Windows

Toward mitigating arbitrary native code execution in Windows 10

Matt Miller, Microsoft Security Response Center (MSRC) @epakskape

May, 2017

Microsoft

Agenda

How we think about mitigating software vulnerabilities

Our progress toward mitigating native code execution

Impact, lessons learned, and future plans

Imagine you could change the laws of physics

Vertical engineering is a super power when it comes to defense

Vertical Engineering

Change or enable apps to better protect themselves

Microsoft Azure

Change the cloud platform to protect online services & data

Windows 10

Change the OS to protect apps, data, & devices

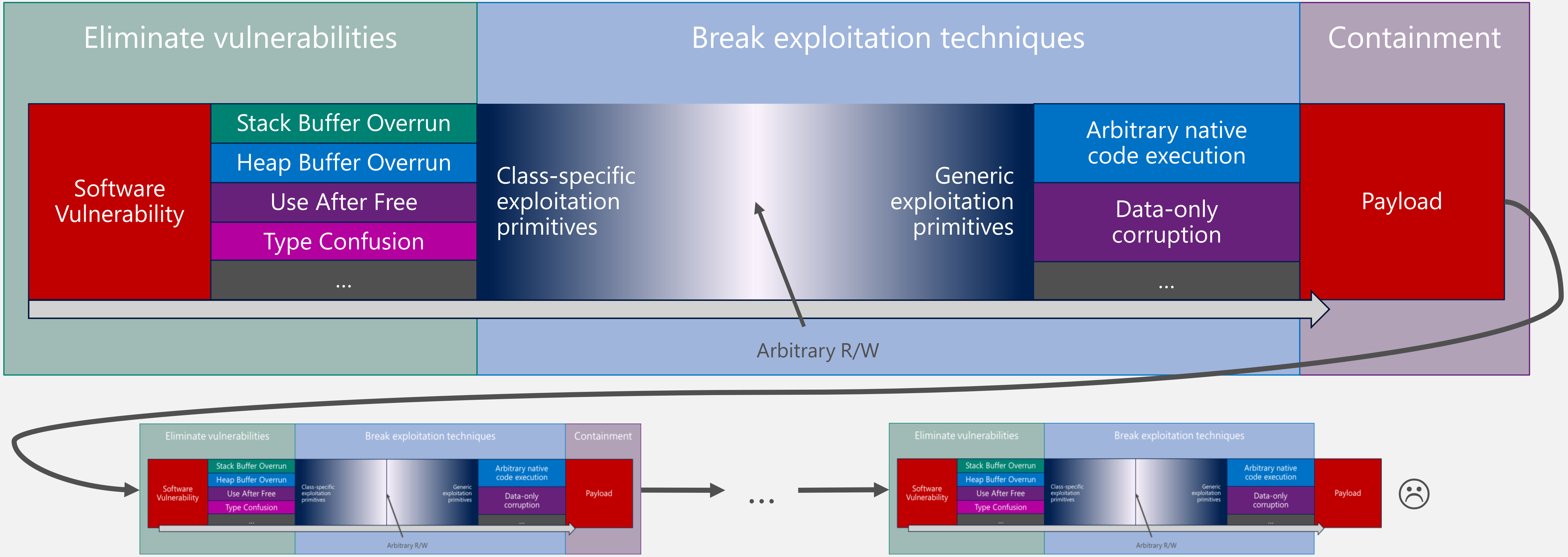
Visual Studio

Change the compiler to produce safer code

Collaborate with hardware partners to improve the foundation

How we think about mitigating software vulnerabilities

Attackers transform software vulnerabilities into tools for delivering a payload to a target device



Attackers typically need to elevate privileges

This means applying the same defenses to privileged attack surfaces

At some point, we lose containment as a defense

This leaves eliminating vulnerabilities & breaking techniques

Layered, data-driven software defense in Windows 10

Our Strategy	Make it difficult & costly to find, exploit, and leverage software vulnerabilities
Our Tactics	Eliminate entire classes of vulnerabilities
	Break exploitation techniques
	Contain damage & prevent persistence
	Limit the window of opportunity to exploit

Today, we'll be focusing on one aspect of breaking exploitation techniques

Chokepoints for breaking exploitation techniques

All exploits rely on combining various primitives to enable the delivery of a payload

Break exploitation techniques

Class-specific exploitation primitives

Weak mitigations

Generic exploitation primitives

Arbitrary native code execution

Data-only corruption

...

Chokepoint #2

Break generic primitives with the assumption that an attacker has arbitrary R/W.

Goal: make it difficult or impossible to deliver a payload independent of the type of vulnerability.

Chokepoint #1

Break class-specific techniques for transforming a vulnerability into generic primitives.

Goal: make it difficult or impossible to exploit certain types of vulnerabilities.

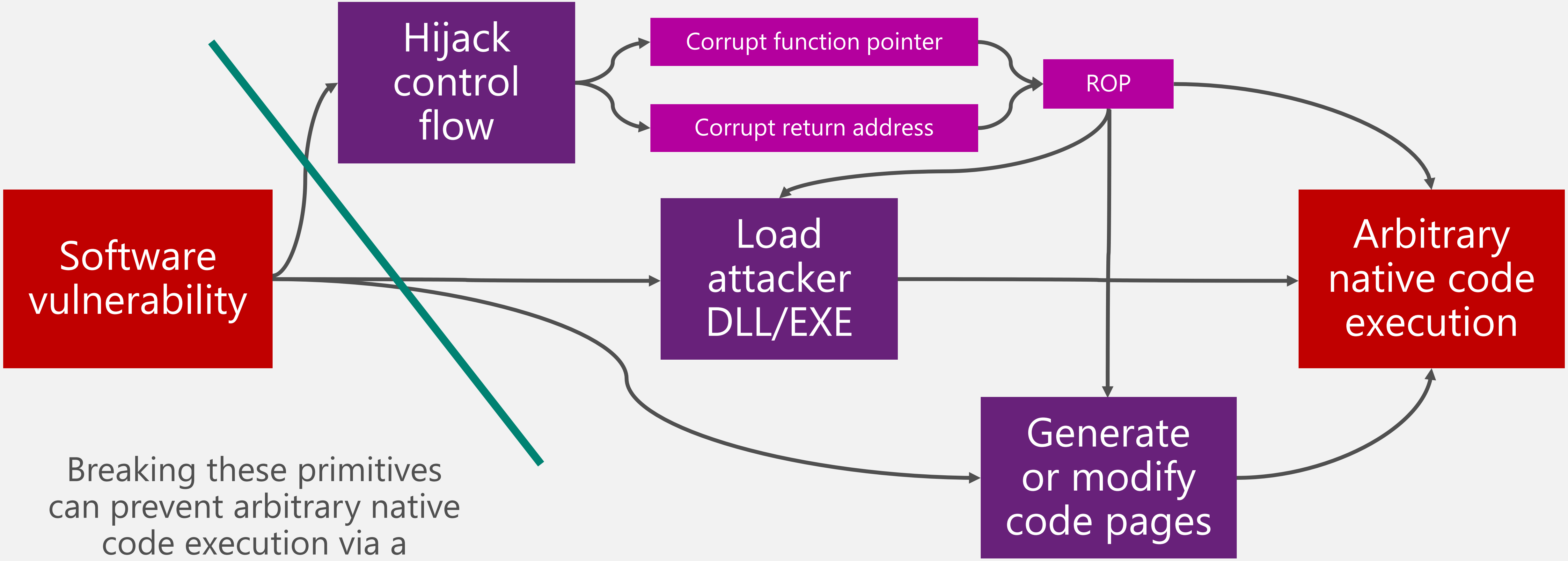
Arbitrary native code execution

- Generic, vulnerability-independent primitive
- Universal & flexible way to execute a payload
- Ubiquitously relied upon by exploits

