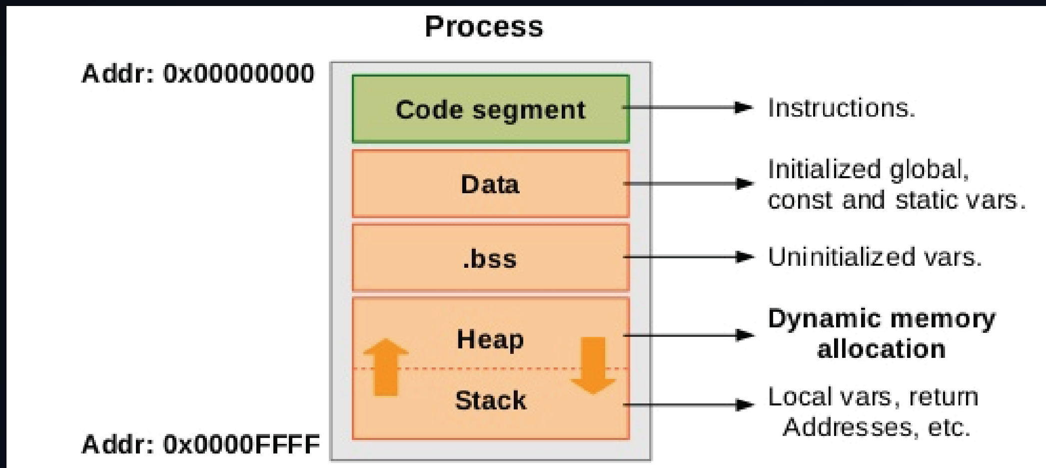
Solution Found?

- Looks like if we deploy both Doppelganger and Autoscopy Jr, the problem will be solved.

- Autoscopy Jr detects code hooking and doppelganger verify static parts and detect data hooking.

Dynamic Memory (Heap)

- Doppelganger can not verify dynamic memory.



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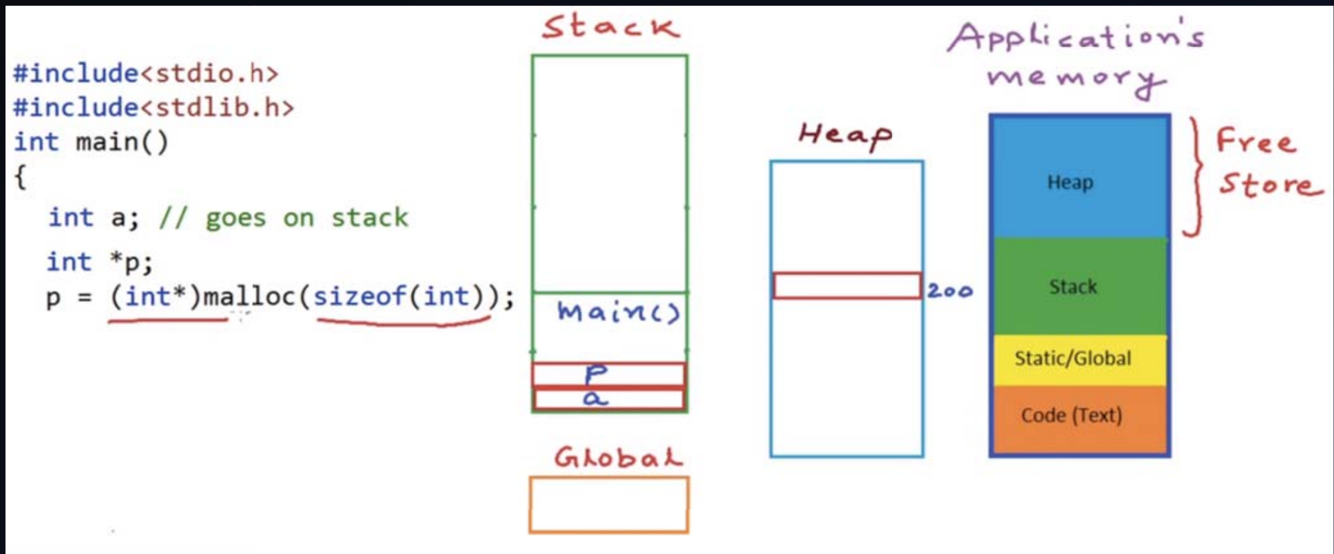
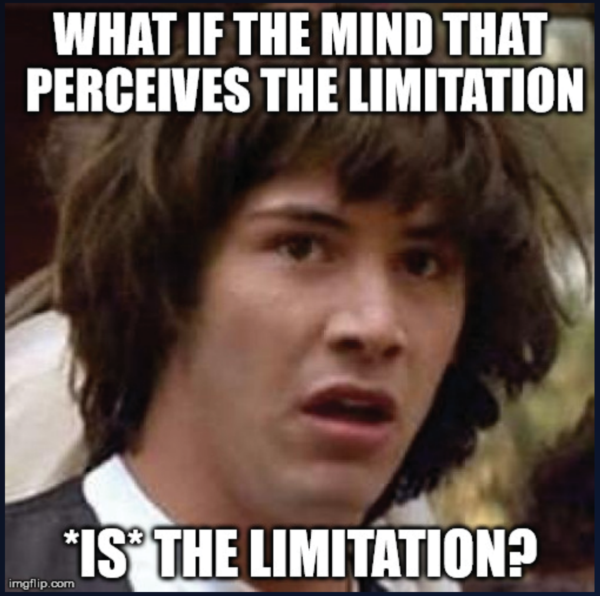


Limitations

- Static Referencing
  - Both Autoscopy Jr and Doppelganger use static references, similar to signature-based approaches.
- Dynamic Memory
  - Doppelganger only verify static memory
- Function Hooking Definition
  - The function hooking definition of Autoscopy Jr is incomplete



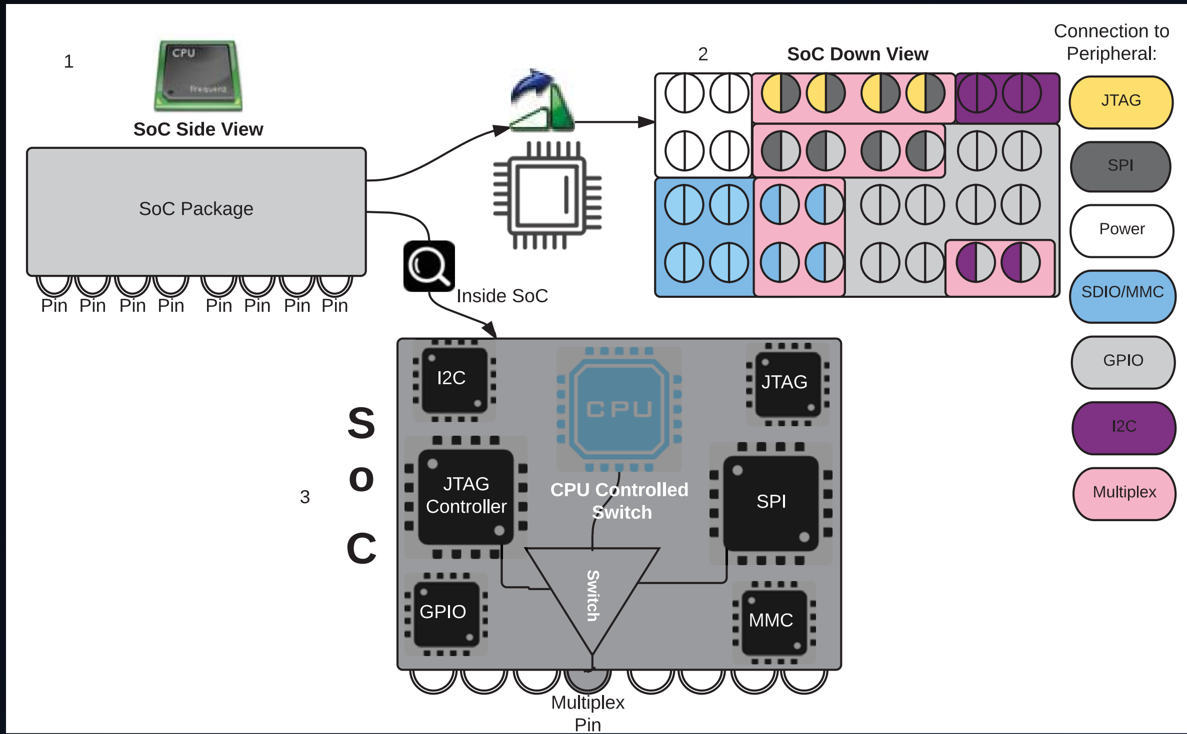
Chapter Two

Background on Pin Control

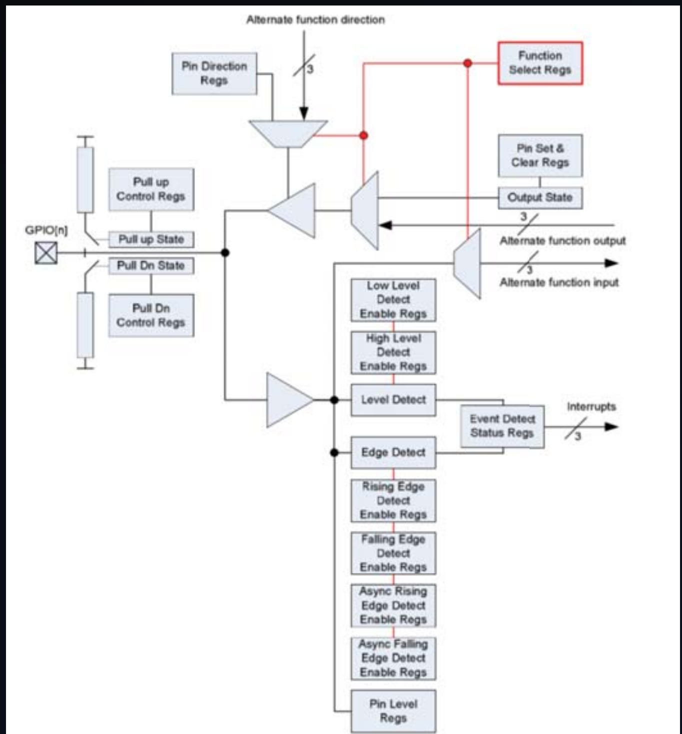
Background on Pin Control

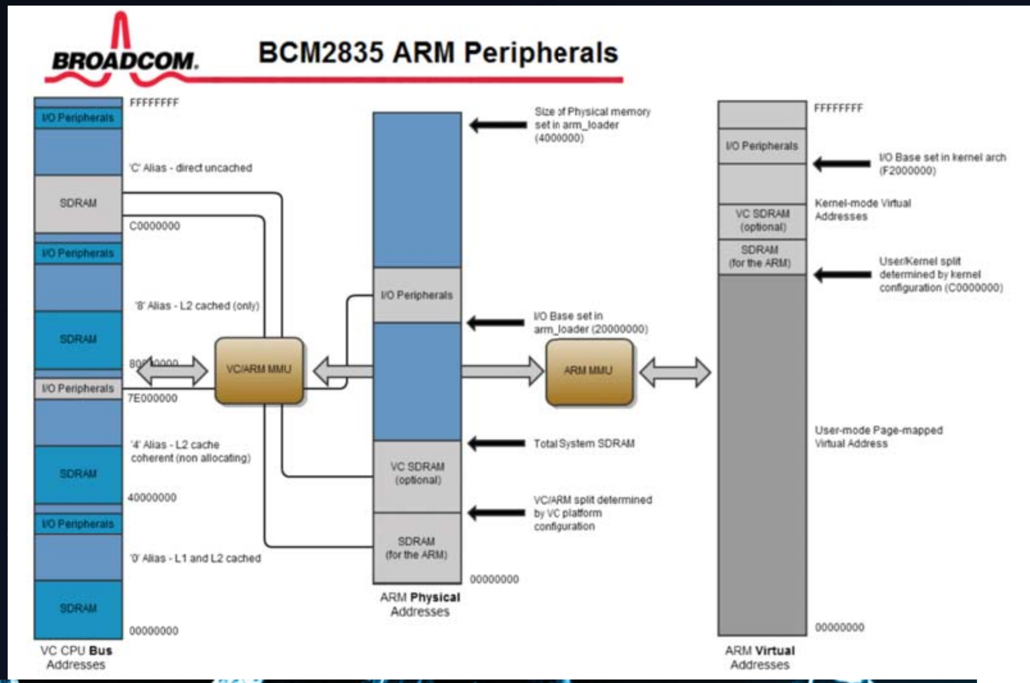
Pin Control Subsystem

- Pin Configuration
- Pin Multiplexing



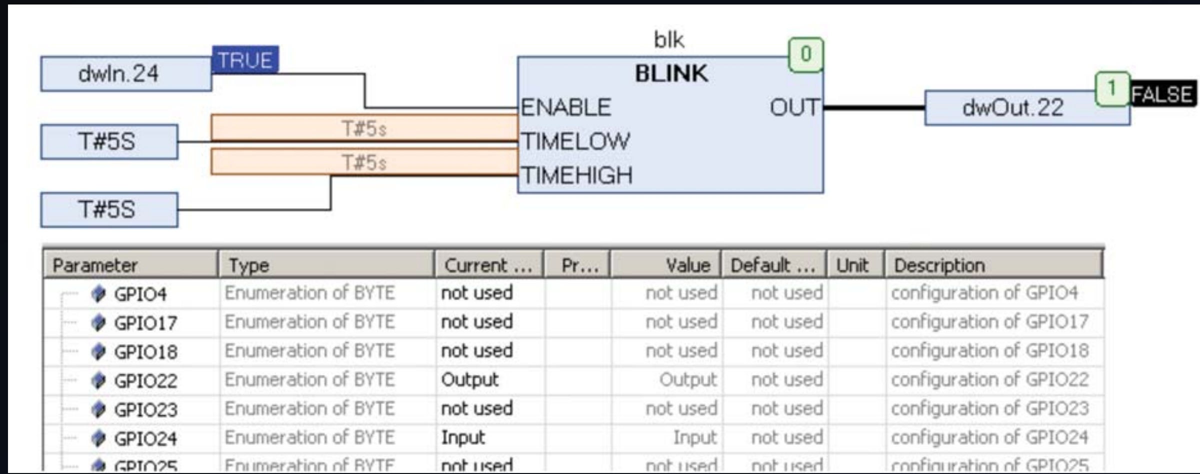
BCM2835 and available I/O Functions





Pin Configuration

- Input Pin
  - readable but not writeable



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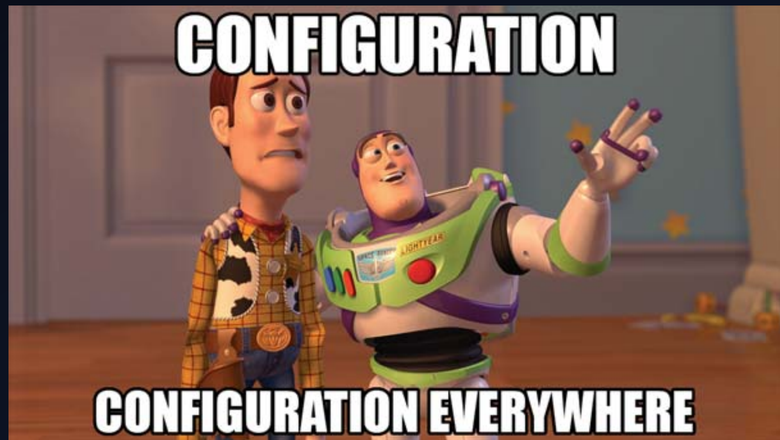
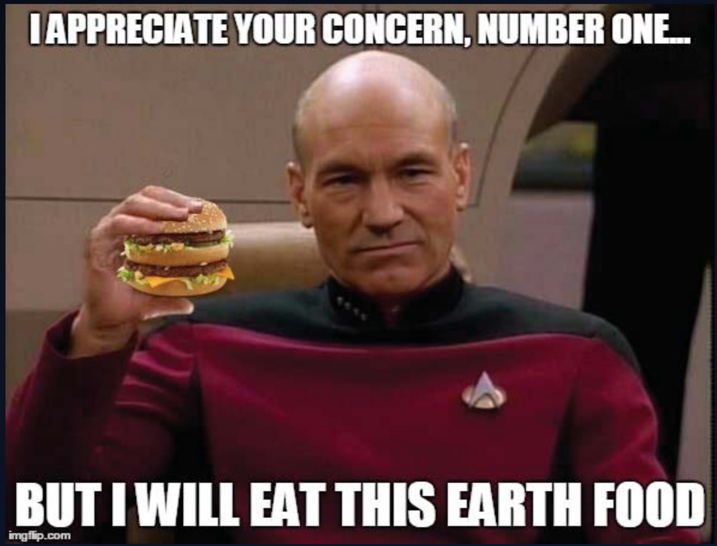
- Output Pin
  - readable and writeable



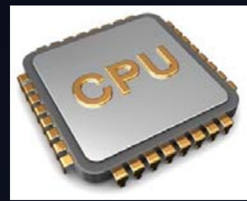
Security concerns regarding Pin Control in PLCs

1. No Interrupt for Pin Configuration
   - How the OS knows about the modification of pin configuration?
2. No Interrupt for Pin Multiplexing
   - What if somebody multiplex a Pin at runtime?



Introducing Pin Control Attack: A Memory Illusion

Operating System/ Kernel



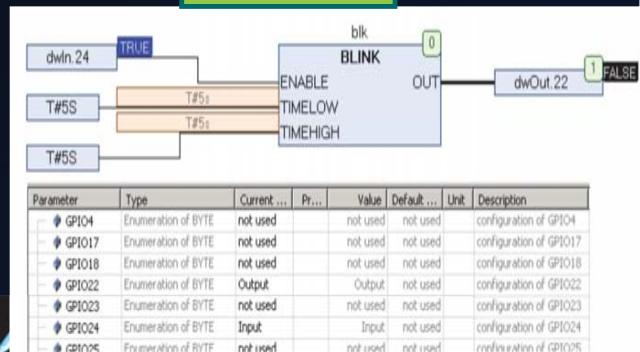
PLC Runtime

Physical I/O Memory

State Register

Write register

Read register



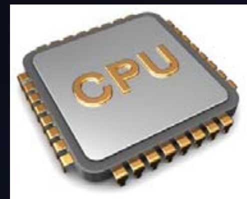
Introducing Pin Control Attack: A Memory Illusion

Request for mapping the physical I/O Memory

Map (I/O Memory, +16bytes)

Operating System/ Kernel

PLC Runtime



Physical I/O Memory

State Register

Write register

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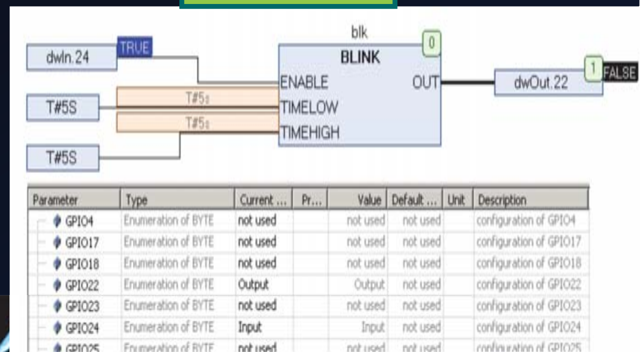

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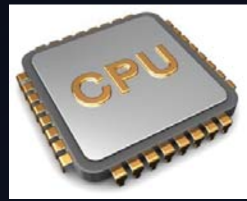
Request for mapping the physical I/O Memory

Map (I/O Memory, +16bytes)

PLC Runtime

Operating System/ Kernel

map via MMU

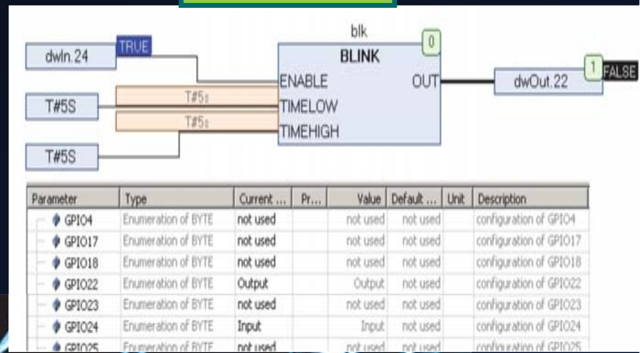


Physical I/O Memory

State Register

Write register

Read register



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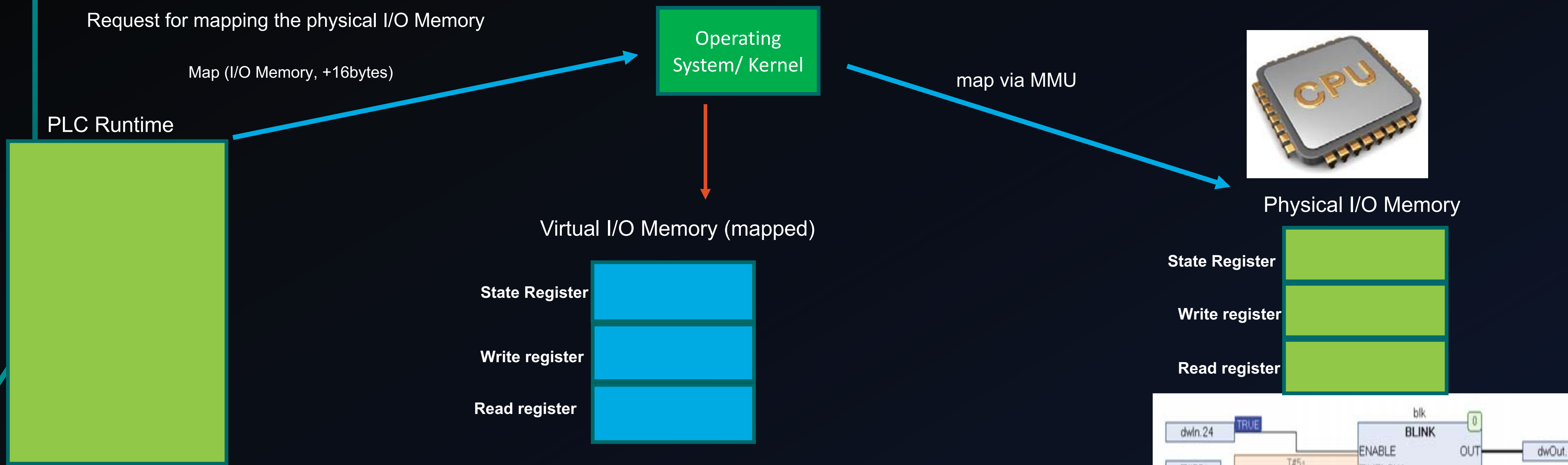

