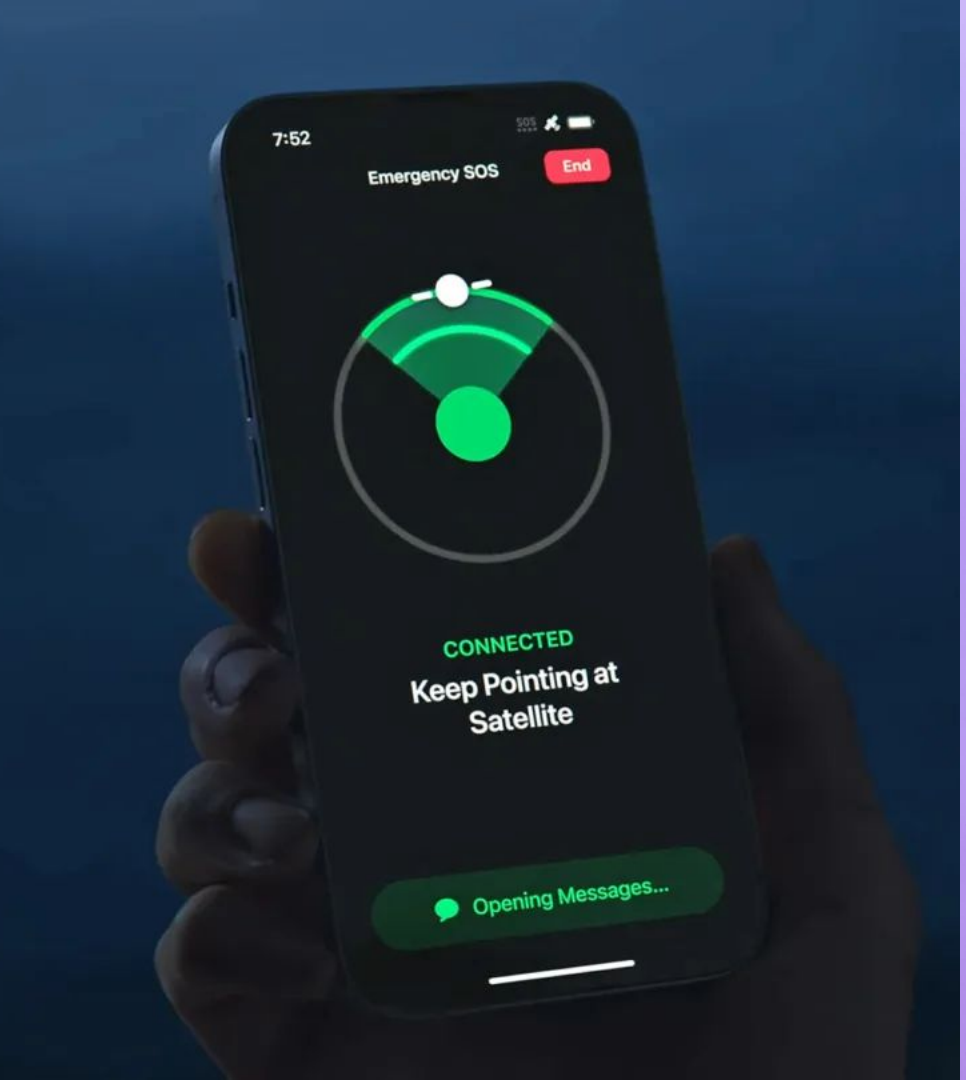
Securing the Next Generation of Cyber-Physical Systems

Efrén López-Morales
PhD Candidate at Texas A&M University-Corpus Christi


7:52
Emergency SOS
End
CONNECTED
Keep Pointing at Satellite
Opening Messages...


DARKREADING
NEWSLETTER SIGN-UP
Cybersecurity Topics
World
The Edge
DR Technology
Events
Resources
Improved, Stuxnet-Like PLC Malware Aims to Disrupt Critical Infrastructure
A newly developed PLC malware does not require physical access to target an ICS environment, is mostly platform neutral, and is more resilient than traditional malware aimed at critical infrastructure.

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'Crash Override': The Malware That Took Down a Power Grid

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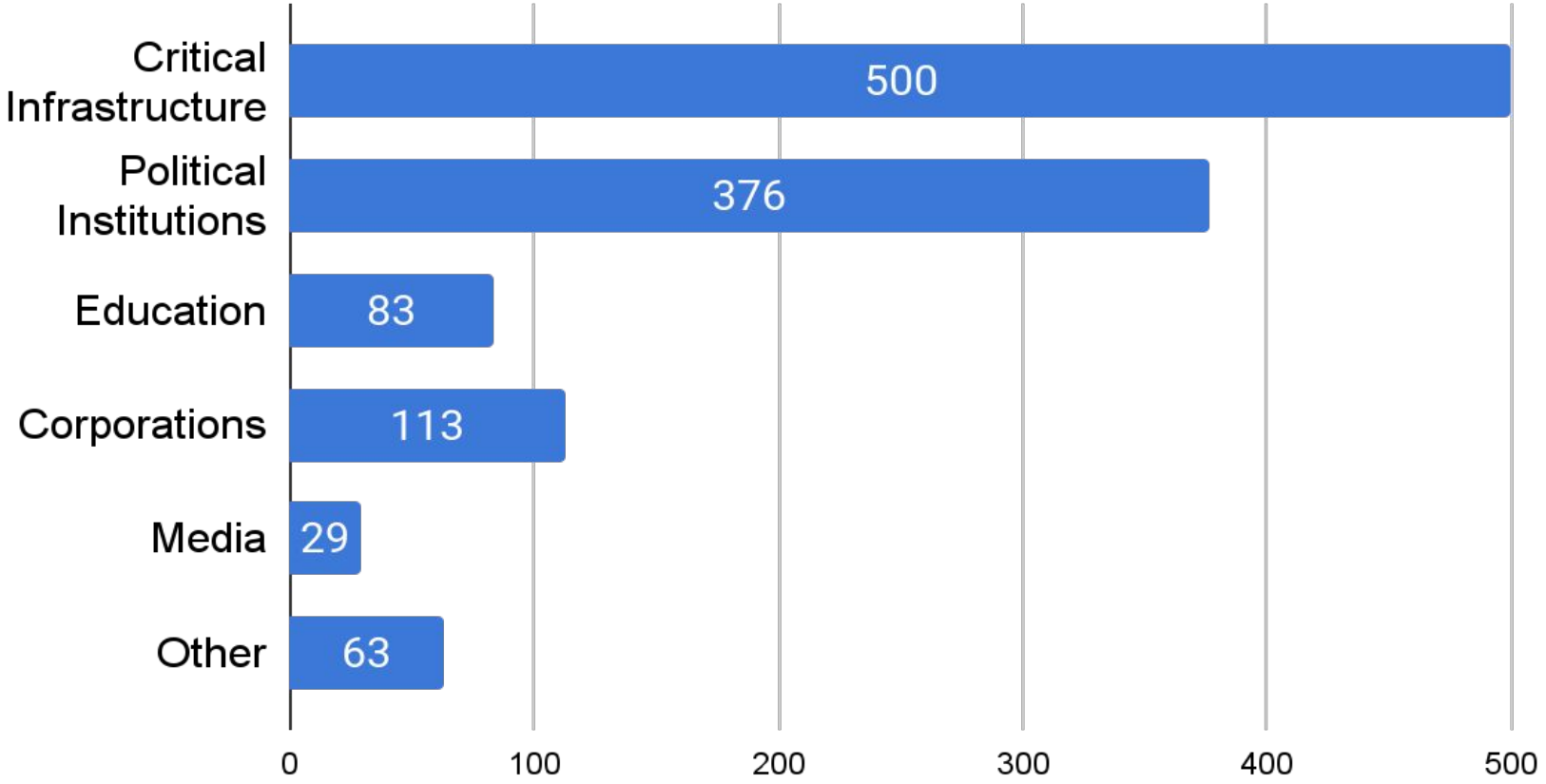
The New York Times

Cyberattack Forces a Shutdown of a Top U.S. Pipeline

The sectors most targeted by cybercrime (2023)



Source: European Repository of Cyber Incidents

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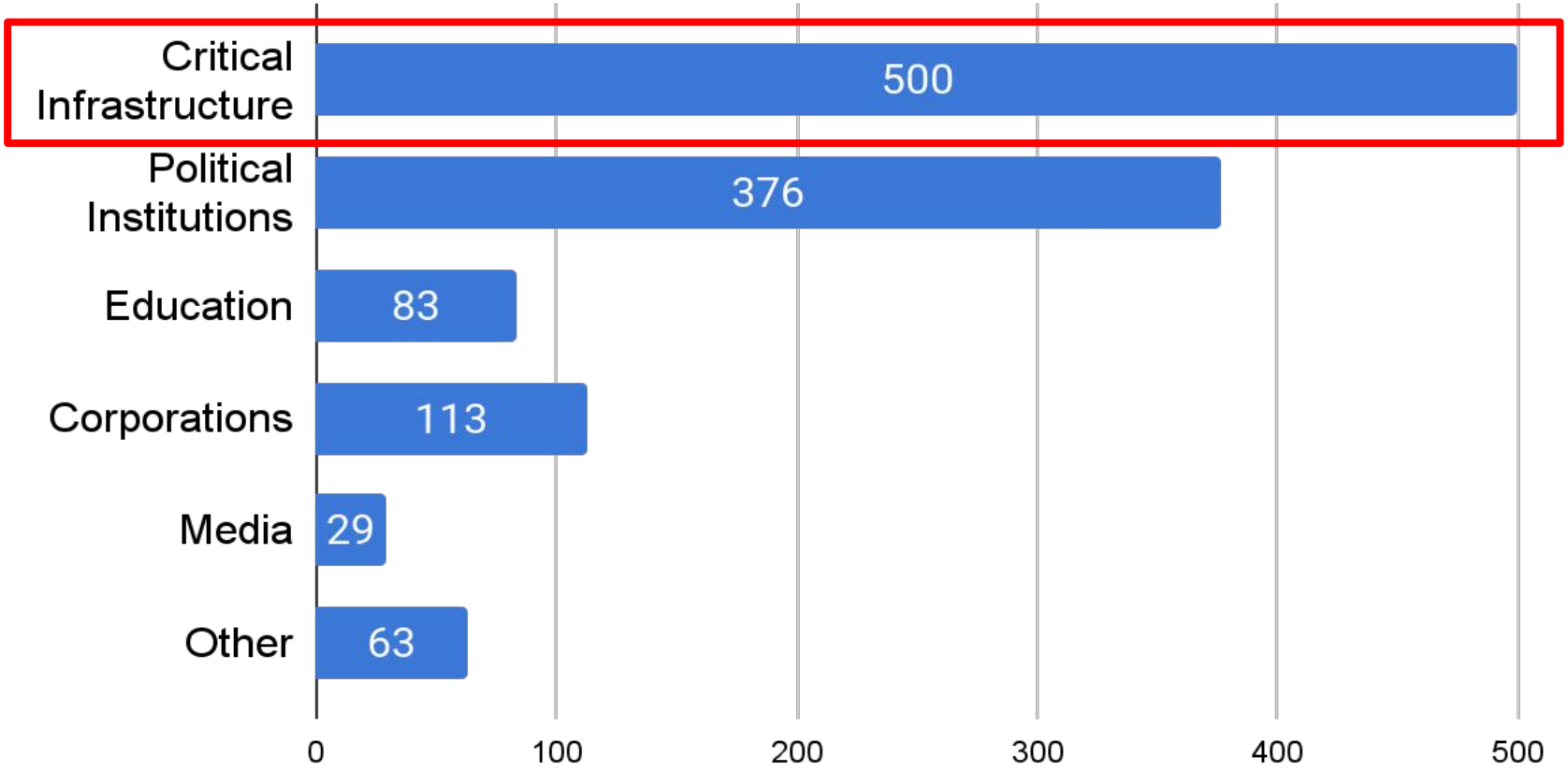

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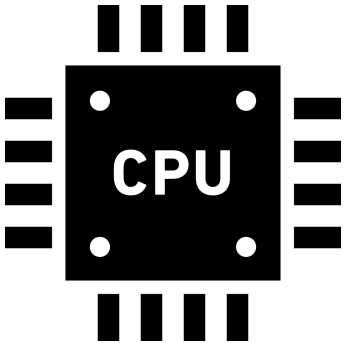
What are Cyber-Physical Systems (CPS)?



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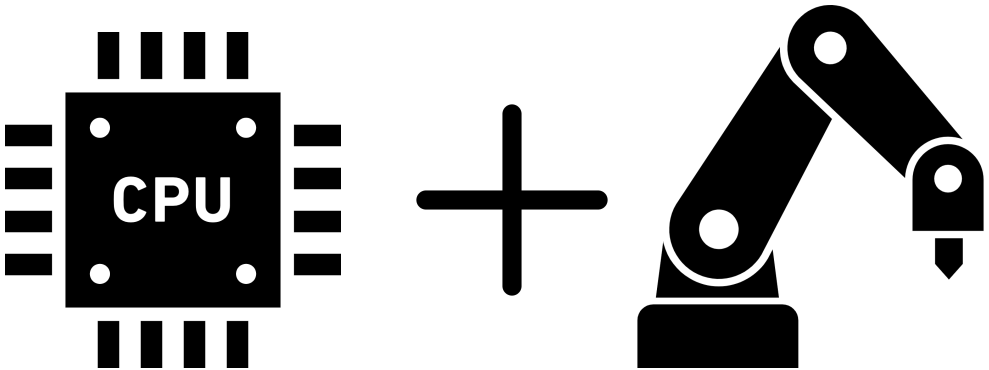

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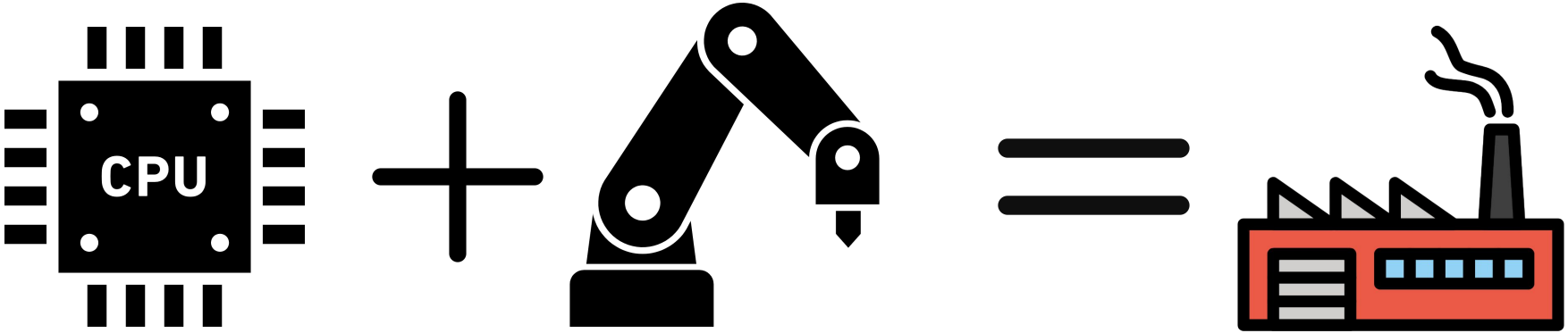

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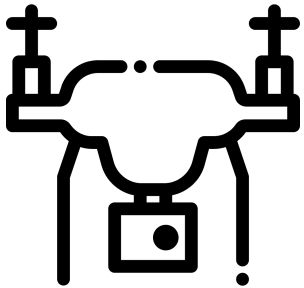

Drones

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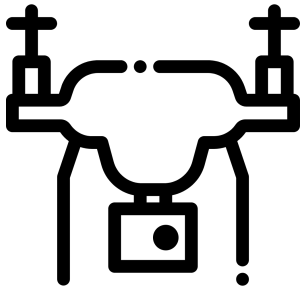

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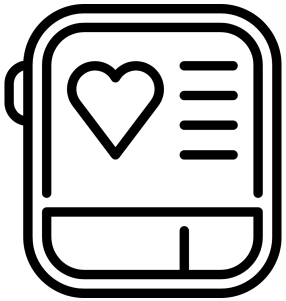

Healthcare

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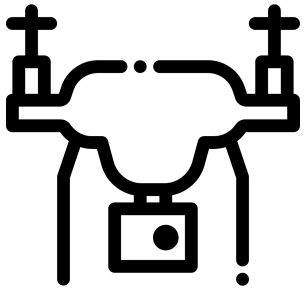

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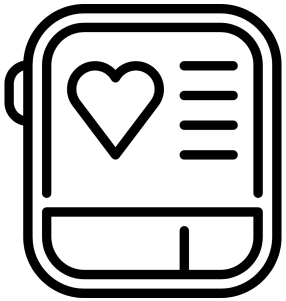

Healthcare

Industrial Control Systems

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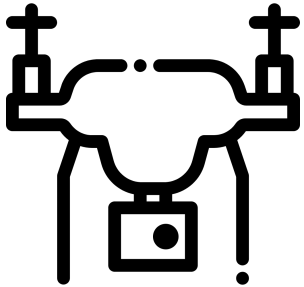

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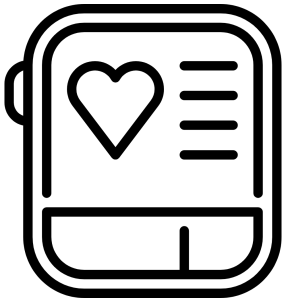

Healthcare

Industrial Control Systems

Connected Vehicles

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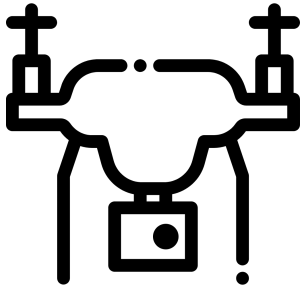

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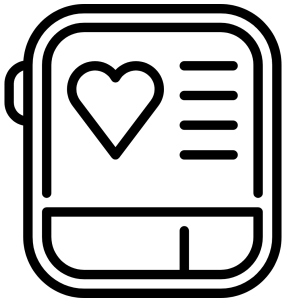

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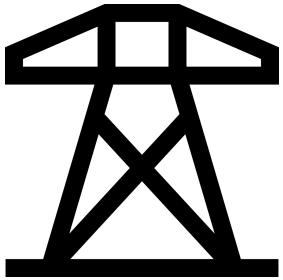

Smart Grid

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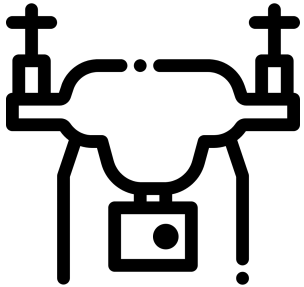

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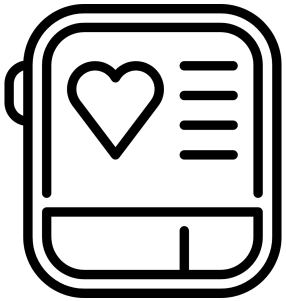

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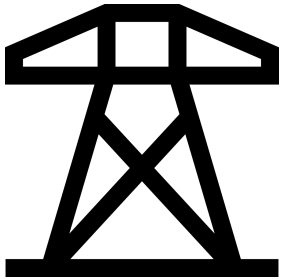

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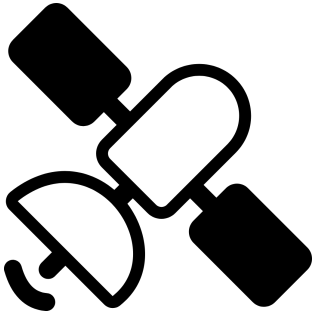

Space Systems

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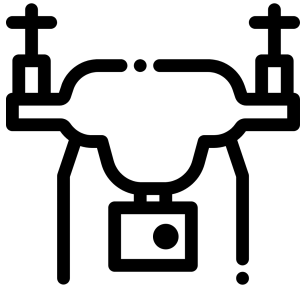

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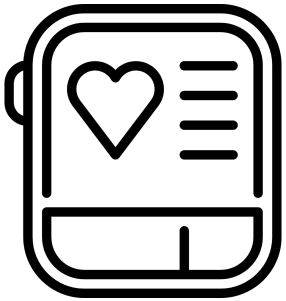

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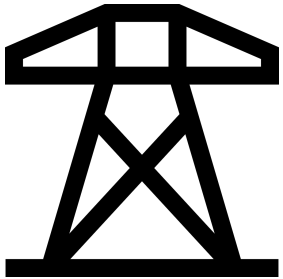

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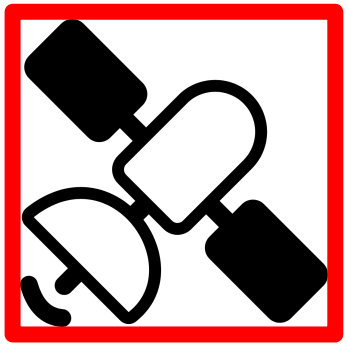

Space Systems

Legacy Cyber-Physical Systems

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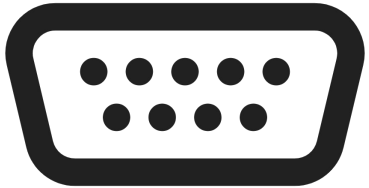
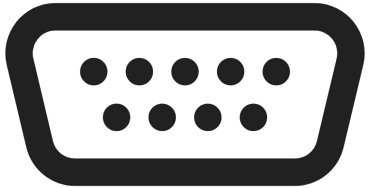


Analog Networks

Legacy Cyber-Physical Systems



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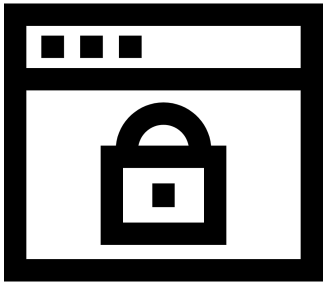
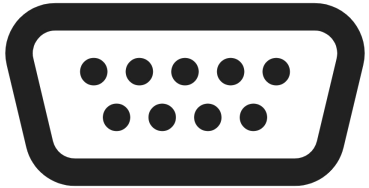


Proprietary Software

Legacy Cyber-Physical Systems



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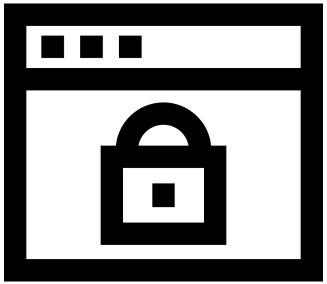
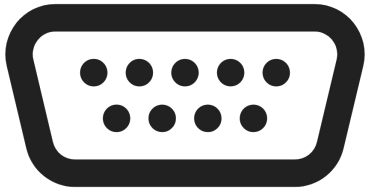


Proprietary Software

Limited Connectivity

Legacy Cyber-Physical Systems



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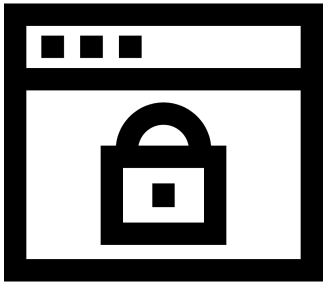

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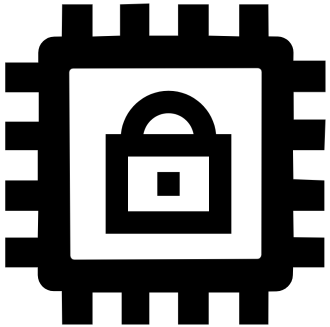

Proprietary Hardware

Next Generation of Cyber-Physical Systems

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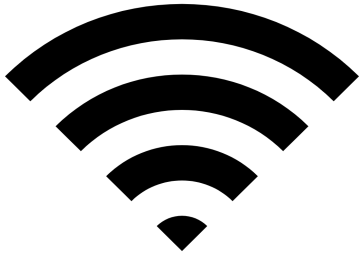
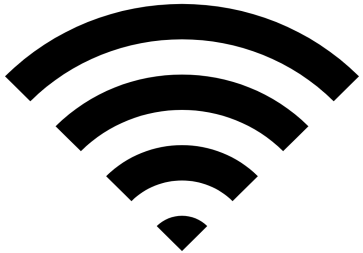


Digital Networks

Next Generation of Cyber-Physical Systems



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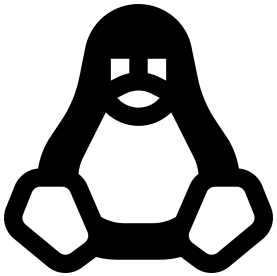
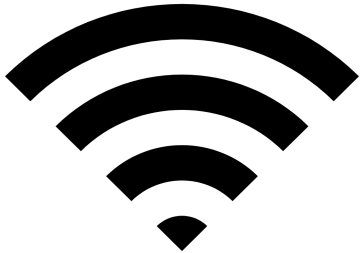


Open Source Software

Next Generation of Cyber-Physical Systems



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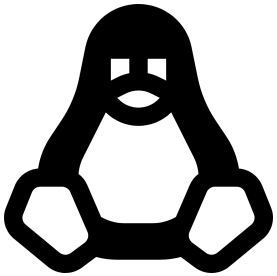
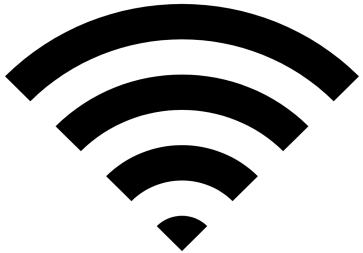


Open Source Software

IoT-Ready

Next Generation of Cyber-Physical Systems



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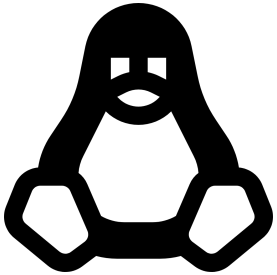

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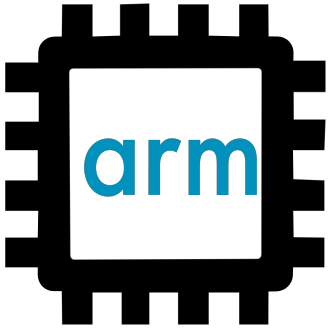

Open Architecture Hardware

Research Gap in the Cybersecurity of Next Gen CPS

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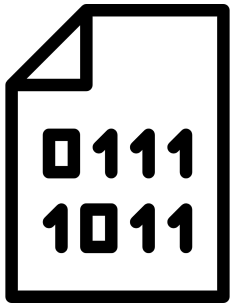

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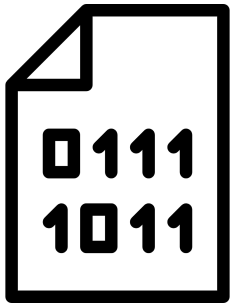

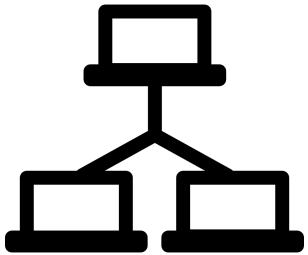

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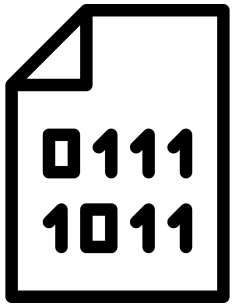
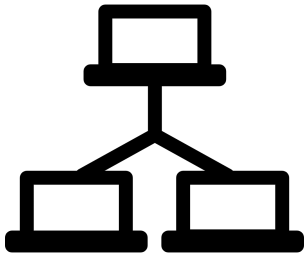
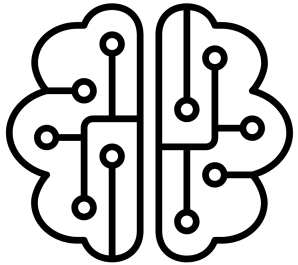
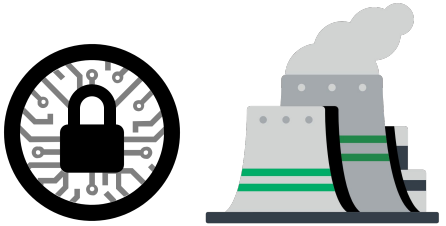






My Research



Develop novel cybersecurity mechanisms to address critical security gaps in next-generation cyber-physical systems.

