IBM Security

Windows 10 Segment Heap Internals

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Agenda: Windows 10 Segment Heap

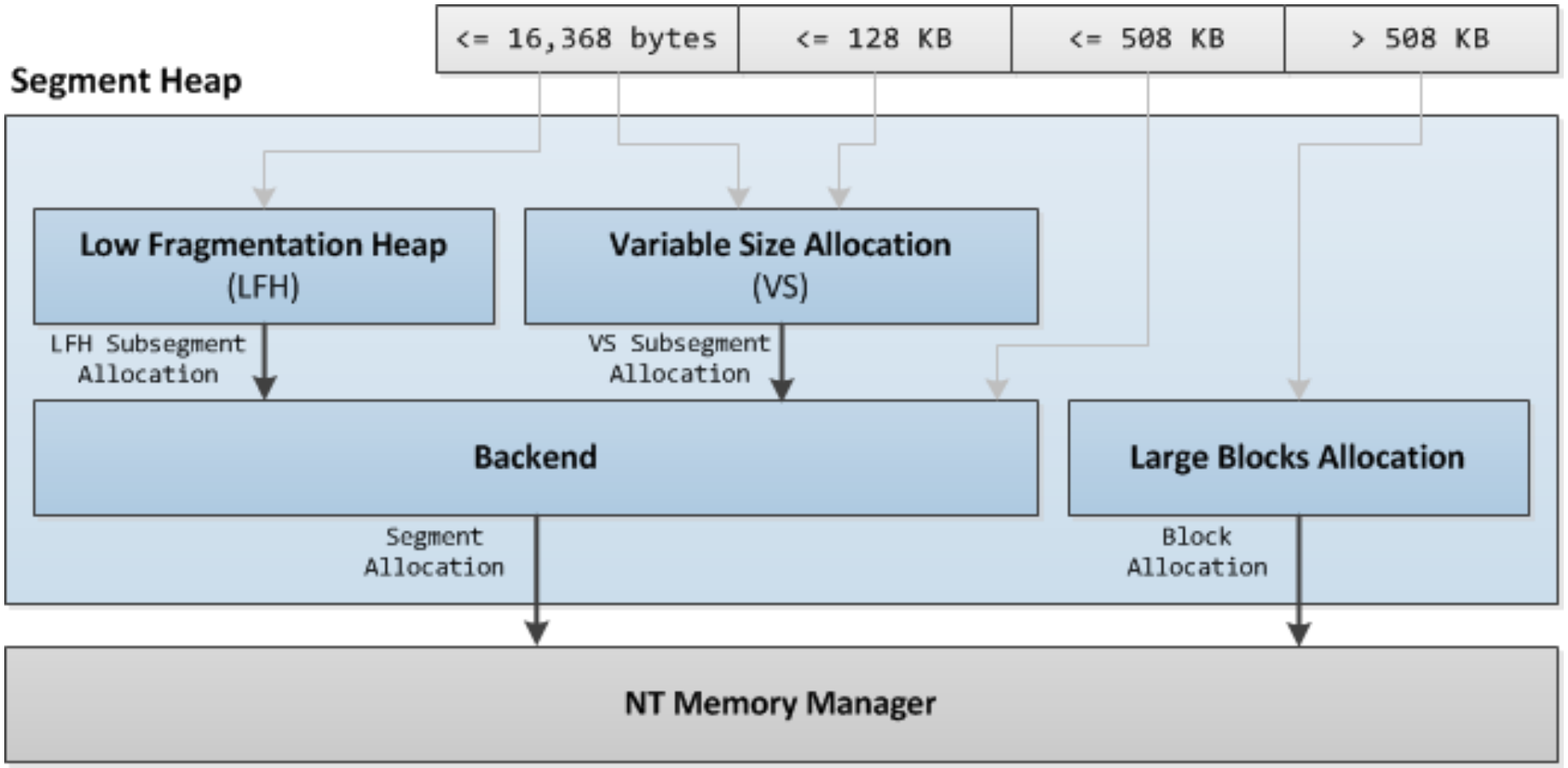
- Internals
- Security Mechanisms
- Case Study and Demonstration

Notes

- Companion white paper is available
  - Details of data structures, algorithms and internal functions
- Paper and presentation are based on the following NTDLL build
  - NTDLL.DLL (64-bit) version 10.0.14295.1000
  - From Windows 10 Redstone 1 Preview (Build 14295)

Internals: Overview

Architecture



Defaults

- Segment Heap is currently an opt-in feature
- Windows apps (Modern/Metro apps) are opted-in by default
  - Apps from the Windows Store, Microsoft Edge, etc.
- Executables with the following names are also opted-in by default (system processes)
  - csrss.exe, lsass.exe, runtimebroker.exe, services.exe, smss.exe, svchost.exe
- NT Heap (older heap implementation) is still the default for traditional applications

Configuration

- Per-executable

```
HKEY_LOCAL_MACHINE\SOFTWARE\Microsoft\Windows NT\
CurrentVersion\Image File Execution Options\(executable)
FrontEndHeapDebugOptions = (DWORD)

Bit 2 (0x04): Disable Segment Heap
Bit 3 (0x08): Enable Segment Heap
```

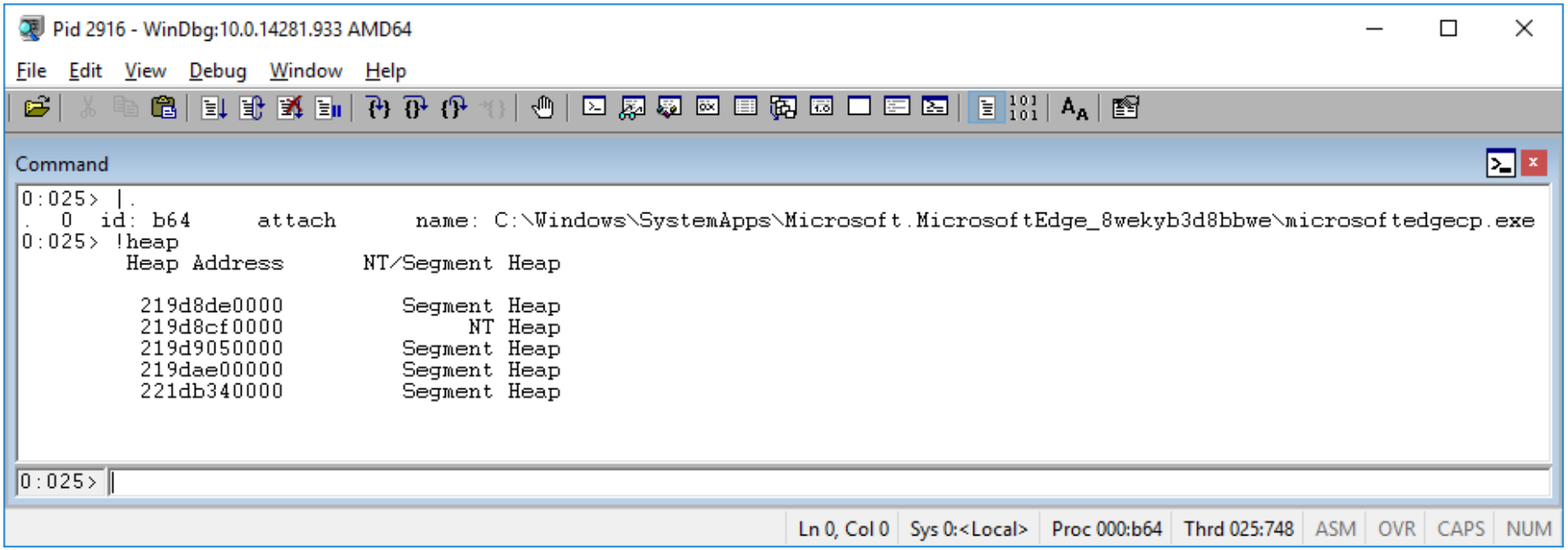
- Global

```
HKEY_LOCAL_MACHINE\SYSTEM\CurrentControlSet\Control\
Session Manager\Segment Heap
Enabled = (DWORD)

0      : Disable Segment Heap
(Not 0): Enable Segment Heap
```

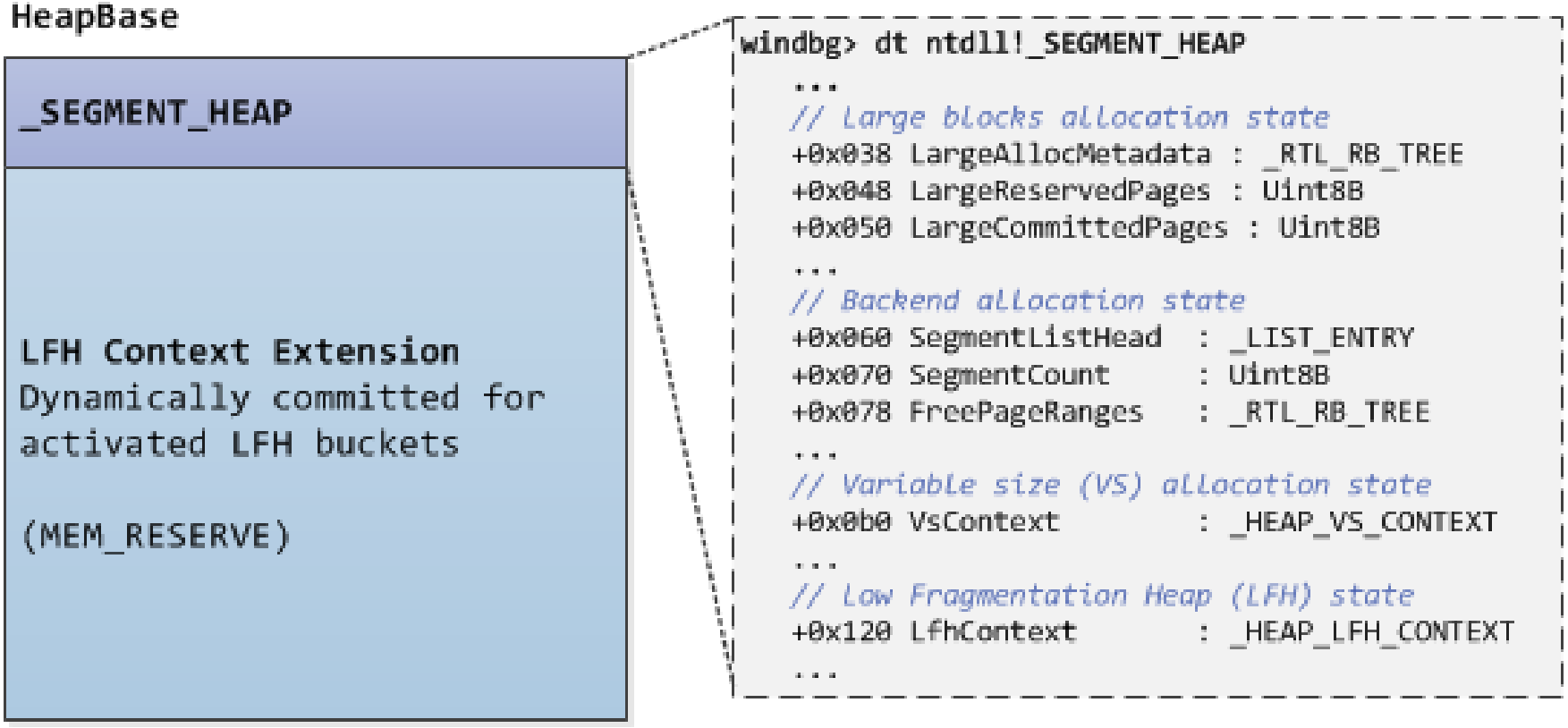
Edge Content Process Heaps

- Segment Heap: default process heap, MSVCRT heap, etc.
- Some heaps are still managed by the NT Heap (e.g.: shared heaps, heaps that are not growable)



HeapBase

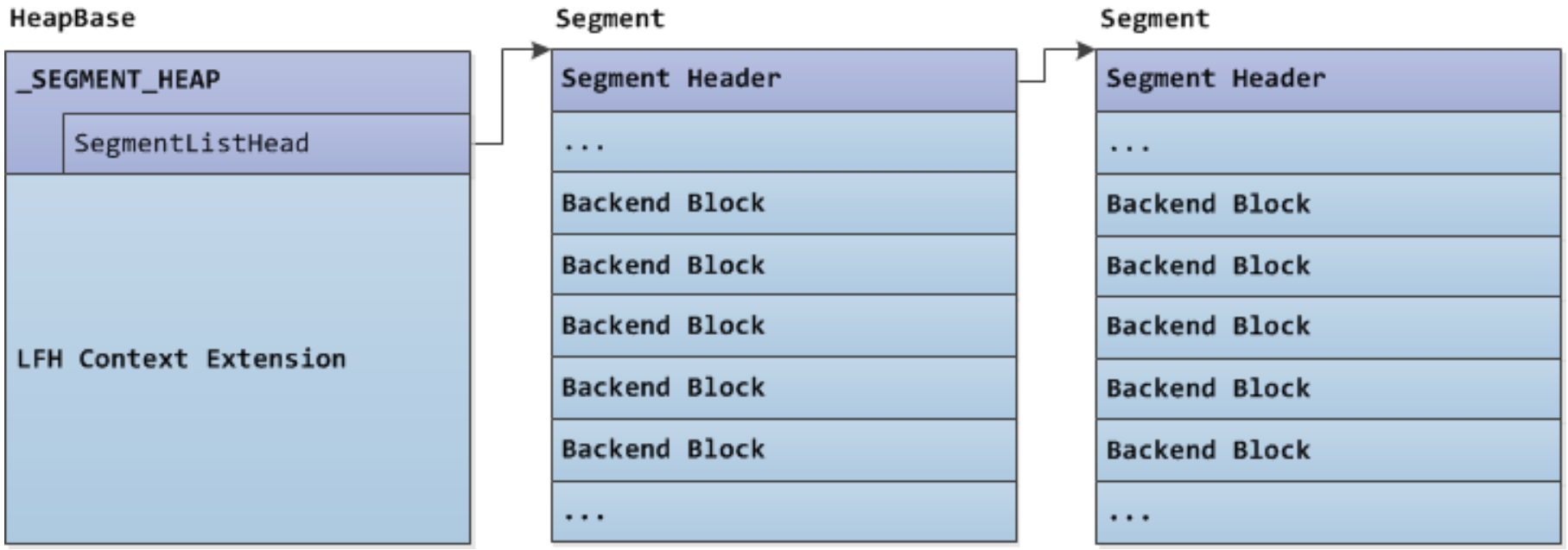
- Heap address/handle returned by `HeapCreate()` or `RtlCreateHeap()`
- Signature field (`+0x10`): `0xDDEEDDEE` (Segment Heap)



Internals: Backend

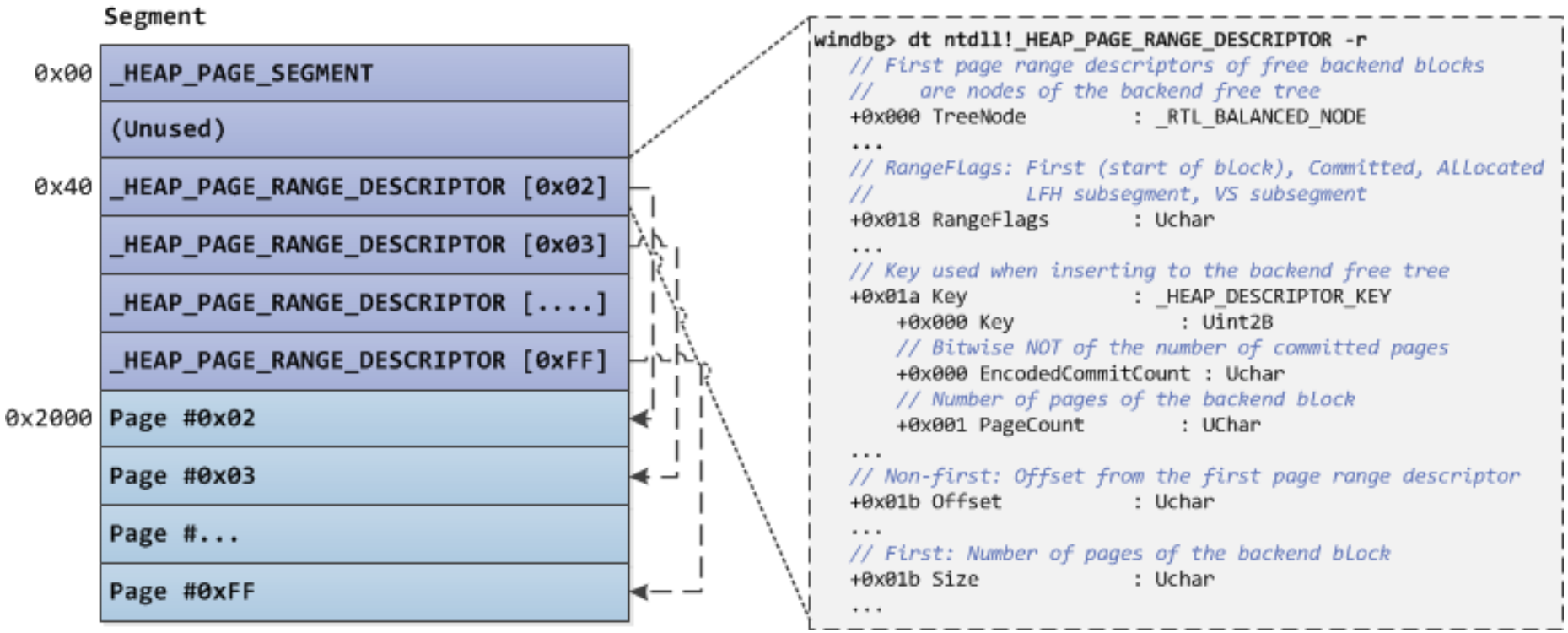
Backend

- Allocation Size: >128KB to 508KB (page size granularity)
- Segments are 1MB virtual memory allocated via `NtAllocateVirtualMemory()`
- Backend blocks are group of pages in a segment



