Effective Entropy for Memory Randomization Defenses

William Herlands, Thomas Hobson, Paula Donovan

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LINCOLN LABORATORY
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User Space Memory Randomization

- User-space memory randomization defenses protect against memory-corruption attacks
  - Attackers require knowledge of the layout of memory
  - Defenses randomize layout
- E.g. Address Space Layout Randomization (ASLR)

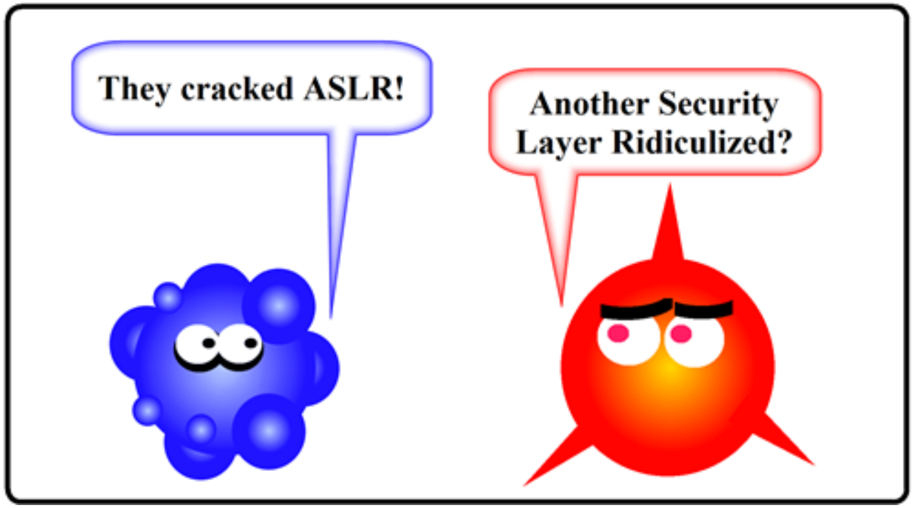

Image Reference: Didier Stevens, yaisc.com

Metric Requirements

- Current metrics use **exploits** or **entropy** to evaluate randomization technologies

Exploits	Entropy
Pro	**Pro**
• "Real life," holistic test against adversary technology	• Quantitative, information theoretic • Easy to compare
Con	**Con**
• Anecdotal • Not comparable • Biased towards existing exploits	• Does not consider threat models • Not holistic

We developed Effective Entropy, a metric which is quantitative, comparable, and indicative of adversary workload

ASLR entropy improvements

Entropy (in bits) by region	Windows 7		Windows 8		
	32-bit	64-bit	32-bit	64-bit	64-bit (HE)
Bottom-up allocations (opt-in)	0	0	8	8	24
Stacks	14	14	17	17	33
Heaps	5	5	8	8	24
Top-down allocations (opt-in)	0	0	8	17	17
PEBs/TEBs	4	4	8	17	17
EXE images	8	8	8	17*	17*
DLL images	8	8	8	19*	19*
Non-ASLR DLL images (opt-in)	0	0	8	8	24

* 64-bit DLLs based below 4GB receive 14 bits, EXEs below 4GB receive 8 bits

ASLR entropy is the same for both 32-bit and 64-bit processes on Windows 7

64-bit processes receive much more entropy on Windows 8, especially with high entropy (HE) enabled

Slide reference: Johnson, K., Miller, M. Microsoft Security Engineering Center. Exploit Mitigation Improvements in Windows 8. Black Hat USA 2012

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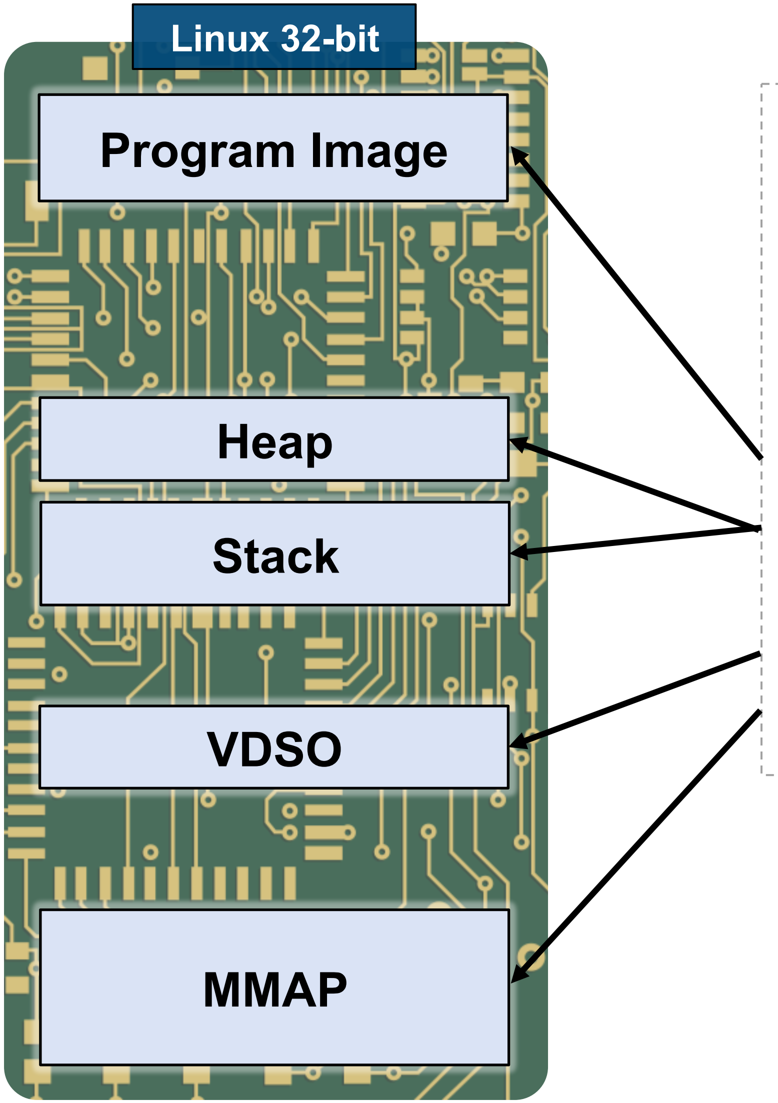
Outline

- **Background on Memory Randomization**
- **Effective Entropy**
- **Evaluation**

User Memory Layout

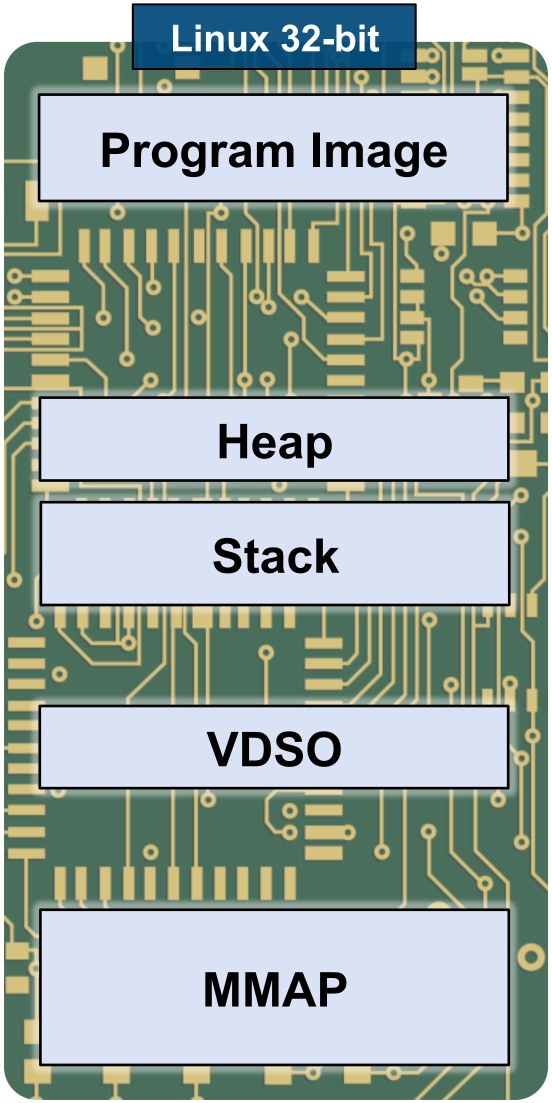


- **Multiple sections required to run a program:**
  - **Code to run ("Program Image")**
  - **Variables used in execution ("Heap" and "Stack")**
  - **Kernel functions ("VDSO")**
  - **Libraries ("MMAP")**