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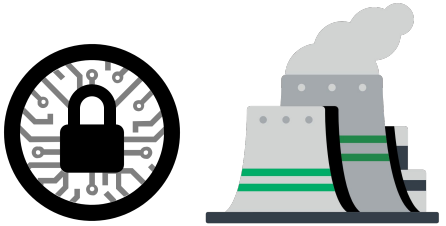

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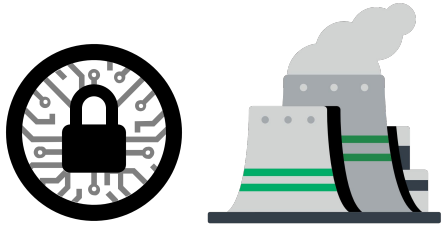

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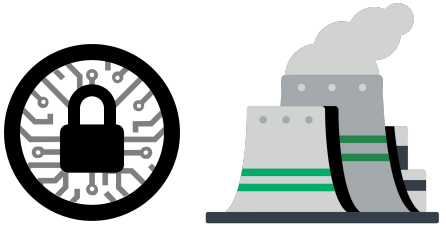

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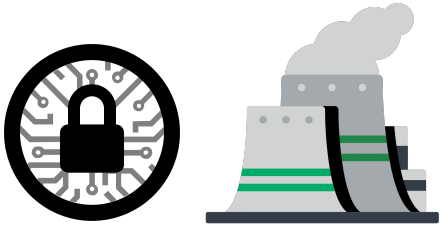

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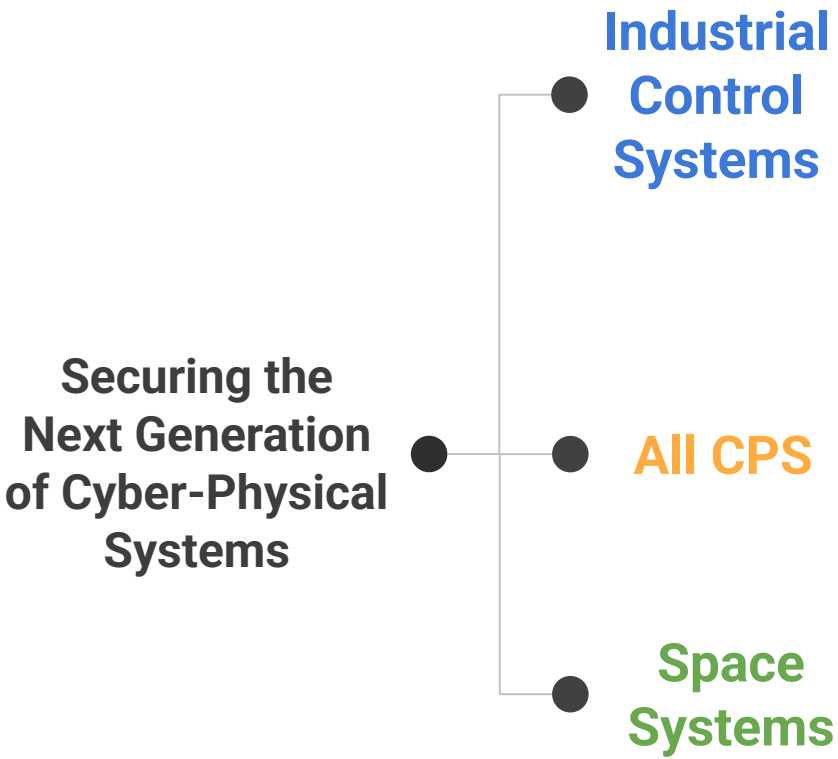
- Develop end-to-end software solutions to protect critical infrastructure
- Design and conduct experiments involving both systems and human factors
- Collaborate with international industry and academia organizations
- Deliver security solutions ready for real-world adoption, and application


Securing the Next Generation of Cyber-Physical Systems
Industrial Control Systems
All CPS
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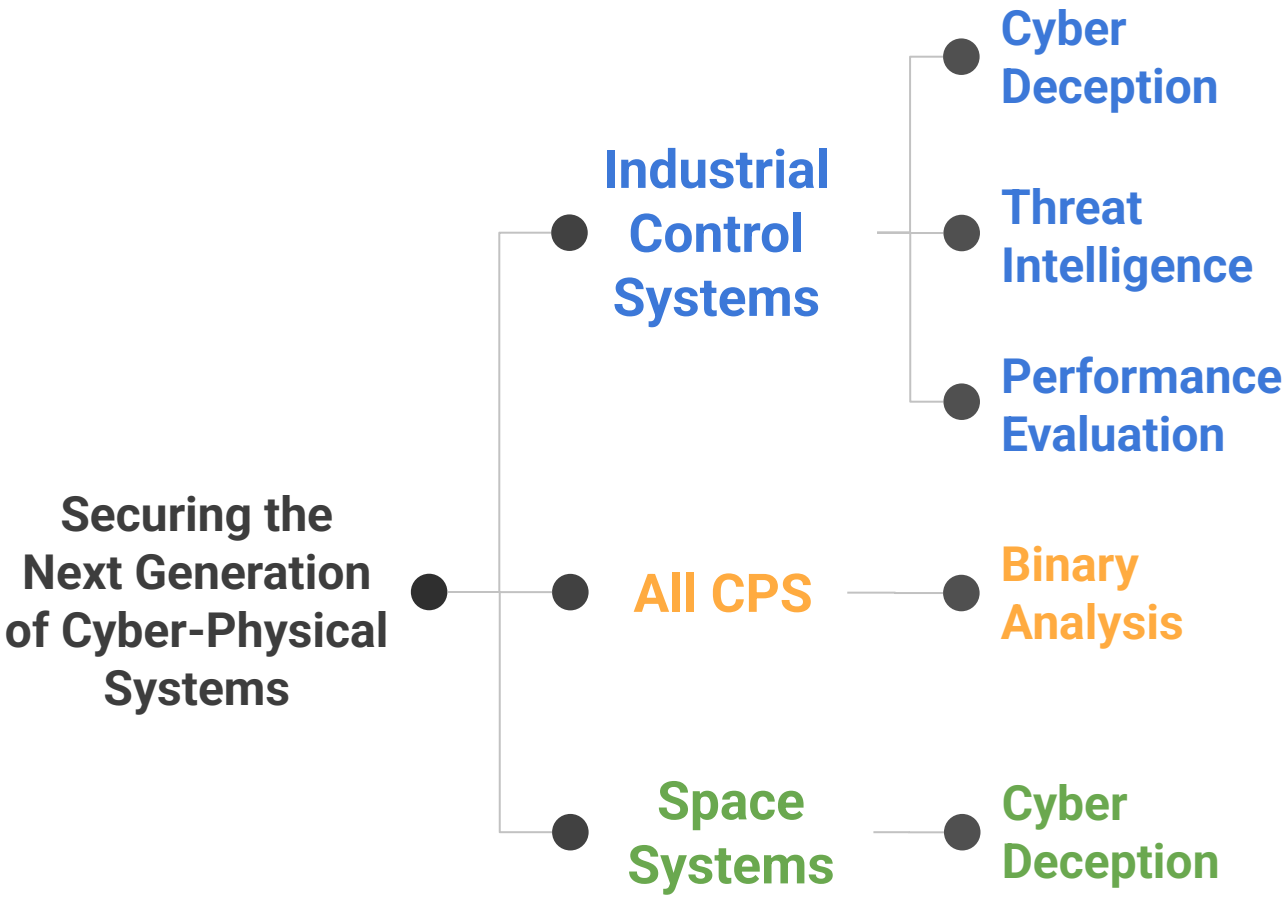
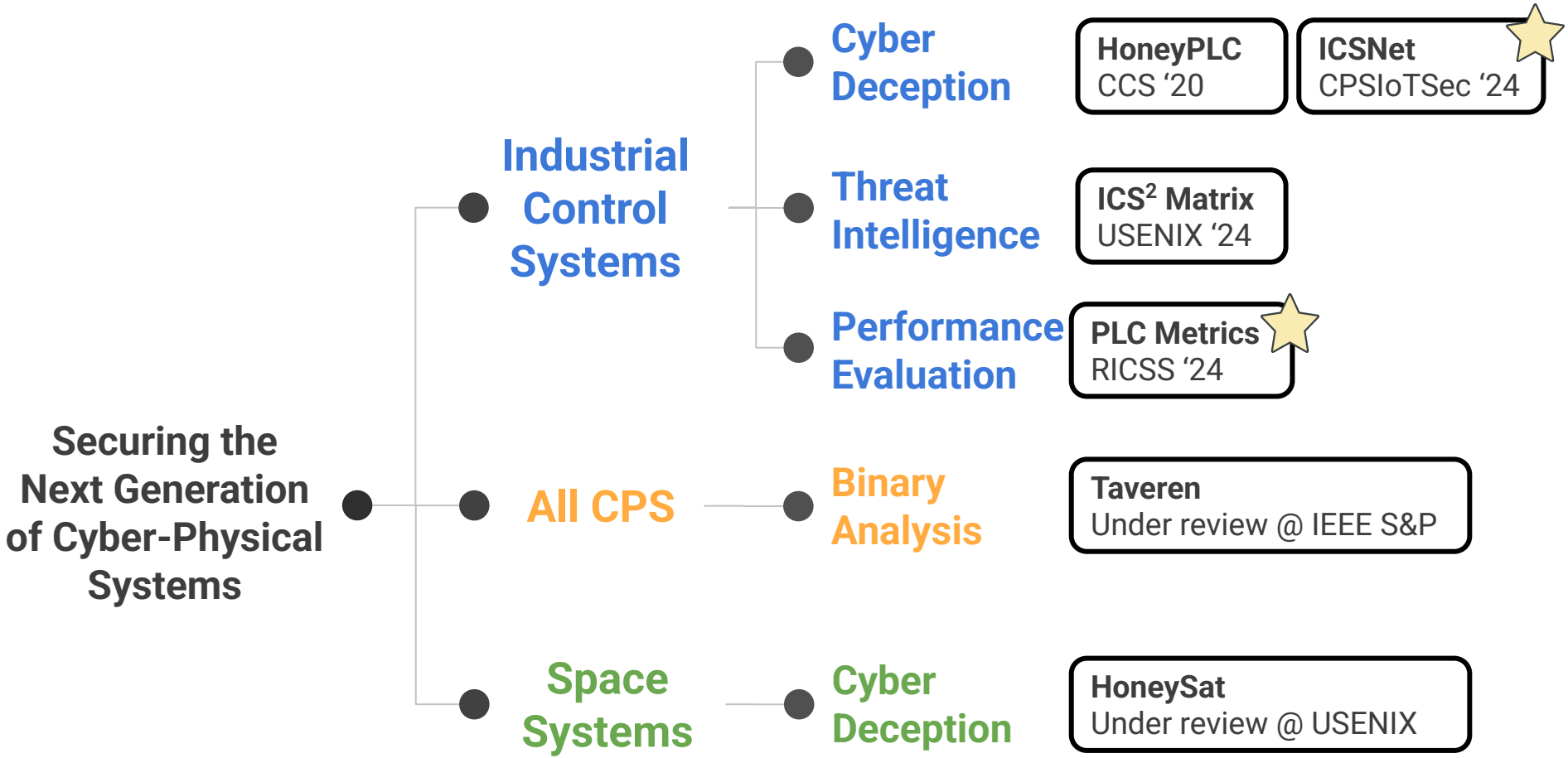

Securing the Next Generation of Cyber-Physical Systems
Industrial Control Systems
Cyber Deception
Threat Intelligence
Performance Evaluation
All CPS
Binary Analysis
Space Systems
Cyber Deception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Industrial Control Systems
Cyber Deception
HoneyPLC
CCS '20
ICSNet
CPSIoTSec '24
Threat Intelligence
ICS² Matrix
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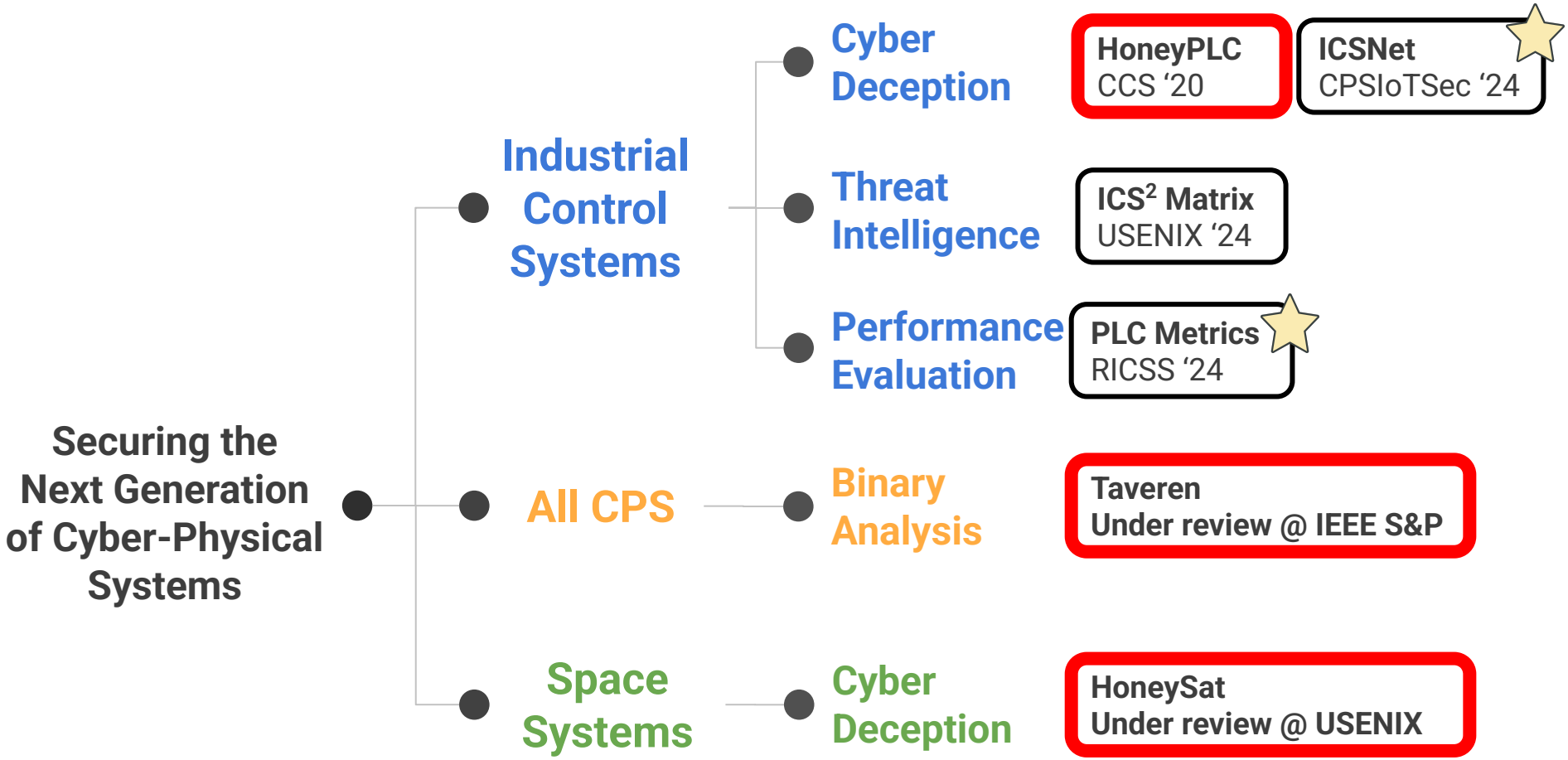
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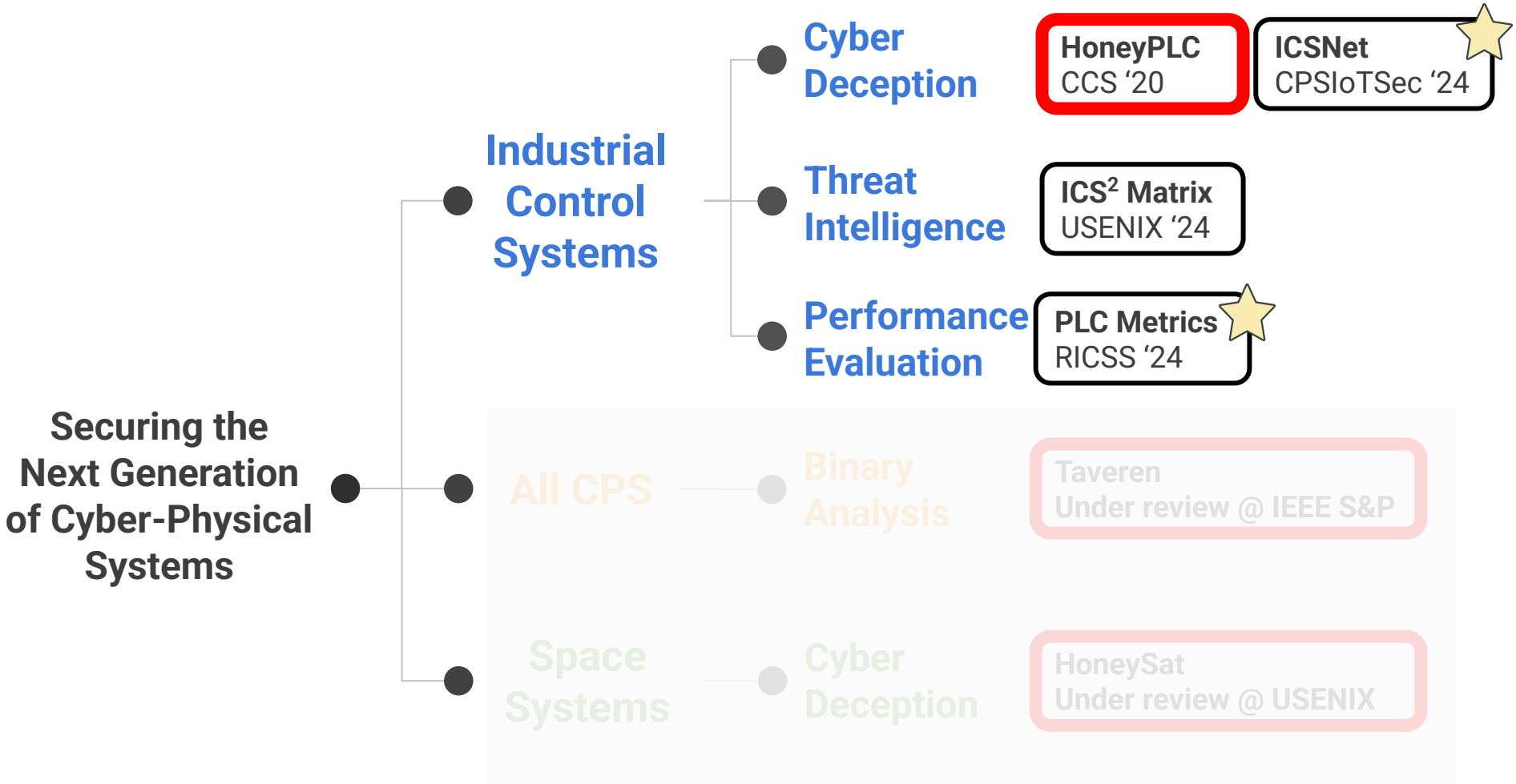
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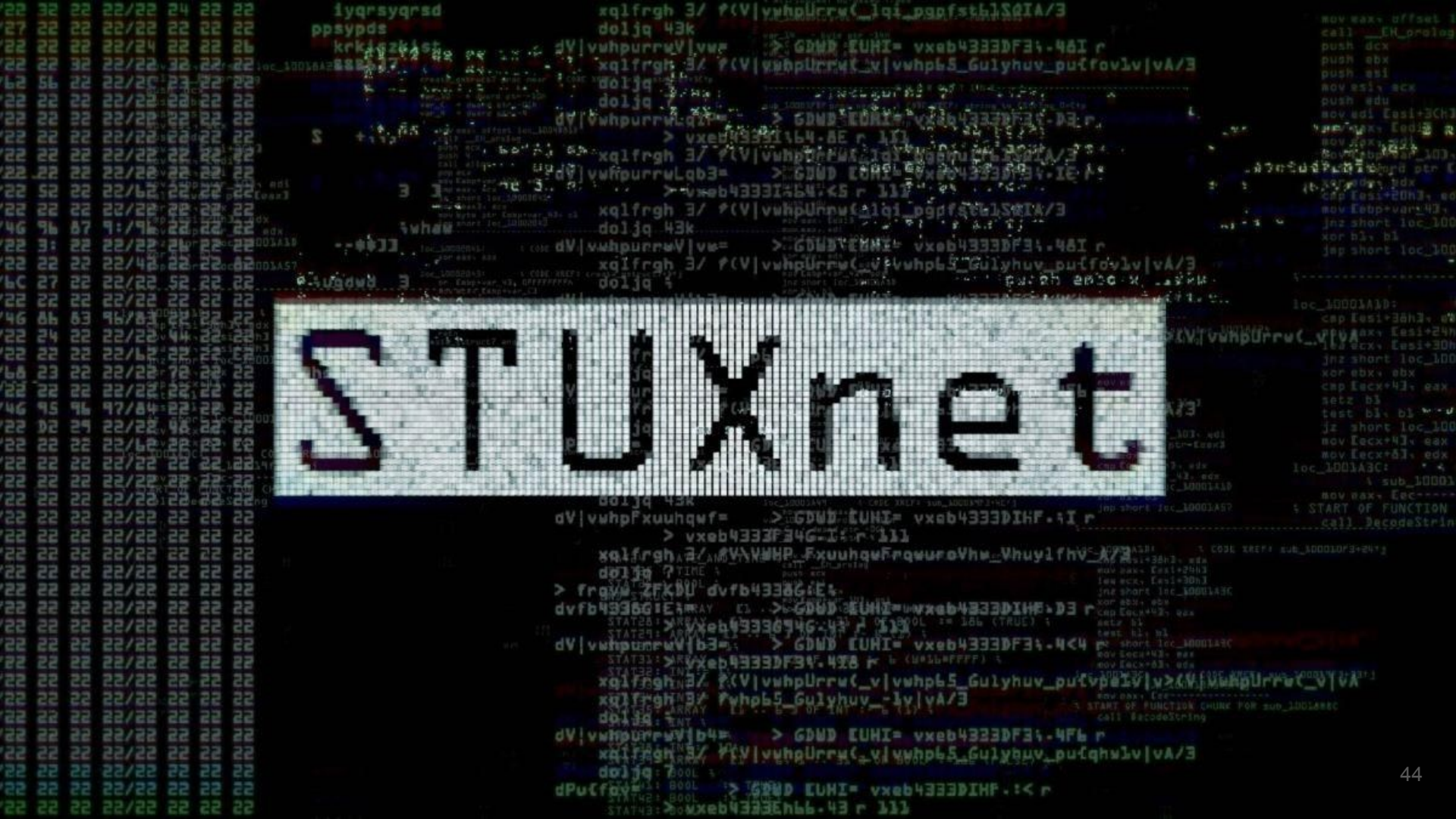
STUXnet

Background: What is a Programmable Logic Controller?

- Vital device in ICS

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- Multiple brands, models, architectures

Background: What is a Programmable Logic Controller?

- Vital device in ICS
- Controls physical equipment (nuclear centrifuge)
- Multiple brands, models, architectures
- Implement different network protocols such as HTTP

Background: What is a honeypot?

- Decoy computer system

Background: What is a honeypot?

- Decoy computer system
- Attracts malicious actors

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Background: What is a honeypot?

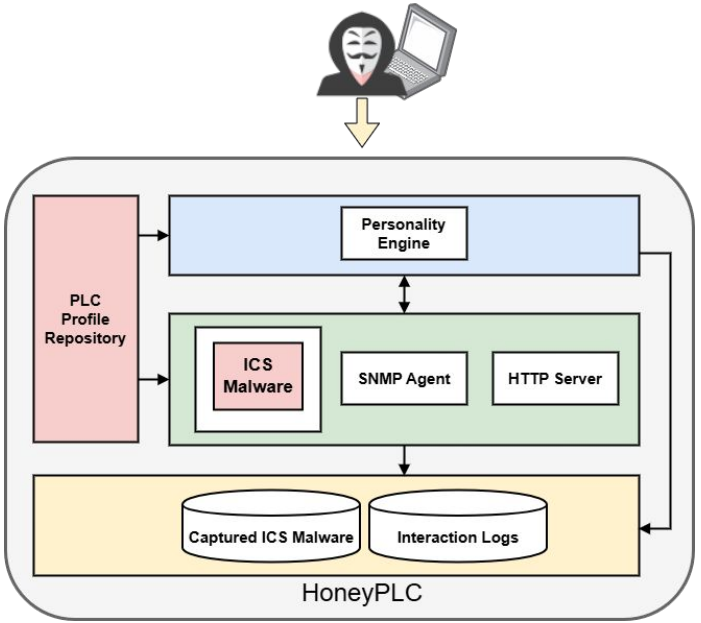
- Decoy computer system
- Attracts malicious actors
- Record all interaction data
- Analyze data to obtain knowledge
- Multiple ICS honeypots (simulate PLCs)

What is the problem?

Current ICS honeypots are limited by the quality of the data they can gather

Our solution: HoneyPLC

- Honeypot that simulates different PLCs



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Our solution: HoneyPLC

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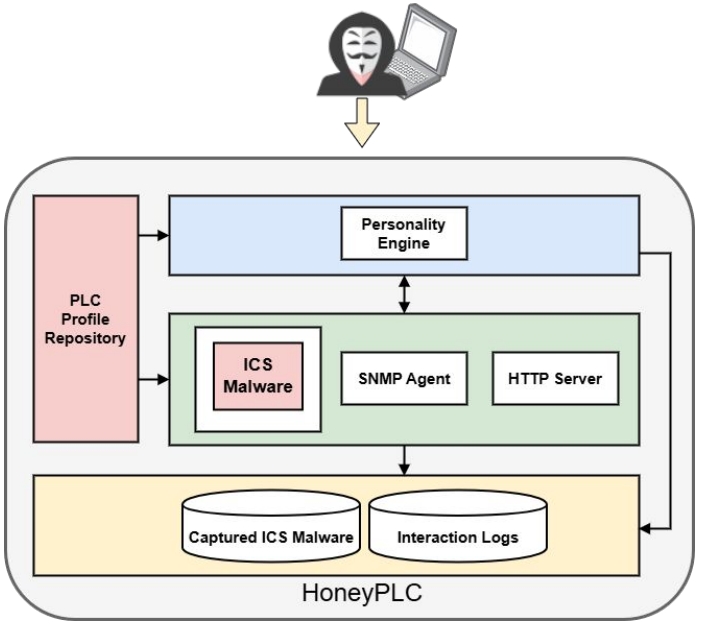
- Simulates ICS-specific network protocols



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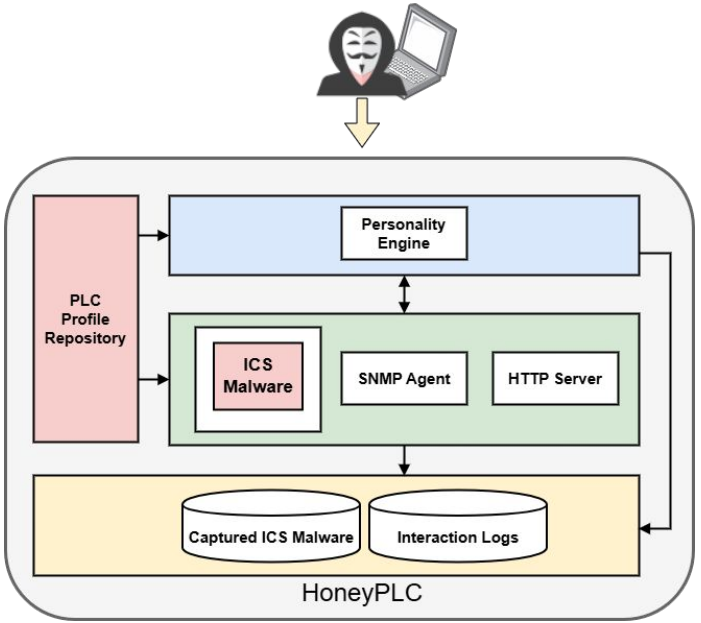

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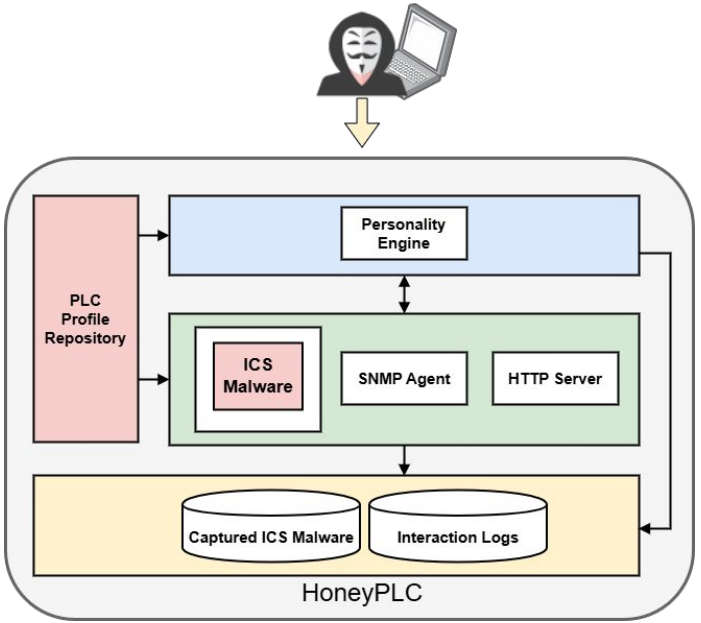
- Honeypot that simulates different PLCs
- Simulates ICS-specific network protocols
- Collects real-world ICS cyberattack data
- Collects ICS-specific malware