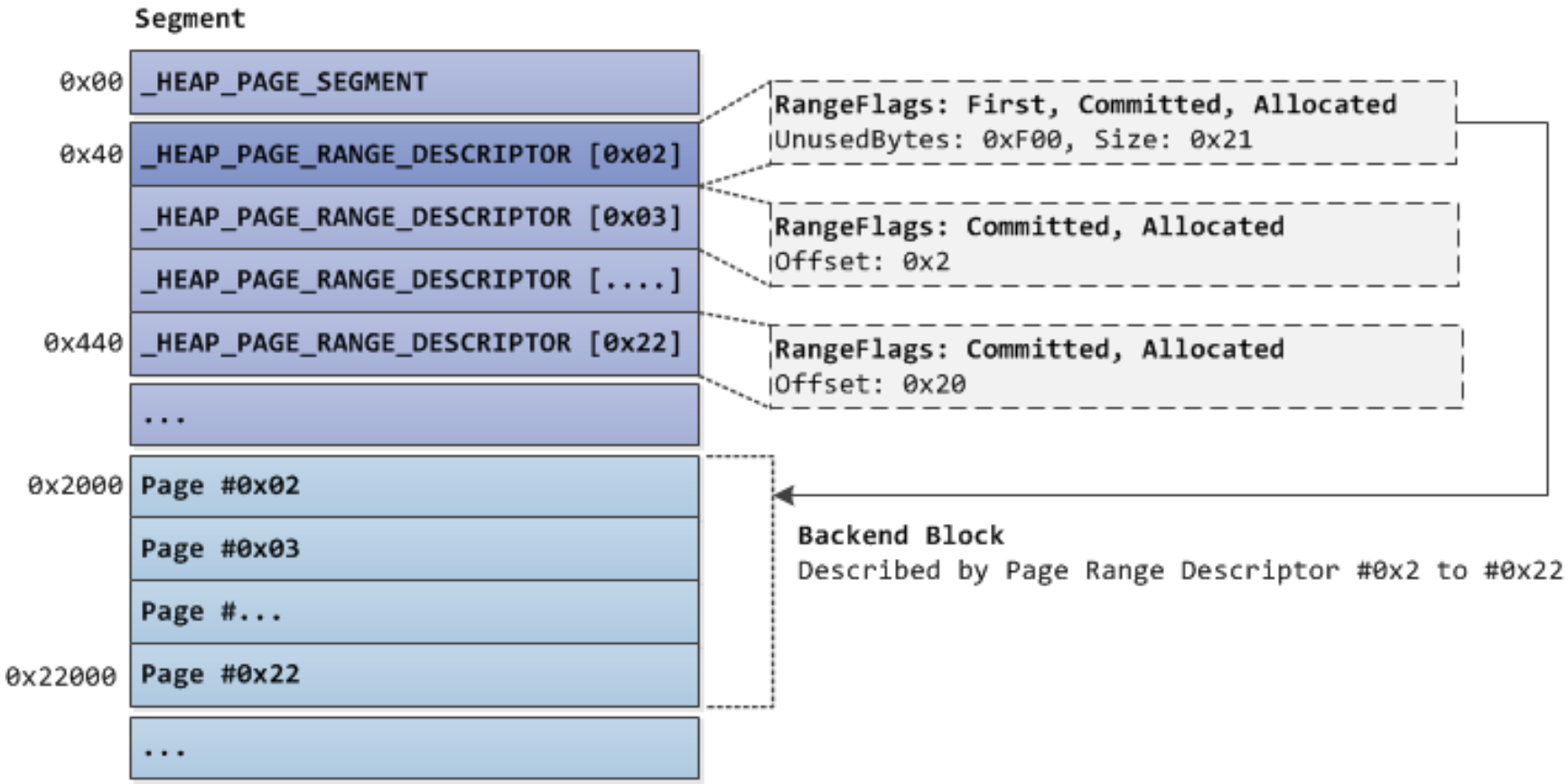
Backend Page Range Descriptors

- Describe the pages in the segment
- “First” page range descriptors additionally describe the start of a backend block



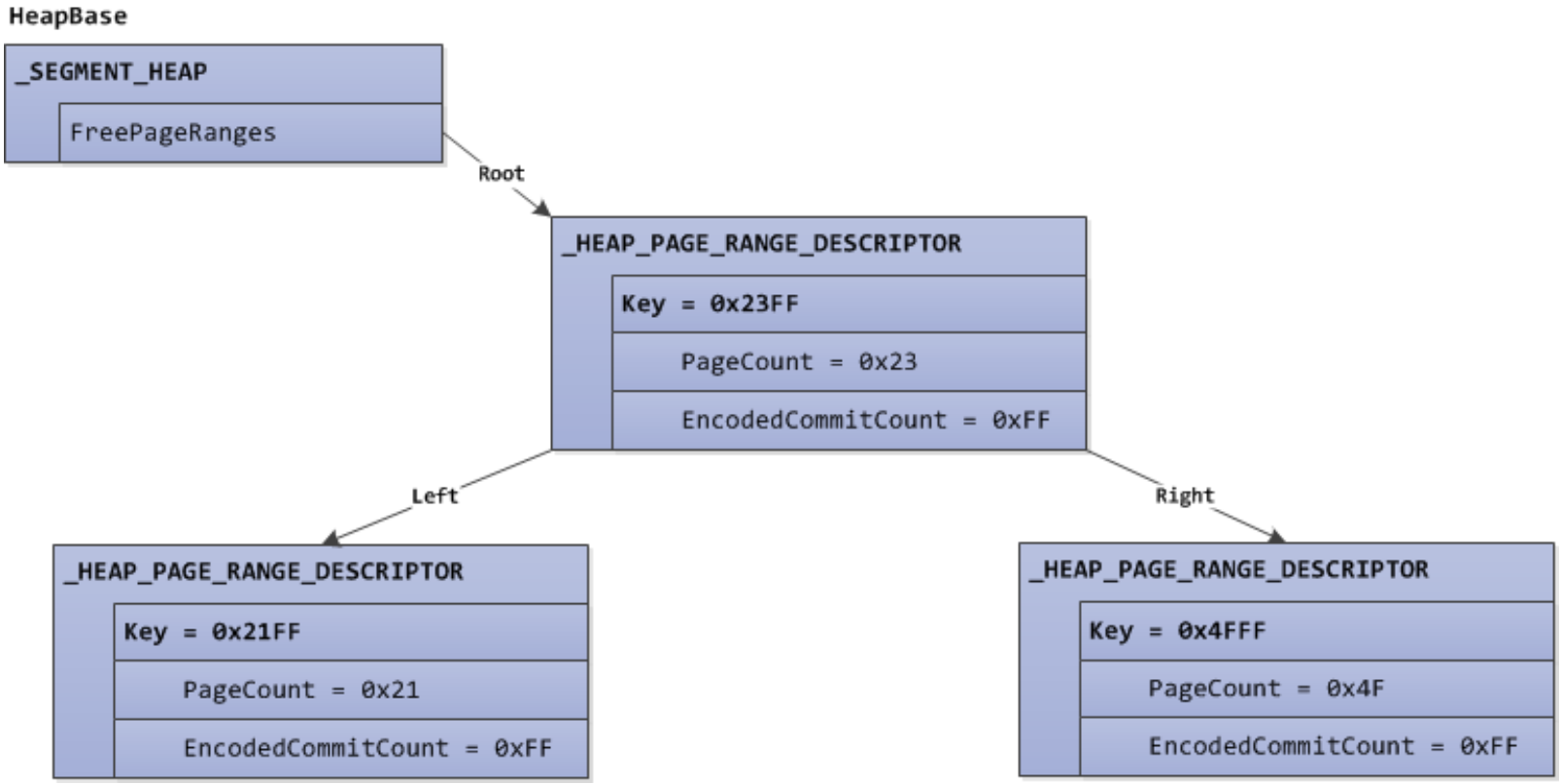
Backend Page Range Descriptors Example

- Example: 131,328 (0x20100) bytes busy backend block
- “First” page range descriptor is highlighted



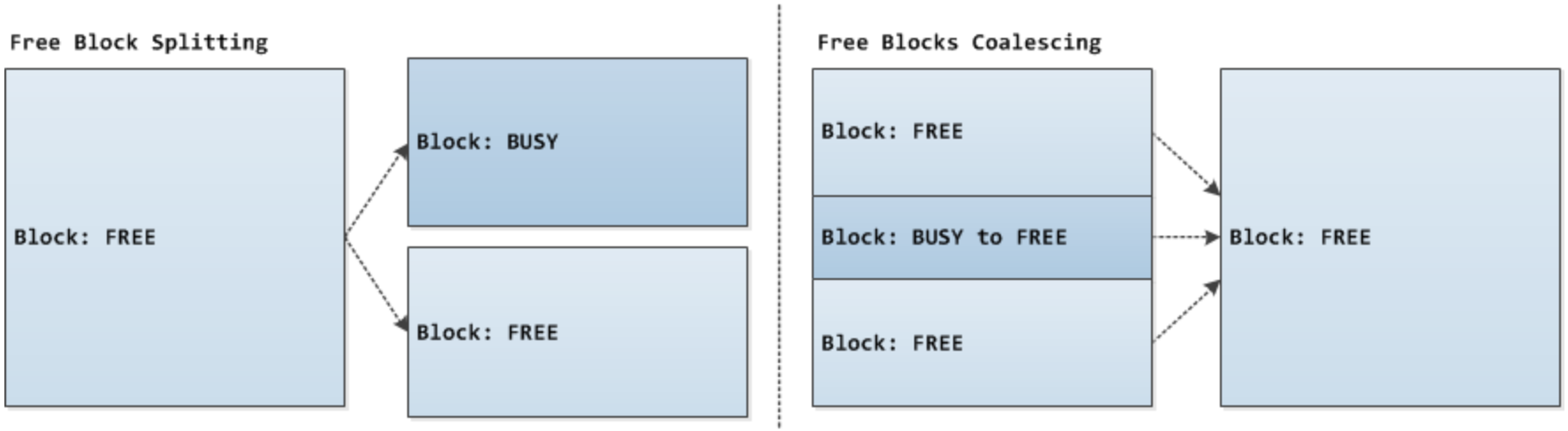
Backend Free Tree

- Red-black tree (RB tree) of free backend blocks
- Key: Page count, encoded commit count (bitwise NOT of the number of committed pages)



Backend Allocation and Freeing

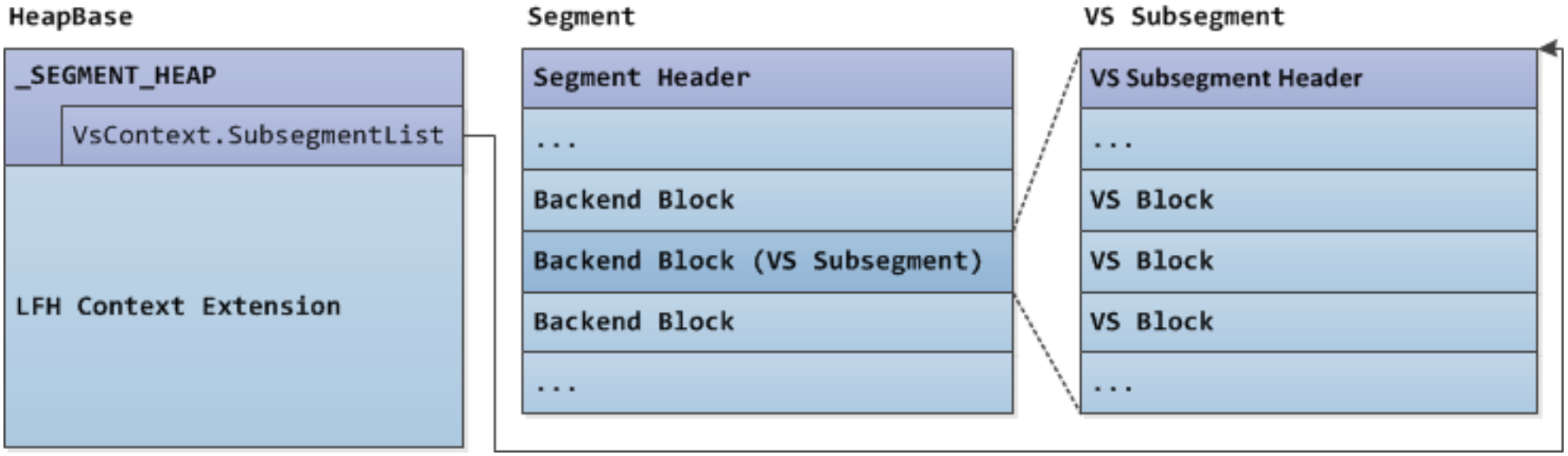
- Allocation
  - Best-fit search with preference to most committed block
  - Large free blocks are split
- Freeing
  - Coalesce to-be-freed block with neighbors



Internals: Variable Size Allocation

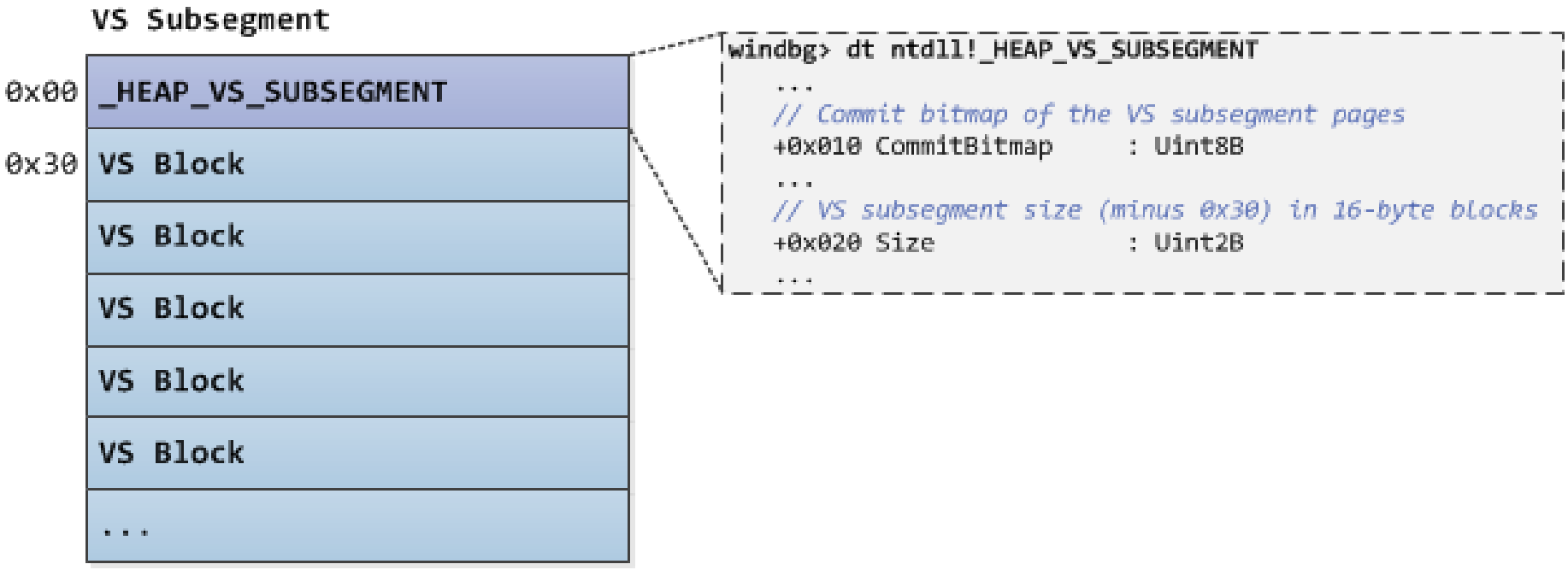
Variable Size (VS) Allocation

- Allocation Size: <=128 KB (16 bytes granularity, 16 bytes busy block header)
- VS blocks are allocated from VS subsegments



