CPS & IoT Security Research

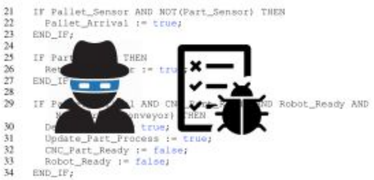
Yue Duan
Illinois Institute of Technology

Towards Automated Safety Vetting of PLC Code in Real-World Plants

Mu Zhang*, Chien-Ying Chen†, Bin-Chou Kao‡, Yassine Qamsane§, Yuru Shao¶, Yikai Lin¶, Elaine Shi*, Sibin Mohan†, Kira Barton§, James Moyne§ and Z. Morley Mao¶

*CS, Cornell; †CS, UIUC; ‡ITI, UIUC; §ME, UMich; ¶EECS, UMich

PLC being a Major Attack Vector



Controller Code w/ Safety Violations

Insider Attacks or Bugs

Programmable Logic Controller (PLC)

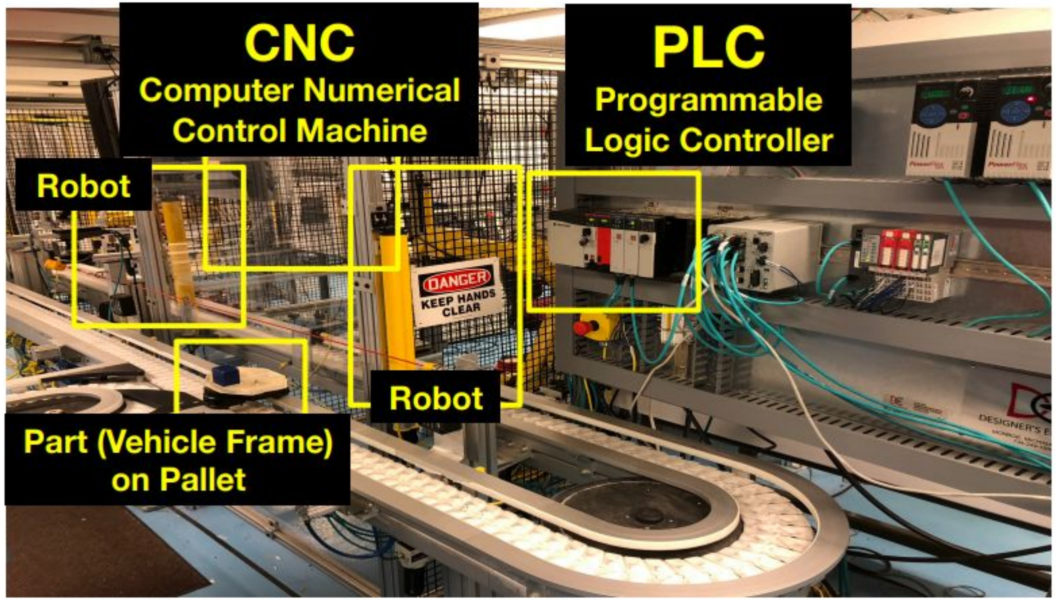
Core Control Unit on the Factory Floor

Physical Damage

Different from Financial Loss Often Seen in Attacks in Consumer Systems

Overlooked Fact:

- ICS is Complex, PLC is NOT Working Alone



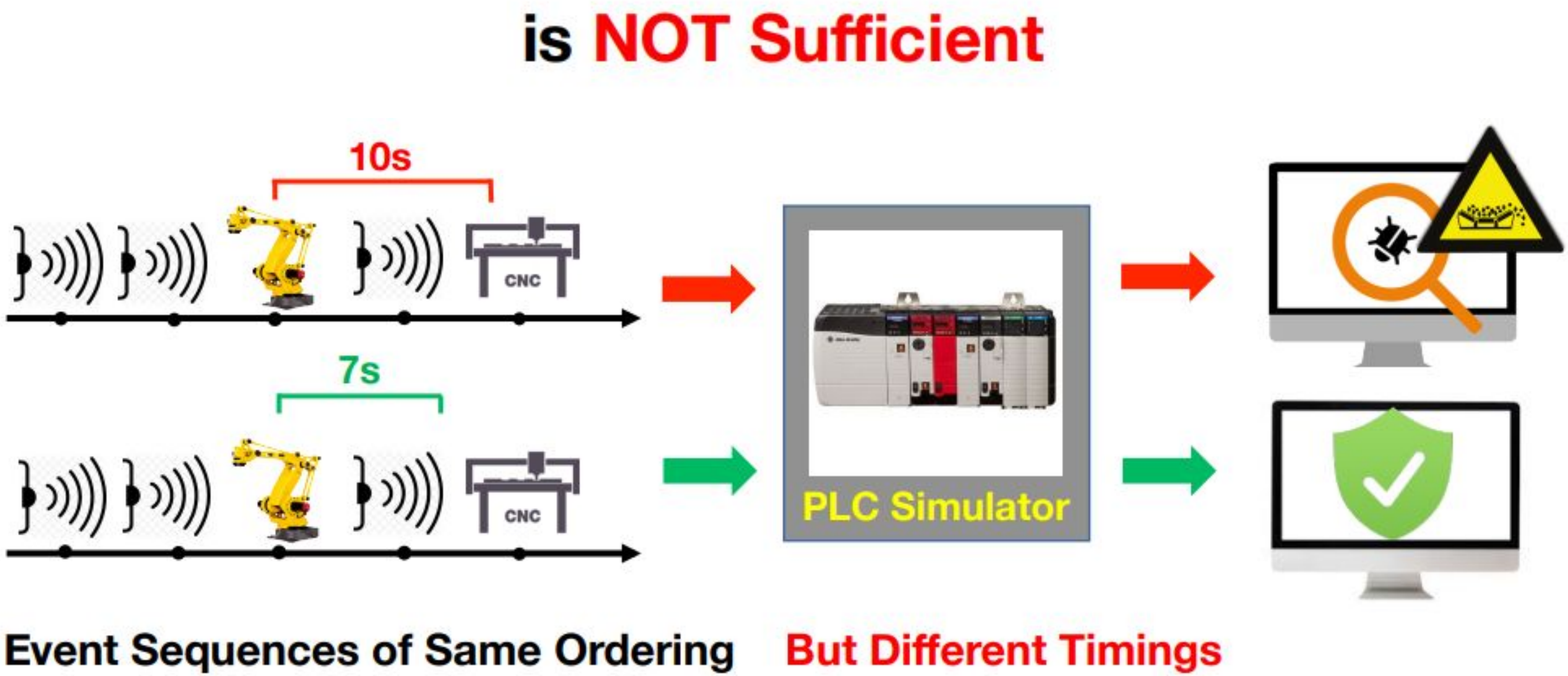
Real-world Automotive Manufacturing Testbed

Developed by **No.1 Vendor** (Rockwell Automation)

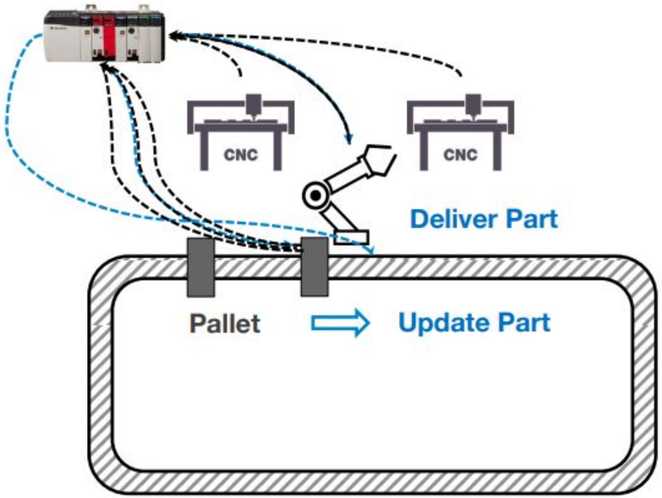
PLCs are **driven by events** from other machines

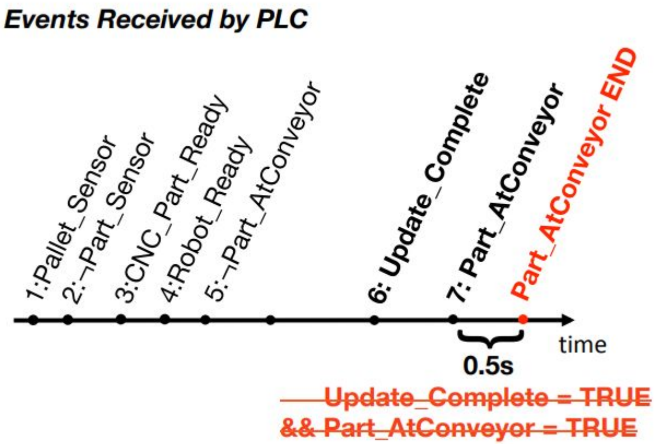
Testing PLC code requires external event inputs