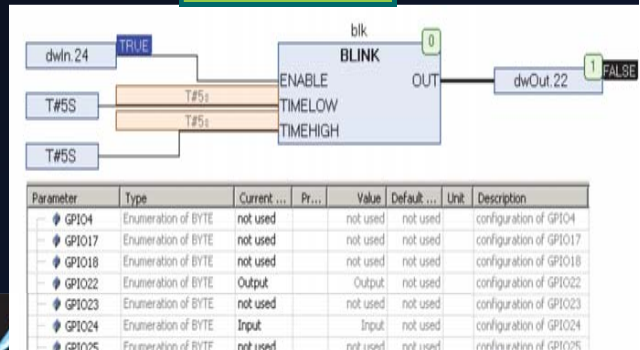

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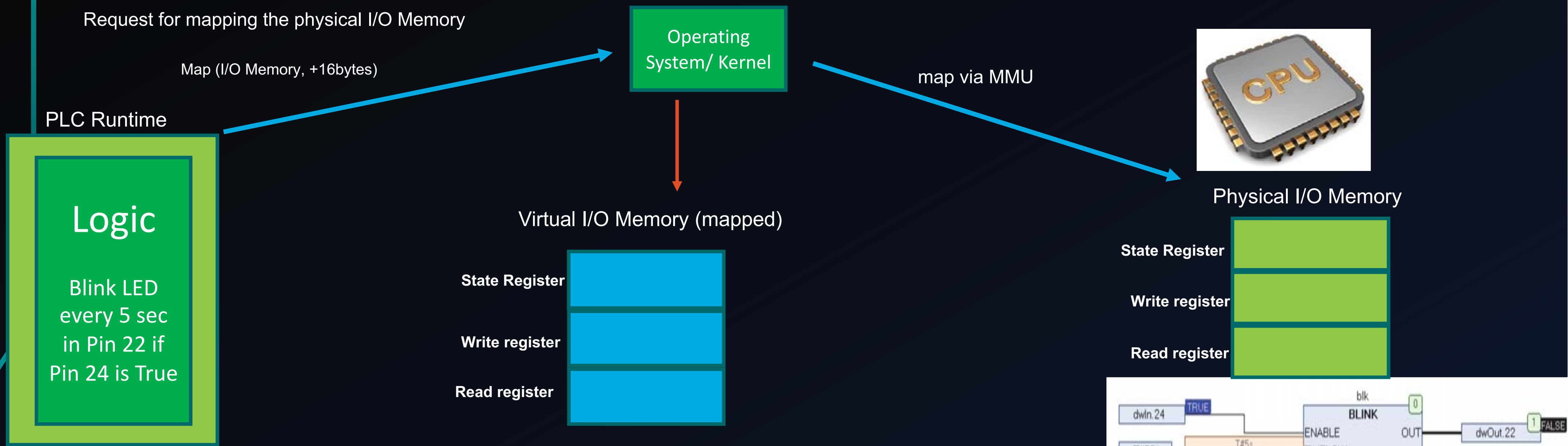

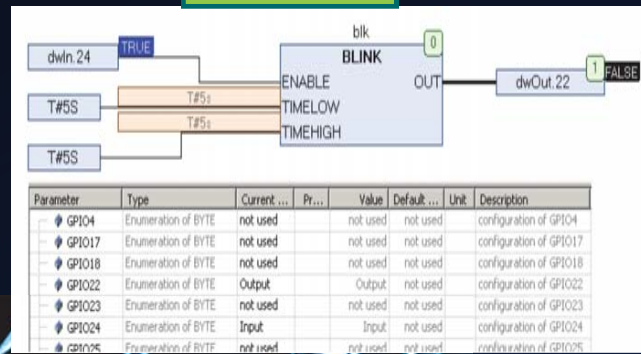

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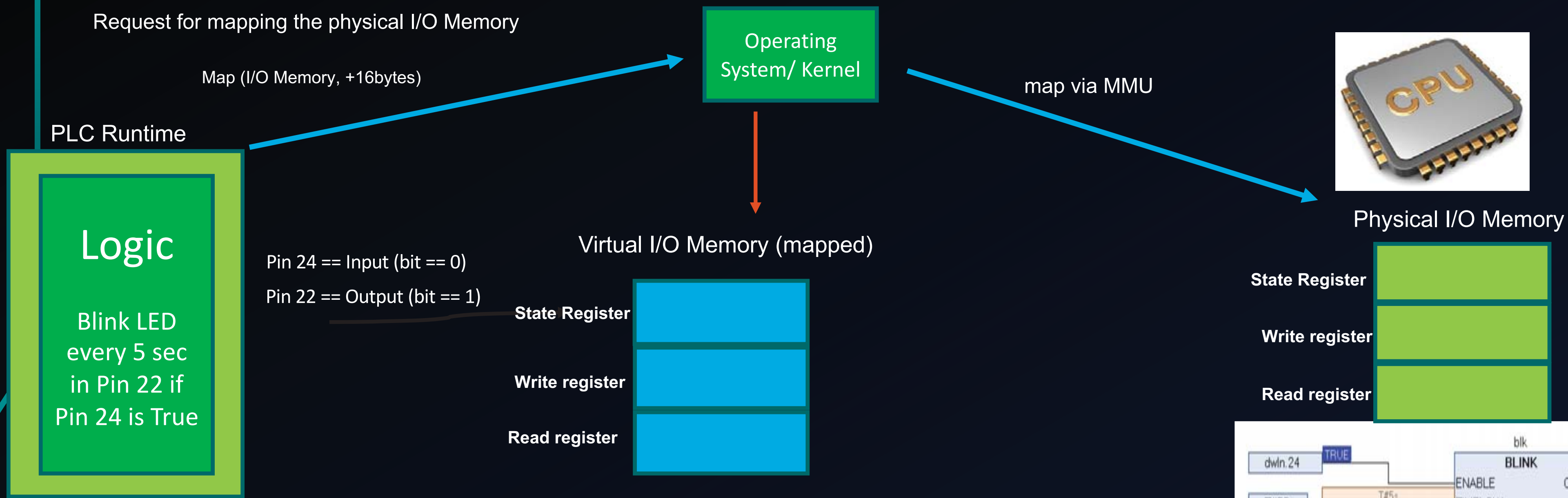

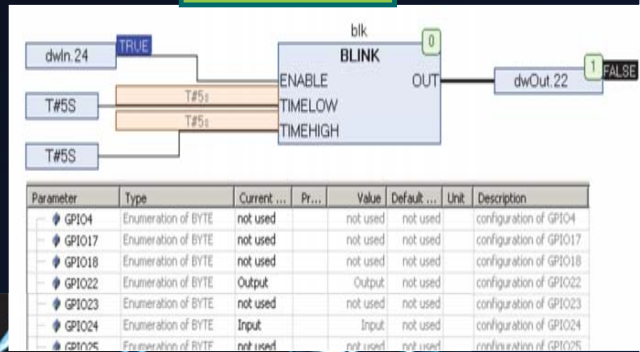

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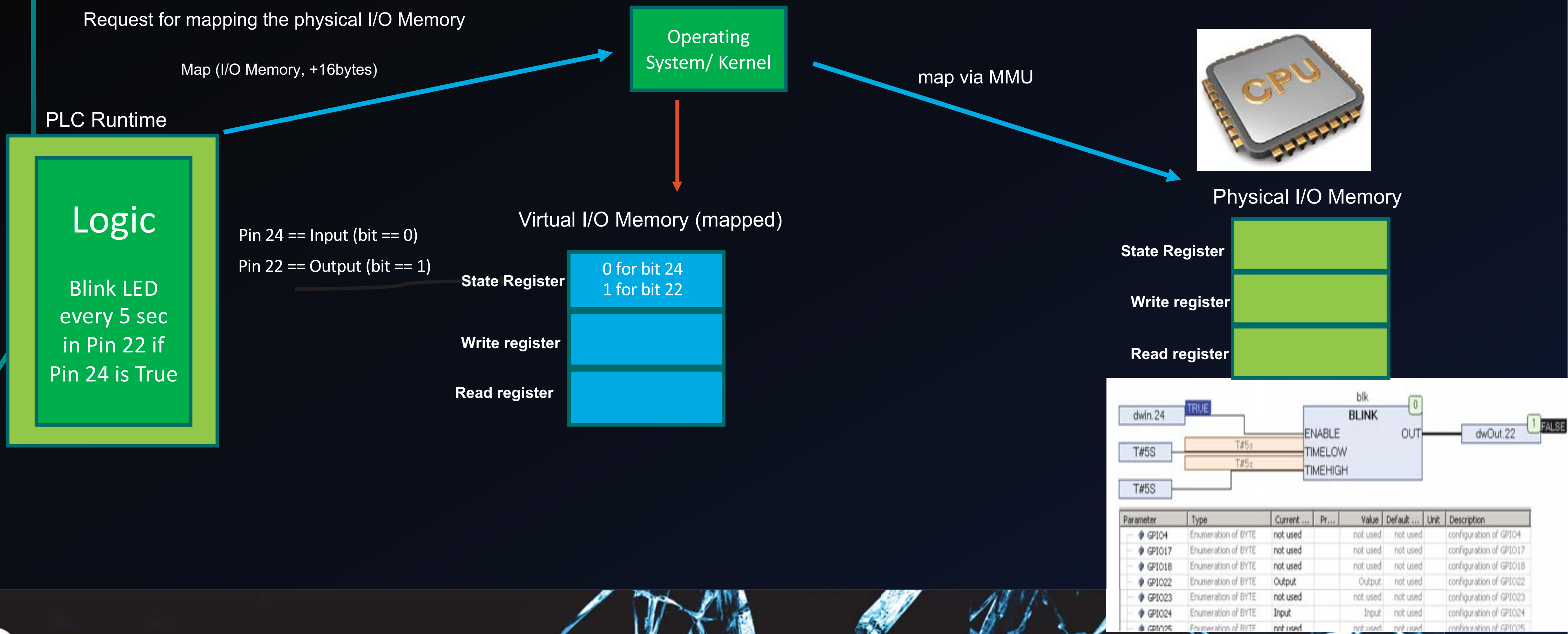

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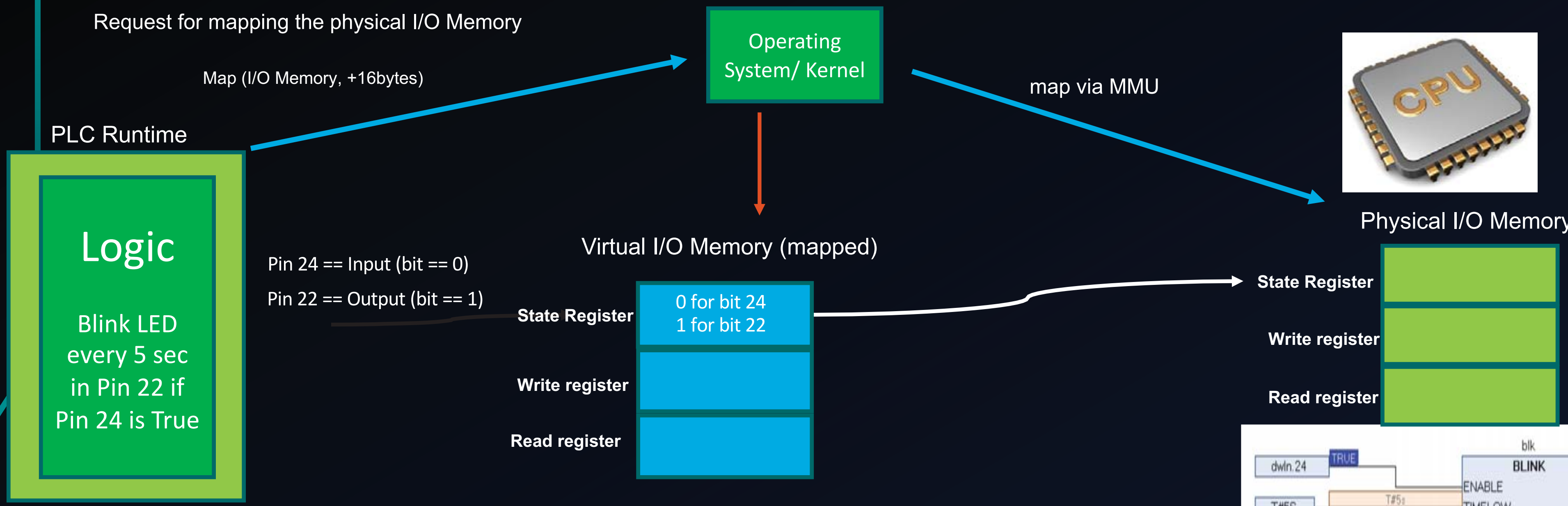

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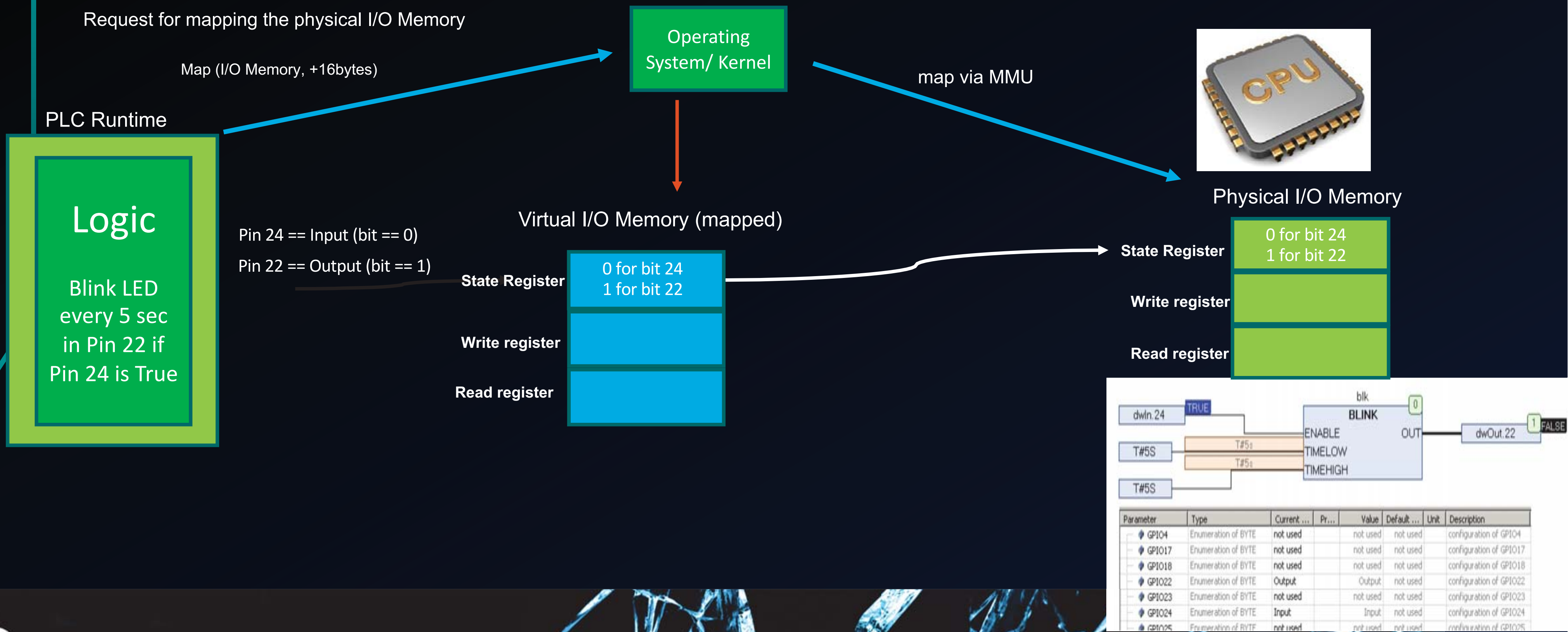


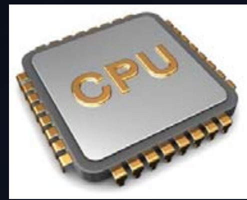
Introducing Pin Control Attack: A Memory Illusion

Request for mapping the physical I/O Memory

Map (I/O Memory, +16bytes)

Operating System/ Kernel

map via MMU



PLC Runtime

Logic

Blink LED every 5 sec in Pin 22 if Pin 24 is True

Pin 24 == Input (bit == 0)

Pin 22 == Output (bit == 1)

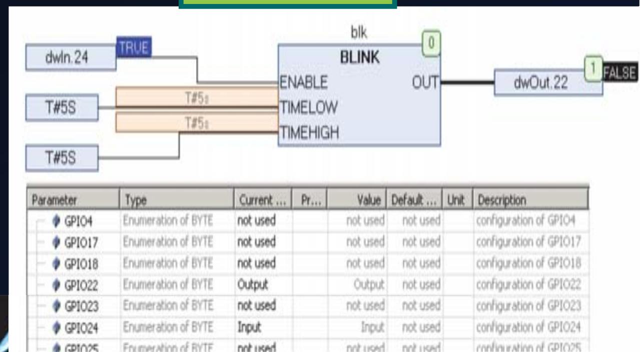
Virtual I/O Memory (mapped)

State Register	0 for bit 24 1 for bit 22
Write register	
Read register	

Read Pin 24

Physical I/O Memory

State Register	0 for bit 24 1 for bit 22
Write register	
Read register	



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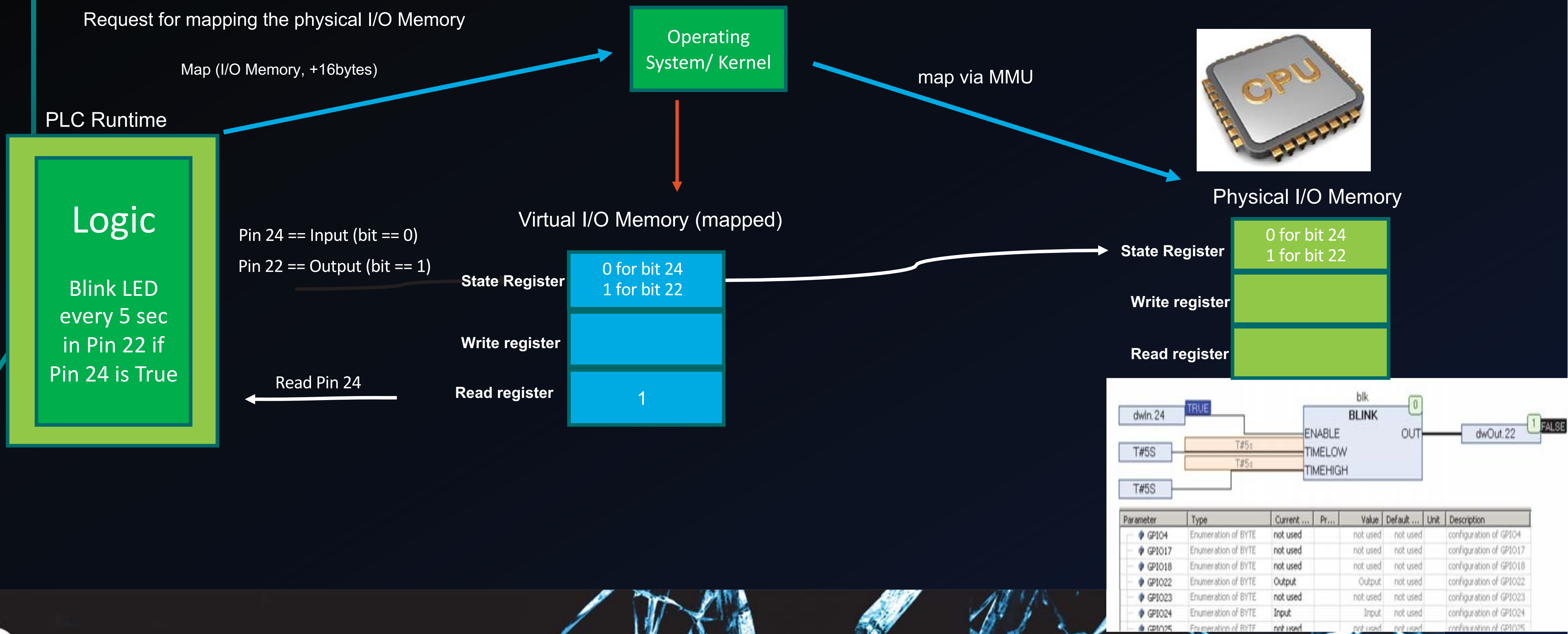