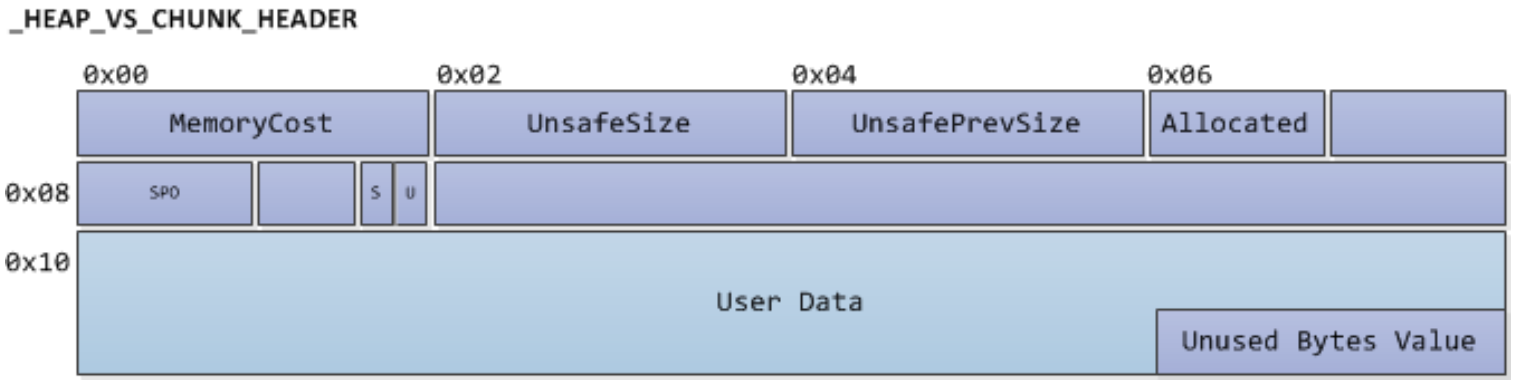
VS Subsegment

- Backend block with “VS Subsegment (`0x20`)” bit set in page range descriptor’s `RangeFlags` field
- VS blocks start at offset `0x30`

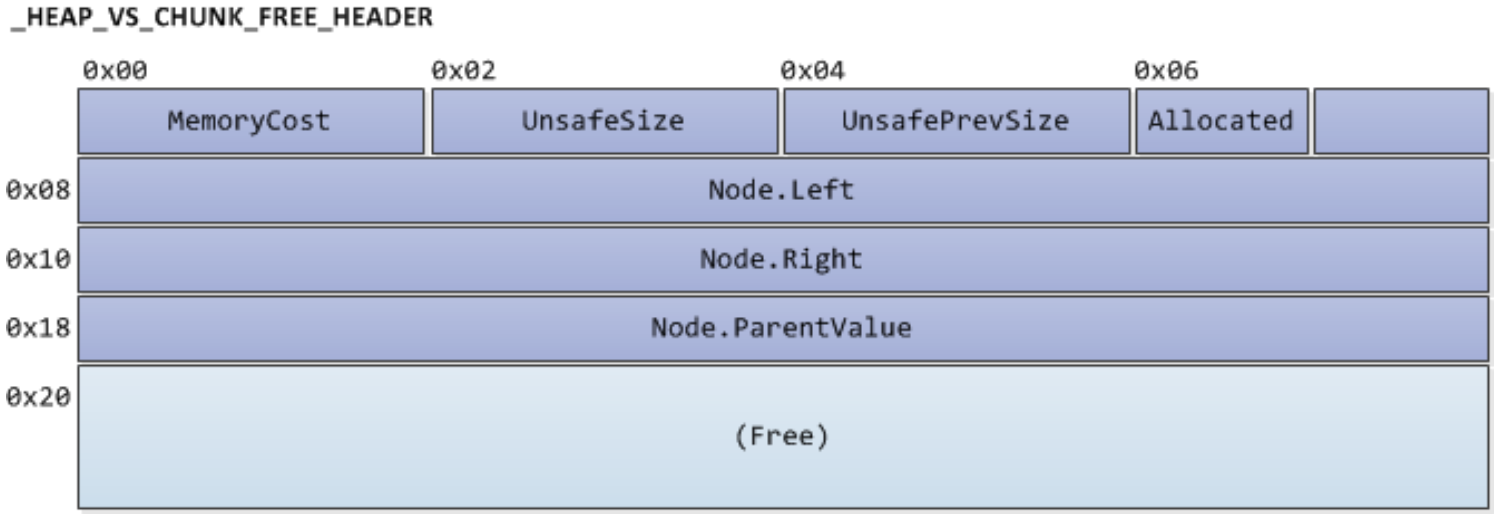


VS Block Header

- Busy VS block (first 9 bytes are encoded)

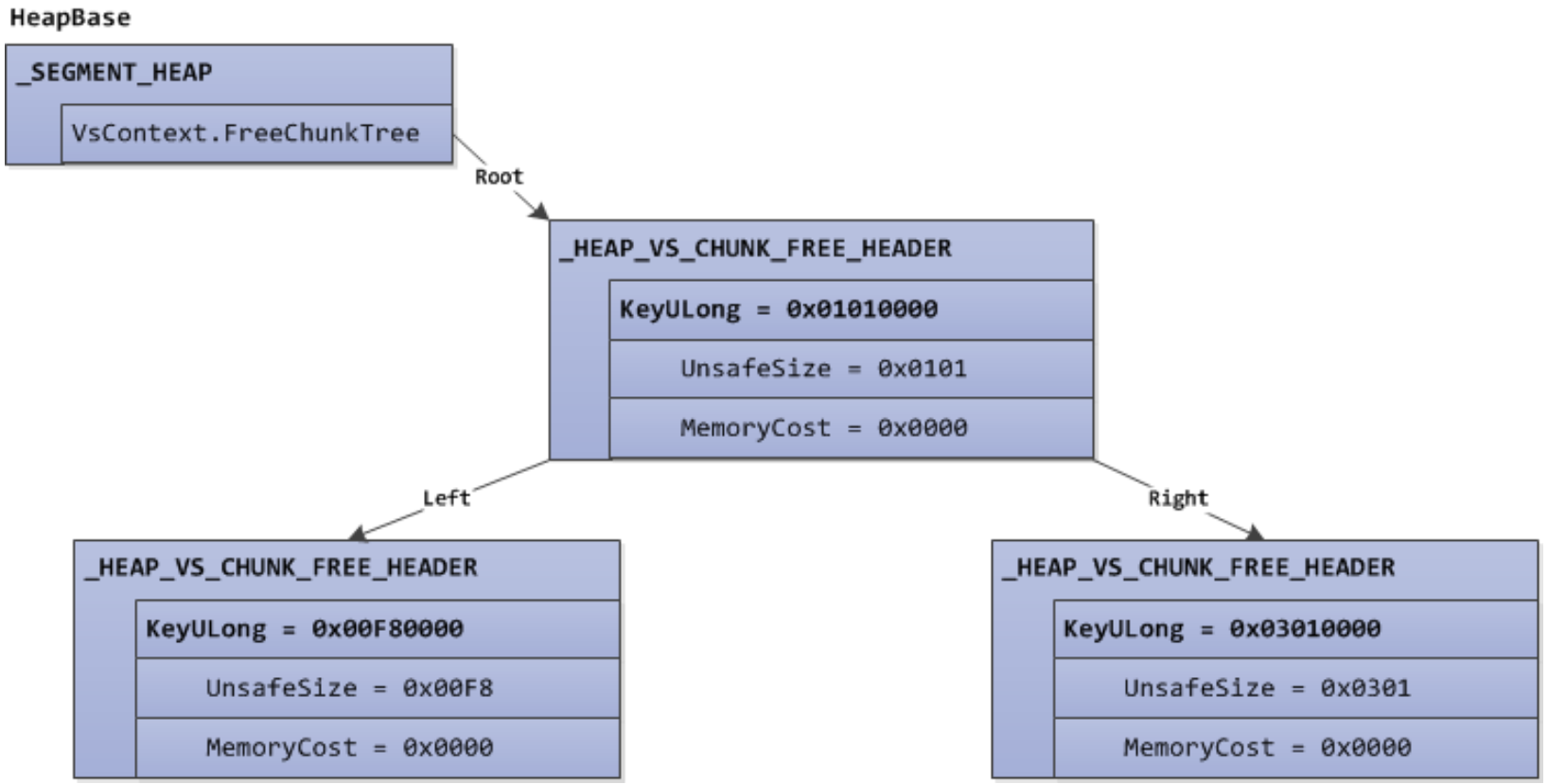


- Free VS block (first 8 bytes are encoded)



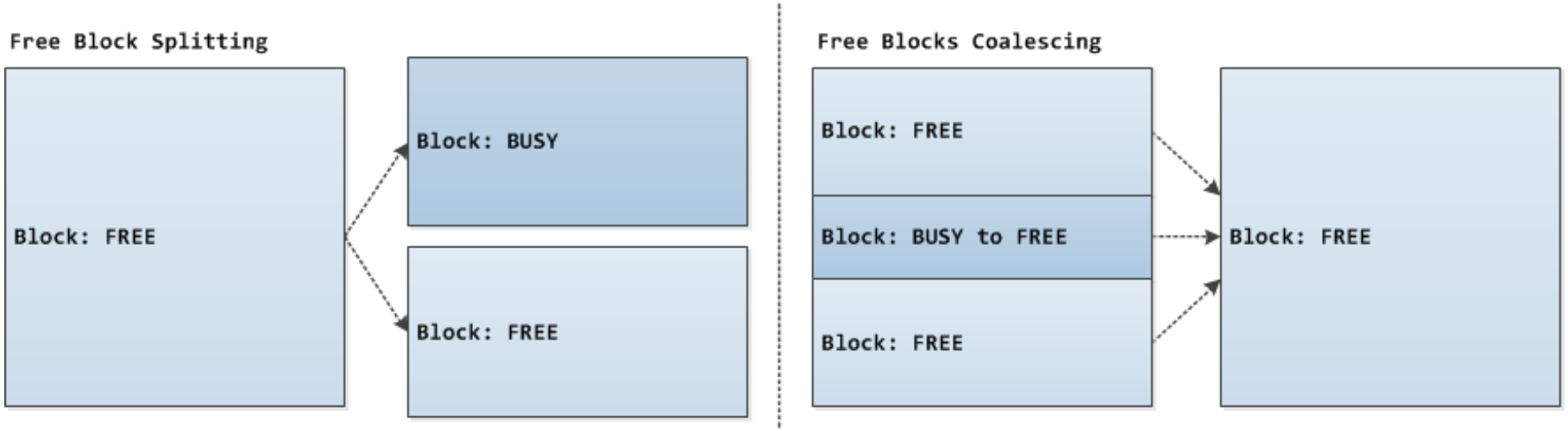
VS Free Tree

- RB tree of free VS blocks
- Key: Block size (in 16-byte blocks), memory cost (most committed blocks have a lower memory cost)



VS Allocation and Freeing

- Allocation
  - Best-fit search with preference to most committed block
  - Large free blocks are split unless the block size of the resulting remaining block will be less than `0x20` bytes
- Freeing
  - Coalesce to-be-freed block with neighbors

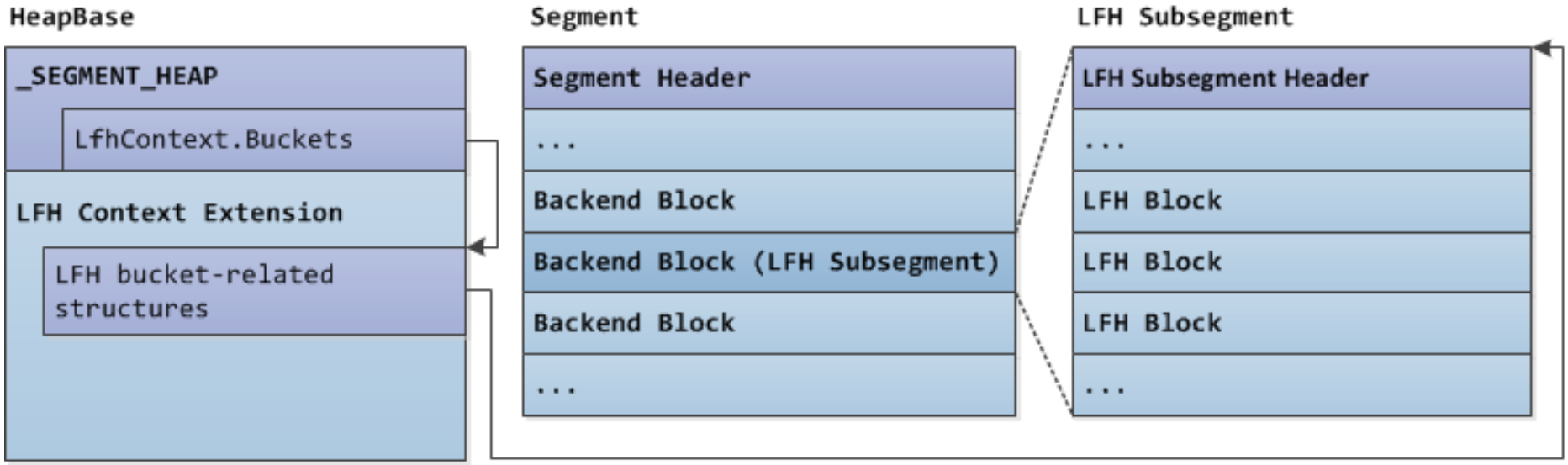


WINDOWS 10 SEGMENT HEAP INTERNALS

Internals: Low Fragmentation Heap

Low Fragmentation Heap (LFH)

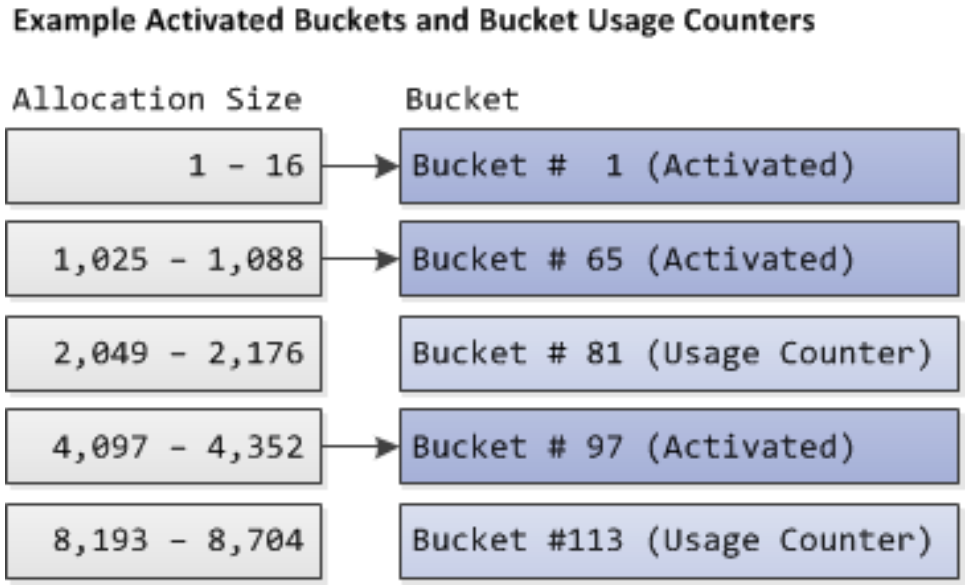
- Allocation Size: <=16,368 bytes (granularity depends on the allocation size)
- Prevents fragmentation by allocating similarly-sized blocks from larger pre-allocated blocks of memory (LFH subsegments)



