Identifying Valuable Pointers In Heap Data

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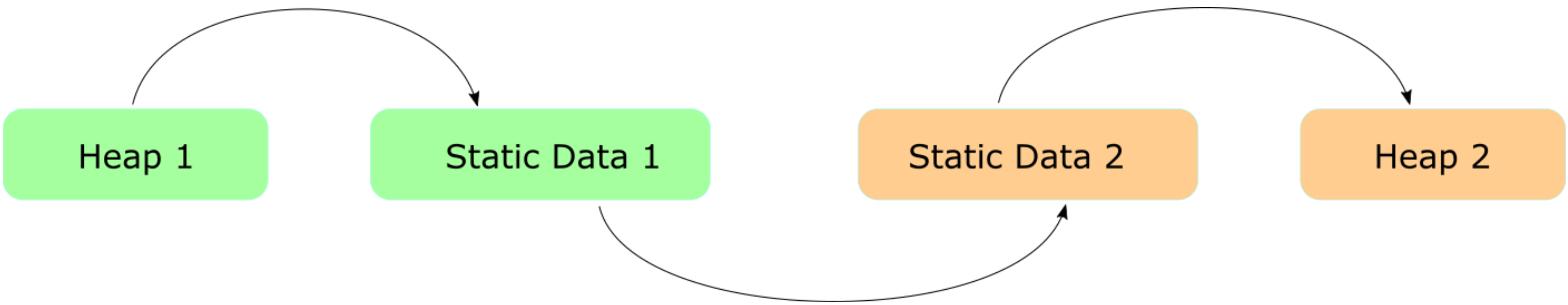
Overview

- Data-oriented attacks manipulate programs while respecting control flow integrity
- Memory cartography is a powerful data-oriented attack
  - An attacker builds a map of pointers between memory regions (e.g., stack, heap, static data)
  - A memory read vulnerability in one region allows the attacker to navigate between regions and read data from the entire address space....
  - … assuming that pointers reside constant offsets within regions!
- Stack and heap regions often have nondeterministic pointer offsets
- We show that an attacker with a memory read vulnerability can identify pointers using a signature-matching algorithm, even in nondeterministic regions



Outline

- Data-Oriented Attacks
- Memory Cartography
- Finding Pointers on The Heap
- Experiments
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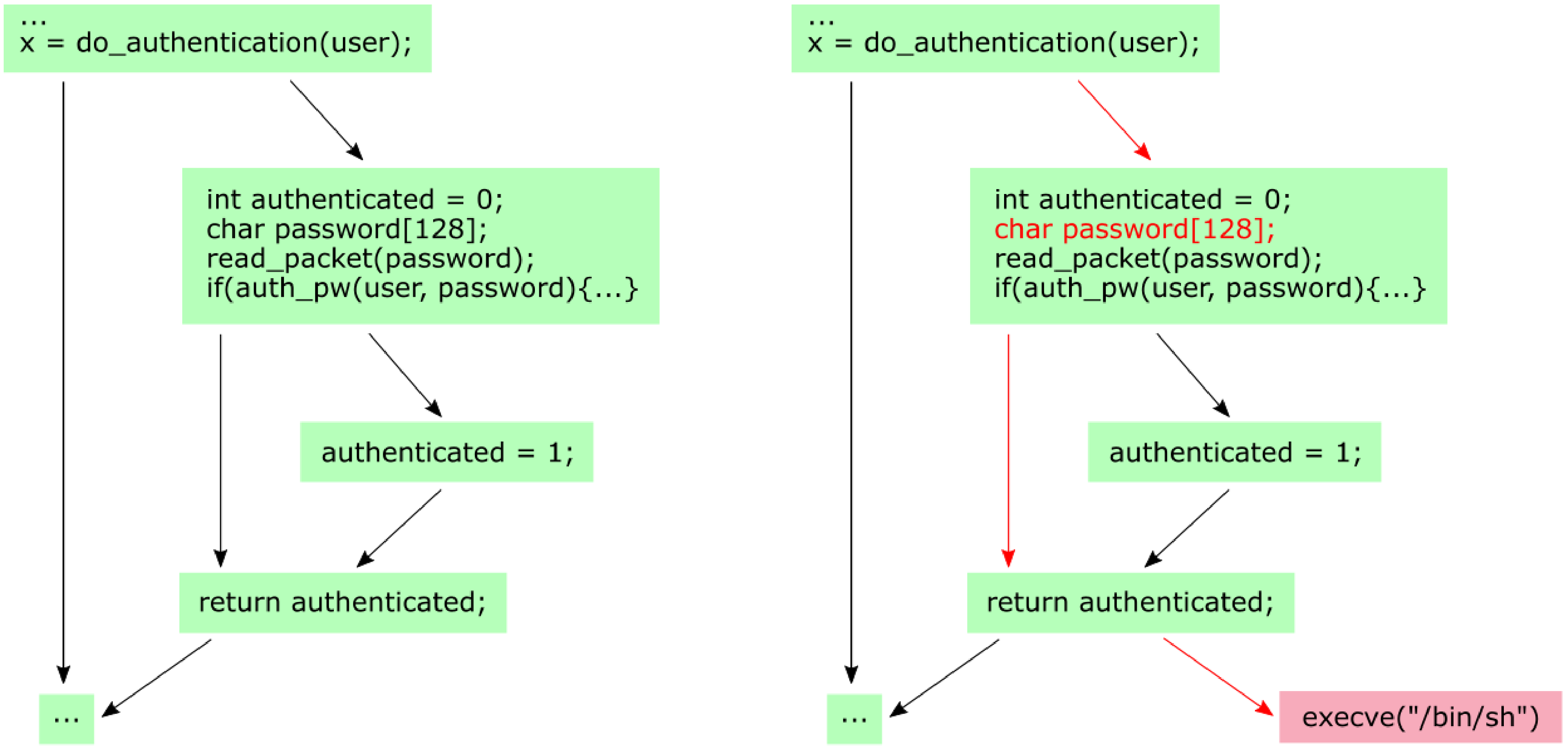
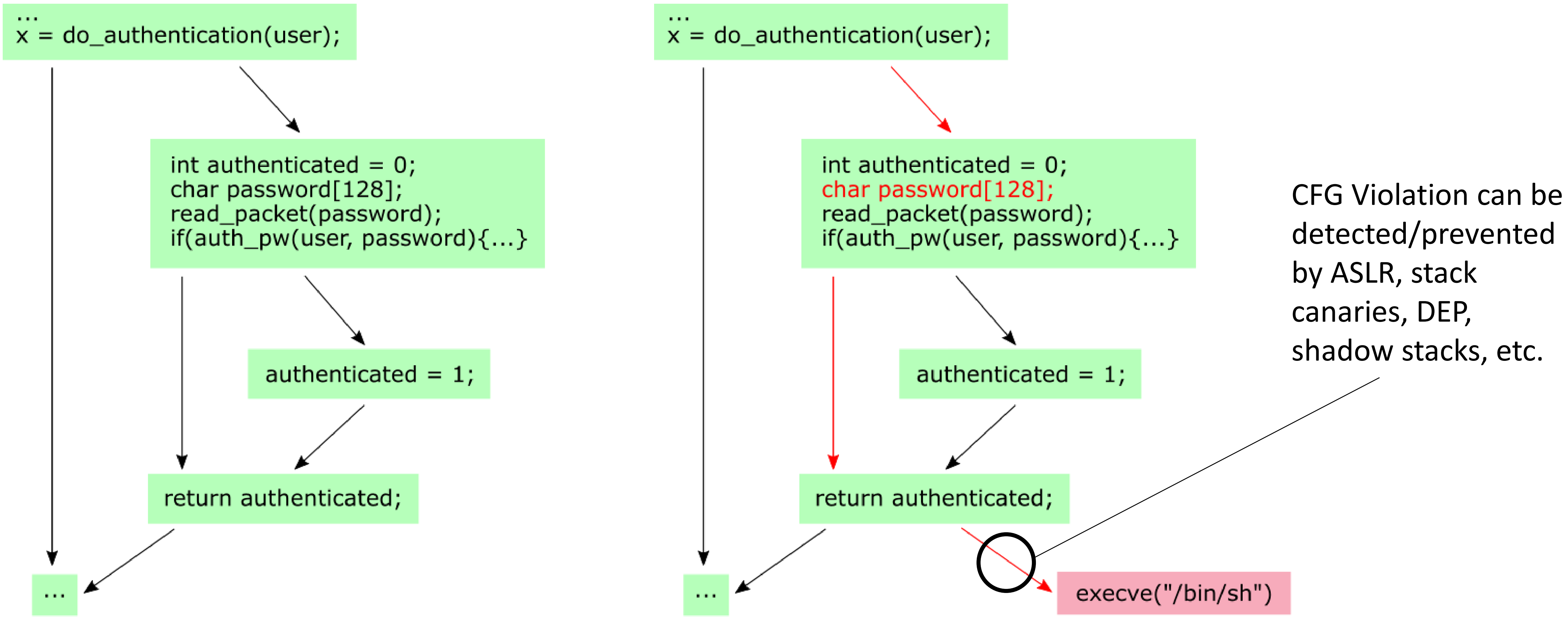
Data-Oriented Attacks