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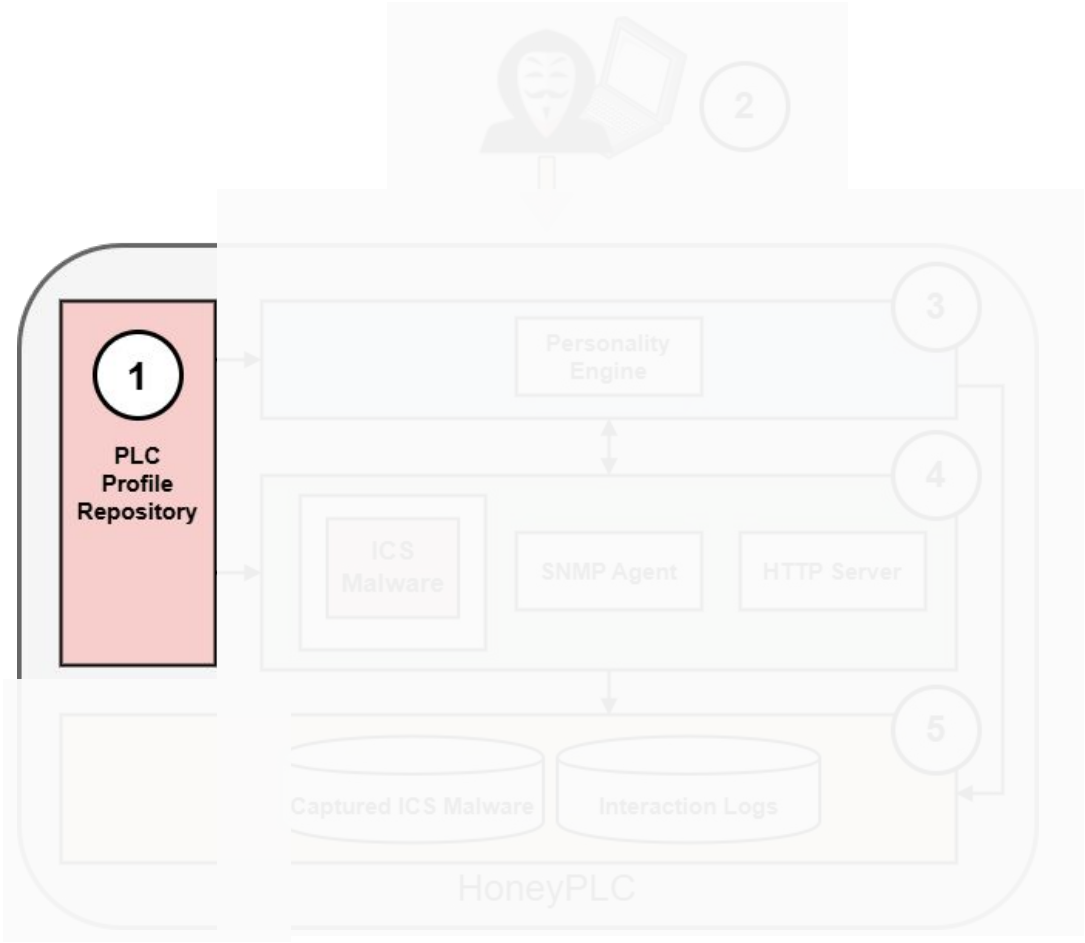
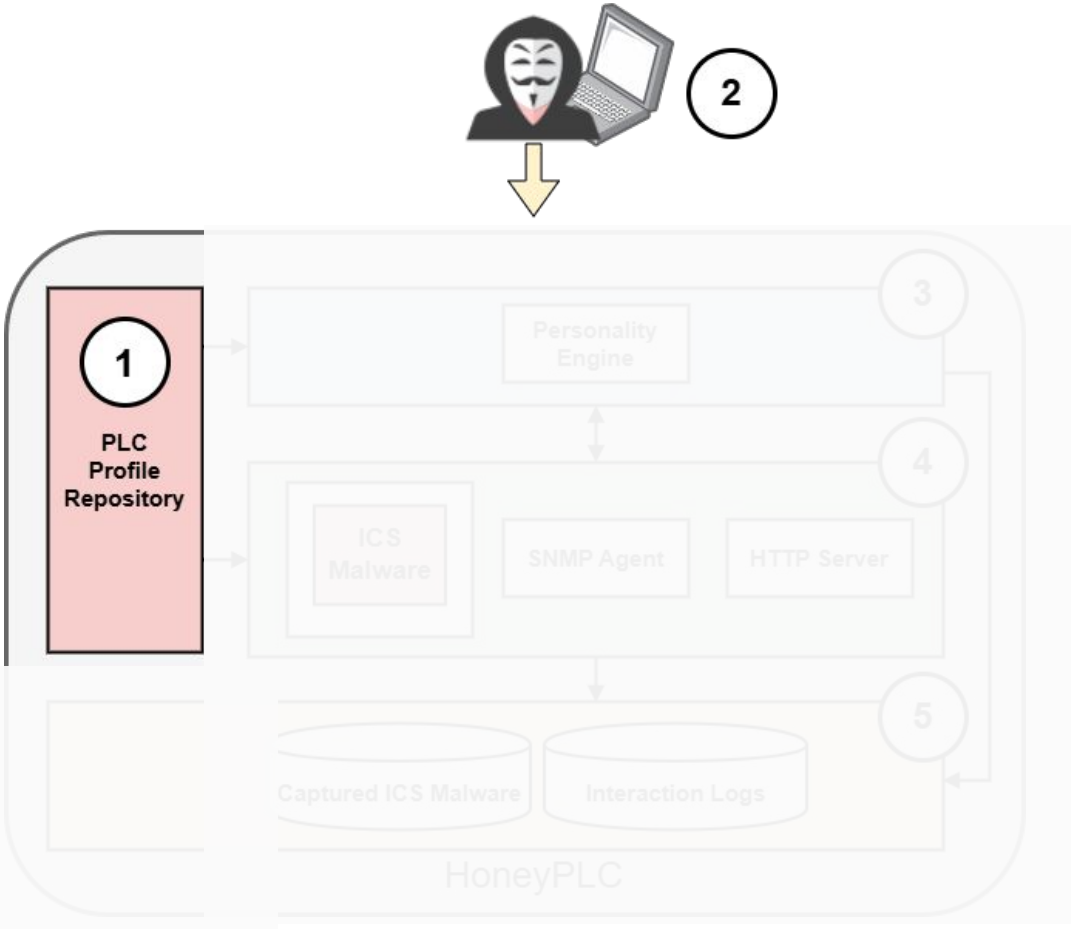

1
PLC
Profile
Repository
2
3
Personality
Engine
4
ICS
Malware
SNMP Agent
HTTP Server
5
Captured ICS Malware
Interaction Logs
HoneyPLC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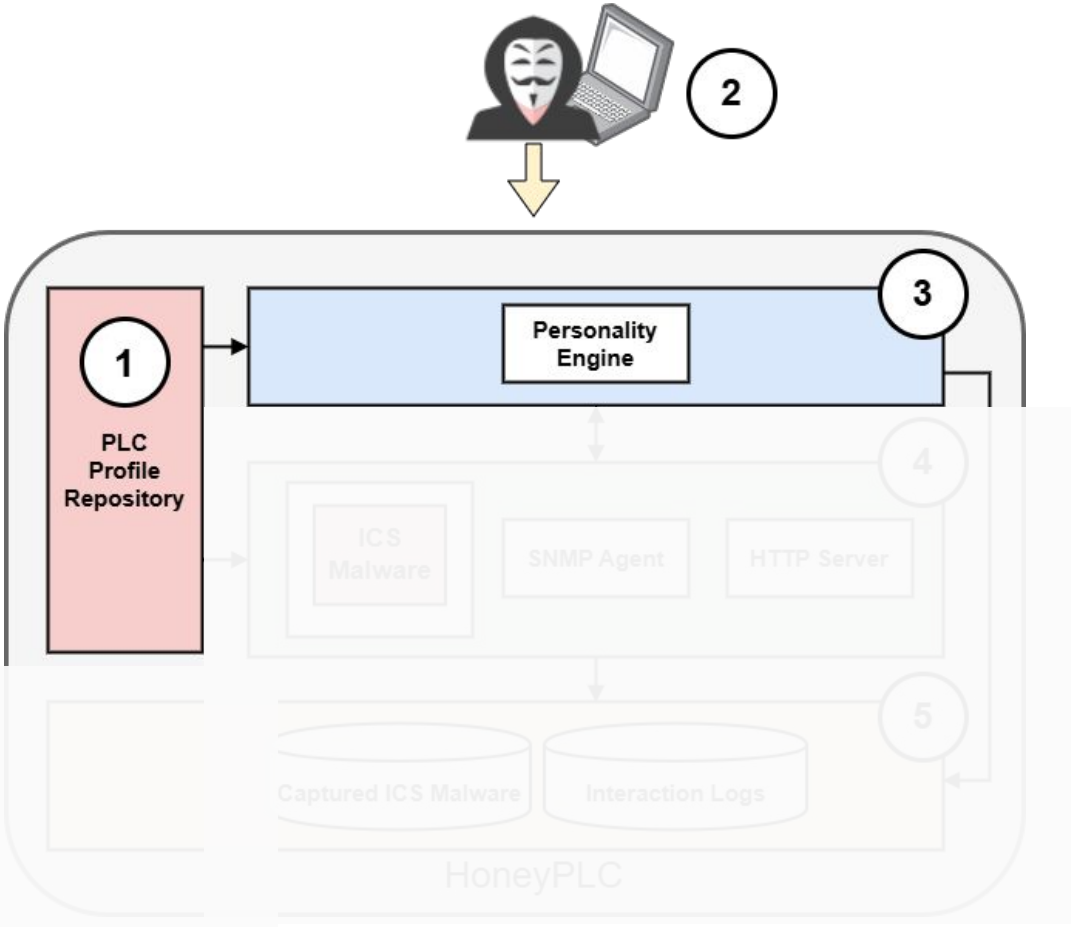
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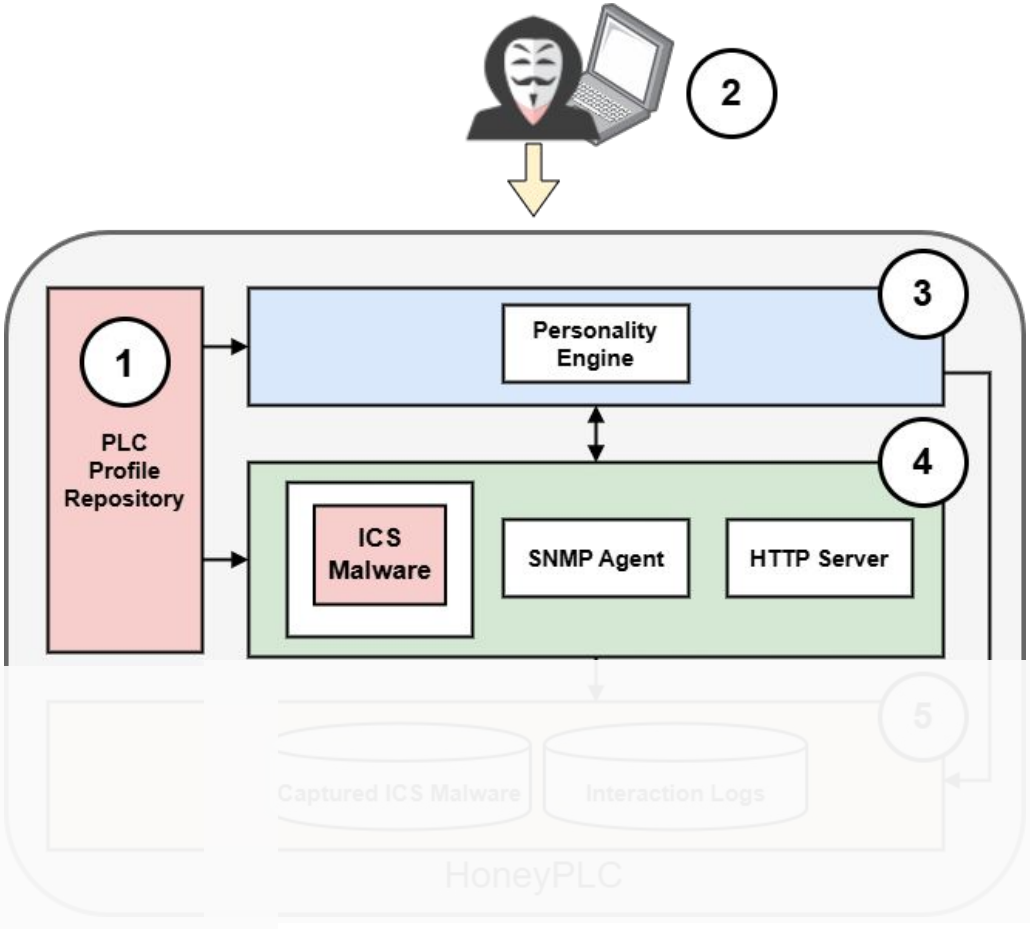
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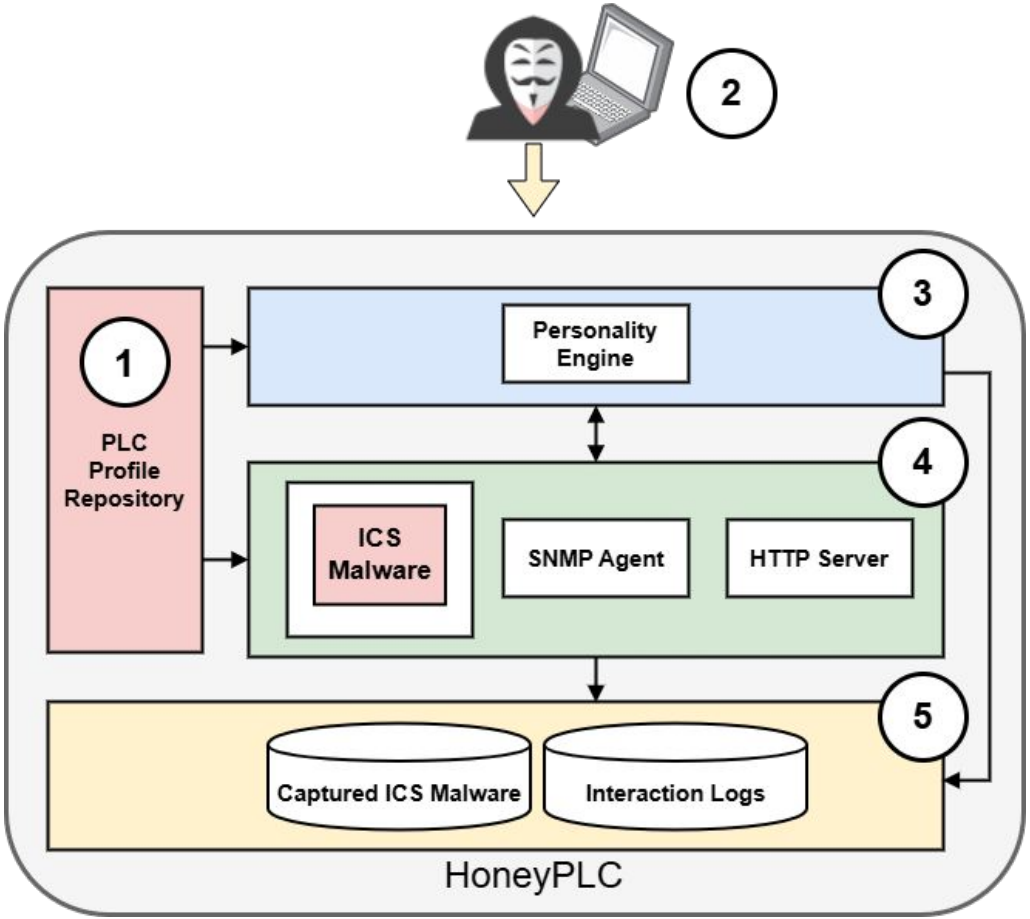
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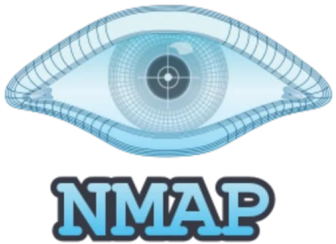
How did we evaluate HoneyPLC?

1. Well-known cybersecurity tools



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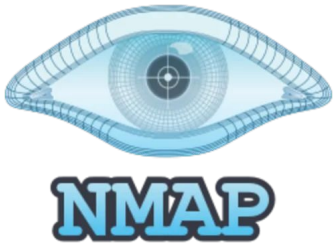

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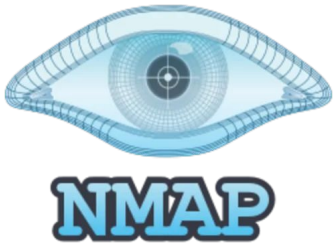

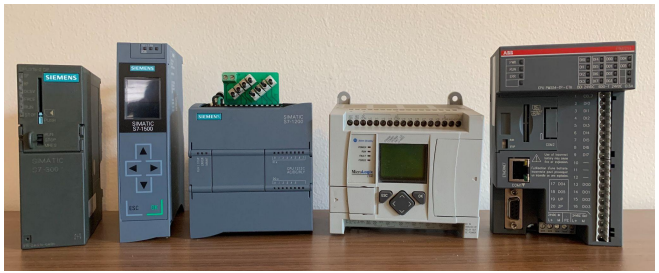

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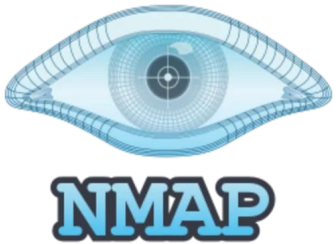
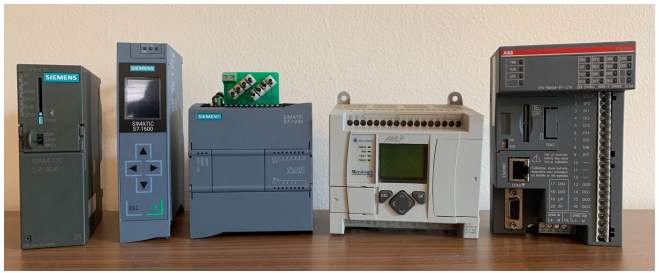
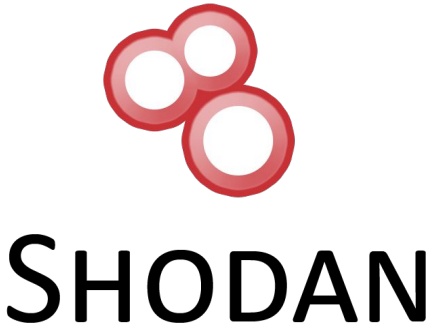




What did we find?

Security Tool
Nmap
Siemens PLC Manager
Shodan
PLCInject
PLCScan



What did we find?

Security Tool	Type
Nmap	Industry
Siemens PLC Manager	Industry
Shodan	Industry
PLCInject	Academia
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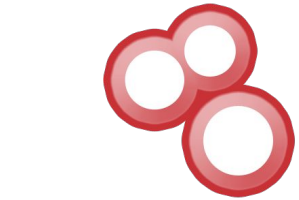

SHODAN

What did we find?

Security Tool	Type	Result
Nmap	Industry	✔
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PLCInject	Academia	✔
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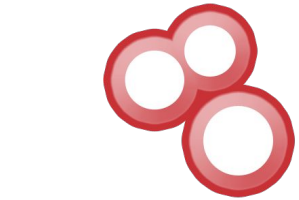
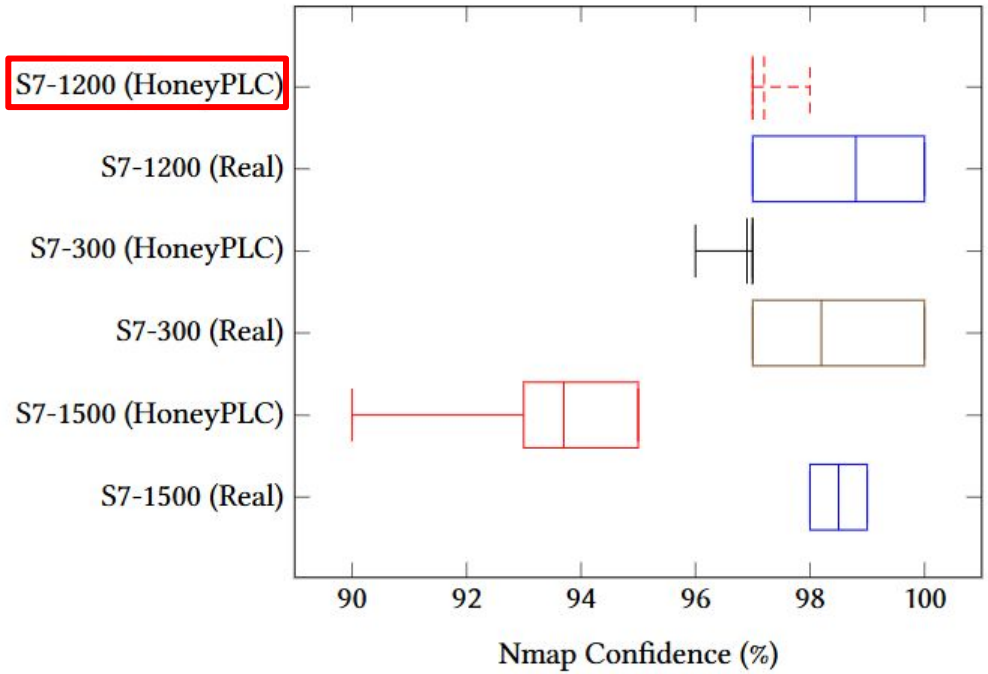


SHODAN

HoneyPLC's Performance versus Nmap



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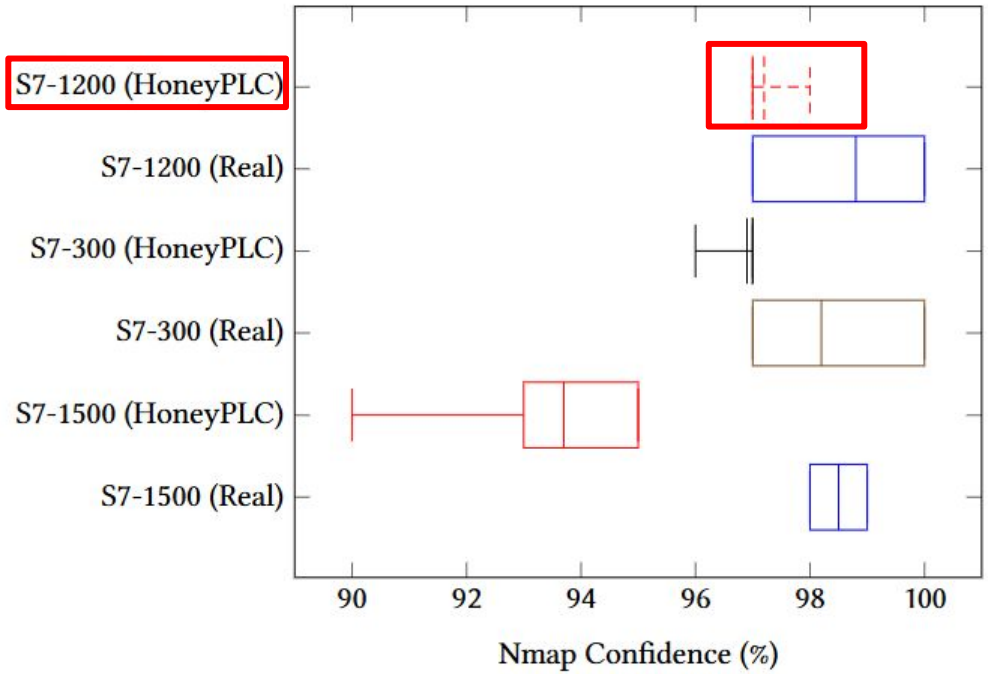

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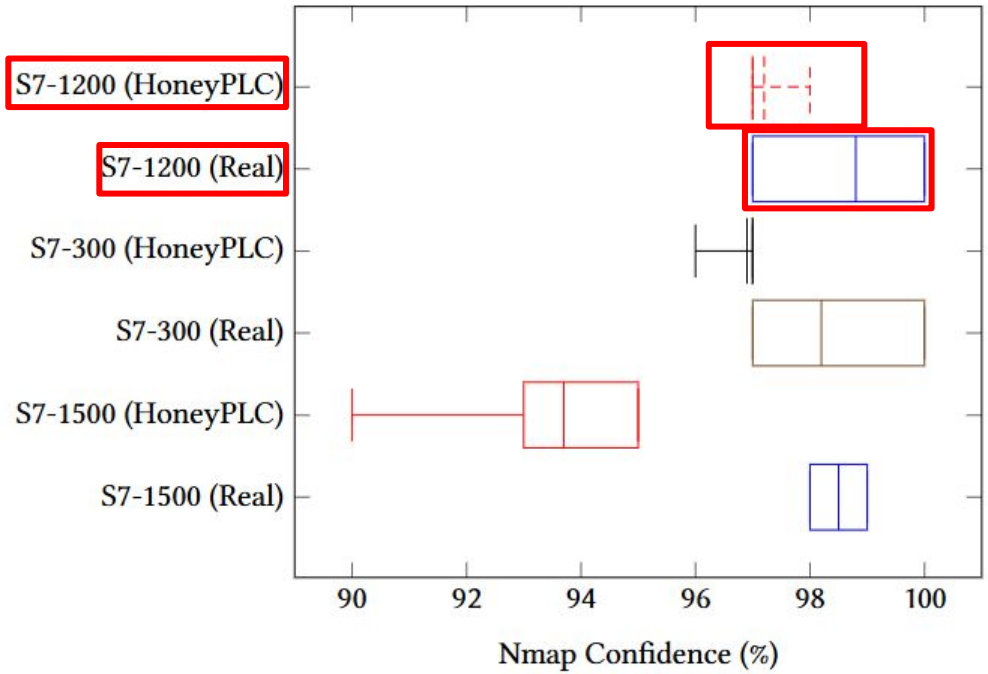

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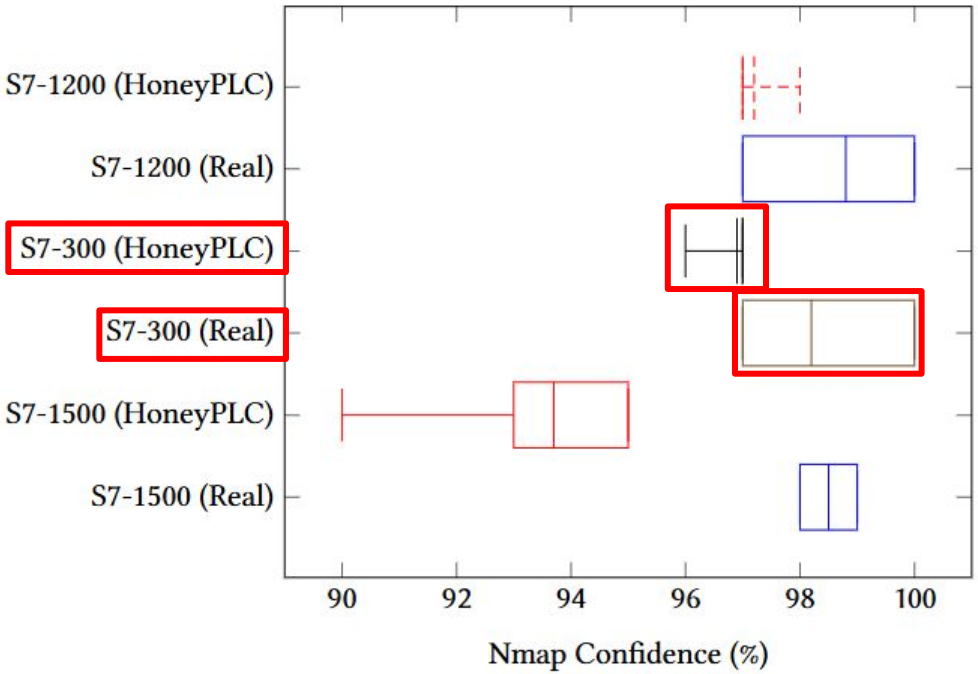

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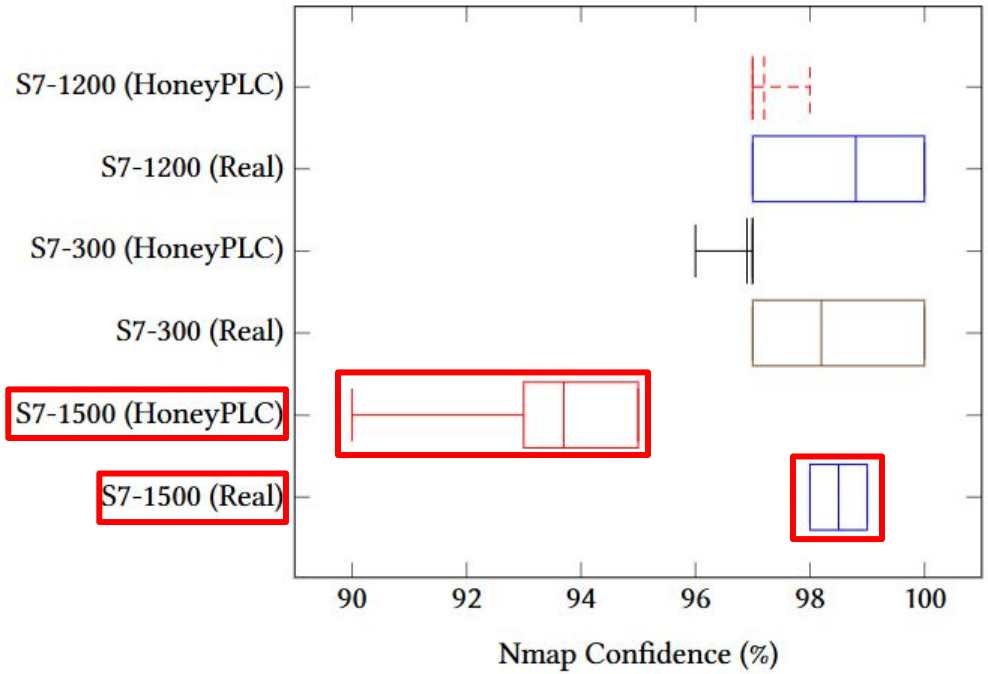

What did we find?

PLC Profile
Siemens S7-300
Siemens S7-1200
Siemens S7-1500

What did we find?

PLC Profile	Connections
Siemens S7-300	600
Siemens S7-1200	202
Siemens S7-1500	292

What did we find?

PLC Profile	Connections	Read PLC Memory
Siemens S7-300	600	80
Siemens S7-1200	202	0
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What did we find?