Good candidate for mitigations ☺

The paths to arbitrary native code execution

There are a finite number of ways to transform a vulnerability into arbitrary native code execution



Breaking these primitives can prevent arbitrary native code execution via a vulnerability

Mitigating arbitrary native code execution

Defining our threat model & assumptions

It is critical to define the key aspects of the threat model that we want to defend against

A vulnerability exists	There is a memory corruption vulnerability that could potentially be exploited
Interactive runtime is present	The attacker is able to leverage an interactive runtime (such as a script engine) in conjunction with their exploit
Arbitrary R/W at arbitrary times	The attacker can read/write arbitrary memory locations, with controlled data, at arbitrary points in time
Address space layout is known	The attacker knows where all discoverable memory regions are located – traditional ASLR is a non-factor

This threat model sets a very high bar, but it is grounded by real-world data & expectations

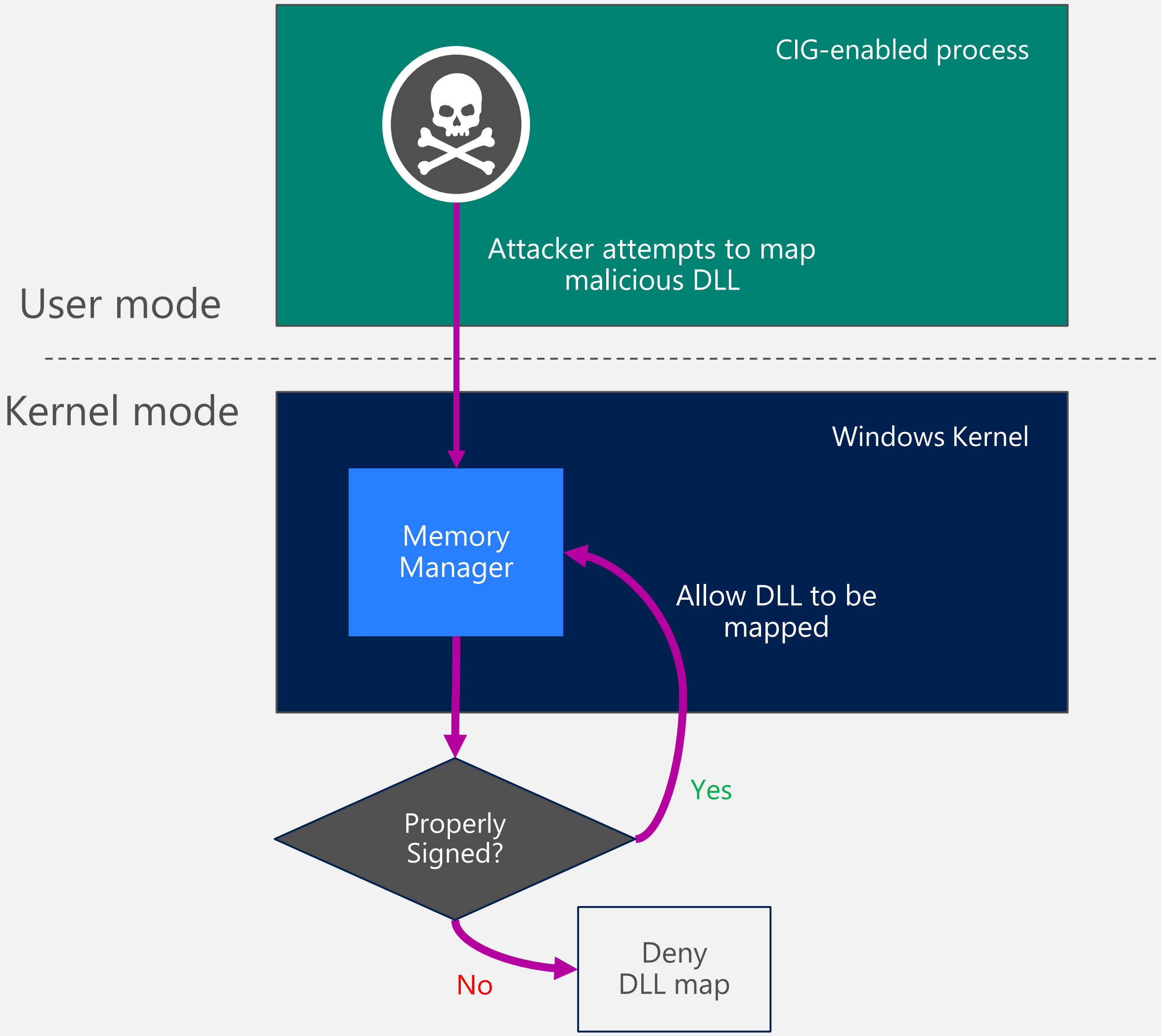
Technologies for mitigating code execution

Prevent arbitrary code generation	**Code Integrity Guard** Images must be signed and load from valid places	**Arbitrary Code Guard** Prevent dynamic code generation, modification, and execution
Prevent control-flow hijacking	**Control Flow Guard** Enforce control flow integrity on indirect function calls	**???** Enforce control flow integrity on function returns