LFH Buckets

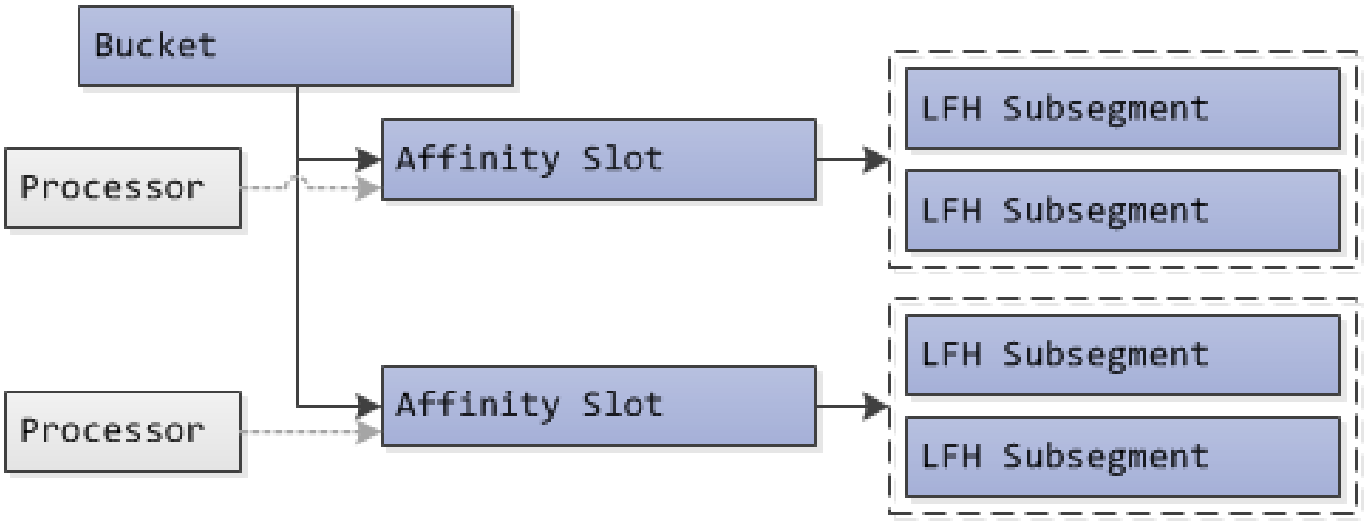
- Allocation sizes are distributed to buckets
- Bucket is activated on the 17th active allocation or the 2,040th allocation request for the bucket's allocation size

Bucket	Allocation Size	Granularity
1 – 64	1 – 1,024 bytes (0x1 – 0x400)	16 bytes
65 – 80	1,025 – 2,048 bytes (0x401 – 0x800)	64 bytes
81 – 96	2,049 – 4,096 bytes (0x801 – 0x1000)	128 bytes
97 – 112	4,097 – 8,192 bytes (0x1001 – 0x2000)	256 bytes
113 – 128	8,193 – 16,368 bytes (0x2001 – 0x3FF0)	512 bytes



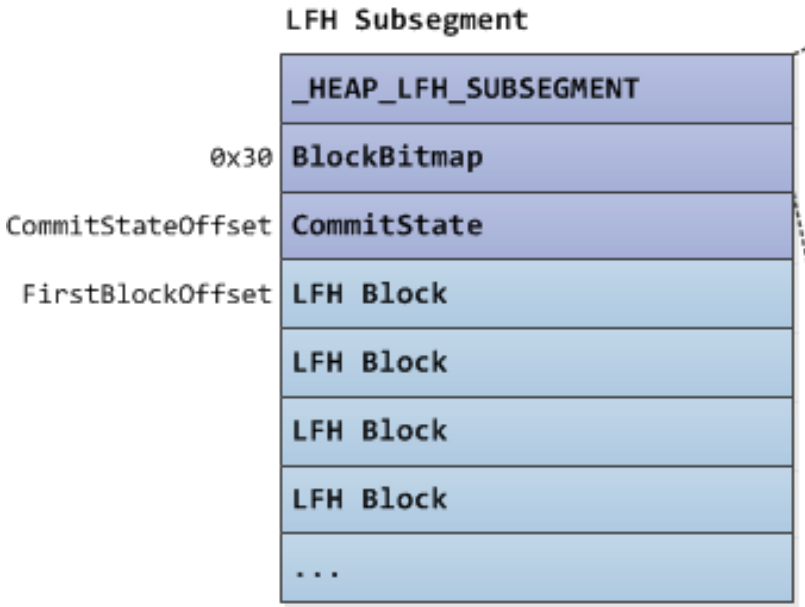
LFH Affinity Slots

- Affinity slots own the LFH subsegments where LFH blocks are allocated from
- After bucket activation: 1 affinity slot is created with all processors assigned to it
- Too much contention: new affinity slots are created and processors are re-assigned to the new affinity slots



LFH Subsegment

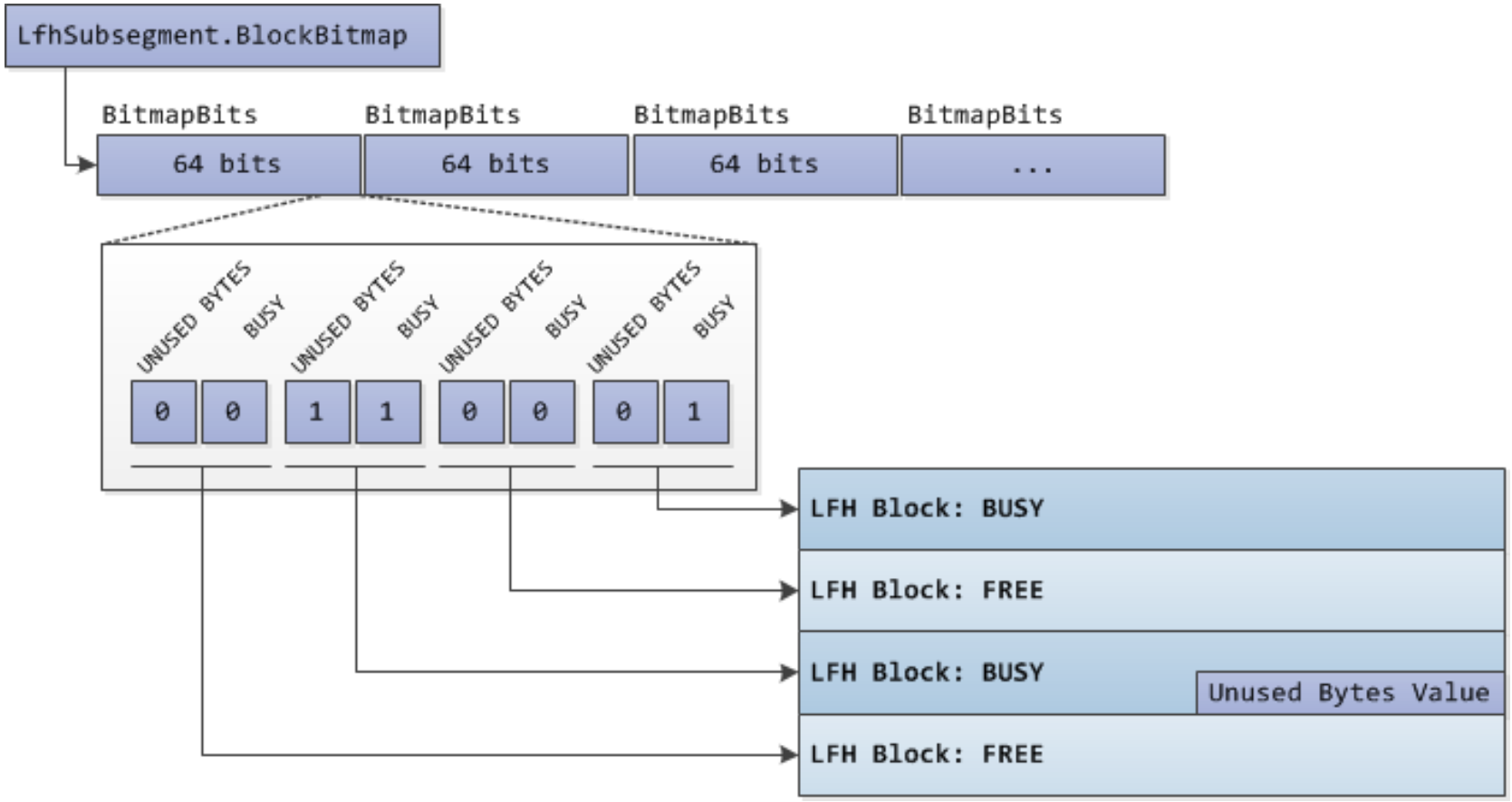
- Backend block with “LFH Subsegment (`0x01`)” bit set in page range descriptor’s `RangeFlags` field
- LFH blocks are stored after the LFH subsegment metadata




```
windbg> dt ntdll!_HEAP_LFH_SUBSEGMENT -r
   ...
   // Number of free LFH blocks
   +0x020 FreeCount        : Uint2B
   ...
   // Total number of LFH blocks
   +0x022 BlockCount       : Uint2B
   ...
   // Size of each block and offset of first block
   // in the LFH subsegment (both encoded)
   +0x028 BlockOffsets     : _HEAP_LFH_SUBSEGMENT_ENCODED_OFFSETS
     +0x000 BlockSize        : Uint2B
     +0x002 FirstBlockOffset : Uint2B
   ...
   // Block bitmap: 2 status bits per LFH block
   +0x030 BlockBitmap      : [1] Uint8B
   ...
```

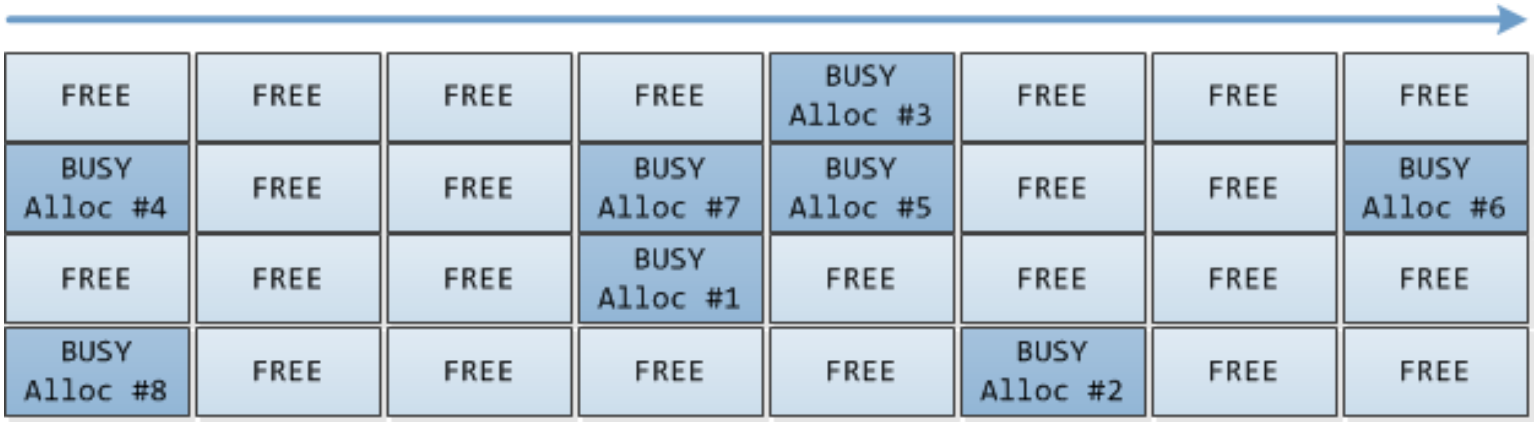
LFH Block Bitmap

- 2 bits per LFH block (BUSY bit and UNUSED_BYTES bit)
- Divided into `BitmapBits` (64 bits each = 32 LFH blocks)



LFH Allocation and Freeing

- Allocation
  - Select a `BitmapBits` from block bitmap (biased by a free hint)
  - Randomly select a bit position (where BUSY bit is clear) in `BitmapBits`, set BUSY and UNUSED BYTES bits; result:

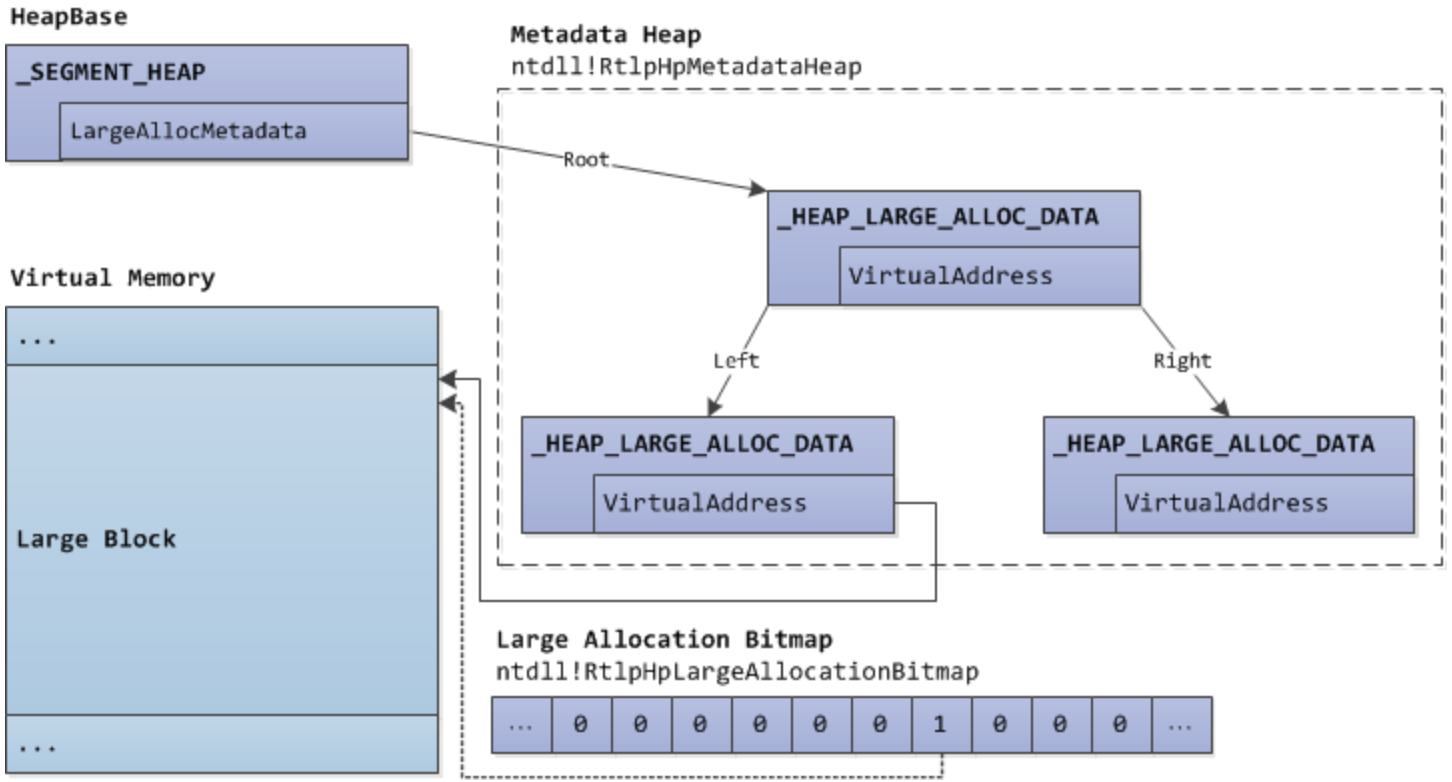


- Freeing
  - Clear block's BUSY and UNUSED BYTES bits in the block bitmap

Internals: Large Blocks Allocation

Large Blocks Allocation

- Allocation Size: >508KB
- Blocks are allocated via `NtAllocateVirtualMemory()`
- Block metadata is stored in a separate heap



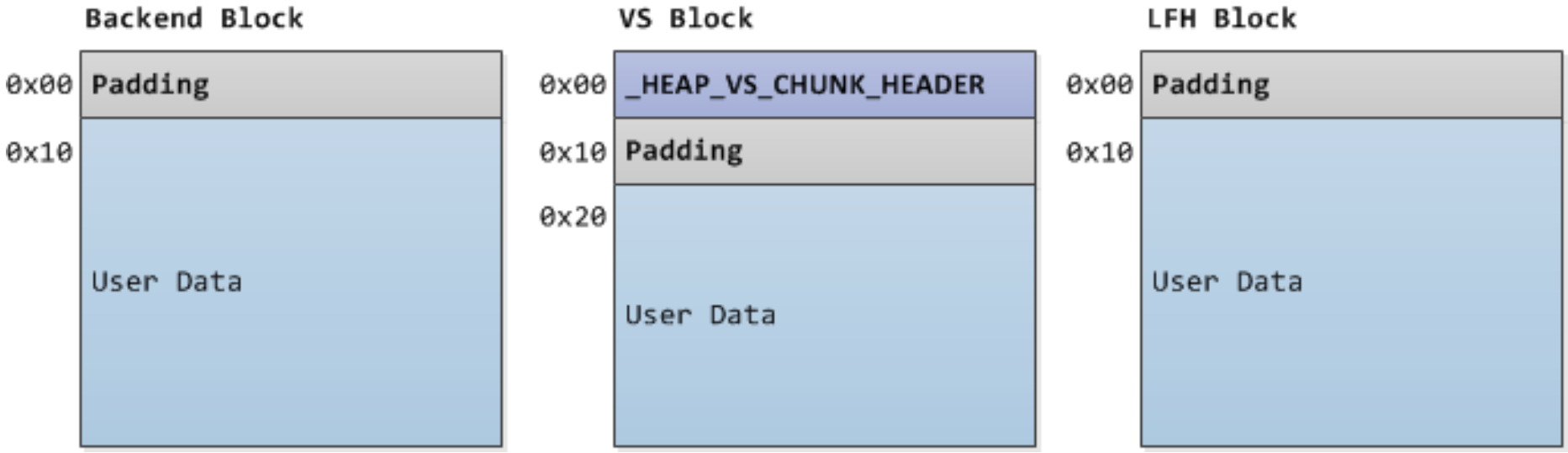
Large Blocks Allocation and Freeing

- Allocation
  - Allocate block's metadata
  - Allocate block's virtual memory
  - Mark block's address in the large allocation bitmap
- Freeing
  - Unmark block's address in the large allocation bitmap
  - Free block's virtual memory
  - Free block's metadata