Rearranging Event Order to Test PLC Code

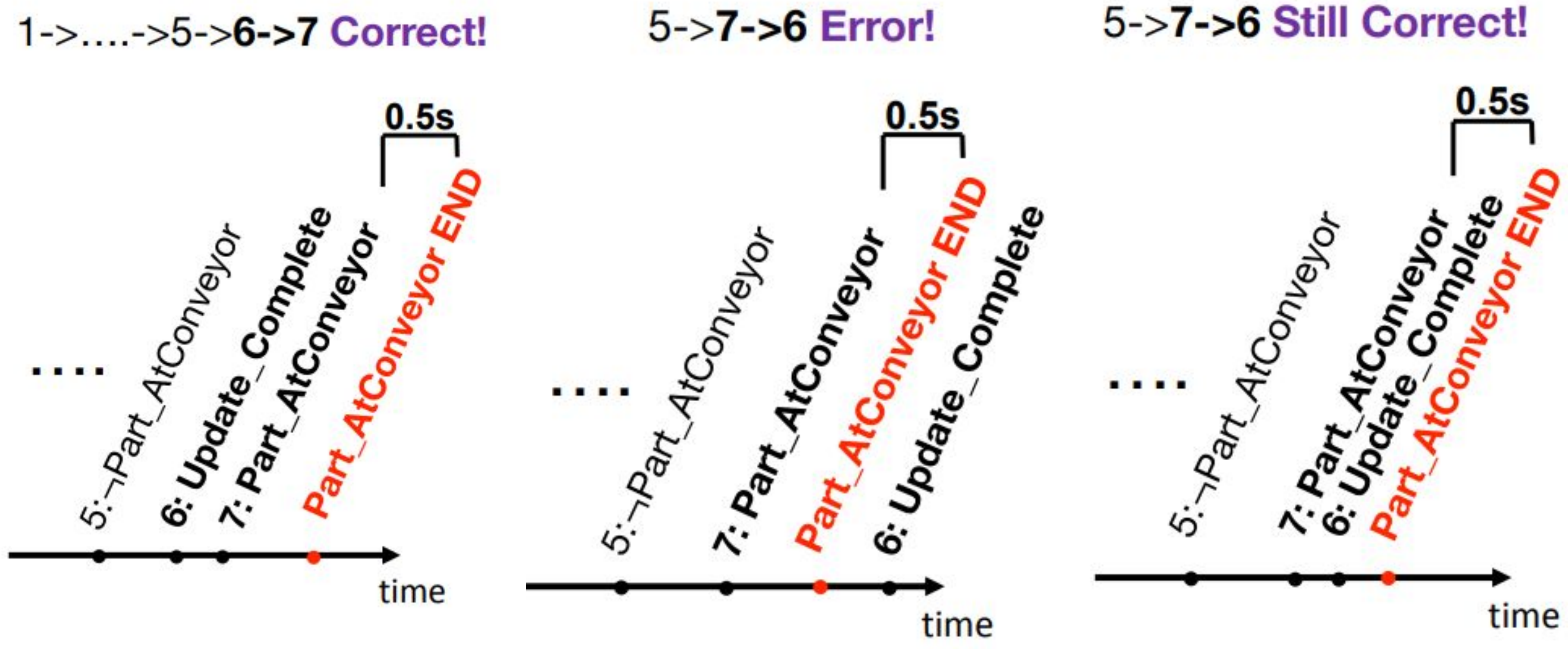


Running Example

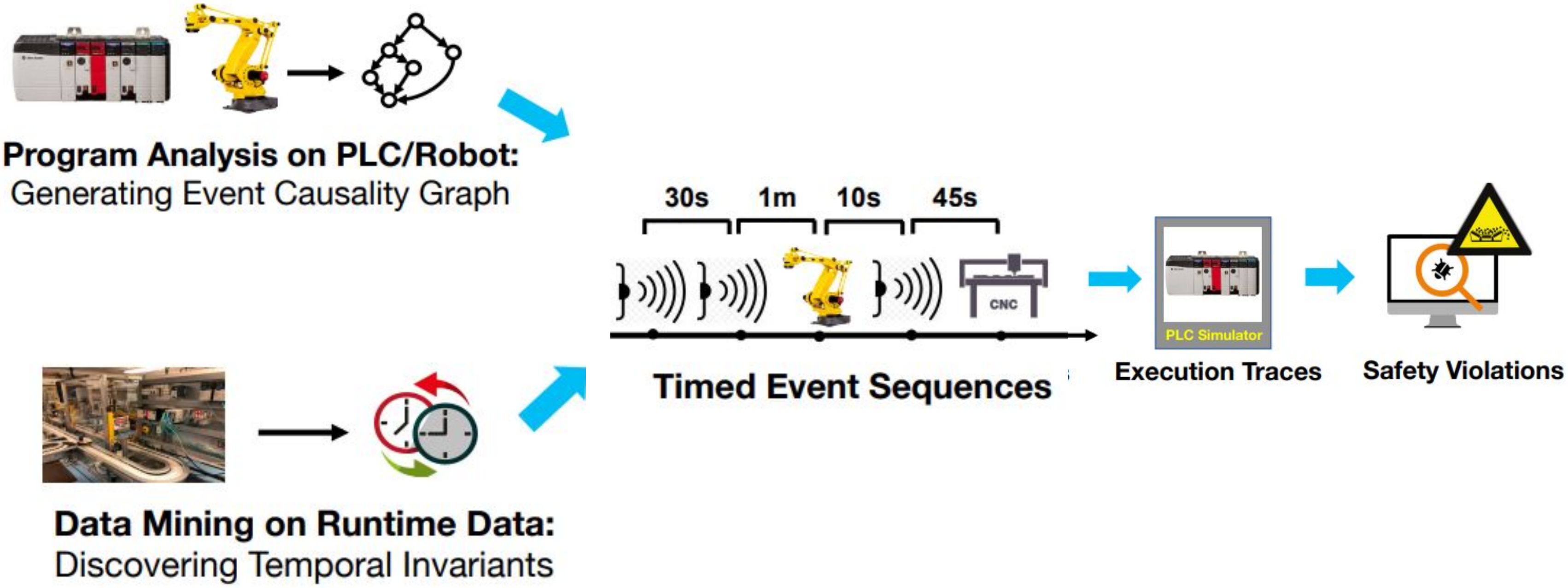




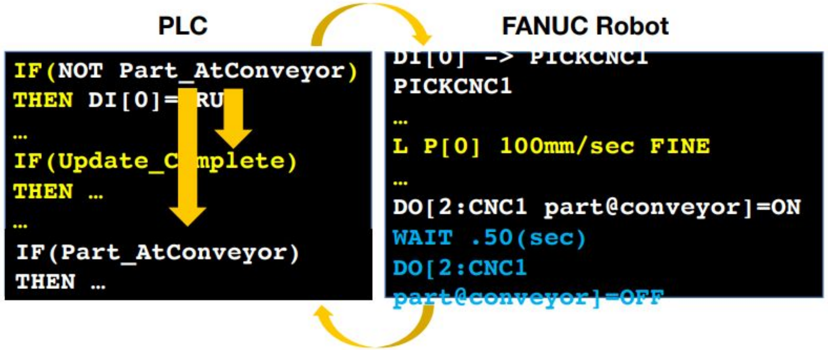
Traditional Event Permutation

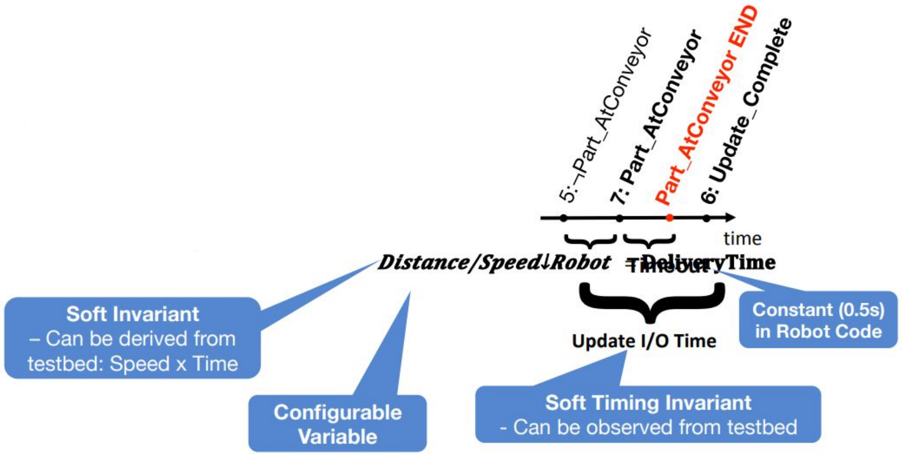


VETPLC: Generating Timed Event Sequences

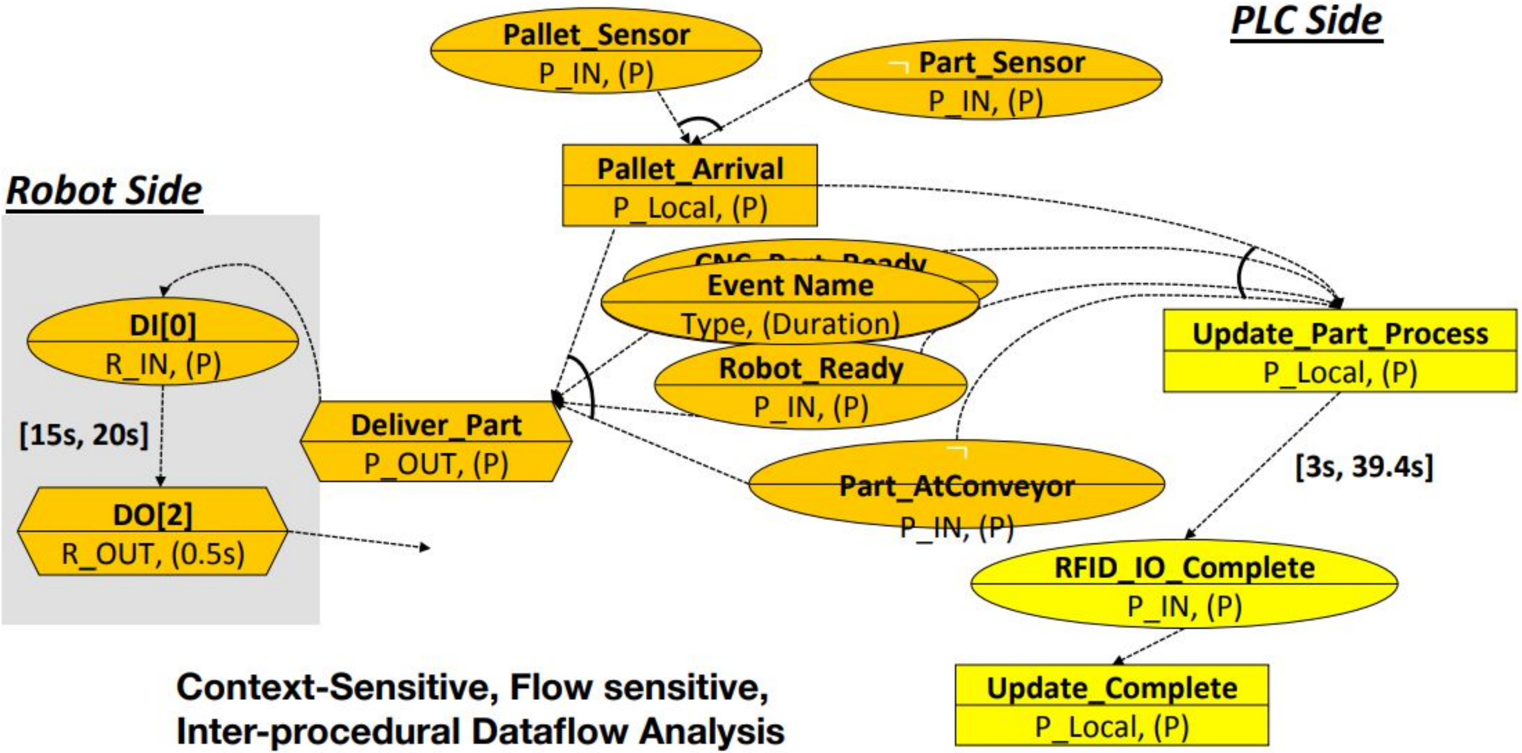


VetPLC


PLC
FANUC Robot
IF(NOT Part_AtConveyor)
THEN DI[0]=
…
IF(Update_C mplete)
THEN …
…
IF(Part_AtConveyor)
THEN …
PICKCNC1
…
L P[0] 100mm/sec FINE
…
DO[2:CNC1 part@conveyor]=ON
WAIT .50(sec)
DO[2:CNC1
part@conveyor]=OFF


5: ¬Part_AtConveyor
7: Part_AtConveyor
Part_AtConveyor END
6: Update_Complete
time
Distance/Speed↓Robot
=DeliveryTime
Timeout
Update I/O Time
Soft Invariant
– Can be derived from testbed: Speed x Time
Configurable Variable
Soft Timing Invariant
- Can be observed from testbed
Constant (0.5s) in Robot Code

Timed Event Causality Graph (TECG)