- Historically, attackers used memory bugs to subvert control flows



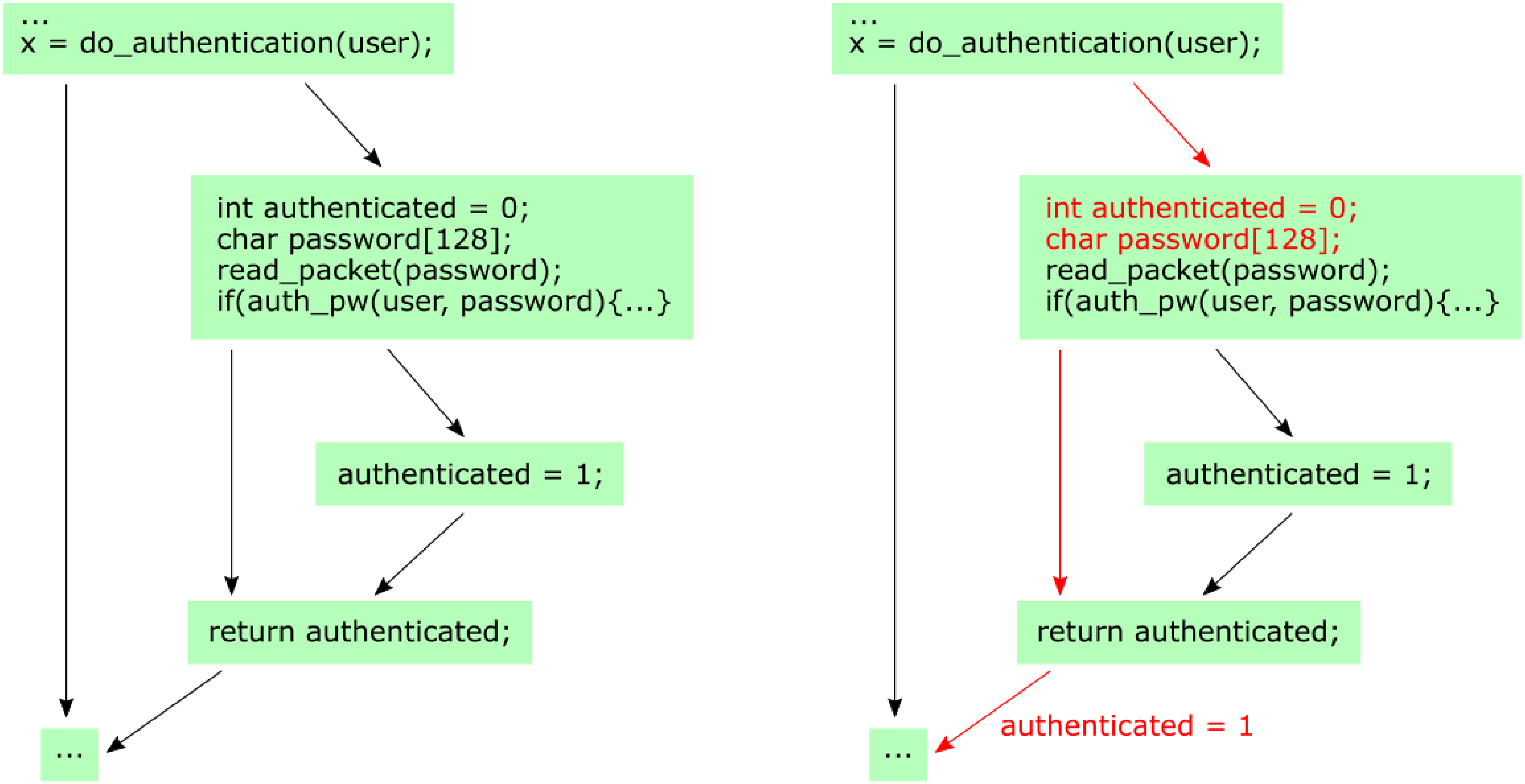
Data-Oriented Attacks

- However, modern mitigations make this more difficult



Data-Oriented Attacks

- Data-oriented exploits avoid modifying control data, respecting the CFG



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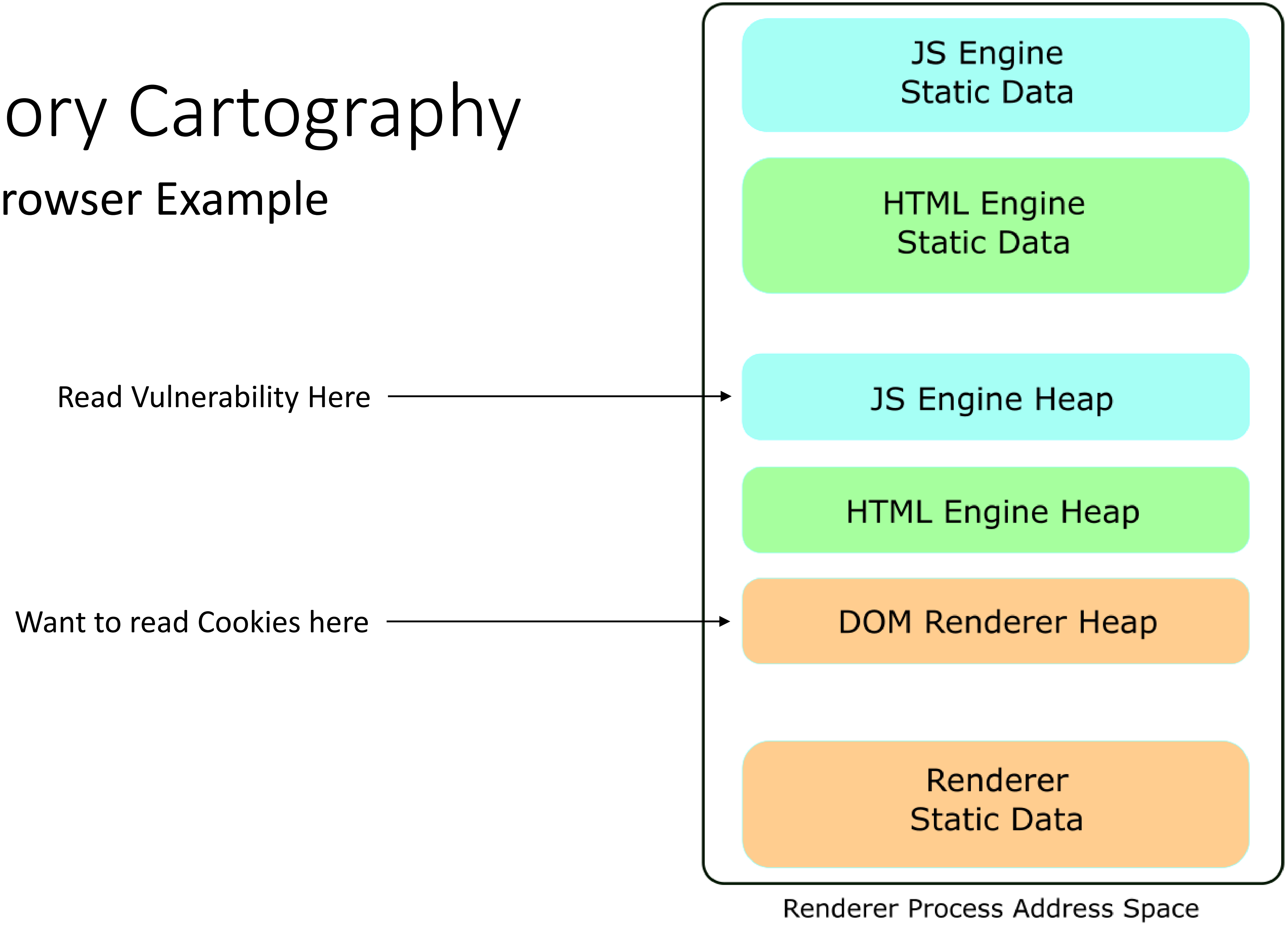
Memory Cartography

- Data-Oriented exploit introduced by Rogowski et al. (2018)
  - Attacker has a local read vulnerability
  - Wants to read from the entire address space without triggering a segmentation fault
  - Difficult due to fragmented nature of memory allocations
- Assumptions:
  - ASLR, DEP, stack canaries, etc. are enabled
  - Attacker can run victim binary locally