PLC Profile	Connections	Read PLC Memory	PLC Stop
Siemens S7-300	600	80	4
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Siemens S7-1200	202	0	0
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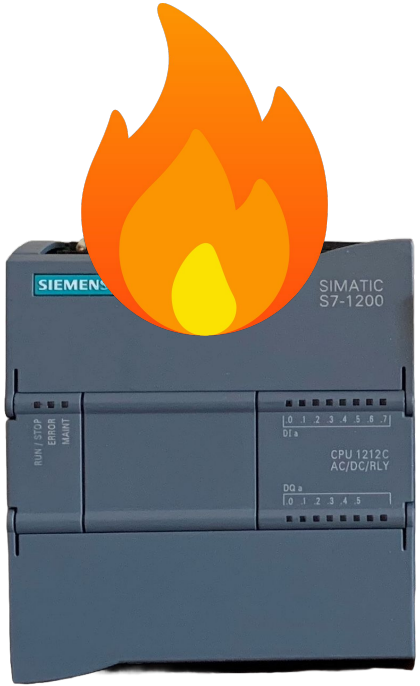

Conclusion: HoneyPLC

- An extensible, realistic honeypot with advanced simulations

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- *“HoneyPLC, which to the best of our knowledge, represents the most advanced ICS honeypot available.” [1]*

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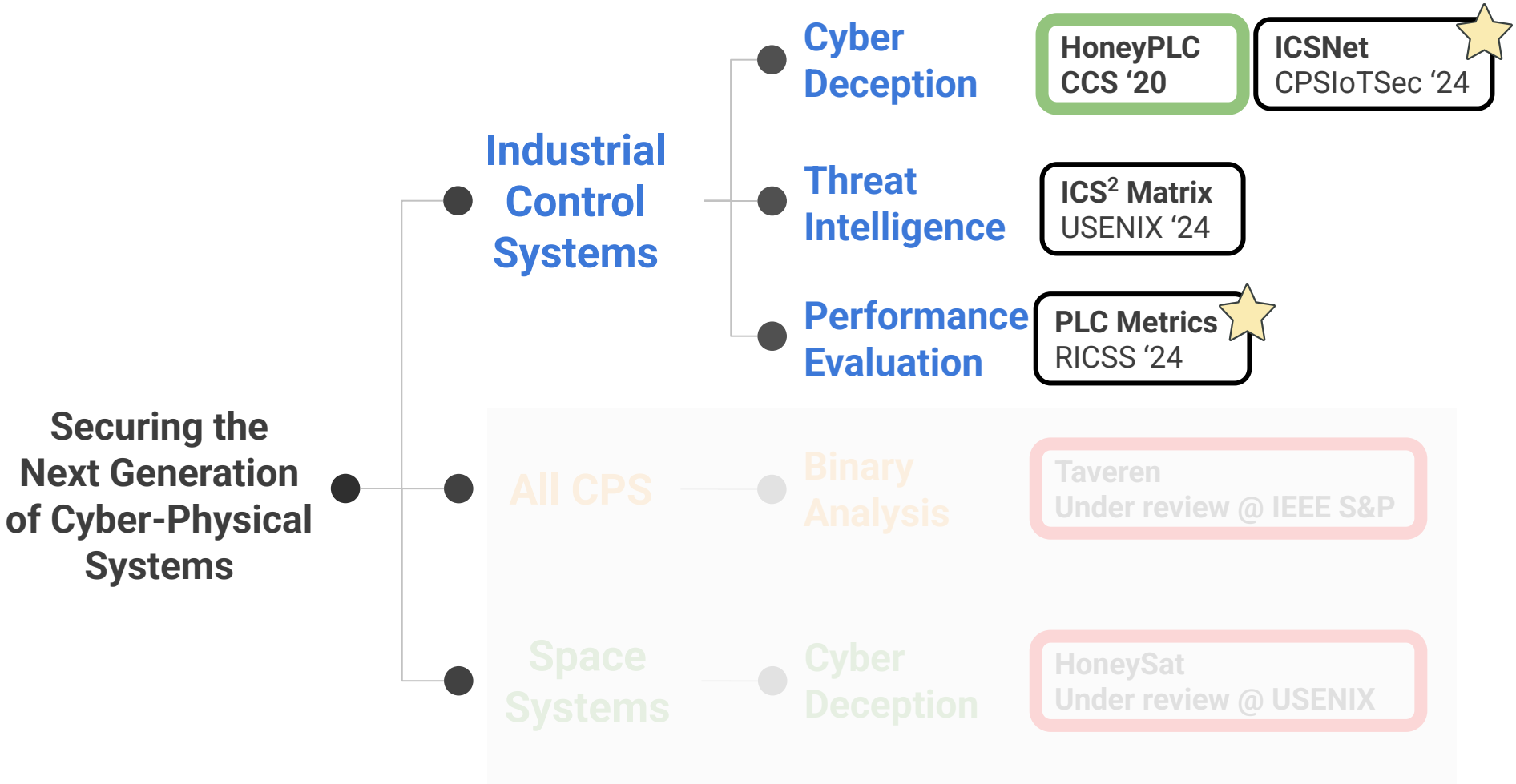
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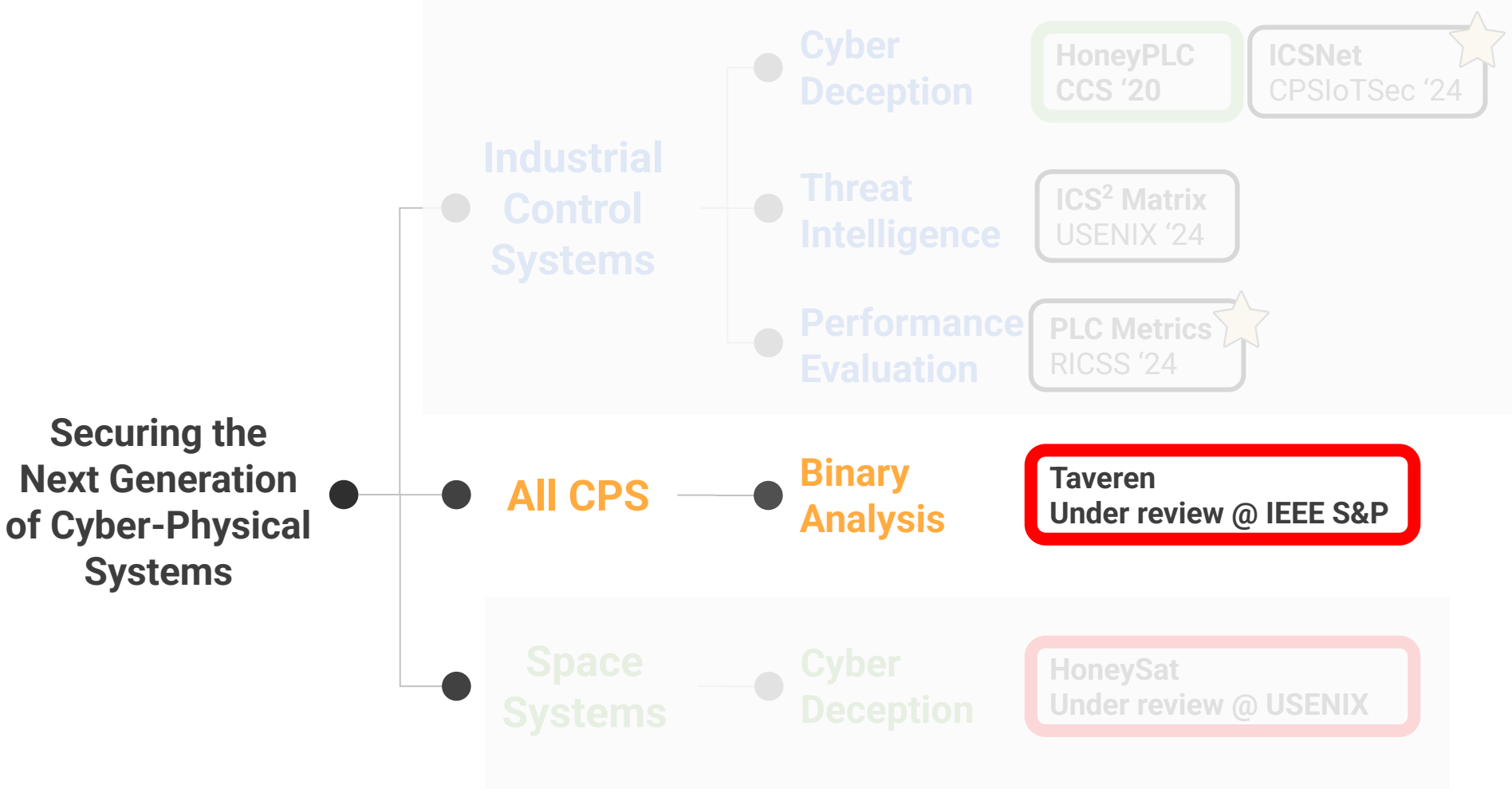
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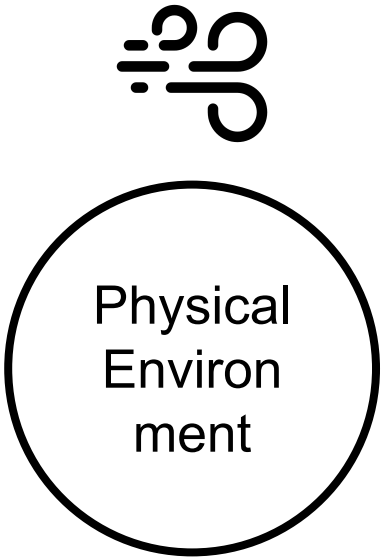
Background: Cyber-Physical Systems' Programs



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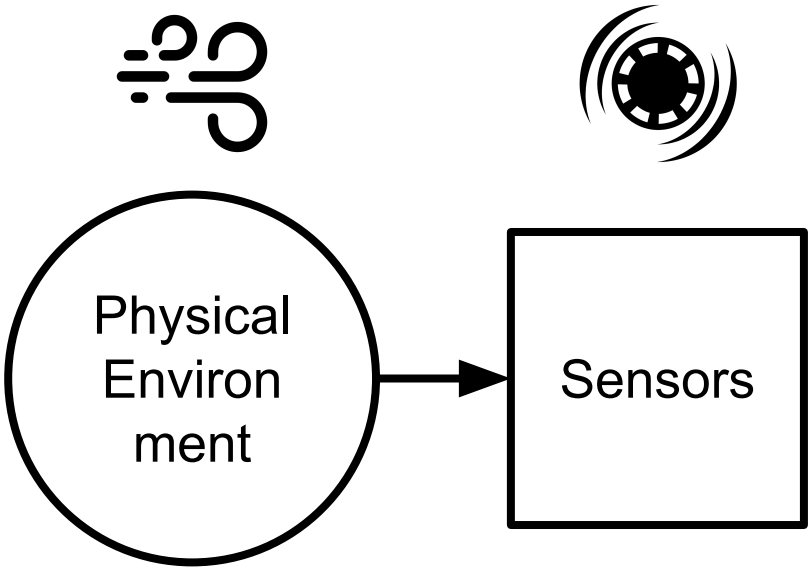

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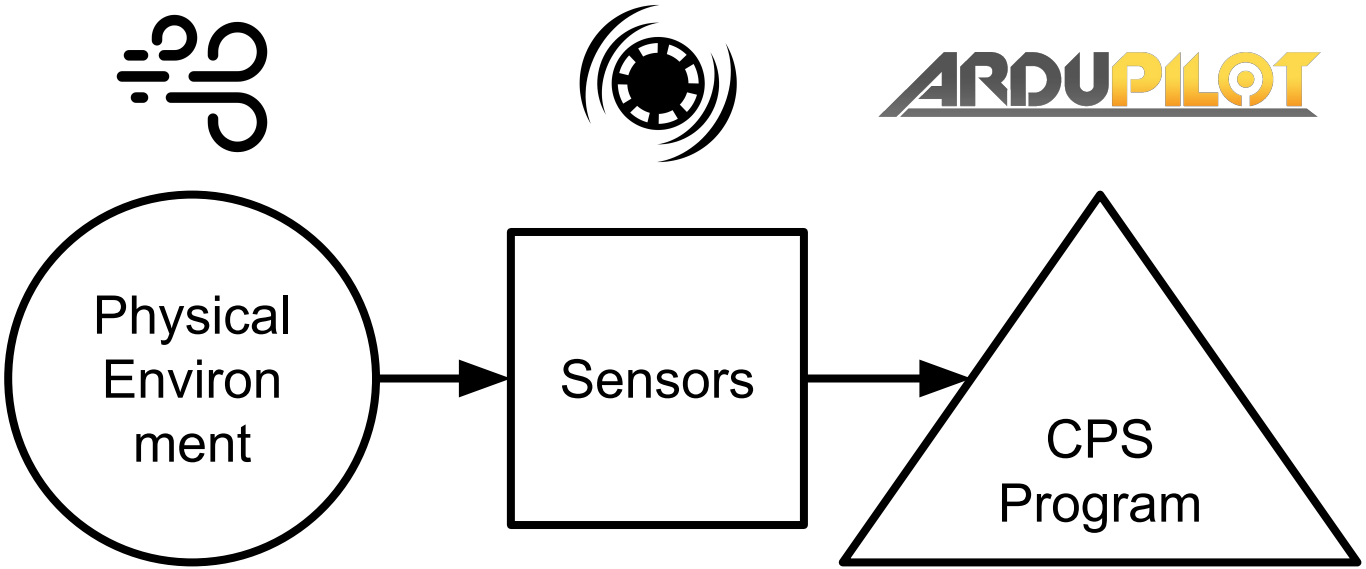

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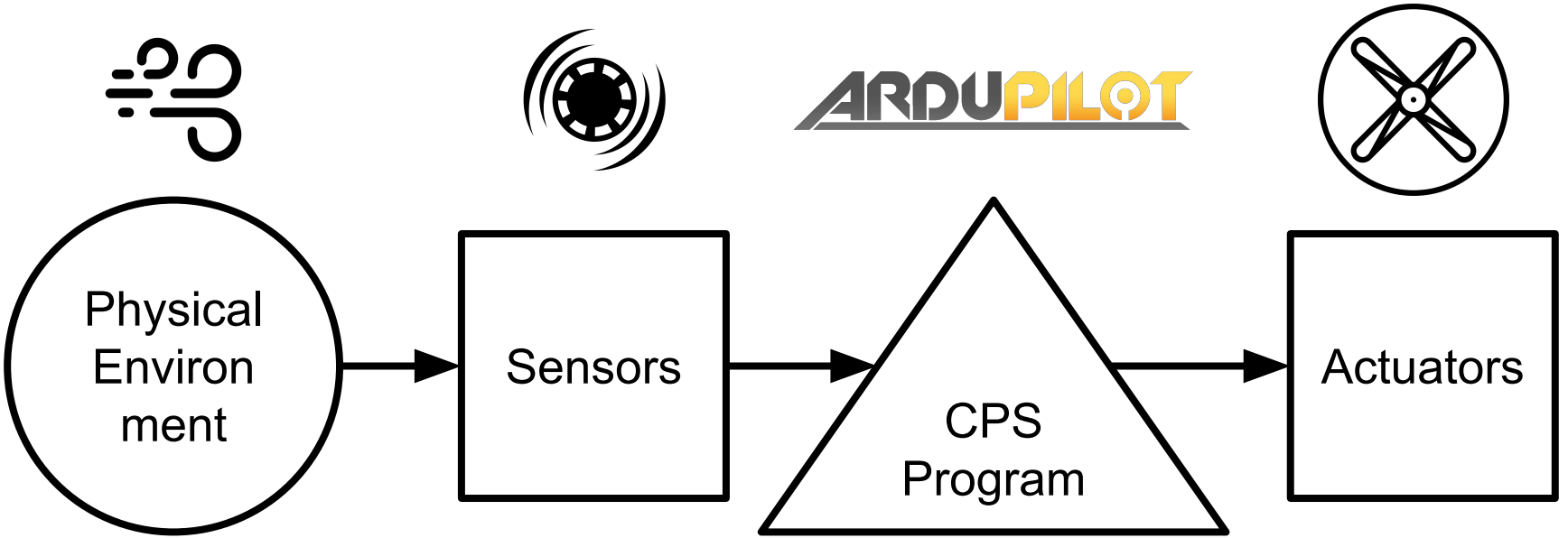

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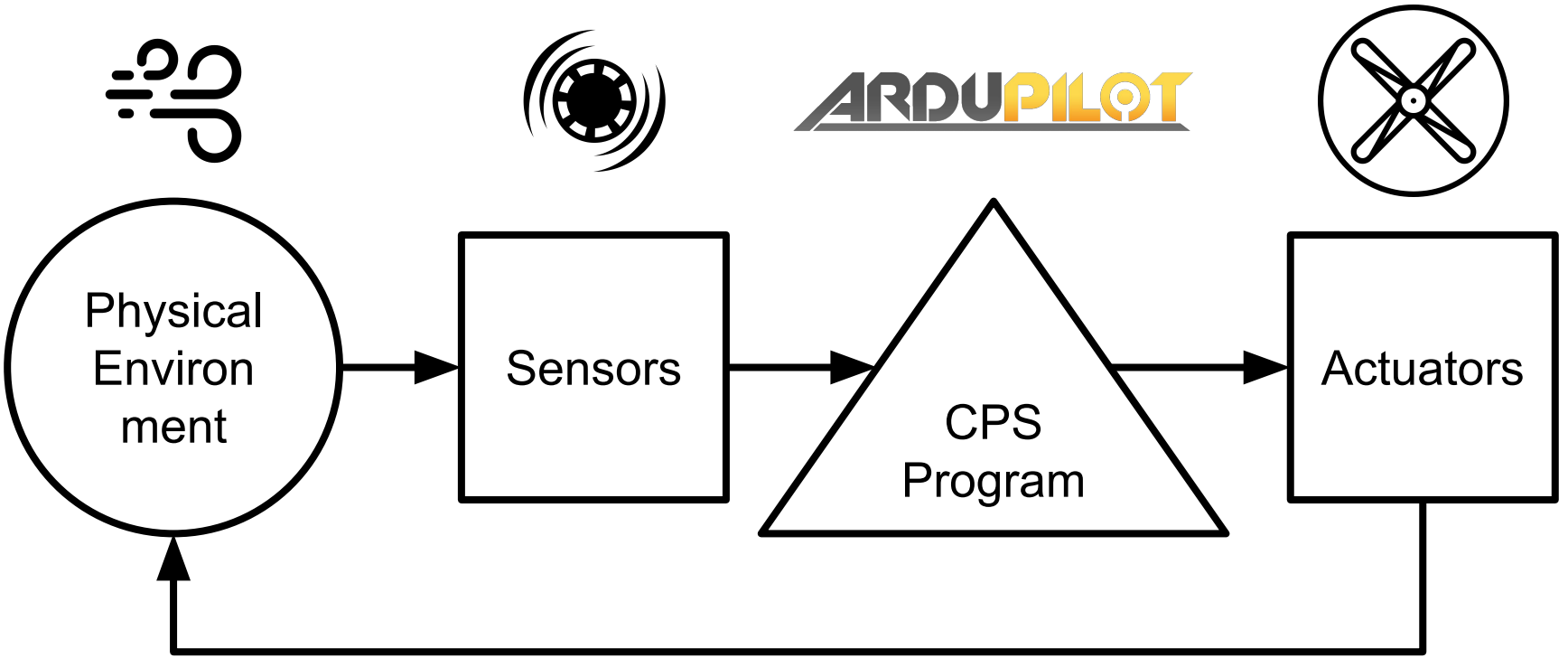
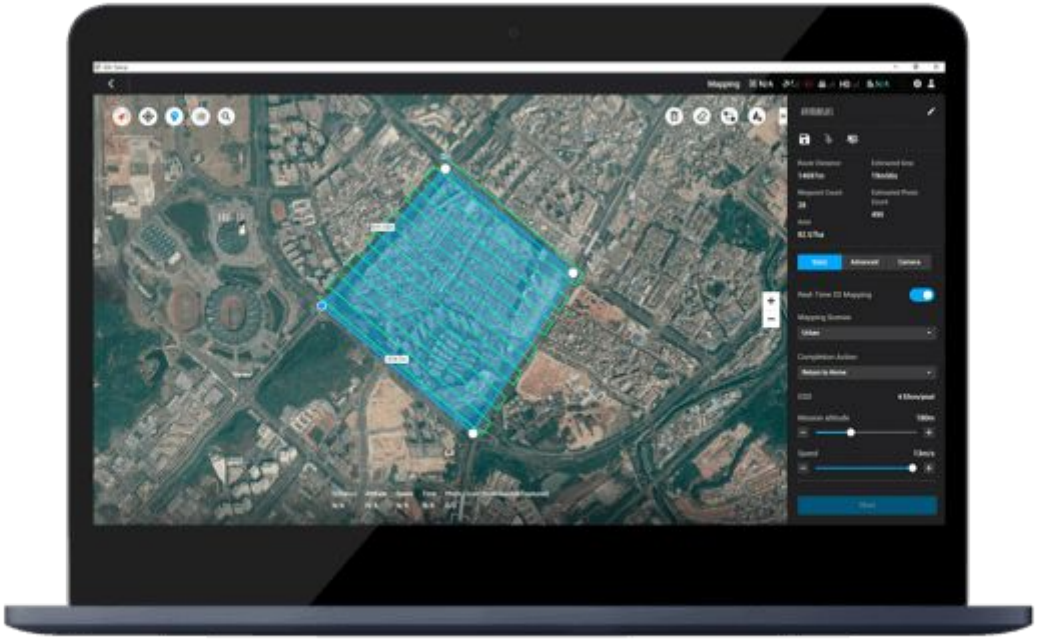


Background: CPS Proprietary Programs



Background: What is binary analysis?

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- Technique used to analyze and review binary code
- Allows us to find vulnerabilities
- Necessary to analyze software when we do not have the source code

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```
int main() {

    printf("Hello, World!\n");

    return 0;
}
```

Human-readable source code

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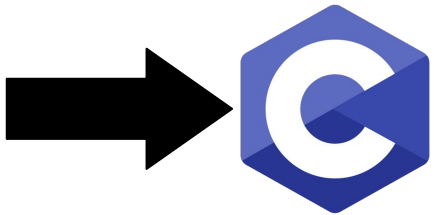

Human-readable source code

Compiler

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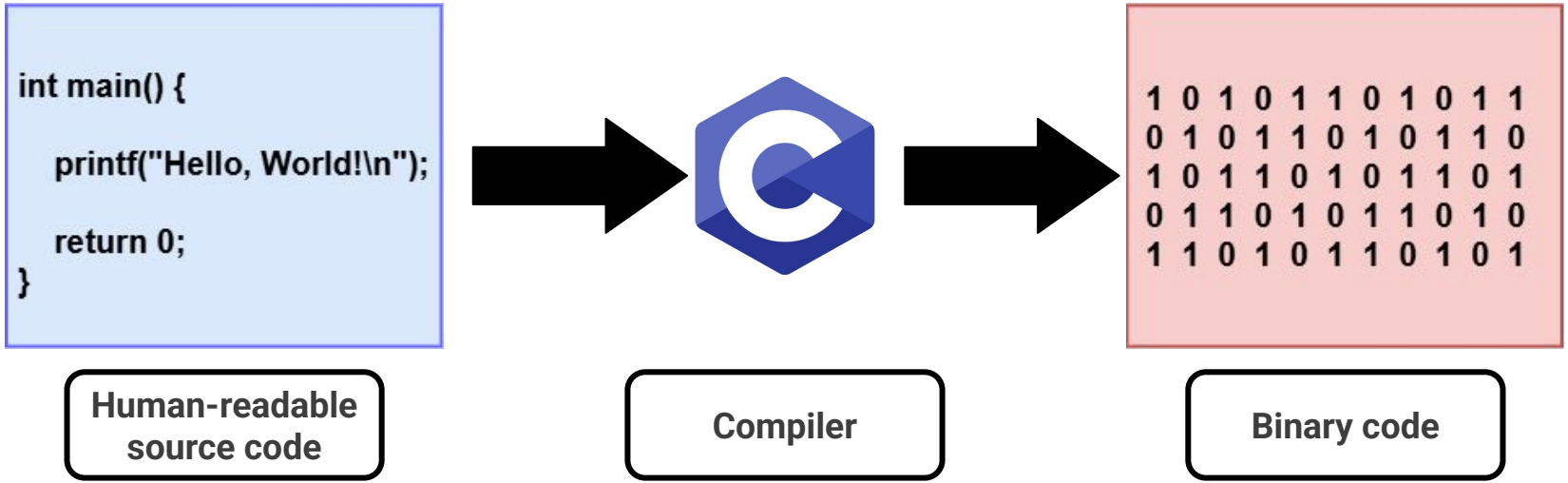

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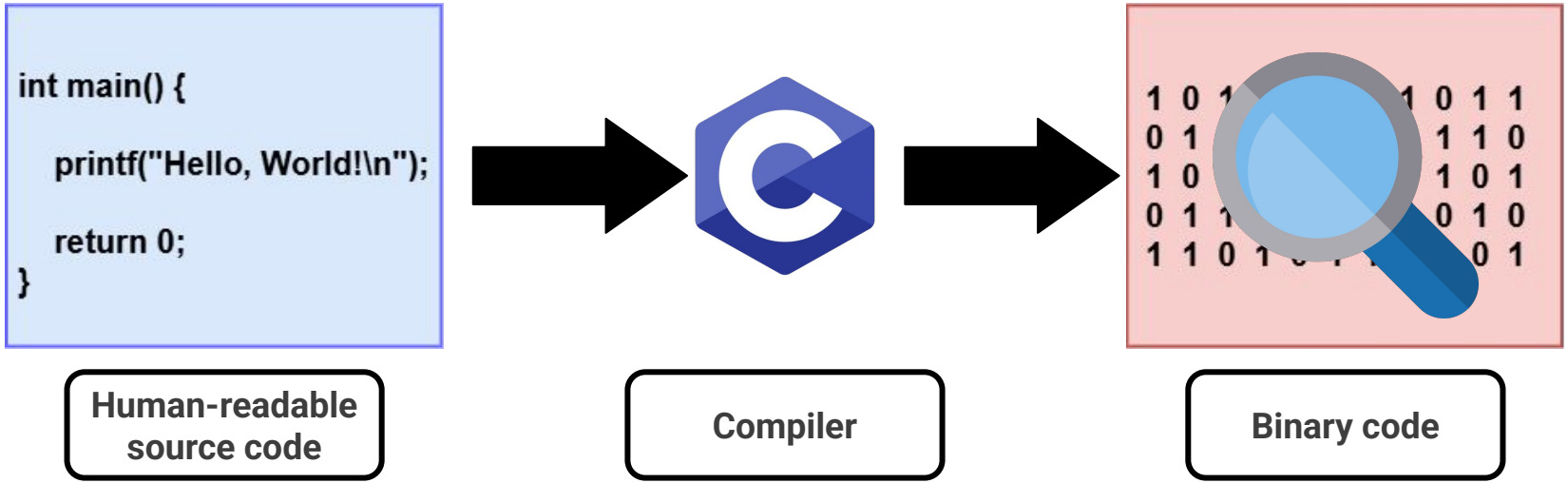

Background: Security versus Safety

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```
#include <string.h>

void foo (char *bar)
{
   char  c[12];

   strcpy(c, bar);  // no bounds
}

int main (int argc, char **argv)
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#include <string.h>

void foo (char *bar)
{
   char  c[12];

   strcpy(c, bar);  // no bounds
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int main (int argc, char **argv)
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   foo(argv[1]);
}
```

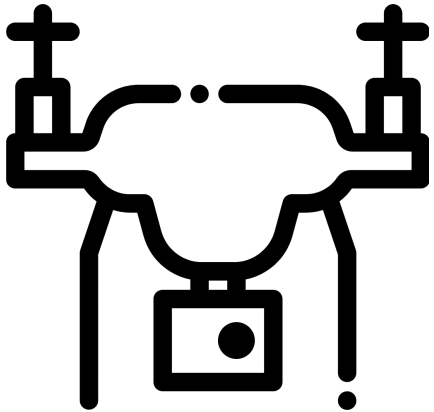

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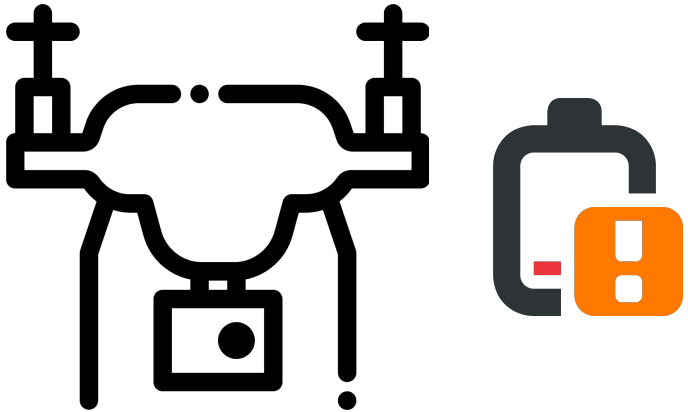

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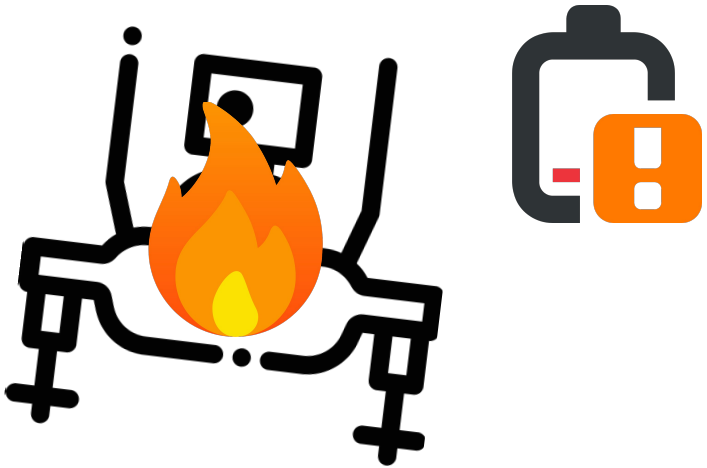

What is the problem?

Current binary analysis methods to analyze CPS programs focus on *security* and cannot find and remove *safety* vulnerabilities.

