Bypassing Mitigations by Attacking JIT Server in Microsoft Edge

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About me

- Security researcher at Google Project Zero
- Previously: Google Security Team, Academia (UNIZG)
- Doing security research for the last 10 years
- Author: Domato, WinAFL, ROPGuard
- @ifsecure on Twitter

Browser exploit flow (example)

Browser exploit flow (example)

Code execution mitigations

- Before:

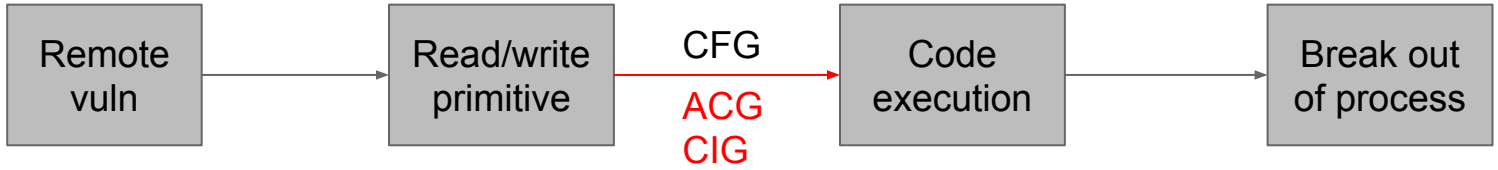
```
mov rbx,qword ptr [rax+8]
call rbx
```

- After:

```
mov rbx,qword ptr [rax+8]
mov rax, rbx
call qword ptr [chakra!_guard_dispatch_icall_fptr]
```

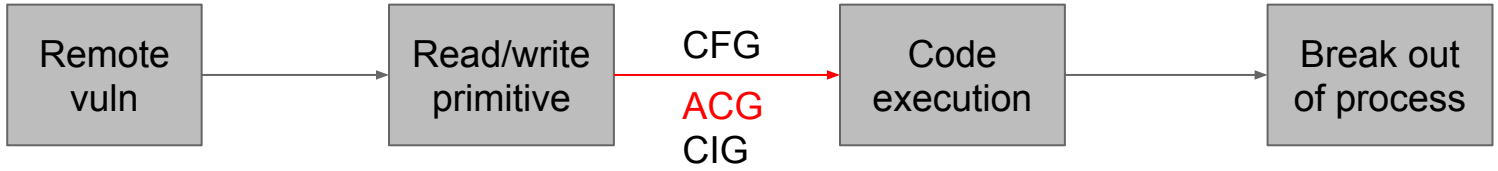
- Bitmap of CFG-allowed targets (some granularity involved)
- Only checks forward edges (doesn’t check return addresses)

Code execution mitigations



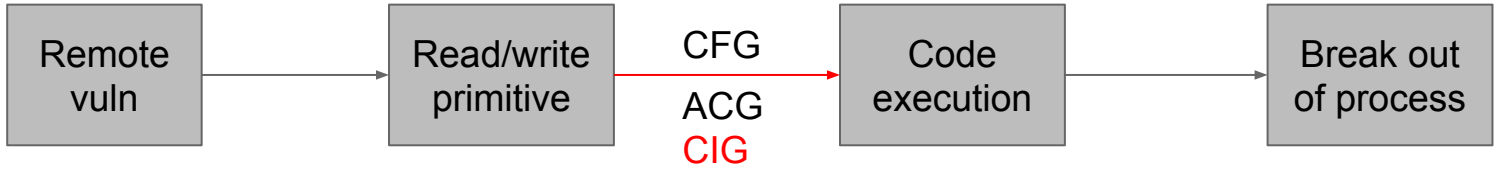
- 2 new mitigations Introduced in Windows 10 creators update (1703)

Code execution mitigations



- Arbitrary Code Guard (ACG)
- Make it impossible to
  - allocate new executable pages
    - e.g. `VirtualAlloc(... ,... ,PAGE_EXECUTE_READWRITE ,...)`
  - make existing executable pages writable
    - e.g. `VirtualProtect(... ,... ,PAGE_EXECUTE_READWRITE ,...)`
- Attempting results in 0xc0000604 STATUS_DYNAMIC_CODE_BLOCKED
- Similar to PaX MPROTECT
- What about JIT? JIT Server.

Code execution mitigations



- Code Integrity Guard (CIG)
  - Can only load properly signed DLLs

Agenda

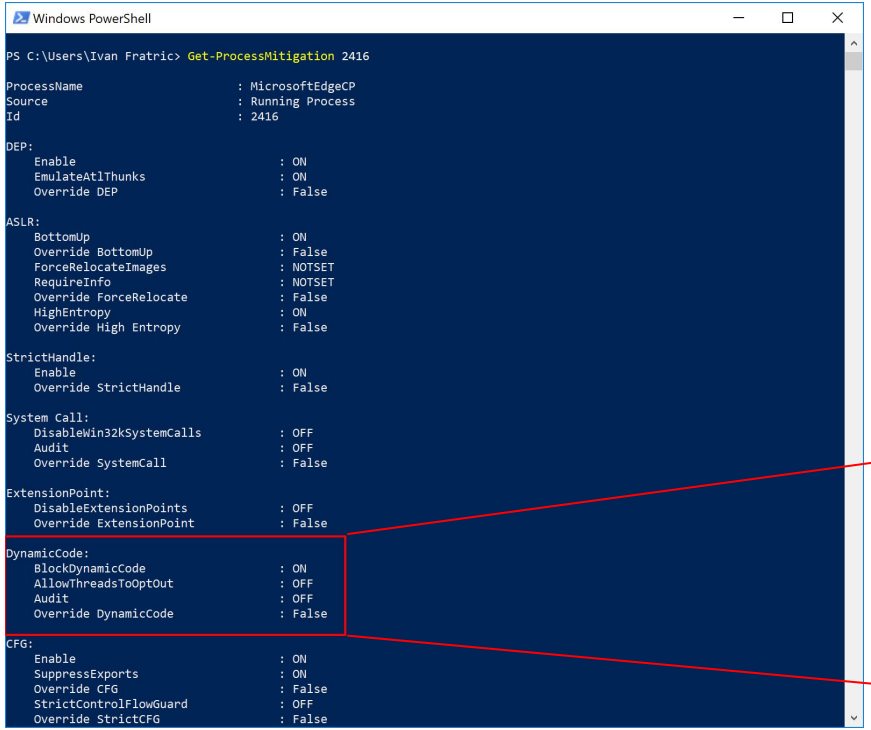
- How ACG works?
- Is it effective?
- How does JIT server work
- Issues (CFG and ACG)