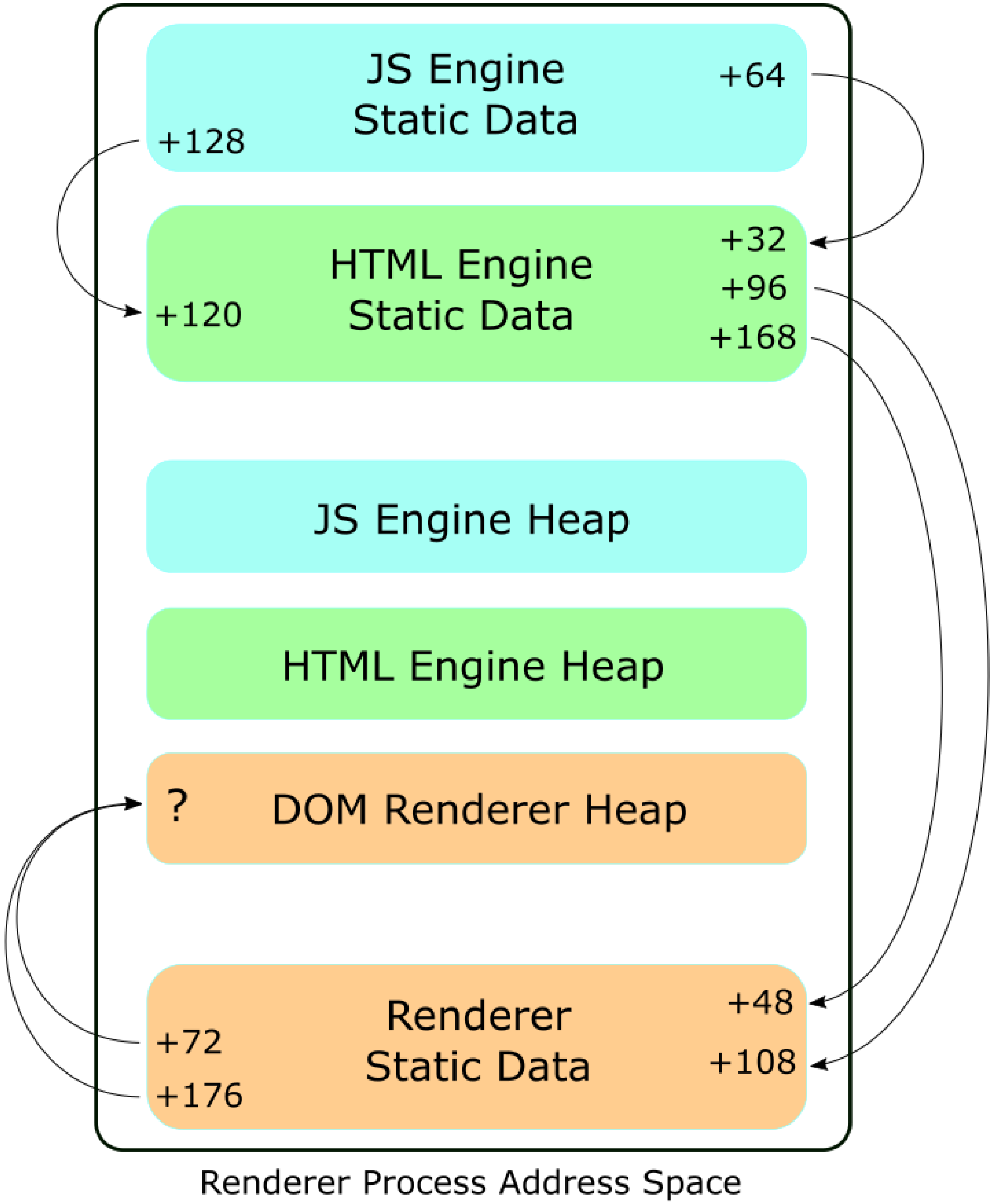
Memory Cartography

- Web Browser Example



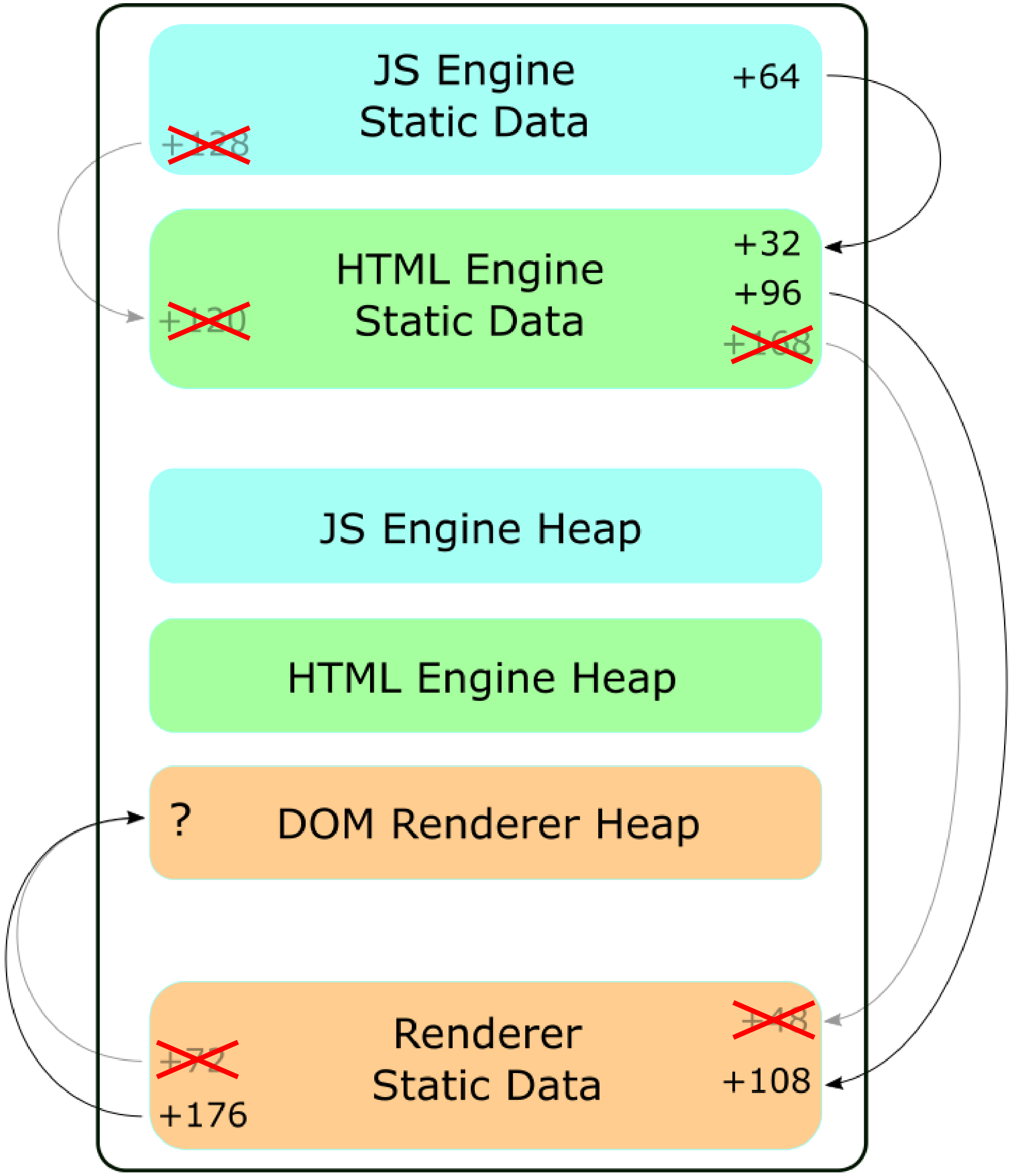
Memory Cartography

- Attacker runs binary locally, scans static data sections for inter-region pointers
- Records pointers in form `(<src_name, src_offset>, <dst_name, dst_offset>)`
- ASLR preserves relative offsets, so these tuples will be consistent across program runs when `src` and `dst` are static data regions