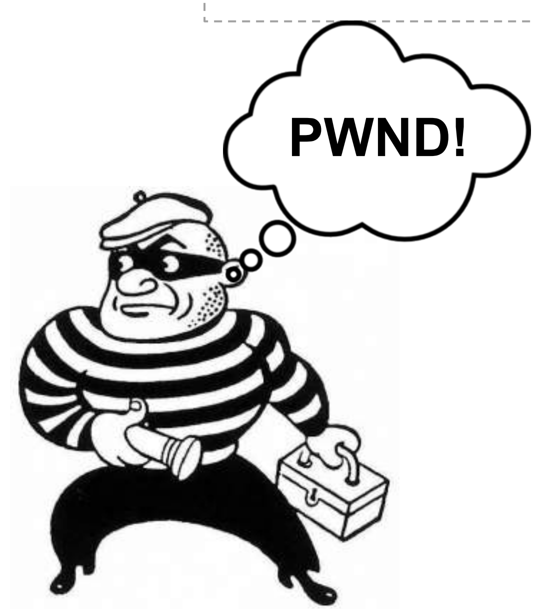
MMAP: Memory Map
VDSO: Virtual Dynamically-linked Shared Objects

User Memory Layout

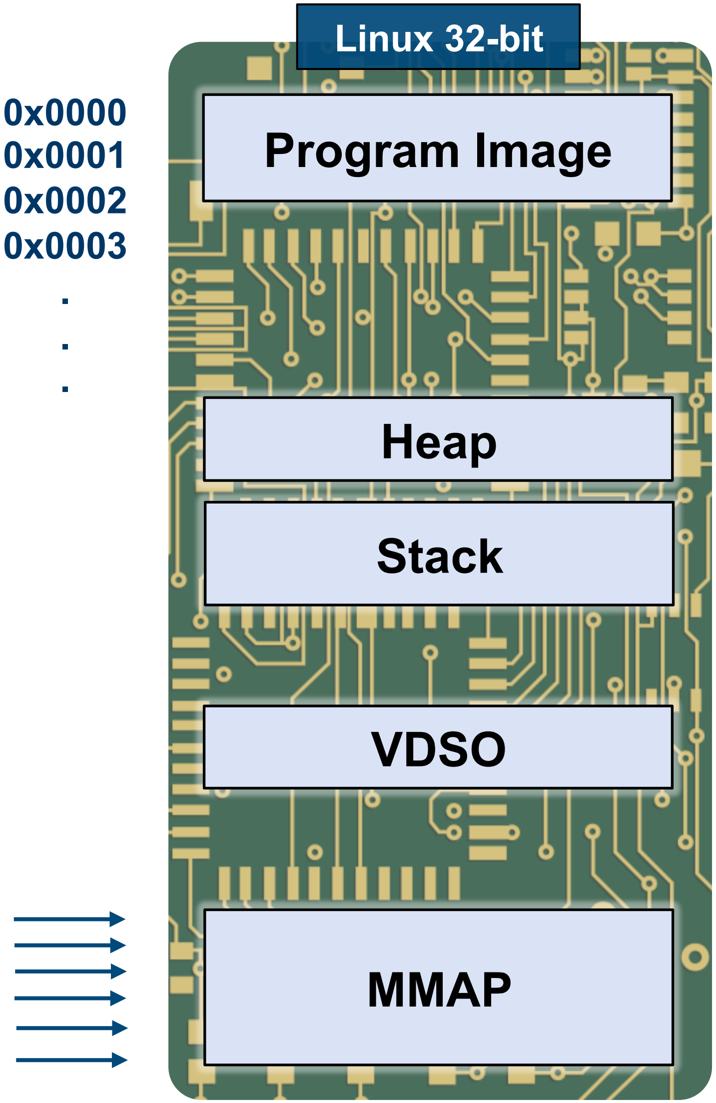
0x0000
0x0001
0x0002
0x0003
.
.
.
.



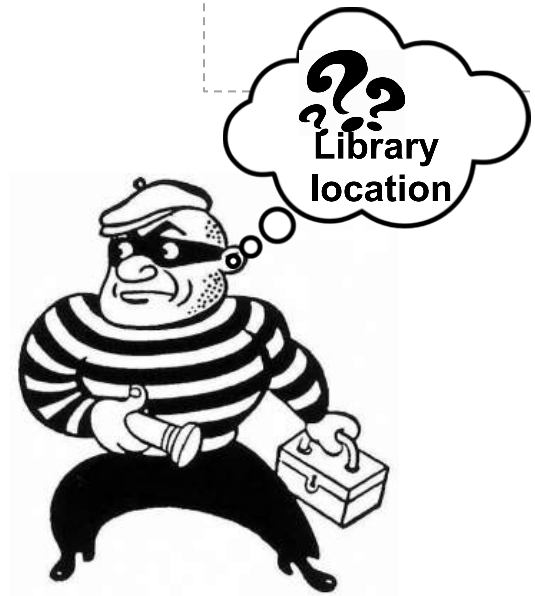
- In a static layout a variety of attacks are possible since an adversary can trivially know the location of objects in memory



Entropy in User Memory Layout



- Memory randomization techniques randomize sections' location in memory
  - Base address randomization
  - E.g. Ubuntu 32-bit provides 256 (2^8) possible MMAP locations



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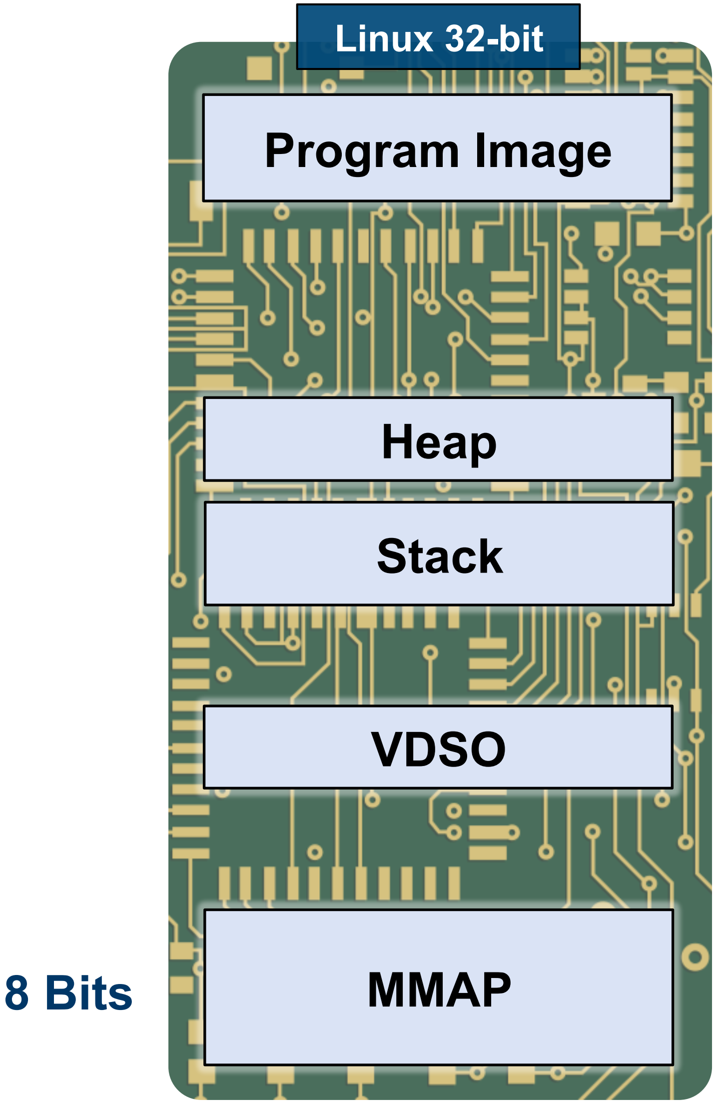
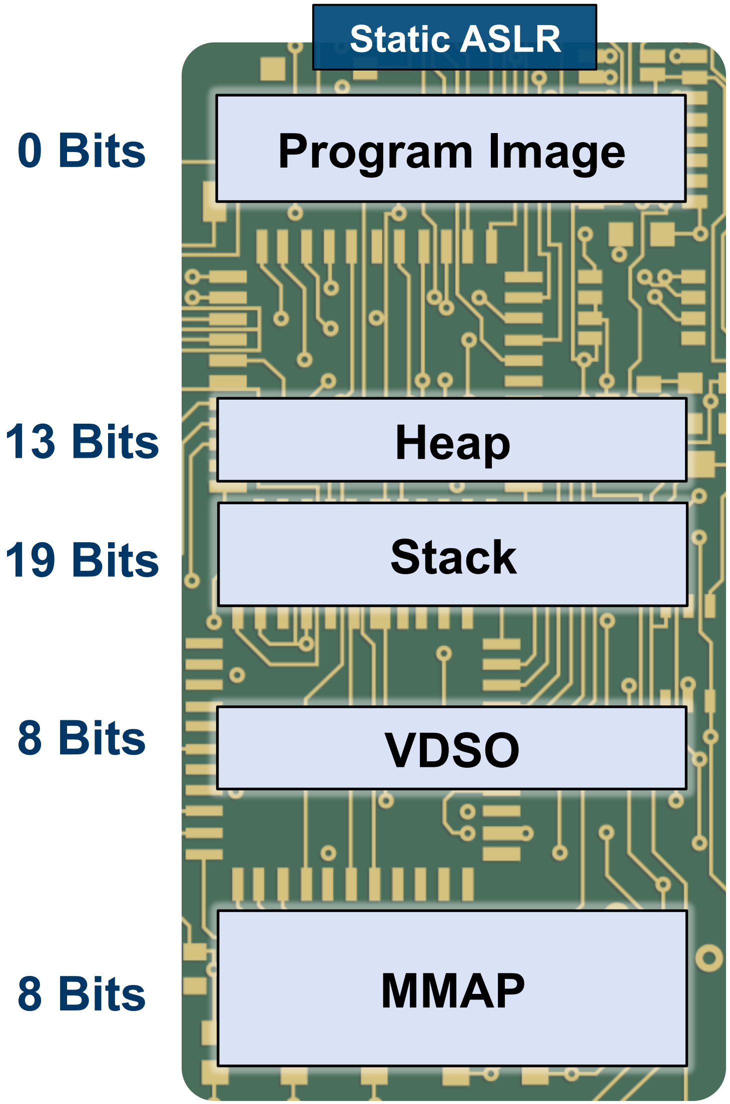