Enabling ACG

- Relies on setting the dynamic code policy
- Enabled by SetProcessMitigationPolicy()
- In Edge:

```
00 KERNELBASE!SetProcessMitigationPolicy
01 MicrosoftEdgeCP!SetProcessDynamicCodePolicy+0xc0
02 MicrosoftEdgeCP!StartContentProcess_Exe+0x164
03 MicrosoftEdgeCP!main+0xfe
04 MicrosoftEdgeCP!_main+0xa6
05 MicrosoftEdgeCP!WinMainCRTStartup+0x1b3
06 KERNEL32!BaseThreadInitThunk+0x14
07 ntdll!RtlUserThreadStart+0x21
```

When is it enabled?



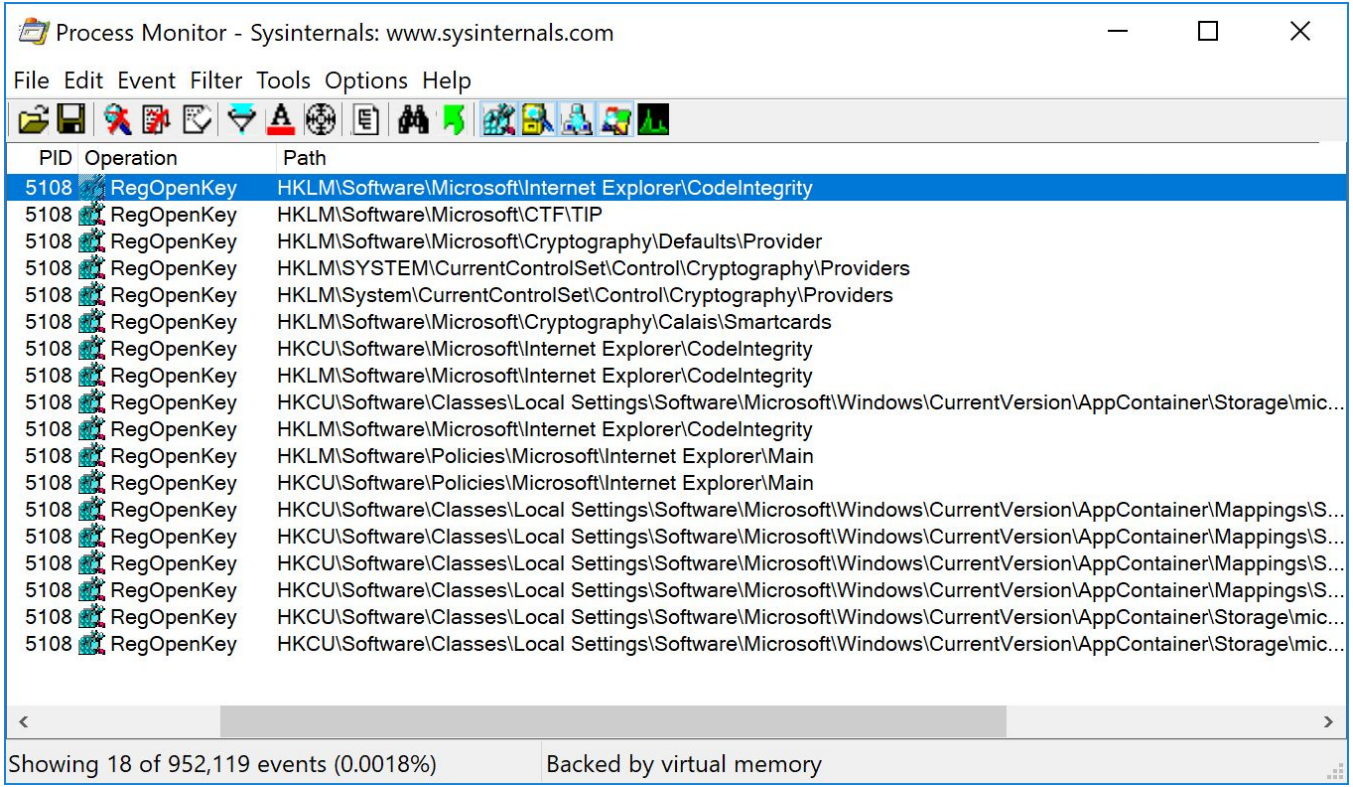

```
DynamicCode:
    BlockDynamicCode                : ON
    AllowThreadsToOptOut            : OFF
    Audit                           : OFF
    Override DynamicCode            : False
```

When is it enabled?