Memory Cartography

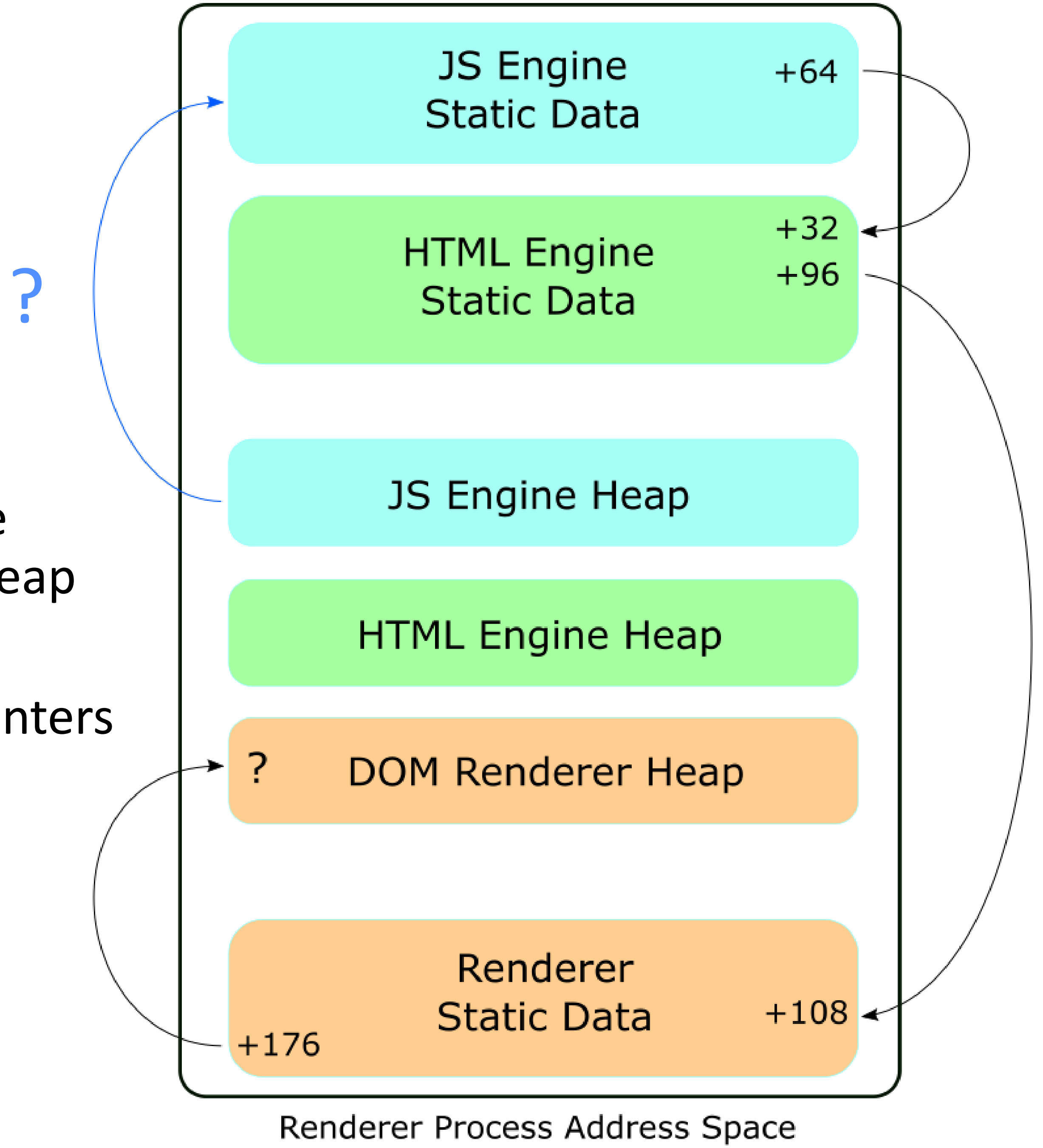
- Some of these pointers may simply be pointer-sized regions that happen to reference external memory regions
- To filter out “false pointers,” the attacker repeats the procedure for multiple independent program loads, and looks for pointers that are consistently present