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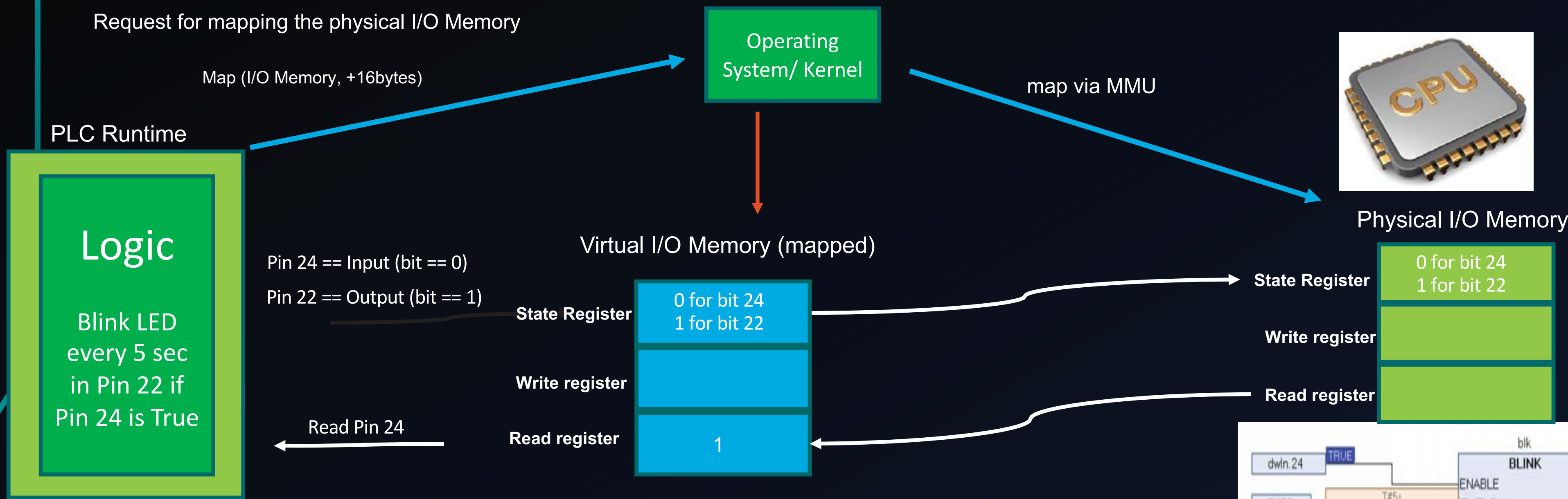

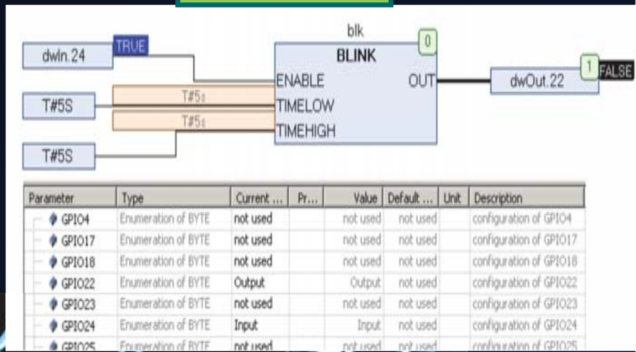

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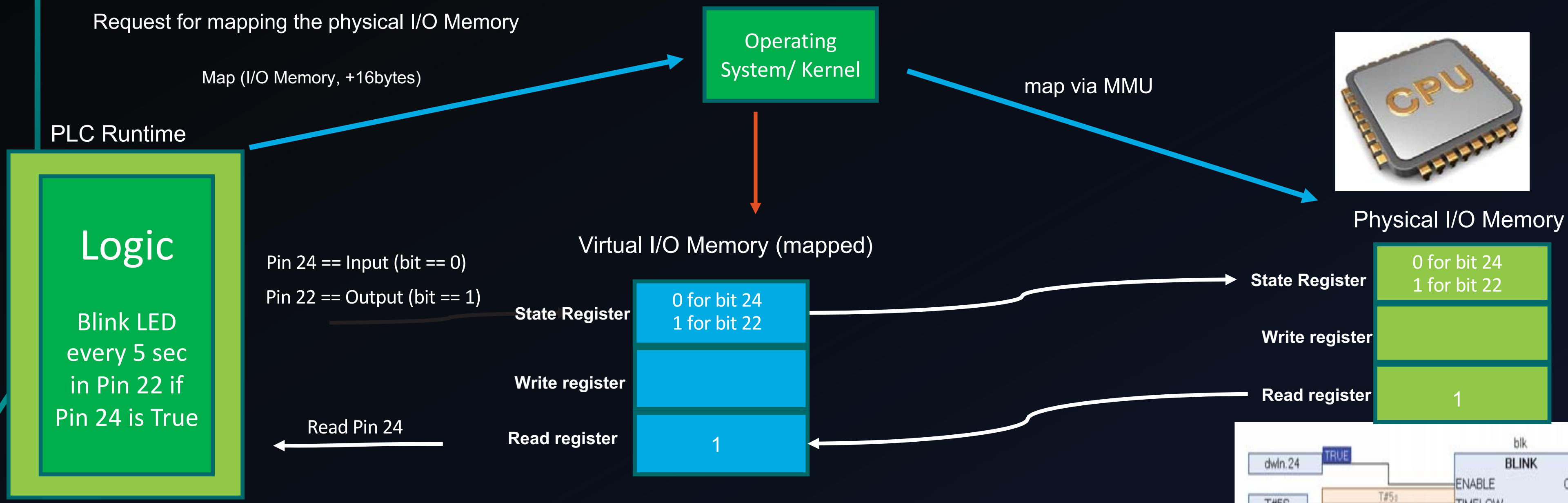
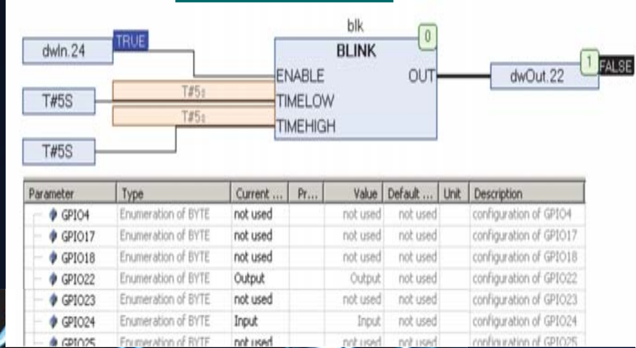
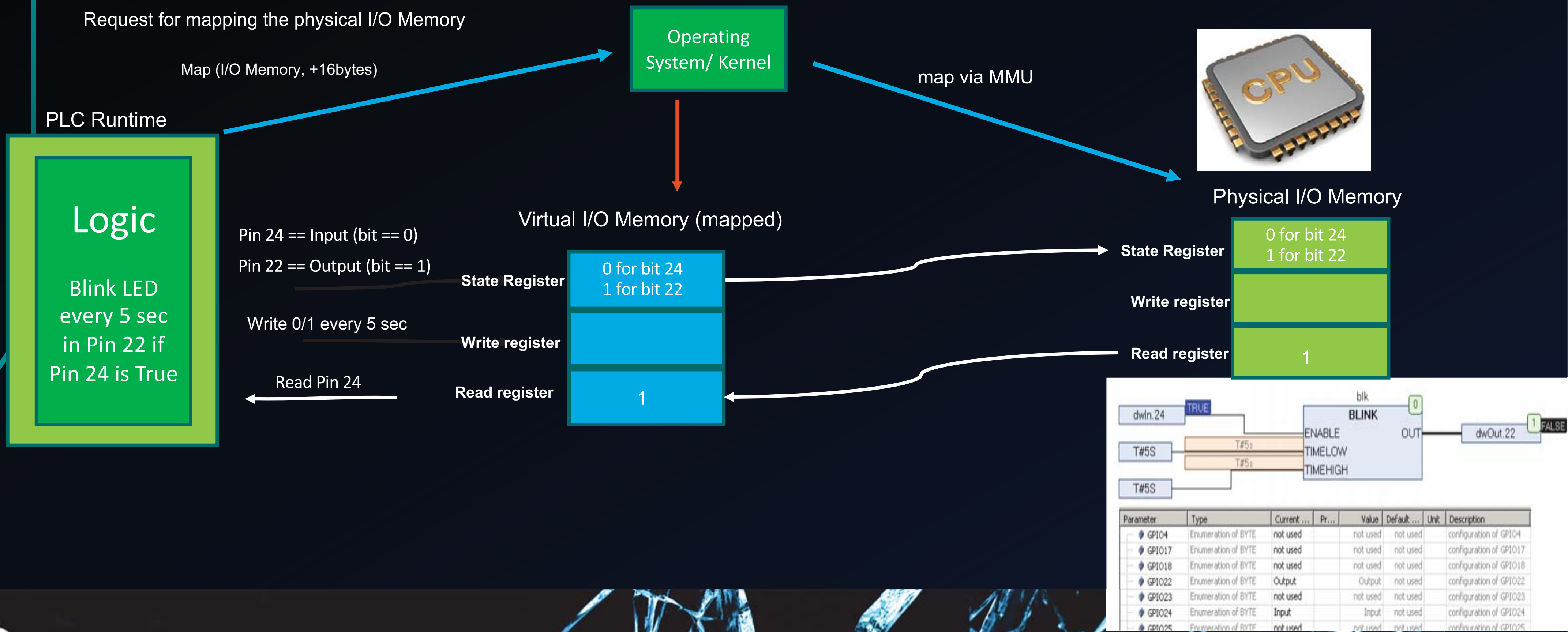
Introducing Pin Control Attack: A Memory Illusion





Parameter	Type	Current ...	Pr...	Value	Default ...	Unit	Description
GPIO4	Enumeration of BYTE	not used		not used	not used		configuration of GPIO4
GPIO17	Enumeration of BYTE	not used		not used	not used		configuration of GPIO17
GPIO18	Enumeration of BYTE	not used		not used	not used		configuration of GPIO18
GPIO22	Enumeration of BYTE	Output		Output	not used		configuration of GPIO22
GPIO23	Enumeration of BYTE	not used		not used	not used		configuration of GPIO23
GPIO24	Enumeration of BYTE	Input		Input	not used		configuration of GPIO24
GPIO25	Enumeration of BYTE	not used		not used	not used		configuration of GPIO25

Introducing Pin Control Attack: A Memory Illusion



Parameter	Type	Current ...	Pr...	Value	Default ...	Unit	Description
GPIO4	Enumeration of BYTE	not used		not used	not used		configuration of GPIO4
GPIO17	Enumeration of BYTE	not used		not used	not used		configuration of GPIO17
GPIO18	Enumeration of BYTE	not used		not used	not used		configuration of GPIO18
GPIO22	Enumeration of BYTE	Output		Output	not used		configuration of GPIO22
GPIO23	Enumeration of BYTE	not used		not used	not used		configuration of GPIO23
GPIO24	Enumeration of BYTE	Input		Input	not used		configuration of GPIO24
GPIO25	Enumeration of BYTE	not used		not used	not used		configuration of GPIO25

Introducing Pin Control Attack: A Memory Illusion

Request for mapping the physical I/O Memory

Map (I/O Memory, +16bytes)

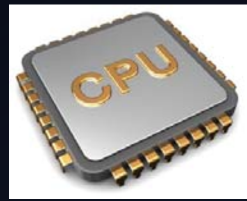
PLC Runtime

Logic

Blink LED every 5 sec in Pin 22 if Pin 24 is True

Operating System/ Kernel

map via MMU



Physical I/O Memory

State Register	0 for bit 24 1 for bit 22
Write register	
Read register	1

Virtual I/O Memory (mapped)

Pin 24 == Input (bit == 0)

Pin 22 == Output (bit == 1)

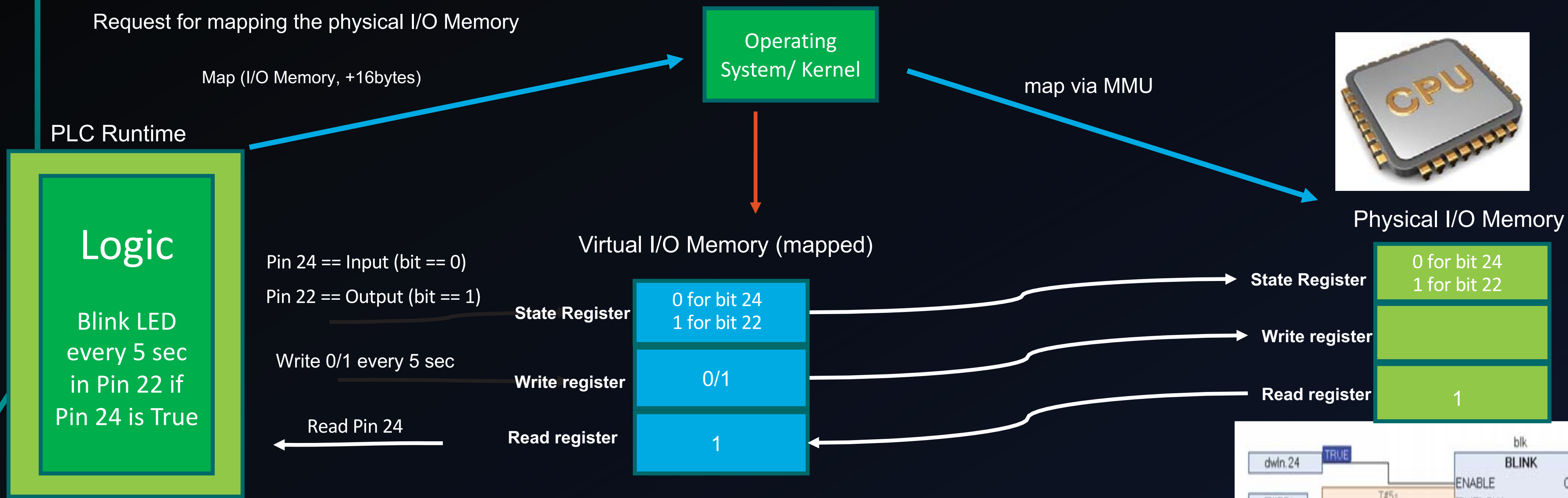
Write 0/1 every 5 sec

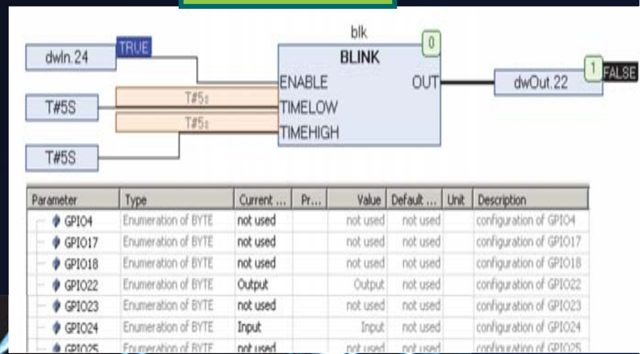
Read Pin 24

State Register	0 for bit 24 1 for bit 22
Write register	0/1
Read register	1

Parameter	Type	Current ...	Pr...	Value	Default ...	Unit	Description
GPIO4	Enumeration of BYTE	not used		not used	not used		configuration of GPIO4
GPIO17	Enumeration of BYTE	not used		not used	not used		configuration of GPIO17
GPIO18	Enumeration of BYTE	not used		not used	not used		configuration of GPIO18
GPIO22	Enumeration of BYTE	Output		Output	not used		configuration of GPIO22
GPIO23	Enumeration of BYTE	not used		not used	not used		configuration of GPIO23
GPIO24	Enumeration of BYTE	Input		Input	not used		configuration of GPIO24
GPIO25	Enumeration of BYTE	not used		not used	not used		configuration of GPIO25

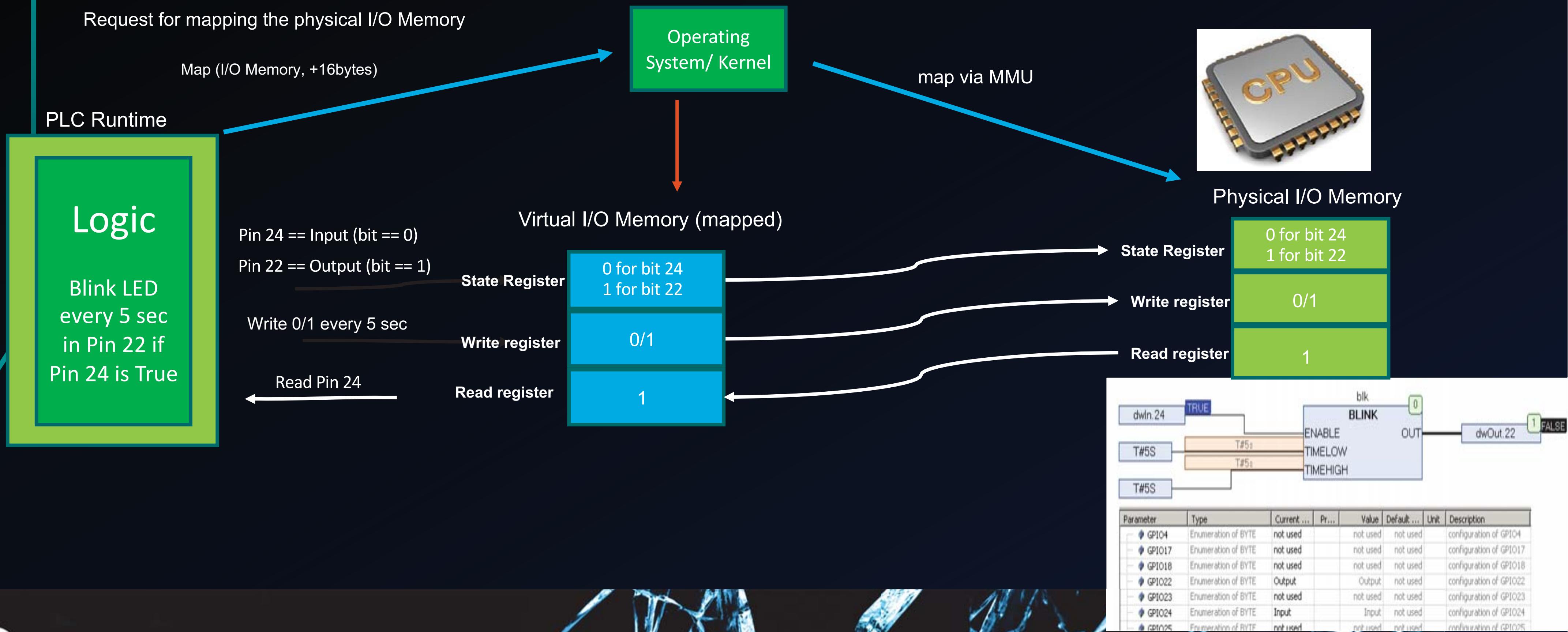
Introducing Pin Control Attack: A Memory Illusion





Parameter	Type	Current ...	Pr...	Value	Default ...	Unit	Description
GPIO4	Enumeration of BYTE	not used		not used	not used		configuration of GPIO4
GPIO17	Enumeration of BYTE	not used		not used	not used		configuration of GPIO17
GPIO18	Enumeration of BYTE	not used		not used	not used		configuration of GPIO18
GPIO22	Enumeration of BYTE	Output		Output	not used		configuration of GPIO22
GPIO23	Enumeration of BYTE	not used		not used	not used		configuration of GPIO23
GPIO24	Enumeration of BYTE	Input		Input	not used		configuration of GPIO24
GPIO25	Enumeration of BYTE	not used		not used	not used		configuration of GPIO25

Introducing Pin Control Attack: A Memory Illusion

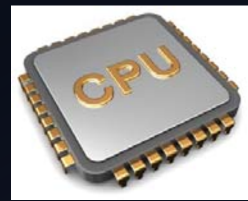


Introducing Pin Control Attack: A Memory Illusion

Introducing Pin Control Attack: A Memory Illusion

Operating System/ Kernel

PLC Runtime

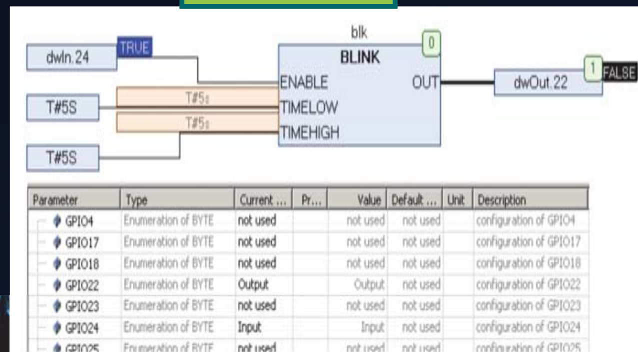


Physical I/O Memory

State Register

Write register

Read register



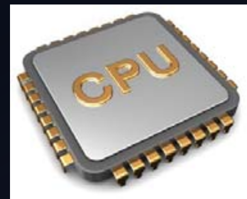
Introducing Pin Control Attack: A Memory Illusion

Request for mapping the physical I/O Memory

Map (I/O Memory, +16bytes)

Operating System/ Kernel

PLC Runtime

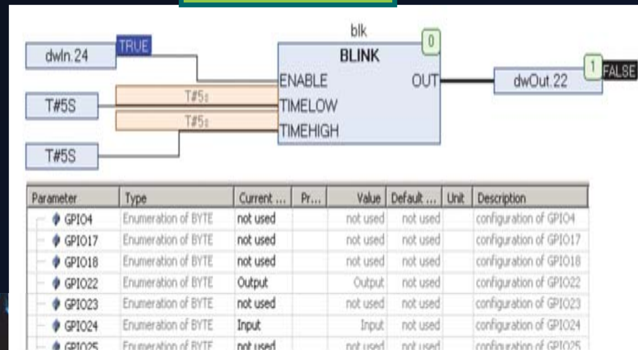


Physical I/O Memory

State Register

Write register

Read register



Introducing Pin Control Attack: A Memory Illusion

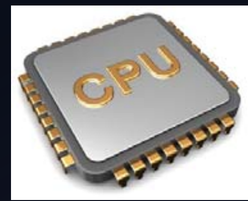
Request for mapping the physical I/O Memory

