Ghost in the Machine

CHALLENGES IN EMBEDDED BINARY SECURITY

JOS WETZELS
ALI ABBASI

ENIGMA

WHOIS

- Jos Wetzels[1,2]
  - samvartaka.github.io
- Ali Abbasi[1,3]
  - http://wwwhome.cs.utwente.nl/~abbasia/

[1]Distributed and Embedded System Security (DIES) group, University of Twente, Netherlands

[2]SEC Group, Eindhoven University of Technology, Netherlands

[3]SYSSEC Group, Ruhr-University Bochum, Germany

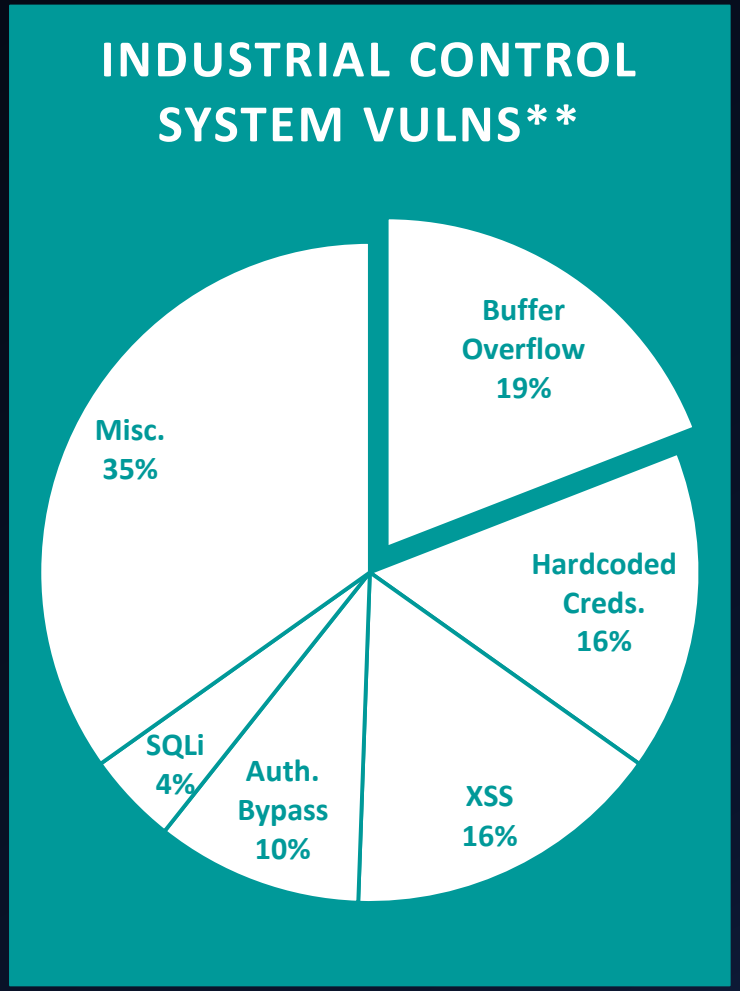
EMBEDDED BINARY SECURITY

- **Claim**
  Embedded binary security lags behind General-Purpose World significantly

- **Claim**
  Catching up will be non-trivial due to embedded constraints

BINARY SECURITY & MEMORY CORRUPTION

- Memory Corruption among most common embedded vulns
- Embedded Development Dominated by C*
- Unsafe Language
  - *"C is a terse and unforgiving abstraction of silicon"*



** 2015 UBM Study, ** 2016 Kaspersky Study*

IMPACT: REMEMBER SHADOW BROKERS?

Shadow Brokers launch auction for Equation Group hacking cache

Shadow Brokers' Tools Pose Zero-Day Risks, Cisco and Fortinet Warn

Kaspersky Says that Shadow Brokers Leaked Malware is Genuine

Shadow Brokers' Cisco vulnerability exploited in the wild

FORTINET®

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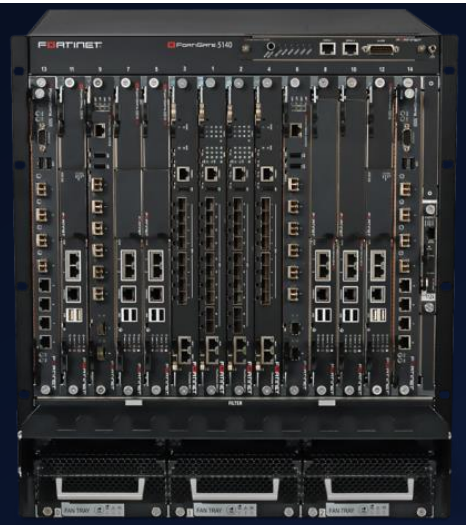
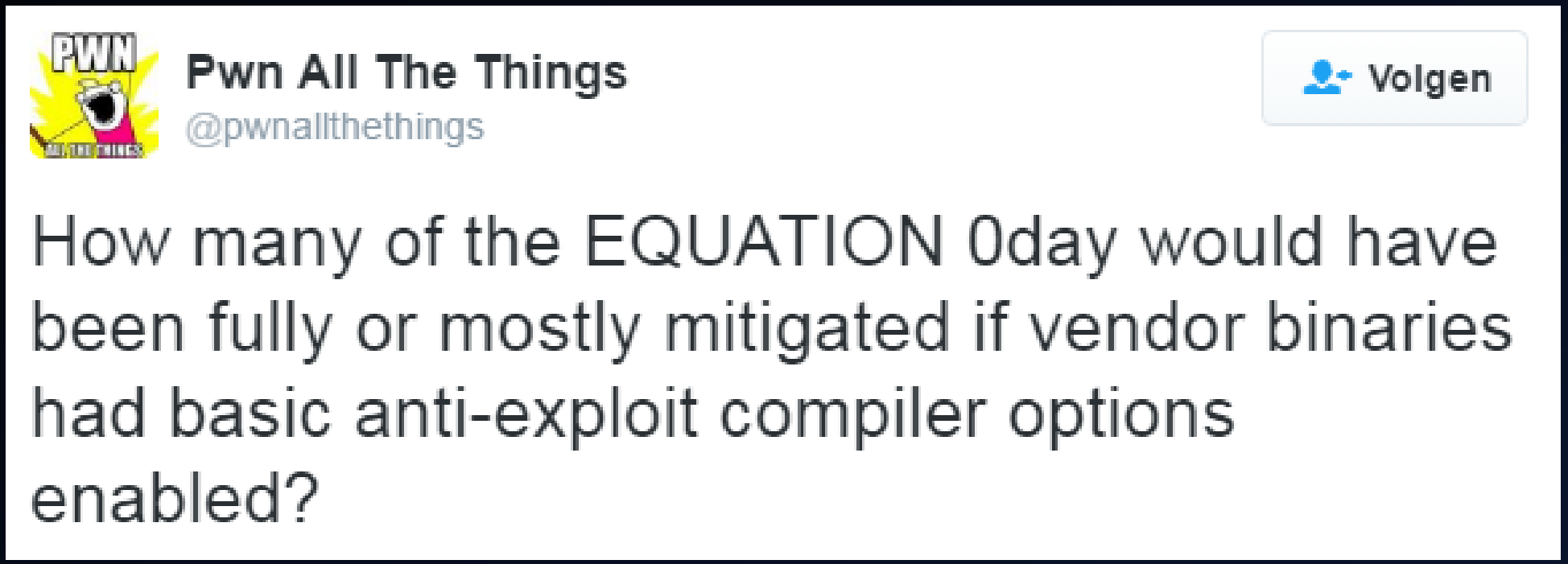


MITIGATIONS: WHAT IF?



WHY EXPLOIT MITIGATIONS?