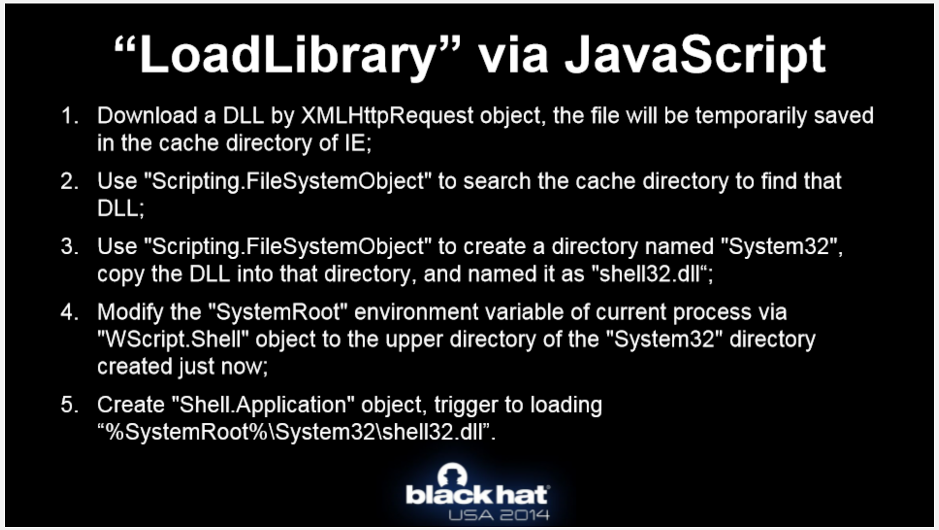
- ✓ Only valid, signed code pages can be mapped by the app
- ✓ Code pages are immutable and cannot be modified by the app
- ✓ Code execution stays "on the rails" per the control-flow integrity policy

Code Integrity Guard (CIG)

CIG leverages code signing restrictions to prevent attacker DLLs from loading



Example of such an attack [provided by Yang Yu](#) @ Black Hat USA 2014



“LoadLibrary” via JavaScript

1. Download a DLL by XMLHttpRequest object, the file will be temporarily saved in the cache directory of IE;
2. Use "Scripting.FileSystemObject" to search the cache directory to find that DLL;
3. Use "Scripting.FileSystemObject" to create a directory named "System32", copy the DLL into that directory, and named it as "shell32.dll";
4. Modify the "SystemRoot" environment variable of current process via "WScript.Shell" object to the upper directory of the "System32" directory created just now;
5. Create "Shell.Application" object, trigger to loading “%SystemRoot%\System32\shell32.dll”.

Code Integrity Policies
Only allow Microsoft-signed DLLs
Only allow Microsoft, Store, or WHQL signed DLLs
Configurable via Device Guard policy

Considerations for enabling CIG for an app

3rd party improperly signed binaries that need to be loaded

- Trade-off between security and functionality
- Microsoft Edge will currently disable CIG when 3rd party IMEs are installed

Arbitrary Code Guard (ACG)

Exploits often rely on creating or modifying executable pages to execute their payload

ACG enables two kernel-enforced W^X policies

✓ Code is immutable

✓ Data cannot become code

Code Integrity Guard (CIG)

✓ Only properly signed code pages can be mapped

The following will fail with ERROR_DYNAMIC_CODE_BLOCKED
`VirtualProtect(codePage, …, PAGE_EXECUTE_READWRITE)`
`VirtualProtect(codePage, …, PAGE_READWRITE)`
`VirtualAlloc(…, PAGE_EXECUTE*)`
`VirtualProtect(dataPage, …, PAGE_EXECUTE*)`
`MapViewOfFile(hPagefileSection, FILE_MAP_EXECUTE, …)`
`WriteProcessMemory(codePage, …)`
…

ACG + CIG ensure the integrity of code pages

Considerations for enabling ACG for an app

Just-in-Time (JIT) compilation no longer works in-proc	• JITs need to move out-of-process or be disabled • Microsoft Edge has moved JITs out-of-process in Windows 10 1703
3rd party binaries may be incompatible	• Binaries must enable /DYNAMICBASE, cannot have RWX sections, and must not merge their import table into a code section • BinSkim has checks for this, see https://github.com/Microsoft/binskim • Microsoft Edge will currently disable ACG when incompatible graphics drivers may be present
Does not prevent code injection from privileged processes	• Privileged code running outside of the app can still inject dynamic code into an ACG-enabled process

Control Flow Guard (CFG)

Exploits have typically relied on hijacking control-flow through an indirect call

Example control-flow hijack via indirect call to a ROP gadget[1]

```
/* Corrupt sound object vtable ptr */
while (1)
{
        if (this.s[index][j] == 0x00010c00 && this.s[index][j+0x09] == 0x1234)
        {
                soundobjref = this.s[index][j+0x0A];
                dec = soundobjref-cvaddr-1;
                this.s[index][dec/4-2] = cvaddr+2*4+4*4;
                break;
        }

        j++;
}
/* Run Payload */
this.sound.toString();
```

Transfers control to a stack pivot ROP gadget

With CFG in place, traditional ROP gadgets and other invalid functions cannot be called indirectly

CFG implements **coarse-grained control-flow integrity** for indirect calls

Compile time

```
void Foo(...) {
   // SomeFunc is address-taken
   // and may be called indirectly
   Object->FuncPtr = SomeFunc;
}
```

Metadata is automatically added to the image which identifies functions that may be called indirectly

```
void Bar(...) {
   // Compiler-inserted check to
   // verify call target is valid
   _guard_check_icall(Object->FuncPtr);
   Object->FuncPtr(xyz);
}
```

A lightweight check is inserted prior to indirect calls which will verify that the call target is valid at runtime

Runtime

Image Load	•Update valid call target data with metadata from PE image
Process Start	•Map valid call target data
Indirect Call	•Perform O(1) validity check •Terminate process if invalid target

[1] https://github.com/rapid7/metasploit-framework/blob/abd76c50000e75bcac0616b96cd8583e1df3927f/external/source/exploits/CVE-2014-0322/AsXploit.as

Control Flow Guard Bypasses & Enhancements

Like all mitigations, CFG has by design limitations that place constraints on its overall effectiveness

- ✓ Return addresses are not protected
- ✓ Valid functions can be called out of context
- ✓ "Fail-open" design for compatibility

Since shipping CFG, researchers have identified bypasses and additional enhancements have been made

Bypass	Status
Non-enlightened Just-in-Time (JIT) compilers	Mitigated in latest version of Edge on Windows 10 (Chakra, Adobe Flash, and WARP)
Multiple non-instrumented indirect calls reported to our Mitigation Bypass Bounty	Mitigated in latest version of Edge on Windows 10
Calling sensitive APIs out of context	NtContinue/longjmp – mitigated for all CFG enabled apps on Windows 10
	VirtualProtect/VirtualAlloc – mitigated in latest version of Microsoft Edge on Windows 10
	LoadLibrary – mitigated in latest version of Microsoft Edge on Windows 10 via CIG
	WinExec – mitigated in Edge on Windows 10 anniversary edition via child process policy
	All exports – mitigated in Edge on Windows 10 1703 via export suppression
Corrupting mutable read-only memory	Known limitation that we are exploring solutions for

What about return addresses?

With CFG in place, we have observed attackers shifting to target return addresses

Protecting return addresses is a decades old (and very difficult) problem

- ✓ Stack cookies (/GS, etc)
  - Only mitigates stack buffer overruns
- ✓ Shadow/split stack solutions
  - E.g. SafeStack (http://clang.llvm.org/docs/SafeStack.html)
- ✓ Fine-grained CFI solutions
  - E.g. RAP (https://www.grsecurity.net/rap_announce.php)

Why have none of the generic solutions achieved mainstream adoption yet?