Map (I/O Memory, +16bytes)

PLC Runtime

Operating System/ Kernel

map via MMU

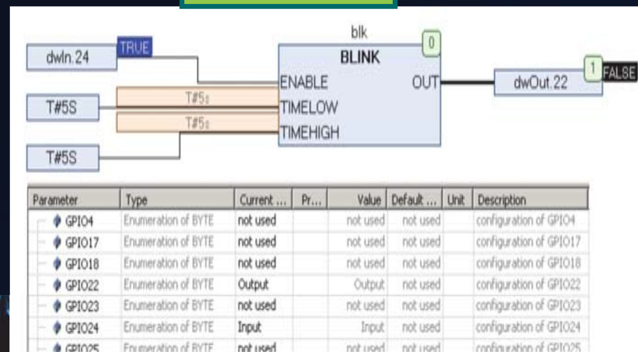


Physical I/O Memory

State Register

Write register

Read register



Parameter	Type	Current ...	Pr...	Value	Default ...	Unit	Description
GPIO4	Enumeration of BYTE	not used		not used	not used		configuration of GPIO4
GPIO17	Enumeration of BYTE	not used		not used	not used		configuration of GPIO17
GPIO18	Enumeration of BYTE	not used		not used	not used		configuration of GPIO18
GPIO22	Enumeration of BYTE	Output		Output	not used		configuration of GPIO22
GPIO23	Enumeration of BYTE	not used		not used	not used		configuration of GPIO23
GPIO24	Enumeration of BYTE	Input		Input	not used		configuration of GPIO24
GPIO25	Enumeration of BYTE	not used		not used	not used		configuration of GPIO25

Introducing Pin Control Attack: A Memory Illusion

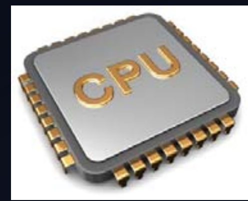
Request for mapping the physical I/O Memory

Map (I/O Memory, +16bytes)

PLC Runtime

Operating System/ Kernel

map via MMU



Physical I/O Memory

State Register

Write register

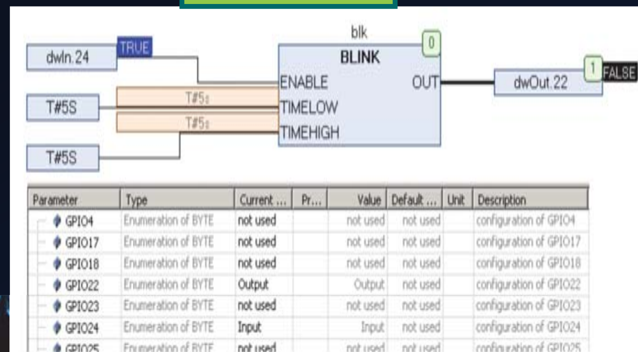
Read register

Virtual I/O Memory (mapped)

State Register

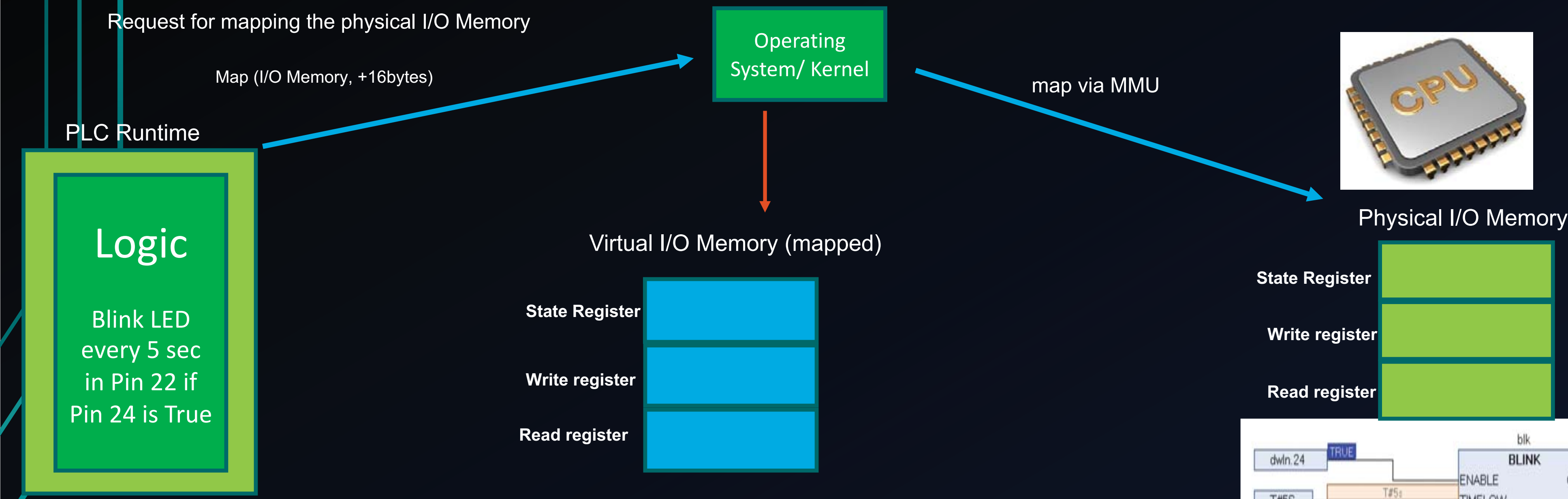
Write register

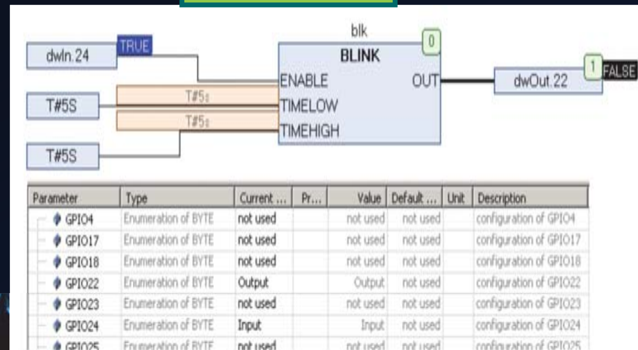
Read register



Parameter	Type	Current ...	Pr...	Value	Default ...	Unit	Description
GPIO4	Enumeration of BYTE	not used		not used	not used		configuration of GPIO4
GPIO17	Enumeration of BYTE	not used		not used	not used		configuration of GPIO17
GPIO18	Enumeration of BYTE	not used		not used	not used		configuration of GPIO18
GPIO22	Enumeration of BYTE	Output		Output	not used		configuration of GPIO22
GPIO23	Enumeration of BYTE	not used		not used	not used		configuration of GPIO23
GPIO24	Enumeration of BYTE	Input		Input	not used		configuration of GPIO24
GPIO25	Enumeration of BYTE	not used		not used	not used		configuration of GPIO25

Introducing Pin Control Attack: A Memory Illusion





Parameter	Type	Current ...	Pr...	Value	Default ...	Unit	Description
GPIO4	Enumeration of BYTE	not used		not used	not used		configuration of GPIO4
GPIO17	Enumeration of BYTE	not used		not used	not used		configuration of GPIO17
GPIO18	Enumeration of BYTE	not used		not used	not used		configuration of GPIO18
GPIO22	Enumeration of BYTE	Output		Output	not used		configuration of GPIO22
GPIO23	Enumeration of BYTE	not used		not used	not used		configuration of GPIO23
GPIO24	Enumeration of BYTE	Input		Input	not used		configuration of GPIO24
GPIO25	Enumeration of BYTE	not used		not used	not used		configuration of GPIO25

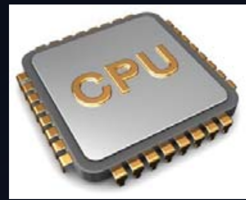
Introducing Pin Control Attack: A Memory Illusion

Request for mapping the physical I/O Memory

Map (I/O Memory, +16bytes)

Operating System/ Kernel

map via MMU



PLC Runtime

Logic

Blink LED every 5 sec in Pin 22 if Pin 24 is True

Pin 24 == Input (bit == 0)

Pin 22 == Output (bit == 1)

Virtual I/O Memory (mapped)

State Register

Write register

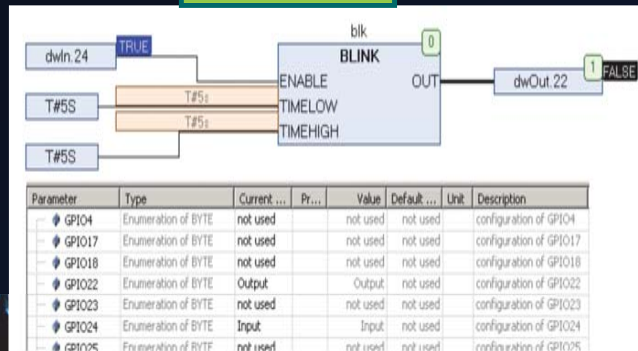
Read register

Physical I/O Memory

State Register

Write register

Read register



Parameter	Type	Current ...	Pr...	Value	Default ...	Unit	Description
GPIO4	Enumeration of BYTE	not used		not used	not used		configuration of GPIO4
GPIO17	Enumeration of BYTE	not used		not used	not used		configuration of GPIO17
GPIO18	Enumeration of BYTE	not used		not used	not used		configuration of GPIO18
GPIO22	Enumeration of BYTE	Output		Output	not used		configuration of GPIO22
GPIO23	Enumeration of BYTE	not used		not used	not used		configuration of GPIO23
GPIO24	Enumeration of BYTE	Input		Input	not used		configuration of GPIO24
GPIO25	Enumeration of BYTE	not used		not used	not used		configuration of GPIO25

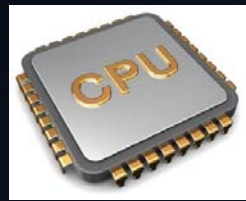
Introducing Pin Control Attack: A Memory Illusion

Request for mapping the physical I/O Memory

Map (I/O Memory, +16bytes)

Operating System/ Kernel

map via MMU



Physical I/O Memory

State Register	
Write register	
Read register	

PLC Runtime

Logic

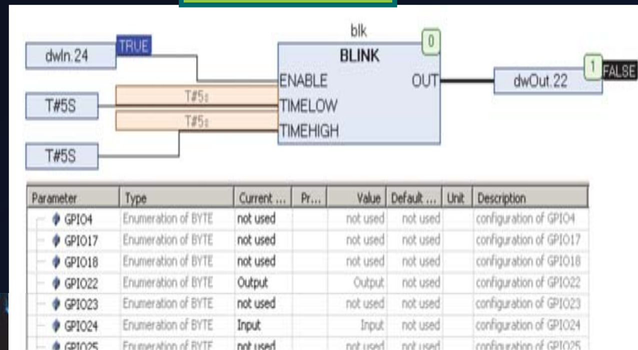
Blink LED every 5 sec in Pin 22 if Pin 24 is True

Pin 24 == Input (bit == 0)

Pin 22 == Output (bit == 1)

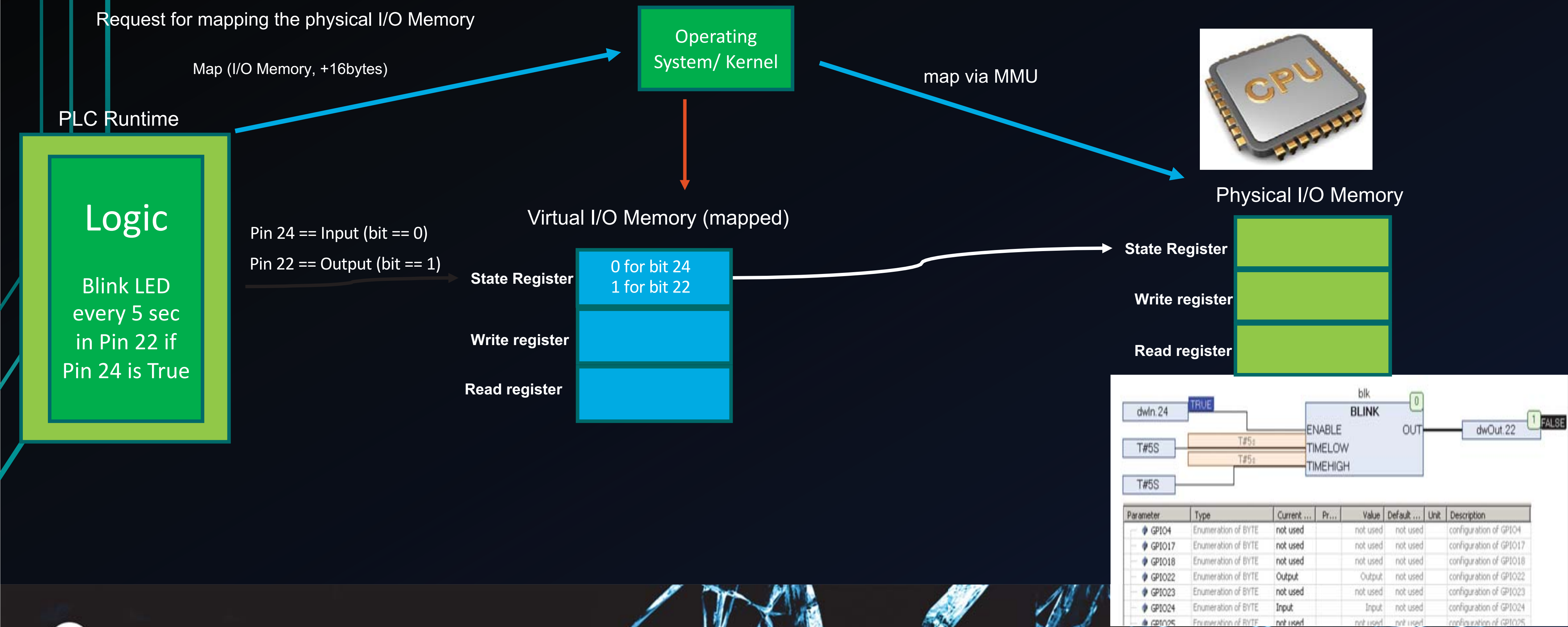
Virtual I/O Memory (mapped)

State Register	0 for bit 24 1 for bit 22
Write register	
Read register	



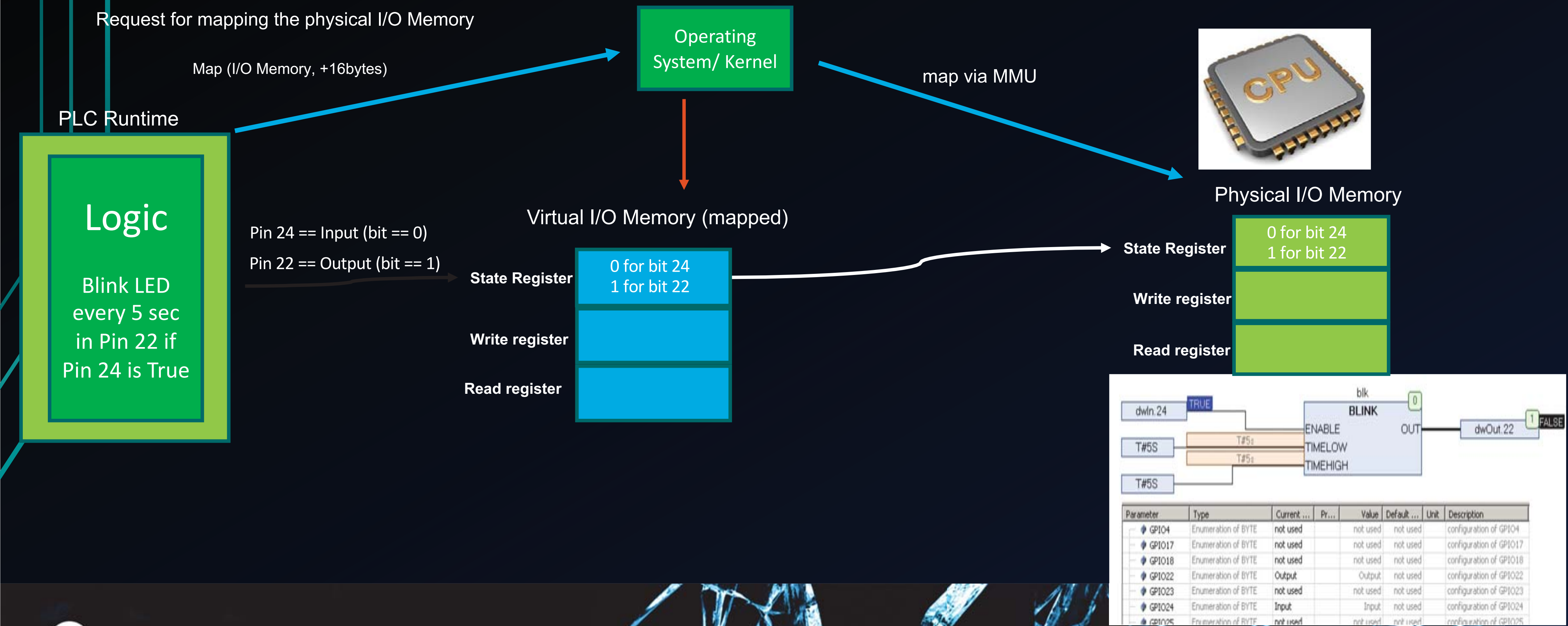
Parameter	Type	Current ...	Pr...	Value	Default ...	Unit	Description
GPIO4	Enumeration of BYTE	not used		not used	not used		configuration of GPIO4
GPIO17	Enumeration of BYTE	not used		not used	not used		configuration of GPIO17
GPIO18	Enumeration of BYTE	not used		not used	not used		configuration of GPIO18
GPIO22	Enumeration of BYTE	Output		Output	not used		configuration of GPIO22
GPIO23	Enumeration of BYTE	not used		not used	not used		configuration of GPIO23
GPIO24	Enumeration of BYTE	Input		Input	not used		configuration of GPIO24
GPIO25	Enumeration of BYTE	not used		not used	not used		configuration of GPIO25

Introducing Pin Control Attack: A Memory Illusion



Parameter	Type	Current ...	Pr...	Value	Default ...	Unit	Description
GPIO4	Enumeration of BYTE	not used		not used	not used		configuration of GPIO4
GPIO17	Enumeration of BYTE	not used		not used	not used		configuration of GPIO17
GPIO18	Enumeration of BYTE	not used		not used	not used		configuration of GPIO18
GPIO22	Enumeration of BYTE	Output		Output	not used		configuration of GPIO22
GPIO23	Enumeration of BYTE	not used		not used	not used		configuration of GPIO23
GPIO24	Enumeration of BYTE	Input		Input	not used		configuration of GPIO24
GPIO25	Enumeration of BYTE	not used		not used	not used		configuration of GPIO25

Introducing Pin Control Attack: A Memory Illusion



Parameter	Type	Current ...	Pr...	Value	Default ...	Unit	Description
GPIO4	Enumeration of BYTE	not used		not used	not used		configuration of GPIO4
GPIO17	Enumeration of BYTE	not used		not used	not used		configuration of GPIO17
GPIO18	Enumeration of BYTE	not used		not used	not used		configuration of GPIO18
GPIO22	Enumeration of BYTE	Output		Output	not used		configuration of GPIO22
GPIO23	Enumeration of BYTE	not used		not used	not used		configuration of GPIO23
GPIO24	Enumeration of BYTE	Input		Input	not used		configuration of GPIO24
GPIO25	Enumeration of BYTE	not used		not used	not used		configuration of GPIO25

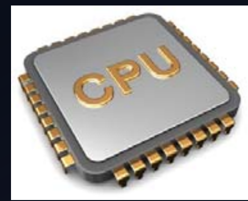
Introducing Pin Control Attack: A Memory Illusion

Request for mapping the physical I/O Memory

Map (I/O Memory, +16bytes)

Operating System/ Kernel

map via MMU



PLC Runtime

Logic

Blink LED every 5 sec in Pin 22 if Pin 24 is True

Pin 24 == Input (bit == 0)

Pin 22 == Output (bit == 1)

Virtual I/O Memory (mapped)