Context-Sensitive, Flow sensitive, Inter-procedural Dataflow Analysis

Mining Temporal Invariants for Events: 2 Steps

Step 1: Qualitative "followed-by":

– Synoptic (*FSE'11*)

$$\textbf{Follows}[\varepsilon_a][\varepsilon_b] = \textbf{Occurrence}[\varepsilon_a]$$

Step 2: Quantitative "with-in":

– Perfume (*ASE'14*)

$$\Box\, t_x.(\varepsilon_a \rightarrow \Diamond t_y.(\varepsilon_b \wedge t_y - t_x \geq \tau_{lower}))$$

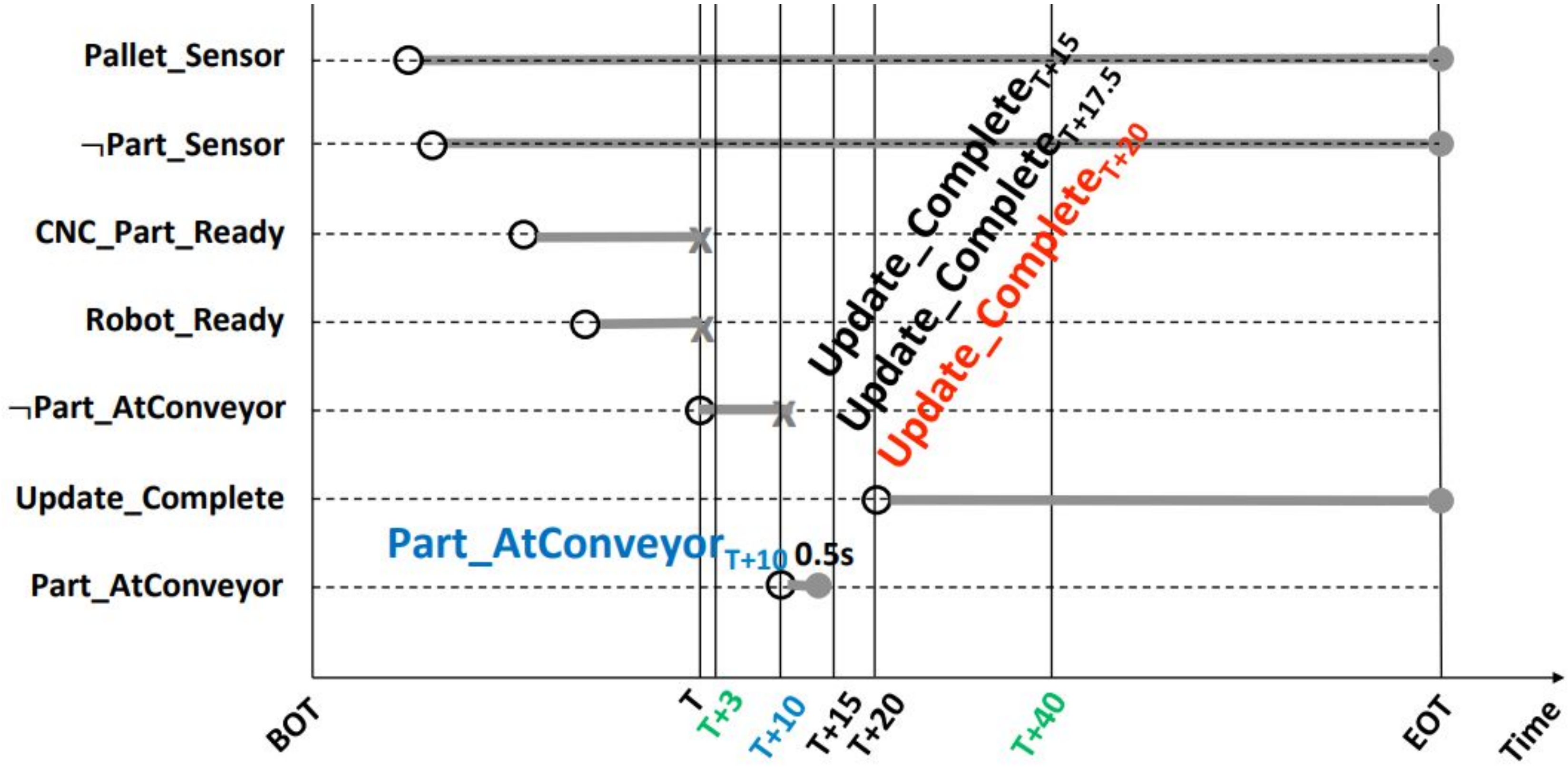
$$\Box\, t_x.(\varepsilon_a \rightarrow \Diamond t_y.(\varepsilon_b \wedge t_y - t_x \leq \tau_{upper}))$$

Results for Motivating Example (1.2 GB data for 10 hours):

TABLE I: Mined Invariants

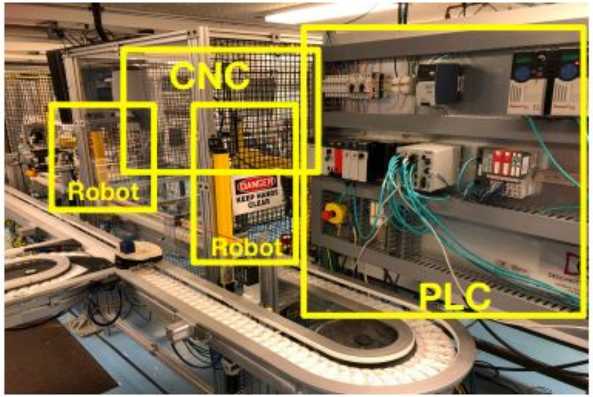
Event Pair	Invariant
$\Box$(Deliver_Part $\rightarrow$ $\Diamond$Part_AtConveyor)	[24.4s, 24.6s]
$\Box$(Update_Part_Process $\rightarrow$ $\Diamond$RFID_IO_Complete)	[15s, 20s]
$\Box$(Update_Part_Process $\rightarrow$ $\Diamond$Update_Complete)	[15s, 20s]