Because software engineering is hard ☺

Protecting return addresses on Windows means satisfying many engineering requirements

Security	Must be robust against our threat model
Performance	Cost must be within reason and proportional to value
Compatibility	Don't break legacy apps
Interoperability	Binary compatibility with previous *and* future versions of Windows
ABI compliant	We can't rebuild the world
Agility	Don't paint ourselves into a corner
Developer friction	Cost for developers to enable should be minimal (ideally zero)

...and satisfying all of these requirements is *very* hard ☺

Return address protection

We have worked with Intel on designing a hardware-assisted solution for return address protection

- ✓ Control-flow Enforcement Technology (CET)
  - Indirect branch tracking via ENDBRANCH
  - Return address protection via a shadow stack
- ✓ Hardware-assists for helping to mitigate control-flow hijacking & ROP
- ✓ Robust against our threat model

Preview specification:

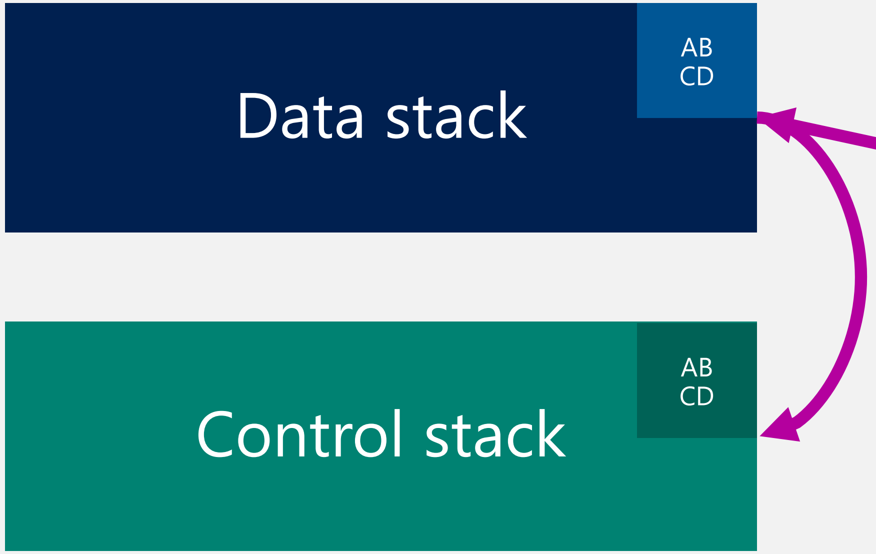
https://software.intel.com/sites/default/files/managed/4d/2a/control-flow-enforcement-technology-preview.pdf

Our red team also came up with a clever solution that works on existing x86_64 hardware

Return Flow Guard (RFG)

Return Flow Guard (RFG)

RFG is an ABI-compliant shadow stack design that leverages x86_64 segmentation to hide the shadow stack




```
VOID Function()
{
    wprintf(L"…\n");
    return;
}
```

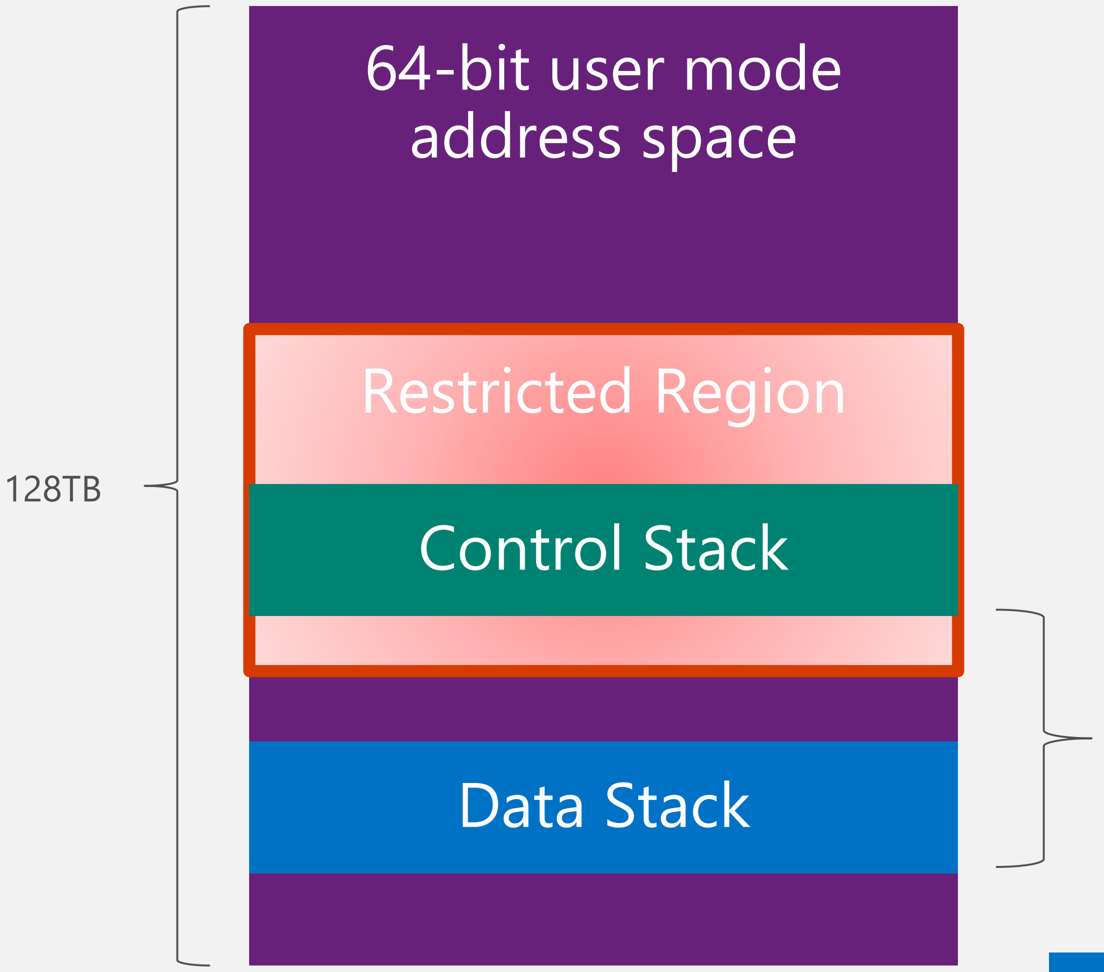
AB CD = AB CD ?