From Microsoft's blog post:

> For compatibility reasons, ACG is currently only enforced on 64-bit desktop devices with a primary GPU running a WDDM 2.2 driver (the driver model released with the Windows 10 Anniversary Update), or when software rendering is use. For experimental purposes, software rendering can be forced via Control Panel ->Internet Options -> "Advanced". Current Microsoft devices (Surface Book, Surface Pro 4, and Surface Studio) as well as a few other existing desktop systems with GPU drivers known to be compatible with ACG are opted into ACG enforcement. We intend to improve the coverage and accuracy of the ACG GPU opt-in list as we evaluate the telemetry and feedback from customers.

When is it enabled?



How effective is ACG?

Assumption: Attacker has a read/write primitive

- Data-only attacks
- Code reuse attacks
  - Do we need a ROP compiler?
- Code second-stage payloads in JavaScript
  - Need a way to call native-code functions from JavaScript and continue running script
  - Libraries already exist (pwn.js from Theori)

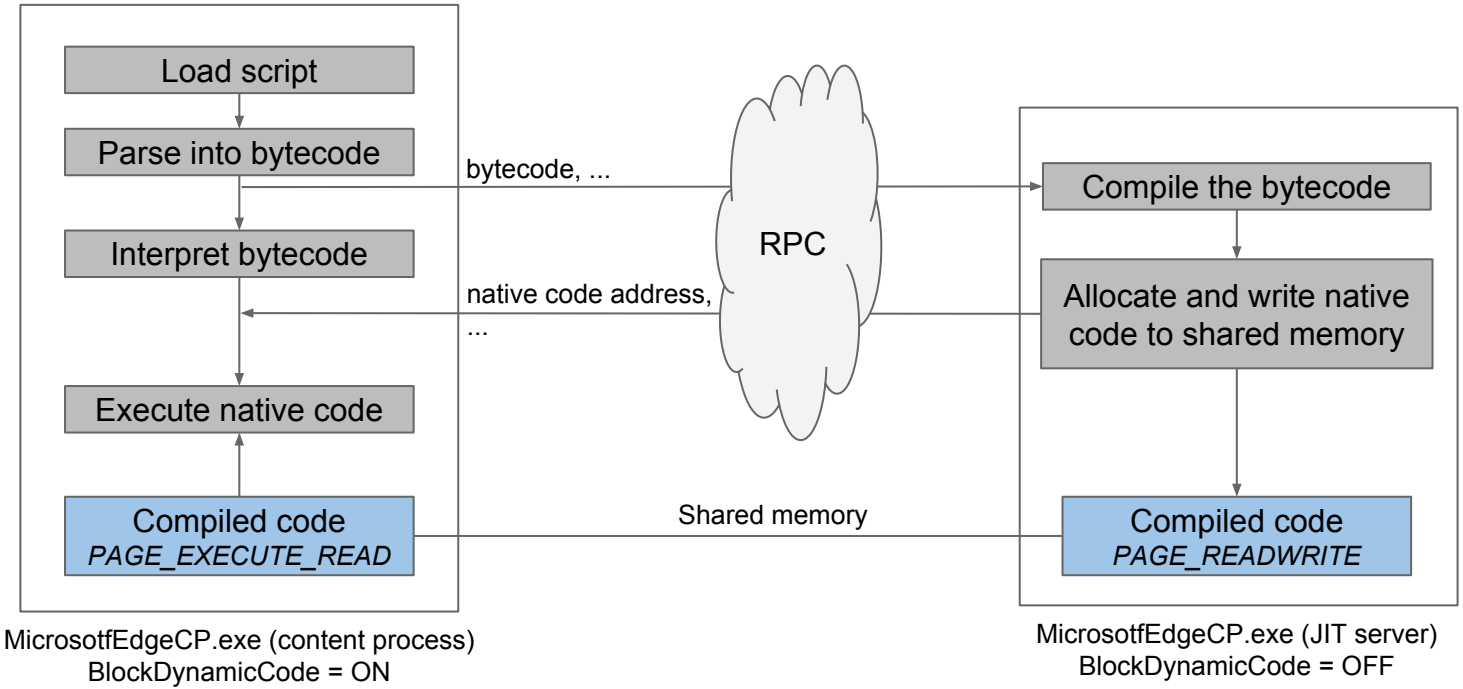
Mitigations that work together

- ACG, CIG, no CFG => ROP, privescs in JavaScript
- CFG, CIG, no ACG => Overwrite/allocate executable memory
- CFG, ACG, no CIG => Load a malicious .dll