Creating Timed Event Sequences

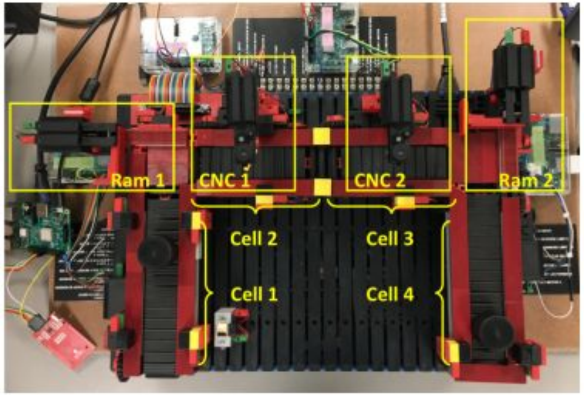


Evaluation on Real Testbeds for Different Scenarios

2 Different Testbeds



***SMART*: Automotive Production Line**



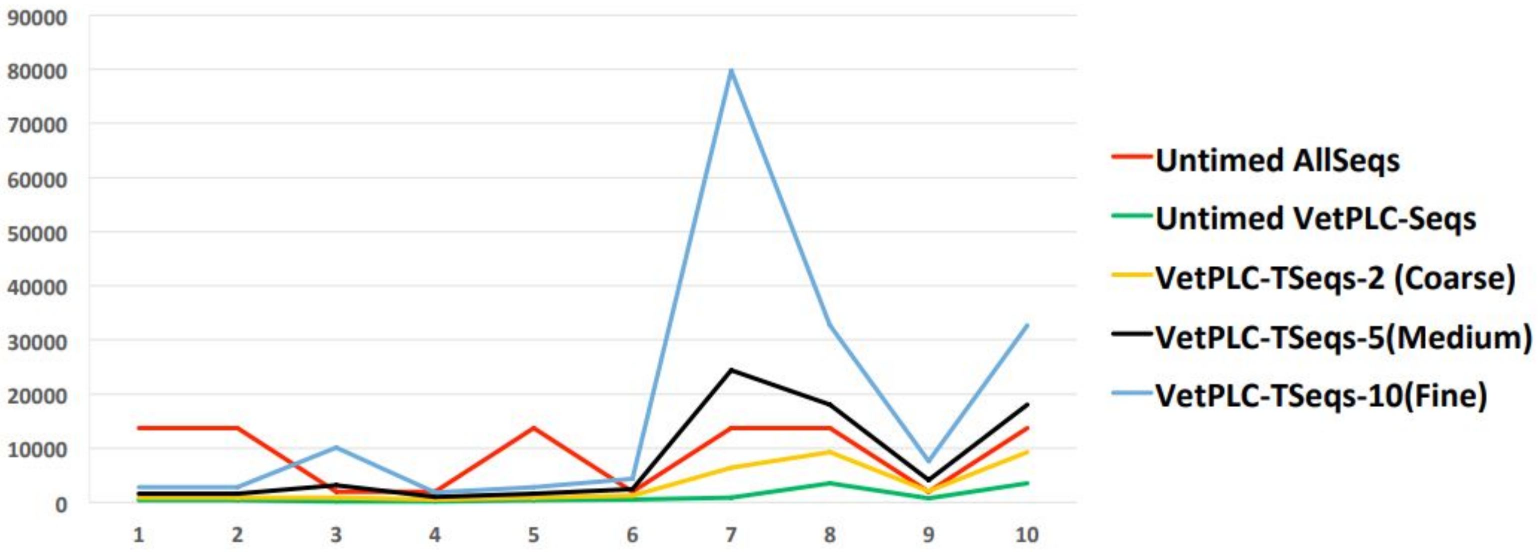
***Fischertechnik*: Part Processing w/ 4 PLCs**

10 Safety-critical Scenarios

S1: Conveyor Overflow #1
S2: Robot in Danger Zone
S3: Conveyor Overflow #2
S4: Part-Gate Collision
S5: CNC Overflow

S6: Ram-Part Collision
S7: CNC-Part Collision
S8: Conveyor Overflow #3
S9: Conveyor Underflow
S10: Ram-Part Collision #2

Evaluation: How many sequences are created?



Red → Green: Program analysis reduces amount of event sequences

Green → Orange → Black → Blue: Time discretization can significantly increases that

Bug Detected? State-of-the-Art vs. VETPLC

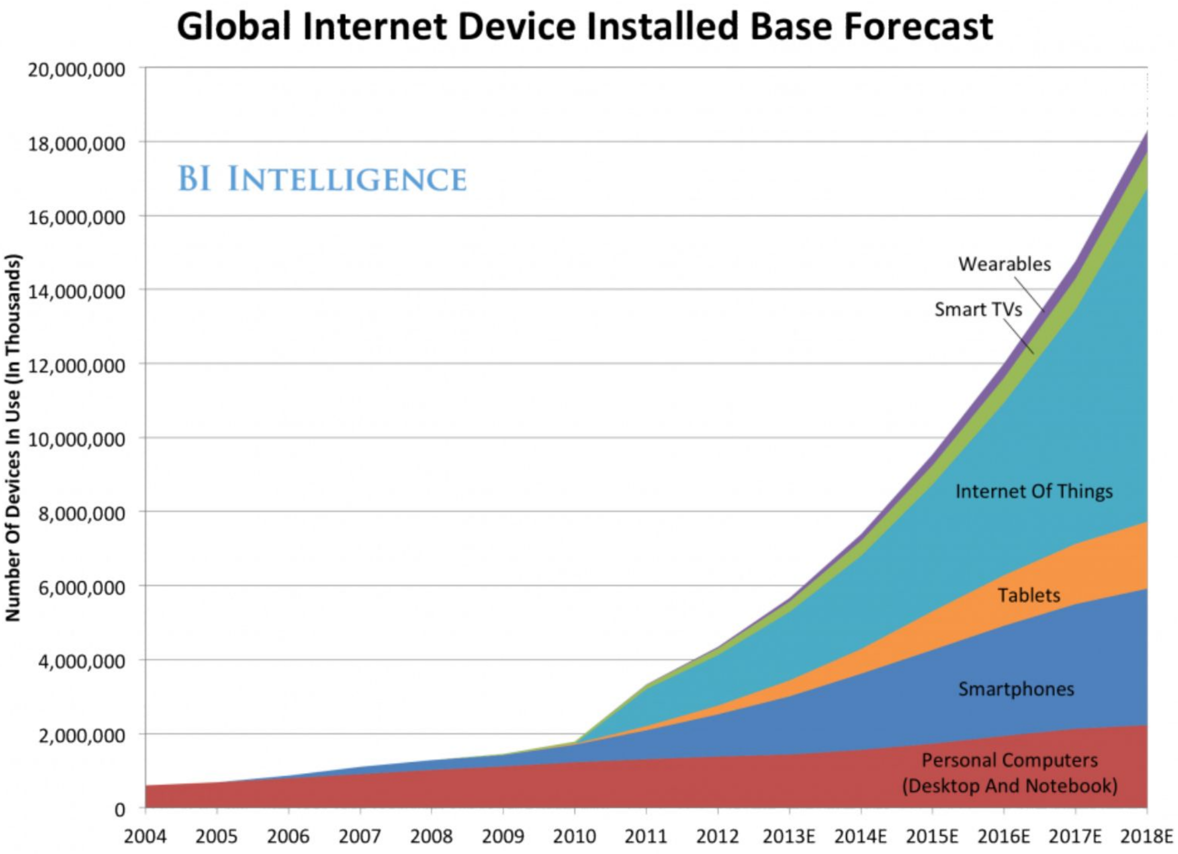
	State-of-the-art		VETPLC		
#	ALLSEQS	VETPLC-SEQS	VETPLC-TSEQS-2	VETPLC-TSEQS-5	VETPLC-TSEQS-10
1	N	N	Y	Y	Y
2	N	N	Y	Y	Y
3	N	N	Y	Y	Y
4	N	N	Y	Y	Y
5	N	N	Y	Y	Y
6	N	N	Y	Y	Y
7	N	N	Y	Y	Y
8	N	N	Y	Y	Y
9	N	N	Y	Y	Y
10	N	N	Y	Y	Y

Firmalice: Automatic Detection of Authentication Bypass Vulnerabilities in Binary Firmware

Yan Shoshitaishvili, Ruoyu Wang, Christophe Hauser, Christopher Kruegel, Giovanni Vigna