Internals: Block Padding

Block Padding

- Added if the application is not opted-in by default to use the Segment Heap
- Padding increases the total block size and changes the layout of backend blocks, VS blocks and LFH blocks



Internals: Summary

Internals: Summary

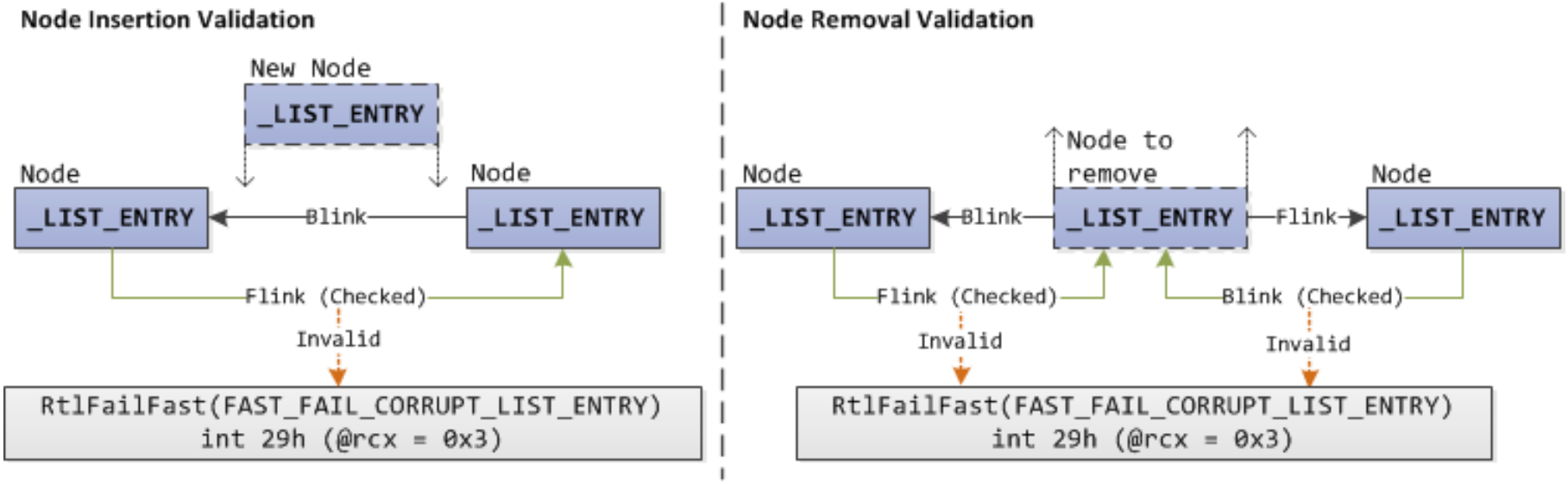
- Four components: Backend, VS allocation, LFH, and large blocks allocation
- Largely different data structures compared to the NT Heap
- Free trees instead of free lists
- Only VS blocks have a header at the beginning of each block
- Backend/VS allocation: Best-fit search algorithm with preference to most committed block
- LFH allocation: Free blocks are randomly selected

WINDOWS 10 SEGMENT HEAP INTERNALS

Security Mechanisms

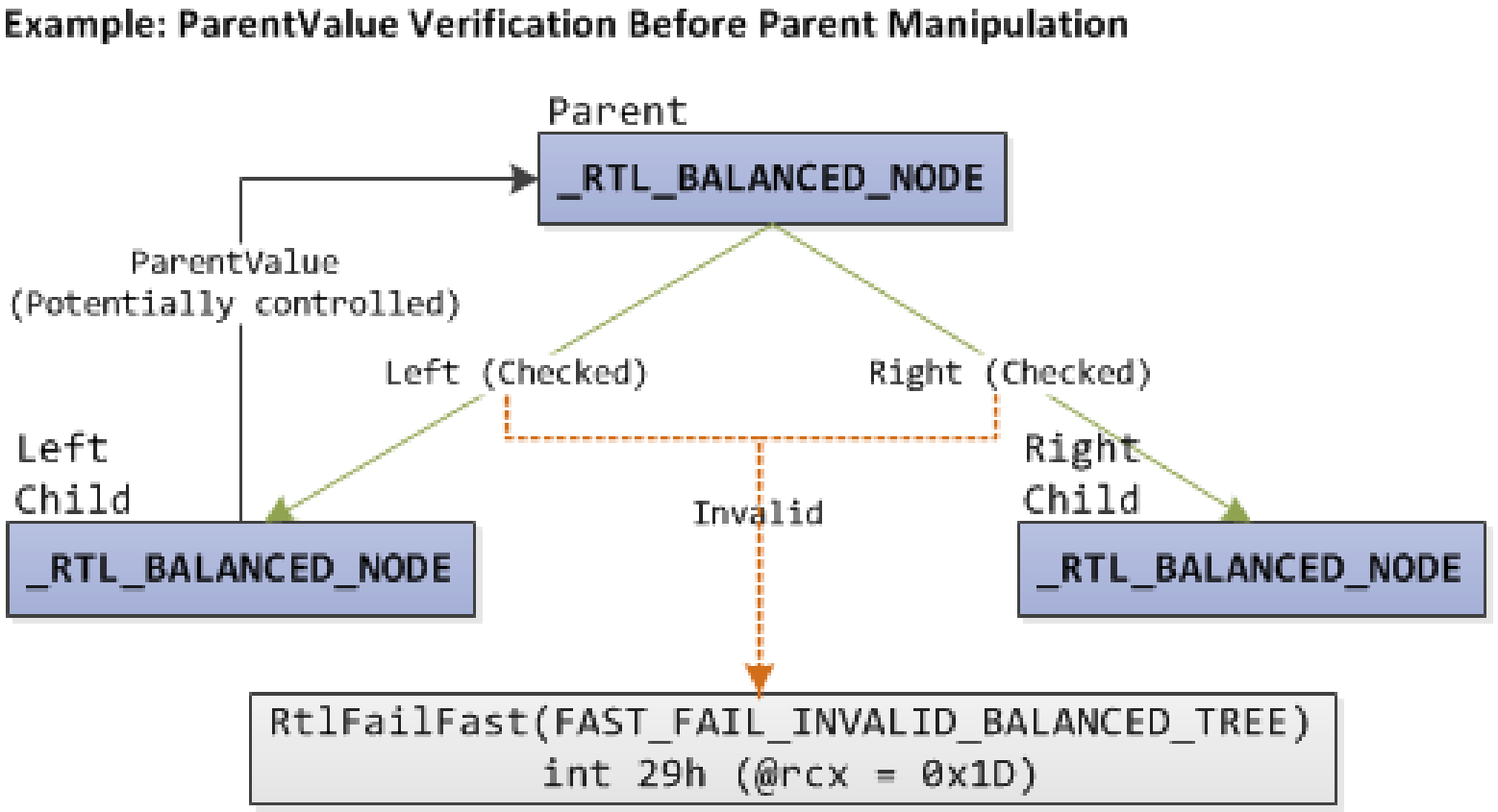
FastFail on Linked List Node Corruption

- Segment and subsegment lists are linked lists
- Prevents classic arbitrary writes due to corrupted linked list nodes



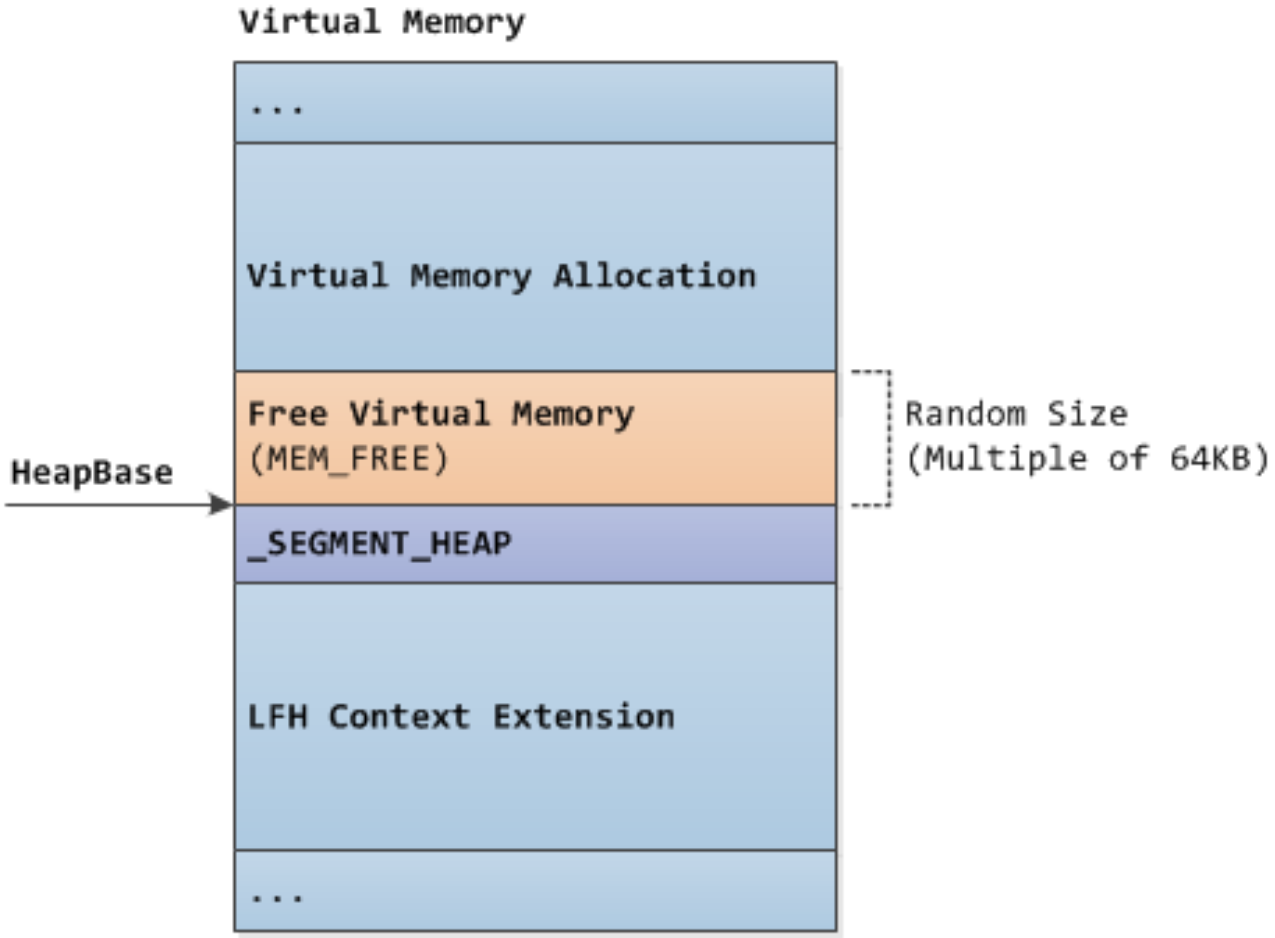
FastFail on Tree Node Corruption

- Backend and VS free trees are RB trees
- Prevents arbitrary writes due to corrupted tree nodes



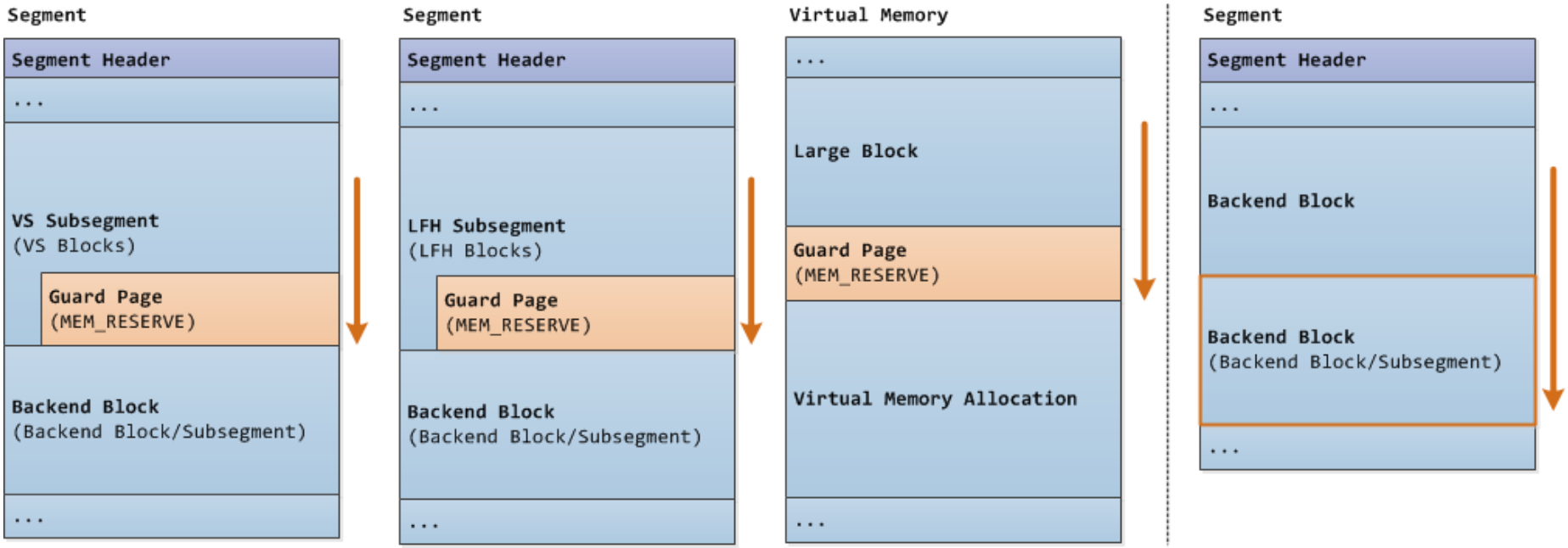
Heap Address Randomization

- Makes guessing of the heap address unreliable



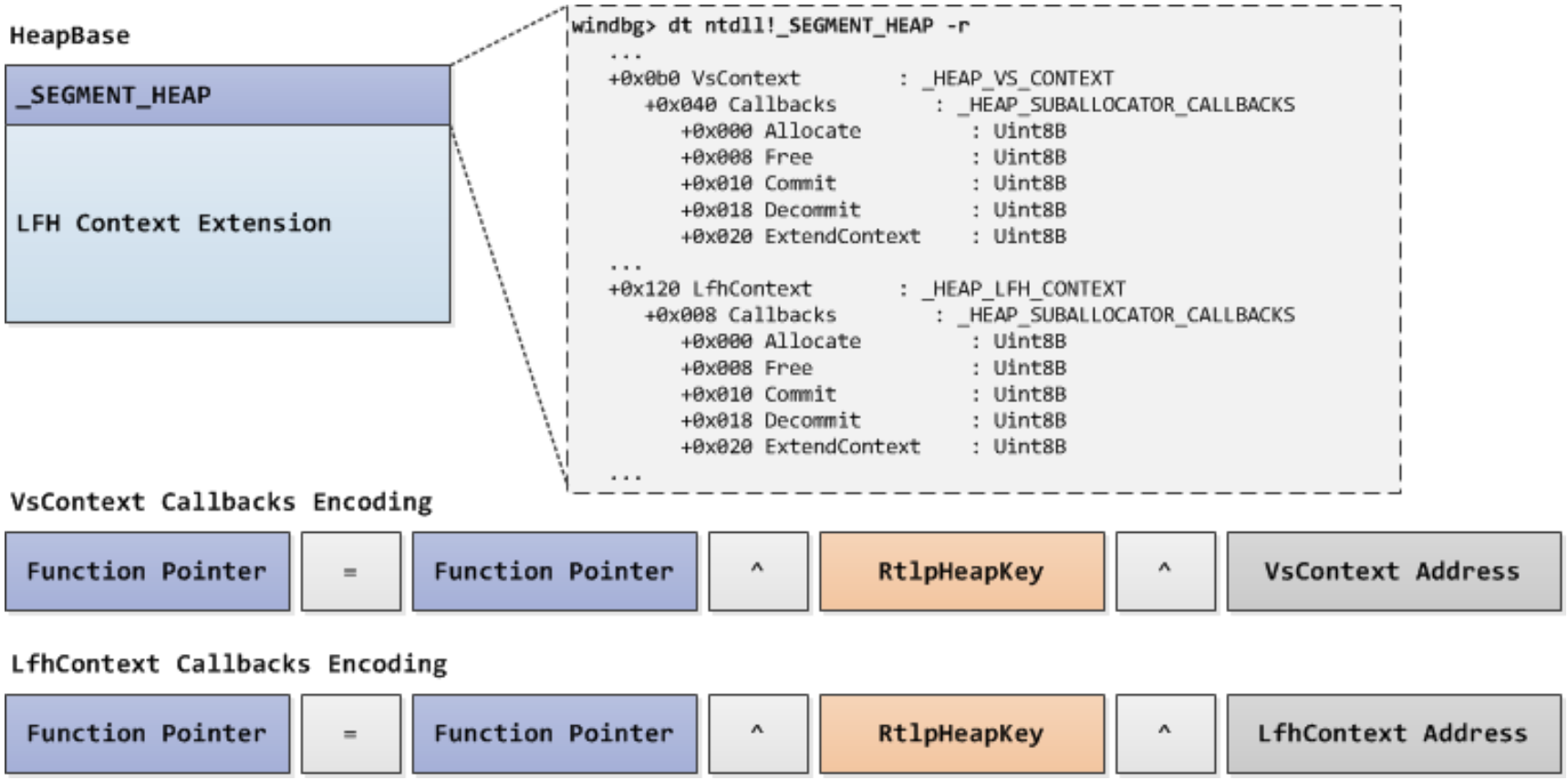
Guard Pages

- Prevents overflow outside the subsegment (VS and LFH blocks) or outside the block (large blocks)
- VS/LFH subsegment size should be >=64KB
- Backend blocks (non-subsegment) do not have a guard page