Renderer Process Address Space

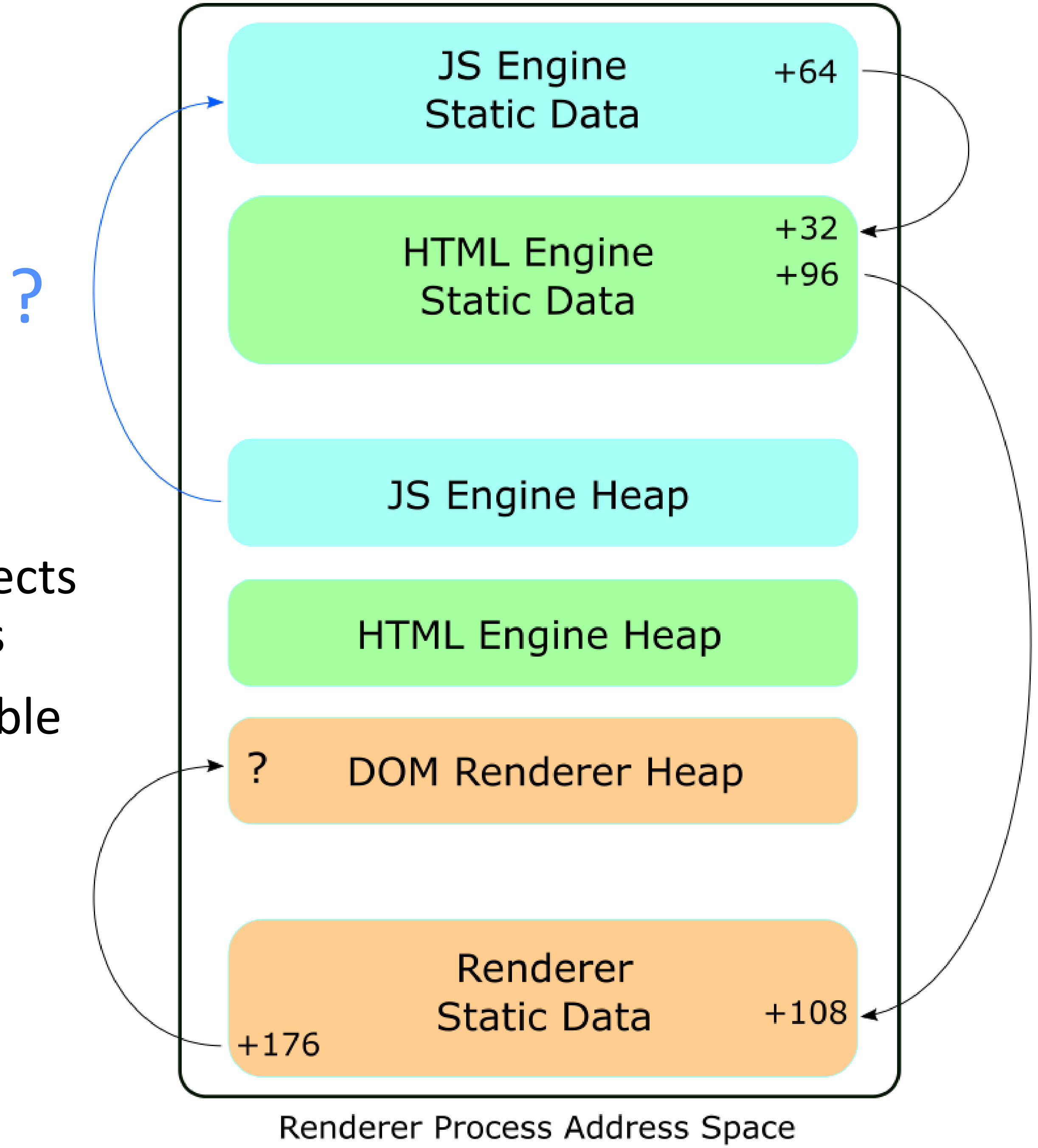
Memory Cartography

- Process results in the ability to navigate across data sections and reach target heap
- Still need a way of jumping from JS heap to a data section. Offsets of pointers in JS heap may not be consistent!



Memory Cartography

- Rogowski et al. accomplished this with a heap spray of easily-recognizable objects containing known data section pointers
- However, this approach may not be viable for all applications



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Finding Pointers on the Heap

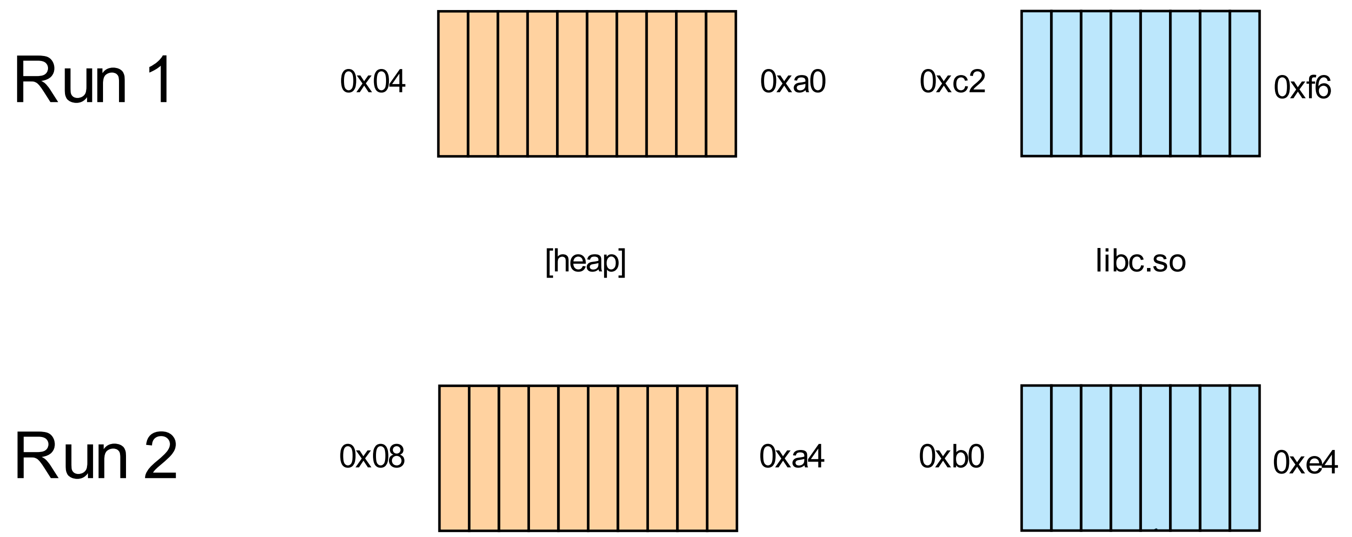
- Like in original cartography setup, attacker has a local heap read vulnerability, wants to read from the entire address space without triggering a fault
- However, the attacker has no influence over contents of the heap. So to find a pointer to another region, the attacker must scan the heap at attack-time and recognize the pointer somehow
- Assumptions:
  - ASLR, DEP, stack canaries, shadow stacks, etc. are enabled
  - Attacker can run the program locally