NDSS 2015

The Rise of Firmware



Emergence of Backdoors

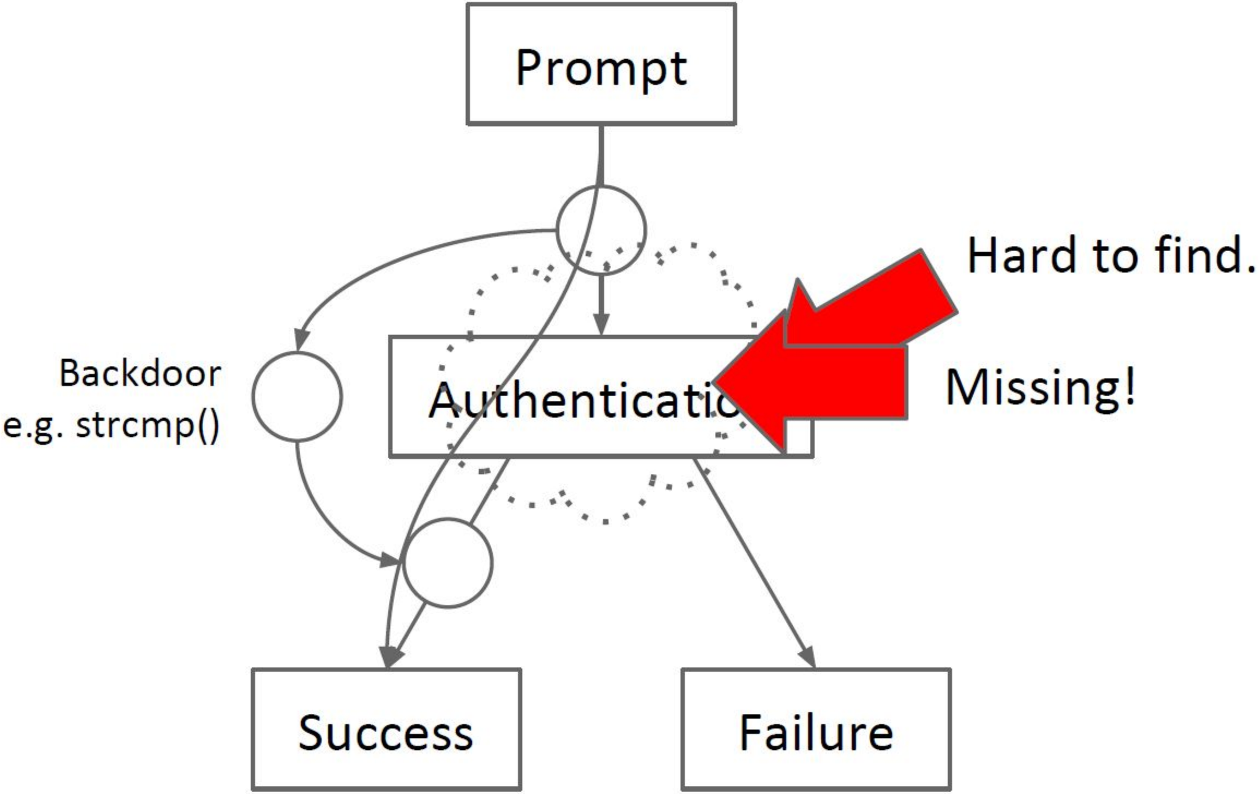
Santamarta, Ruben. "HERE BE BACKDOORS: A Journey Into The Secrets Of Industrial Firmware." *Black Hat USA* (2012).

Heffner, Craig. "Reverse Engineering a D-Link Backdoor" /dev/ttys0 (2013).

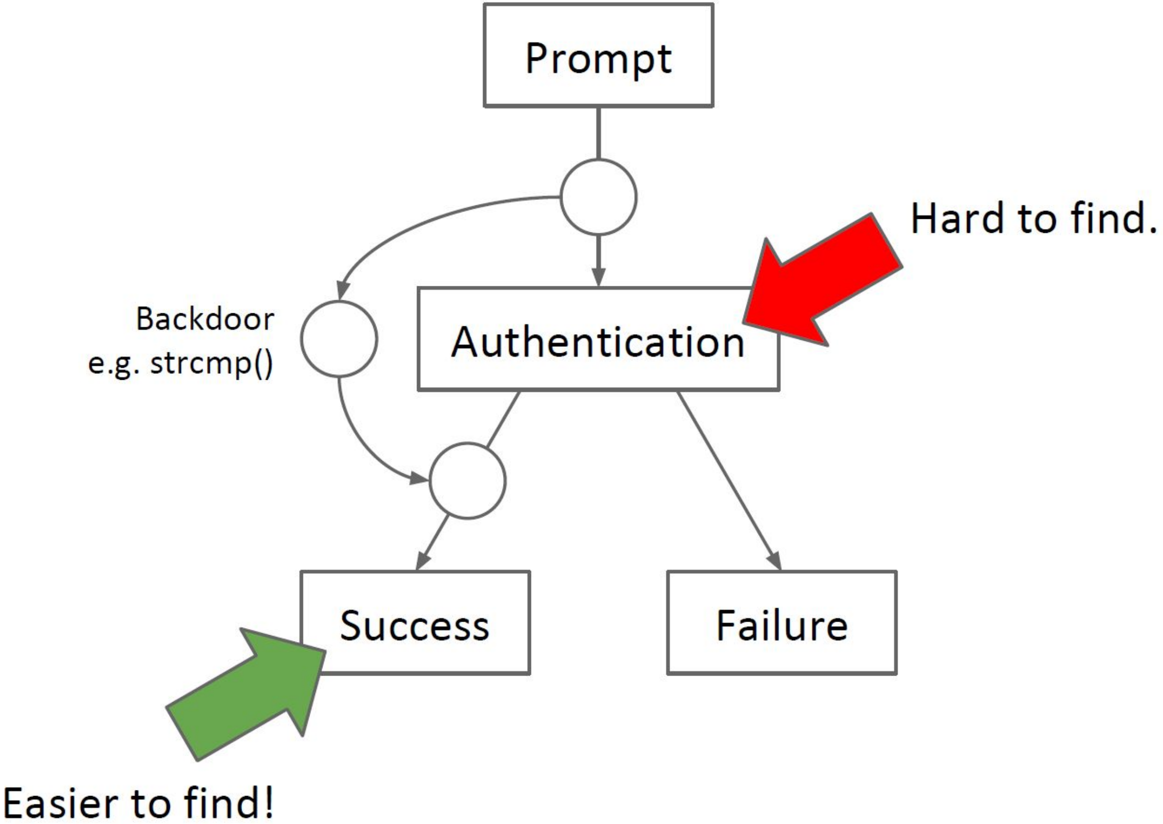
Vanderbeken, Eloi. "TCP/32764 backdoor, or how linksys saved Christmas!" GitHub (2013).

Heffner, Craig. "Finding and Reversing Backdoors in Consumer Firmware." EELive! (2014).