Our Solution: Taveren

- **Binary analysis tool** for CPS Programs

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- Enforces **user-generated *safety* policies**

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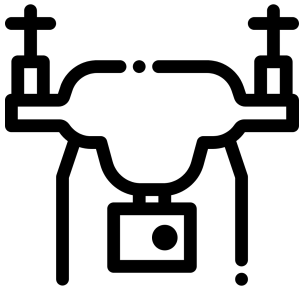
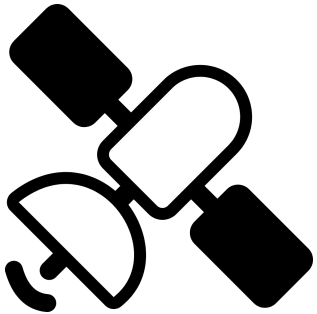
- Enforces **user-generated *safety* policies**
- Works for **multiple CPS programs and architectures**





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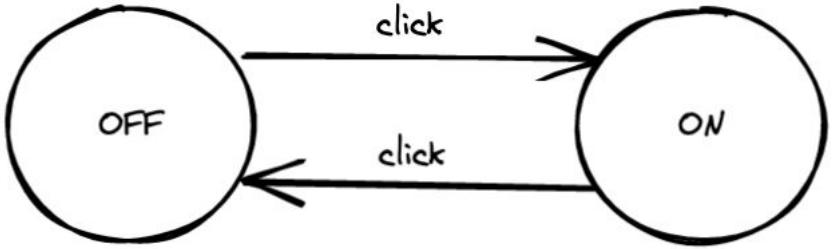
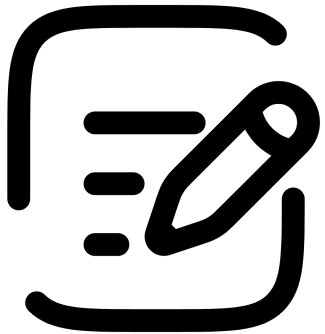
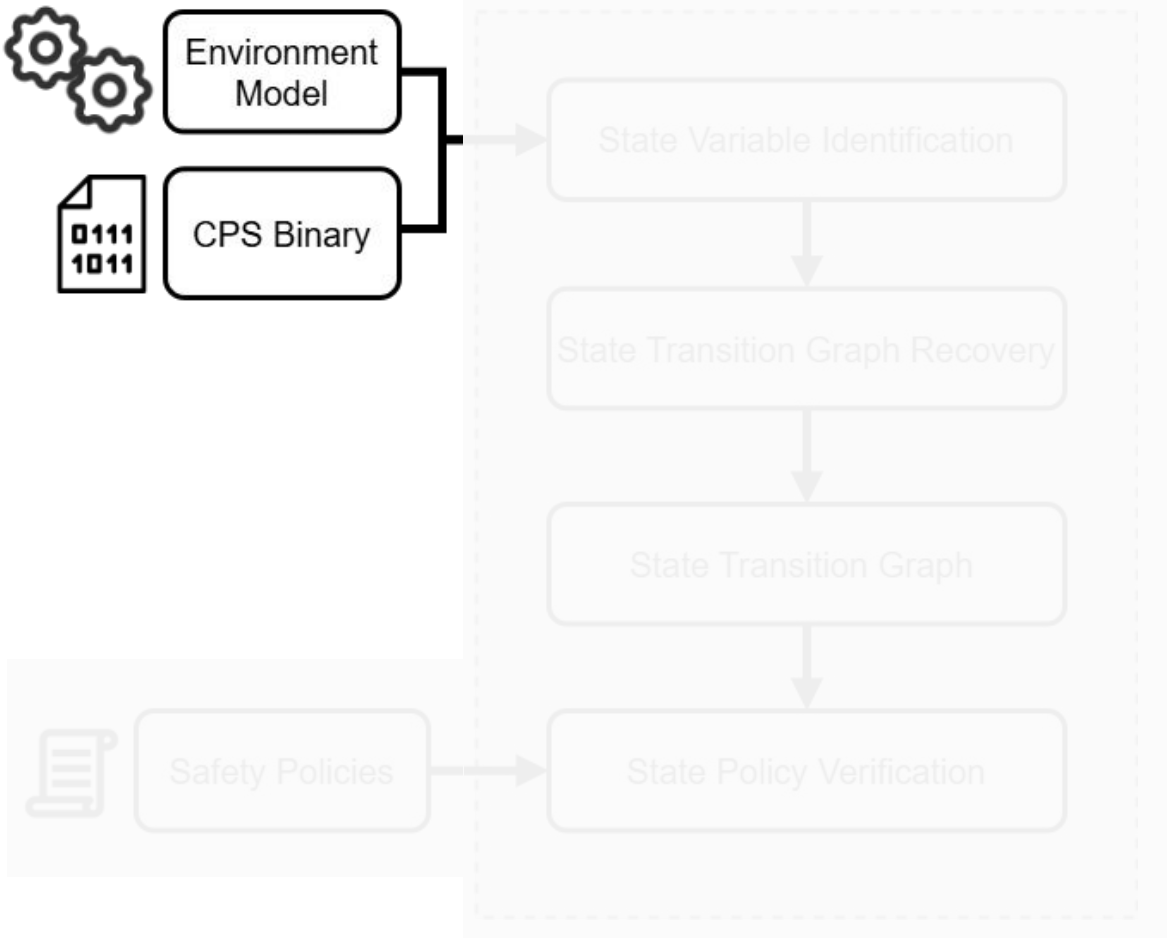
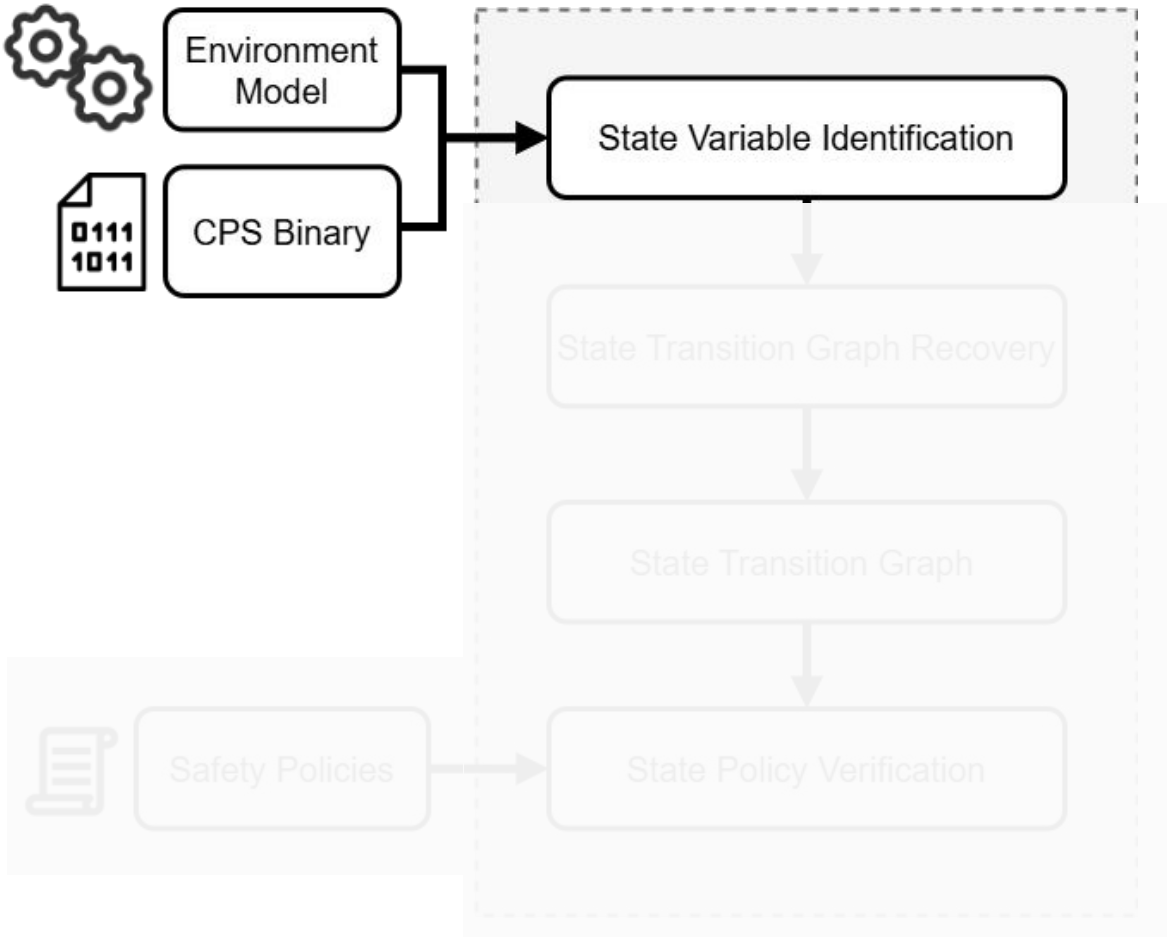


How does Taveren work?

- Built on top of **angr** (open-source binary analysis platform)
- Uses **finite-state machines** to model CPS' complexity
- Requires **CPS program**, ***safety*** **policies,** and **environment model**




Environment Model
CPS Binary
0111
1011
State Variable Identification
State Transition Graph Recovery
State Transition Graph
Safety Policies
State Policy Verification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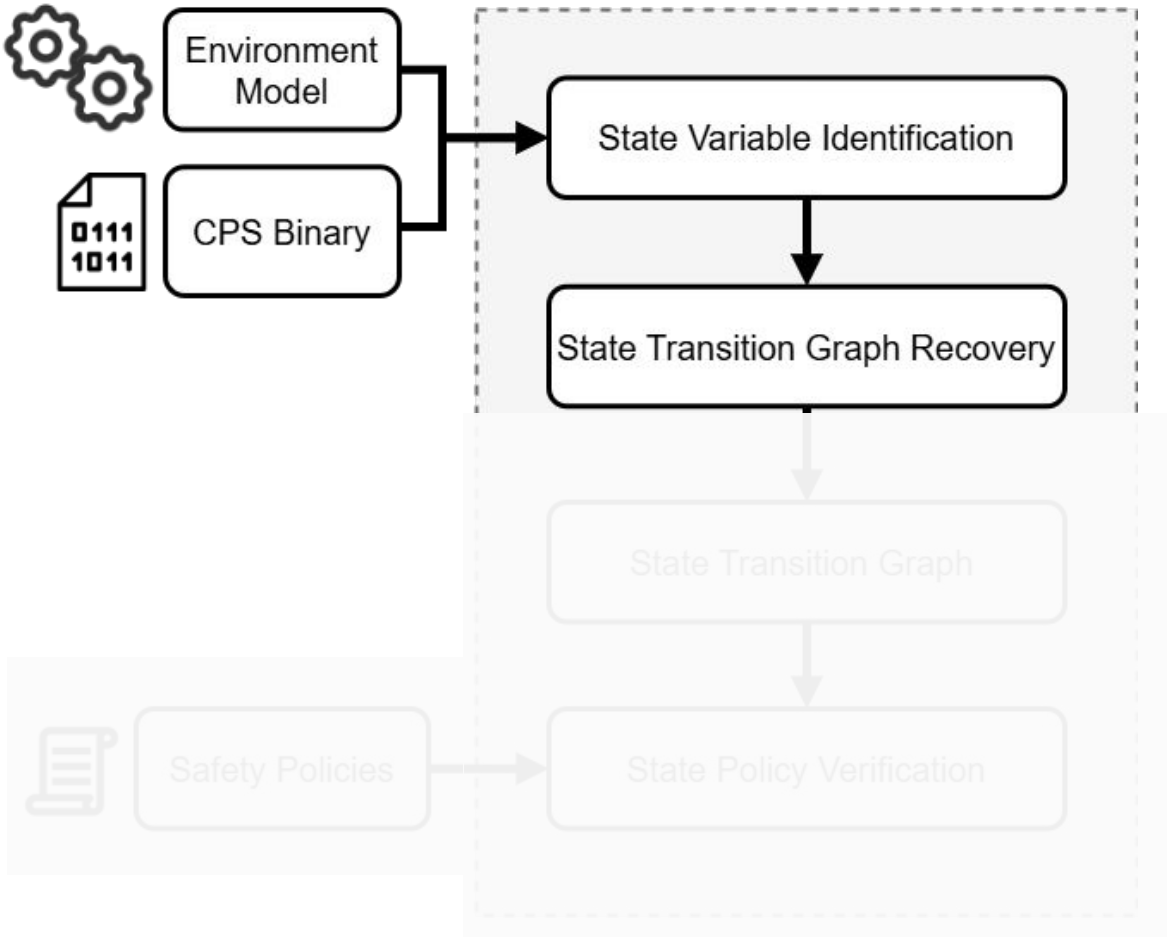
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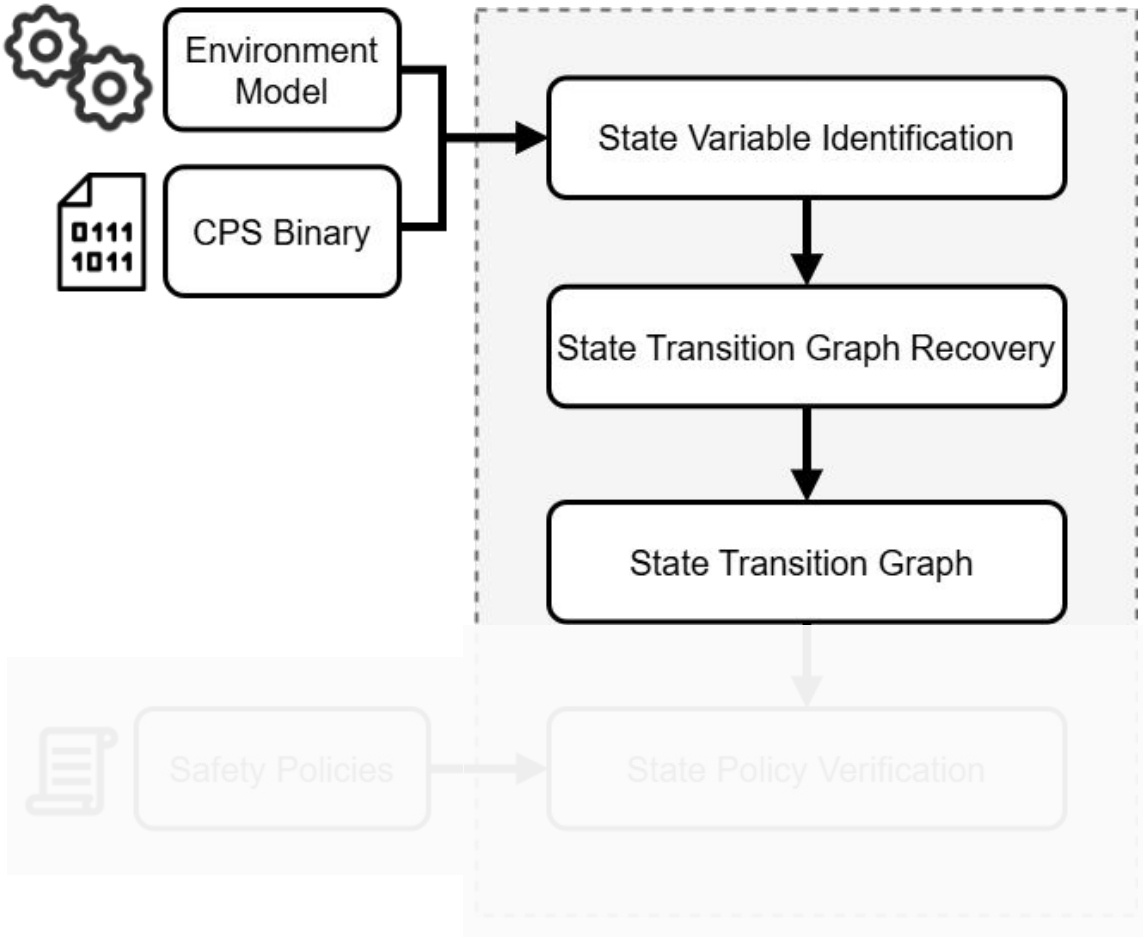
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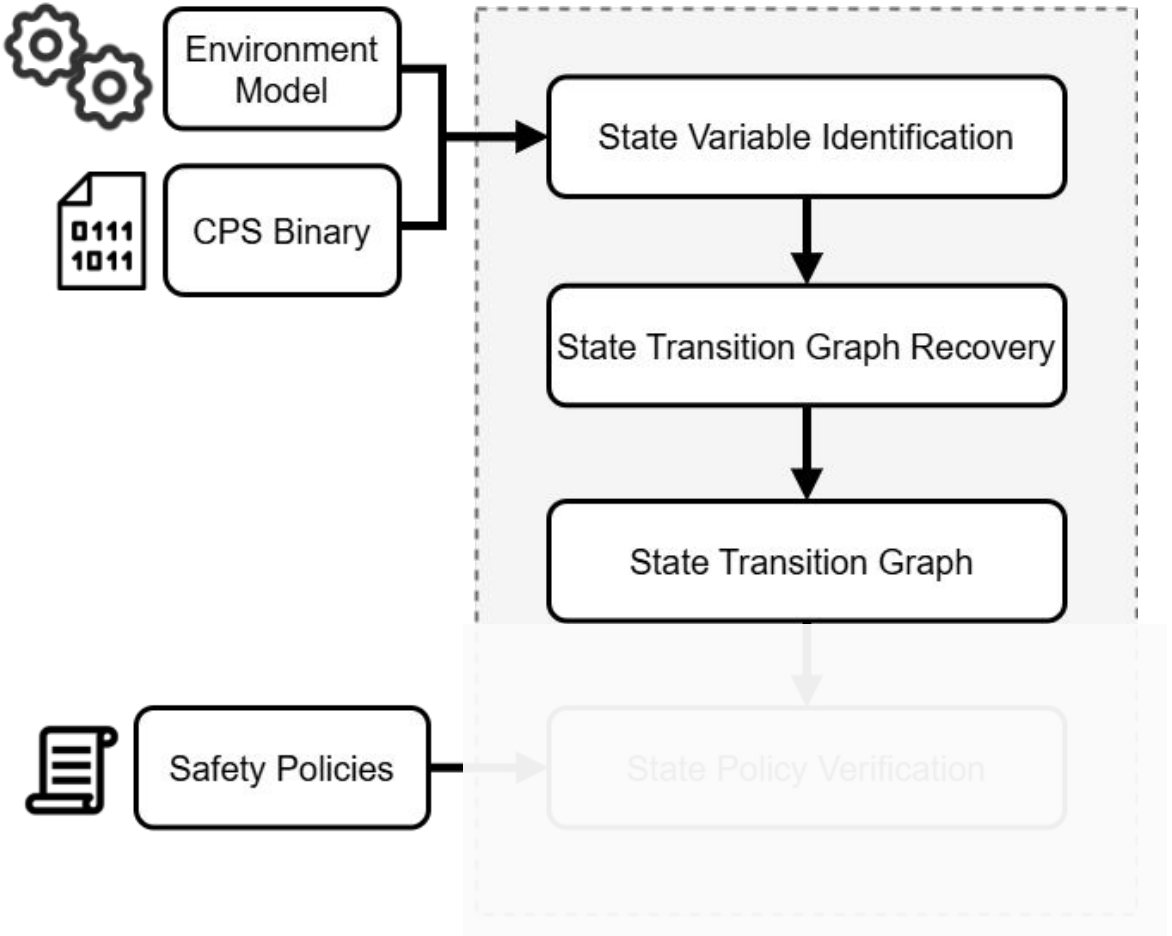
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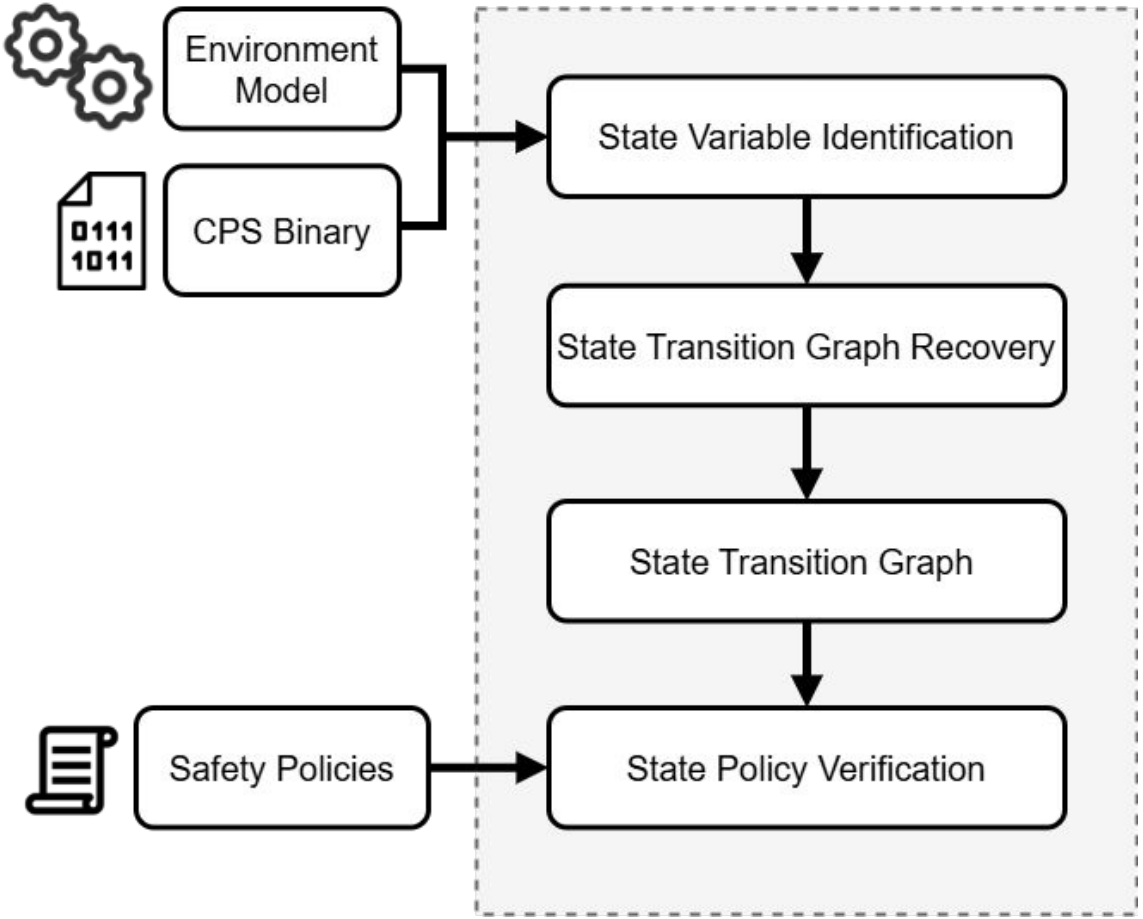
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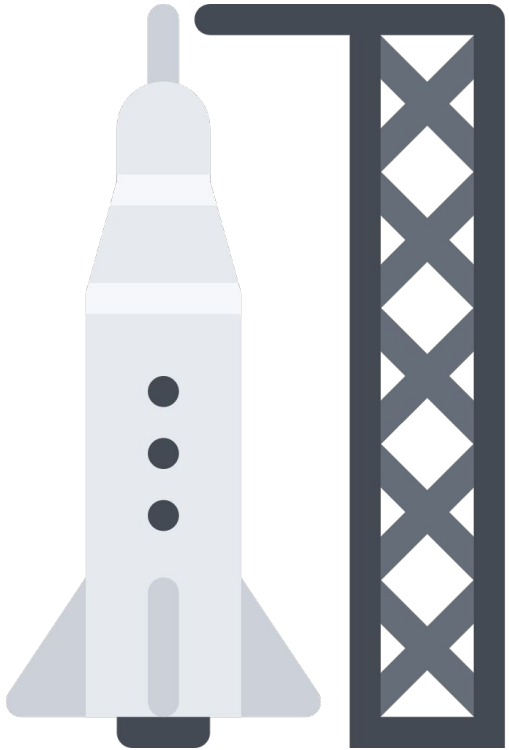
How did we evaluate Taveren?

- Dataset with 19 CPS Program Binaries



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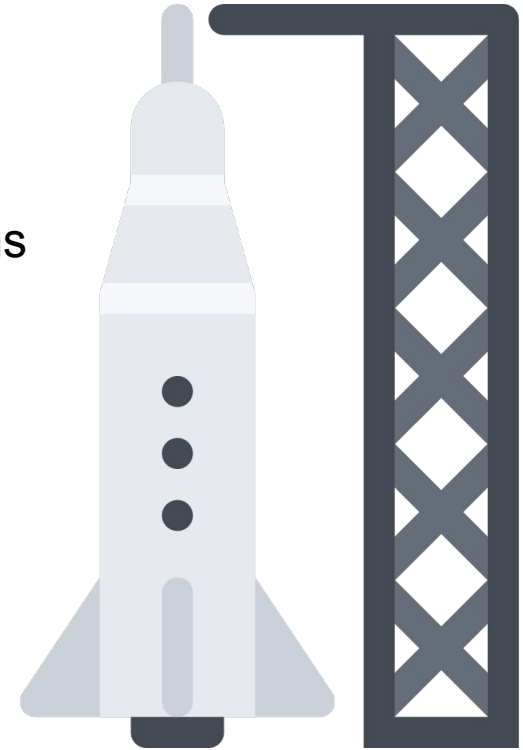
- Dataset includes **ICS, UAV, space and vehicle** programs



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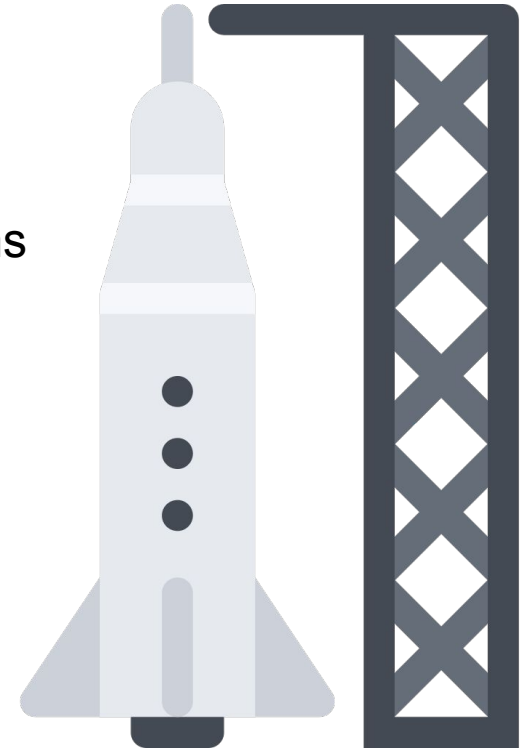

How did we evaluate Taveren?

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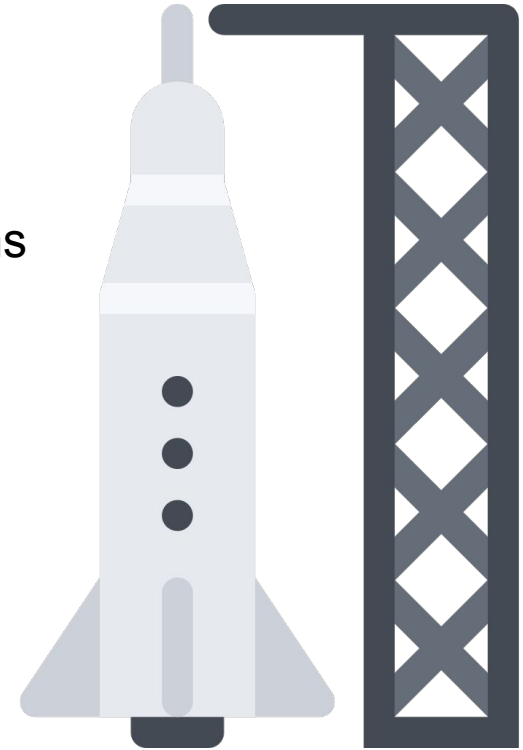
- Dataset includes **ICS, UAV, space and vehicle** programs
- ARM and x86 architectures
- 21 safety policies



What did we find?

- Taveren recovered all **19 CPS programs' transition graphs**
- Taveren has a **95% accuracy** enforcing safety policy

Safety Policy Enforcement Accuracy Results

Safety Policy Enforcement Accuracy Results

#	P.Copter.1	P.Copter.2	Correct?
Copter.1	T	T	Y
Copter.2	T	T	Y
#	**P.Rover.1**		**Correct?**
Rover.1	F		Unknown
#	**P.Lift.1**	**P.Lift.2**	**Correct?**
Lift.1	T	F	N
#	**P.WT.1**	**P.WT.2**	**Correct?**
WT.1	F	F	Y
WT.2	T	T	Y
WT.3	F	F	Y
#	**P.Pack.1**	**P.Pack.2**	**Correct?**
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Pack.1	T	F	Y

#	P.TL.1	P.TL.2	P.TL.3	Correct?
TL.4	T	F	T	Y
TL.5	T	F	T	Y
TL.6	T	F	T	Y
TL.7	T	F	F	Y
TL.8	F	F	T	Y
TL.9	T	T	T	Y
TL.10	T	F	F	Y
TL.11	T	T	T	Y
#	**P.Abort.1**	**P.Abort.2**		**Correct?**
Abort.3	F	T		Y
#	**P.Oven.1**	**P.Oven.2**	**P.Oven.3**	**Correct?**
Oven.1	T	T		Y
#	**P.Vend.1**			**Correct?**
Vend.1	F			Y
#	**P.Elev.1**	**P.Elev.2**	**P.Elev.3**	**Correct?**
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Safety Policy Enforcement Accuracy Results

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TL.6	T	F	T	Y
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TL.8	F	F	T	Y
TL.9	T	T	T	Y
TL.10	T	F	F	Y
TL.11	T	T	T	Y
#	P.Abort.1	P.Abort.2		Correct?
Abort.3	F	T		Y
#	P.Oven.1	P.Oven.2	P.Oven.3	Correct?
Oven.1	T	T		Y
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Safety Policy Enforcement Accuracy Results

CPS Binary
ArduCopter 1
ArduCopter 2

Safety Policy Enforcement Accuracy Results

CPS Binary	**Policy 1:** Do not apply throttle when in unknown position
ArduCopter 1	Patch Applied
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Safety Policy Enforcement Accuracy Results

CPS Binary	**Policy 1:** Do not apply throttle when in unknown position	**Policy 2:** Flip maneuvers cannot last more than 2.5 seconds
ArduCopter 1	Patch Applied	Patch Applied
ArduCopter 2	Patch Applied	Patch Applied

Safety Policy Enforcement Accuracy Results

CPS Binary	**Policy 1:** Do not apply throttle when in unknown position	**Policy 2:** Flip maneuvers cannot last more than 2.5 seconds	**Taveren Result**
ArduCopter 1	Patch Applied	Patch Applied	Correct
ArduCopter 2	Patch Applied	Patch Applied	Correct