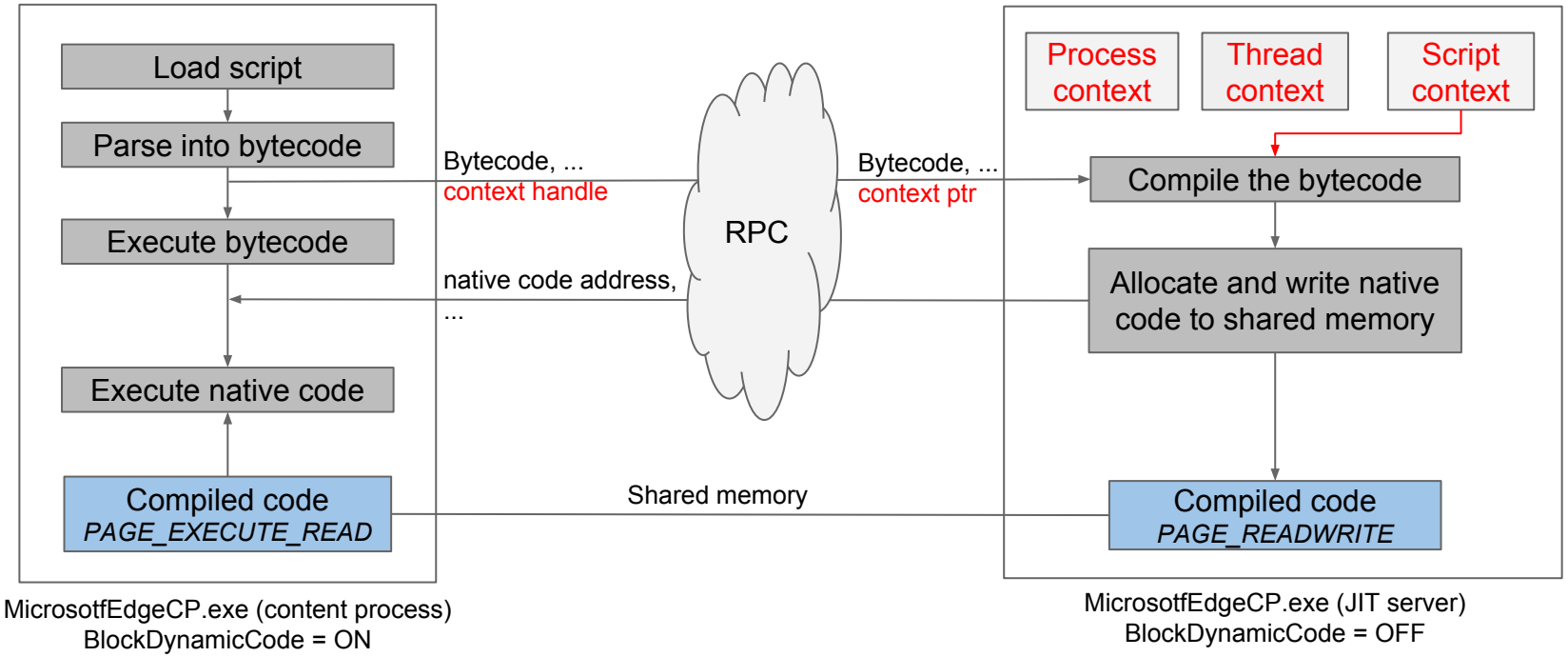
ACG Bypasses, prior work

- Abusing thread opt-out (no longer the case)
- Bypass using Warbird DRM framework (Alex Ionescu)

JIT server (simplified)



JIT server, maintaining state



Exposed methods / managing contexts

- (!) ConnectProcess - Connects a new Content Process and creates the corresponding Process Context
- (!) InitializeThreadContext - Creates a ServerThreadContext object on the server. Also pre-reserves memory for compiled code and JIT thunks.
- InitializeScriptContext - Creates a ServerThreadContext object on the server.
- CleanupThreadContext - Marks Thread context as closed, removes it from the Thread context dictionary and closes all associated ScriptContexts
- CloseScriptContex - Marks Script context as closed and removes it from the Script context dictionary
- CleanupScriptContex - Closes script context if not closed already and deletes the associated ServerScriptContext object
- Shutdown - Deletes closed context objects, deletes allocated pages and unregisters RPC server

Exposed methods / updating data in contexts

- UpdatePropertyRecordMap
- AddDOMFastPathHelper
- AddModuleRecordInfo
- SetWellKnownHostTypeId
- SetIsPRNGSeeded

Exposed methods / working with thunks

- Thunk == short trampoline that jumps to function implementation
  - Executable code
  - Every function gets one

- NewInterpreterThunkBlock - Allocates a new executable buffer and fills it with interpreter thunks.
- DecommitInterpreterBufferManager - Decommits all memory pages used for thunk allocations.
- IsInterpreterThunkAddr - Checks if address is in one of the interpreter thunk blocks

Exposed methods / working with compiled code

- (!) RemoteCodeGen
  - This is where the magic happens
  - Large structure as input/output
    - Bytecode
    - Type information, caches, inlinee information, addresses
- IsNativeAddr - checks if address is in one of the JIT blocks
- (!) FreeAllocation - Frees executable memory allocation made previously by the server and clears CFG targets

JIT phases (1/2)

- (!) Build Intermediate Representation (IR) from bytecode
- Function inlining
- Build flow graph
- Global optimizations
- Lower IR into machine-specific representation (not yet encoded)
- Encode large constants (security)
- Insert stack probes
- Register allocation

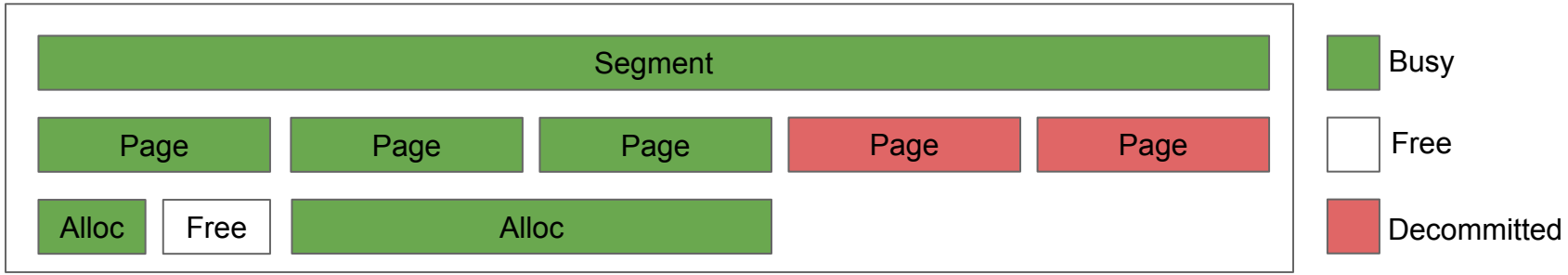
JIT phases (2/2)