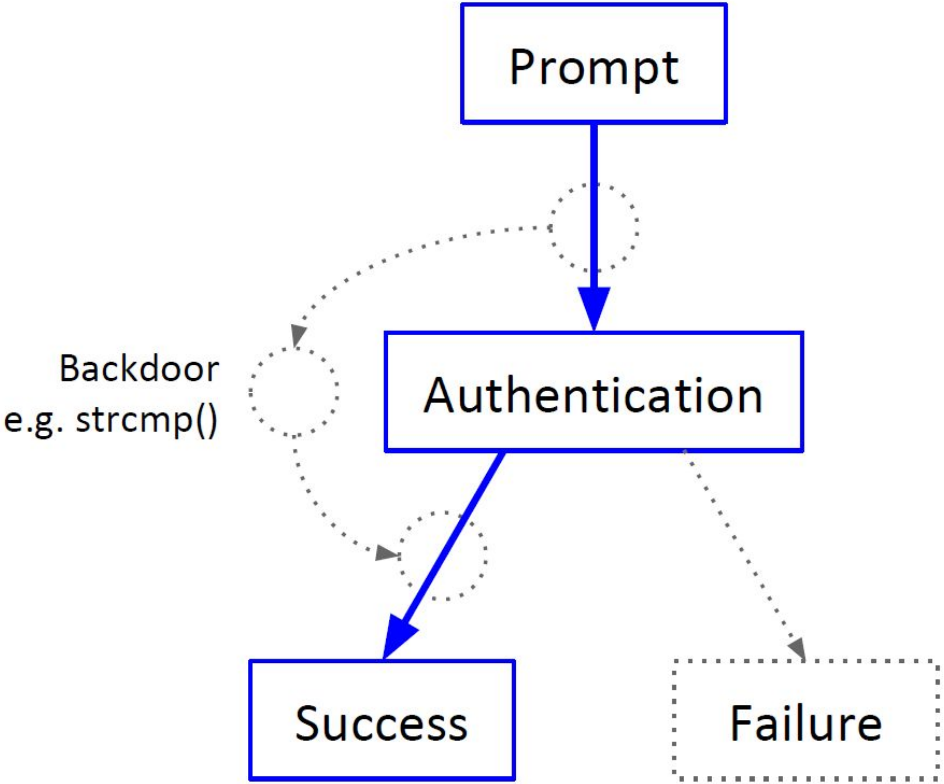
Backdoor Discovery



Solution: Input Determinism



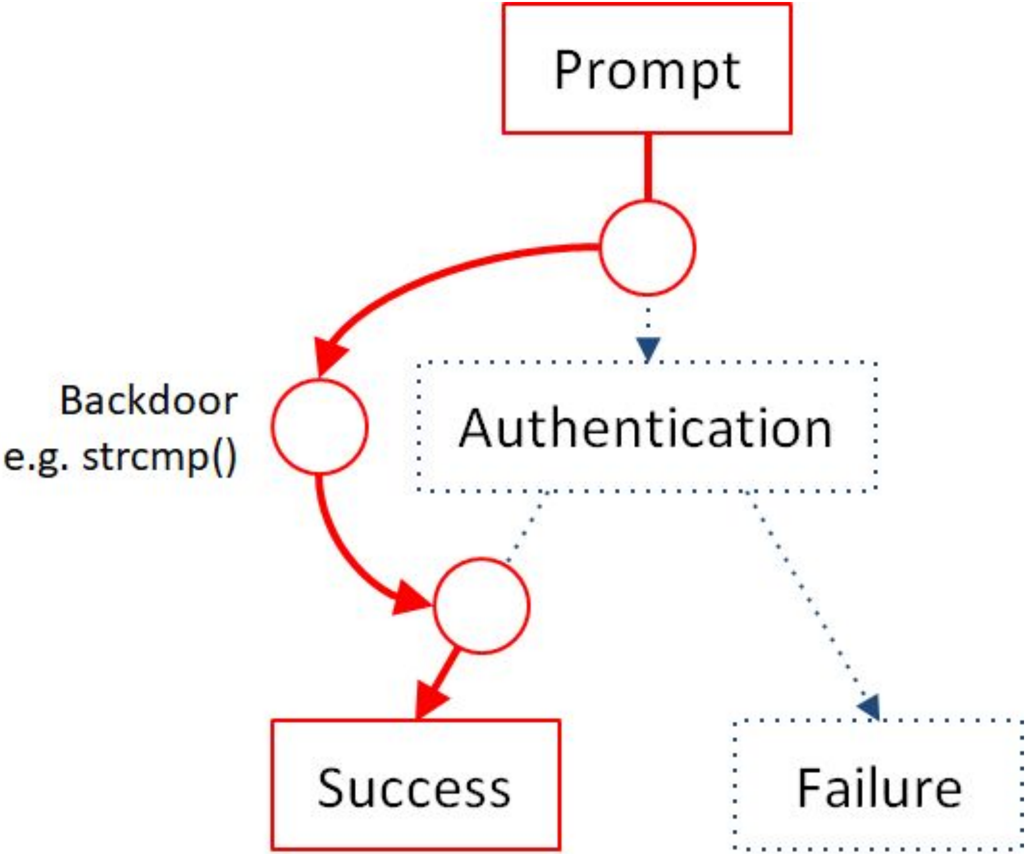
Input Determinism



Can we determine the input needed to reach the success function, just by analyzing the code?

The answer is NO

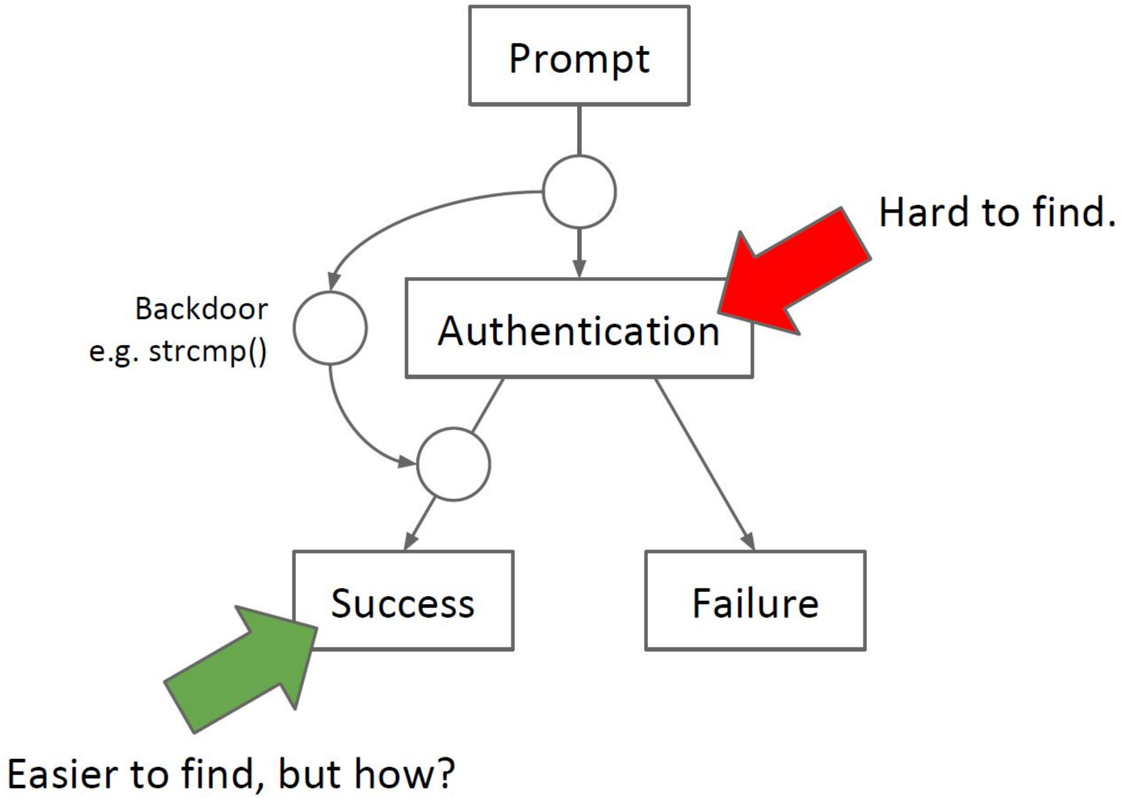
Input Determinism



Can we determine the input needed to reach the success function, just by analyzing the code?

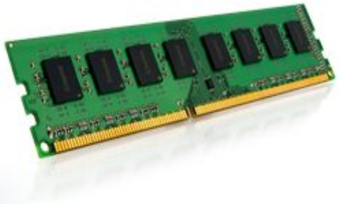
The answer is YES

Challenge


Prompt
Hard to find.
Backdoor
e.g. strcmp()
Authentication
Success
Failure
Easier to find, but how?

Finding “Authenticated Point”

- Without OS/ABI information:



With ABI information:

Firmalice

Inputs:

- Firmware Sample
- Security Policy

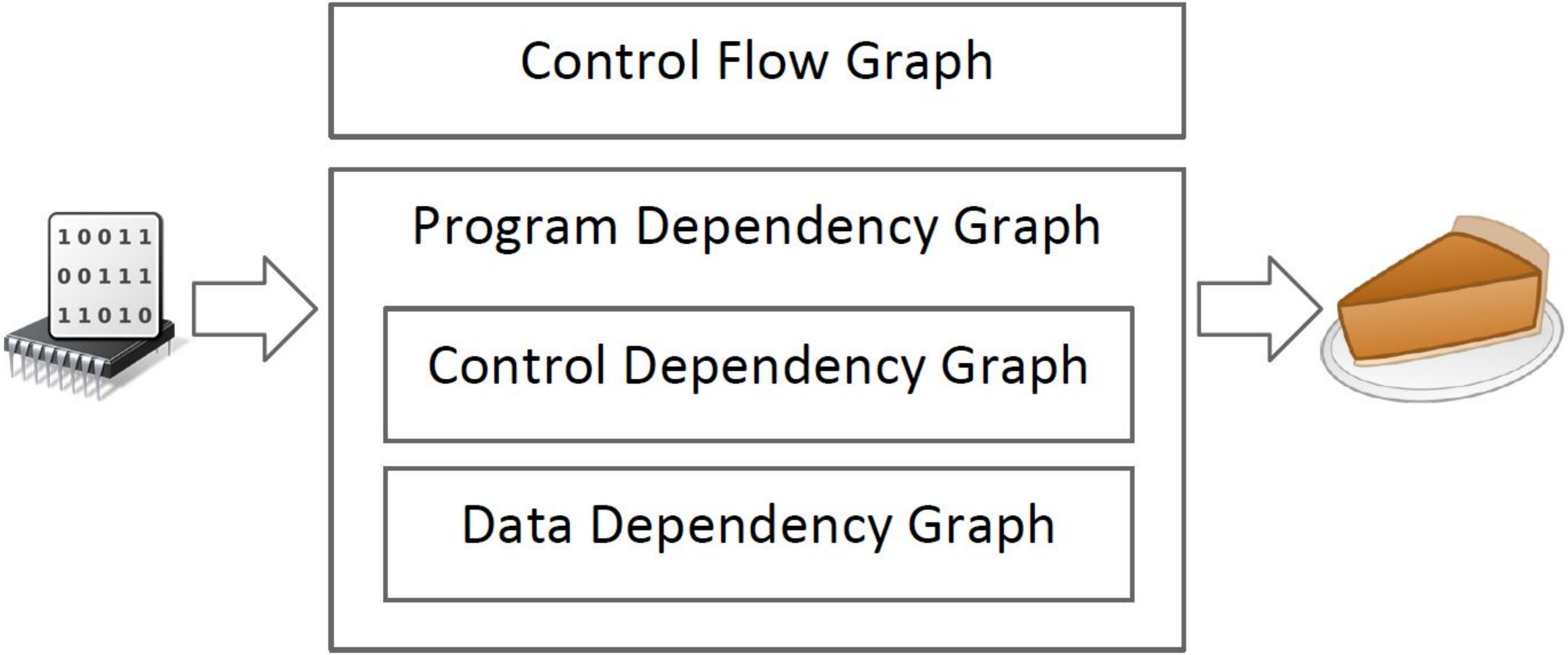
Challenges:

- Large binary programs
- Unrelated user input

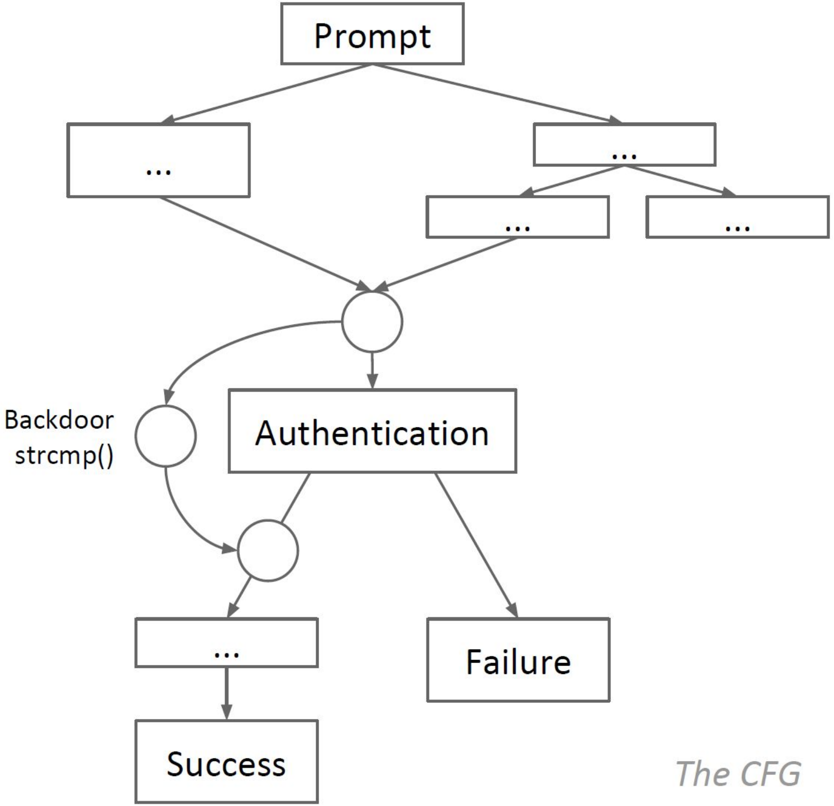
Analysis Steps:

- Static Analysis (backwards program slicing)
- Dynamic Symbolic Execution
- Authentication Bypass Check