Buffer Overflow

Shell

VS

Buffer Overflow

Infoleak

ROP Payload

Sandbox Escape

Shell

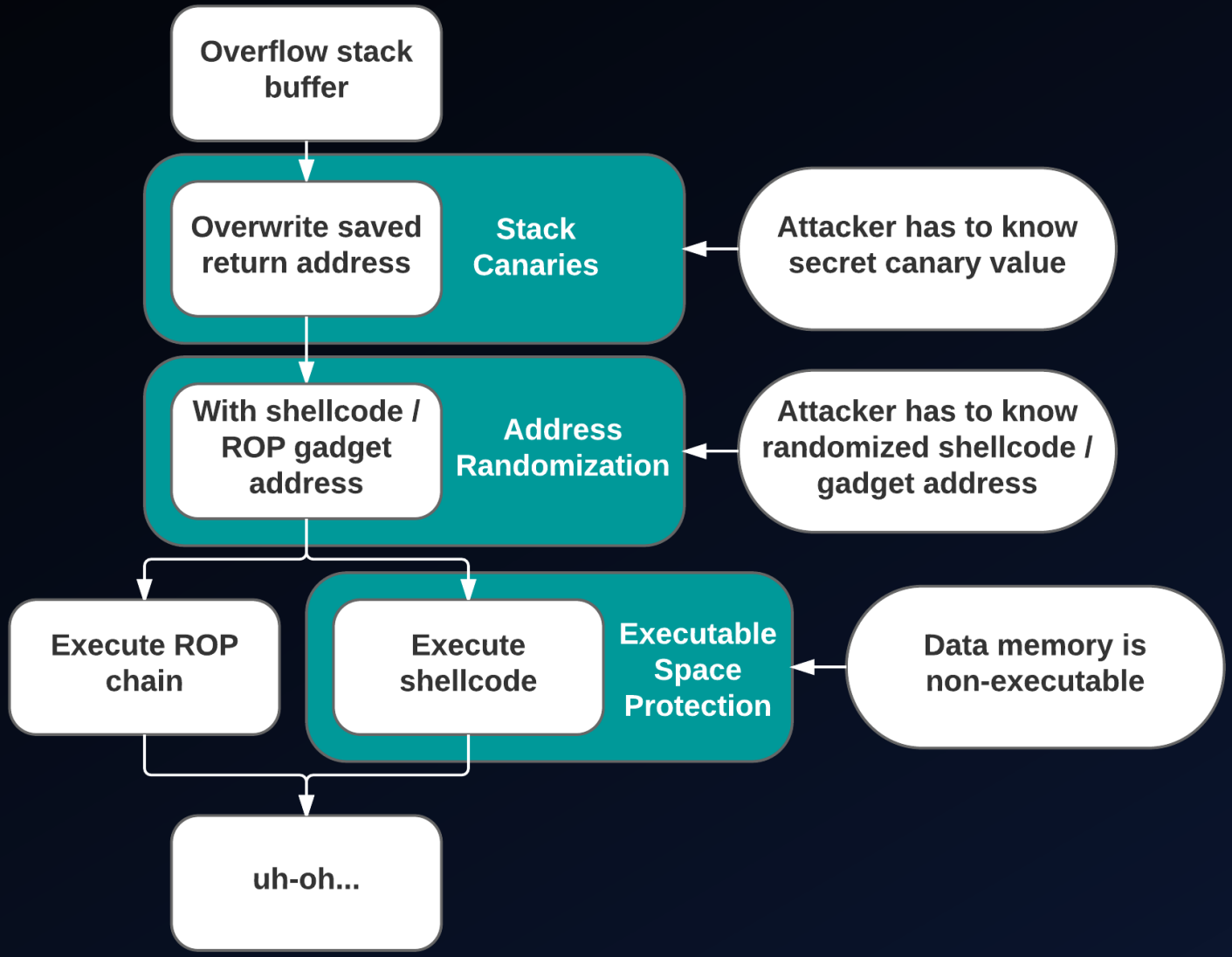
WHY EXPLOIT MITIGATIONS?

- But why not tackle things at the root (eg. safe langs)?
  - Portability → C Toolchain For Nearly Every Platform and OS
  - Functionality → ‘Close To Metal’
  - Performance → Critical for Embedded
  - Existing Codebases → Billions of Lines of Legacy Code
- Need Short-Term Solution

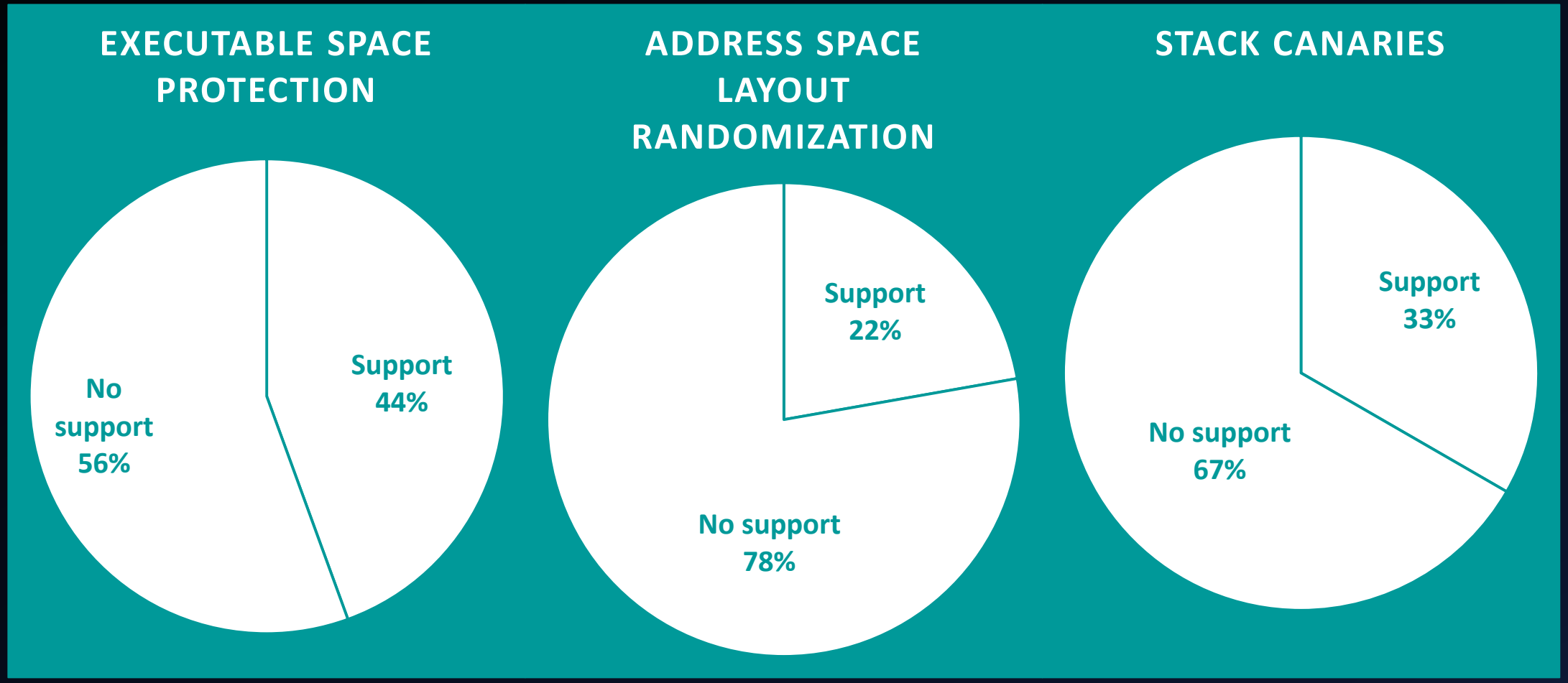
WHAT MITIGATIONS ARE WE TALKING ABOUT?

- Complementary Baseline
  - Executable Space Protection (ESP)
    - DEP, ExecShield, W ^ X
  - Address Space Layout Randomization (ASLR)
  - Stack Canaries
    - Stack Smashing Protector (SSP), /GS
- Future Work: Advanced Mitigations
  - Control-Flow Integrity (CFI)