State Register: 0 for bit 24, 1 for bit 22

Write register

Read register

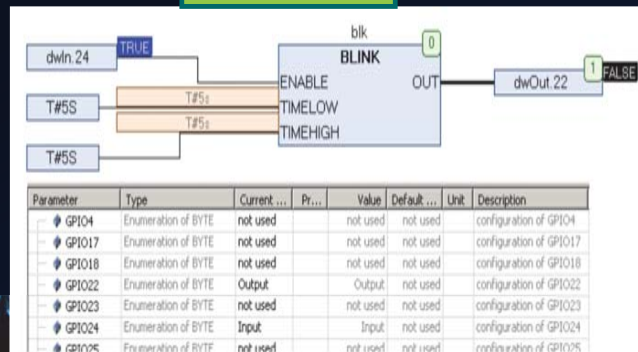
Read Pin 24

Physical I/O Memory

State Register: 0 for bit 24, 1 for bit 22

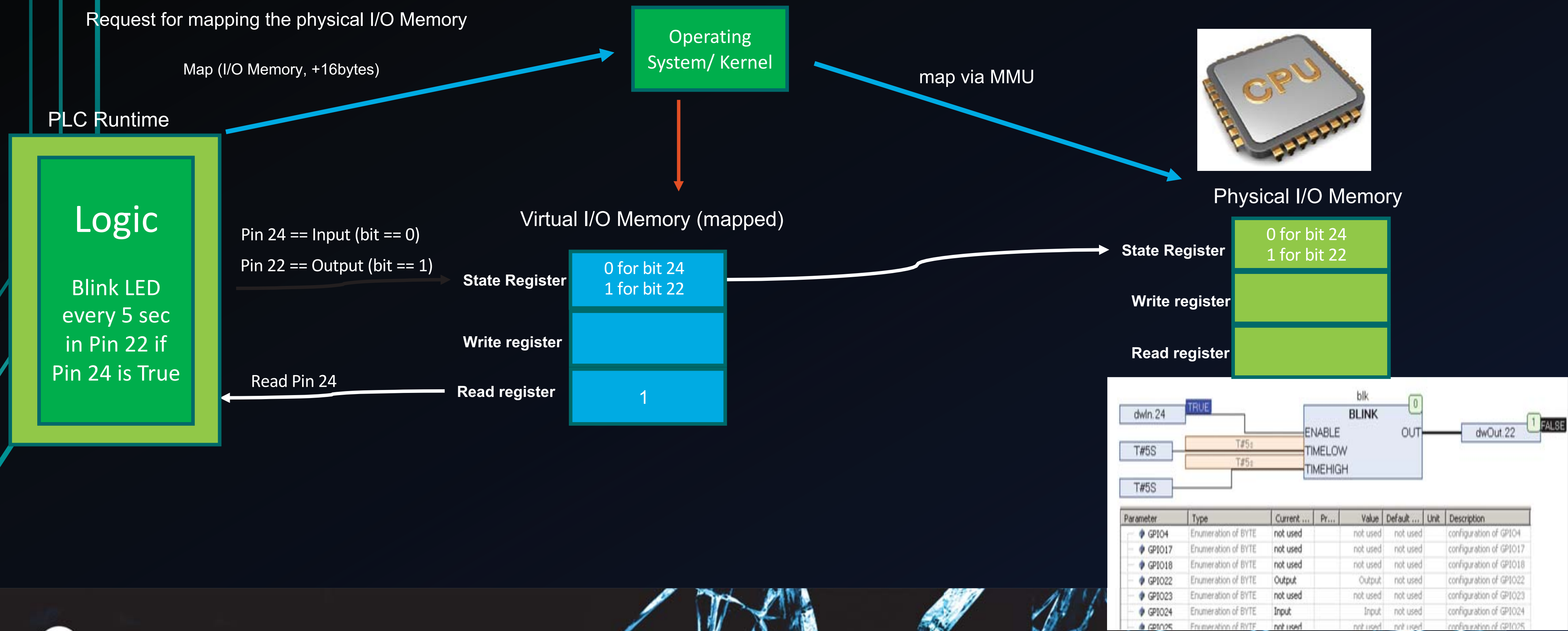
Write register

Read register



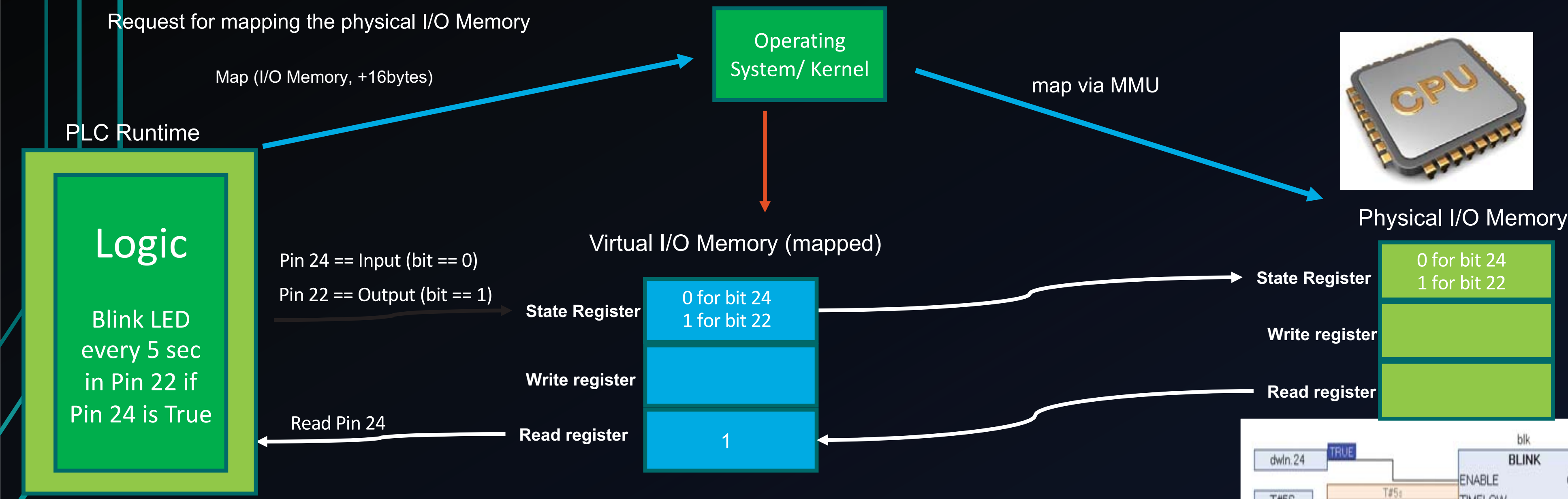
Parameter	Type	Current ...	Pr...	Value	Default ...	Unit	Description
GPIO4	Enumeration of BYTE	not used		not used	not used		configuration of GPIO4
GPIO17	Enumeration of BYTE	not used		not used	not used		configuration of GPIO17
GPIO18	Enumeration of BYTE	not used		not used	not used		configuration of GPIO18
GPIO22	Enumeration of BYTE	Output		Output	not used		configuration of GPIO22
GPIO23	Enumeration of BYTE	not used		not used	not used		configuration of GPIO23
GPIO24	Enumeration of BYTE	Input		Input	not used		configuration of GPIO24
GPIO25	Enumeration of BYTE	not used		not used	not used		configuration of GPIO25

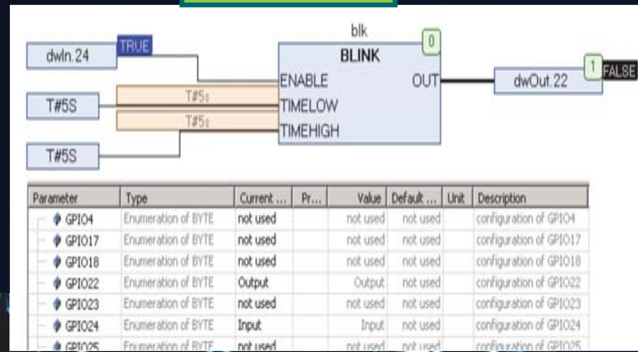
Introducing Pin Control Attack: A Memory Illusion



Parameter	Type	Current ...	Pr...	Value	Default ...	Unit	Description
GPIO4	Enumeration of BYTE	not used		not used	not used		configuration of GPIO4
GPIO17	Enumeration of BYTE	not used		not used	not used		configuration of GPIO17
GPIO18	Enumeration of BYTE	not used		not used	not used		configuration of GPIO18
GPIO22	Enumeration of BYTE	Output		Output	not used		configuration of GPIO22
GPIO23	Enumeration of BYTE	not used		not used	not used		configuration of GPIO23
GPIO24	Enumeration of BYTE	Input		Input	not used		configuration of GPIO24
GPIO25	Enumeration of BYTE	not used		not used	not used		configuration of GPIO25

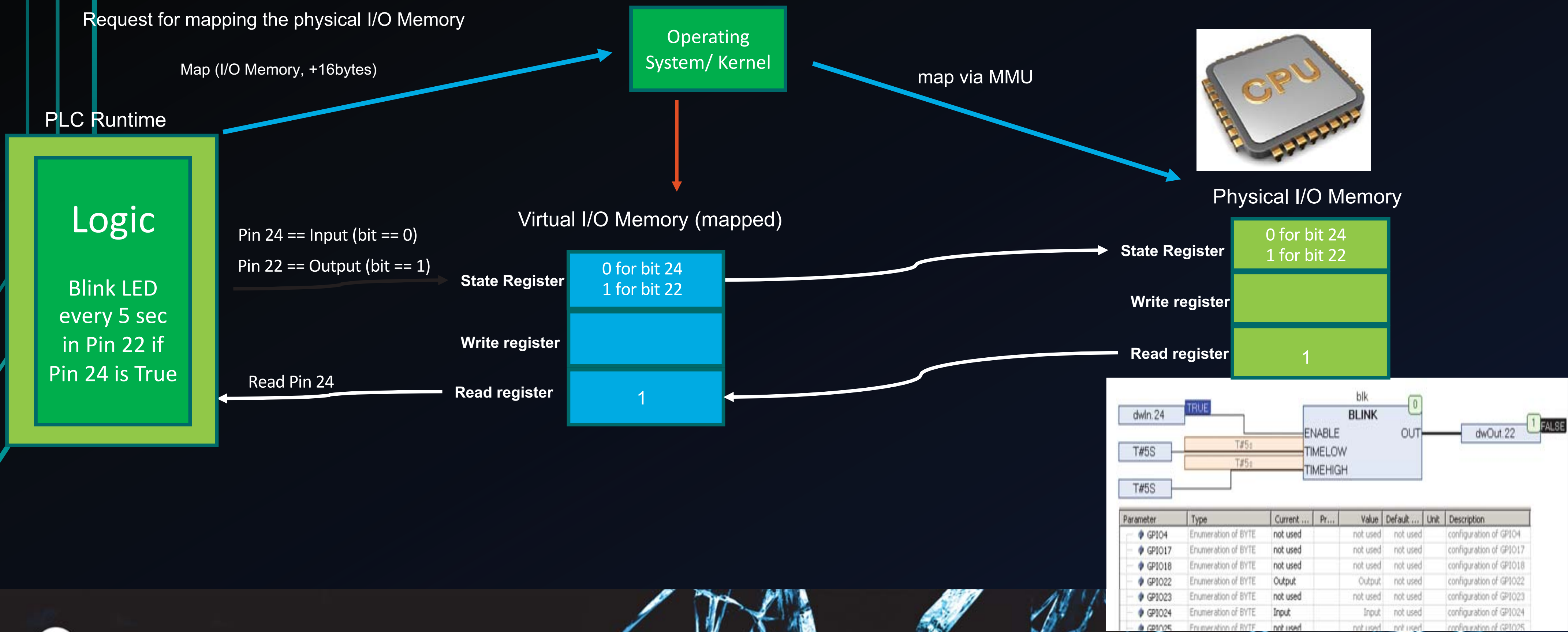
Introducing Pin Control Attack: A Memory Illusion



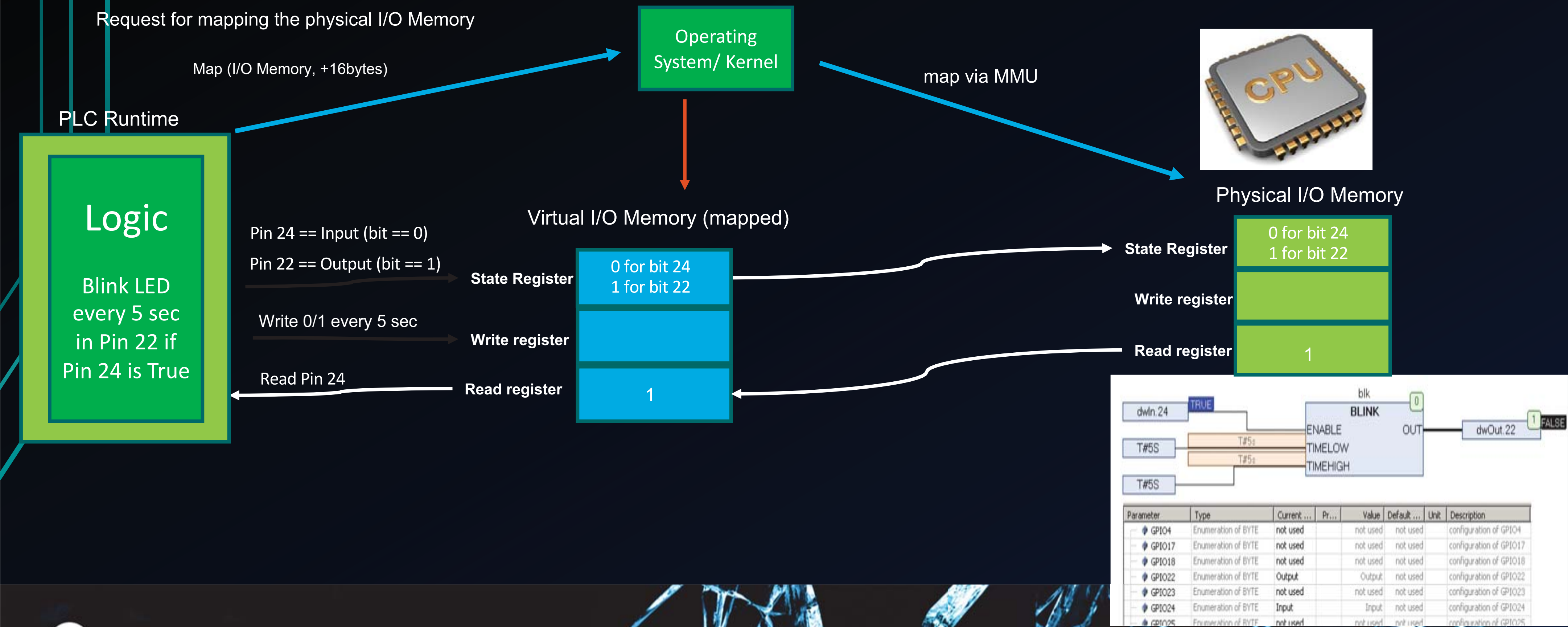


Parameter	Type	Current ...	Pr...	Value	Default ...	Unit	Description
GPIO4	Enumeration of BYTE	not used		not used	not used		configuration of GPIO4
GPIO17	Enumeration of BYTE	not used		not used	not used		configuration of GPIO17
GPIO18	Enumeration of BYTE	not used		not used	not used		configuration of GPIO18
GPIO22	Enumeration of BYTE	Output		Output	not used		configuration of GPIO22
GPIO23	Enumeration of BYTE	not used		not used	not used		configuration of GPIO23
GPIO24	Enumeration of BYTE	Input		Input	not used		configuration of GPIO24
GPIO25	Enumeration of BYTE	not used		not used	not used		configuration of GPIO25

Introducing Pin Control Attack: A Memory Illusion

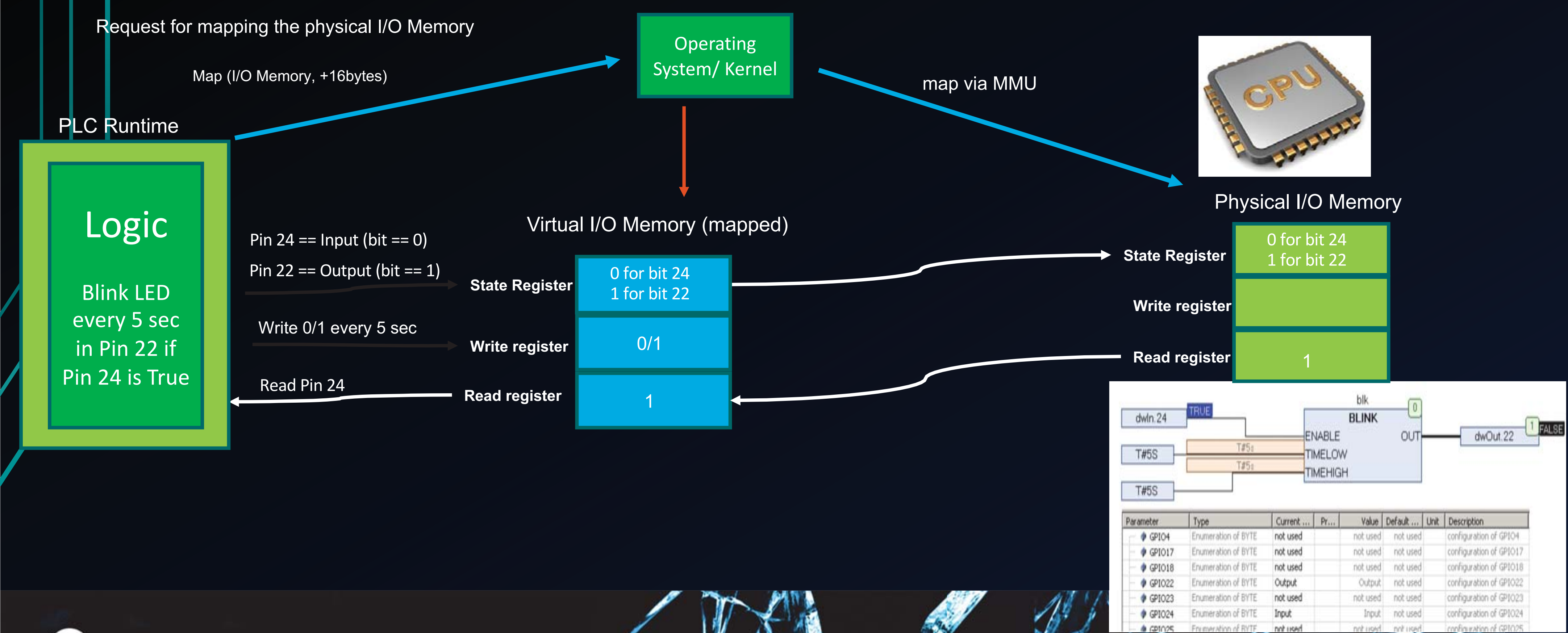


Introducing Pin Control Attack: A Memory Illusion



Parameter	Type	Current ...	Pr...	Value	Default ...	Unit	Description
GPIO4	Enumeration of BYTE	not used		not used	not used		configuration of GPIO4
GPIO17	Enumeration of BYTE	not used		not used	not used		configuration of GPIO17
GPIO18	Enumeration of BYTE	not used		not used	not used		configuration of GPIO18
GPIO22	Enumeration of BYTE	Output		Output	not used		configuration of GPIO22
GPIO23	Enumeration of BYTE	not used		not used	not used		configuration of GPIO23
GPIO24	Enumeration of BYTE	Input		Input	not used		configuration of GPIO24
GPIO25	Enumeration of BYTE	not used		not used	not used		configuration of GPIO25

Introducing Pin Control Attack: A Memory Illusion



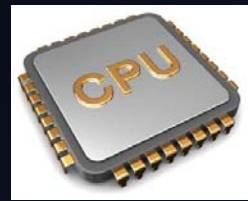
Introducing Pin Control Attack: A Memory Illusion

Request for mapping the physical I/O Memory

Map (I/O Memory, +16bytes)

Operating System/ Kernel

map via MMU



PLC Runtime

Logic

Blink LED every 5 sec in Pin 22 if Pin 24 is True

Pin 24 == Input (bit == 0)

Pin 22 == Output (bit == 1)

Write 0/1 every 5 sec

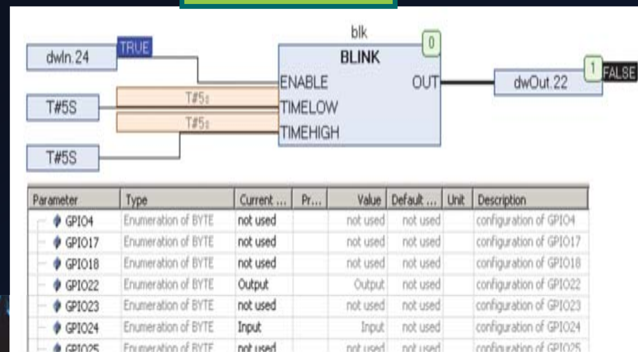
Read Pin 24

Virtual I/O Memory (mapped)