Finding Pointers on the Heap

- High-level idea:
  - Run the program locally several times, and identify recurring pointers to specific offsets within data sections
  - Use the bytes surrounding those frequent pointers to build an identifiable “signature”
  - At attack-time, scan the heap using a local read vulnerability and match bytes to the signature from offline analysis
  - If the bytes surrounding an aligned, pointer-sized region match the signature, follow the pointer-sized region to a known offset within a data section
  - From there, perform further memory cartography as normal

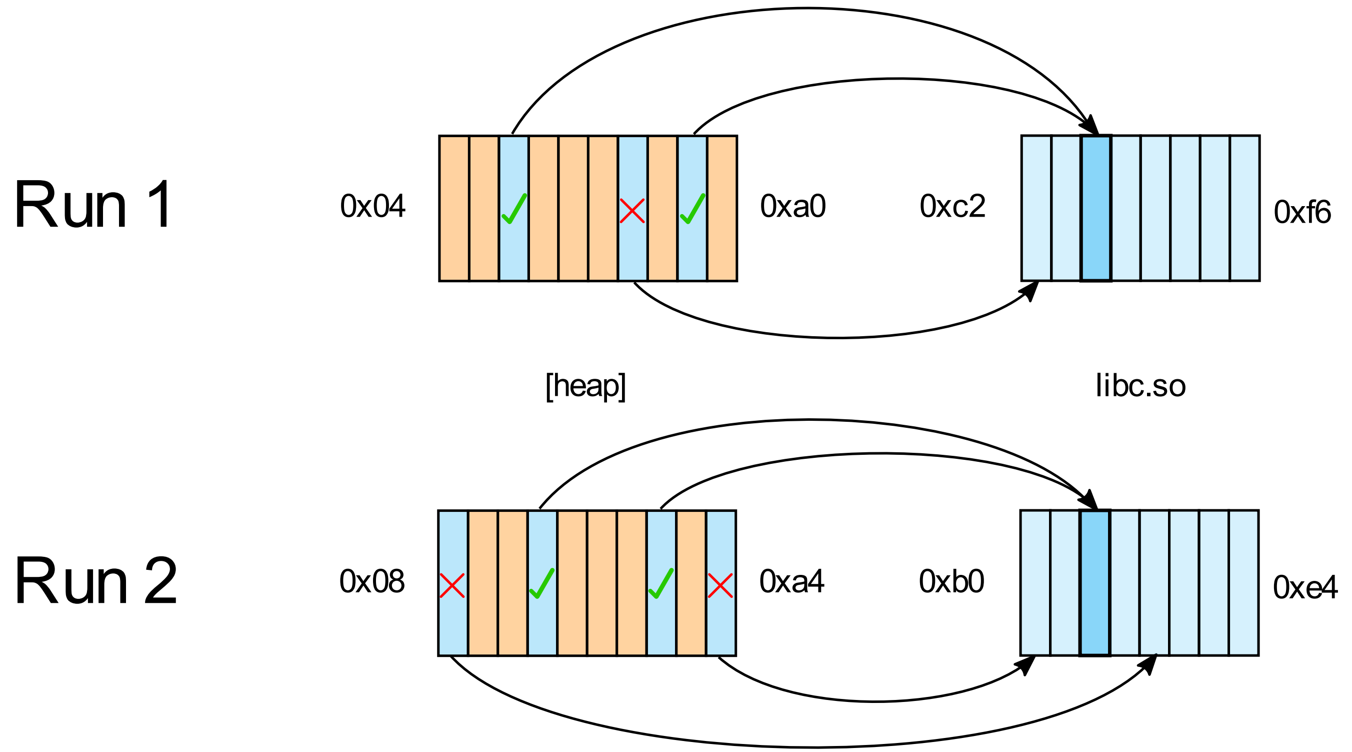
Finding Pointers on the Heap

- Attacker runs the program locally and determines the boundaries of allocated regions (by looking at `/proc/<pid>/maps`, for example)
- Note that the "heap" can actually comprise multiple VMAs (as when the program uses an `mmap`-based allocator)



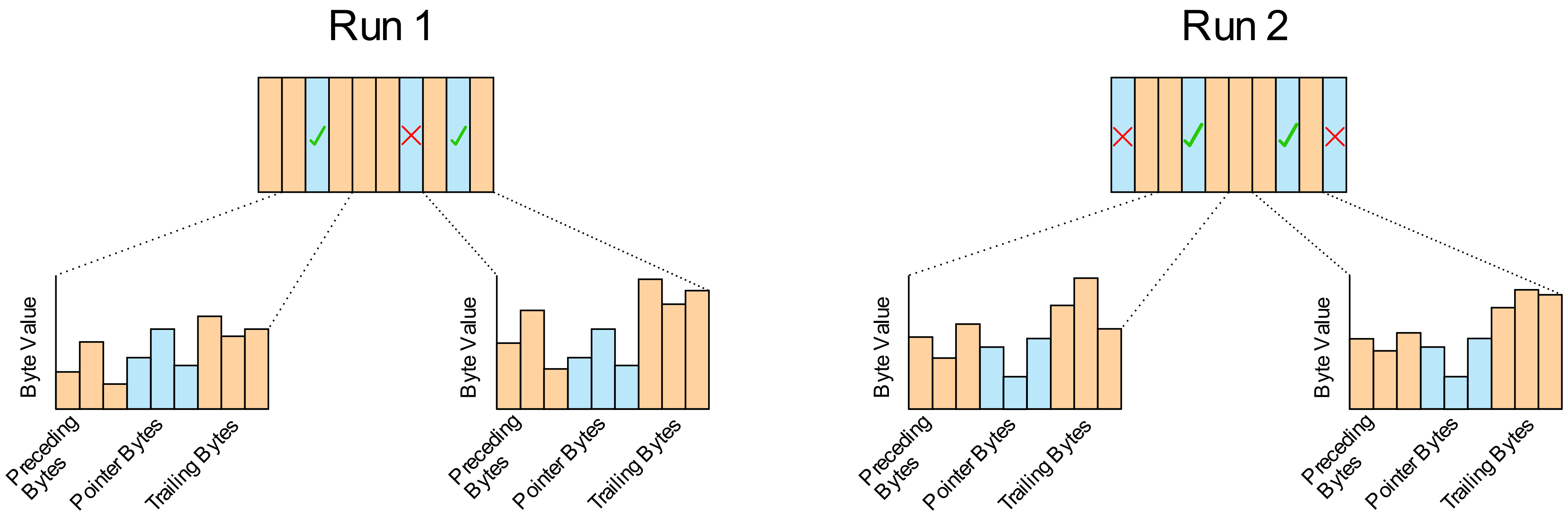
Finding Pointers on the Heap

- Attacker then scans the heap, looking for pointers to other regions, and identifies the most frequent pointer destinations
  - "Most frequent" meaning the `(dst_name, dst_offset)` pairs that were observed the most times across multiple program runs