- Entropy is a means of measuring randomness
  - E.g. MMAP base can take 2^8 values with equal probability so it has 8 bits of entropy
  - Standard calculation of entropy measures total uncertainty of a variable in bits

$$H(X) = -\sum_{i=1}^{n} p(x_i) \log p(x_i)$$

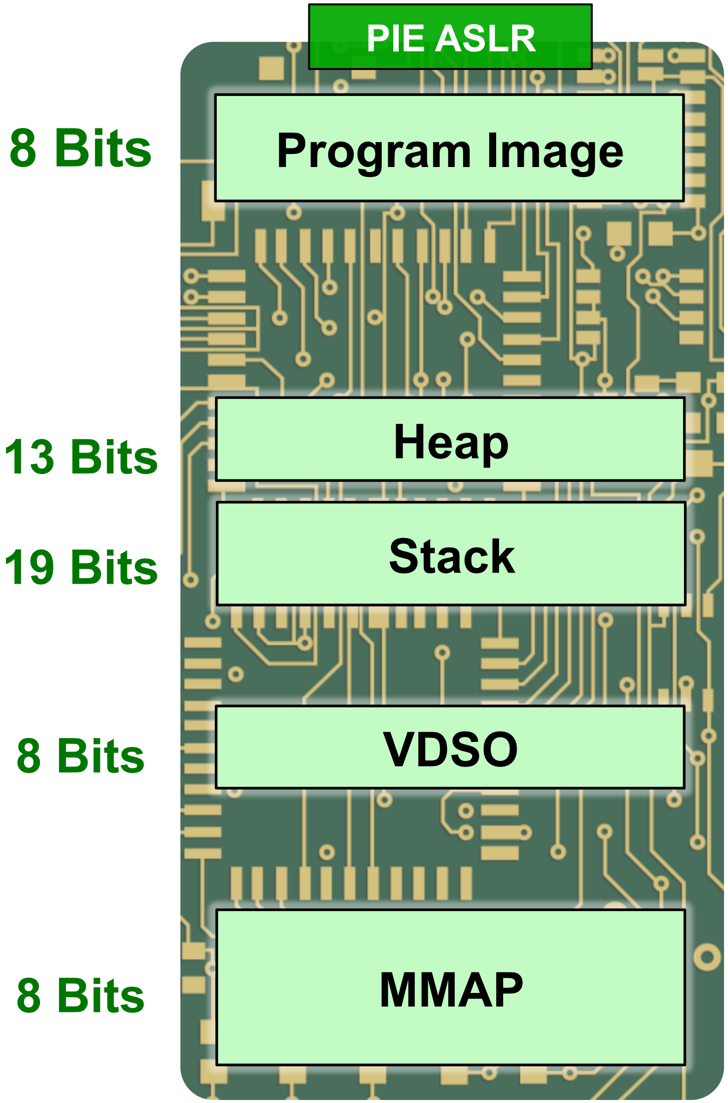
Static Address Space Layout Randomization (ASLR)



- Static (non-PIE) ASLR randomizes base addresses of memory sections
  - Heap, stack, VDSO, and MMAP randomized independently
  - Program image not randomized
- Implemented in most modern operating systems
  - Windows, OS X, Linux, OpenBSD

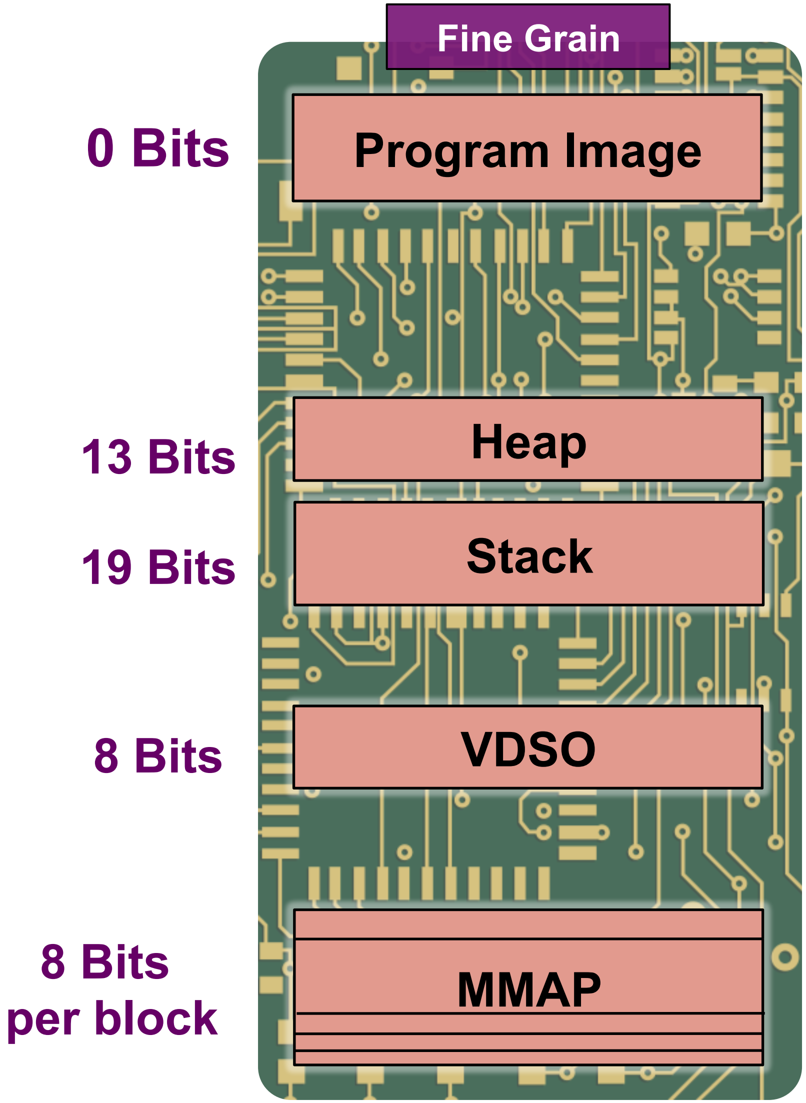
PIE ASLR

- **Position Independent Executable (PIE) ASLR randomizes all base addresses of memory**
  - **Heap, stack, VDSO, MMAP, and program image randomized independently**
- **Increasingly prevalent**
  - **Compiler option in GCC**
  - **Default in OpenBSD 5.3**



Fine Grain Randomization

- Fine grain randomization
  - Randomize smaller blocks, not only section base addresses
  - E.g. Independent library randomization
  - “Address Space Layout Permutation (ASLP): Towards Fine-Grained Randomization of Commodity Software”, Kil et al.