State Register	0 for bit 24 1 for bit 22
Write register	0/1
Read register	1

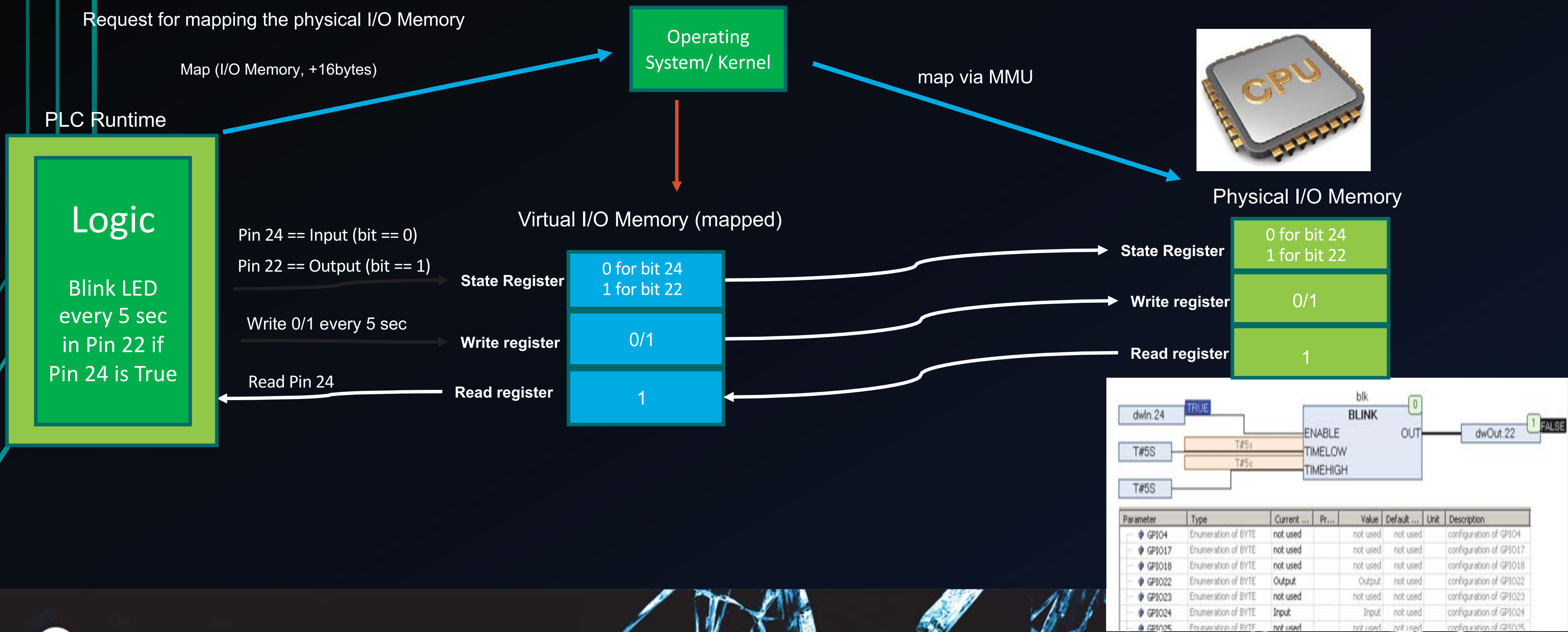
Physical I/O Memory

State Register	0 for bit 24 1 for bit 22
Write register	
Read register	1



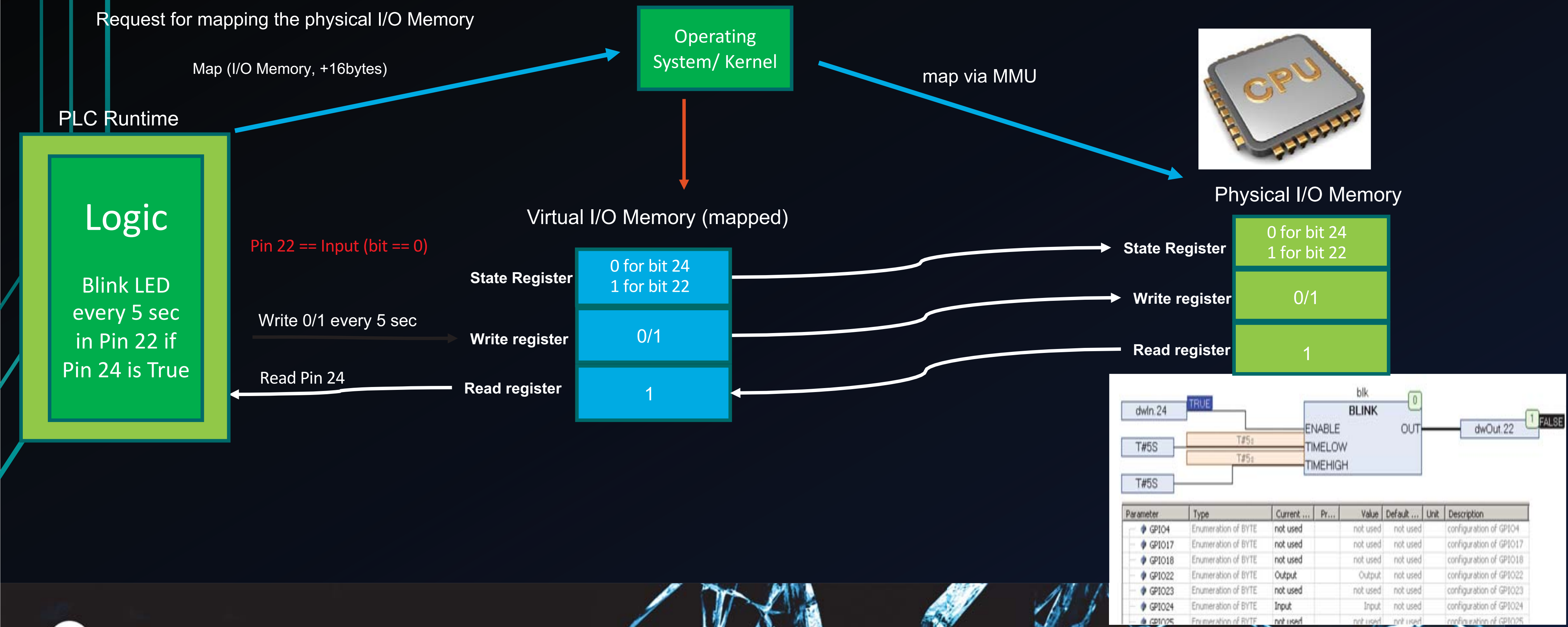
Parameter	Type	Current ...	Pr...	Value	Default ...	Unit	Description
GPIO4	Enumeration of BYTE	not used		not used	not used		configuration of GPIO4
GPIO17	Enumeration of BYTE	not used		not used	not used		configuration of GPIO17
GPIO18	Enumeration of BYTE	not used		not used	not used		configuration of GPIO18
GPIO22	Enumeration of BYTE	Output		Output	not used		configuration of GPIO22
GPIO23	Enumeration of BYTE	not used		not used	not used		configuration of GPIO23
GPIO24	Enumeration of BYTE	Input		Input	not used		configuration of GPIO24
GPIO25	Enumeration of BYTE	not used		not used	not used		configuration of GPIO25

Introducing Pin Control Attack: A Memory Illusion

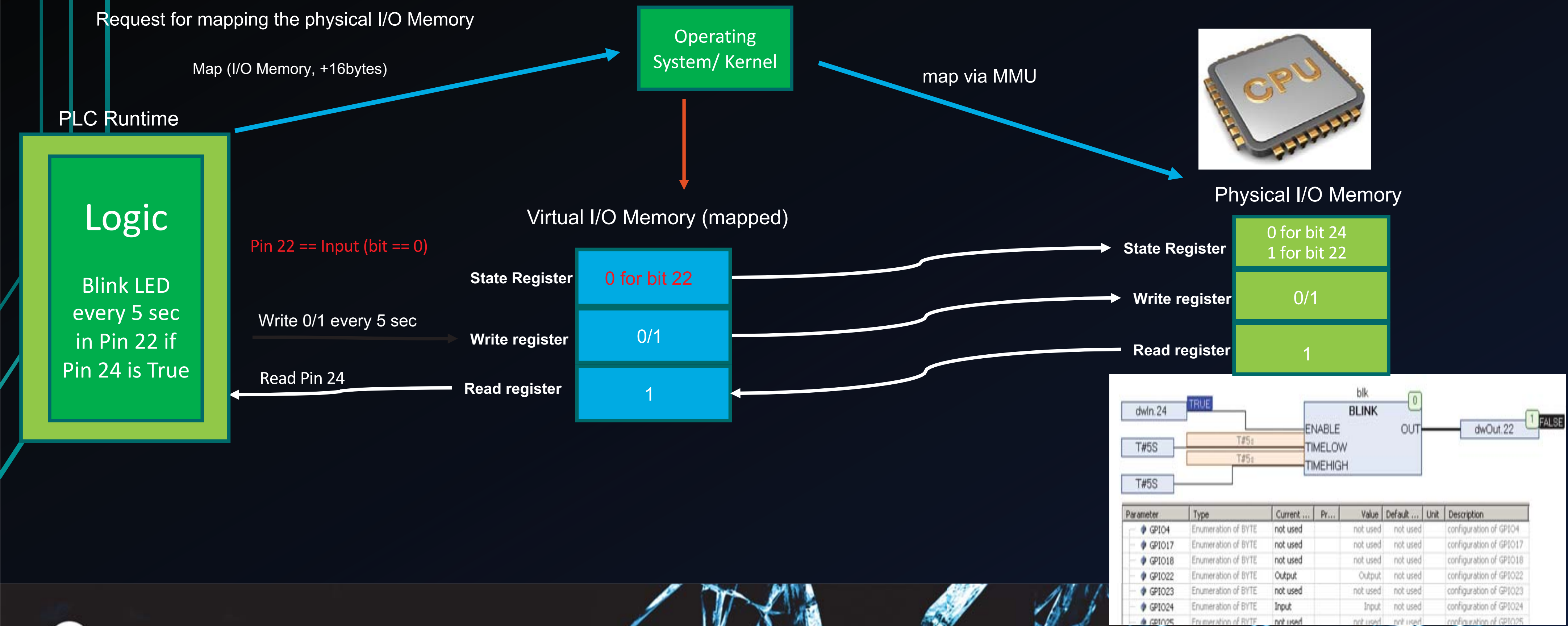


Parameter	Type	Current ...	Pr...	Value	Default ...	Unit	Description
GPIO4	Enumeration of BYTE	not used		not used	not used		configuration of GPIO4
GPIO17	Enumeration of BYTE	not used		not used	not used		configuration of GPIO17
GPIO18	Enumeration of BYTE	not used		not used	not used		configuration of GPIO18
GPIO22	Enumeration of BYTE	Output		Output	not used		configuration of GPIO22
GPIO23	Enumeration of BYTE	not used		not used	not used		configuration of GPIO23
GPIO24	Enumeration of BYTE	Input		Input	not used		configuration of GPIO24
GPIO25	Enumeration of BYTE	not used		not used	not used		configuration of GPIO25

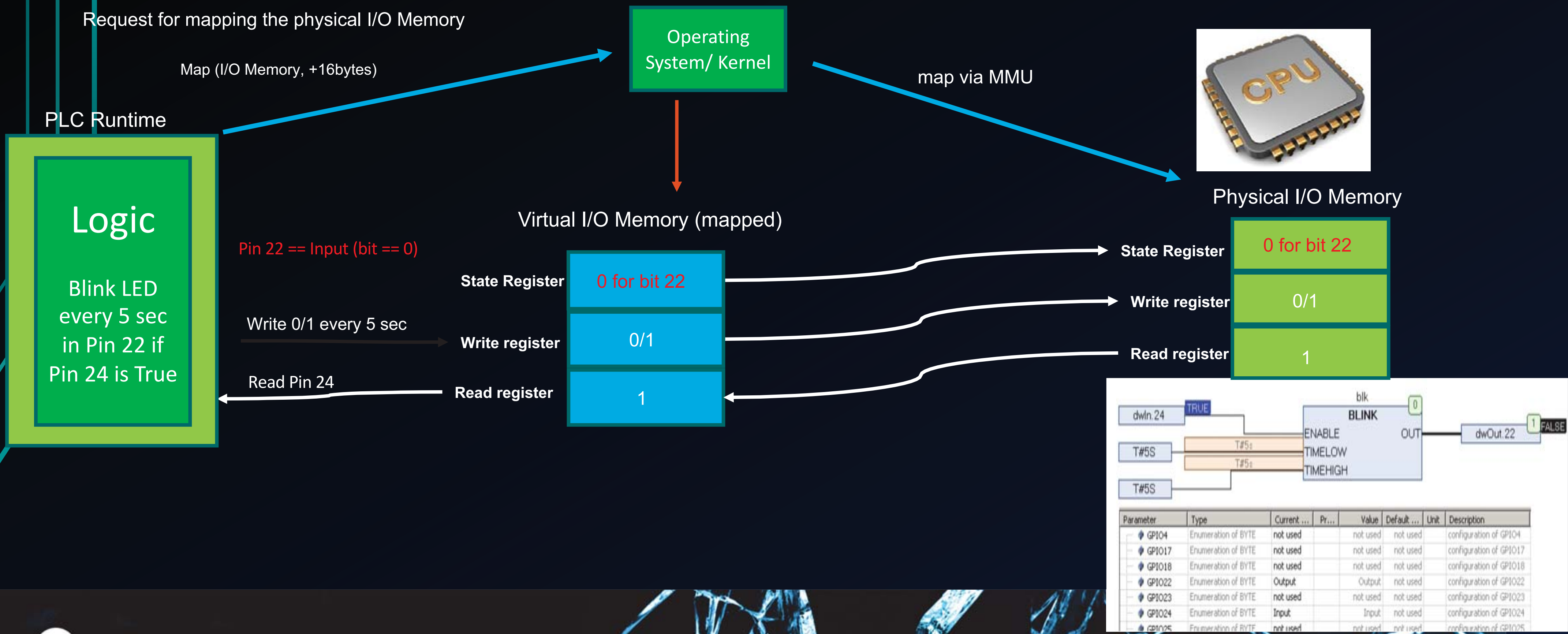
Introducing Pin Control Attack: A Memory Illusion



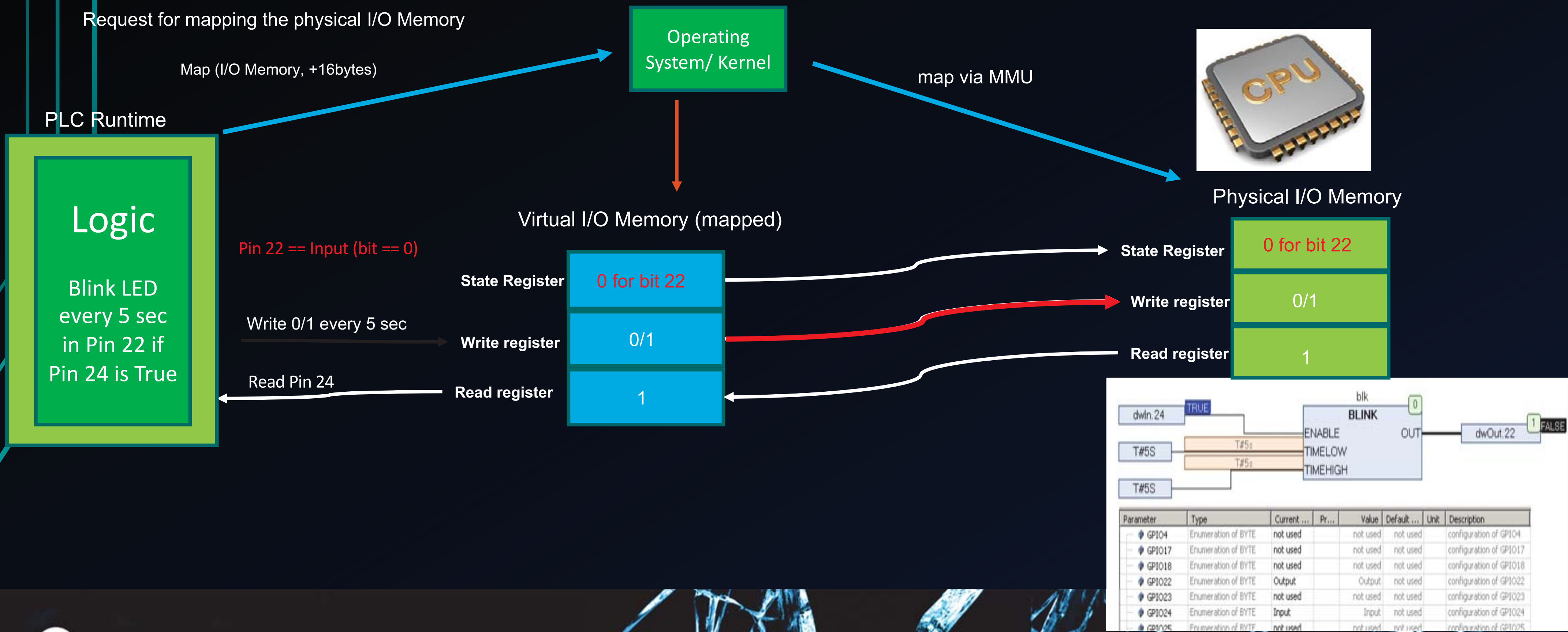
Introducing Pin Control Attack: A Memory Illusion



Introducing Pin Control Attack: A Memory Illusion



Introducing Pin Control Attack: A Memory Illusion



Parameter	Type	Current ...	Pr...	Value	Default ...	Unit	Description
GPIO4	Enumeration of BYTE	not used		not used	not used		configuration of GPIO4
GPIO17	Enumeration of BYTE	not used		not used	not used		configuration of GPIO17
GPIO18	Enumeration of BYTE	not used		not used	not used		configuration of GPIO18
GPIO22	Enumeration of BYTE	Output		Output	not used		configuration of GPIO22
GPIO23	Enumeration of BYTE	not used		not used	not used		configuration of GPIO23
GPIO24	Enumeration of BYTE	Input		Input	not used		configuration of GPIO24
GPIO25	Enumeration of BYTE	not used		not used	not used		configuration of GPIO25

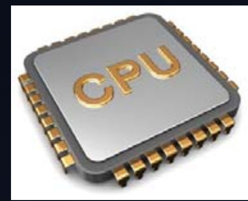
Introducing Pin Control Attack: A Memory Illusion

Request for mapping the physical I/O Memory

Map (I/O Memory, +16bytes)

Operating System/ Kernel

map via MMU



PLC Runtime

Logic

Blink LED every 5 sec in Pin 22 if Pin 24 is True

Physical I/O Memory

Virtual I/O Memory (mapped)

Pin 22 == Input (bit == 0)

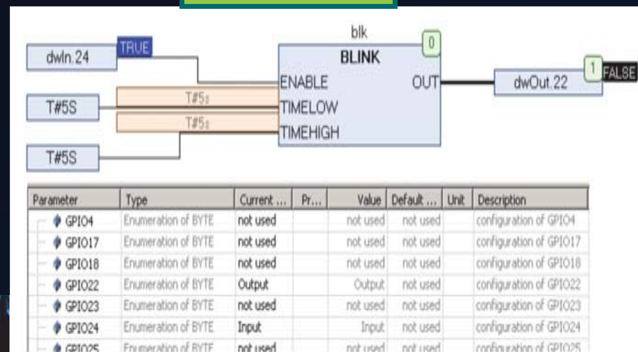
Write 0/1 every 5 sec

Read Pin 24

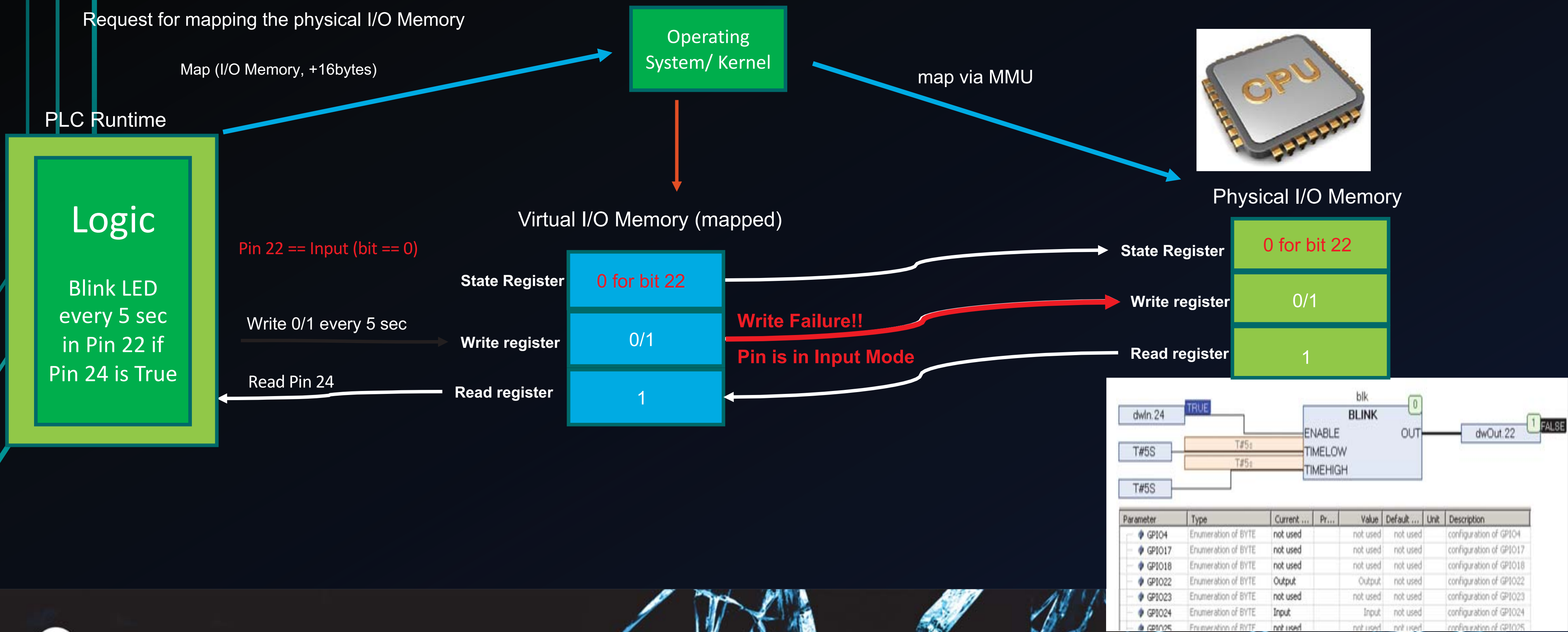
State Register	0 for bit 22
Write register	0/1
Read register	1

Physical I/O Memory:

State Register	0 for bit 22
Write register	0/1
Read register	1



Introducing Pin Control Attack: A Memory Illusion



Parameter	Type	Current ...	Pr...	Value	Default ...	Unit	Description
GPIO4	Enumeration of BYTE	not used		not used	not used		configuration of GPIO4
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GPIO18	Enumeration of BYTE	not used		not used	not used		configuration of GPIO18
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GPIO23	Enumeration of BYTE	not used		not used	not used		configuration of GPIO23
GPIO24	Enumeration of BYTE	Input		Input	not used		configuration of GPIO24
GPIO25	Enumeration of BYTE	not used		not used	not used		configuration of GPIO25

Problem statement

- What if we create an attack using pin control that:
  - Do not do function hooking
  - Do not modify executable contents of the PLC runtime.
  - Do not change the logic file
- Obviously we consider other defenses available (e.g. logic checksum is also there)

Pin Control Attack

- Pin Control Attack:
  - manipulate the I/O configuration (Pin Configuration Attack)
  - manipulate the I/O multiplexing (Pin Multiplexing Attack)
- PLC OS never knows about it.