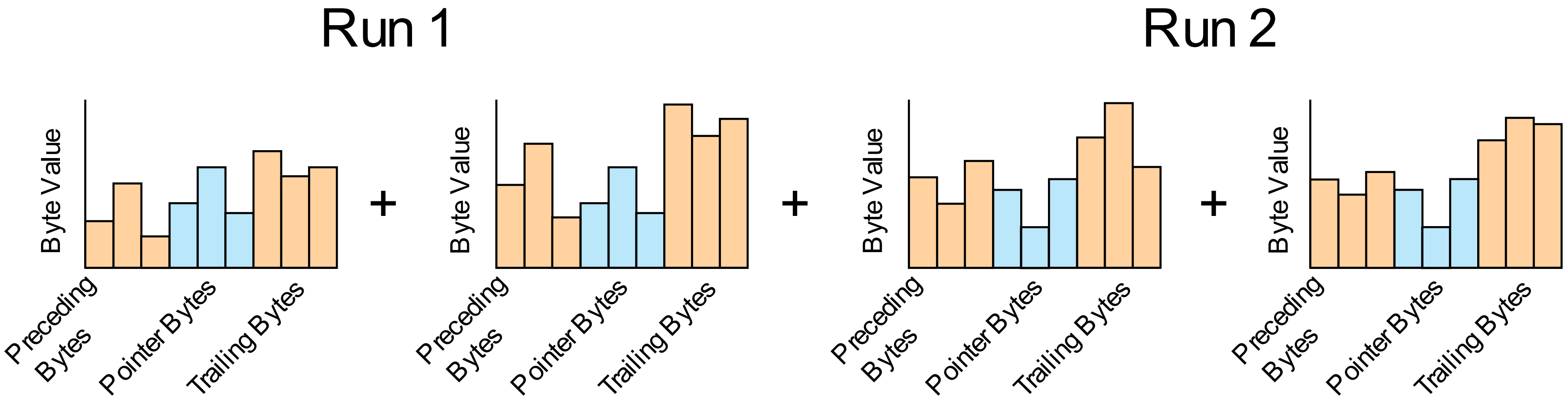
Finding Pointers on the Heap

- Attacker examines the bytes surrounding pointers to frequent destinations



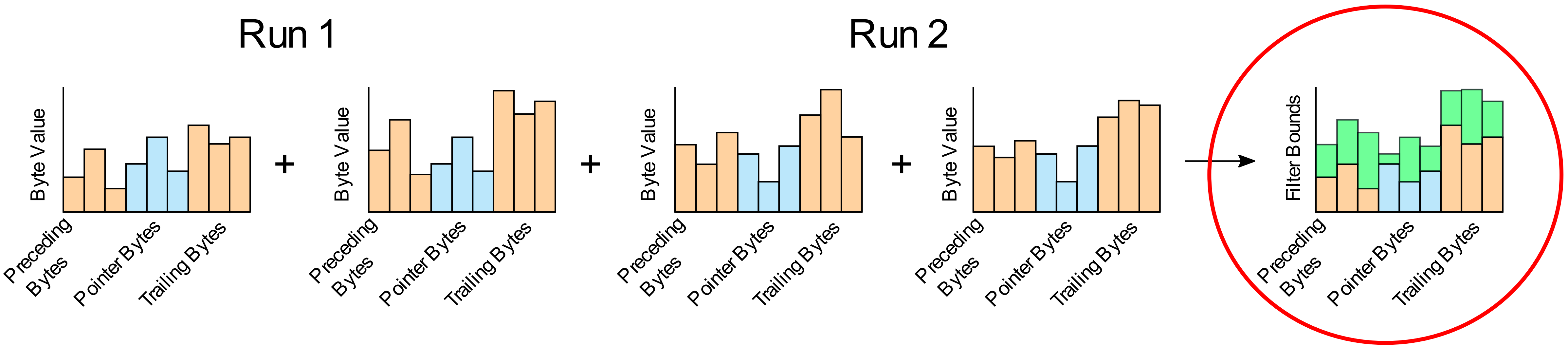
Finding Pointers on the Heap

- Attacker uses bytes surrounding pointers to build a filter
- Filter is simply a sequence of lower bounds and upper bounds on each byte in a fixed-width window surrounding the pointer. Filter bounds are determined by taking the highest and lowest byte value observed in each position during local program runs



Finding Pointers on the Heap

- Finally, filter bounds are used to identify a pointer to a known destination during an attack-time memory scan



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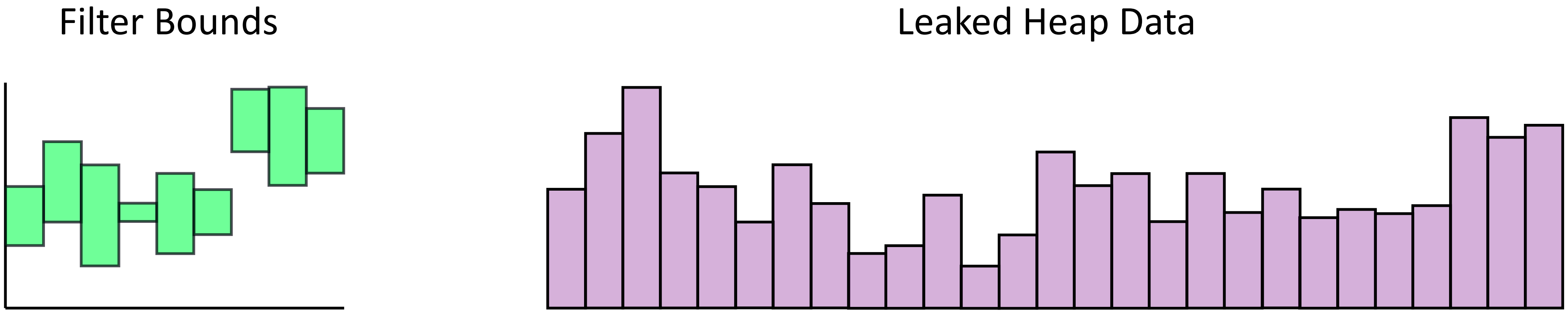