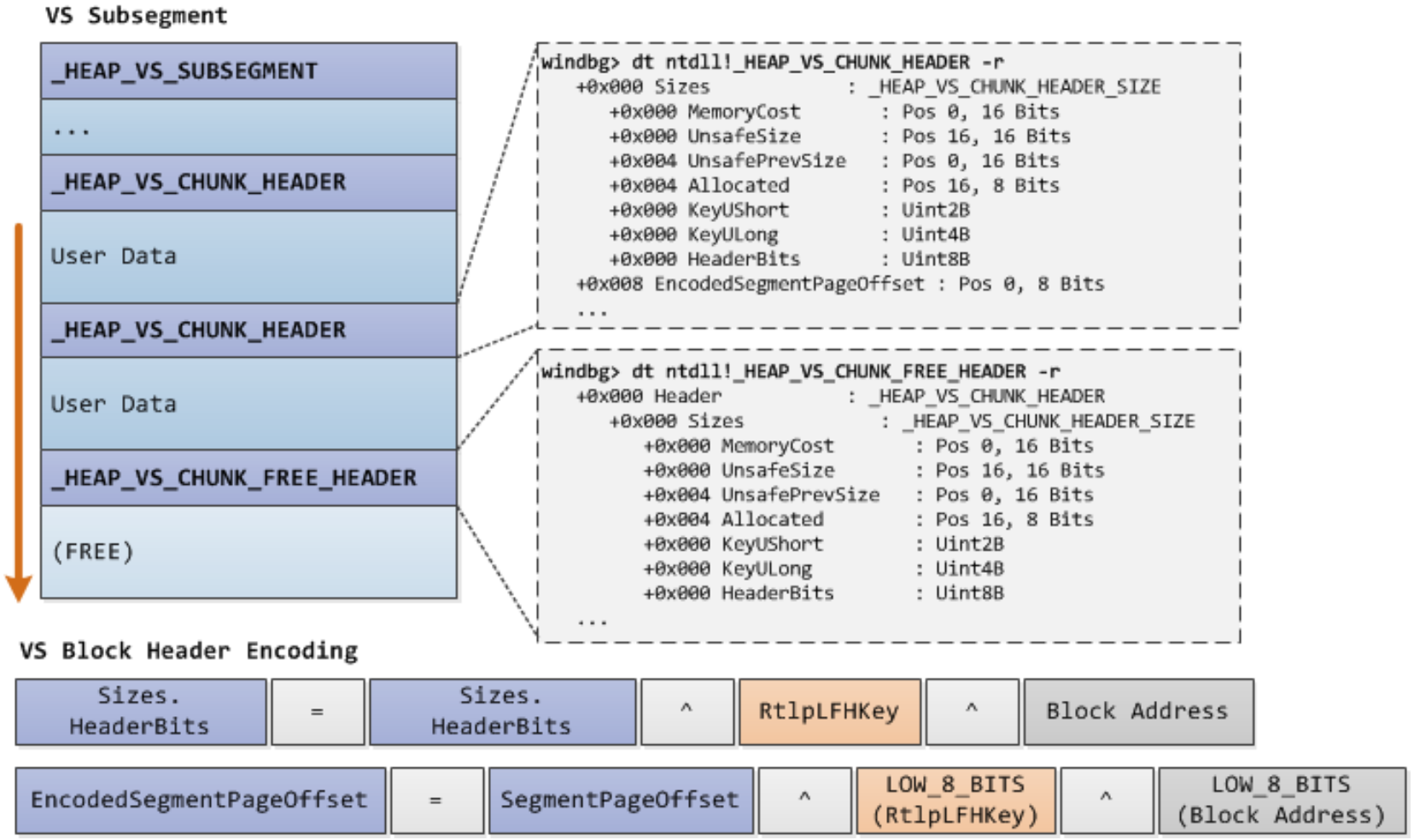
Function Pointer Encoding

- Protects function pointers in the HeapBase from trivial modification



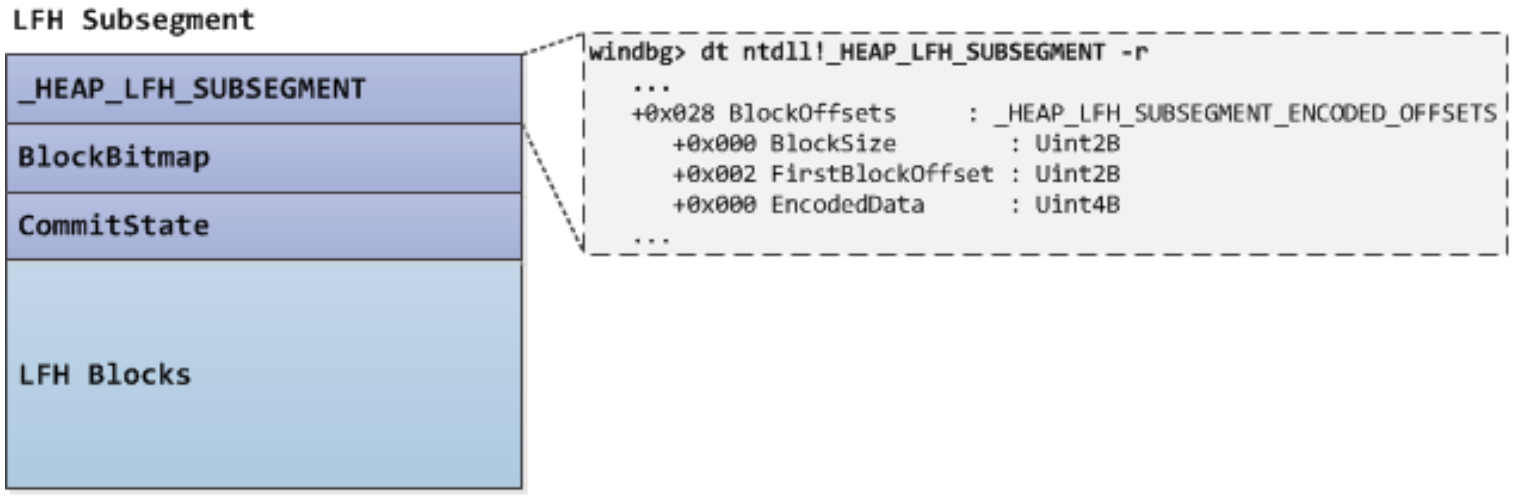
VS Block Header Encoding

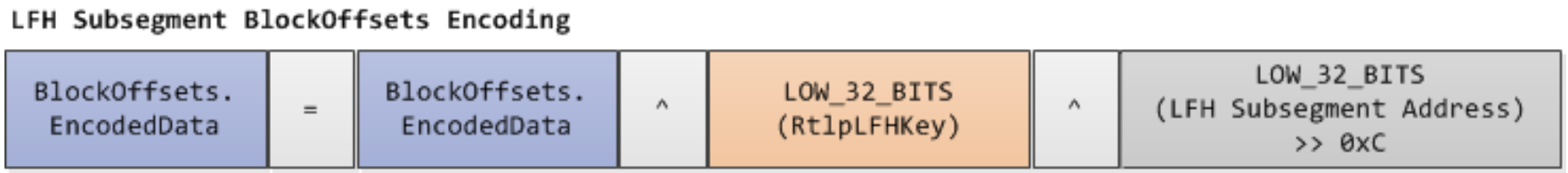
- Protects important VS block header fields from trivial modification



LFH Subsegment BlockOffsets Encoding

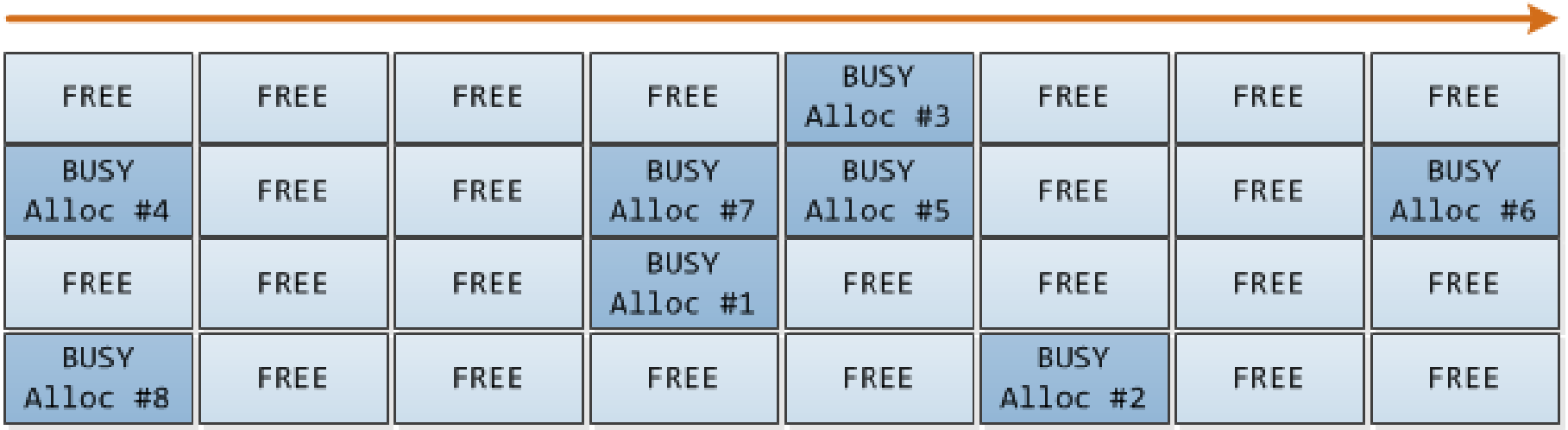
- Protects important LFH subsegment header fields from trivial modification





LFH Allocation Randomization

- Makes exploitation of LFH-based buffer overflows and use-after-frees unreliable
- Example: 8 sequential allocations in a new LFH subsegment



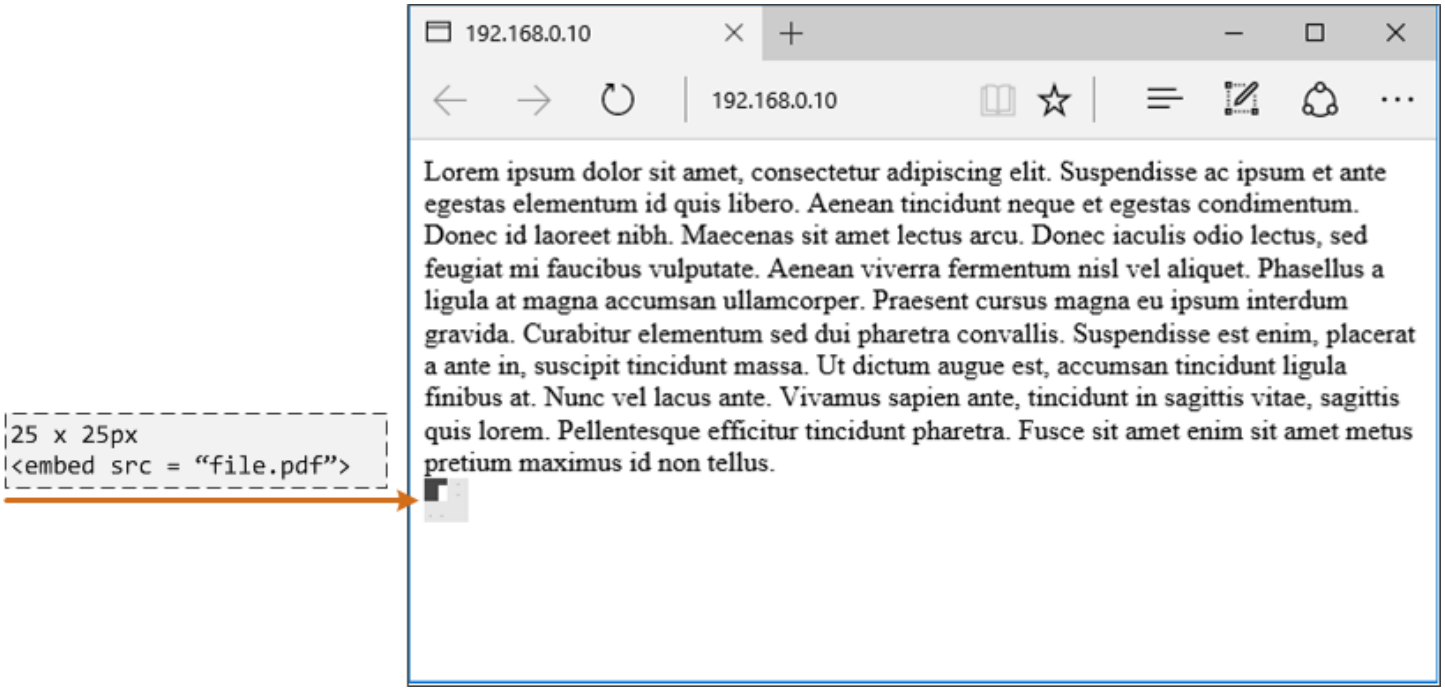
Security Mechanisms: Summary

- Important Segment Heap metadata are encoded
- Linked list nodes and tree nodes are checked
- Guard pages and some randomization are added
- Precise LFH allocation layout manipulation is difficult
- Precise backend and VS allocation layout manipulation is achievable (no randomization)