Conclusion: Taveren

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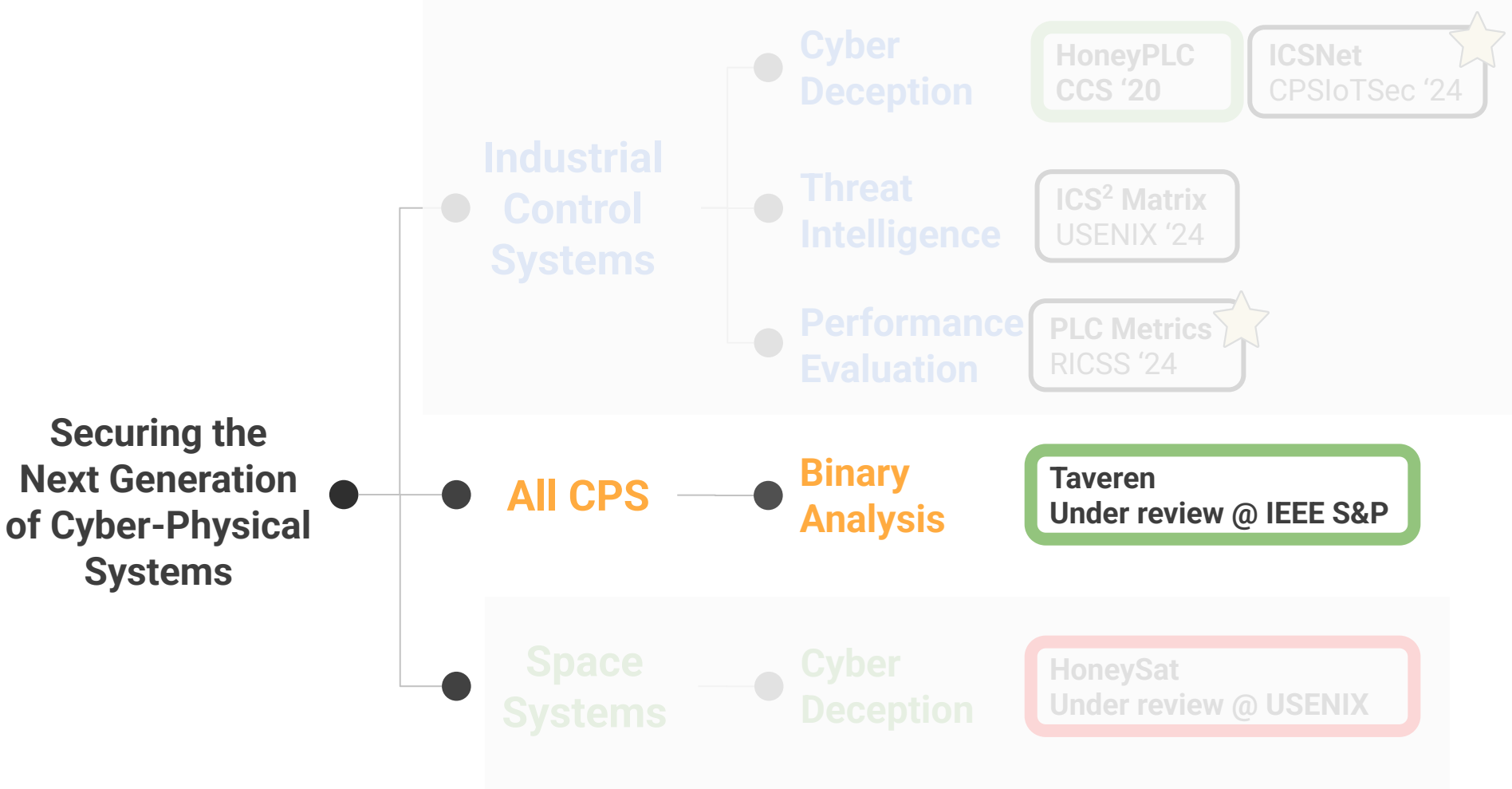
- First binary analysis tool to find safety vulnerabilities in CPS programs
- Works with multiple types of CPS
- Evaluated using real-world CPS programs
- Improves the cybersecurity of CPS by finding previously unknown safety vulnerabilities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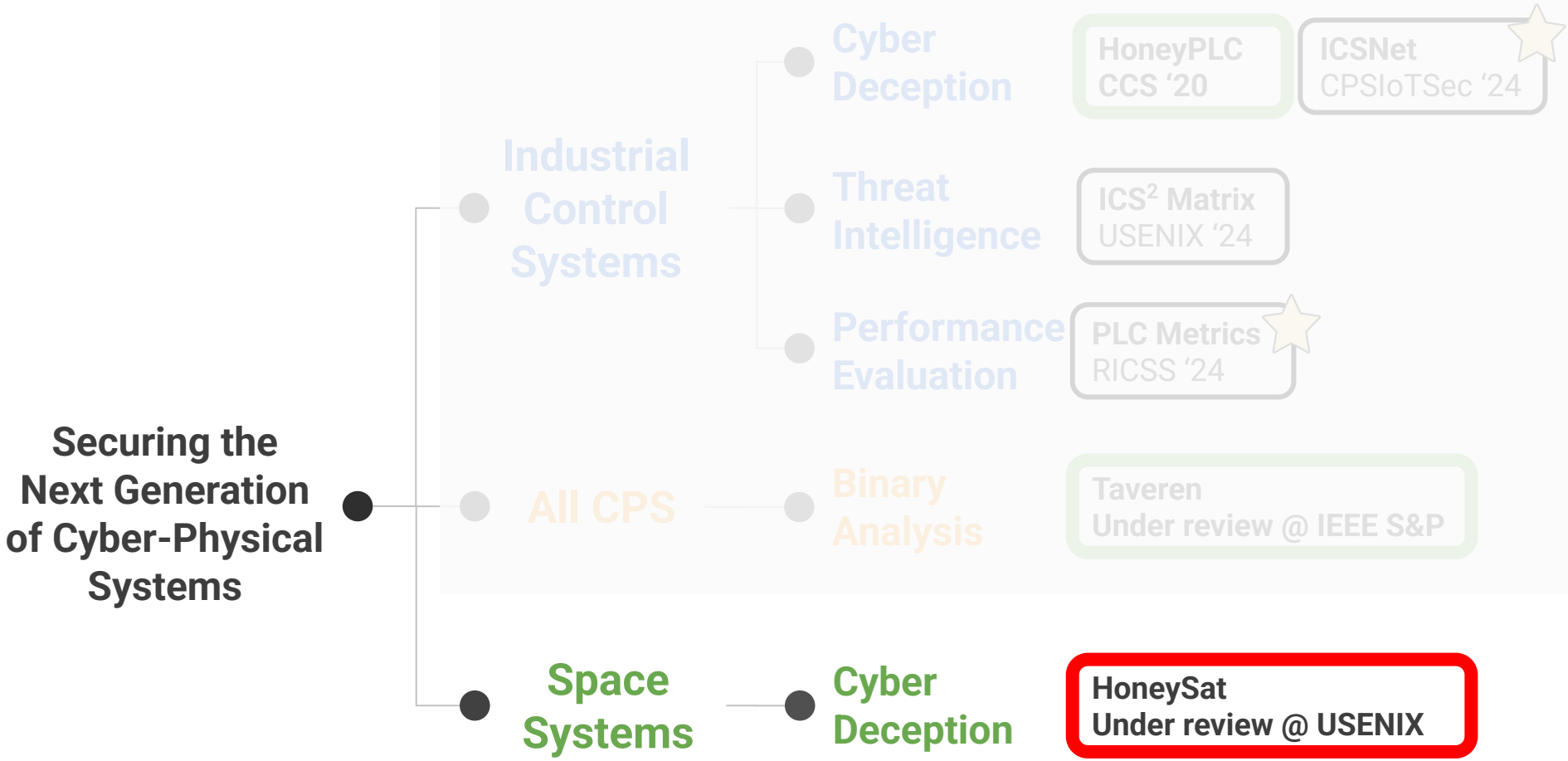
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SPACEX

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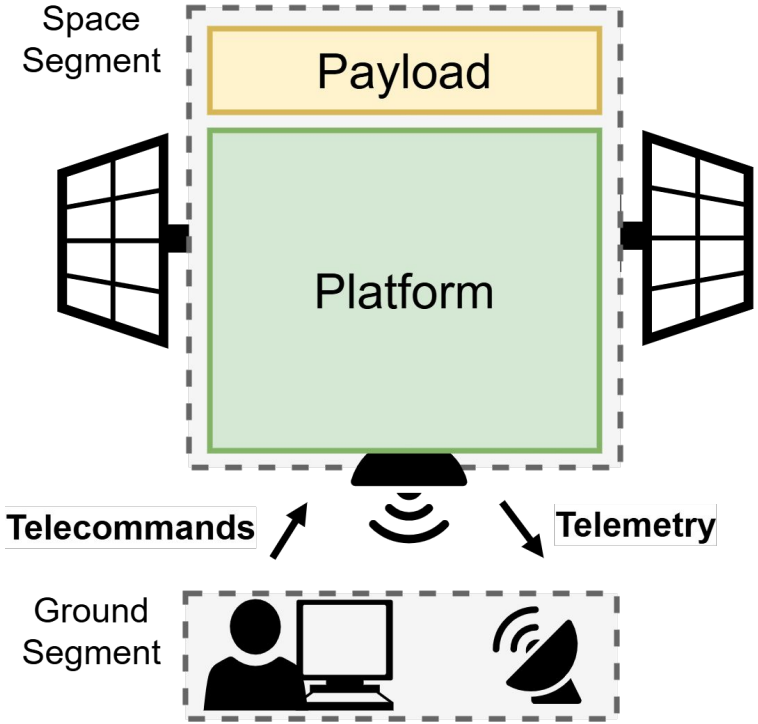
New Star Wars Plan: Pentagon Rushes to Counter Threats in Orbit

Background: Anatomy of a Satellite Mission



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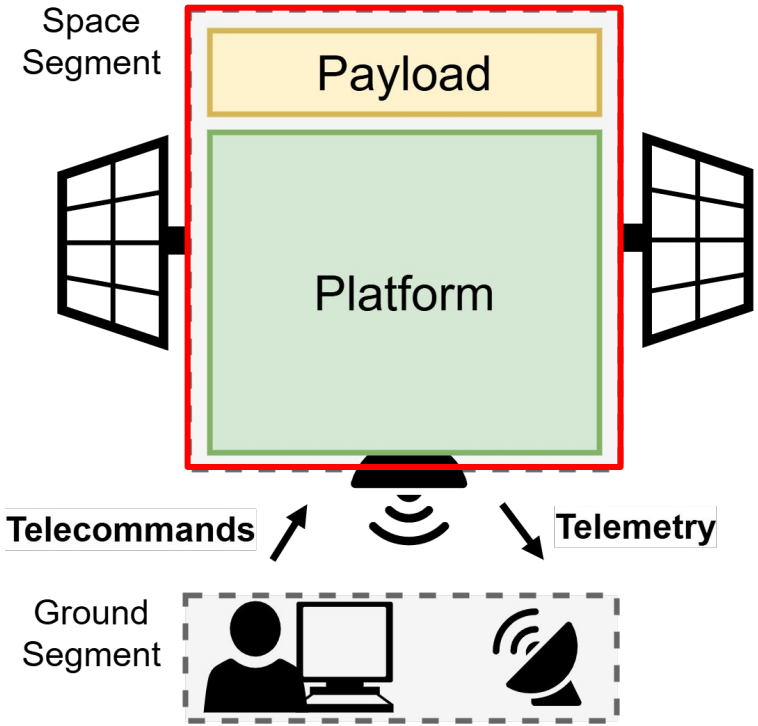

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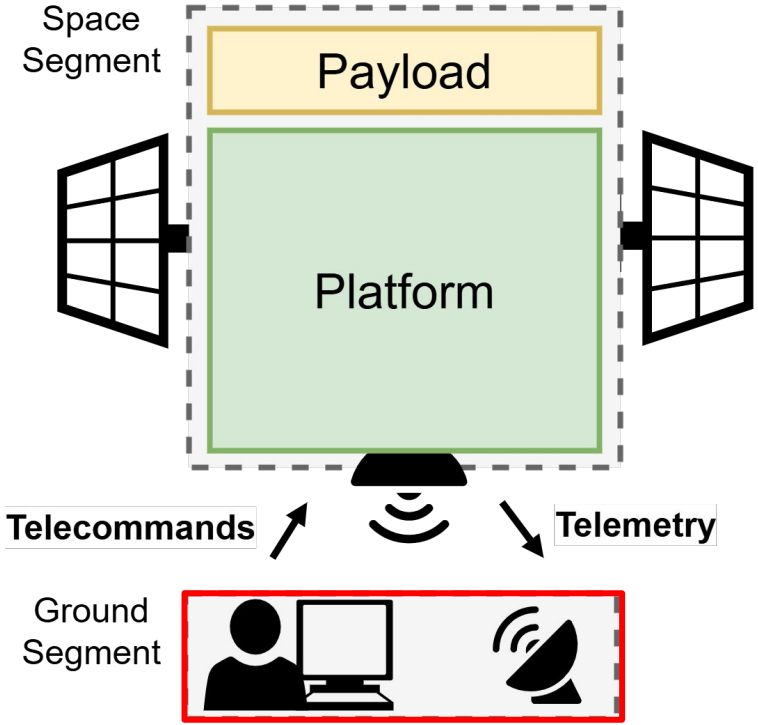

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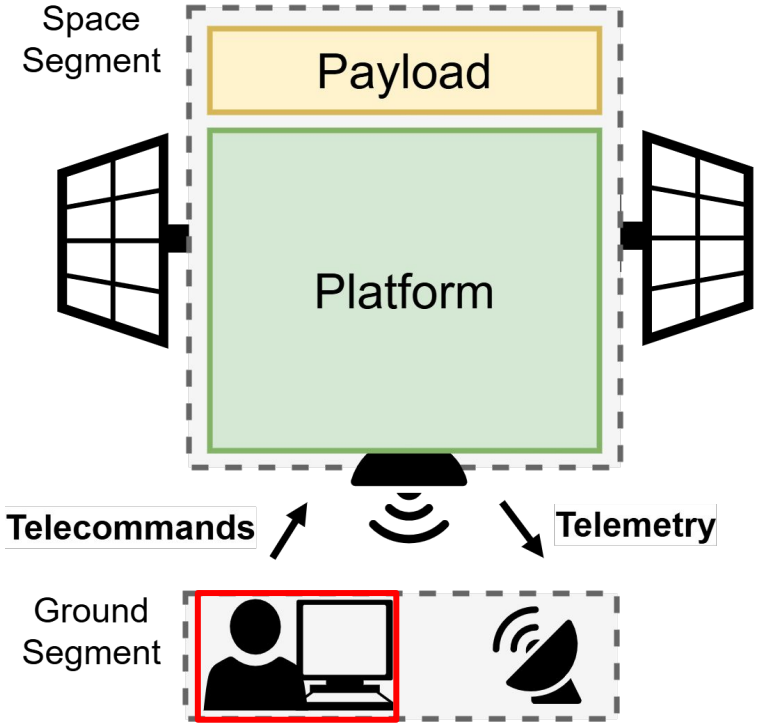

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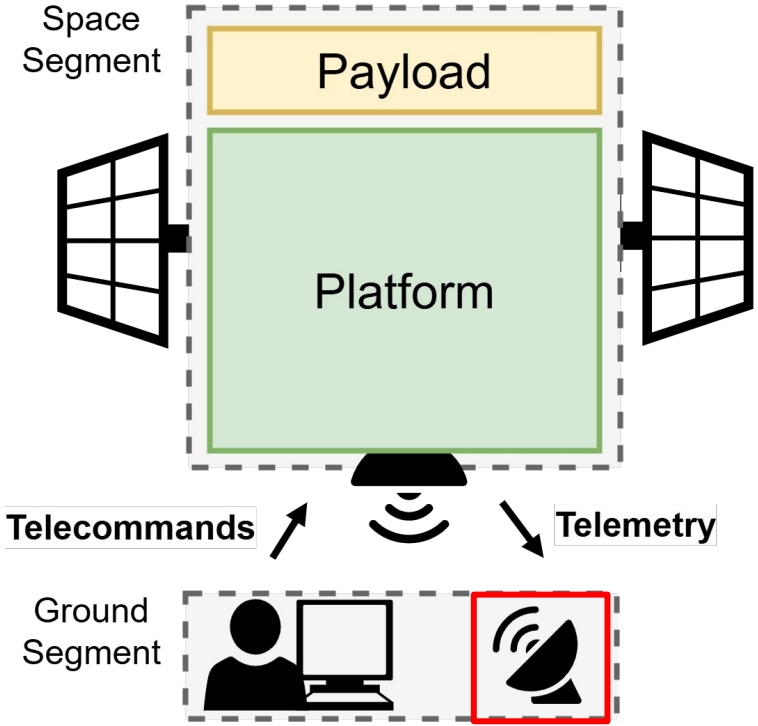

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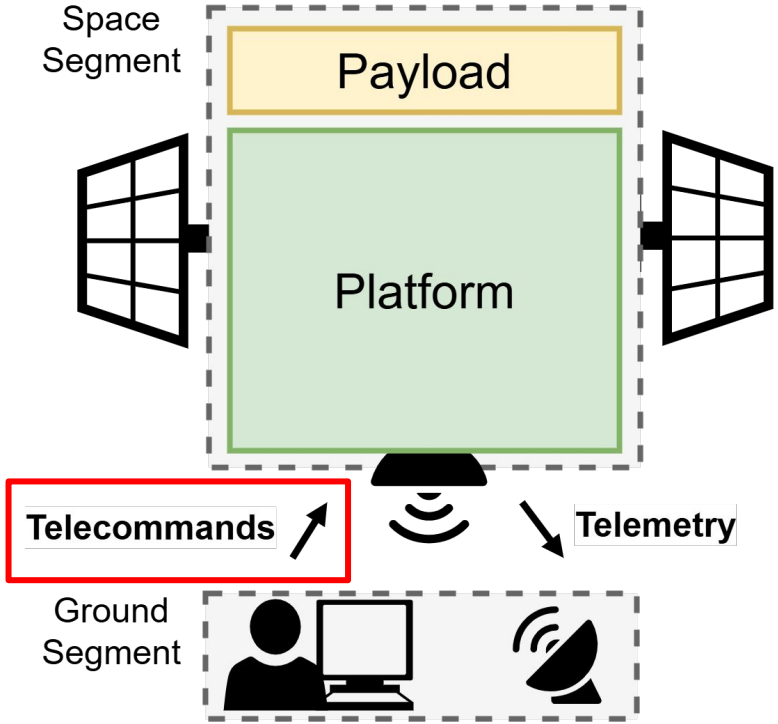

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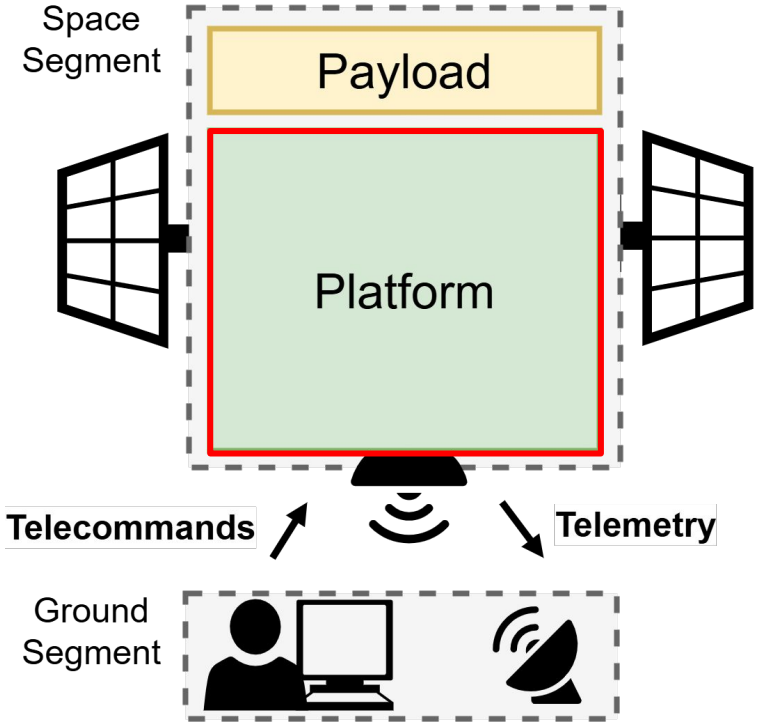

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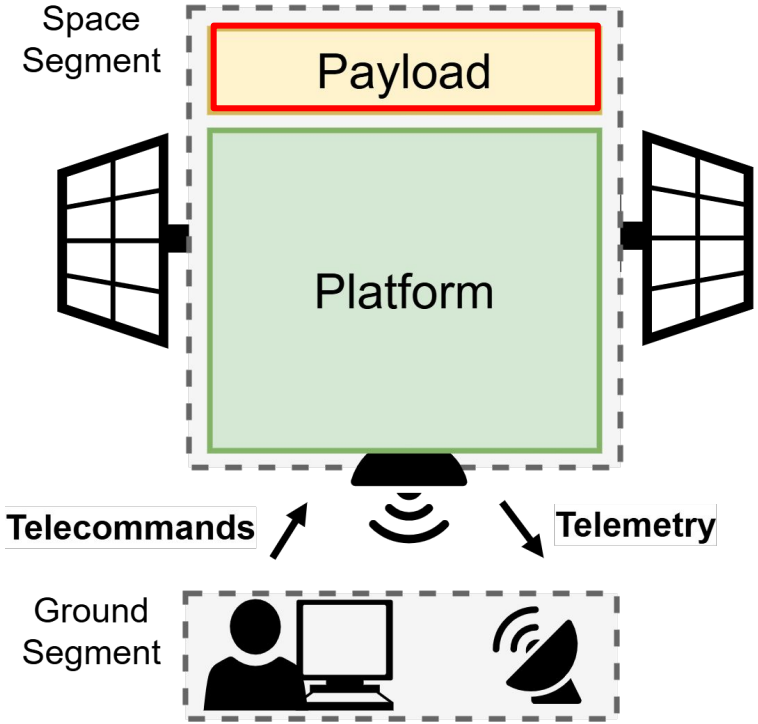

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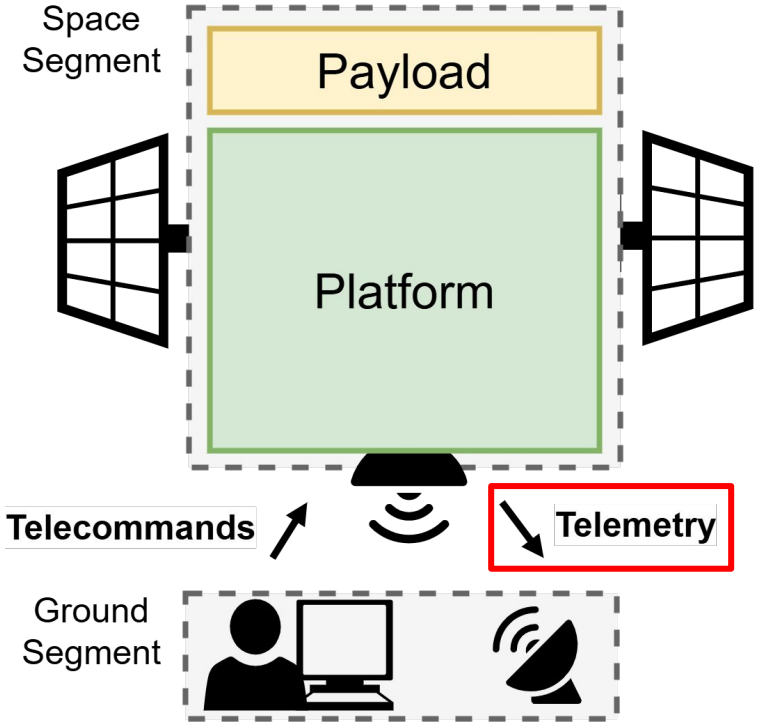

Background: Refresher on Honeypots

- Decoy computer system

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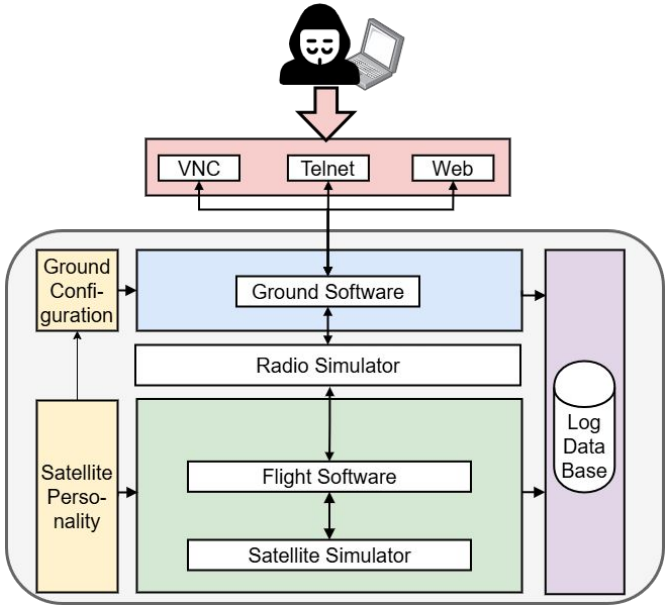
- Decoy computer system
- Attracts malicious actors
- Record all interaction data
- Analyze data to obtain knowledge
- There is no satellite honeypot!

What is the problem?

There is no way to collect data regarding cyberattacks that target satellites.

Our solution: HoneySat

- Honeypot that multiple real satellite missions



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- Honeypot that multiple real satellite missions
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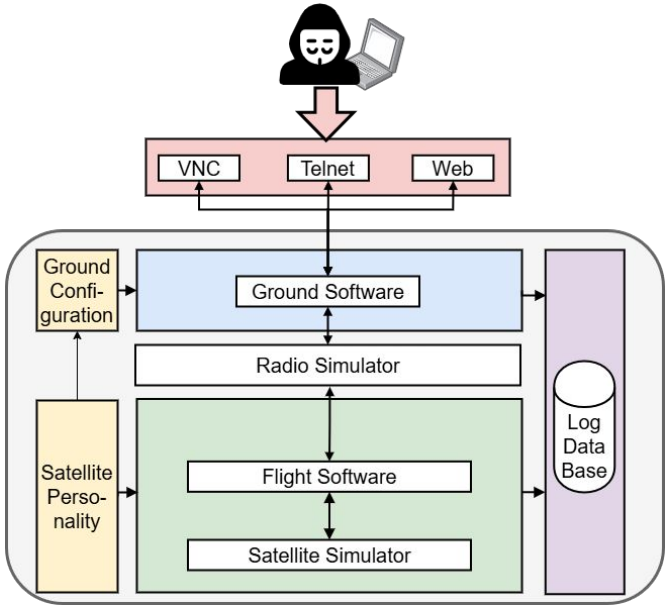

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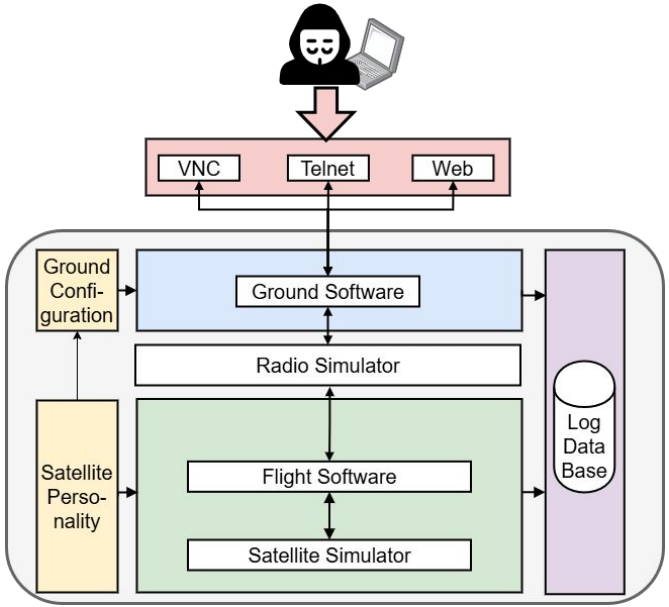
- Honeypot that multiple real satellite missions
- Accessible via the Internet
- Uses real satellite software



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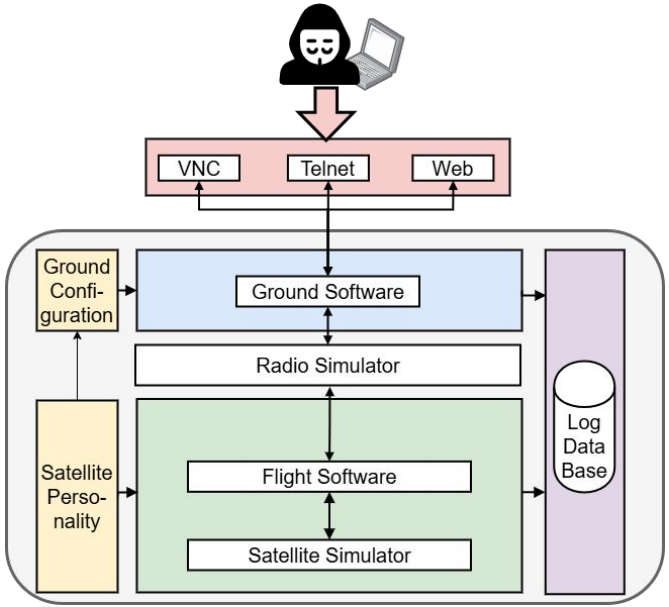
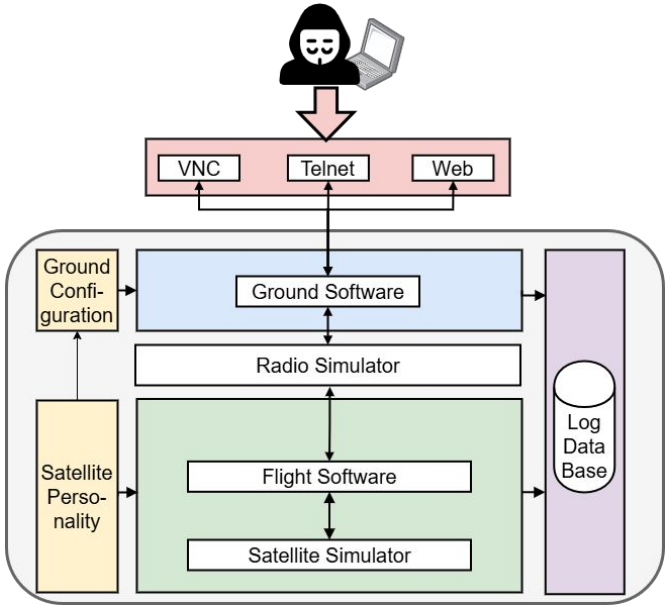
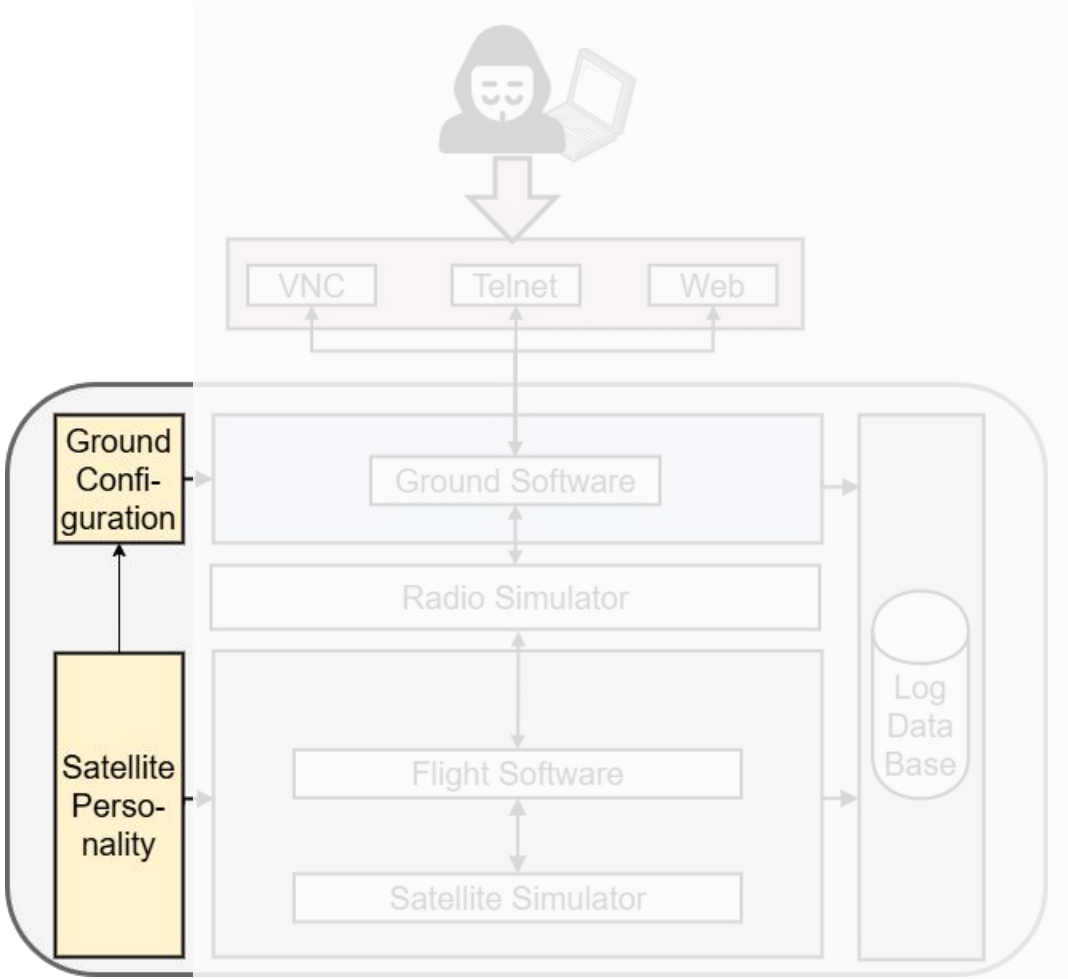