EXPLOIT-FLOW VS MITIGATIONS

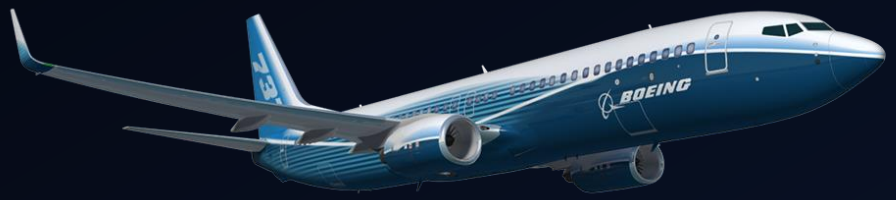


EMBEDDED OS MITIGATION SUPPORT*



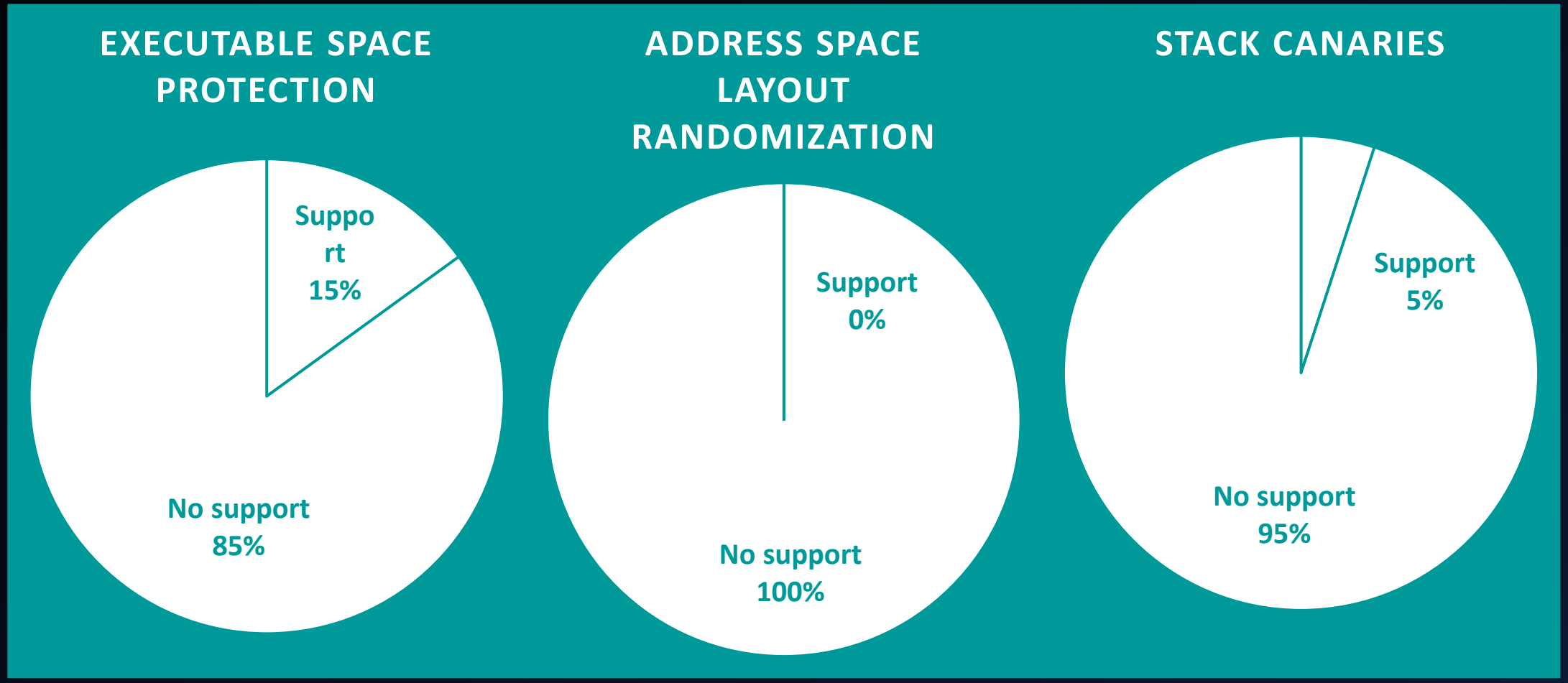
* Based on our research into 36 popular embedded OSes