On function entry, a copy of the return address is stored in the control stack

On function exit, the return address in both stacks is compared

If they mismatch, terminate the process

RFG key design concepts



Per-function instrumentation is materialized at page-in

Prologue (9 bytes)

```
488b0424         mov      rax,qword ptr [rsp]
6448890424       mov      qword ptr fs:[rsp],rax
```

Epilogue (15 bytes)

```
644c8b1c24       mov      r11,qword ptr fs:[rsp]
4c3b1c24         cmp      r11,qword ptr [rsp]
0f8518a00300     jne      DLL!__guard_ss_verify_failure
```

FS segment base set to displacement between control & data stack

Thread->UserFsBase = ControlStack.BaseAddress – DataStack.BaseAddress

Context switch

```
mov     eax, ThUserFsBase[rsi]  ; load the bottom of the control stack delta FS base address
mov     edx, ThUserFsBase + 4[rsi] ; load the top of the control stack delta FS base address
mov     ecx, MSR_FS_BASE        ; get the FS base MSR number
wrmsr                           ; write the control stack delta FS base address
```

No pointers to a control stack exist in user mode memory

RFG appeared to meet all of our requirements

✖	**Security**	Must be robust against our threat model
✓	**Performance**	Cost must be within reason and proportional to value
✓	**Compatibility**	Don't break legacy apps
✓	**Interoperability**	Binary compatibility with previous *and* future versions of Windows
✓	**ABI compliant**	We can't rebuild the world
✓	**Agility**	Don't paint ourselves into a corner
✓	**Developer friction**	Cost for developers to enable should be minimal (ideally zero)

But there was just one big problem…

Our red team found a critical weakness

Using real vulnerabilities to evaluate RFG

Array.prototype.slice() Type Confusion

Takes a JavaScriptArray as input, returns a newly created JavaScriptArray

```
var fruits = ['Banana', 'Orange', 'Lemon', 'Apple', 'Mango'];
var citrus = fruits.slice(1, 3);

// fruits contains ['Banana', 'Orange', 'Lemon', 'Apple', 'Mango']
// citrus contains ['Orange','Lemon']
```

MS16-084	Scripting Engine Memory Corruption Vulnerability	CVE-2016-3260	Jordan Rabet of Microsoft Offensive Security Research Team

https://github.com/Microsoft/ChakraCore/commit/17f3d4a4852dcc9e48de7091685b1862afb9f307

Exploit Sequence

- Create a NativeFloatArray fake_obj_arr which contains a fake object
- Use CVE-2016-3260 to leak its address
- Use CVE-2016-3260 to create a JavaScript variable fake_obj pointing to fake_obj_arr + data_offset
- …and a few other steps we won't be talking about today ☺

```
// build a fake dataview object
// could do this with a typedbuffer but would need to have the vtable address probably
fake_object_arr[0] = hex2float(0) // vtable
fake_object_arr[1] = hex2float(fake_type_addr) // type
fake_object_arr[2] = hex2float(0) // auxSlots
fake_object_arr[3] = hex2float(0) // objectArray / flags
fake_object_arr[4] = hex2float(0xffffffff) // length
fake_object_arr[5] = hex2float(locate_object(real_ab)) // arrayBuffer
fake_object_arr[6] = hex2float(0) // byteOffset
fake_object_arr[7] = hex2float(0xdeadbabedad) // buffer pointer
// create fake type for dataview
fake_object_arr[fake_type_offset] = hex2float(56) // TypeIds_DataView
fake_object_arr[fake_type_offset + 1] = hex2float(fake_object_start_addr) // javascriptLibrary : needs to be valid ptr

var fake_dv = create_offseted_object(fake_object_arr, arr_inlineslots_offset)
```

Exploit was used as a platform to confirm a design-level bypass for RFG

Sticking to our threat model

The attack against RFG violated the assumptions of our threat model

- ✓ Accepting a weaker threat model would mean significant drop in ROI
- ✓ Long-term impact on cost to exploit would not be high enough to warrant long-term cost of feature
- ✓ Red team was key to vetting the solution
- ✓ @zer0mem also reported some interesting attacks ☺

RFG remains a research project; CET not affected

- ✓ Reminder: Microsoft has an ongoing $100,000 USD bounty for defensive ideas ☺
- ✓ https://technet.microsoft.com/en-us/security/dn425049.aspx
- ✓ https://blogs.technet.microsoft.com/srd/2015/09/08/what-makes-a-good-microsoft-defense-bounty-submission/

Windows 10 1703 supports ACG, CIG, and CFG – RFG is not supported

Enabling code execution mitigations

Windows 10 provides multiple ways to enable mitigations for an app

Opt-in method	Details	Precedence
Runtime API	See `SetProcessMitigationPolicy`	4
EXE flag	Mitigation-specific flag in PE headers	3
Process creation attribute	See `UpdateProcThreadAttribute` with `PROC_THREAD_ATTRIBUTE_MITIGATION_POLICY`	2
Image File Execution Option (IFEO)	Set `MitigationOptions` (REG_BINARY) IFEO for an EXE Same bits as process creation attribute	1

Mitigation	Relevant policies	Runtime API	EXE bit	Process creation attribute	IFEO
CIG	`ProcessSignaturePolicy`	Yes	No	Yes	Yes
ACG	`ProcessDynamicCodePolicy`	Yes	No	Yes	Yes
CFG	`ProcessControlFlowGuardPolicy`	No	Yes (/guard:cf)	Yes	Yes
No Child Process	CHILD_PROCESS_POLICY process creation attribute	No	No	Yes	No

See also: https://docs.microsoft.com/en-us/windows/threat-protection/overview-of-threat-mitigations-in-windows-10

Checking if mitigations are enabled

Handy PowerShell cmdlets can be used to see what mitigations are enabled

Administrator: Windows PowerShell

```
Windows PowerShell
Copyright (C) 2016 Microsoft Corporation. All rights reserved.

PS C:\WINDOWS\system32> Install-Module -Name ProcessMitigations
```

Administrator: Windows PowerShell

```
PS C:\WINDOWS\system32> Get-ProcessMitigation -Name vmwp.exe -RunningProcess

ProcessName: vmwp
Source     : Running Process
Id         : 2836

DEP:
    Enable                          : ON
    Disable ATL                     : OFF

ASLR:
    BottomUp                        : ON
    ForceRelocate                   : ON
    HighEntropy                     : ON
    DisallowStripped                : OFF

StrictHandle:
    RaiseExceptionOnInvalid         : ON
    HandleExceptionsPermanently     : ON

System Call:
    DisallowWin32kSysCalls          : ON

ExtensionPoint:
    DisableExtensionPoints          : ON

DynamicCode:
    ProhibitDynamicCode             : ON
    AllowThreadOptOut               : OFF
    AllowRemoteDowngrade            : OFF

CFG:
    EnableCFG                       : ON
    EnableExportSuppression         : OFF
    StrictMode                      : ON

BinarySignature:
    MicrosoftSignedOnly             : ON
    StoreSignedOnly                 : OFF
    MitigationOptIn                 : OFF

FontDisable:
    DisableNonSystemFonts           : ON
    AuditNonSystemFontLoading       : OFF

ImageLoad:
    NoRemoteImages                  : ON
    NoLowMandatoryLabelImages       : ON
    PreferSystem32Images            : ON
```

Protected apps in Windows 10 1703

	Microsoft Edge	Hyper-V VMWP
ACG	✓	✓
CIG	✓	✓
CFG	✓	✓
No Child Process	✓	✓

- For Microsoft Edge, ACG and CIG are disabled in the presence of certain 3rd party extensions (e.g. IMEs, legacy graphics drivers). ACG is currently enabled only on 64-bit.
- For Hyper-V VMWP, the no child process mitigation is disabled when certain features are used (vTPM)

What about the Windows kernel?