Outline

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- ➡ Effective Entropy
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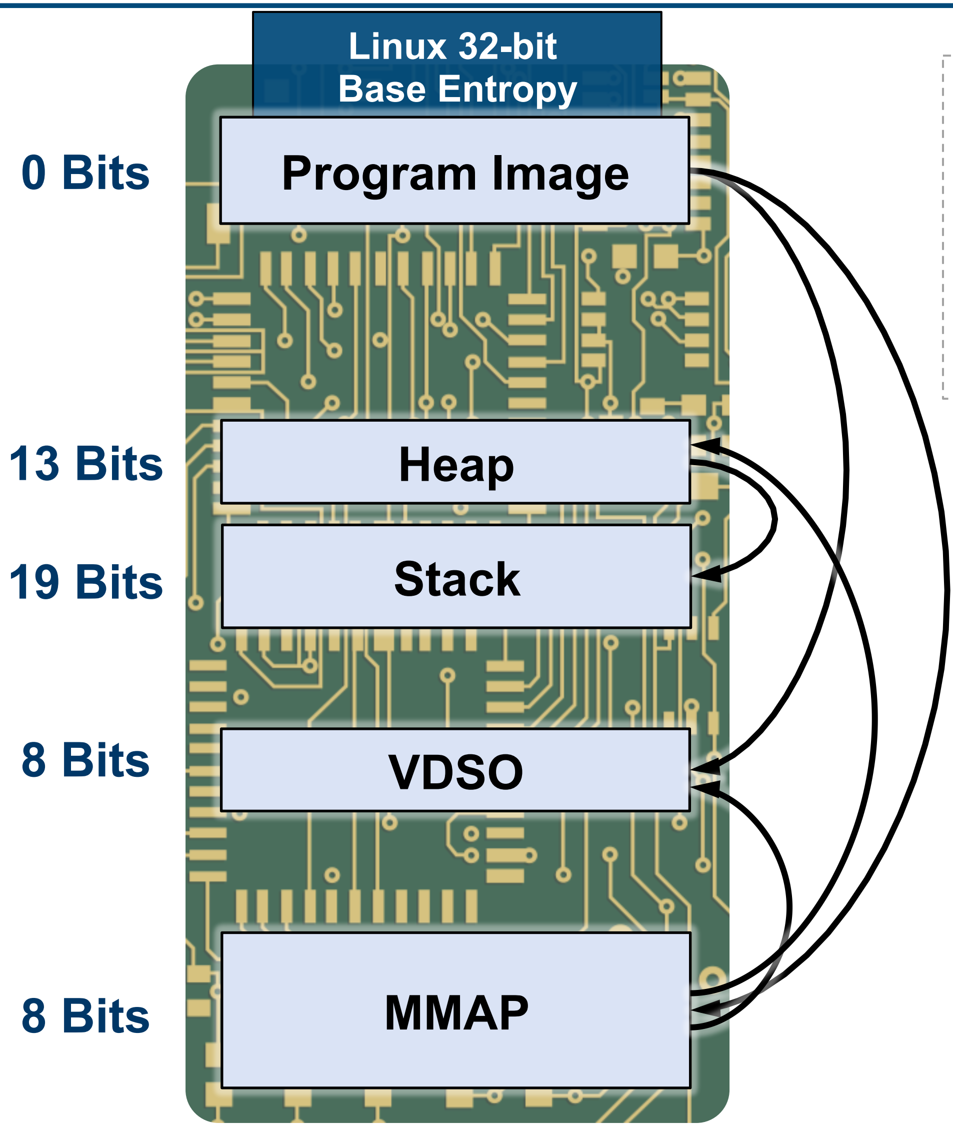
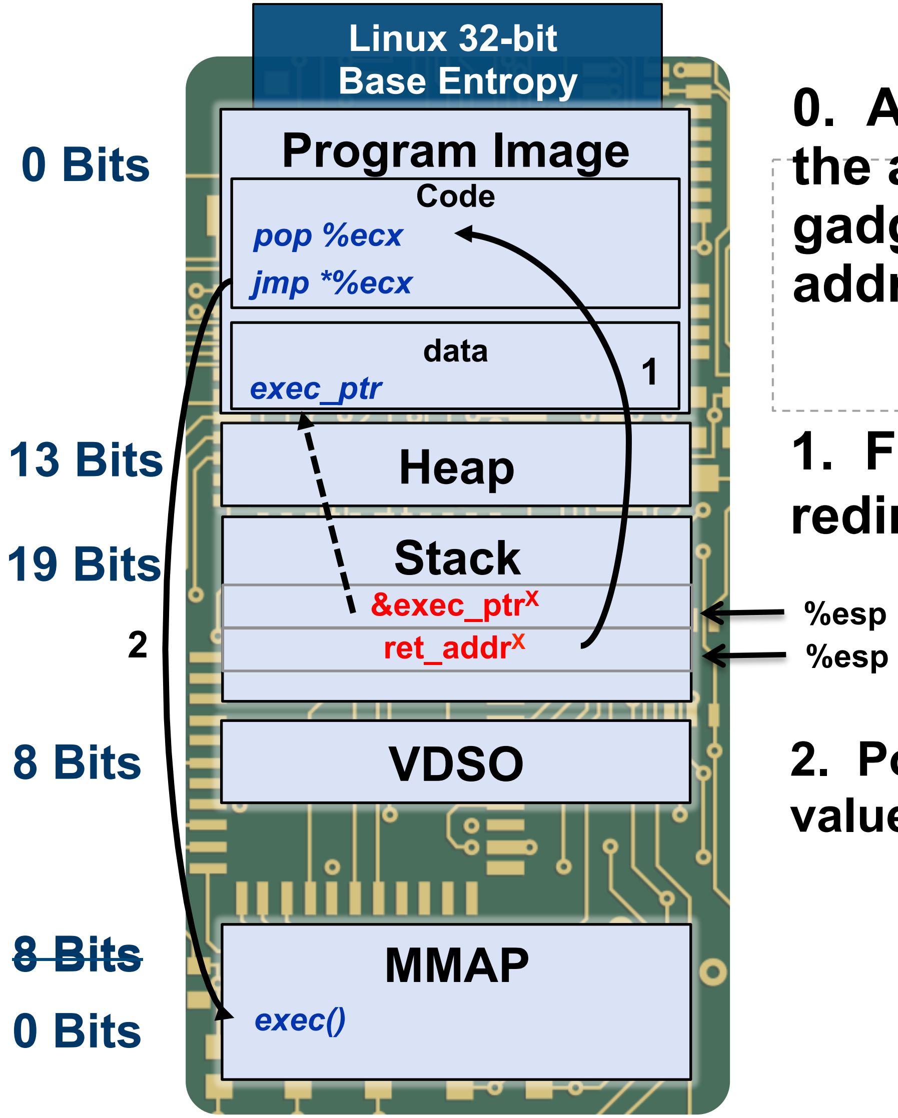
Connections in User Memory Layout



- Not so simple
- Interconnectedness
  - Control flow instructions
  - Pointers

Connections in User Memory Layout



0. Attacker uses buffer overflow to write the address of '*pop %ecx, jmp *%ecx*' gadget into ret addr, followed by the address of *exec_ptr*