EMBEDDED SYSTEMS ARE DIVERSE

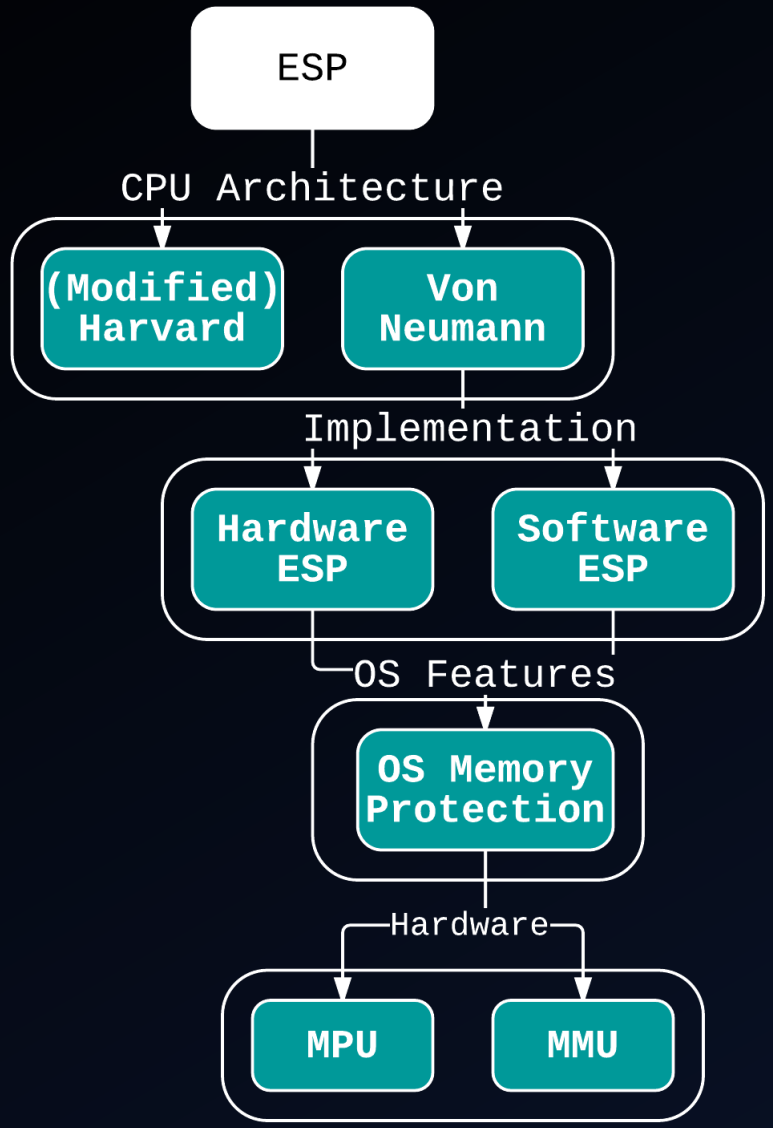


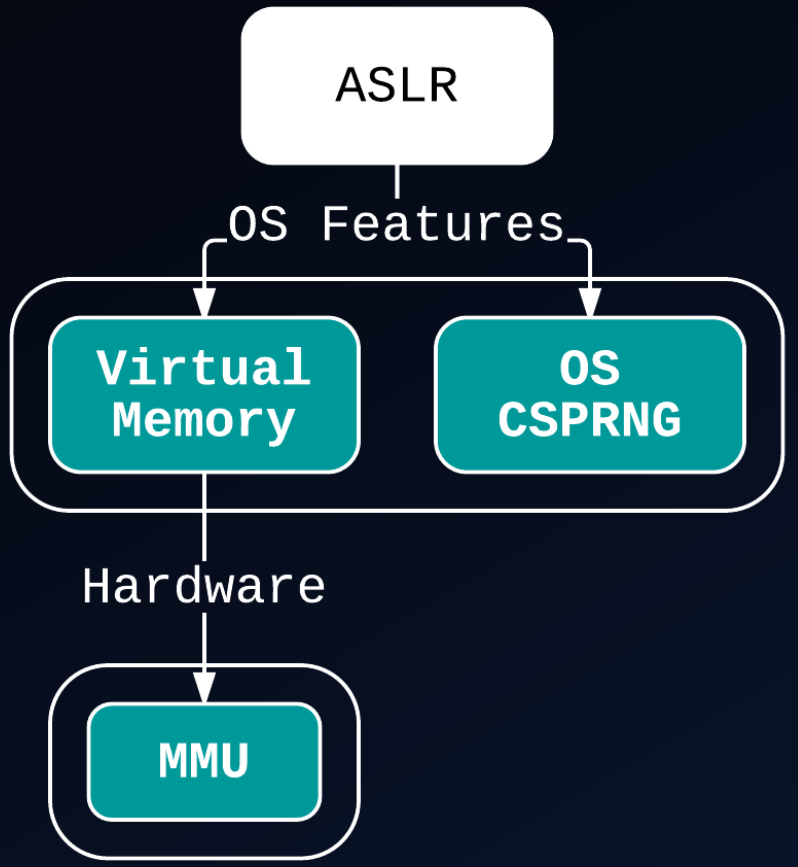
VS

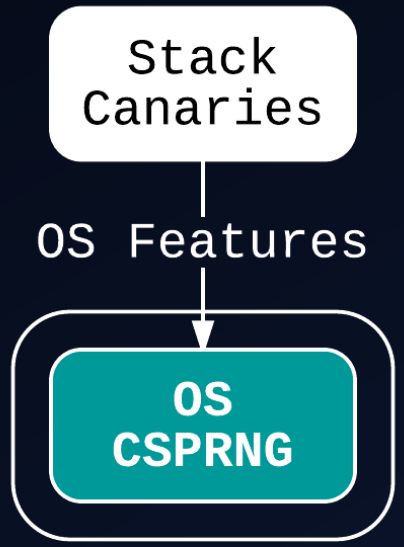
SUPPORT AMONG MOST CONSTRAINED OSES



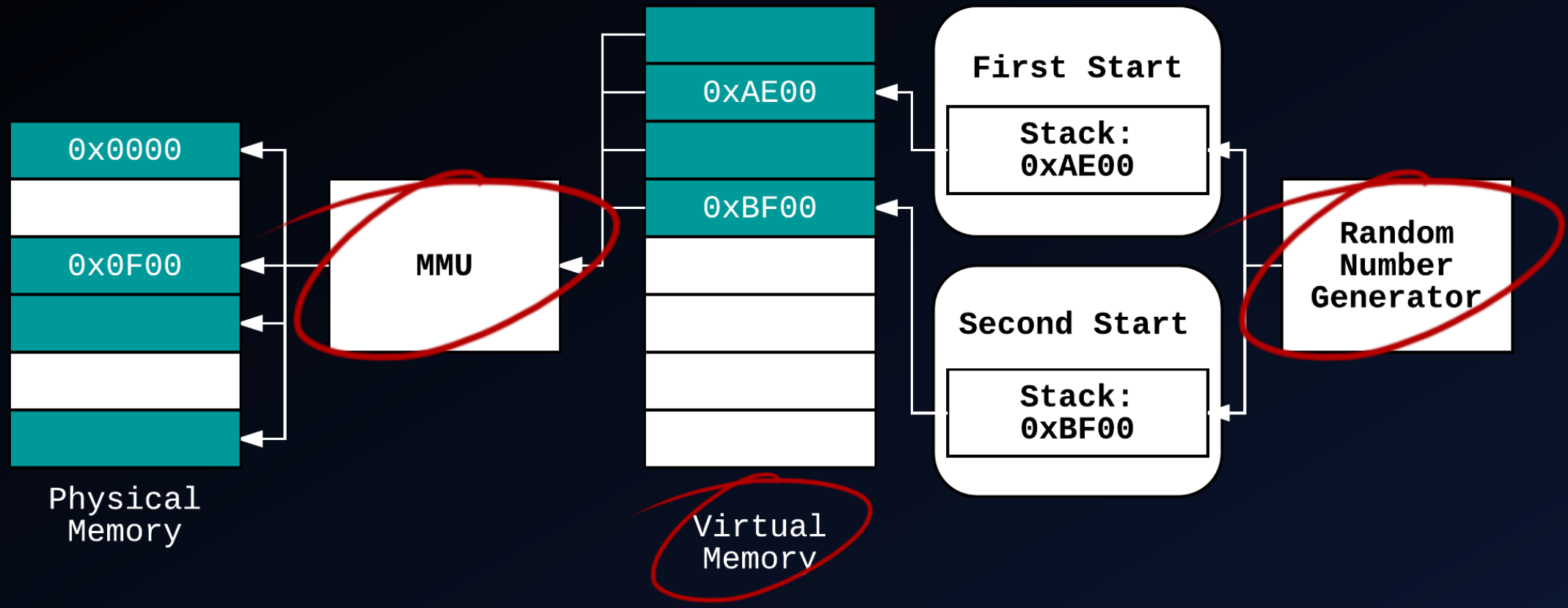
MITIGATION DEPENDENCIES



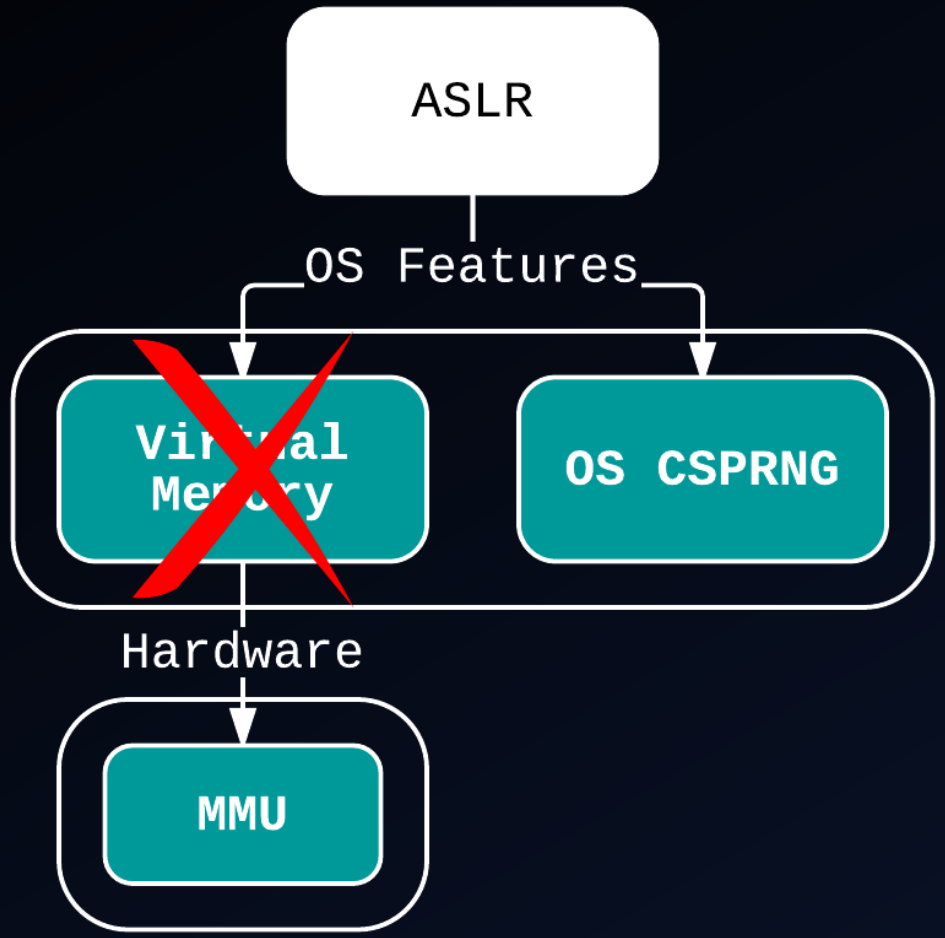


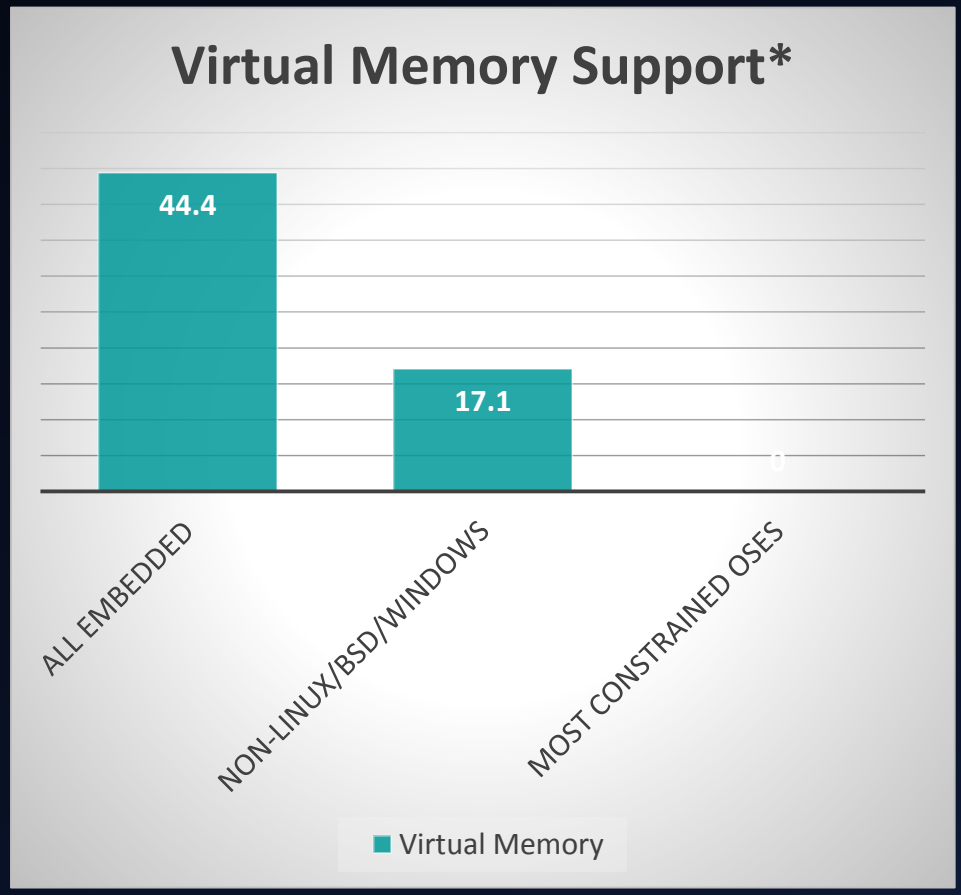


ADDRESS SPACE LAYOUT RANDOMIZATION (ASLR)