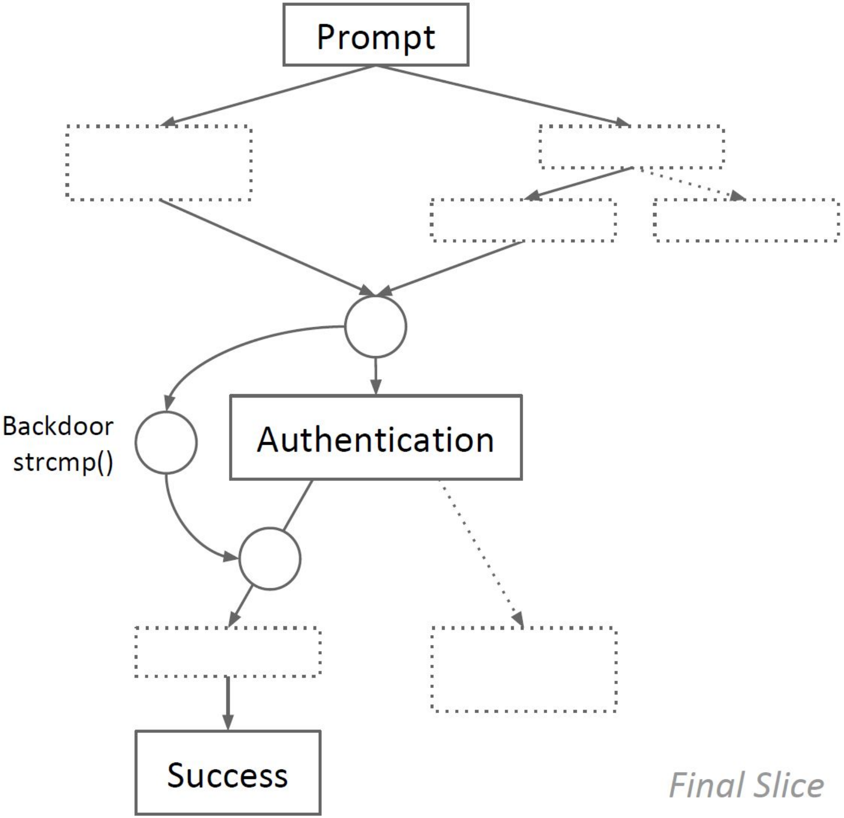
Static Analysis



CFG

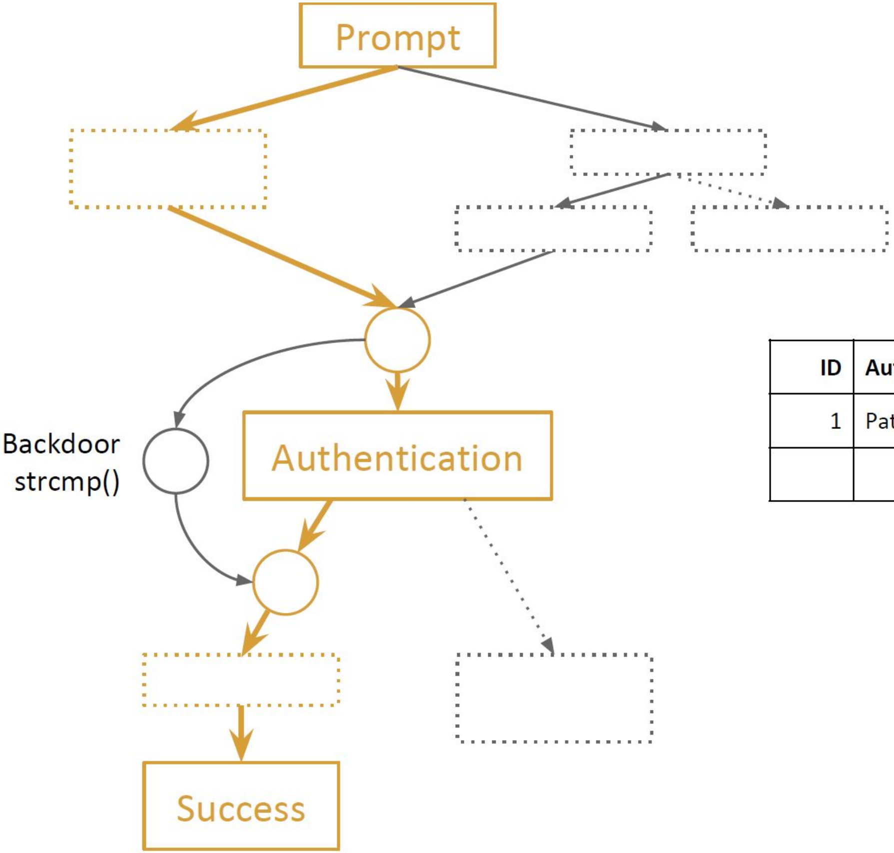


The CFG



Final Slice

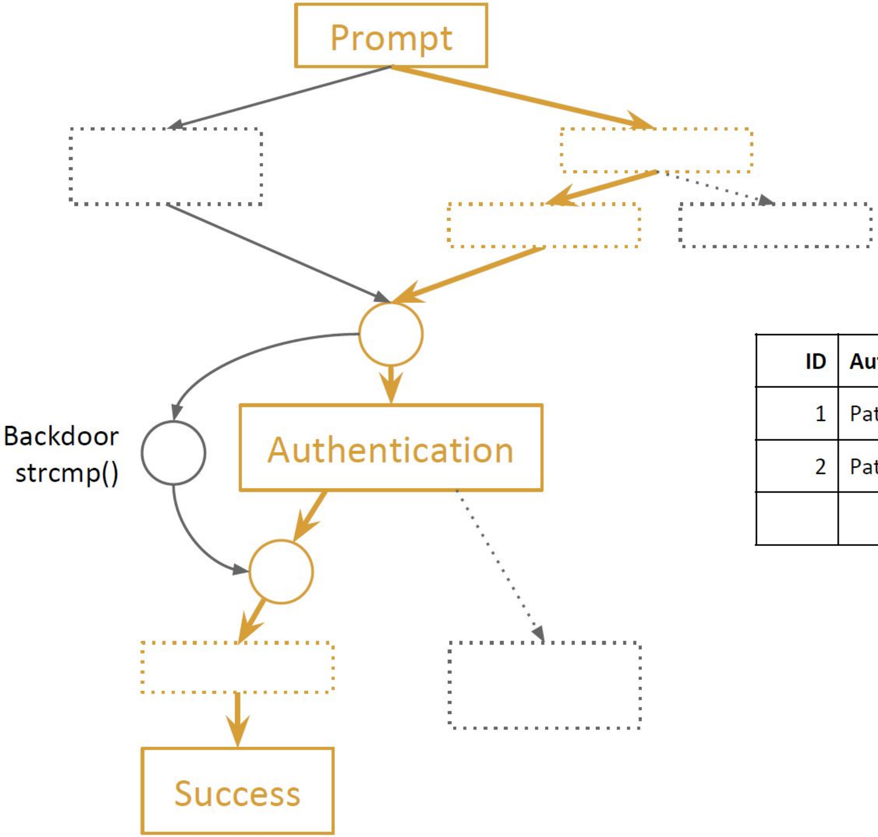
Dynamic Symbolic Execution



ID	Authenticated Paths
1	Path 1

Path 1

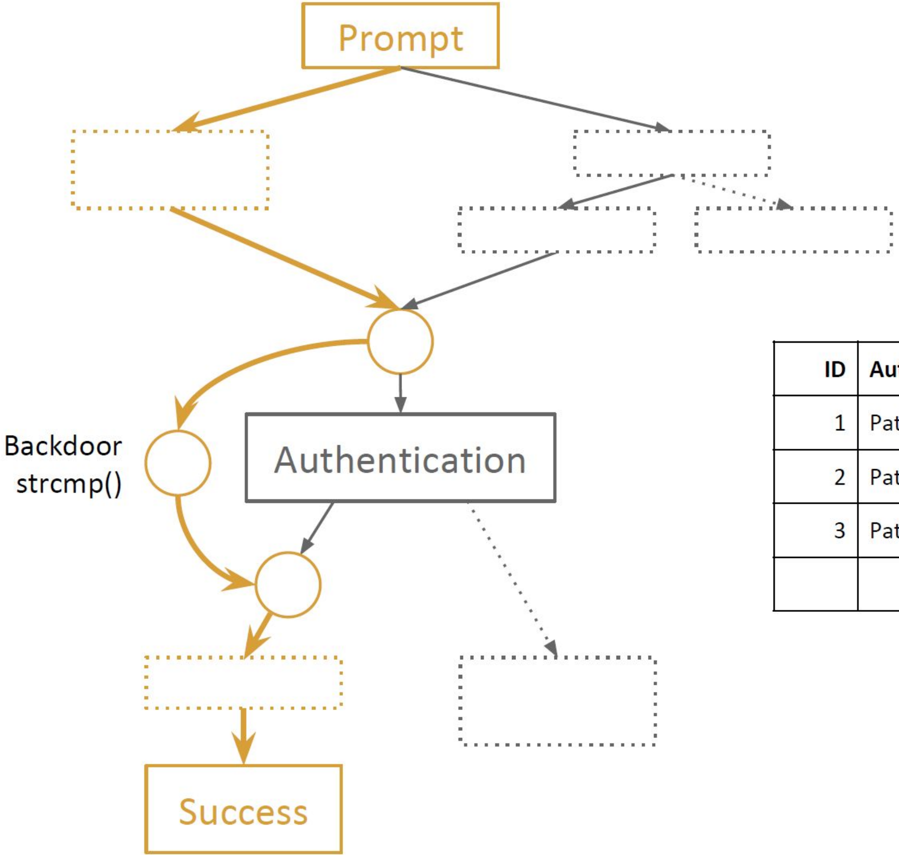
Dynamic Symbolic Execution



ID	Authenticated Paths
1	Path 1
2	Path 2

Path 2

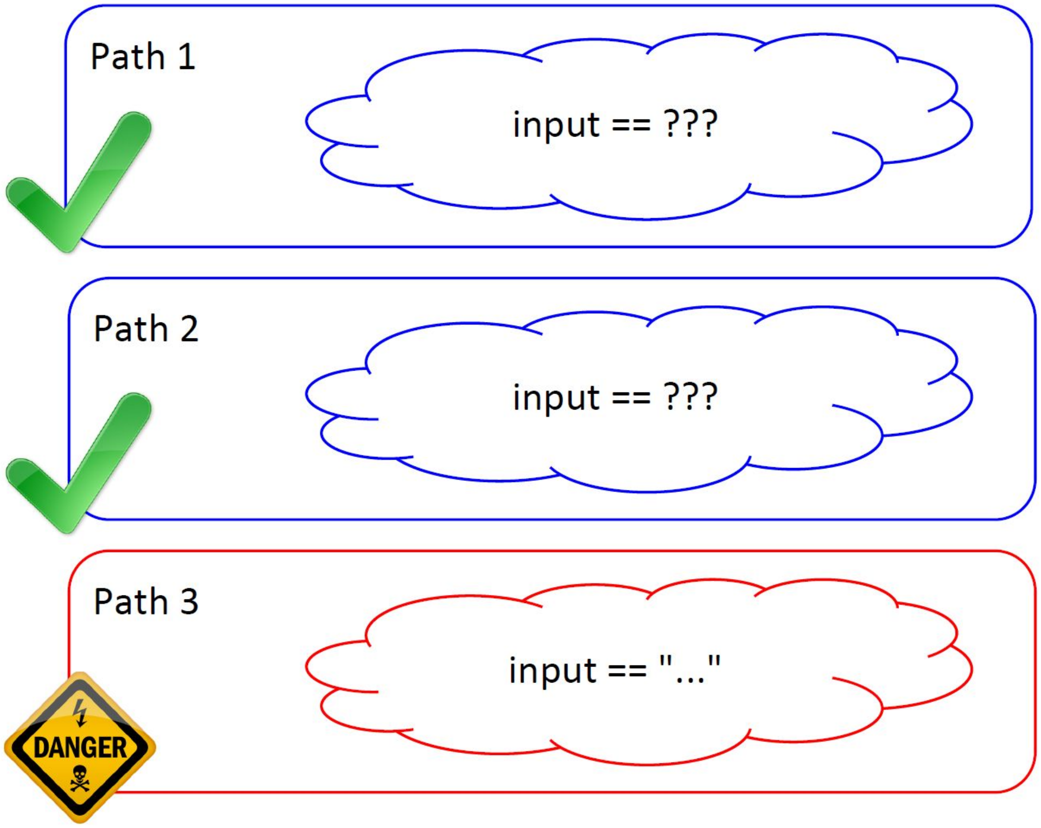
Dynamic Symbolic Execution



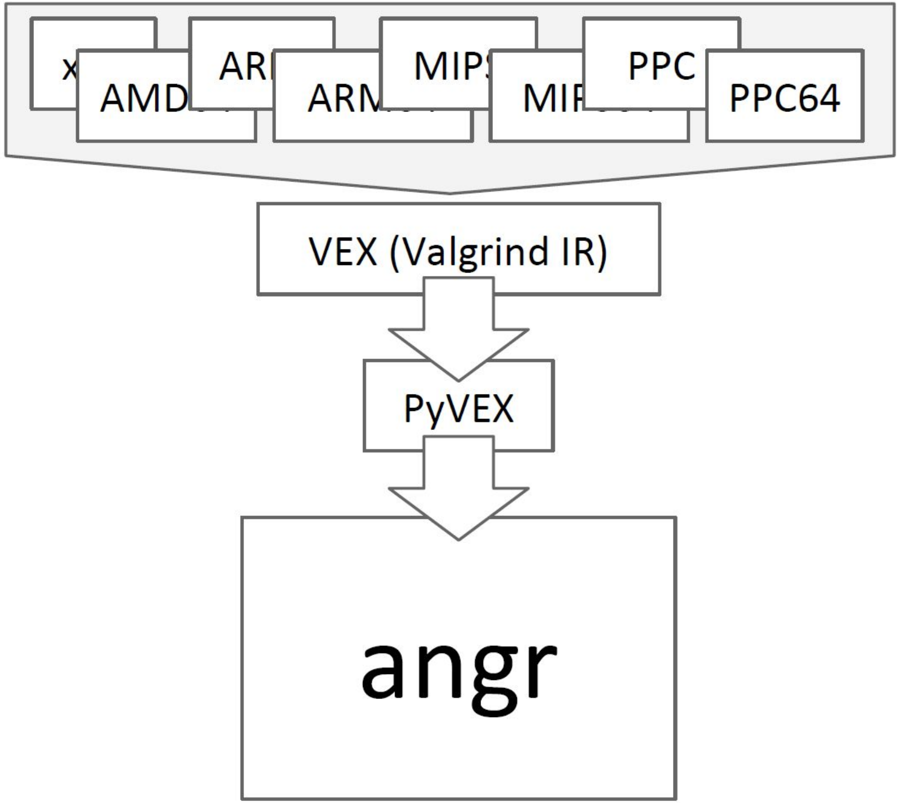
ID	Authenticated Paths
1	Path 1
2	Path 2
3	Path 3

Path 3

Authentication Bypass



Implementation



Backdoor Example: 3S Vision N5072

Slicing
- ➔ 5m
- ➔ 212 bb

DSE
- ➔ 26m

- Linux embedded device.
- HTTP server for management and video monitoring.
- Security Policy
  - Authentication required for footage access
  - "Image-Type" header
- Backdoor
  - Hard-coded user credentials
  - Username: 3sadmin
  - Password: 27988303