Case Study and Demonstration

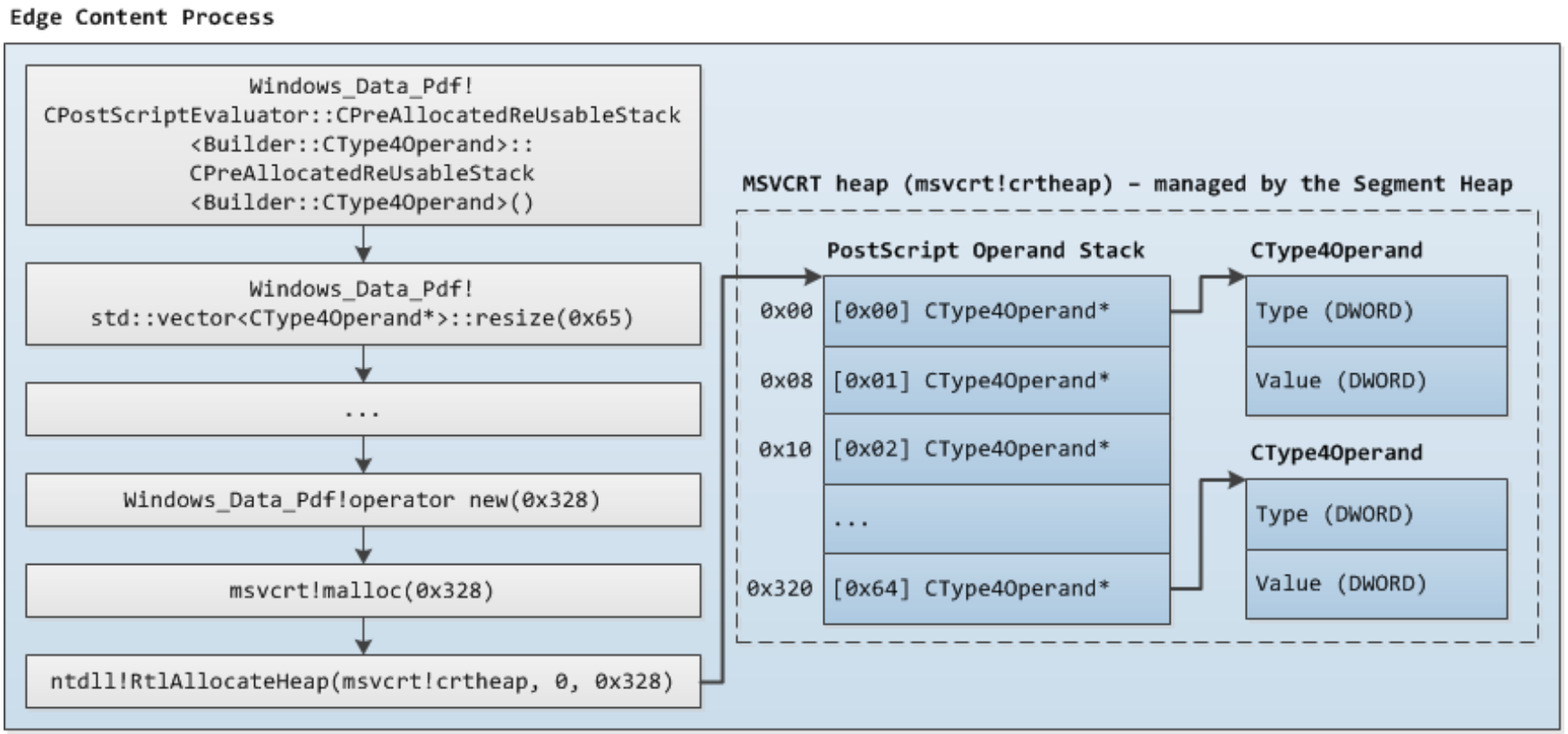
WinRT PDF

- Built-in PDF library since Windows 8.1 (Windows.Data.Pdf.dll)
- Used by Edge in Windows 10 to render PDFs
- Vulnerabilities can be used in Edge drive-by attacks



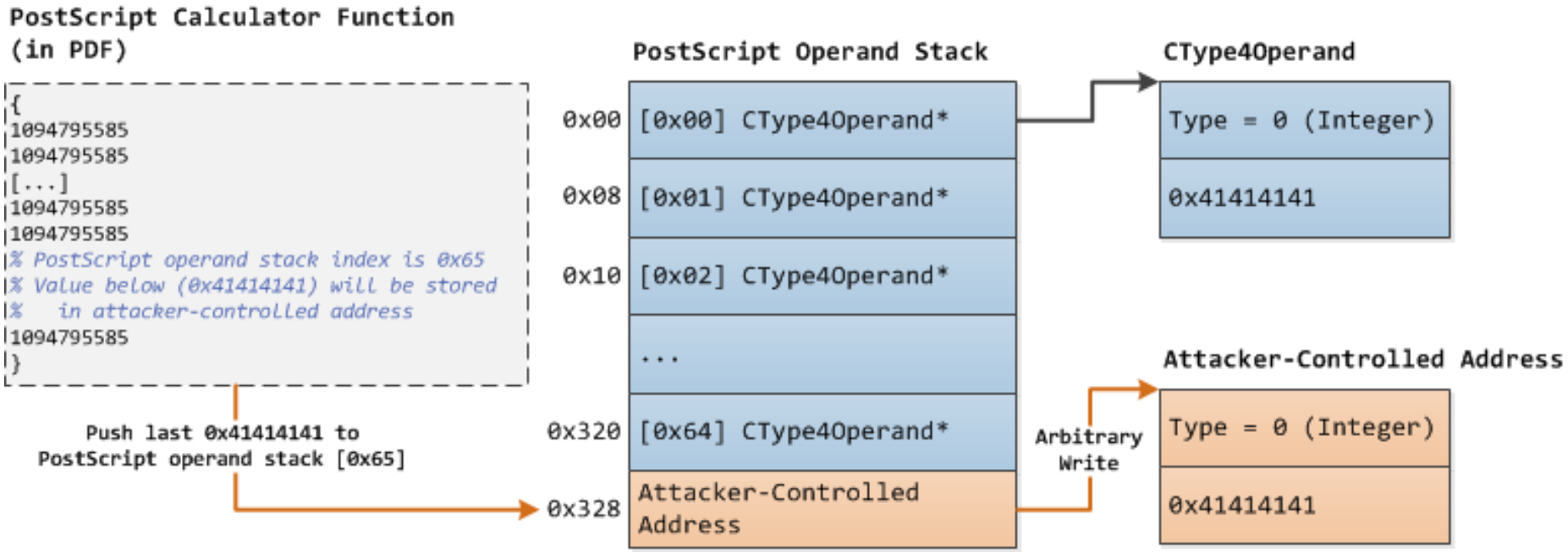
WinRT PDF: PostScript Operand Stack

- Used by the WinRT PDF's PostScript interpreter for Type 4 (PostScript Calculator) functions
- `0x65` `CType4Operand` pointers stored in the MSVCRT heap



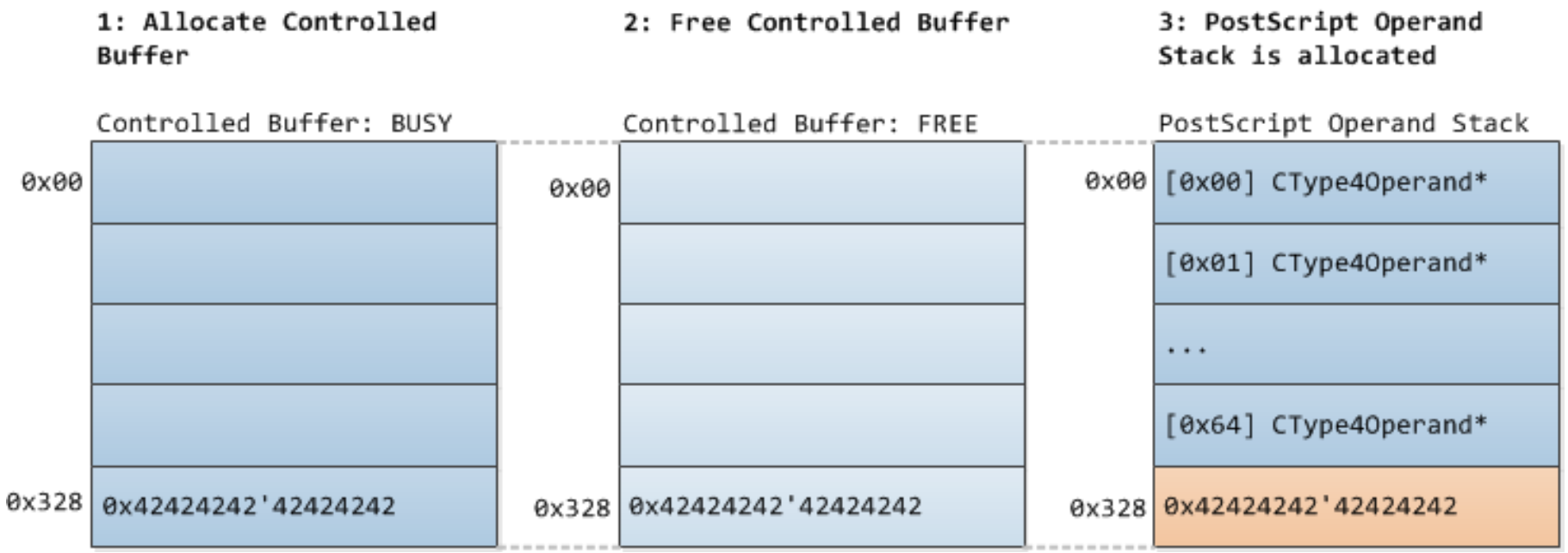
WinRT PDF: CVE-2016-0117

- PostScript interpreter allows access to PostScript operand stack index 0x65 (out-of-bounds)
- Arbitrary write possible if value after the end of PostScript operand stack is attacker-controlled



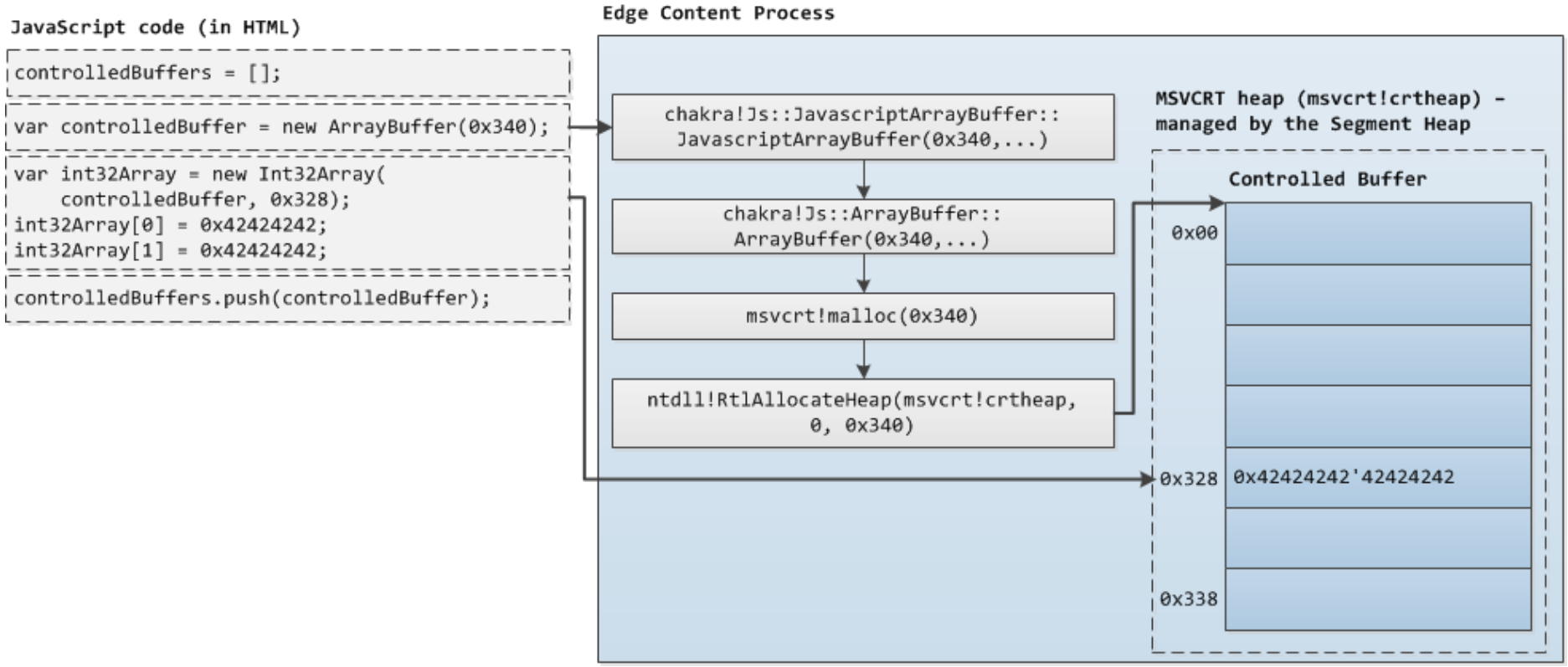
Plan for Implanting the Target Address

- Allocate a controlled buffer, free it, and the PostScript operand stack will be allocated in its place
- Controlled buffer and PostScript operand stack will be VS-allocated for reliability



Problem #1: MSVCRT Heap Manipulation

- Embedded JavaScript in PDF could potentially help, but it is not currently supported in WinRT PDF
- Solution: Chakra (Edge's JS engine) and Chakra's `ArrayBuffer`



Problem #1: MSVCRT Heap Manipulation

- LFH bucket activation

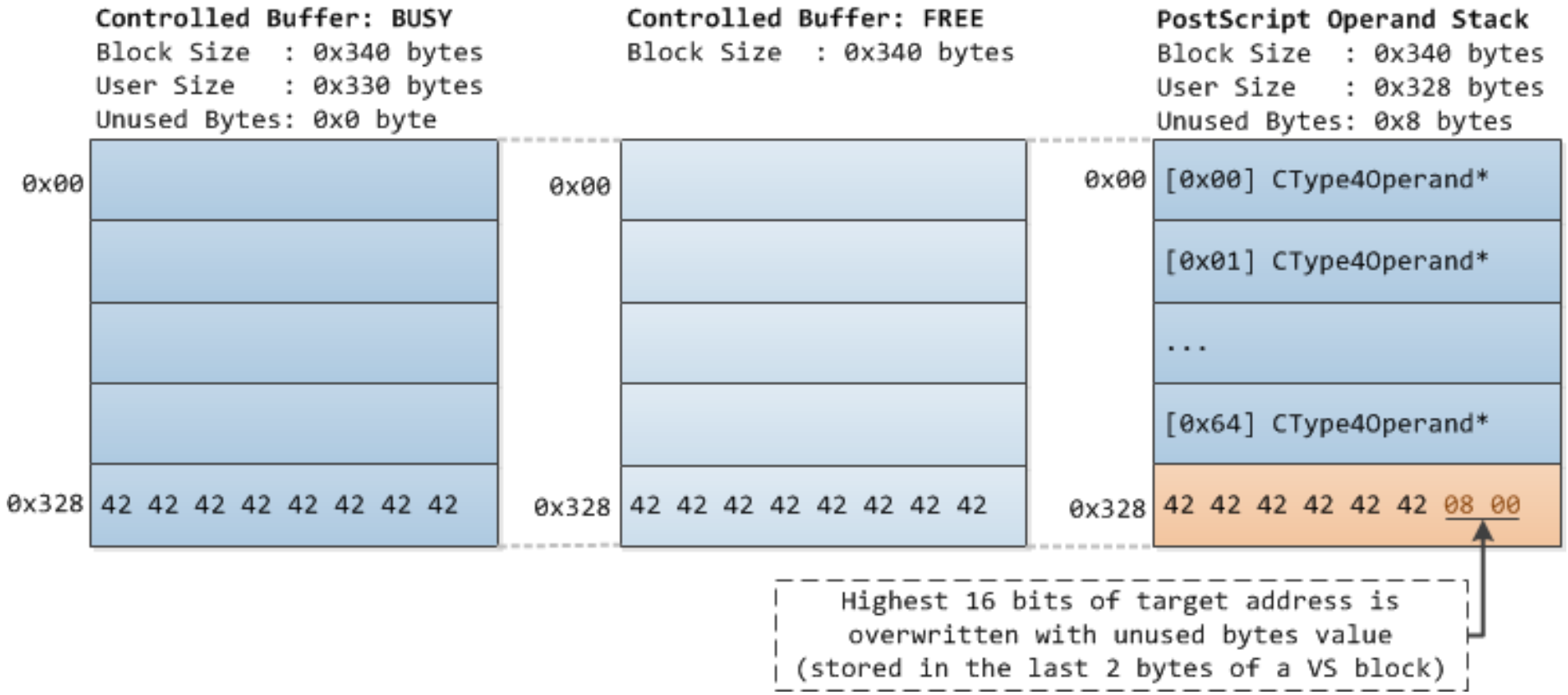
```
lfhBucketActivators = [];
for (var i = 0; i < 17; i++) {
    lfhBucketActivators.push(new ArrayBuffer(blockSize));
}
```

- `CollectGarbage()` does not work in Edge, but concurrent garbage collection can be triggered

```
// trigger concurrent garbage collection
gcTrigger = new ArrayBuffer(192 * 1024 * 1024);
// then call afterGcCallback after some delay (adjust if needed)
setTimeout(afterGcCallback, 1000);
```