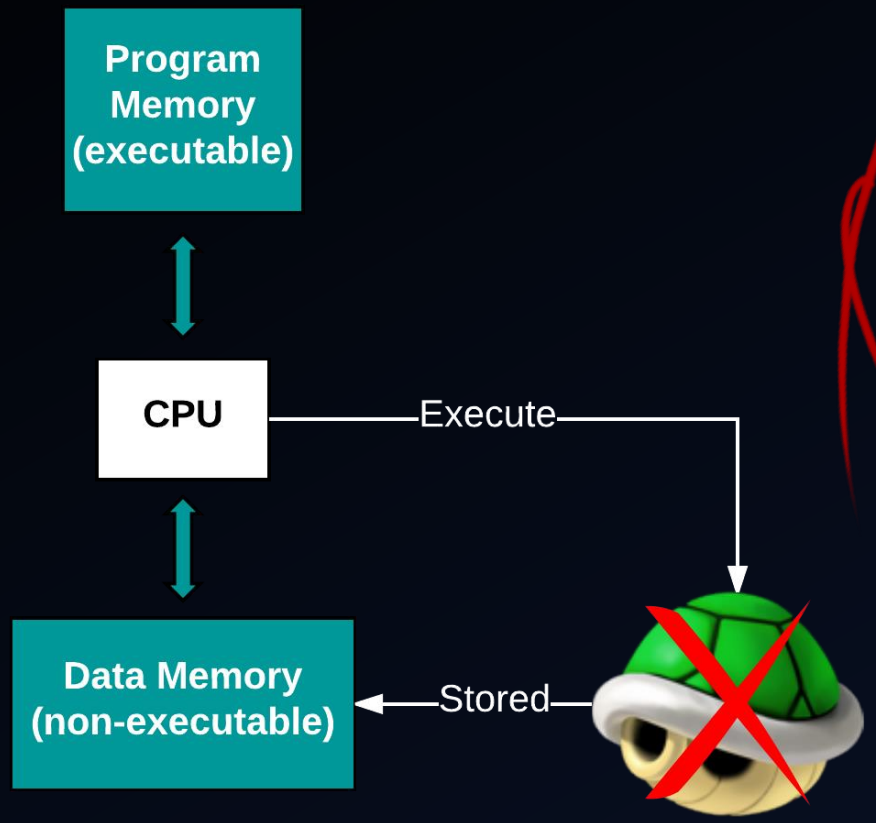
VIRTUAL MEMORY



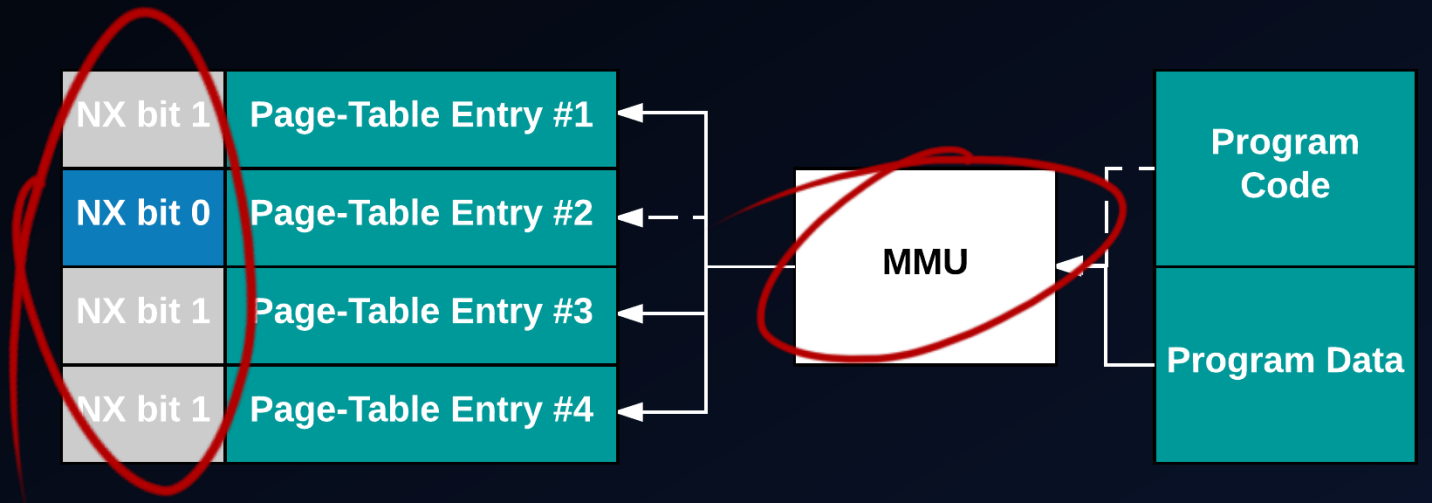


** Based on our research into 36 popular embedded OSes*

EXECUTABLE SPACE PROTECTION (ESP)