Our solution: HoneySat

- Honeypot that multiple real satellite missions
- Accessible via the Internet
- Uses real satellite software
- Simulates space physics (orbital mechanics)
- Collects real-world satellite cyberattack data

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Log Data Base
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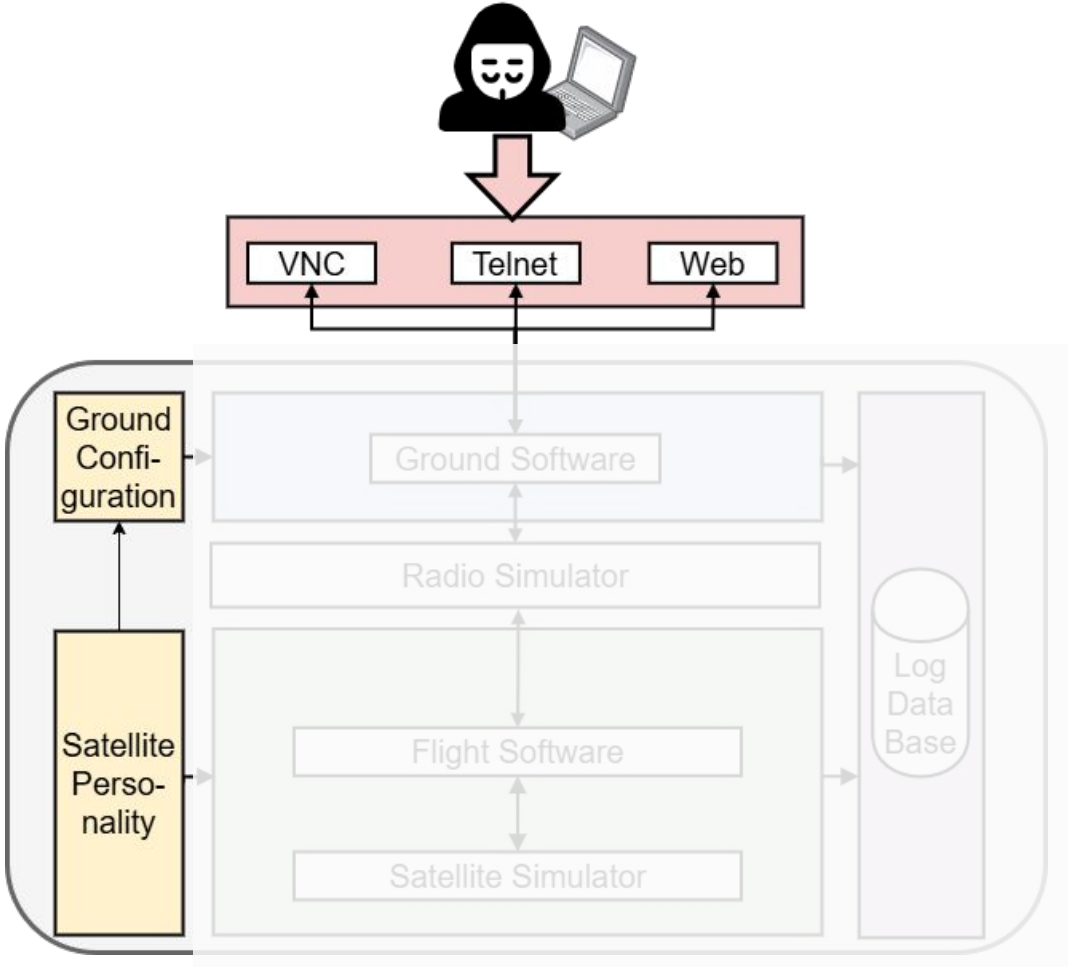
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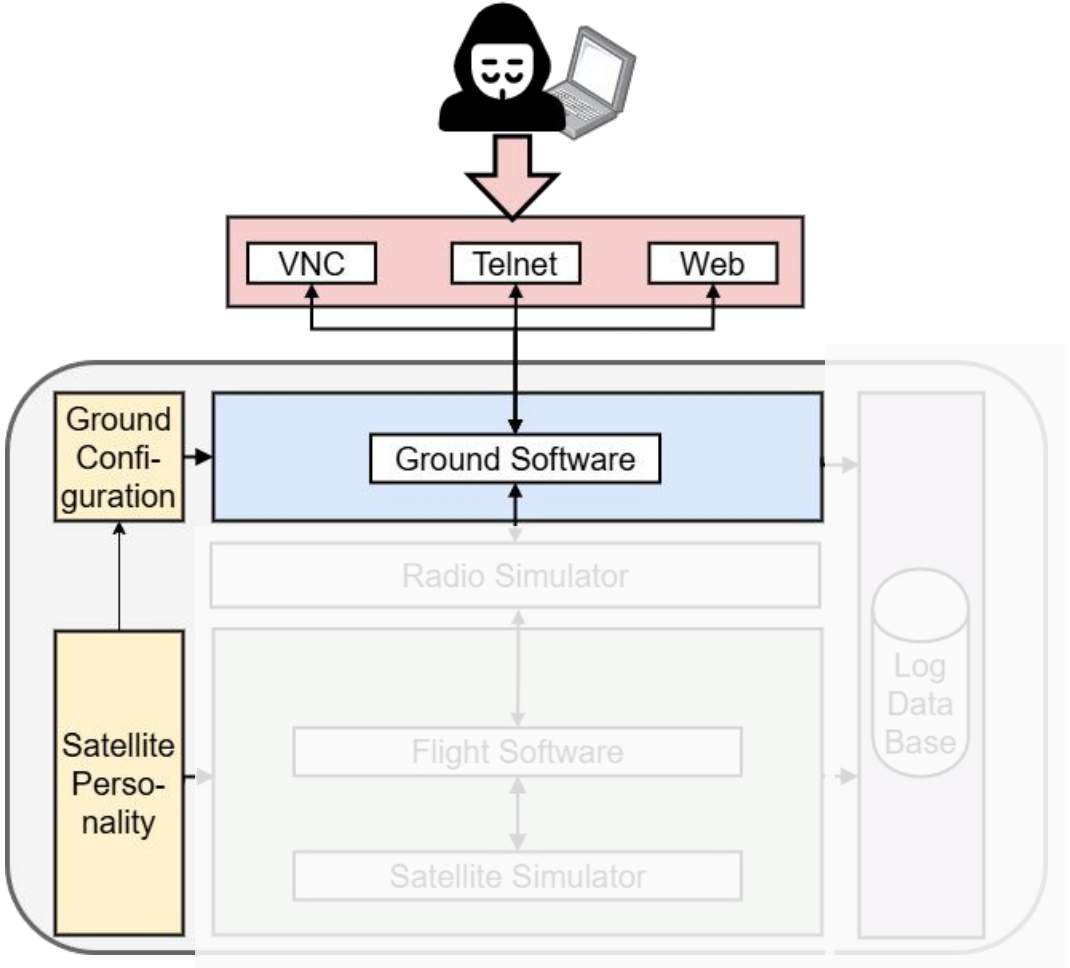
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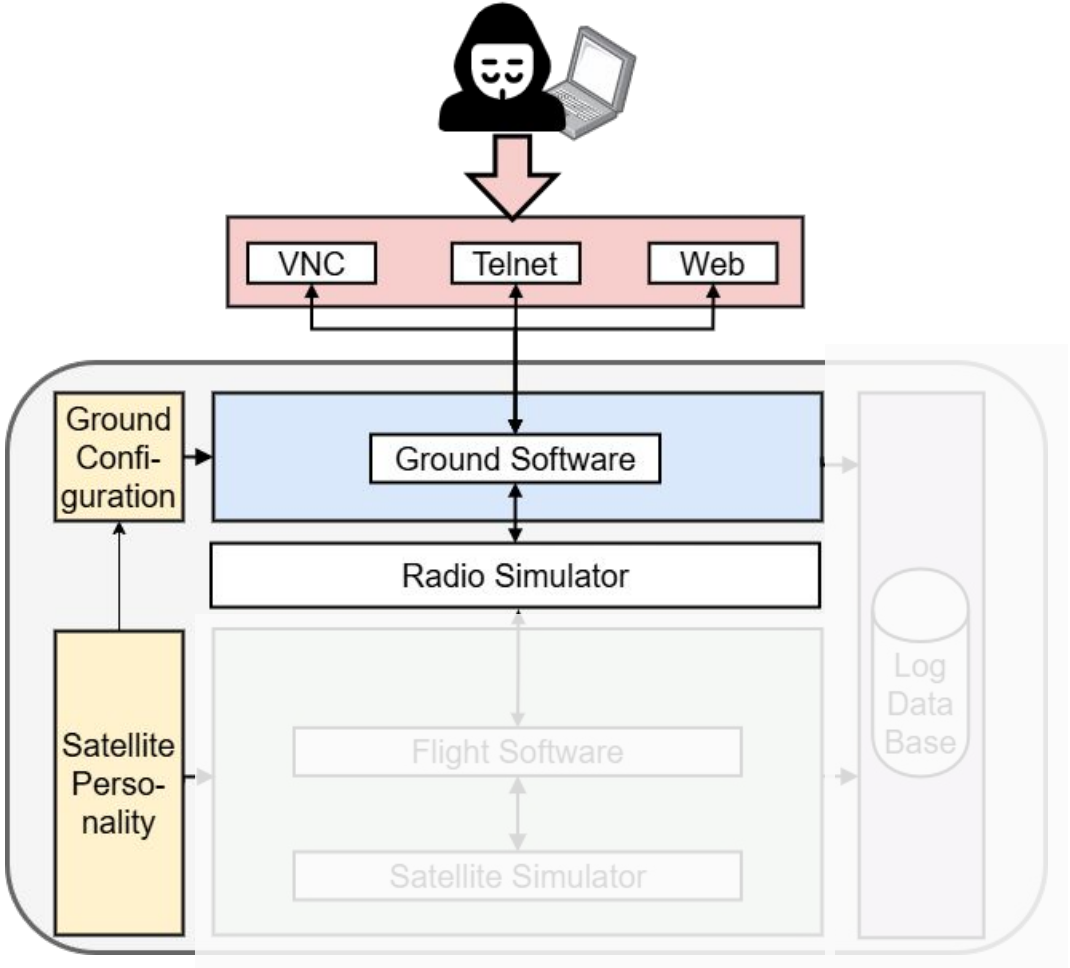
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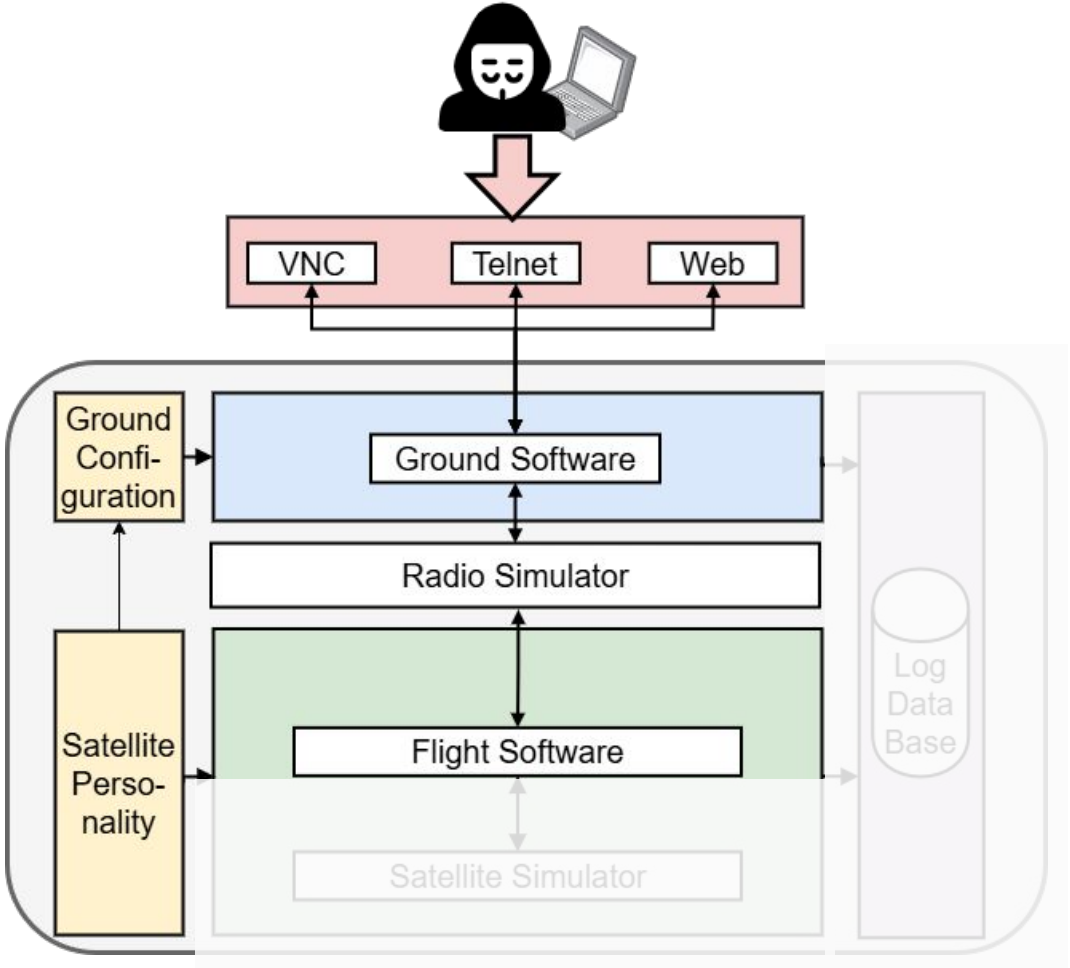
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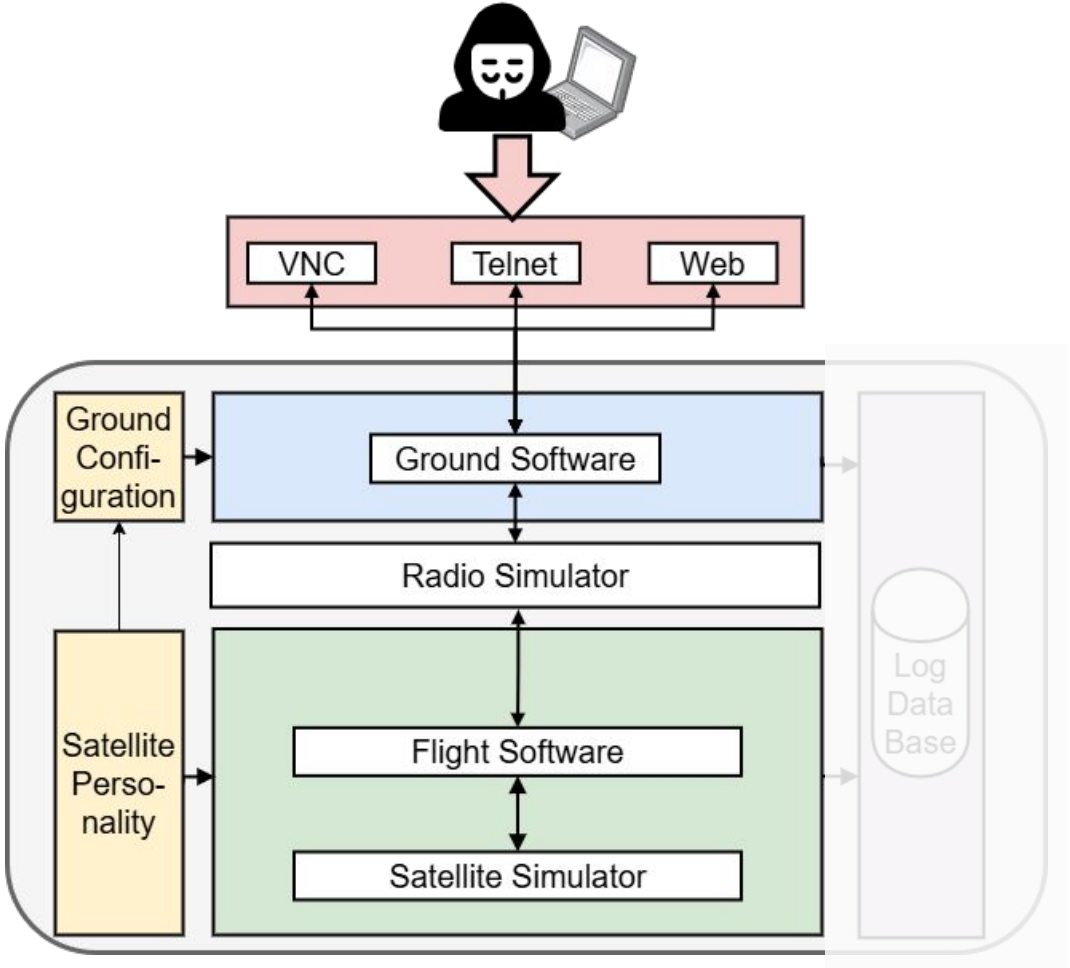
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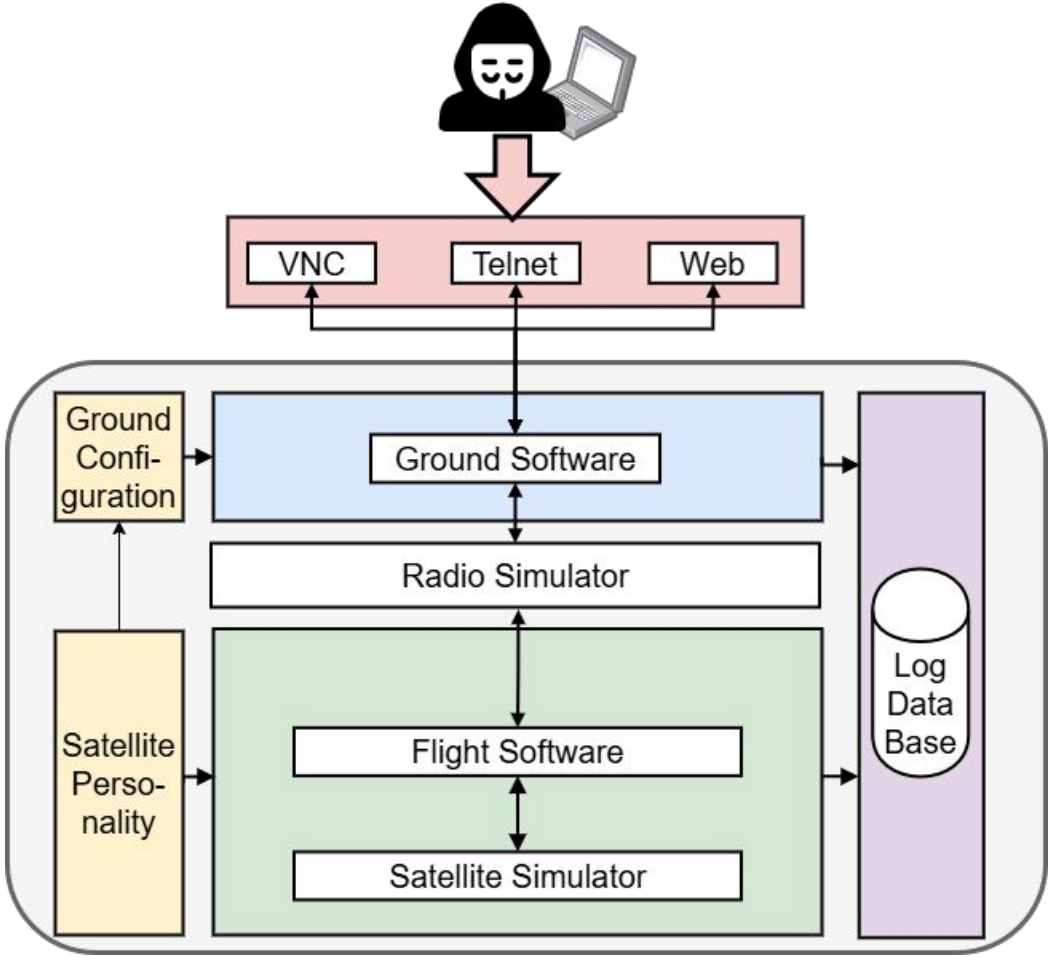
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  - Satellite's orbit
  - Battery
  - 3D-space orientation
  - Temperature
  - Magnetic field
  - Payload

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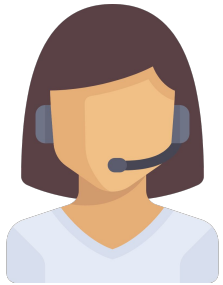

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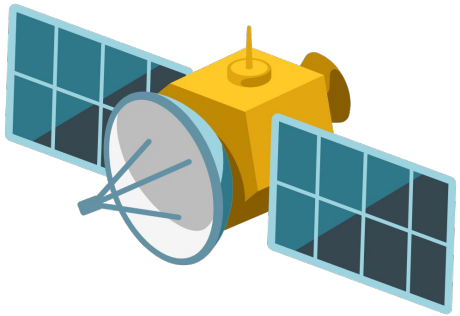
- One adversary interacted with HoneySat for 2 hours

Conclusion: HoneySat

- First satellite honeypot ever



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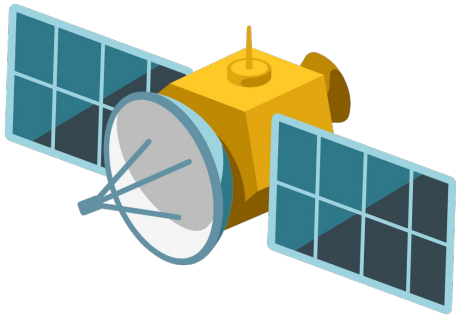

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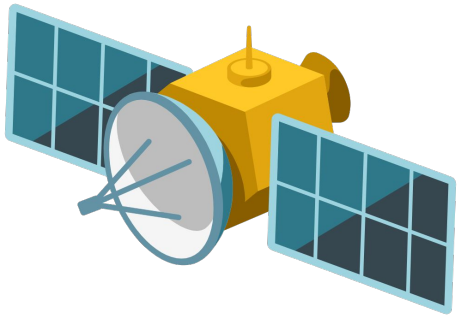

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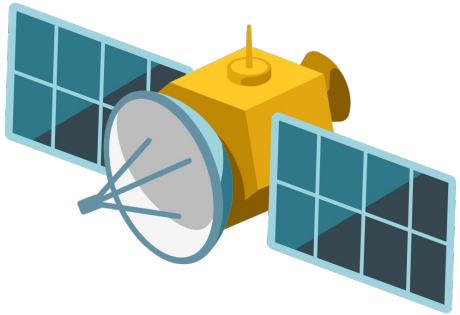

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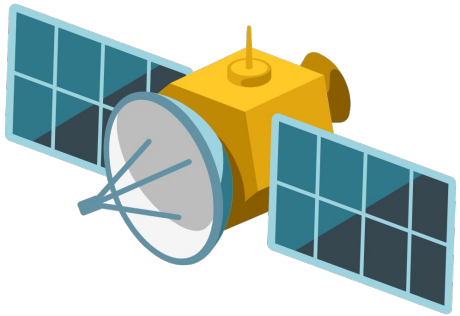