- Peephole optimizations
- Layout
- Insert bailouts
- Insert NOPs at random points (security)
- Insert function prolog and epilog
- Final lower
- (!) Encoder
- Fixups on data allocated by JIT process

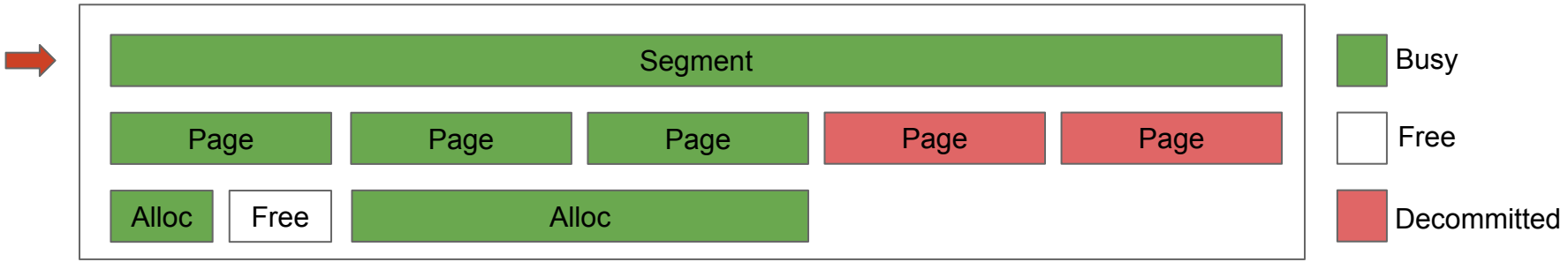
Encoder phase (Encoder.cpp)

- Prepares the buffer with compiled code
  - Encoded instructions
  - Jump tables for switch statements
- Allocates memory for executable code
- Copies the buffer

Allocating memory

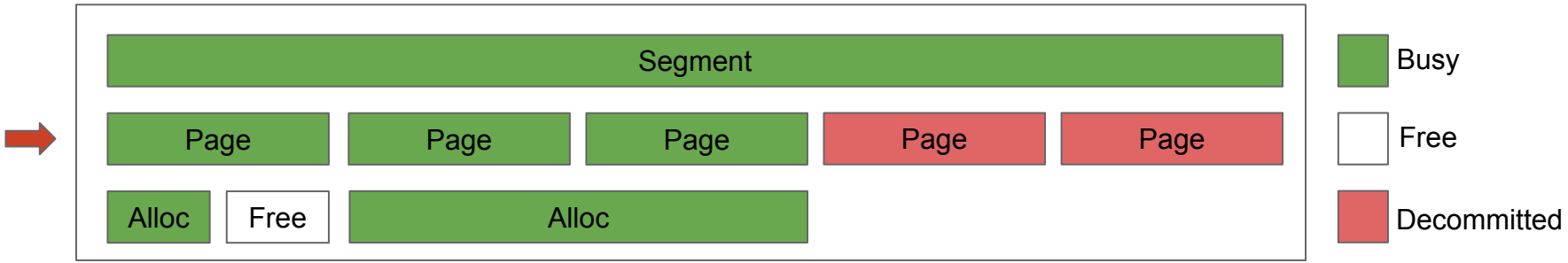


Allocating memory / Segments (SectionAllocWrapper.cpp)



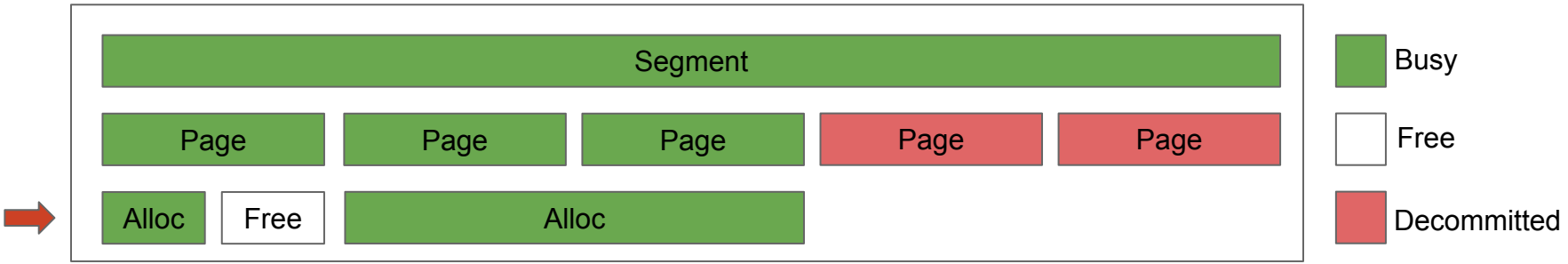
- Segment == Shared memory object (created via CreateFileMapping)
- Mapped into each process using MapViewOfFile2
  - PAGE_EXECUTE_READ for content process
  - PAGE_READWRITE for JIT process
- In JIT process unmapped immediately after writing

Allocating memory / Pages (PageAllocator.cpp)



- Pages start as decommitted -> committed using VirtualAllocEx when needed
- Each segment has 2 bit vectors for free pages and decommitted pages
- Once a page gets committed it gets filled with 0xCC (int 3)
- When sufficient number of pages is freed, pages start getting decommitted

Allocating memory / Allocations (CustomHeap.cpp)



- Large allocations (>pagesize) get the corresponding number of pages
- For smaller allocations, pages get divided into 128-byte blocks
  - Bitmap of free blocks inside a page
- Pages get put in buckets for allocations of size 128, 256, 512, 1024, 2048, 4096
- Metadata is not stored together with data, stored in Allocation objects on the server only
- Upon freeing, data is filled with 0xCC (int 3)

Issues

- CFG
  - Issues that rely on return address overwrite
  - Issues that don’t rely on return address overwrite
- ACG
  - Memory corruption issues in the JIT process
  - Logic issues in the JIT process

Controlling bytecode

- What can we do with bytecode?
- T. Dullien: “Exploitation and state machines”
  - Arbitrary read/write
  - Overwriting the stack (in Chakra e.g. OP_ArgOut_A)

Call instructions in the JIT code

- What happens when JIT code needs to call a function, e.g.

```
call chakra!helper_function
```

- JIT server needs to know address of DLLs in the Content Process
  - Q: How does it know?
  - A: Content Process tells it.