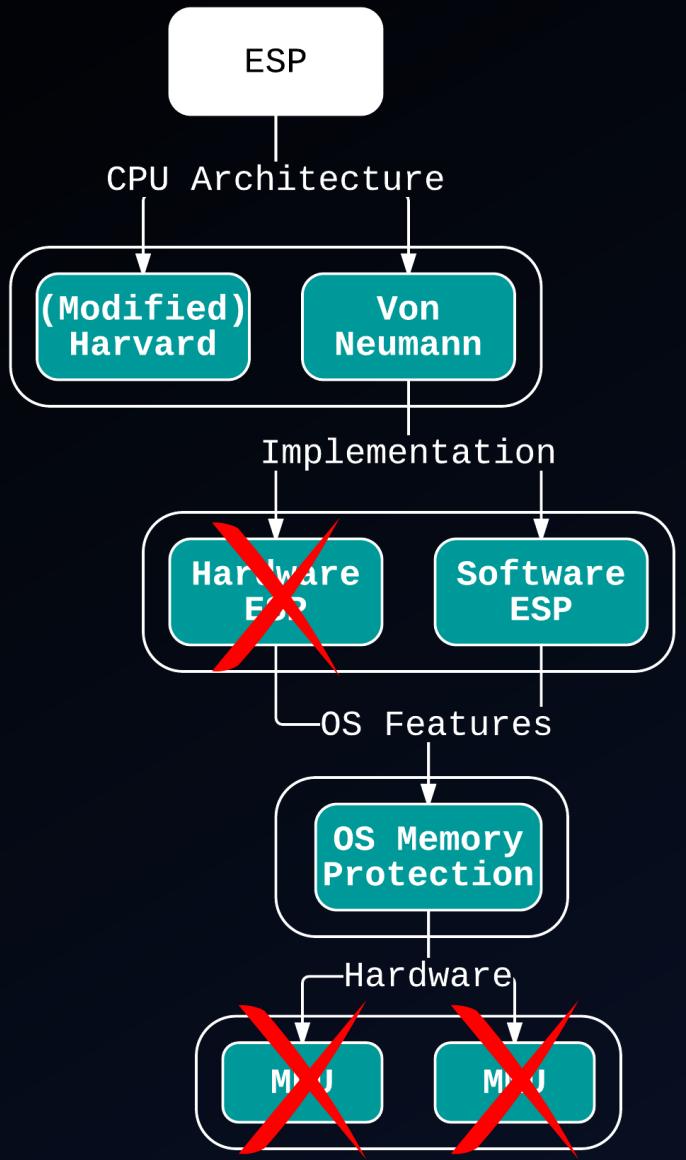
Harvard Architecture

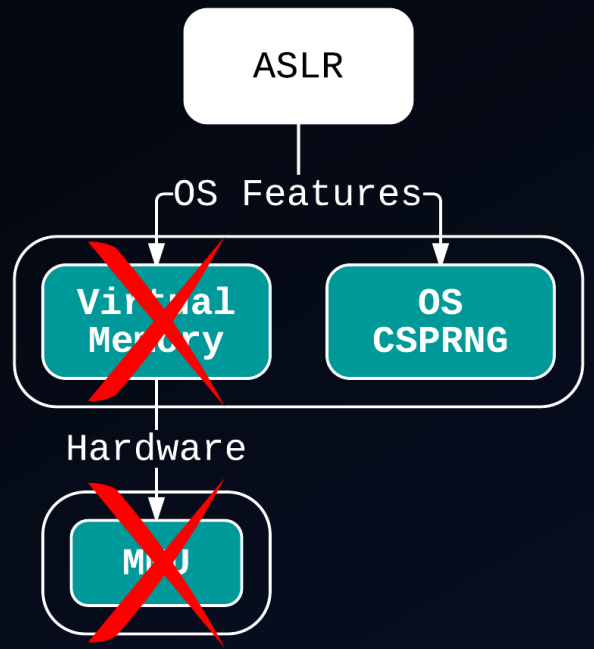


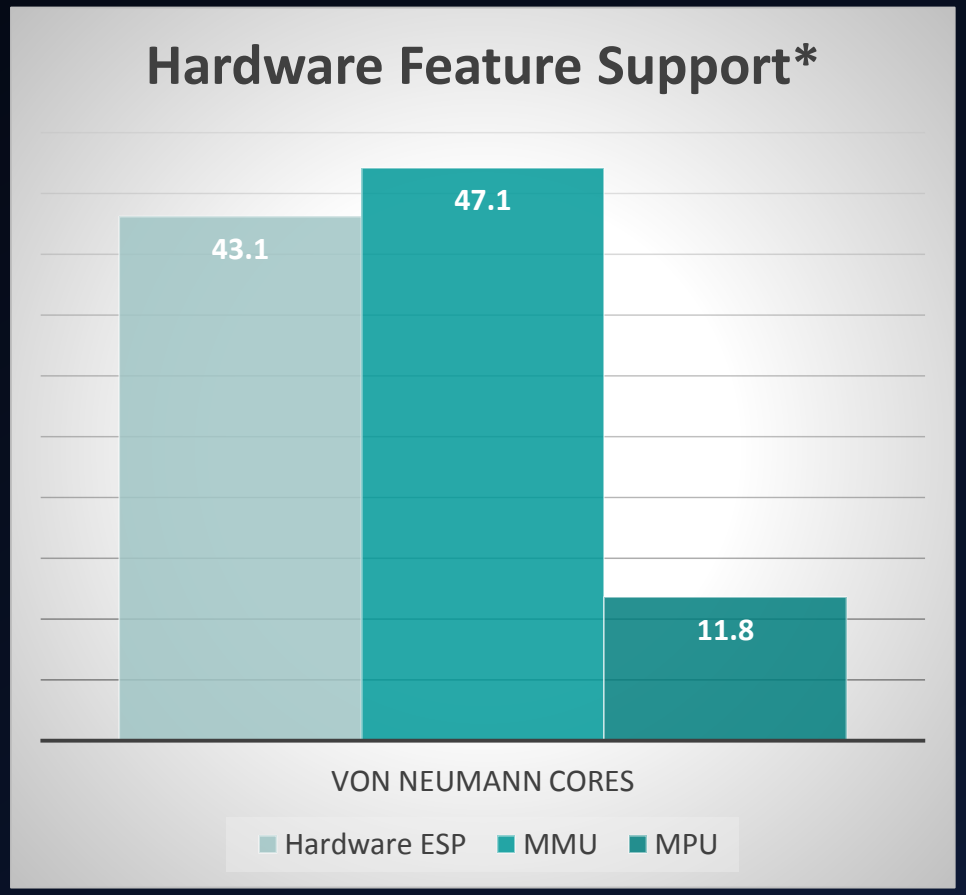
Hardware ESP

Software ESP

HARDWARE FEATURES



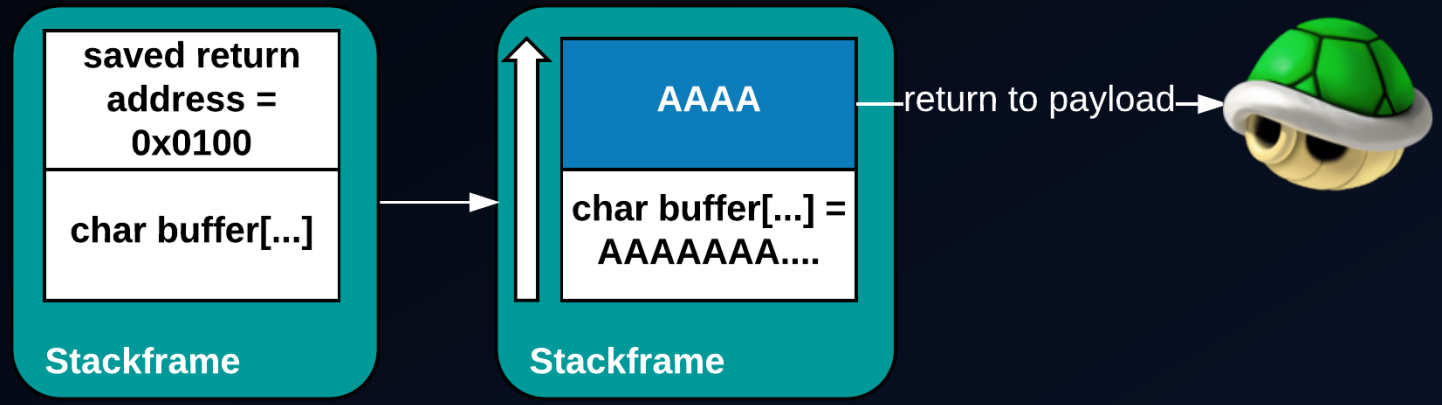




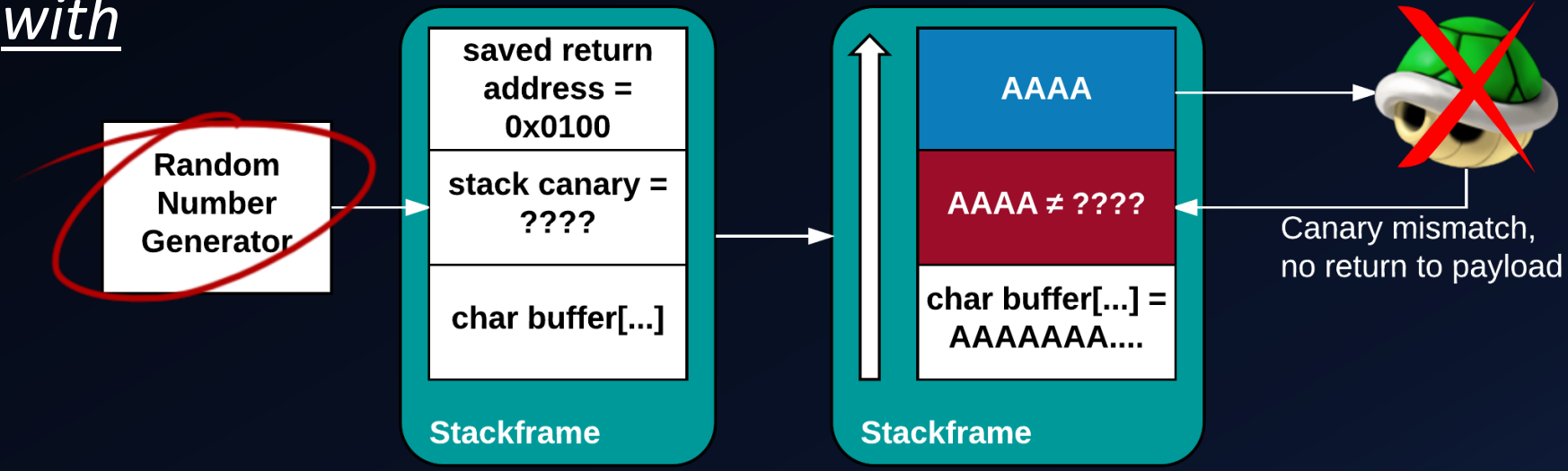
** Based on our research into 51 popular embedded core families*