Two variants of the work and bypassing the protections

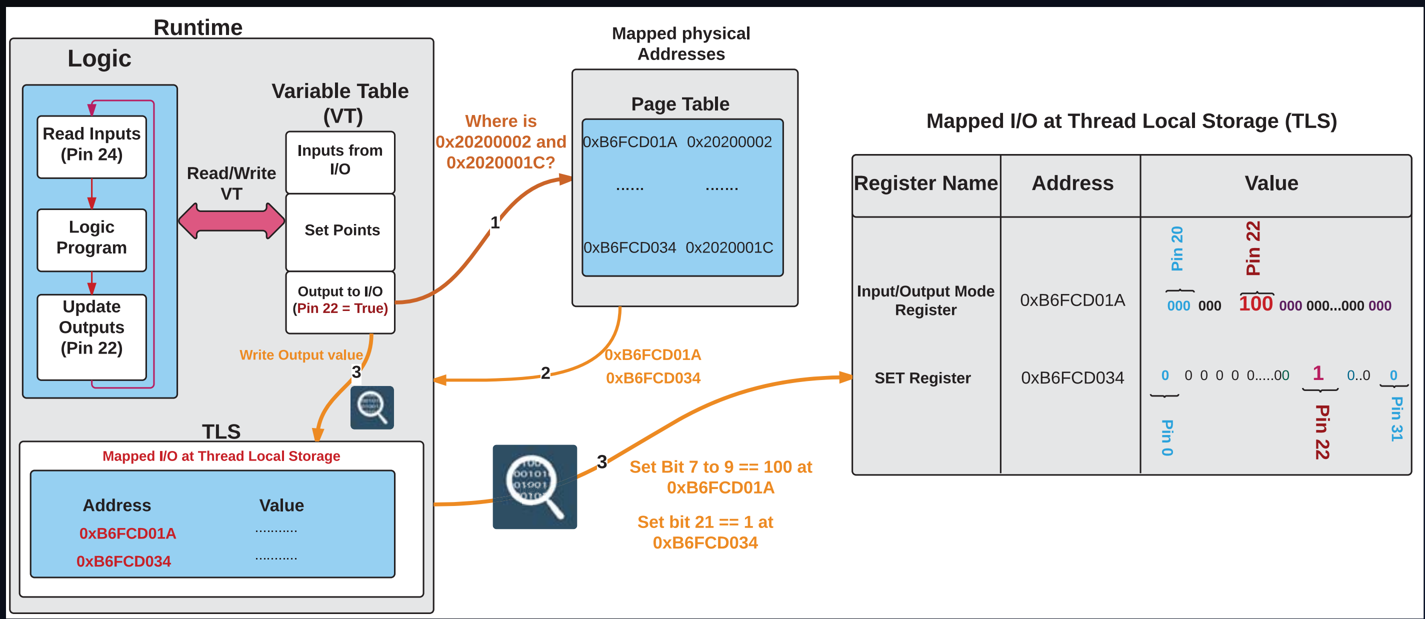
- 1. a rootkit which manipulates the Pin Configuration.
- 2. a malicious C code which can do the same.

What do we need for a Pin Control Attack

- First variant (rootkit)
  - Root privilege
  - Knowledge of SoC registers
  - Knowledge of mapping between I/O pins and the logic
- Second variant:
  - Equal privilege as PLC runtime
  - Knowledge of mapping between I/O pins and the logic

How actually a PLC Controls its I/O (very basic)

- PLC Prepares I/O for the logic:
  - Map physical I/O base addresses
  - Enable Input/Output Mode of the register and use it (write or read it)



First variant (rootkit), precise I/O manipulation

- Exploiting the I/O configuration.
- Utilizing Processor Debug Registers.

Debug Registers

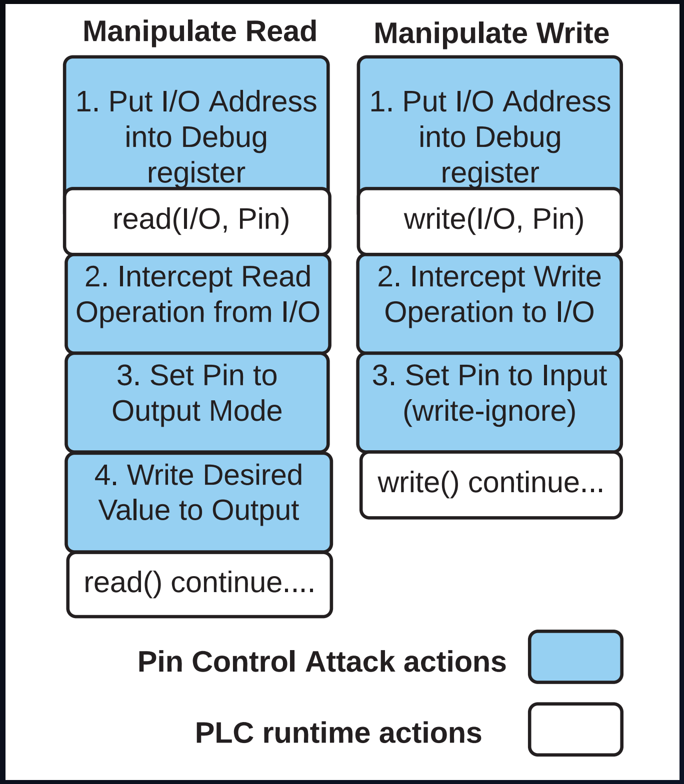
- Designed for debugging purpose.
- Function hooking intercept the function call and manipulate the function argument.
- We use debug registers in ARM processors to intercept memory access (No function interception, no function argument manipulation)

```
                         ==Phrack Inc.==

           Volume 0x0c, Issue 0x41, Phile #0x08 of 0x0f

|=---------------------=[ Mistifying the debugger, ]=--------------------=|
|=---------------------=[    ultimate stealthness  ]=--------------------=|
|=-----------------------------------------------------------------------=|
|=-----------------------=[ halfdead@phear.org ]=------------------------=|

--[ Introduction

Over the years, there have been a plethora of techniques and methods of
```

Devil is in detail…

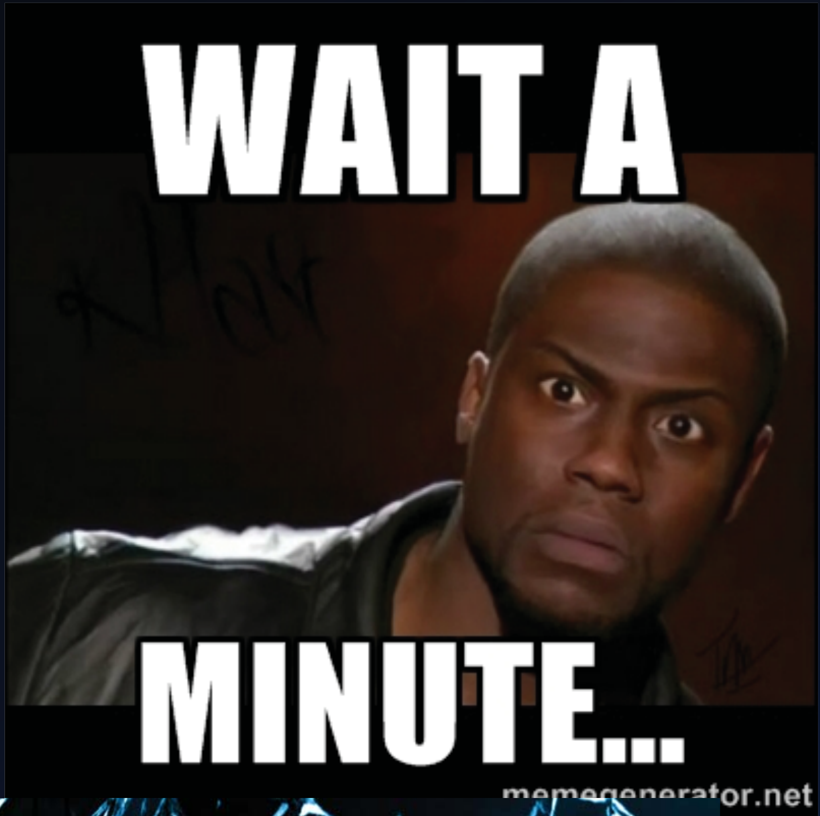
- Combination of Pin configuration registers and ARM Processor Debug register
  - Put the mapped I/O address to the debug register.
  - Manipulate the Pin Configuration or multiplexing upon I/O memory access.

How Pin Configuration Attack Works?



Wait a minute!

- Shouldn't the PLC runtime fail or get terminated because of I/O failure?
  - Nope!
  - Remember no interrupt therefore, everything looks fine to the PLC runtime!

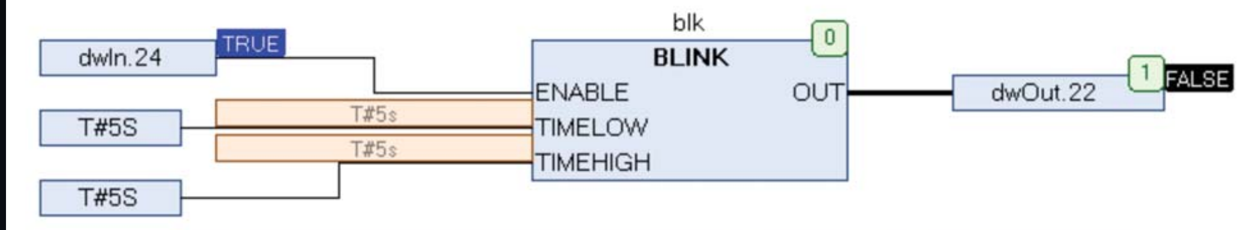


Implementation of the attack

- Before implementation we have to know how the PLC runtime interact with the I/O in physical world!.
- We need to know more about I/O registers
- We actually need to write the driver for target I/O in our PLC.

Simple Logic

Lets test it with a simple Function Block Language Logic.



Parameter	Type	Current ...	Pr...	Value	Default ...	Unit	Description
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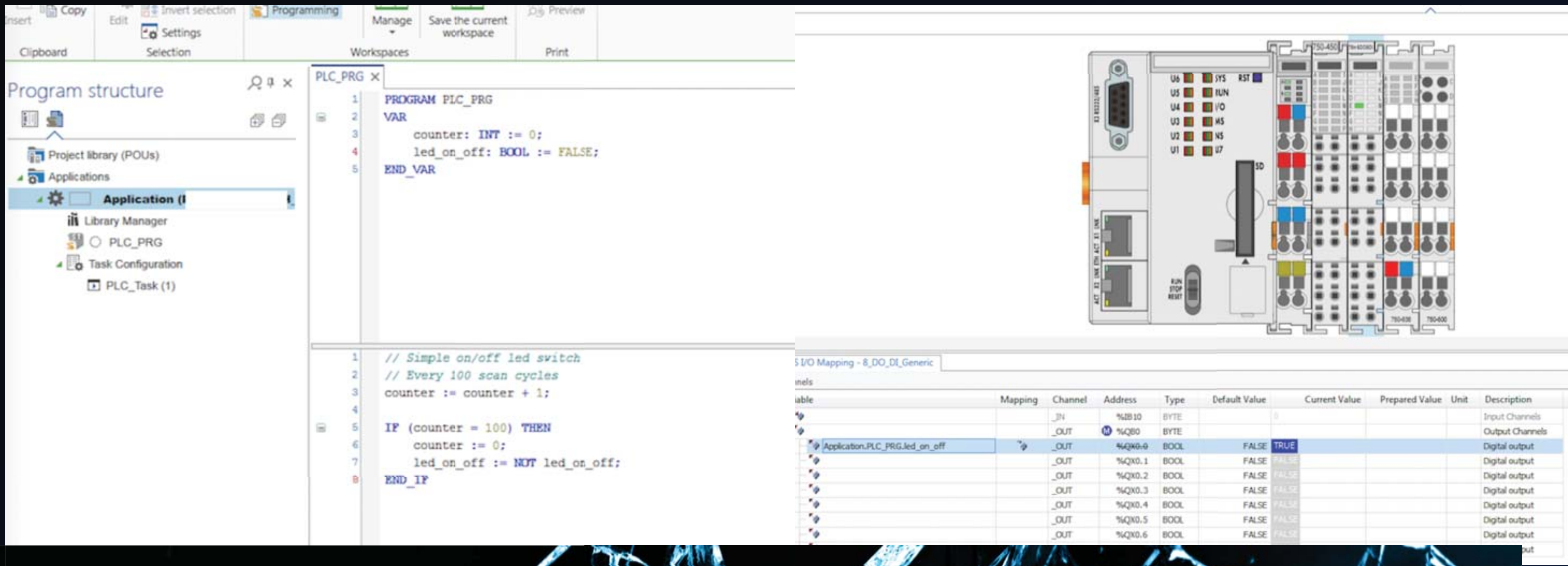
GPIO24	Enumeration of BYTE	Input		Input	not used		configuration of GPIO24
GPIO25	Enumeration of BYTE	not used		not used	not used		configuration of GPIO25

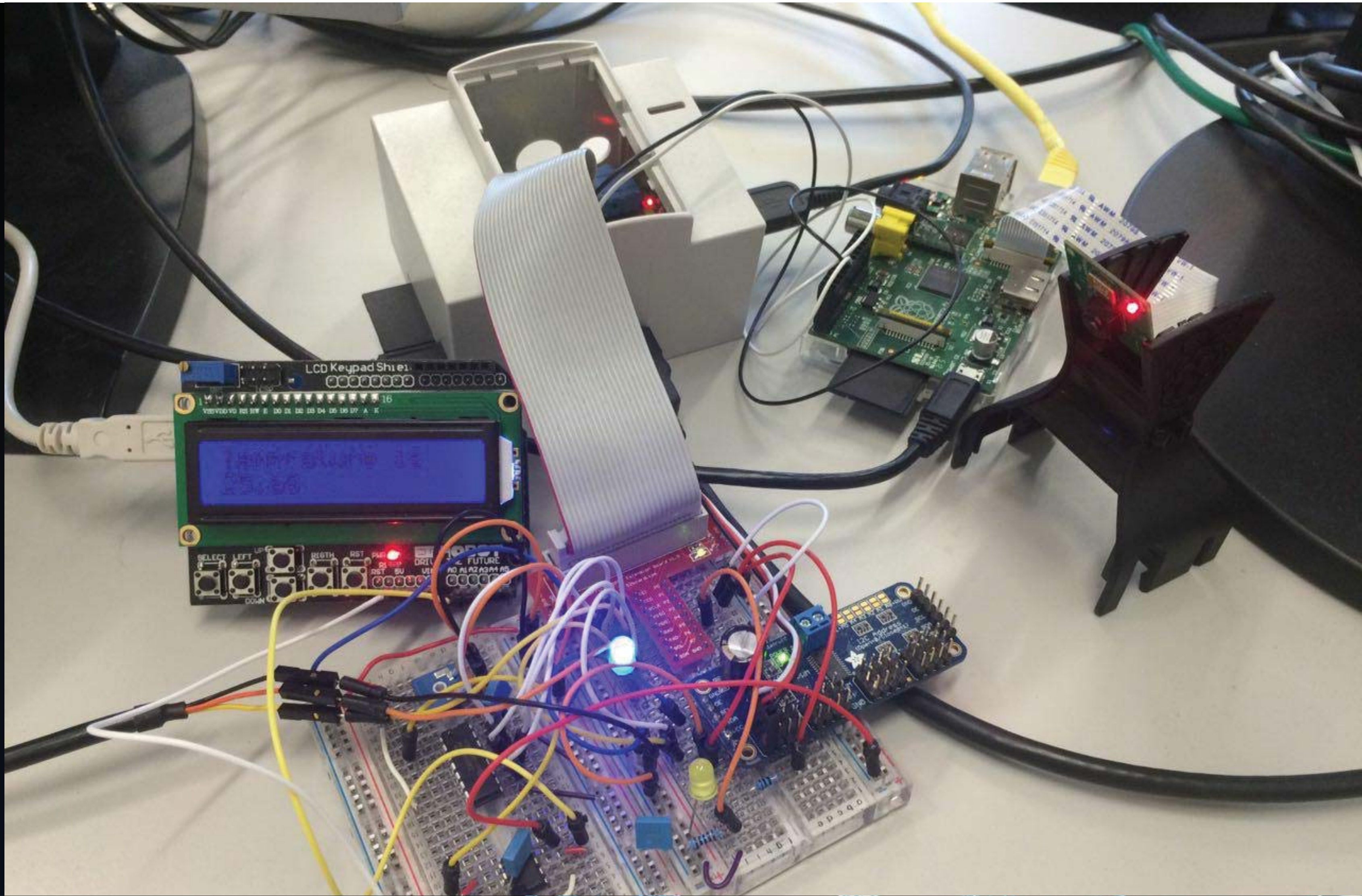
input : State of $In.24$
output: State of $Out.22$

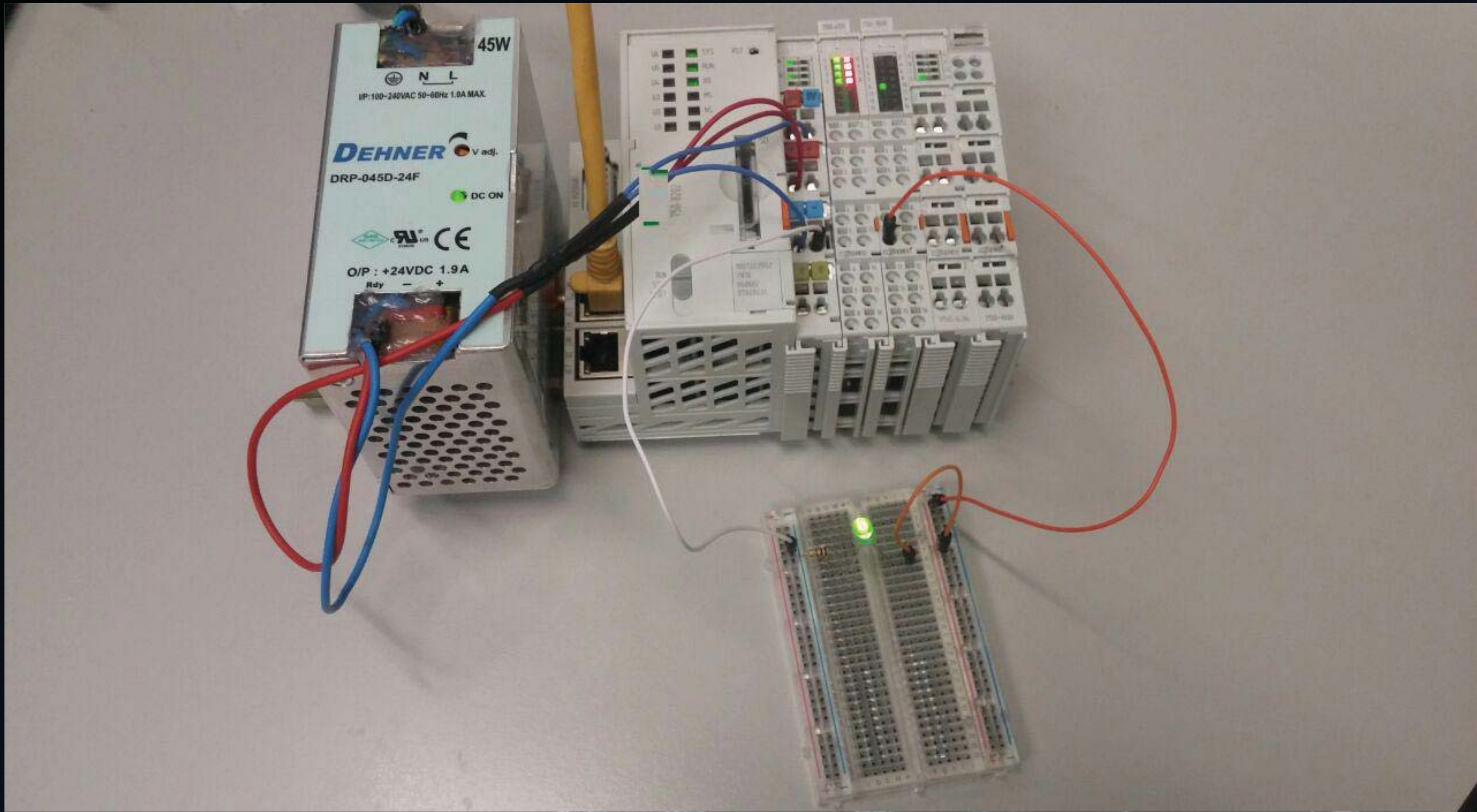
Main Logic;
while *True* **do**
    read input;
    while *input True* **do**
        switch_state(output, five seconds);
        //states are High or Low.
    end
    if *input False* **then**
        hold the state of the output;
    else
        go to first while;
    end
end

Simple Logic 2

- Second Logic for a real PLC






45W
N L
I/P: 100~240VAC 50~60Hz 1.0A MAX.
DEHNER
V adj.
DRP-045D-24F
DC ON
O/P : +24VDC 1.9A
Rdy – +

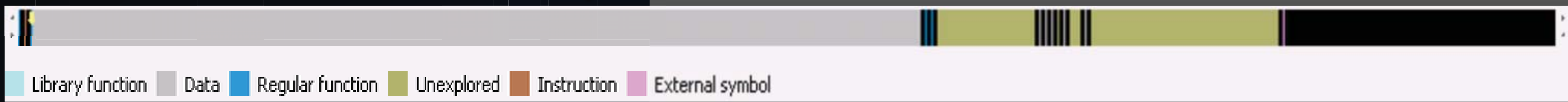
Lets look at it.