Windows 10 leverages Hyper-V Virtualization Based Security (VBS) to enable CIG, ACG, and CFG for the Windows kernel

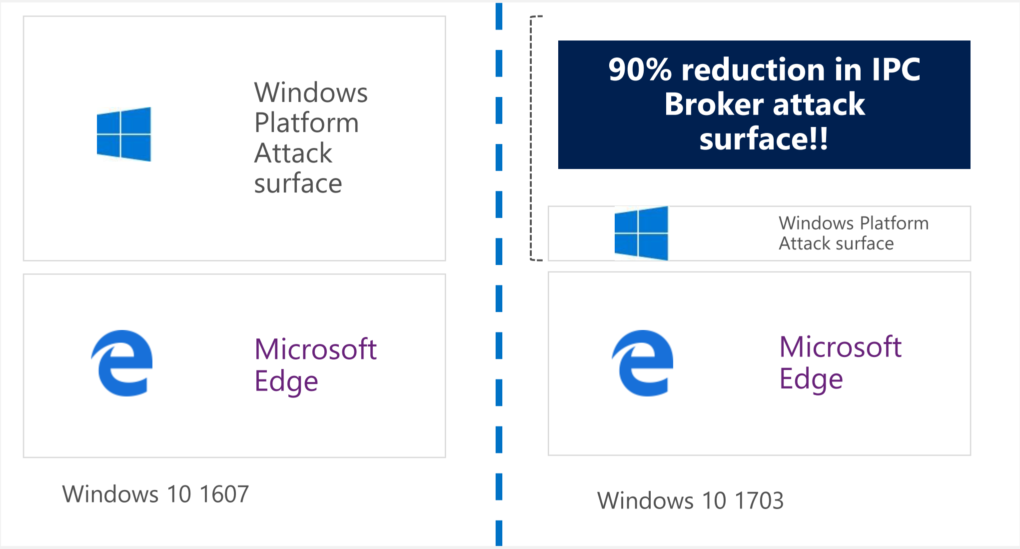
Kernel Mode		Windows 10 1703
	ACG	✓ Enabled with Hypervisor-Enforced Code Integrity (HVCI) via Device Guard
	CIG	
	CFG	

Conclusion & next steps

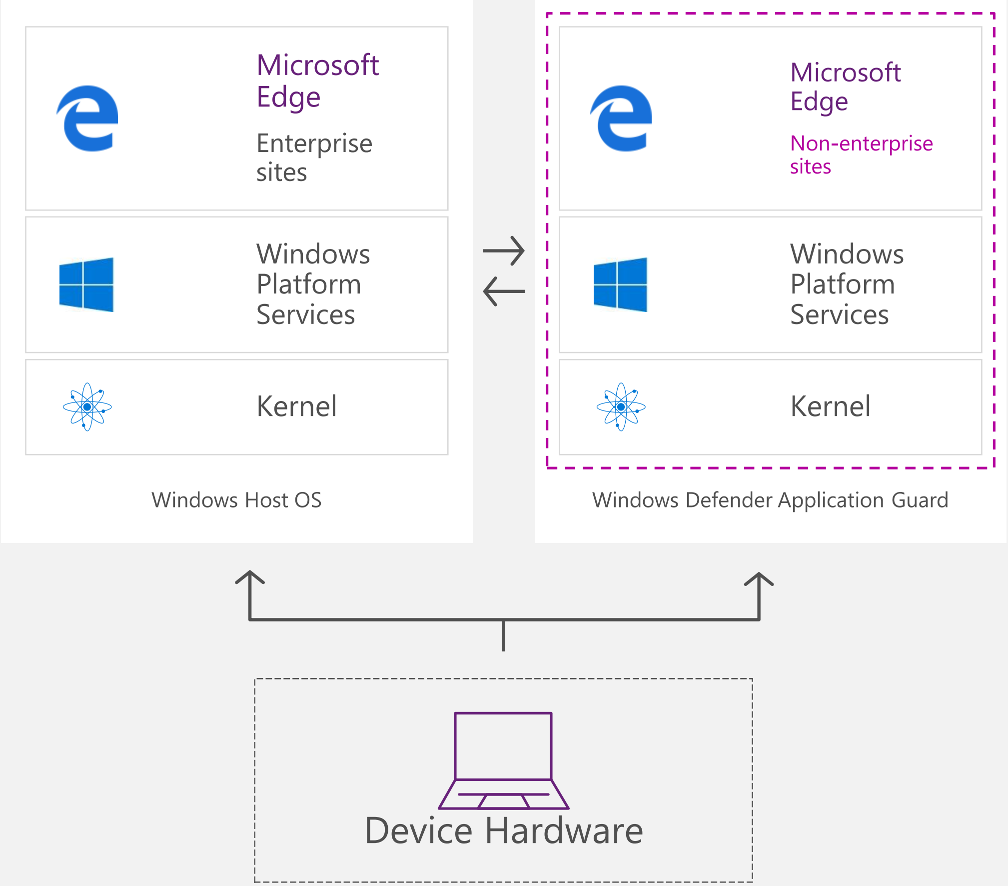
It's not RCE mitigations *or* sandboxing – it's both

We are continuing to invest in improved isolation technologies as part of our layered strategy

Improved software isolation (Microsoft Edge AppContainer Profile)