Checking module address in Content Process

- VirtualQueryEx on the first page and check:
  - Return value of VirtualQueryEx is correct
  - allocation base address is the same as provided by the client
  - memory type is MEM_IMAGE
  - memory state is MEM_COMMIT
  - region size is not smaller than 4096 bytes
- Get image headers and check:
  - number of sections is correct
  - number of symbols is correct
  - checksum in the header is correct
  - image size is correct
- Bypassable by modifying the header region of another module

Dangling CFG target

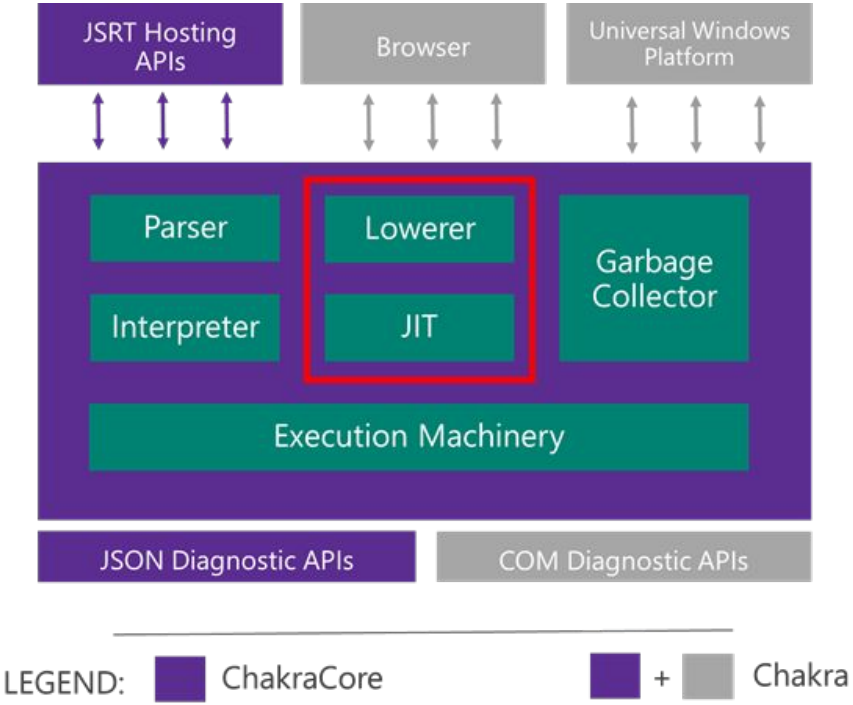
- From ServerFreeAllocation:

```
context->SetValidCallTargetForCFG((PVOID)codeAddress, false);
context->GetCodeGenAllocators()->emitBufferManager.FreeAllocation((void*)codeAddress);
```

- codeAddress inside allocation -> FreeAllocation() succeeds
  - But CFG target doesn’t get unset

- Possible to free allocation without clearing CFG flags

JIT server attack surface



Memory corruption issues

- Integer overflows (CVE-2017-8637)

```
offsetToInstructionCount = lastOffset + 2;
m_offsetToInstruction = JitAnewArrayZ(m_tempAlloc, IR::Instr *, offsetToInstructionCount);

m_saveLoopImplicitCallFlags = (IR::Opnd**)func->m_alloc->Alloc(sizeof(IR::Opnd*) * loopCount);
this->tempMap = (SymID*)m_tempAlloc->AllocZero(sizeof(SymID) * tempCount);
```

- Out-of-bound writes (CVE-2017-8659)

```
this->m_saveLoopImplicitCallFlags[num] = saveOpnd;
```

- Bytecode fuzzing produces crashes

Memory corruption issues

- Does it make sense to exploit another memory corruption bug?
- Pros:
  - Lots of them
  - ASLR already bypassed
- Cons:
  - CFG
  - Heap ASLR
  - Exploit stability

The trouble with handles

- JIT Server needs to be able to allocate memory in Content Process
  - JIT Server has a handle to Content Process
- Content Process needs to give its handle
  - Needs to call DuplicateHandle() first
- Content Process needs a handle to JIT server to call DuplicateHandle()
  - ...with PROCESS_DUP_HANDLE permissions

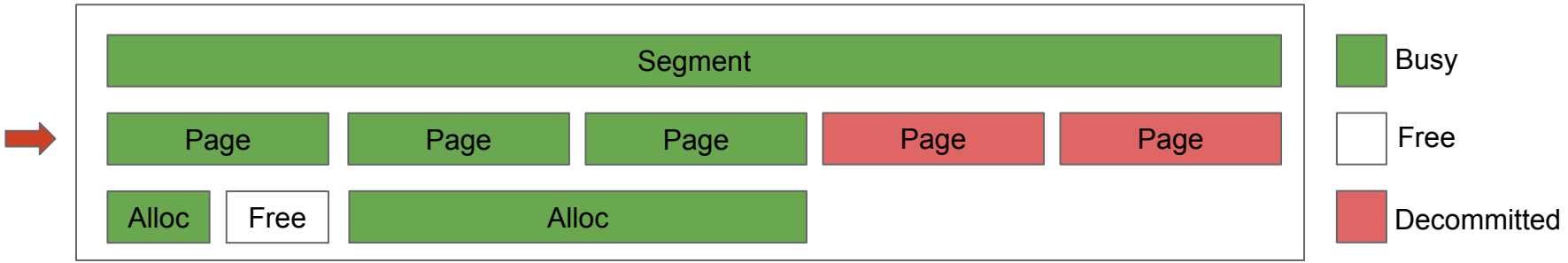
The trouble with handles

The trouble with handles

- The issue:

> **Warning** A process that has some of the access rights noted here can use them to gain other access rights. For example, if process A has a handle to process B with **PROCESS_DUP_HANDLE** access, it can duplicate the pseudo handle for process B. This creates a handle that has maximum access to process B. For more information on pseudo handles, see **GetCurrentProcess**.

Exploiting memory management



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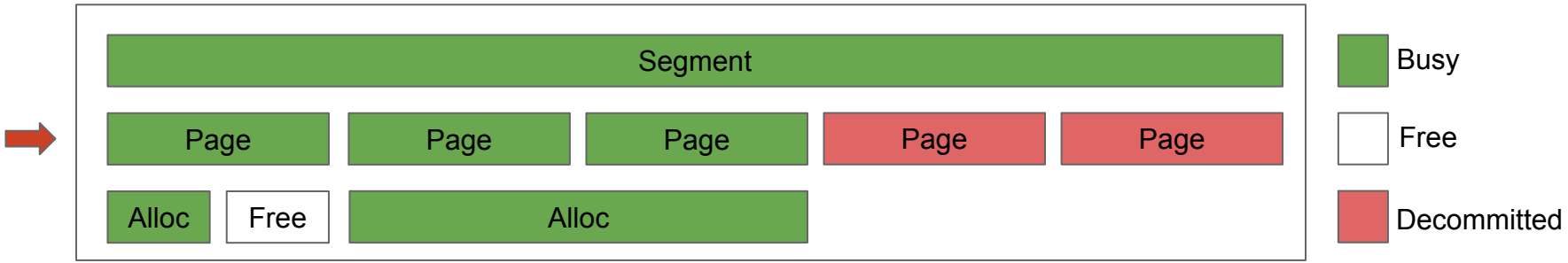

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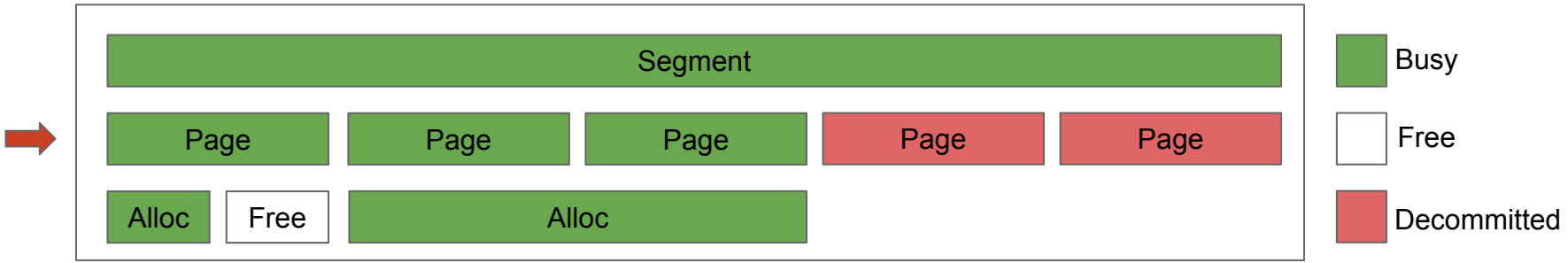
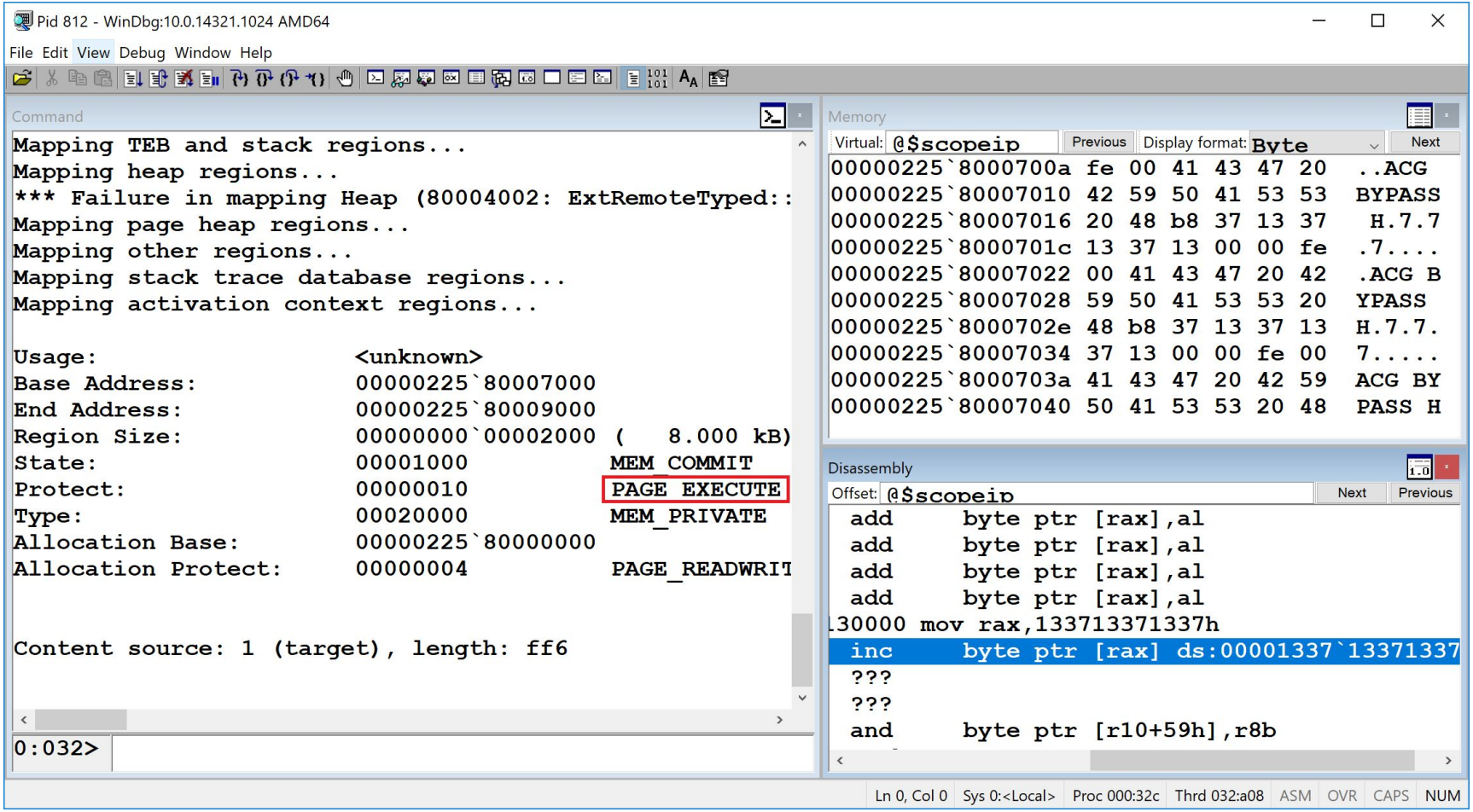