1. Function attempts to return, control redirected to gadget in Program Image

2. Pops *&exec_ptr* from stack and jumps to value at that address (*exec function in MMAP)*

X - Attacker supplied values

Connections in User Memory Layout

—— **Absolute connections**

- Read-only pointers
- Direct jumps

- - - **Dynamic connections**

- Writable pointers
- Indirect branches

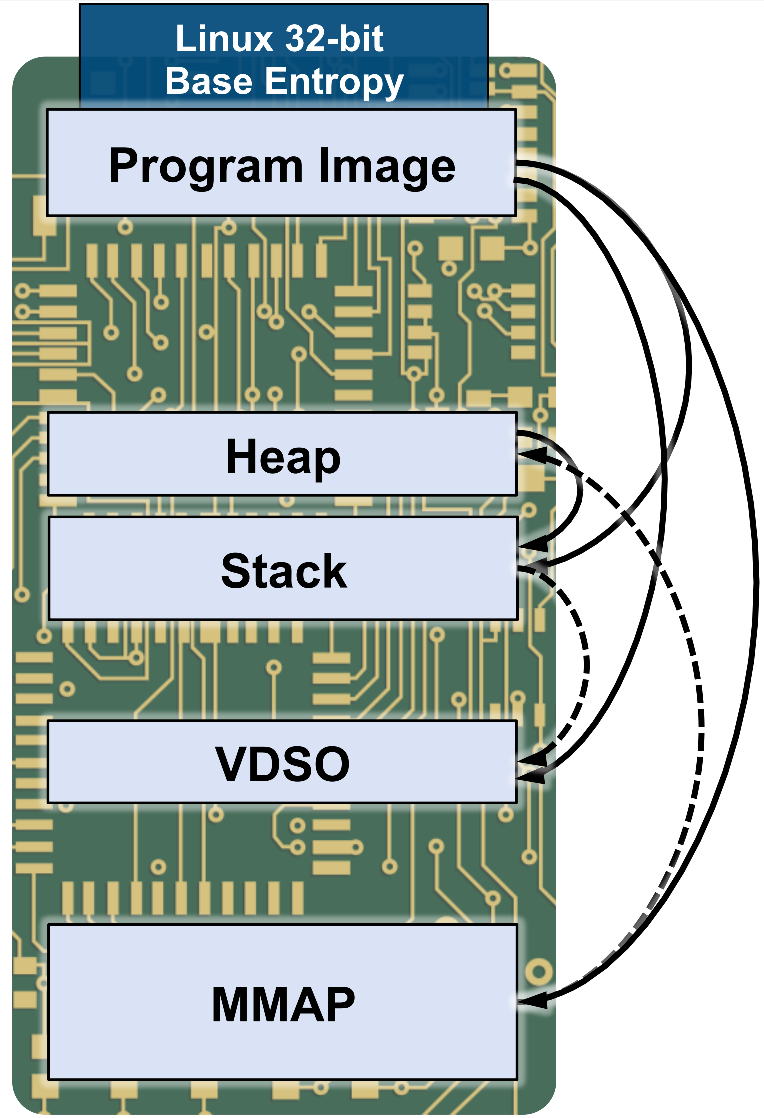
0 Bits

~~13 Bits~~ ? Bits

~~19 Bits~~ ? Bits

~~8 Bits~~ ? Bits

~~8 Bits~~ ? Bits



Connections in User Memory Layout

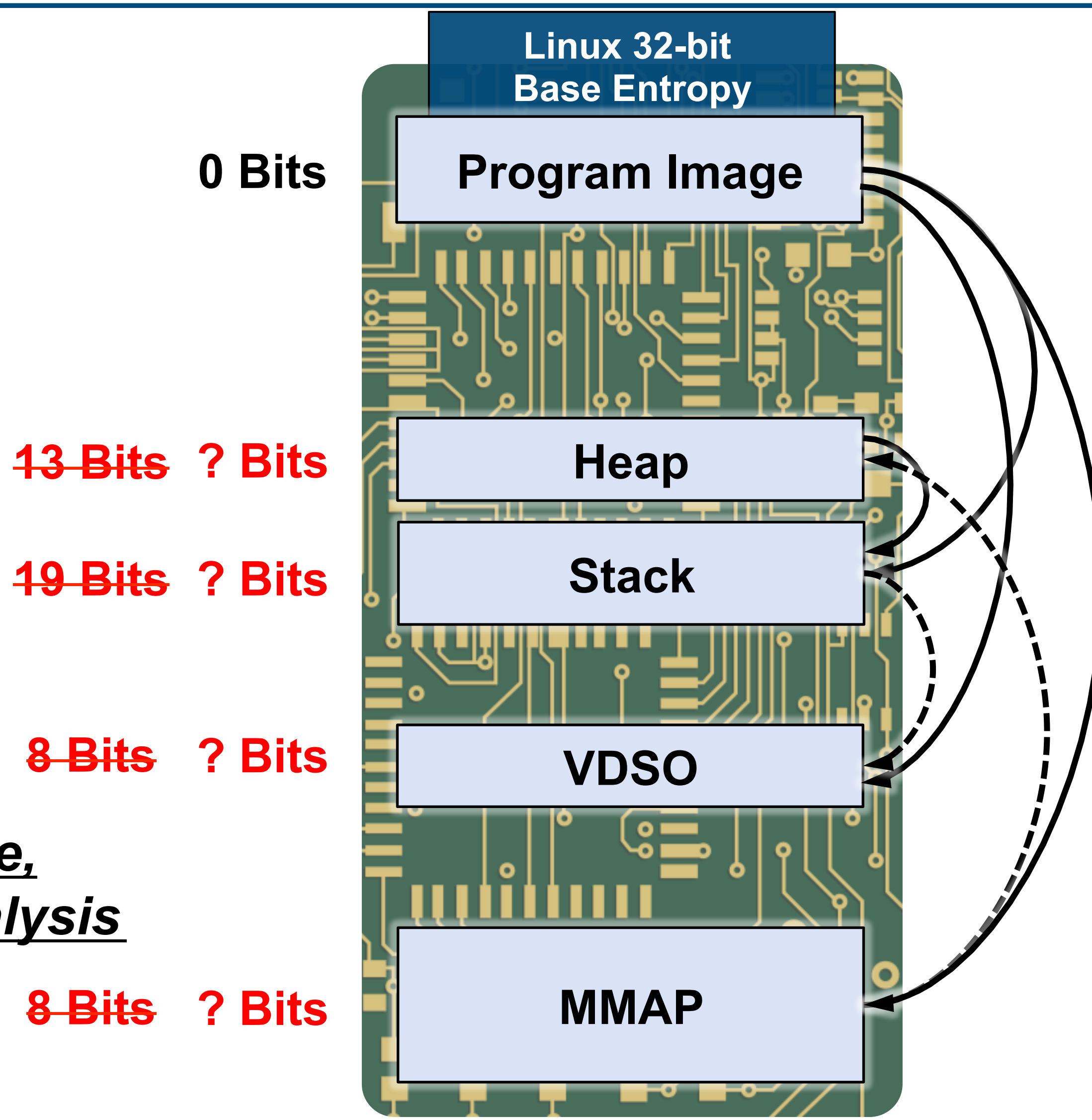
— Absolute connections

- Read-only pointers
- Direct jumps

--- Dynamic connections

- Writable pointers
- Indirect branches

<u>Difficult to determine, requires runtime analysis</u>



Identifying Dynamic Pointers

Run deterministic execution path twice:

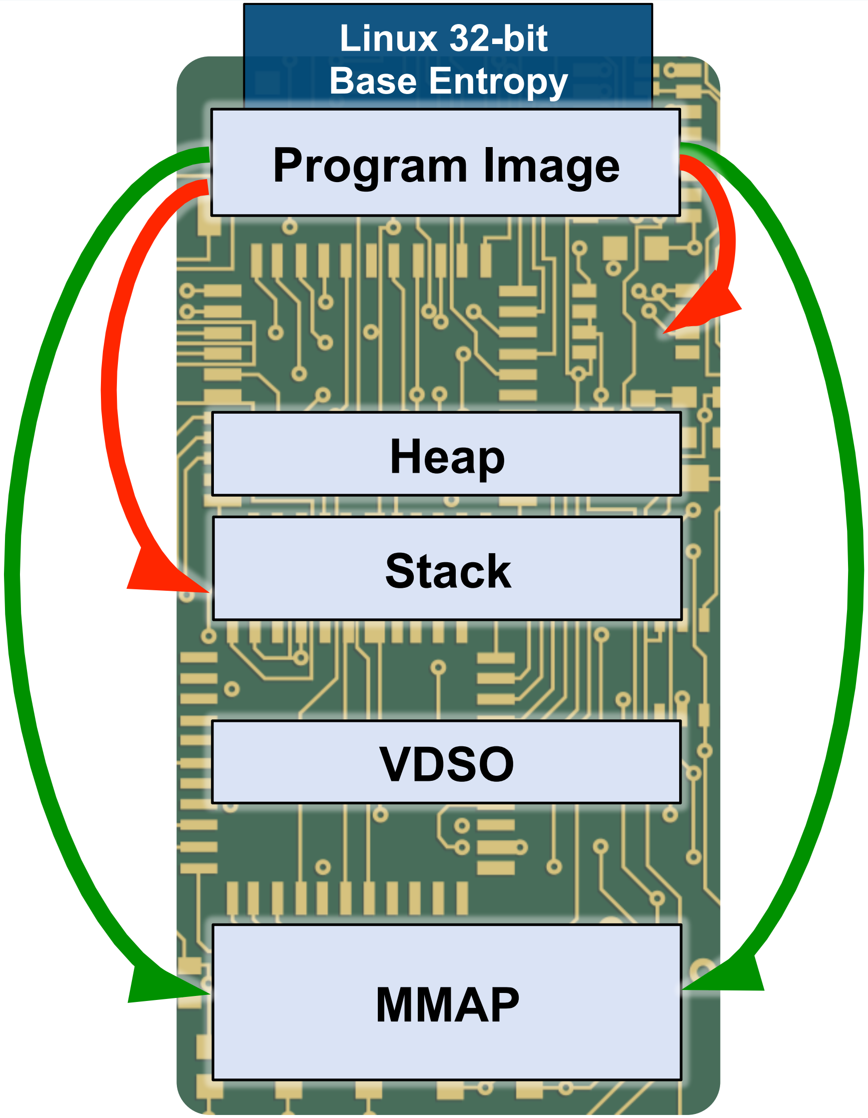
Examine writeable memory at every control flow statement