Demo

Digital

Codesys Dynamic and Static Analysis

- I/O Mapping
- Look for Base Addresses of I/O



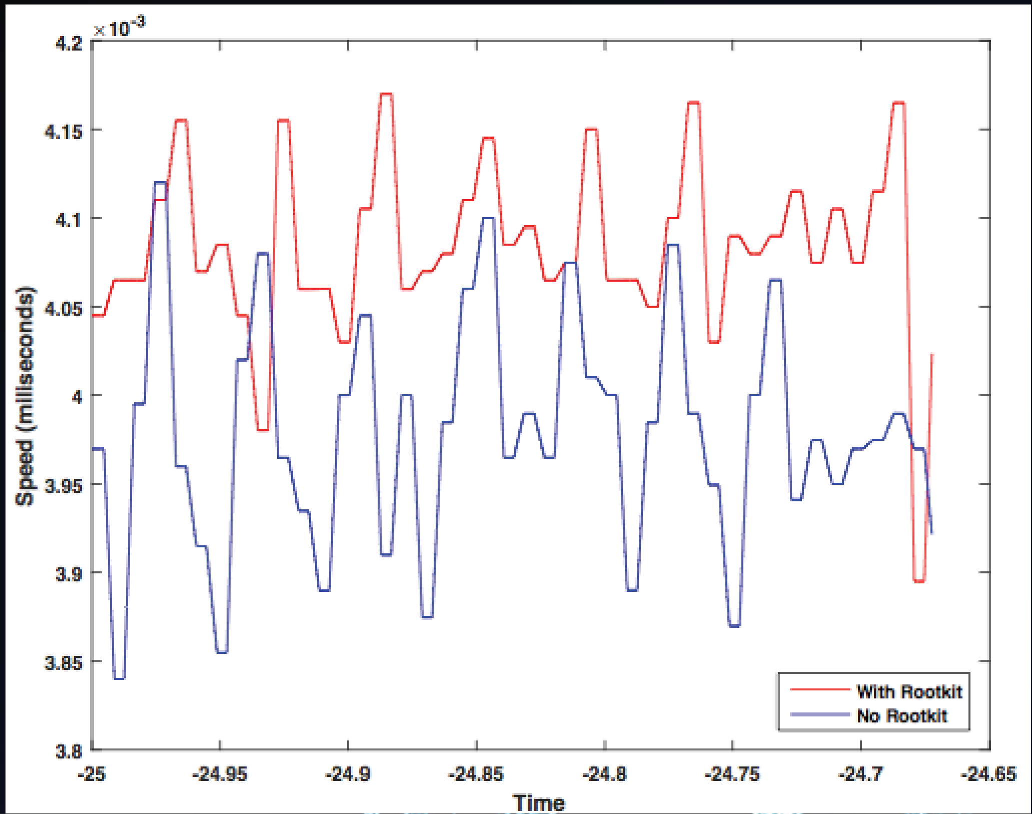

```
DCD 0x72322A06, 0x8003FB5D, 0xD182CBBC, 0x575B9332, 0x836A03F9
DCD 0xD1F2679A, 0xD1B89713, 0xD9BAA704, 0xB6C6F738, 0x3FA85B8C
DCD 0xB78538F5, 0x3D4C2D10, 0x282FF5B0, 0x2B081994, 0x1848E56D
DCD 0xAA8C7B82, 0xDE23AF80, 0xE6144FFD, 0xFE82BA1B, 0x18604BA9
DCD 0x223D3D45, 0x1A00B106, 0x825AC9E5, 0xF425FFE6, 0xB19B375B
DCD 0xEF878EA7, 0x172C1C83, 0x40E54D04, 0x588CDBC8, 0x1B19AC0F
DCD 0x7ED50852, 0xE0C950C8, 0x9C67C354, 0x3DA8F807, 0x421FBB11
DCD 0x2C816A17, 0xFB3E4375, 0x60DB663, 0xF15C6122, 0x64514032
DCD 0xDA75AF94, 0x9929D1B3, 0x3D910885, 0x8984059F, 0x4F66A58
DCD 0x97F2C7D9, 0x4808685D, 0xB24602AE, 0x75828FCA, 0x734C7E16
DCD 0xD39E5C65, 0x4BF3B903, 0x952C30A7, 0x2F92553B, 0xD2FBF6E7
DCD 0xD2AD2C07, 0x47B449B9, 0x46CF816A, 0x5B1A9B0D, 0x9B61780
DCD 0xE7864462, 0xA5DA033E, 0x4B3A8C38, 0xA57A4FD0, 0x235575B9
```

```
[b6e47f54] open("/etc/3S.dat", O_RDONLY) = 8 <0.001979>
[b6df334c] close(8) = 0 <0.001878>
[b6e47f54] open("/proc/cpuinfo", O_RDONLY) = 8 <0.001354>
[b6df334c] close(8) = 0 <0.007677>
[b6f2c7e4] open("/dev/mem", O_RDWR) = 8 <0.001182>
[b6e53998] mmap2(NULL, 4096, PROT_READ|PROT_WRITE, MAP_SHARED, 8, 0x2020)
[b6f2bd04] close(8) = 0 <0.001246>
[b6f2c7e4] open("/dev/i2c-1", O_RDWR) = 8 <0.00134
[b6f2c7e4] open("/dev/spidev0.0", O_RDWR) = 9 <0.001886>
```

I/O Attack: Rootkit

- Rootkit needs root user to install its code as a Loadable Kernel Module (LKM).
- vmalloc() allocates our LKM. It bypasses Doppelganger.
- Do not do any kind of function hooking, bypasses Autoscopy Jr.
- Can change the logic regardless of logic operation.

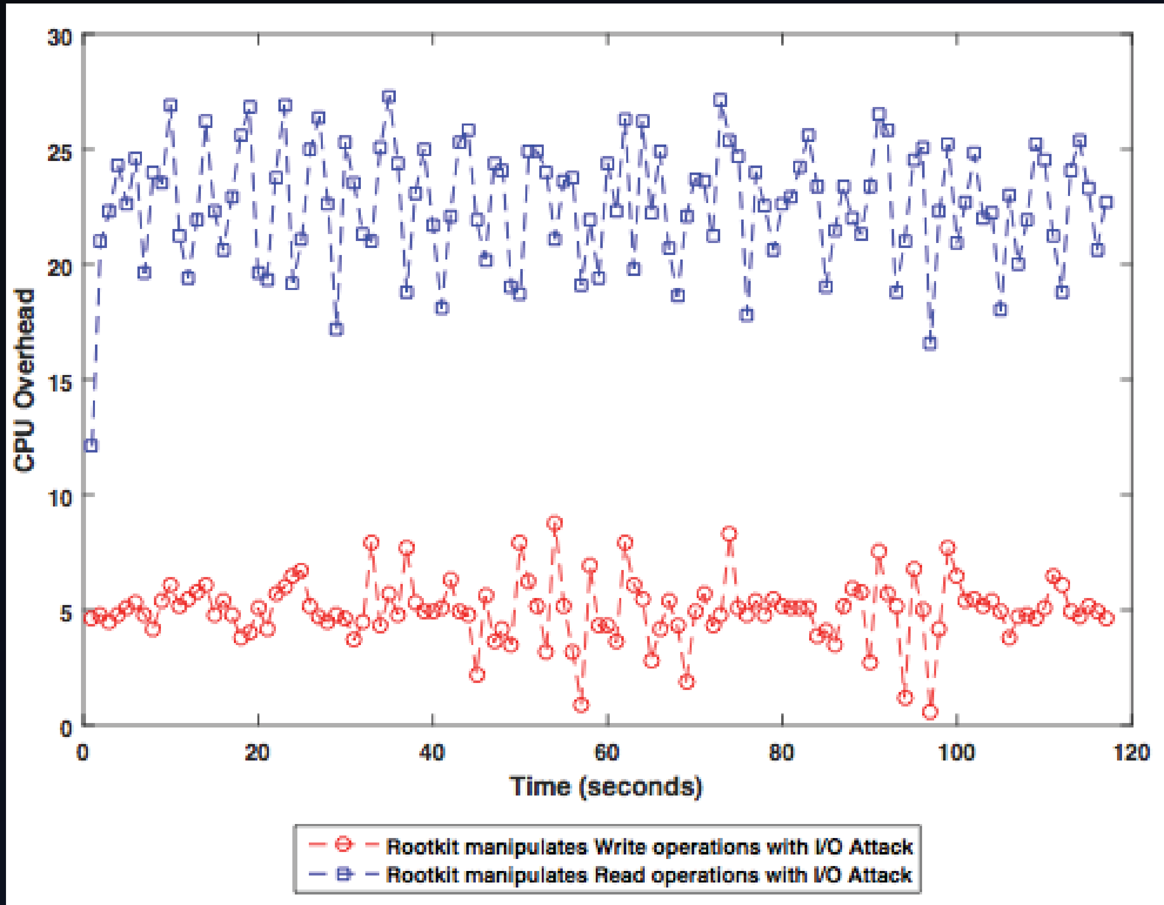
I/O Performance of rootkit variant



CPU Overhead

Write Manipulation: ~ 5%

Read Manipulation: ~ 23%



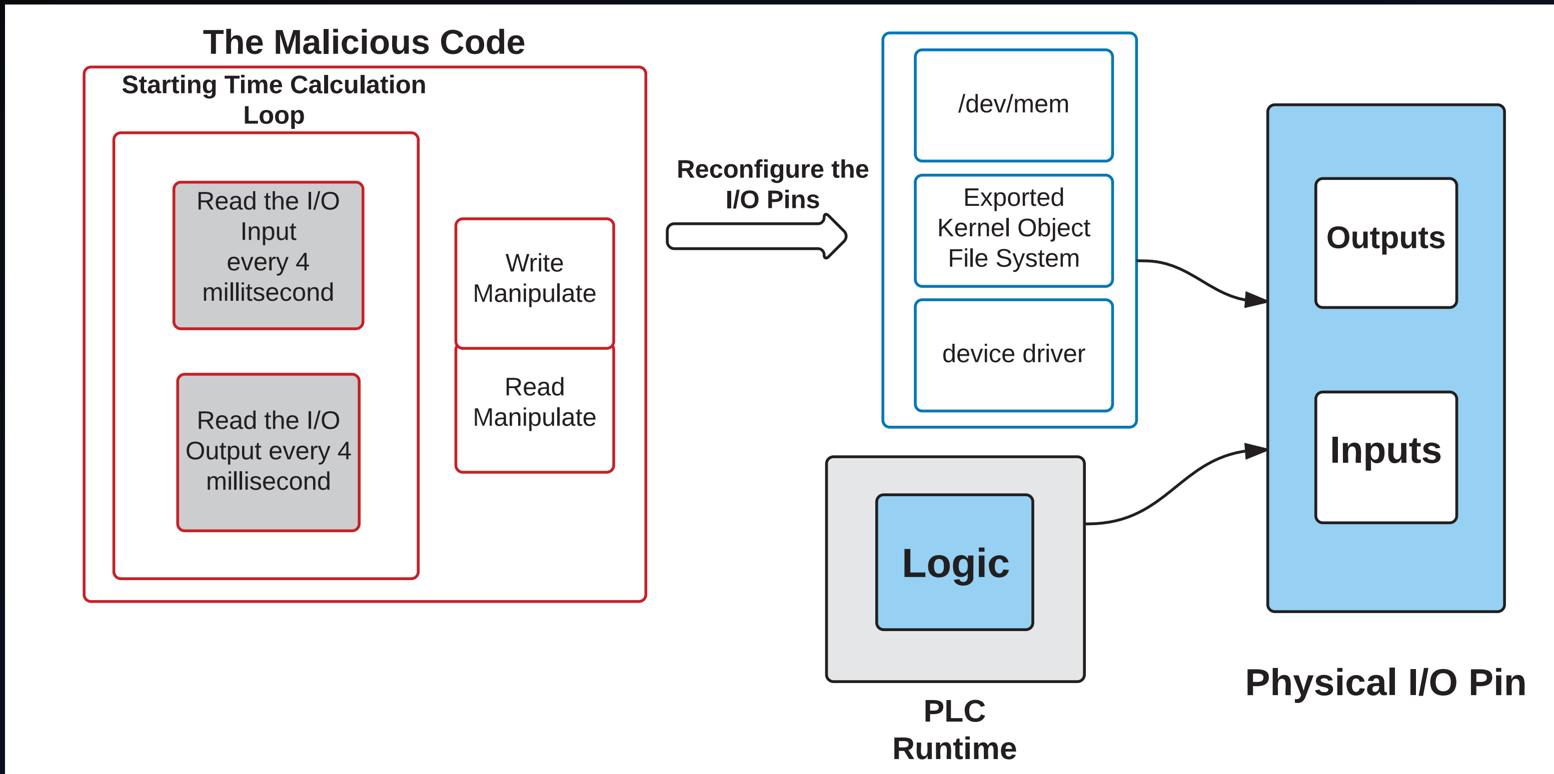
Real-Time Features

- Priority Inheritance Mutex support
  - no priority inversion problem in the rootkit!
- Implementation without using any Kernel API with generic spin-locks.
- Using IRQF_NODELAY for ARM debug registers.
- Works in Linux RT, QNX, Lynx, VxWorks (with MMU) RTOSes.

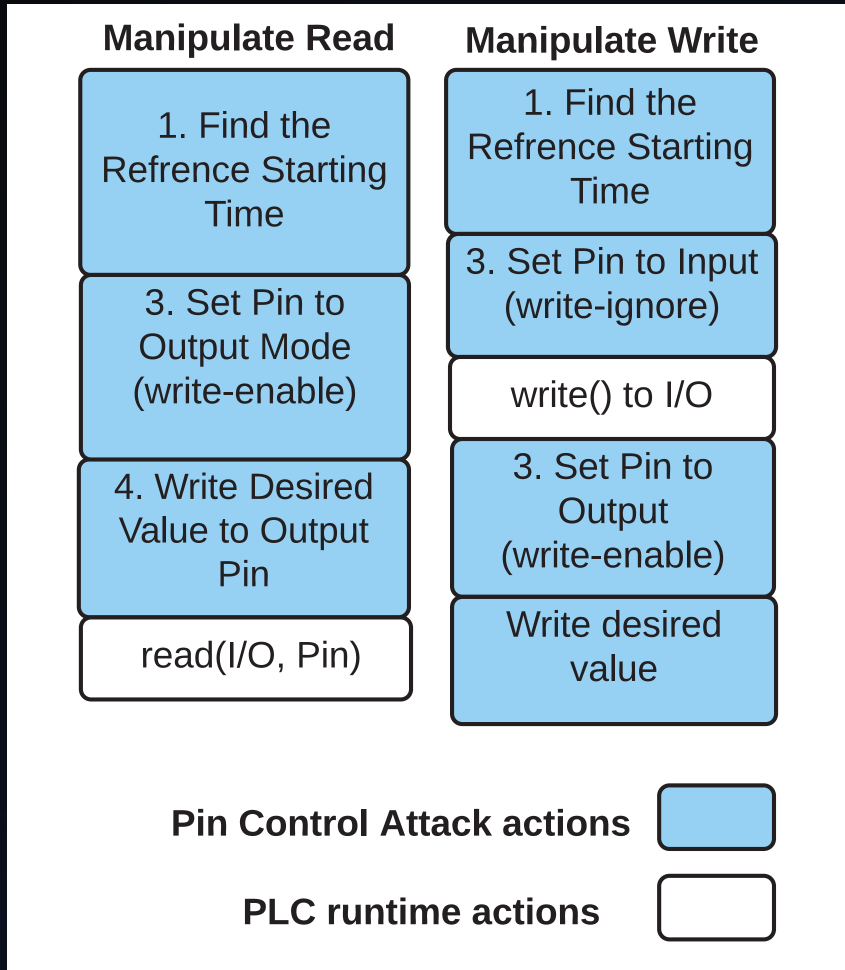
Second Variant of the Attack – No Rootkit ! No Root!

- No need to have rootkit!
- We can do the same with the PLC runtime privilege.
- Overhead below 1%.
- We can either remap the I/O or use already mapped I/O address.

Second variant



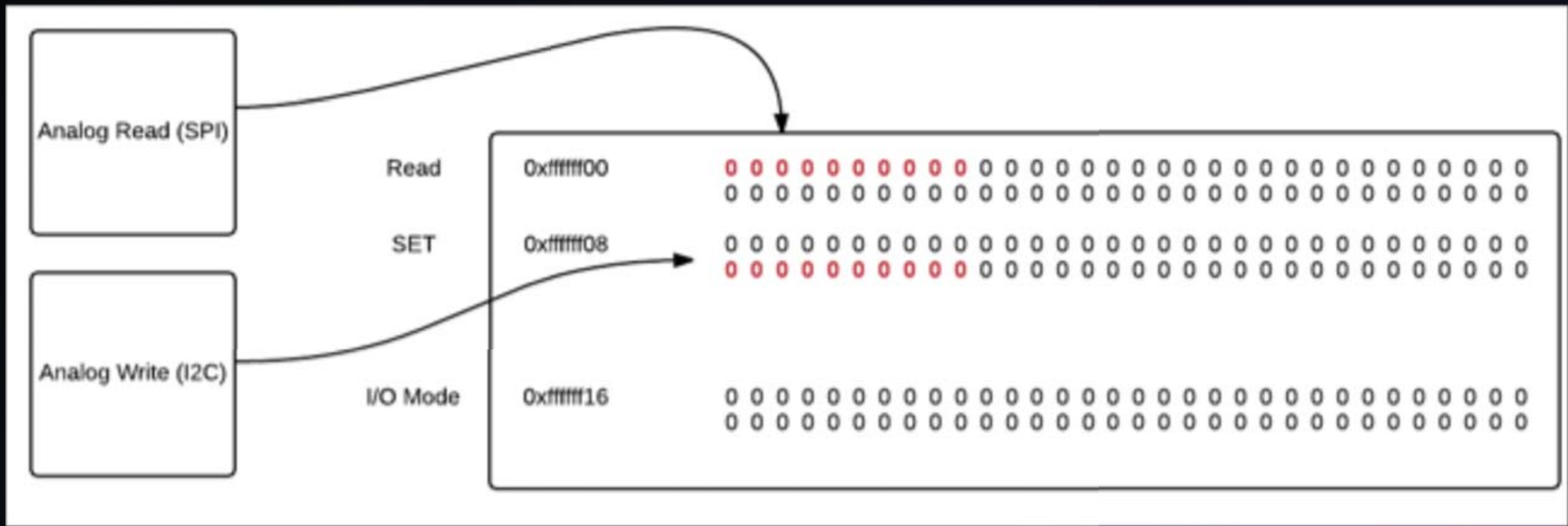
Second Variant



What about Analog Control?

- Analog signals are basically aggregation of digital signals.
- Two ways to do it:
  - 1. If part of or entire analog memory can get multiplexed to digital pins attacker can multiplex the pin and write digital bits and basically control the values in the analog memory
  - 2. Using the technique which we can PC+1, we tell the interrupt handler to return the control to the next instruction within the PLC runtime, basically avoiding write operation occur

Analog I/O Manipulation



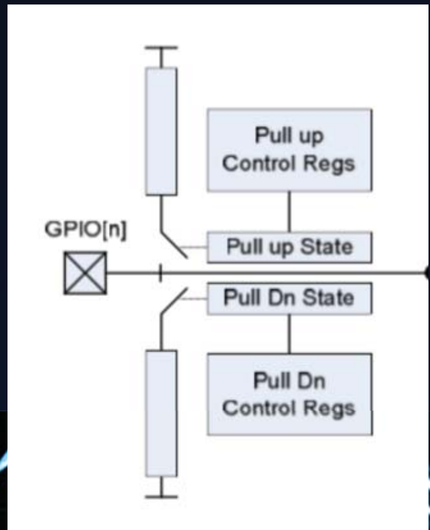
Lets look at it.

Demo

Analog

Other Future Possibilities!

- Attacking pull-up and pull-down resistors in I/O interfaces
- What if we disable them?
- Remotely manipulate the I/O via a powerful electromagnetic field!



Discussions

- For now attacker can:
  - Simply change the logic
  - Modify PLC Runtime executable
- Fixing these attacks are trivial:
  - Proper Authentication
  - Proper Logic Checksum
  - PLC Runtime integrity verification
- Next Step for attackers:
  - Achieve its goal without actually modifying the Logic or Runtime or hooking functions

Conclusions

- Need to focus on system level security of control devices In future more sophisticated techniques come that evade defenses.
  - Pin Control attack is an example of such attacks.
- Pin Control Attack:
  - lack of interrupt for I/O configuration registers
  - Significant consequences on protected PLCs and other control devices such as IEDs.
- Solution:
  - It is hard to handle I/O interrupts with existing real-time constraints.
  - Monitoring I/O Configuration Pins for anomalies.
  - User/Kernel space separation for I/O memory.

Questions?

Everything that has a beginning has an end.

The Matrix Revolutions.

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