STACK CANARIES

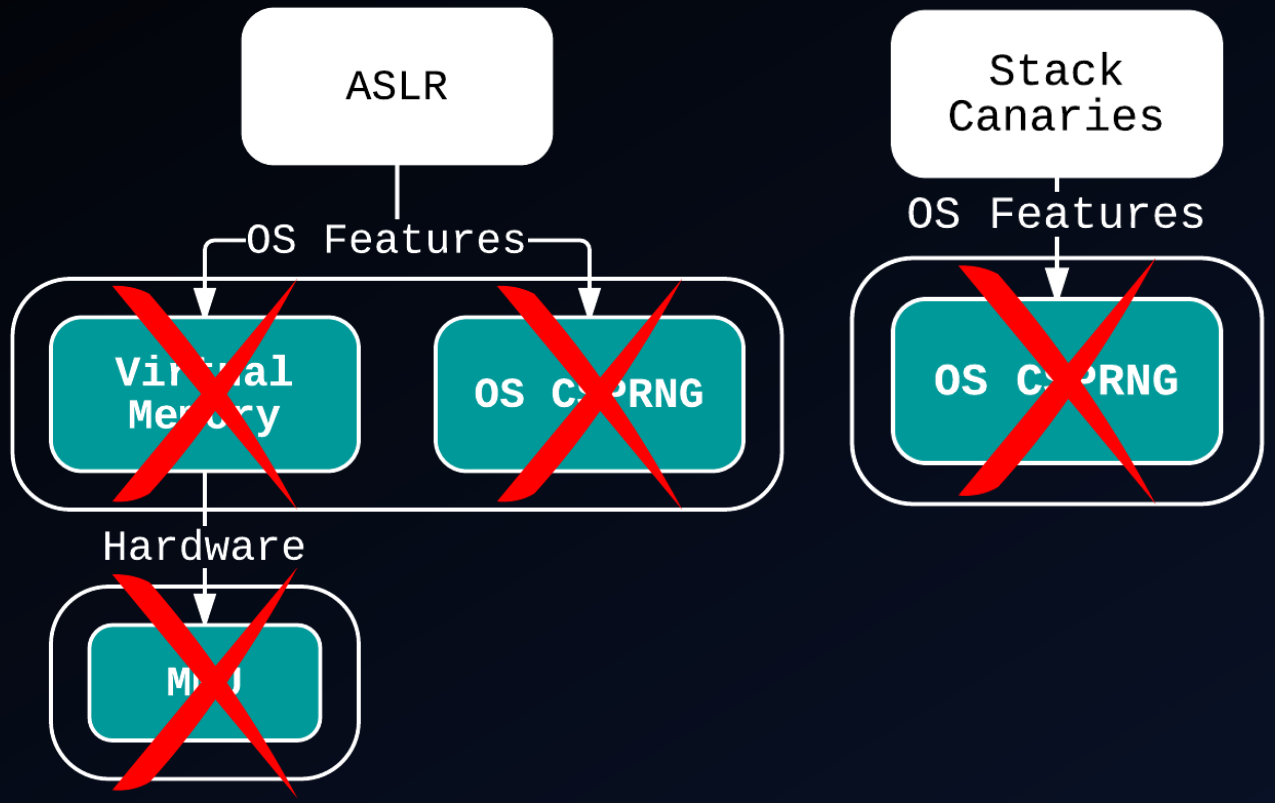
- Compiled without canaries

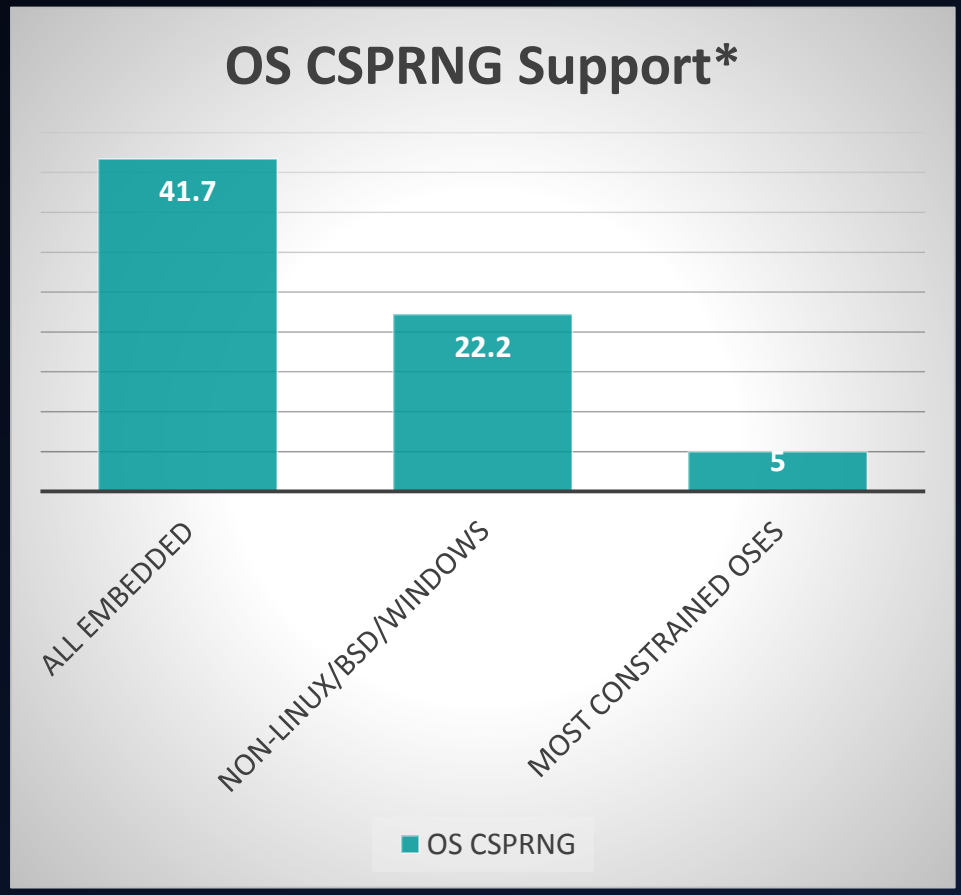


- Compiled *with* canaries



OS CSPRNGs (eg. /dev/urandom)

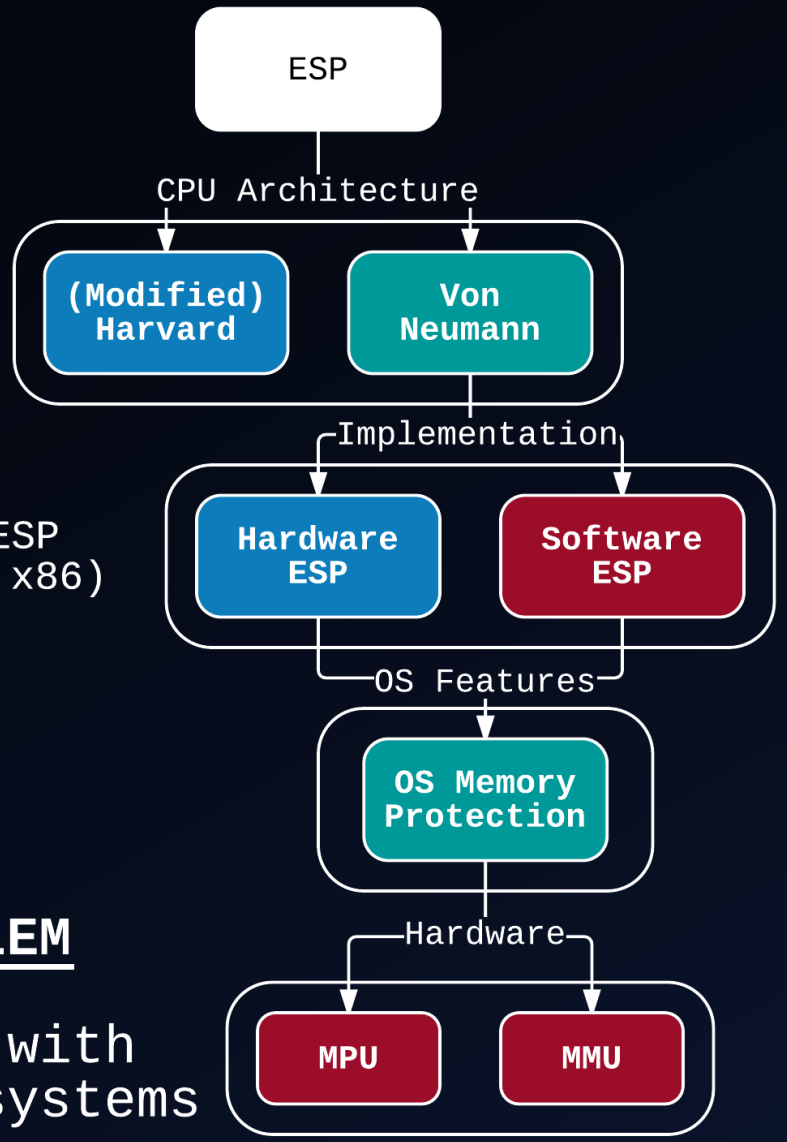




** Based on our research into 36 popular embedded OSes*

THAT DOESN’T LOOK GOOD…

ADDRESSING ESP CHALLENGES



Use Harvard CPUs
(eg. AVR,8051,PIC)

Or Neumann with HW ESP
(eg. ARMv6+,MIPS32r3+,x86)

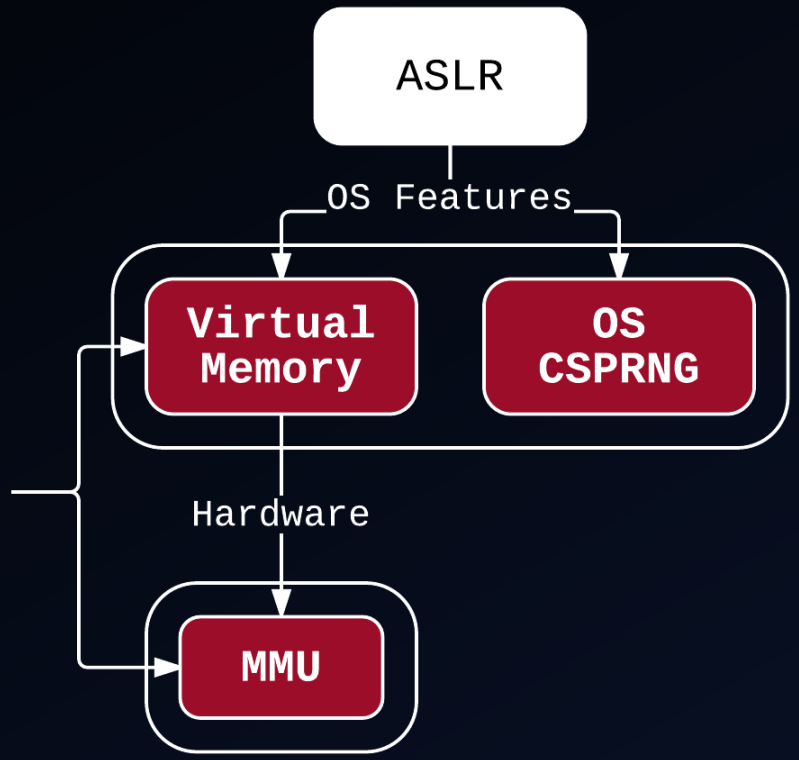
OPEN PROBLEM

Multi-Arch, Low Overhead SW ESP for Embedded OSes

OPEN PROBLEM

How to deal with MPU/MMU-less systems

ADDRESSING ASLR CHALLENGES



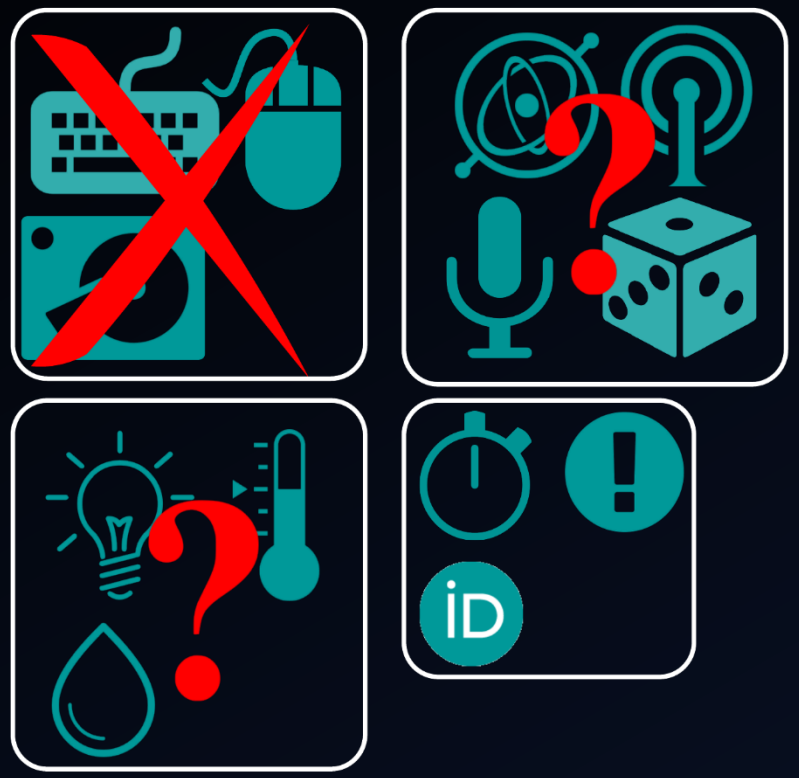
Inherent Problem (real-time conflicts, overhead, expensive, etc.)