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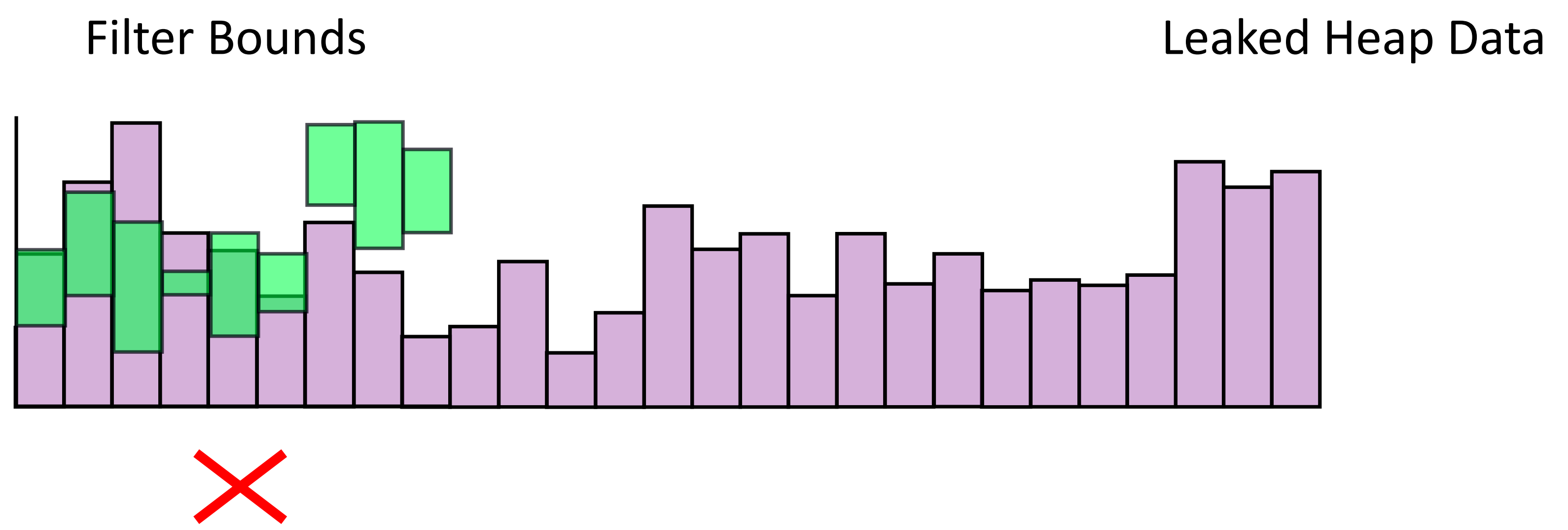

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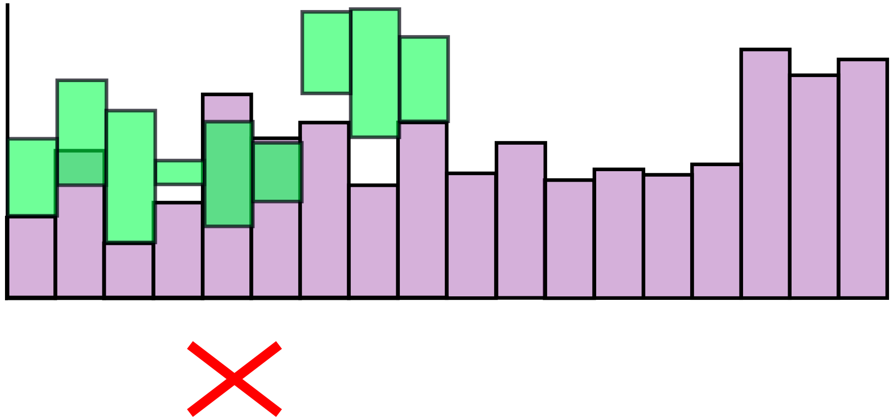
Filter Bounds



Leaked Heap Data

Finding Pointers on the Heap

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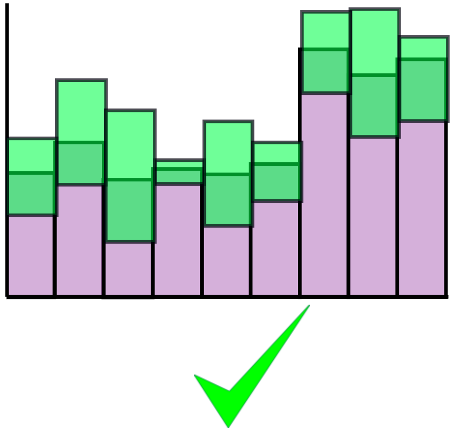
Filter Bounds



Leaked Heap Data

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Methodology

- General setup: run the program 10 times, dumping memory each time
  - Each run is a fresh ASLR load
- Use the first nine program runs to compute filters as described previously
  - Create and evaluate pointers for the four most frequent pointer destinations observed across all runs
- Use the holdout run to test the accuracy of the filter in identifying the pointer of interest
  - We hold out each run one-by-one and average the results (10-fold cross validation)

Methodology

- To test the performance of a filter, we simply ran it over all aligned pointer-sized regions in the dumped heap from a held-out run
  - Future work should demonstrate an end-to-end attack with a real read vulnerability. We assumed the presence of such a vulnerability and simulated it by dumping the heap
- Filter performance metrics:

$$\text{Precision} = \frac{\text{True Filter Matches}}{\text{True Filter Matches} + \text{False Filter Matches}}$$

$$\text{Recall} = \frac{\text{True Filter Matches}}{\text{Total True Pointers Scanned}}$$

Experiments: Vim

- Simple single-threaded test program with a single, well-defined heap region

Rank	Region	Offset	True Positives	False Positives	Precision	Recall
1	vim_basic_4	90912	25650 / 25650	0 / 1525680	1.0	1.0
2	libc-2.31.so_5	3040	25451 / 25452	160 / 3077198	.994	.999
12	libc-2.31.so_5	2816	2360 / 2361	1375 / 3100289	.632	.999
14	libc-2.31.so_5	3072	800 / 802	1378 / 3101848	.367	.998

Experiments: Firefox

- Wanted to simulate vulnerability in JS engine heap
- Unlike Vim, Firefox JS engine uses an mmap-based allocator (jemalloc), so the heap is spread over multiple VMAs
- Identified jemalloc heap "chunks" by size, treated the aggregate contents of these regions as the effective program heap

Rank	Region	Offset	True Positives	False Positives	Precision	Recall	Precision (worst region)
1	libxul.so_2	21438312	310724 / 310735	662 / 6242515	.998	.999	.988
2	libxul.so_2	21438264	299715 / 299716	755 / 6253534	.997	.999	.993
3	libxul.so_1	27080560	23704 / 25603	2369 / 1612697	.909	.926	0.0
4	libxul.so_1	27085200	17300 / 18850	38 / 800250	.998	.918	0.0

Experiments: Firefox

- Indicates the worst-case performance if attacker were limited to reading from a single randomly-chosen heap chunk

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Experiments: Apache

- Used OpenSSL 1.0.1, which is vulnerable to HeartBleed
- Identified pointers in heap region containing the vulnerable HeartBleed buffer
- Served a WordPress site with simulated traffic

Rank	Region	Offset	True Positives	False Positives	Precision	Recall
1	libphp5.so_1	252140	48542 / 51565	84 / 3655165	.998	.941
2	libphp5.so_0	3119280	45109 / 45109	11 / 3661621	.999	1.0
3	libphp5.so_0	3100304	26020 / 26020	0 / 3680710	1.0	1.0
4	libphp5.so_0	3213931	21850 / 21850	0 / 3684880	1.0	1.0

Experiments: Take-home Point

- In all tested programs, we were able to identify pointers to static data sections with very high precision
- We were able to reliably reach static data sections with high connectivity to the rest of the address space, making them ideal starting points for memory cartography attacks
- This means powerful memory cartography attacks are possible even when the attacker has no control of the heap layout

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Conclusions

- A simple signature-matching algorithm facilitates powerful memory cartography attacks, even when the attacker does not have control over heap contents
- Some caveats:
  - As in original memory cartography paper, assumes that inter-region pointers are located at the same offsets on the local machine and the victim machine
  - Time/bandwidth constraints imposed by real-world exploits may limit the attacker's ability to scan the entire heap