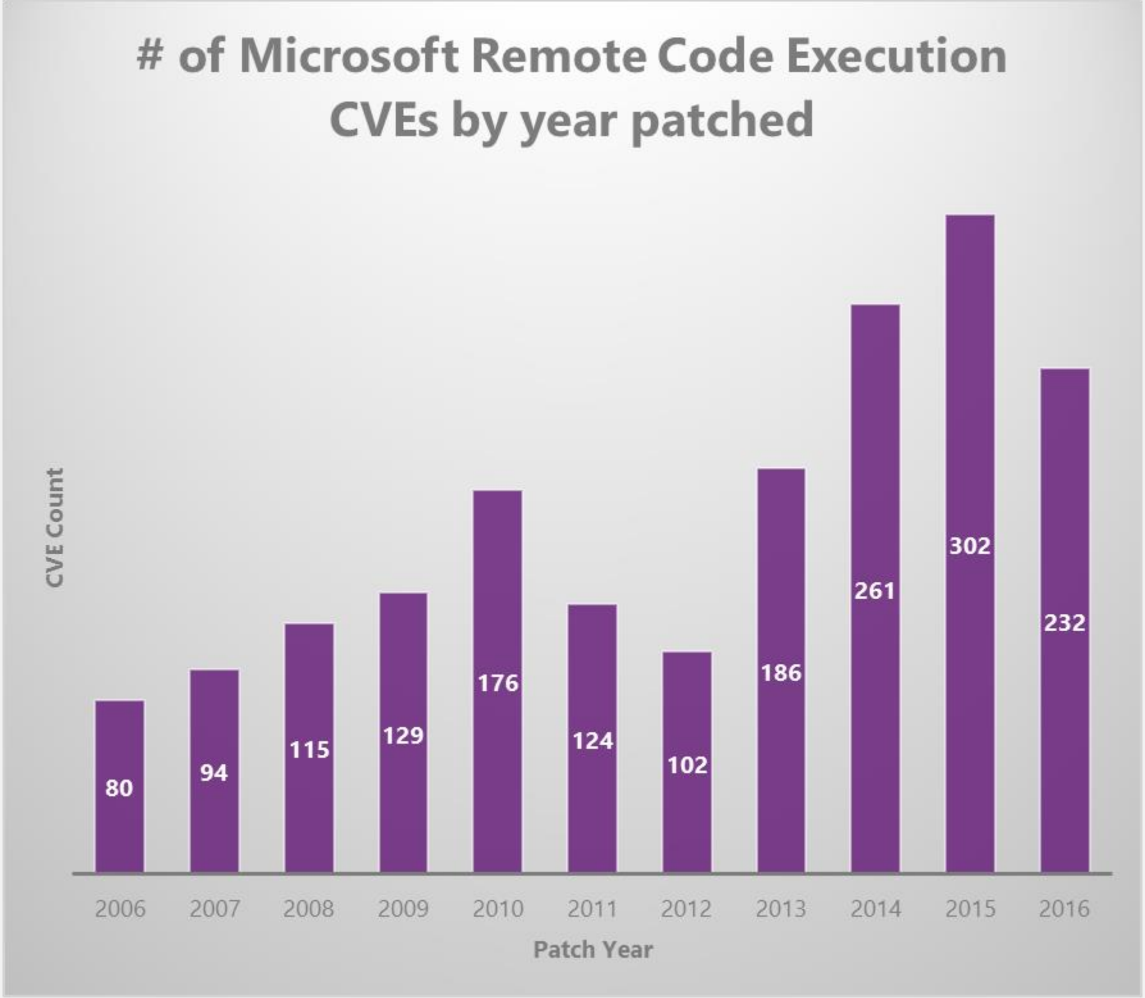
Virtualized Isolation (Application Guard)

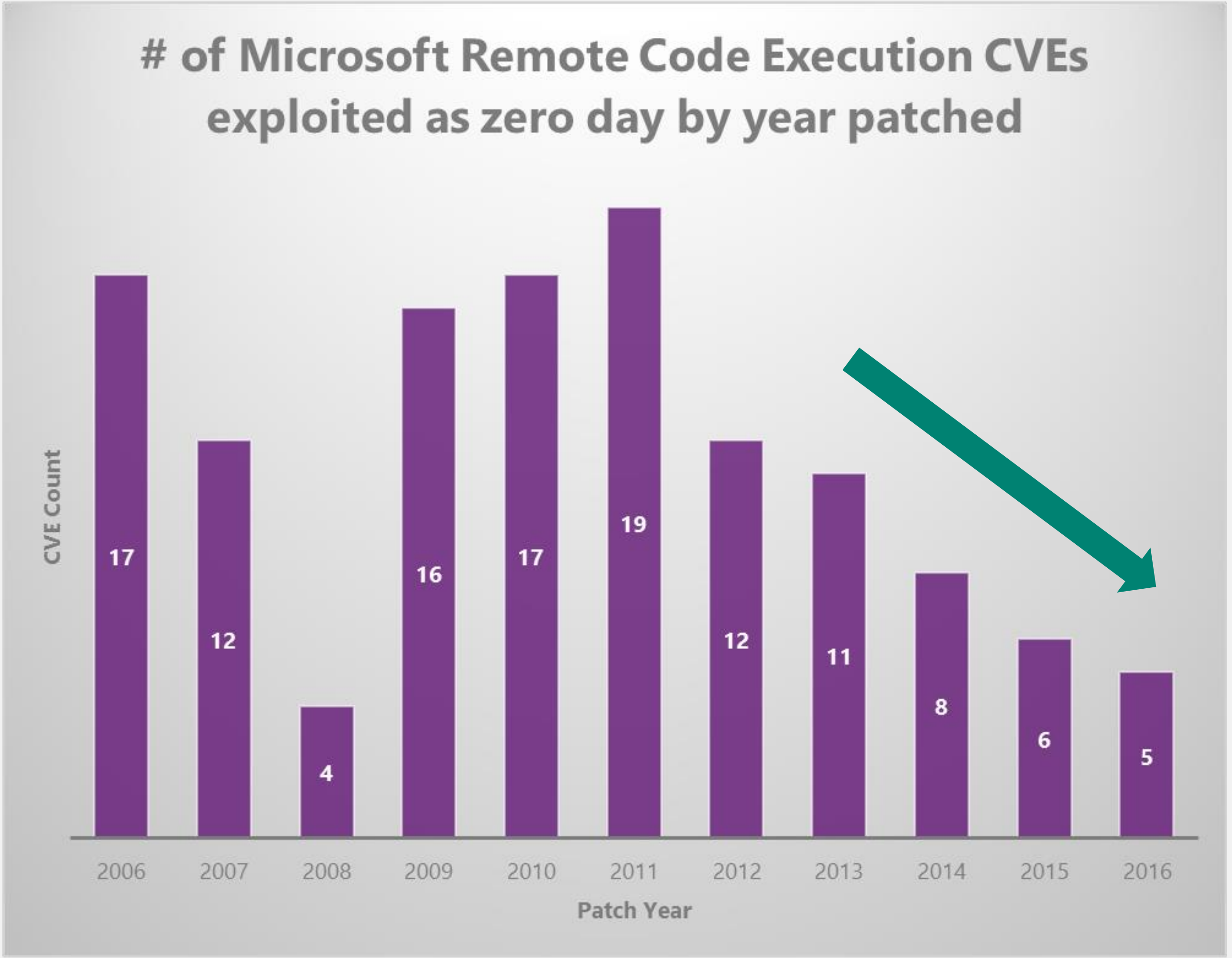


To learn more:
https://blogs.windows.com/msedgedev/2017/03/23/strengthening-microsoft-edge-sandbox