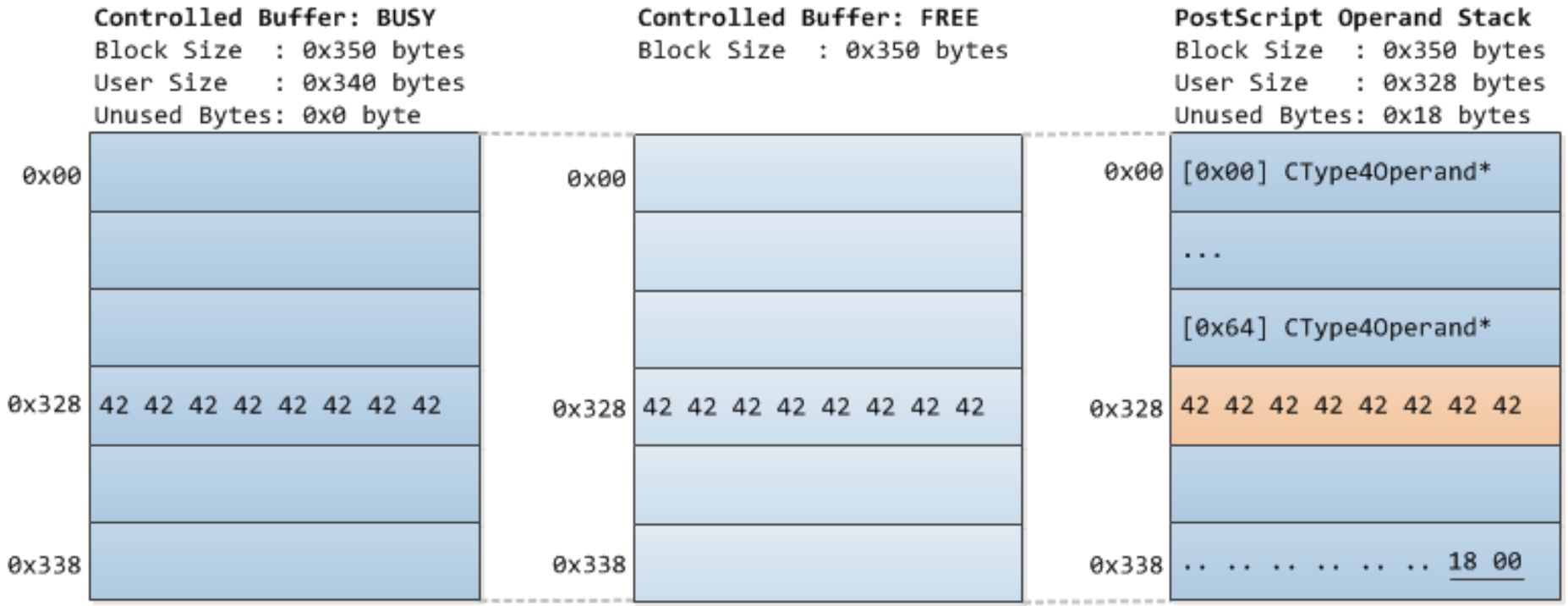
Problem #2: Target Address Corruption

- Showstopper: Target address will become corrupted by VS unused bytes value



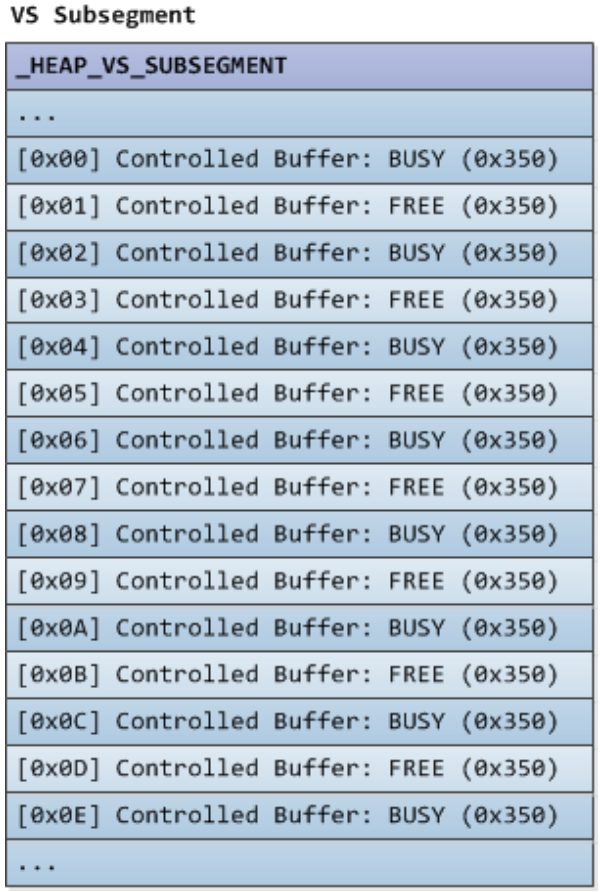
Problem #2: Target Address Corruption

- VS internals: “Large free blocks are split unless the block size of the resulting remaining block will be less than `0x20` bytes”
- Solution: Use `0x340` bytes controlled buffer (block size: `0x350`): `0x350` free block – `0x340` block allocation == `0x10` (no split)



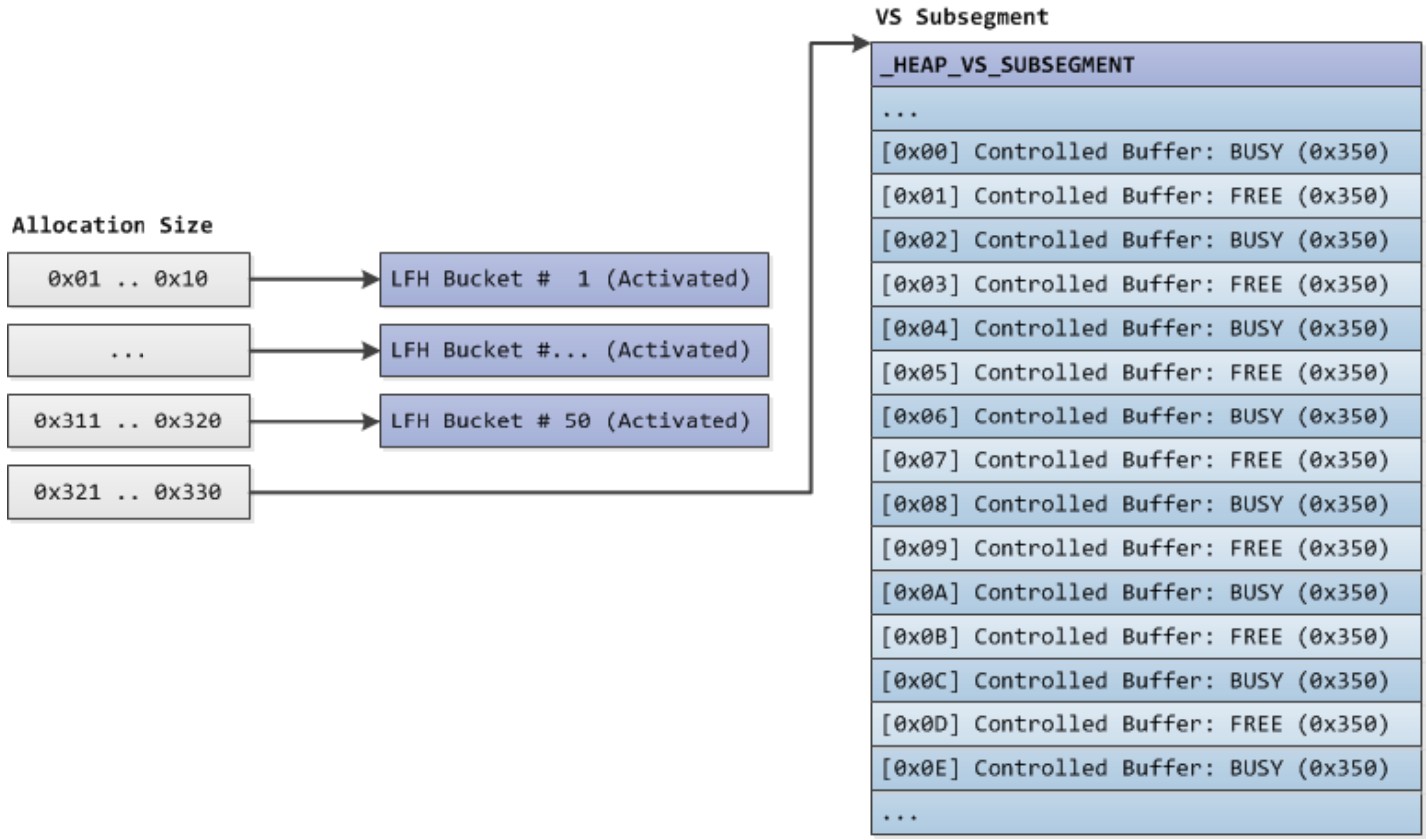
Problem #3: Free Blocks Coalescing

- Free VS block of freed controlled buffer will be coalesced
- Solution: Alternating busy and free controlled buffers
- Actual allocation patterns will not always exactly match the illustration, but the chance of an un-coalesced freed controlled buffer block is increased



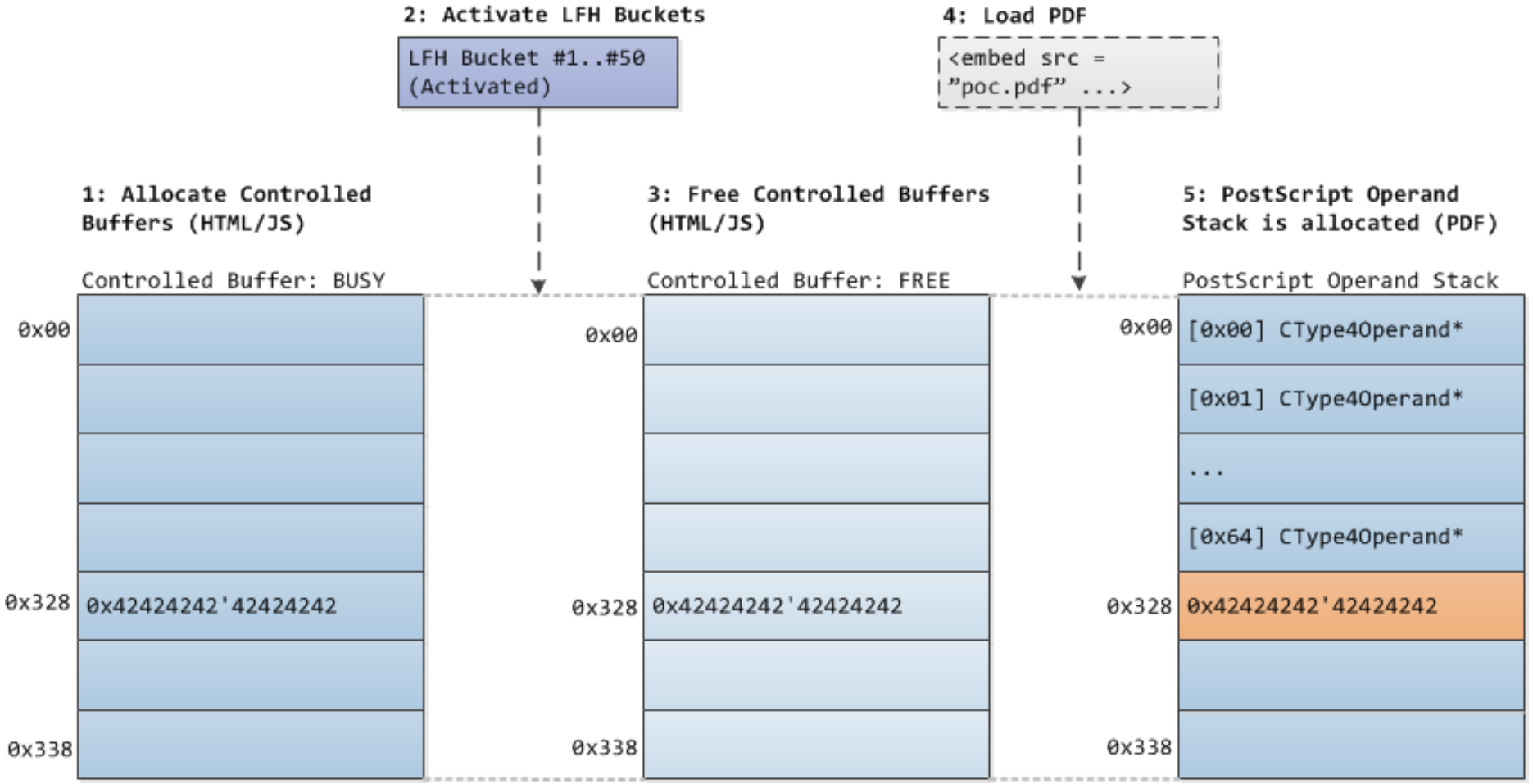
Problem #4: Unintended Use of Free Blocks

- Free VS blocks of freed controlled buffers will be split and will be used for small allocations
- Solution: Redirect small allocation sizes to the LFH

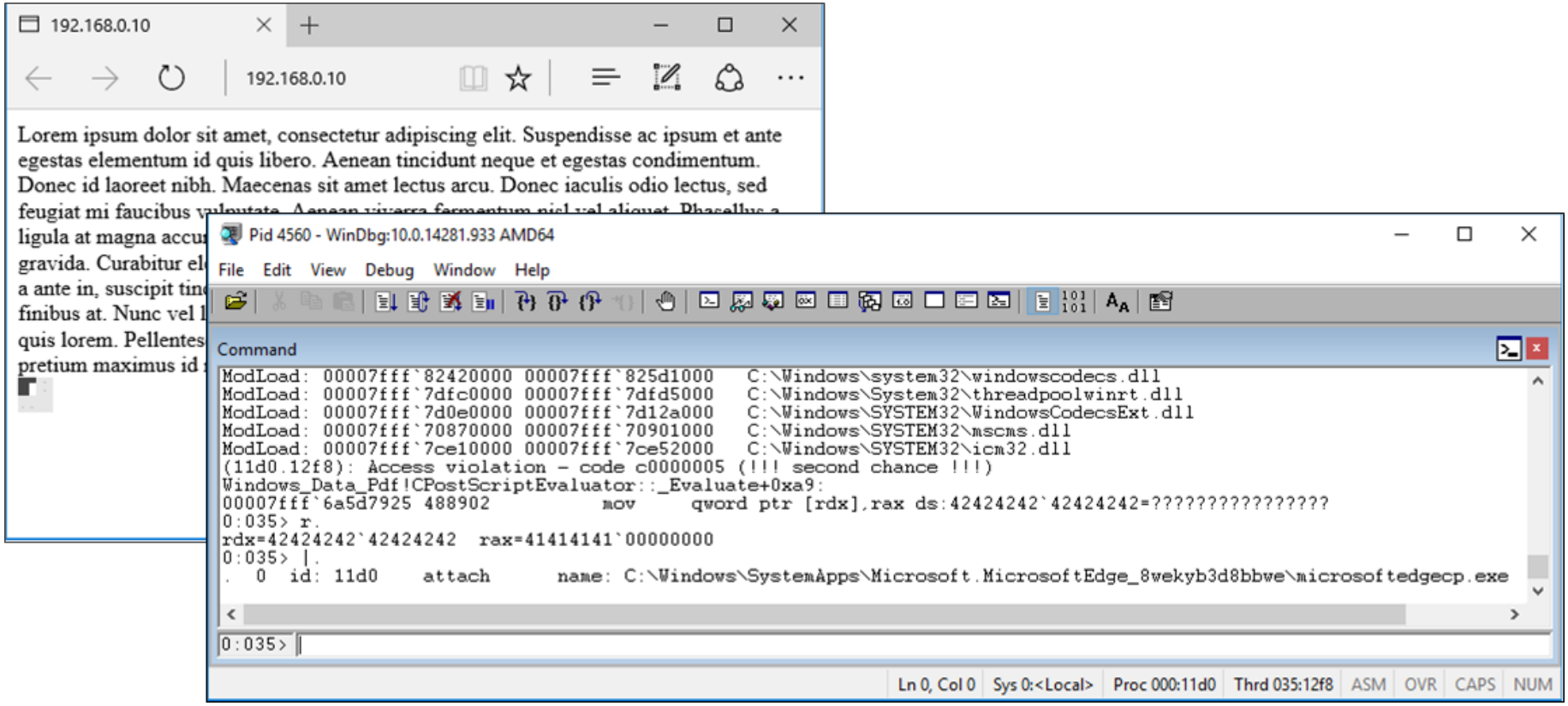


Adjusted Plan for Implanting the Target Address

- HTML/JS will setup the MSVCRT heap layout, PDF will trigger the vulnerability



Demo: Successful Arbitrary Write



Case Study: Summary

- Precise layout manipulation of VS allocations was performed
- LFH can be used to preserve the controlled VS allocations layout by servicing unintended allocations
- Scripting capability (Chakra) plus a common heap between components (Chakra's `Arraybuffer` and WinRT PDF's PostScript interpreter) are key to the heap layout manipulation
- Seemingly unresolvable problems can potentially be solved by knowledge of heap implementation internals

Conclusion

Conclusion

- Internals of the Segment Heap and the NT Heap are largely different
- Security mechanisms are comparable with the NT Heap
- New data structures are interesting for metadata attack research
- Precise heap layout manipulation is achievable in certain cases
- Refer to the white paper for more detailed information

Prior Works / References

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