OPEN PROBLEM

Need Embedded Alternative for ASLR

- ASLR is *runtime* diversification
- Potential Alternatives w/o VM
  - *Compile-time* Diversification
  - *Install-time* Diversification
- Downsides: less effective
  - Only between builds or devices
  - Only code, not data memory

ADDRESSING OS CSPRNG CHALLENGES

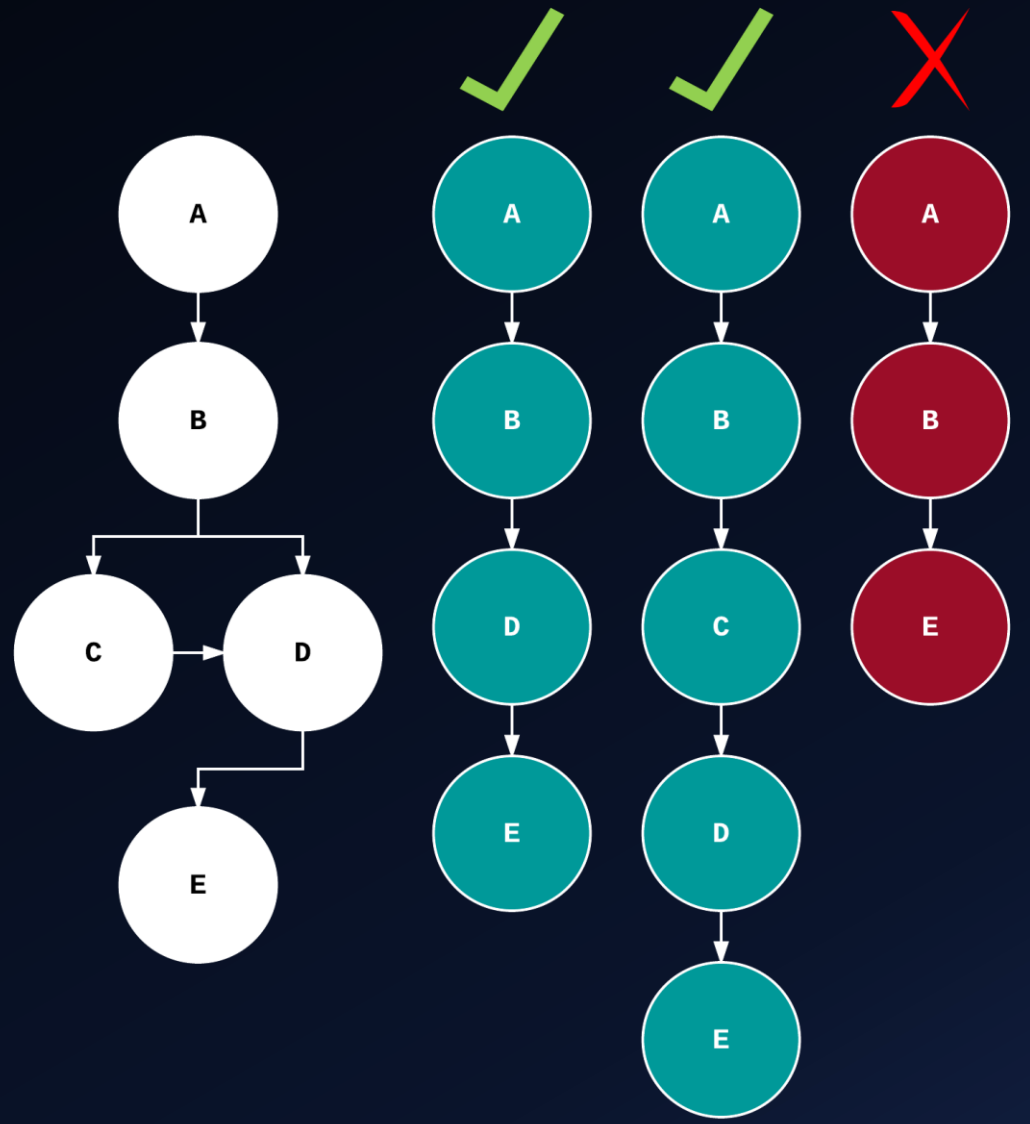


- Cannot trivially port existing designs*
  - Entropy Problems, Resource Constraints, …
- Ideal: Omnipresent On-Chip high-throughput TRNGs
- PRNG Research Directions
  - Lightweight Crypto (eg. ACRYPT Project)
  - Omnipresent Entropy Sources: SRAM Start-Up Values, Clock Jitter, …

** See our 33C3 Talk "Wheel of Fortune: Analyzing Embedded OS Random Number Generators"*

FUTURE: ADVANCED EMBEDDED MITIGATIONS

- Control-Flow Integrity (CFI) for High-End Embedded Systems
  - Enforces program execution matches legitimate Control-Flow Graph
  - Prevents Control-Flow Hijacking
  - Recently rolled out in GP world (eg. MS CFG, Clang CFI, PaX RAP, etc.)

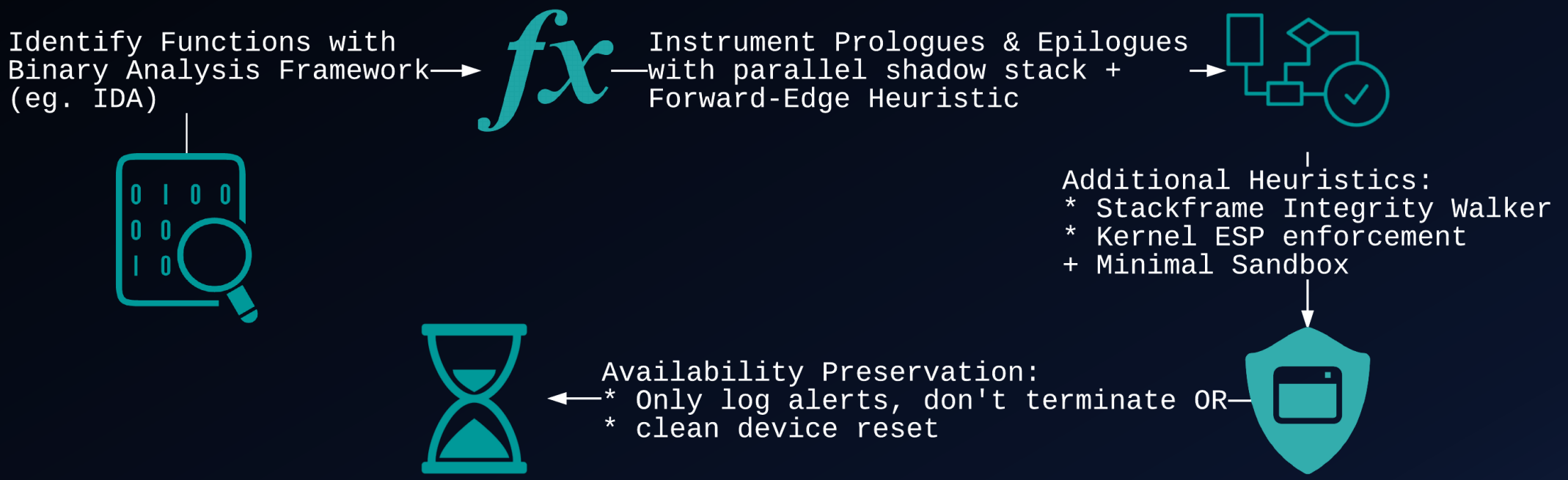


EMBEDDED CFI CHALLENGES

- Low *Worst-case* Runtime & Memory Overheads
- Real-Time Friendliness
  - Predictable, deterministic response times
- Availability Preservation
  - Eg. mitigation terminating powerplant PLC runtime
- COTS Binary Support
  - Drivers, PLC runtimes, …
- Hardware Agnostic
  - eg. no CET, LBR, PMU reliance

OUR WORK: µSHIELD & ECFI

- PREEMPTIVE* EU FP7 Project (papers forthcoming)
  - µShield**: COTS binary support + Heuristics
  - ECFI: Real-Time Friendly



* http://preemptive.eu, ** https://github.com/preemptive-FP7/uShield

CALL TO ACTION

- (Keep) Raising Awareness
  - Continue to demonstrate urgency & impact of embedded vulns
- Short term solutions
  - Address mitigation challenges (researchers)
  - Adopt mitigations (OS Devs)
- Long term solutions
  - Embedded Safe Language Adoption
  - Secure Embedded Patching & Updating (see FTC $25k prize)
  - Need for IoT Standardization, Policy & Regulation (*"Security by Design"*)