↓

Eliminate inconsistencies

↓

Identify dynamic pointers



Effective Entropy (EffH)

$$EffH_s = min \begin{cases} h_s \\ min(H^x_{conn}) \\ min(H^p_{conn}) + min(H^x) \end{cases}$$

$$H^p_{conn} = \{h^p_j : \exists connection(j,s)\}$$

$$H^x_{conn} = \{h^x_j : \exists connection(j,s)\}$$

Measuring Randomization Technologies

- EffH is a property of a randomization technology and threat model
- On any particular platform, sufficiently large programs exhibit similar memory interconnections
  - E.g. Global Offset Table → Library functions
- Any non-degenerate execution of a program is representative of all non-degenerate executions with respect to memory usage
  - Connections are drawn from same distribution

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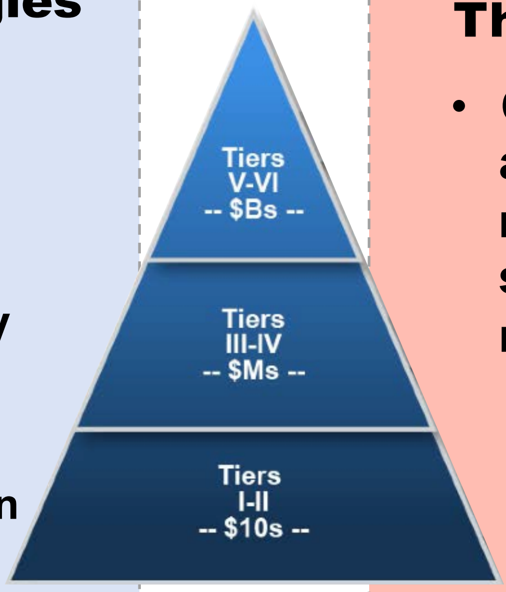
Experiment Overview

- Goals:
  - Evaluate current and emerging security technologies against realistic threat models
  - Assess utility of the EffH metric

Security Technologies Considered

- Static ASLR
- PIE ASLR
- Independent Library Randomization
  - Simulation of fine grain randomization technique



Threat Models

- Consider viable adversaries at multiple tiers of sophistication and resources

Image Reference: Defense Science Board, Jan 2013: Resilient Military Systems and the Advanced Cyber Threat

Threat Model

- **Moderate Adversary**
  - **Control flow hijacking vulnerability**
  - **Modern exploitation methods including Return Oriented Programming (ROP)**
- **Memory Disclosure Adversary**
  - **Control flow hijacking vulnerability**
  - **Modern exploitation methods including ROP**
  - ***Memory disclosure vulnerability that reveals location of one memory section***

Return Oriented Programming

- **Use snippets of executable code called "ROP gadgets"**
- **Combine gadgets to create a custom exploit**

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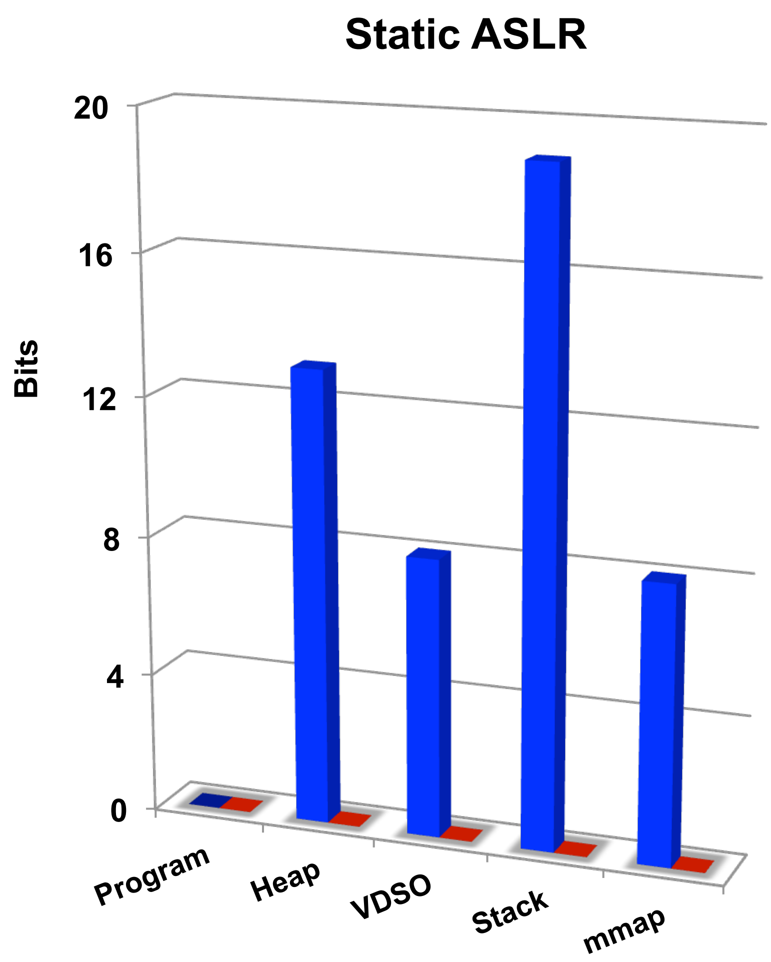
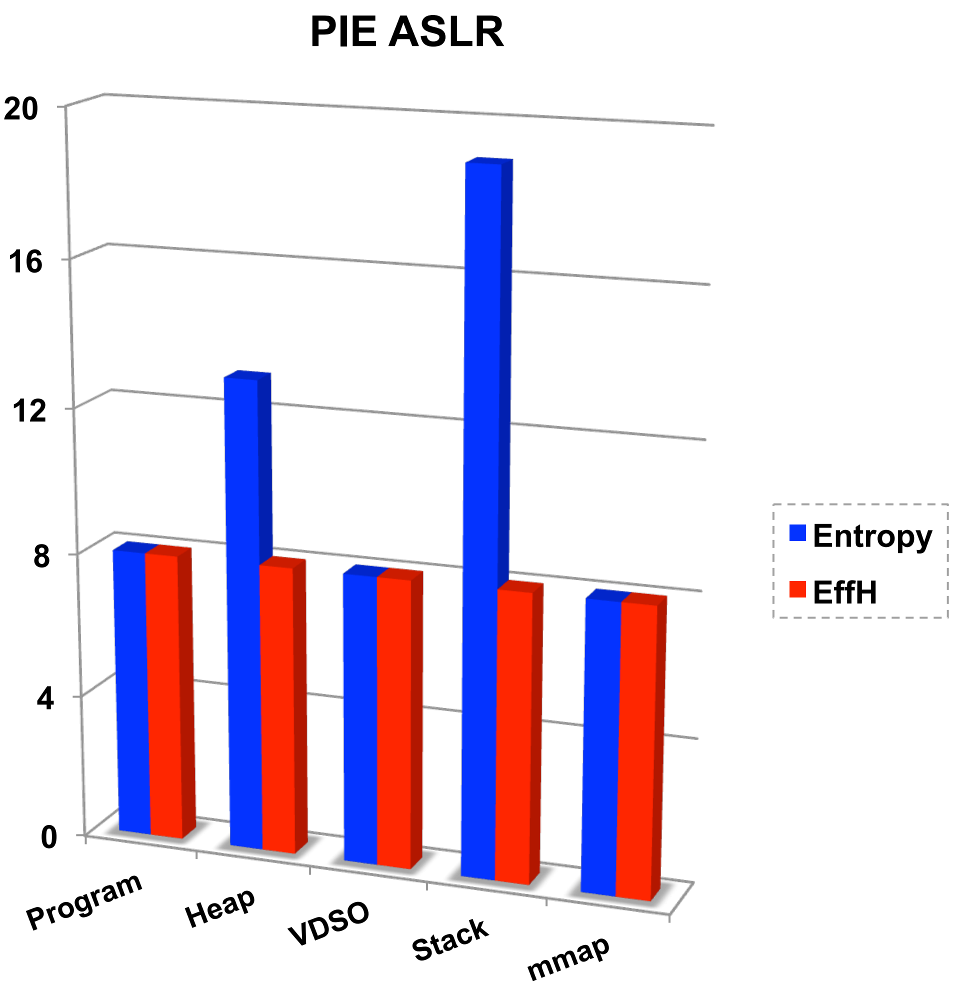
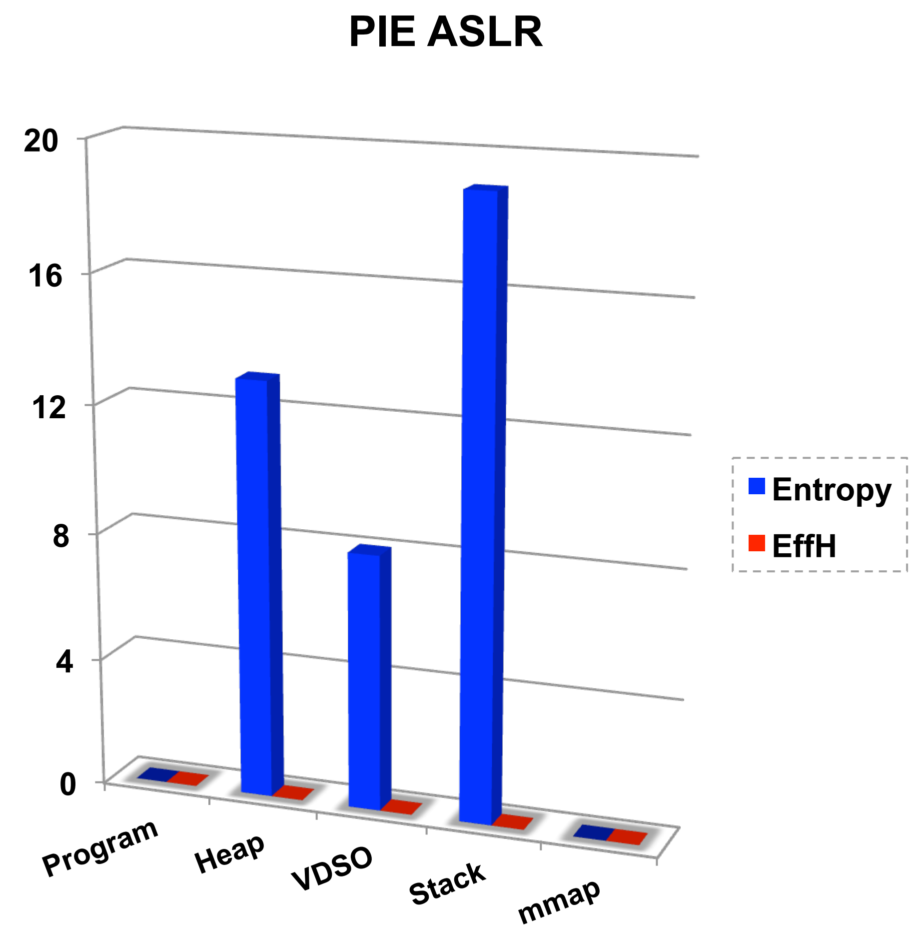
Moderate Adversary - ASLR