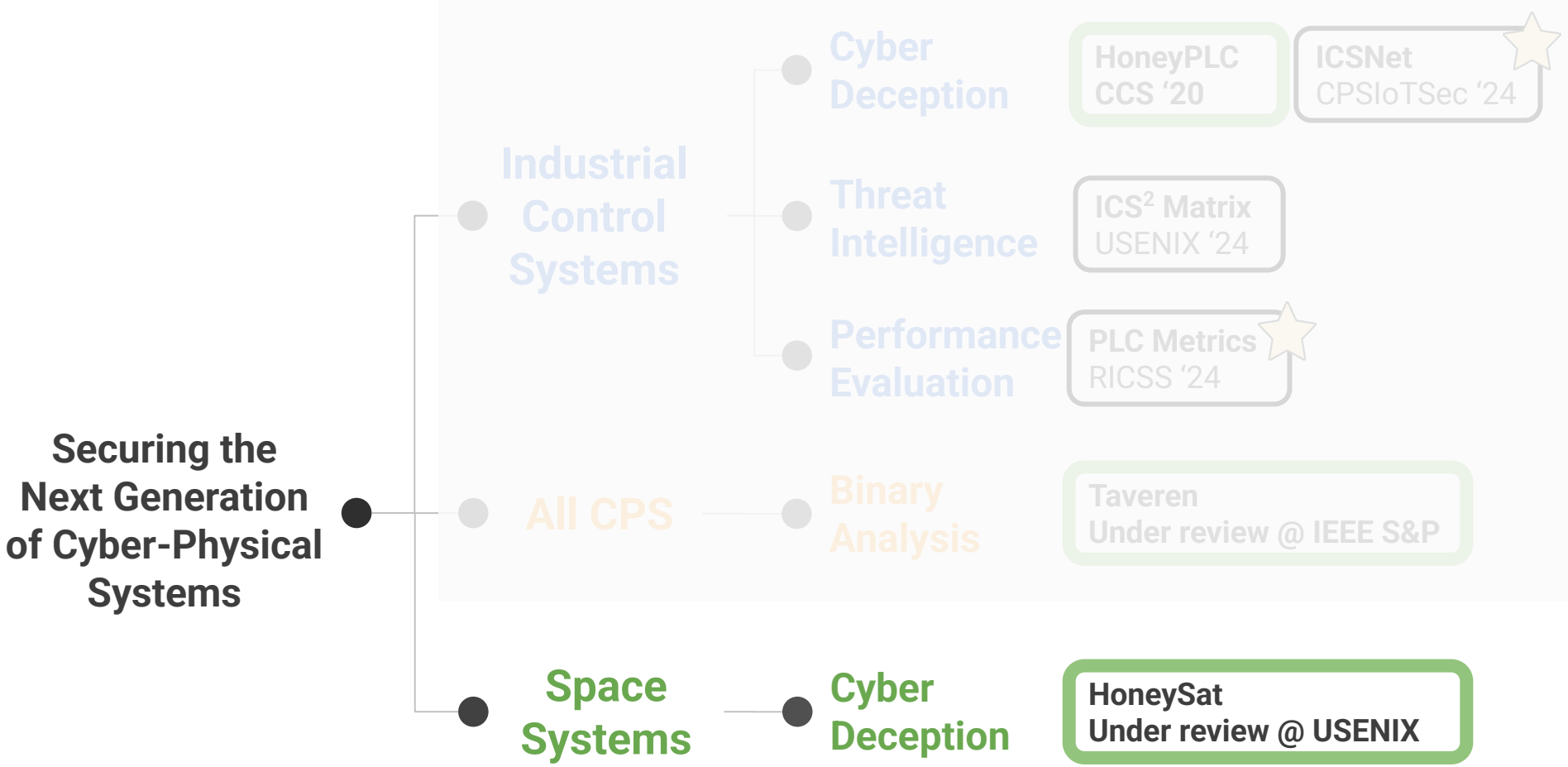
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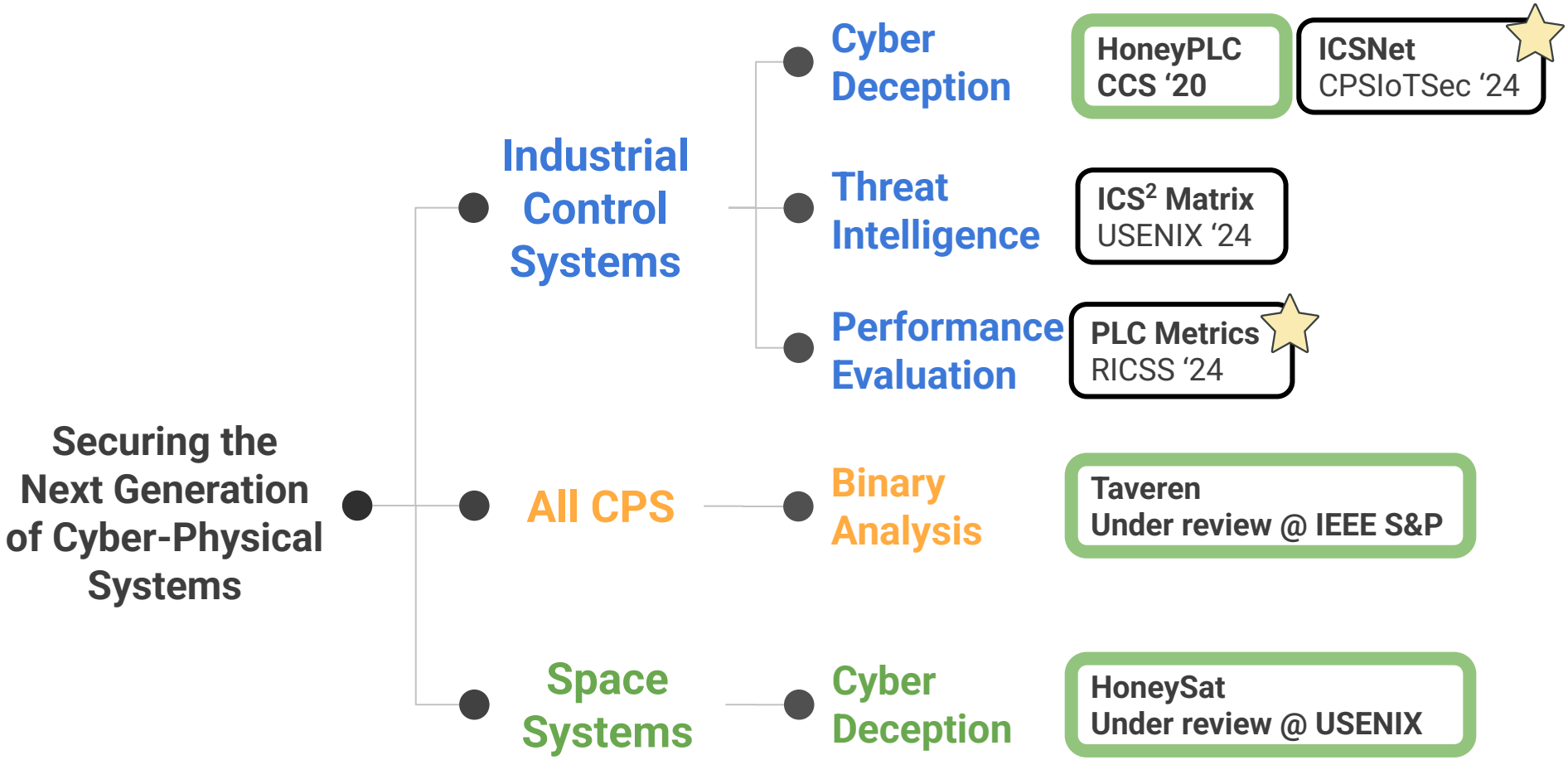
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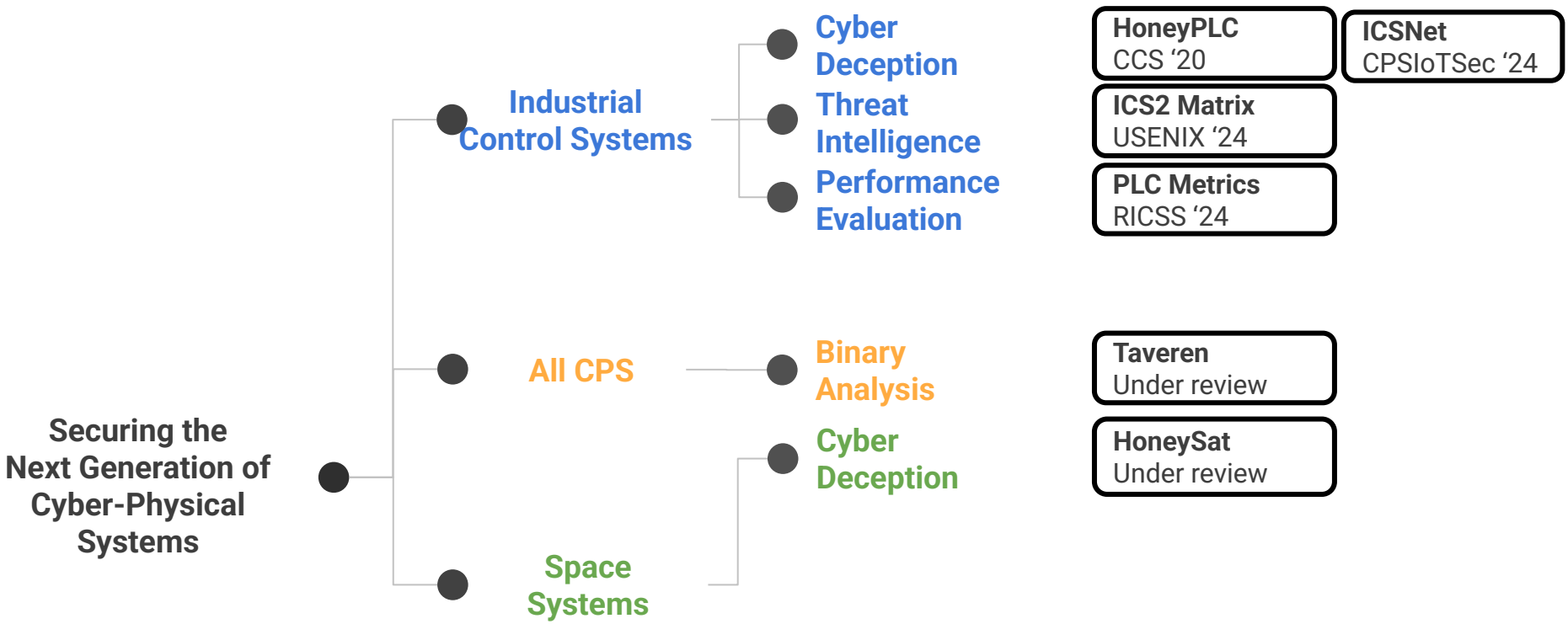
Future Research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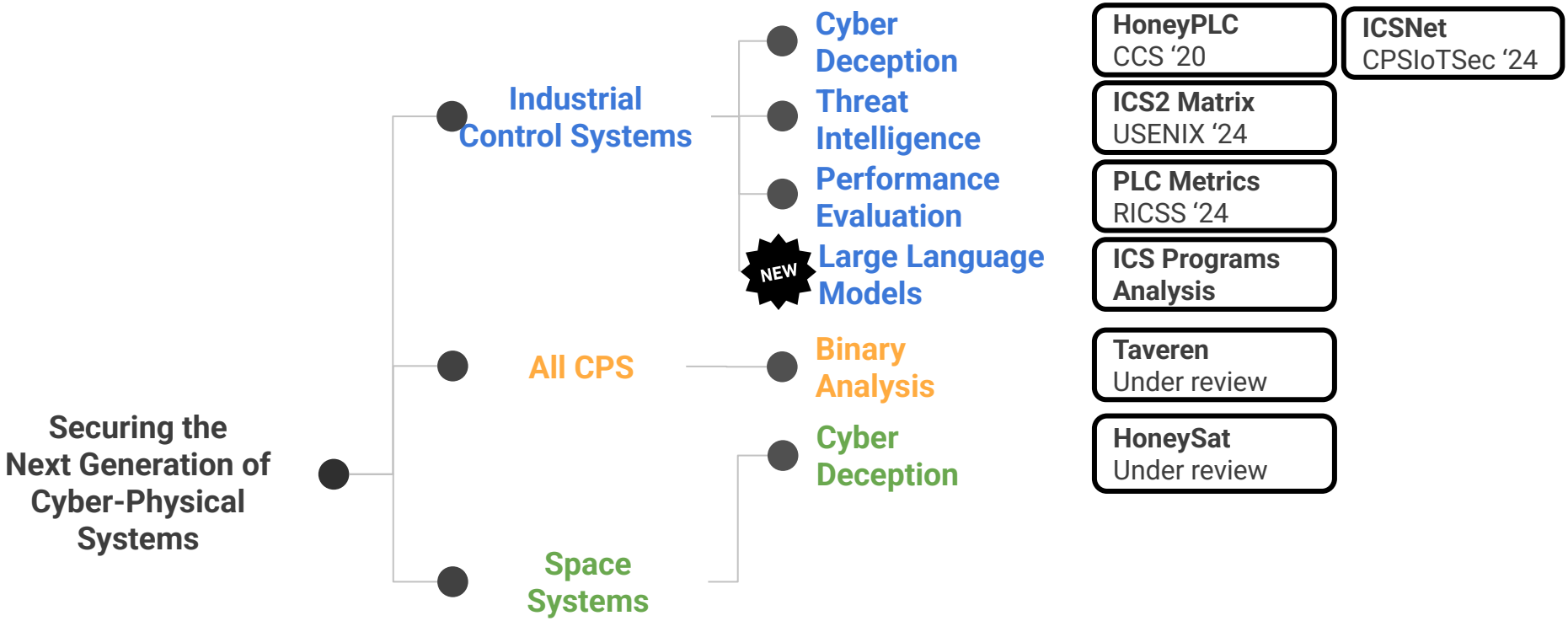
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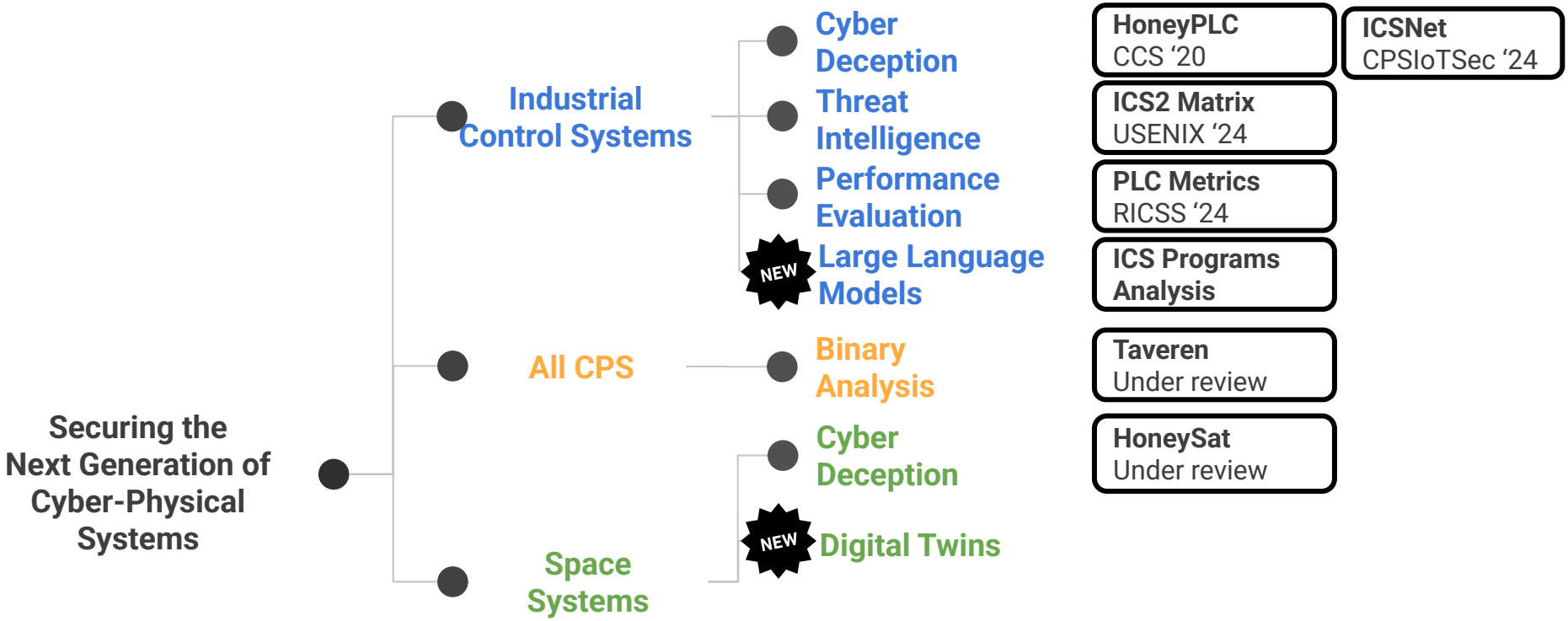
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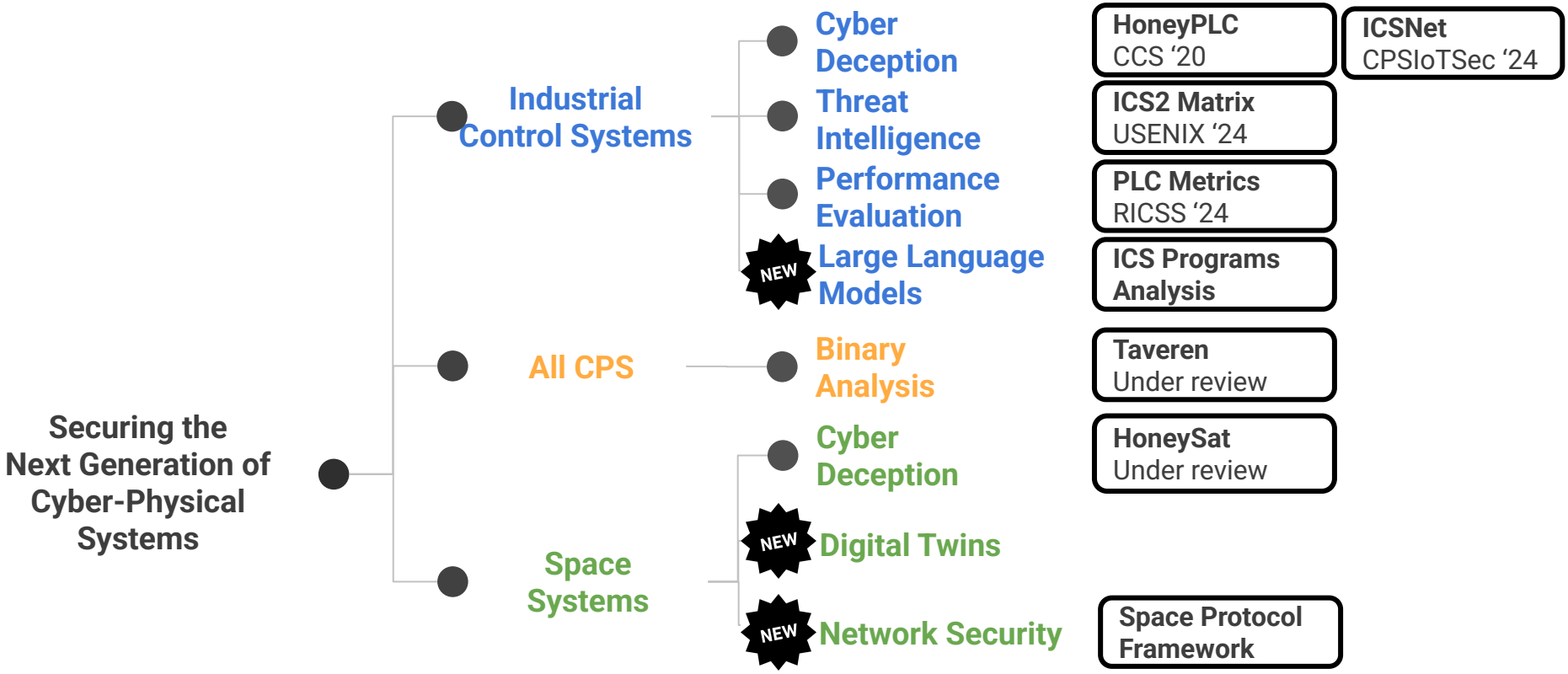
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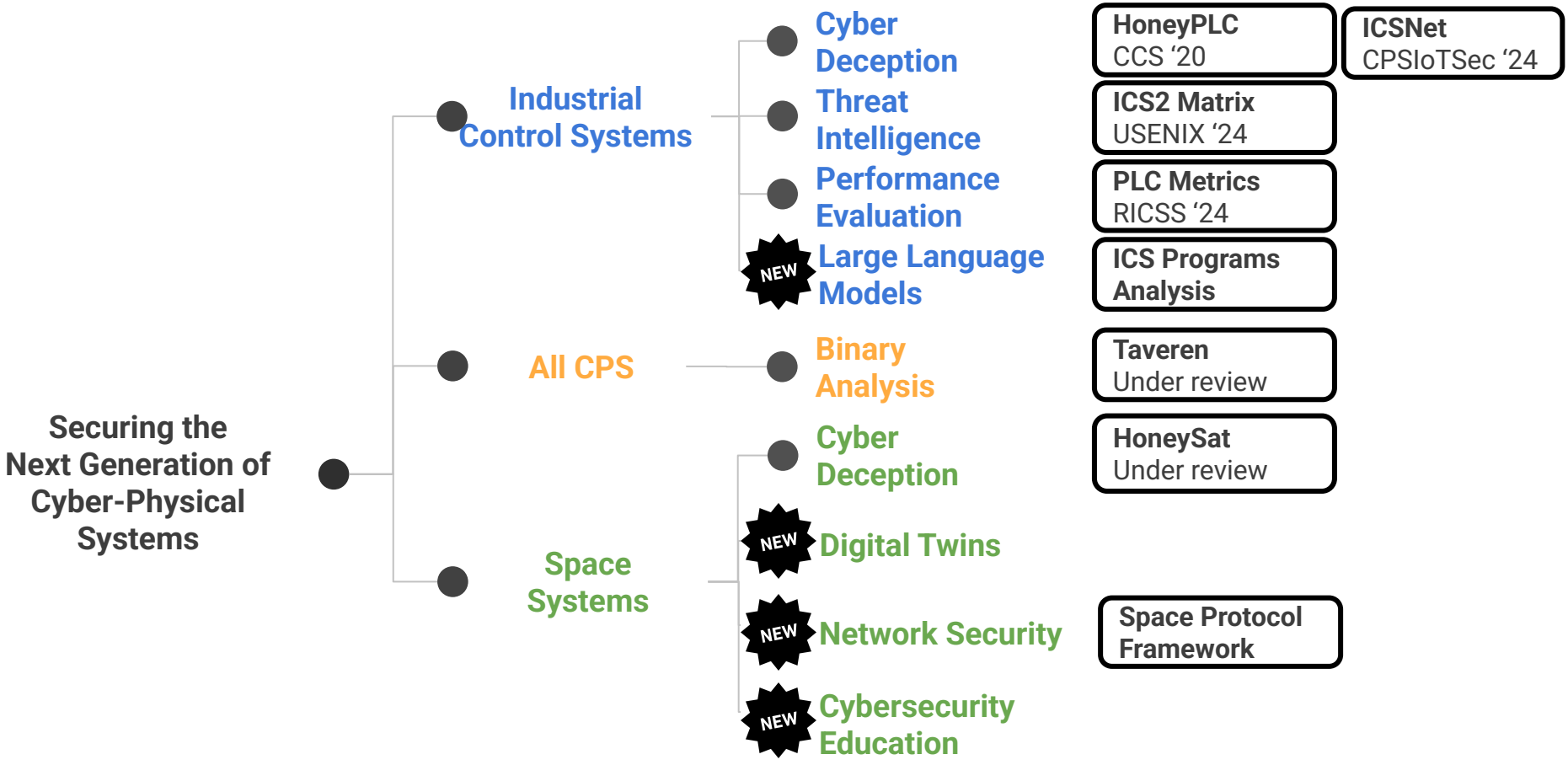
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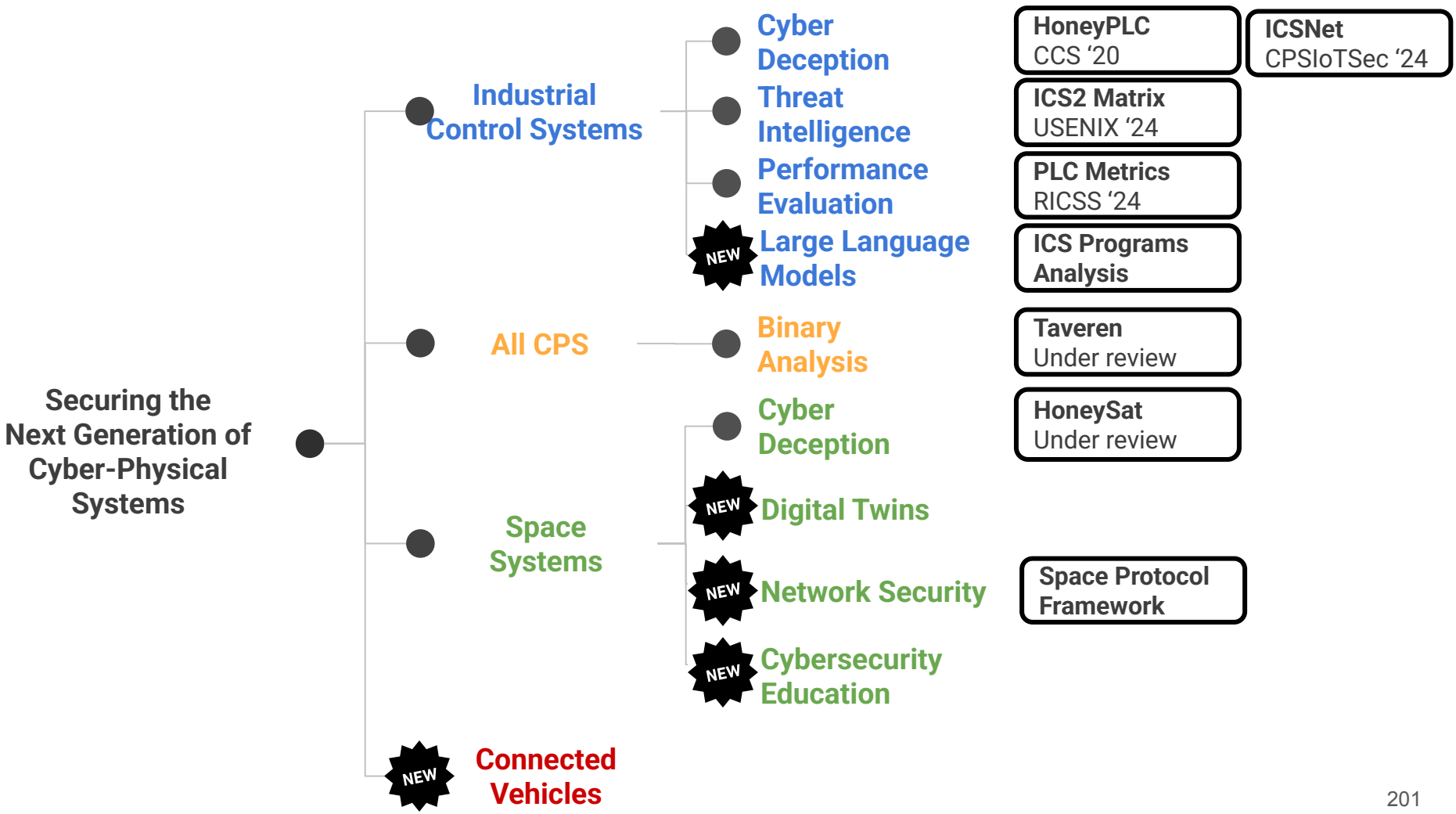
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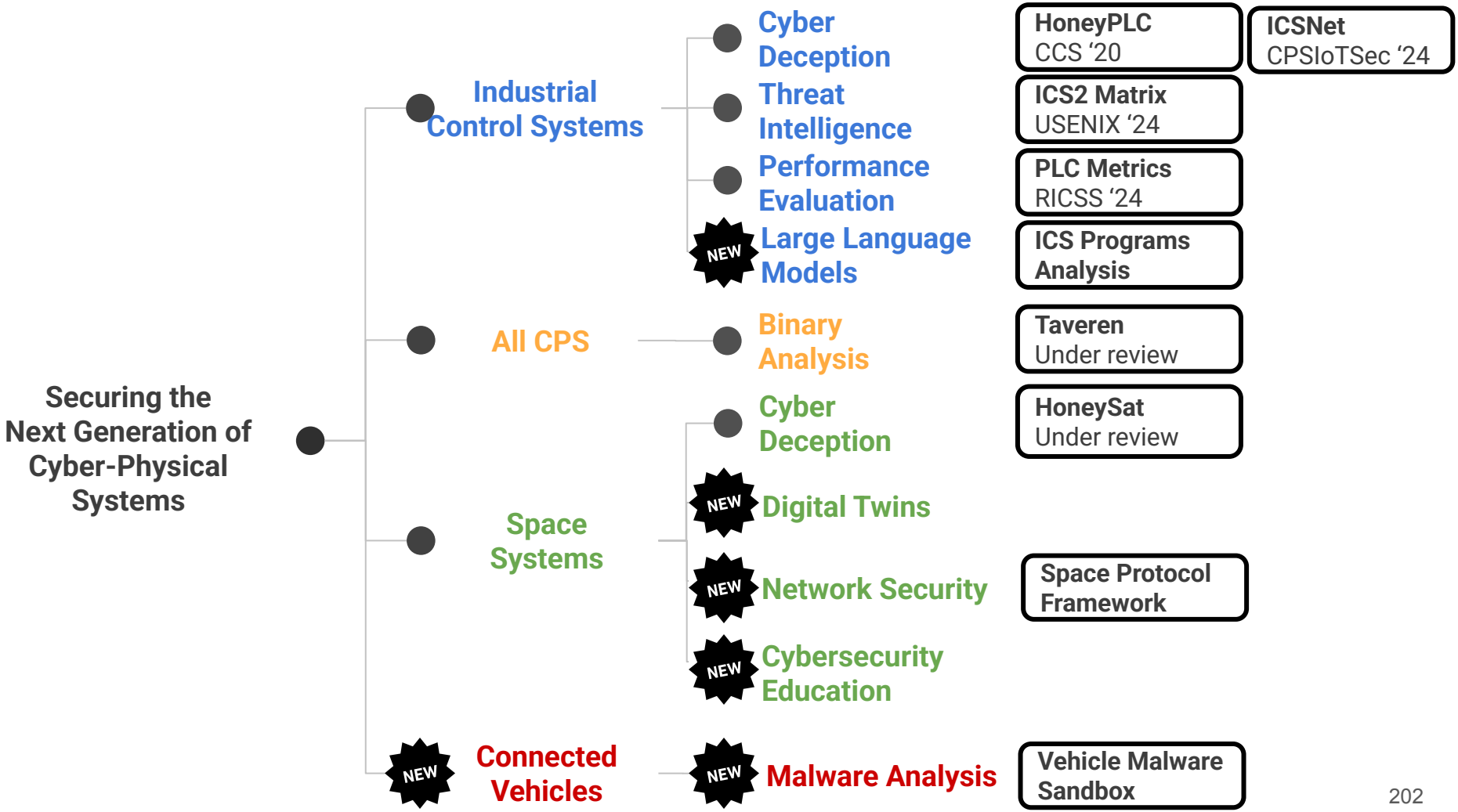
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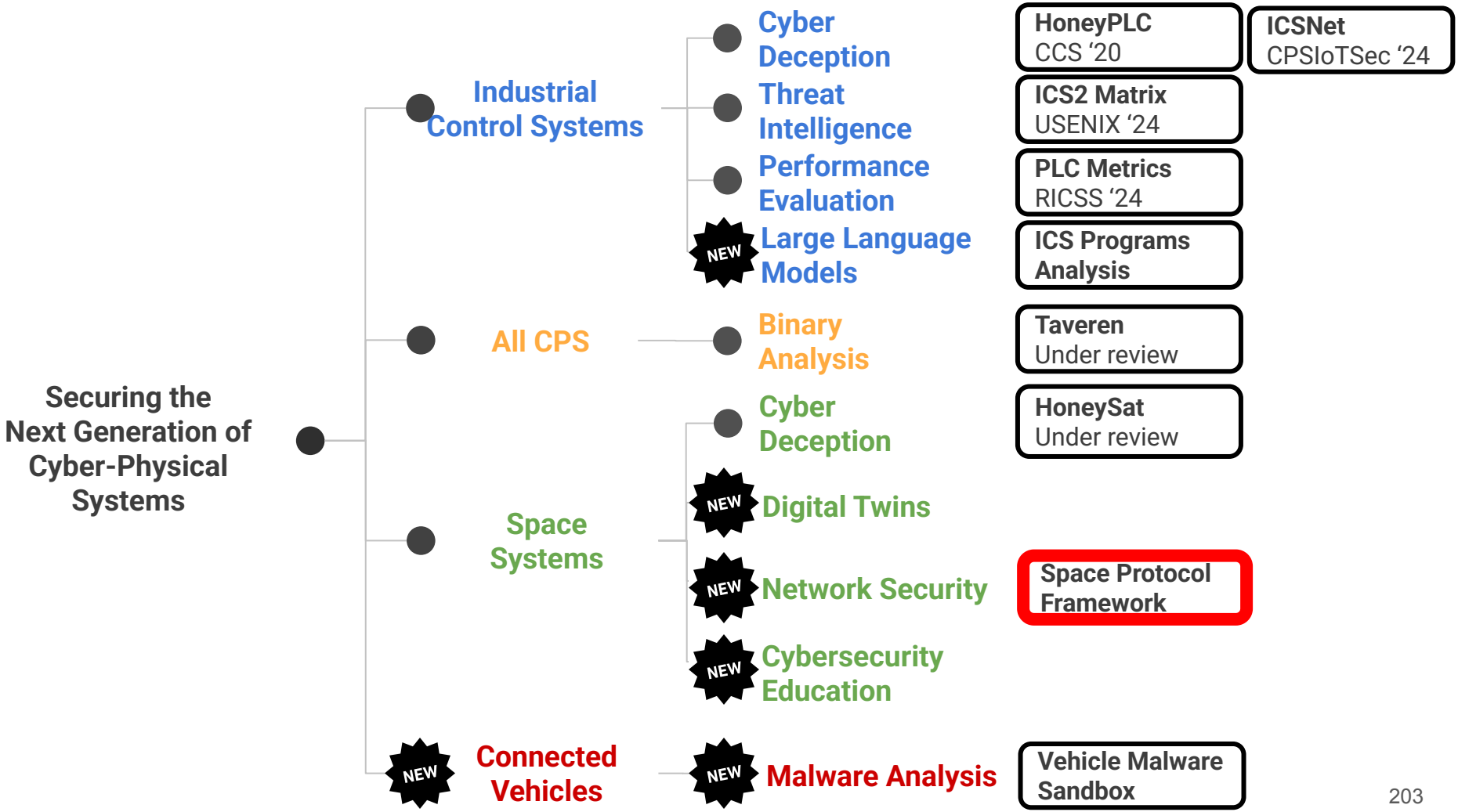
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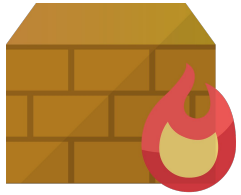

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- Faculty Early Career Development Program (**CAREER**)

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- New Mexico Space Grant Consortium

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- Education Enhancement Grant

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- Postdoctoral Fellowship

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- CAHSI REU

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My Research's Broader Impact

Academic Collaborations

Industry Collaborations

DLR Deutsches Zentrum für Luft- und Raumfahrt
German Aerospace Center

MITRE

European Space Agency
Agence spatiale européenne

Open Source Projects

HoneyPLC

HoneySat

ICS^2 Matrix

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