- Pages start as decommitted -> committed using VirtualAllocEx when needed
  - VirtualAllocEx called with flProtect = PAGE_EXECUTE_READ

Exploiting memory management

- Predict the address of next JIT allocation.
- Unmaps the shared memory with UnmapViewOfFile()
- Allocate same pages with PAGE_READWRITE
- Write payload
- Wait


Pid 812 - WinDbg:10.0.14321.1024 AMD64
File Edit View Debug Window Help
Command
Mapping TEB and stack regions...
Mapping heap regions...
*** Failure in mapping Heap (80004002: ExtRemoteTyped::
Mapping page heap regions...
Mapping other regions...
Mapping stack trace database regions...
Mapping activation context regions...
Usage: <unknown>
Base Address: 00000225`80007000
End Address: 00000225`80009000
Region Size: 00000000`00002000 (8.000 kB)
State: 00001000 MEM_COMMIT
Protect: 00000010 PAGE_EXECUTE
Type: 00020000 MEM_PRIVATE
Allocation Base: 00000225`80000000
Allocation Protect: 00000004 PAGE_READWRIT
Content source: 1 (target), length: ff6
0:032>
Memory
Virtual: @$scopeip
Previous
Display format: Byte
Next
00000225`8000700a fe 00 41 43 47 20 ..ACG
00000225`80007010 42 59 50 41 53 53 BYPASS
00000225`80007016 20 48 b8 37 13 37 H.7.7
00000225`8000701c 13 37 13 00 00 fe .7....
00000225`80007022 00 41 43 47 20 42 .ACG B
00000225`80007028 59 50 41 53 53 20 YPASS
00000225`8000702e 48 b8 37 13 37 13 H.7.7.
00000225`80007034 37 13 00 00 fe 00 7.....
00000225`8000703a 41 43 47 20 42 59 ACG BY
00000225`80007040 50 41 53 53 20 48 PASS H
Disassembly
Offset: @$scopeip
Next
Previous
add byte ptr [rax],al
add byte ptr [rax],al
add byte ptr [rax],al
add byte ptr [rax],al
130000 mov rax,133713371337h
inc byte ptr [rax] ds:00001337`13371337
???
???
and byte ptr [r10+59h],r8b
Ln 0, Col 0
Sys 0:<Local>
Proc 000:32c
Thrd 032:a08
ASM
OVR
CAPS
NUM

Enabling ACG

- Relies on setting the dynamic code policy
- Enabled by SetProcessMitigationPolicy()
- In Edge:

```
00 KERNELBASE!SetProcessMitigationPolicy
01 MicrosoftEdgeCP!SetProcessDynamicCodePolicy+0xc0
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03 MicrosoftEdgeCP!main+0xfe
04 MicrosoftEdgeCP!_main+0xa6
05 MicrosoftEdgeCP!WinMainCRTStartup+0x1b3
06 KERNEL32!BaseThreadInitThunk+0x14
07 ntdll!RtlUserThreadStart+0x21
```

Disabling ACG

- ACG gets enabled too early for the Content Process to disable it for itself
- But…
  - James Forshaw: Did you know one Content Process can open another?
  - Me: Nah, I tried that, didn’t work
  - [try again]
  - Me: Oh, snap...

- One MicrosoftEdgeCP.exe can disable ACG in another MicrosoftEdgeCP.exe
  - Both processes need to be in the same App Container
  - True for Internet sites
  - The race is easily winnable

Conclusion

- ACG needs strong CFG to be effective
- Attacker’s perspective: Business as usual (mostly)
  - Abundant CFG bypasses + calling native functions with JavaScript
  - Implementation issues, large attack surface of the JIT server
- What can Microsoft do
  - Make CFG useful (RFG? CET?)
  - Stronger Content Process <-> JIT Process boundary