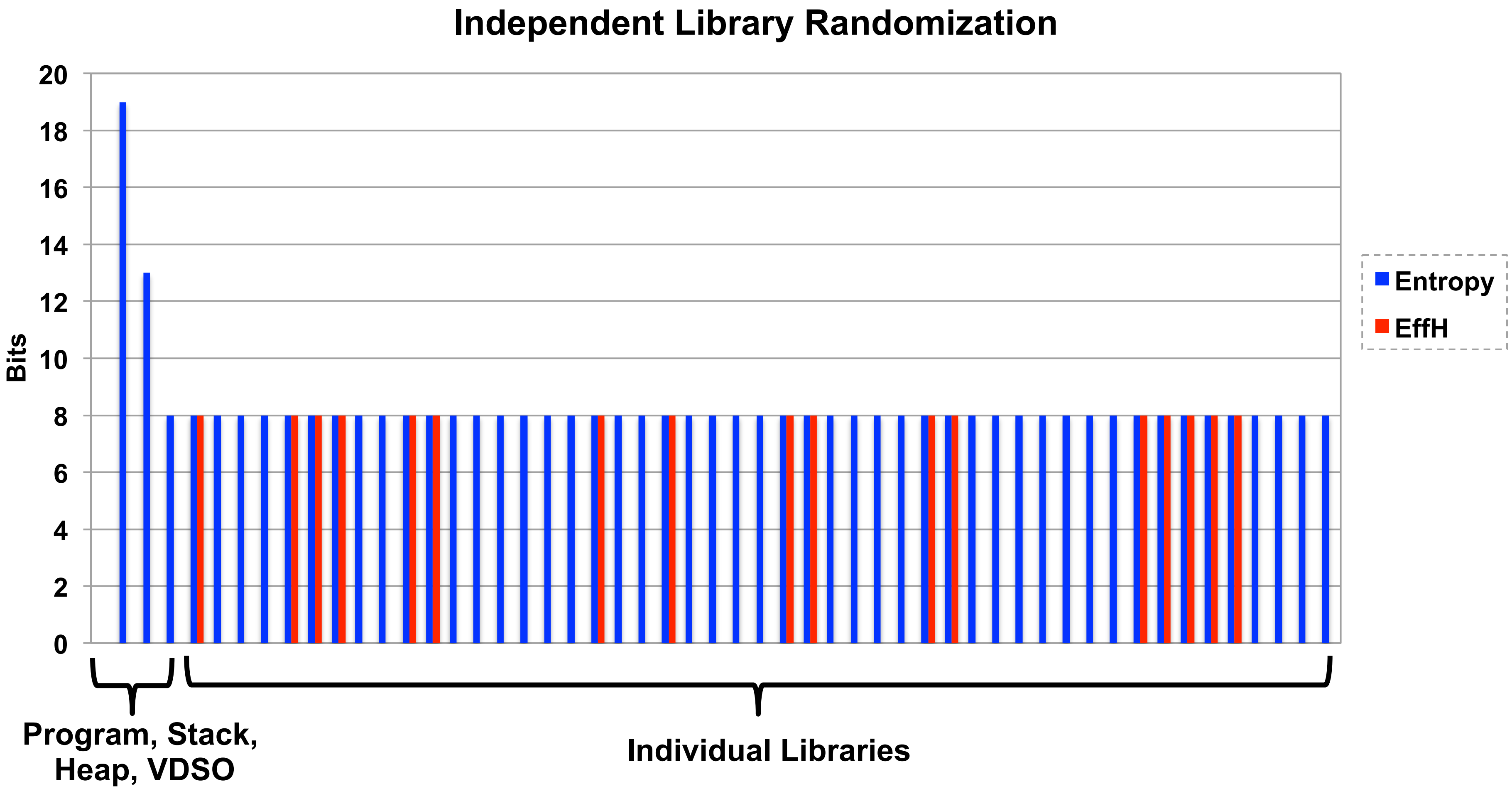
Static ASLR provides zero bits of EffH to Moderate Adversary