Our work is having a measurable impact

of known zero day RCE exploits has declined despite increase in known vulnerabilities

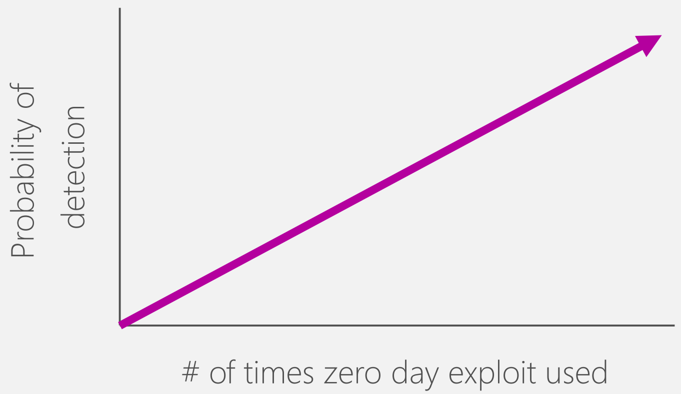




What about the zero days we don't know about?

We cannot effectively measure the number of unknown zero day exploits, but we don't really need to

Hypothesis: increased exploit costs drive selective use



- ✓ Probability of detection increases with zero day use
    - Attackers are incentivized to minimize use
    - Targets that detect zero day may alert vendor
- ✓ Selective use reduces downstream supply
    - Many actors lack means and capability to acquire

Assertion: economics of the zero day market have shifted

- ✓ Windows 10 is always up to date
    - Poor ROI for exploiting patched vulnerabilities
    - Rapid evolution of defensive technologies
- ✓ Mass-market exploit kits struggling to maintain supply
    - Decrease in reusable & public exploits
    - Cost to acquire exceeds expected ROI
- ✓ Market has shifted toward social engineering
    - Macros, tech support scams, so on

MAGNITUDE ACTOR ADDS A SOCIAL ENGINEERING SCHEME FOR WINDOWS 10

MARCH 08, 2017 Kafeine https://www.proofpoint.com/us/threat-insight/post/magnitude-actor-social-engineering-scheme-windows-10

Rapid evolution of defense in Windows 10

New & improved defenses are shipping with nearly every Windows Insider Preview (WIP) build

Matt Miller @epakskape
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vmwp.exe (Hyper-V VM worker proc) enables nearly all mitigations in Windows 10 1703. Easy to see using this cmdlet: powershellgallery.com/packages/Proce…

1:21 PM - 10 Apr 2017

Dave dwizzzle Weston @dwizzzleMSFT
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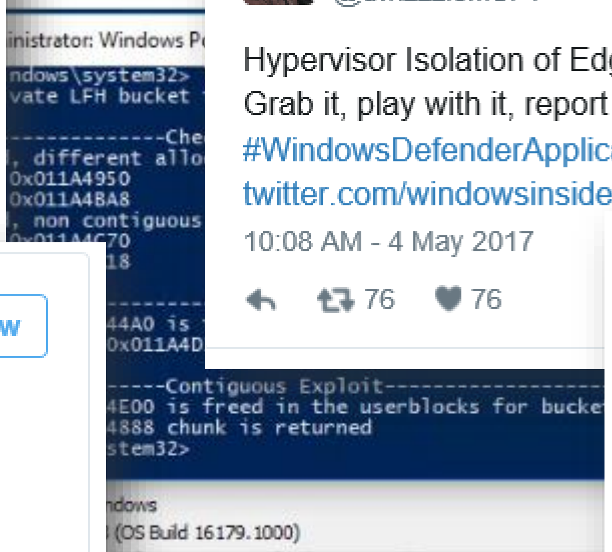
Hypervisor Isolation of Edge is available in this weeks flight!! Grab it, play with it, report bugs. #WindowsDefenderApplicationGuard #WDAG twitter.com/windowsinsider…

10:08 AM - 4 May 2017

76 76



Dave dwizzzle Weston @dwizzzleMSFT
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If you instal Windows 10 1703 and enable HVCI we now also enable kCFG. Kernel mode exploits are subject to control flow integrity in Win10

7:57 PM - 14 Apr 2017

62 65

Matt Miller @epakskape
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Say goodbye to exploit techniques that rely on the fixed HAL heap kernel mapping with the Creators Update of Windows 10 64-bit twitter.com/bluefrostsec/s…

7:16 AM - 11 May 2017

57 69

Miller kskape

Windows 10 build 16179 has a subtle heap randomization improvement that breaks this primitive: github.com/saaramar/Deter…

3:13 PM - 26 Apr 2017

86 109

Live life in the WIP Fast Ring to get the latest defenses ☺

Lessons learned

3rd party binary extensions are security's nemesis

- Very difficult to maintain compatibility and interoperability with 3rd party binary extensions
- Apps need to tightly control their binary extension points to maintain security agility

We're not done yet with mitigating arbitrary native code execution

- CET should provide robust protection for return addresses once available

Layered, data-driven, and red-team-assisted defense is key

- No silver bullets exist in security
- Focus investments on defensible positions

What's next?

We believe our strategy is working & are continuing to execute on it

Kill more bug classes

Drive down attack surface

Break more exploitation techniques

Improve least privilege containment

Lots of exciting things in store. Stay tuned to the WIP Fast Ring!

Fascinated by what you saw? Want to help us make the online world safer?

MICROSOFT BOUNTY PROGRAM
MSRC
aka.ms/bugbounty

Report vulnerabilities & mitigation bypasses via our bounty programs!

https://aka.ms/bugbounty

Or come work with us. We're hiring ☺

https://aka.ms/cesecurityopenjobs

https://aka.ms/wdgsecurityjobs

Bounty program update!

Hyper-V & Mitigation Bypass Bounty Updates

We've clarified and expanded the scope of our Hyper-V bounty program

- Increased Hyper-V payout up to $150,000 USD
- Denial of Service and Information Disclosure are now in scope for the Hyper-V bounty
- Clarified the payout structure for the Hyper-V and Mitigation Bypass bounty programs
- Hyper-V bounty is now separate from the Mitigation Bypass Bounty

aka.ms/bugbounty

Hyper-V bounty page: https://technet.microsoft.com/en-us/security/mt784431
Mitigation bypass bounty page: https://technet.microsoft.com/en-us/security/dn425049

Acknowledgements

Tons of people worked hard to help make this possible!

Thanks to the following groups & teams for their contributions:

- Windows kernel and Hyper-V teams
- Visual C++ team
- Microsoft Edge security team
- WDG Offensive Security Research team
- Microsoft Security Response Center
- And everyone else who contributed!

Microsoft