Memory Disclosure Adversary – PIE ASLR



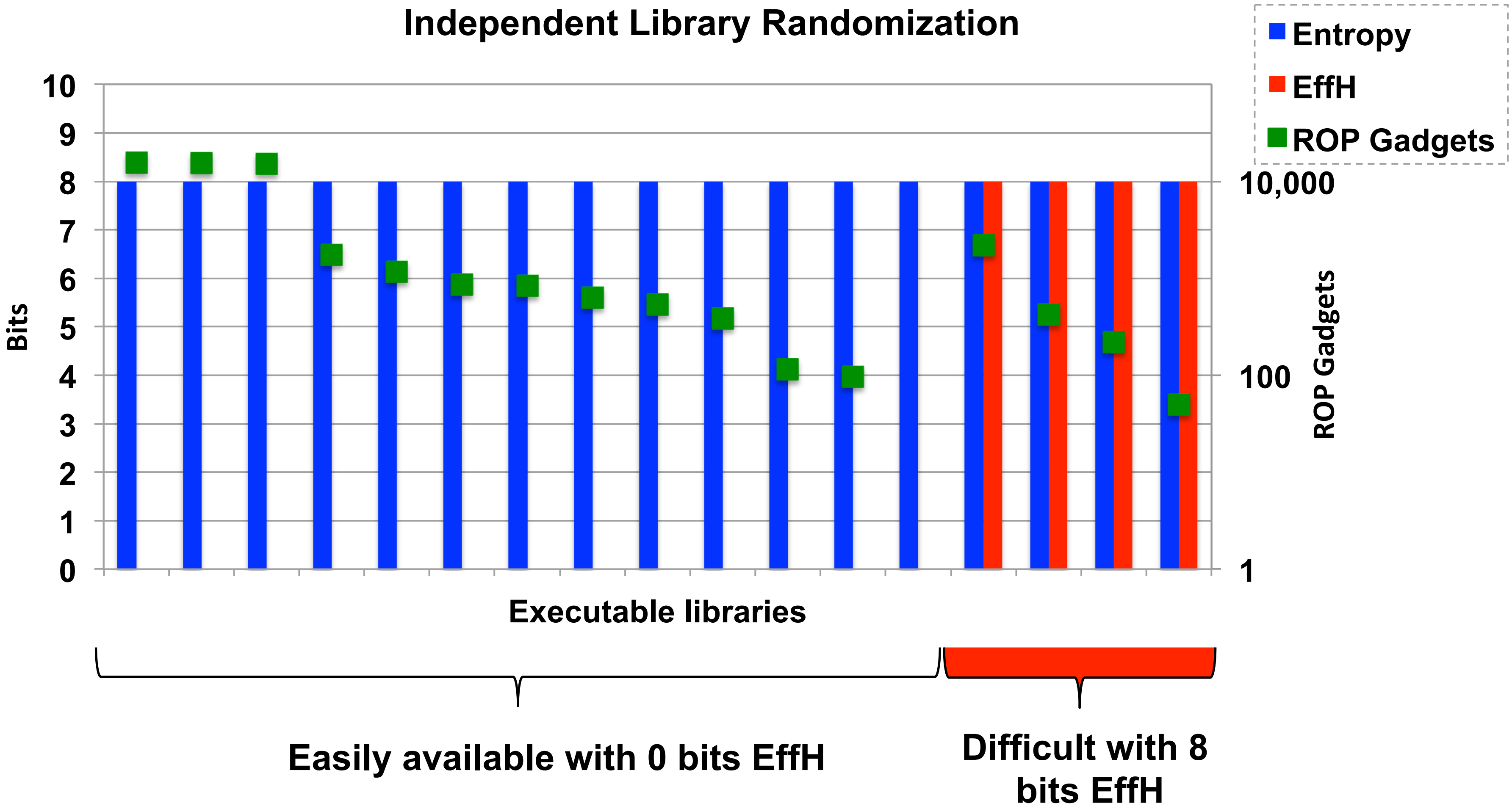
PIE ASLR provides zero bits of EffH to Adversary disclosing Program Image

Memory Disclosure Adversary - Fine Grain



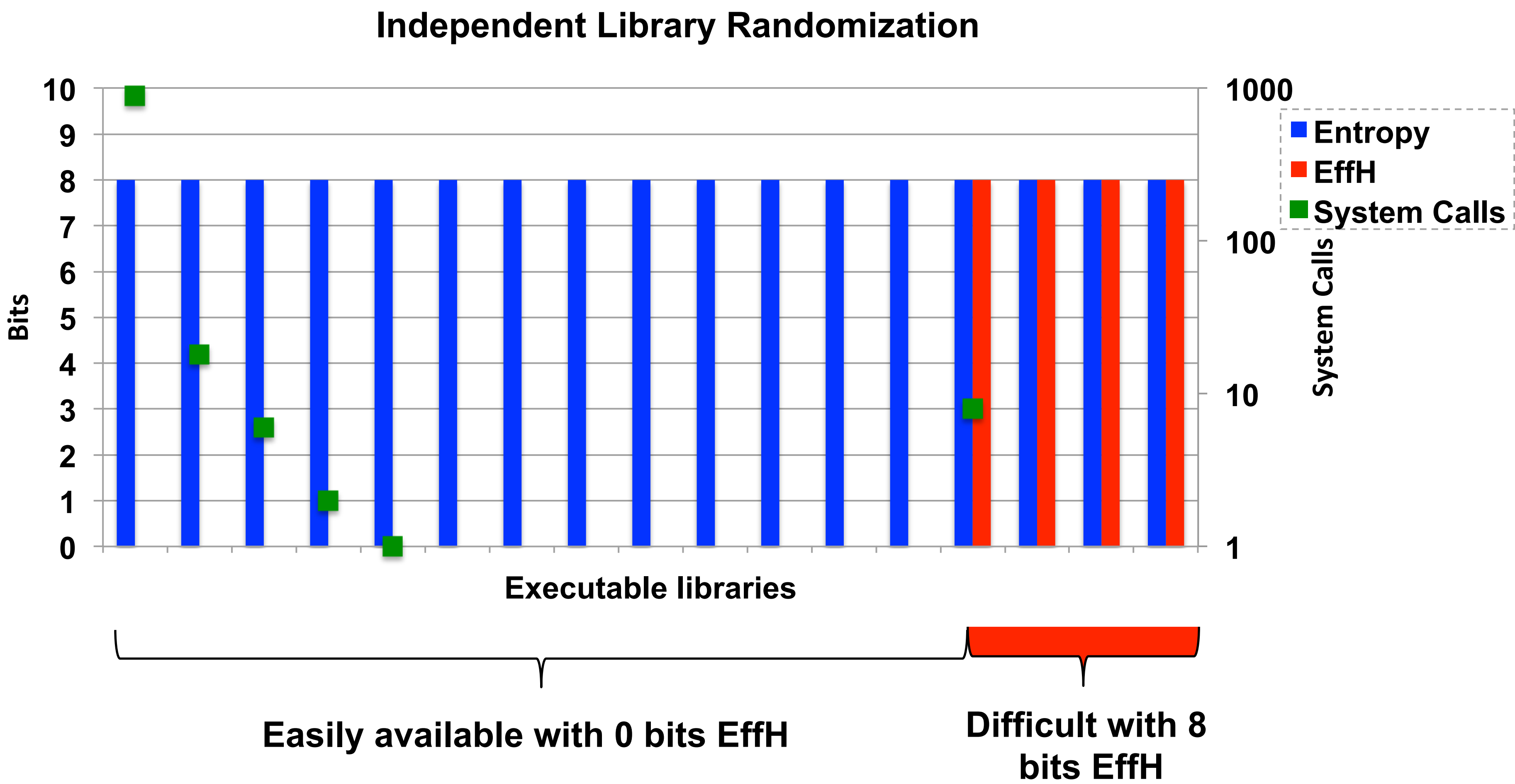
Fine Grain provides 8 bits of EffH for some but not all libraries

Memory Disclosure Adversary - Fine Grain



Protecting only some libraries does not mitigate attacks

Memory Disclosure Adversary - Fine Grain



Protecting only some libraries does not mitigate attacks

Conclusions on Memory Randomization

- Static ASLR does not provide effective defense against adversaries
- PIE ASLR and independent library randomization improve EffH
- Sophisticated adversaries can overcome more advanced randomization techniques
  - Memory disclosure adversary can overcome PIE ASLR and independent library randomization
- Minimum entropy often more important than mean or max

Summary

- **Effective Entropy metric for memory randomization security**
  - **Quantitative**
  - **Comparable between techniques**
  - **Provides insight into adversary difficulty**
- **Fundamental weaknesses in randomization techniques**
- **Raise minimum entropy and limit connectivity**