



Windows 10 Mitigation Improvements

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Agenda

Microsoft's approach to data-driven software defense

How we've adapted red teams to accelerate learnings

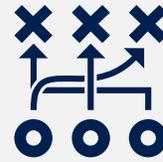
Latest & greatest mitigation features in Windows 10

Problem: Augmenting Preventative Security



Preventative Security

- Preventative Strategy – SDL “Find all the bugs” before shipping
- Static Security Boundaries
- Focus on component level security – customer assets, configuration, 3rd party software largely out-of-scope
- Investigation of exploit and other attack techniques out-of-scope
- Engineering driven - Focus on abstraction to support scale and process
- Mitigation design and offensive security research is ad-hoc and specialized



Attackers are agile, adaptive, and results focused – effective techniques often don’t map to security boundaries



Market value for exploits is 10x vulnerabilities – preventative security is focused on lowest value asset



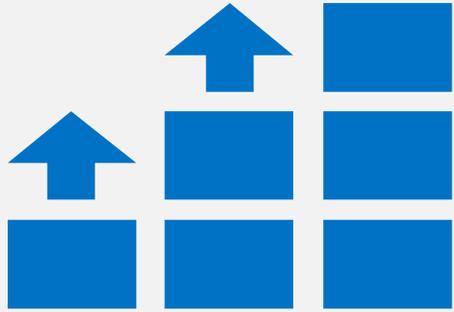
Attackers invest in developing tool sets and libraries – no proactive disruption, reactive response only after attacks



The cost for attackers is unknown – The current approach to security is abstracted from attacks – security effectiveness against real attacks unknown

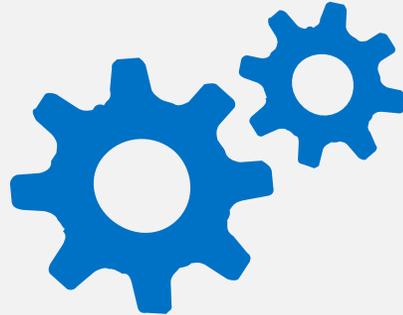
“Assume breach” mitigation strategy augments preventative security

Strategy: Data-Driven Software Defense



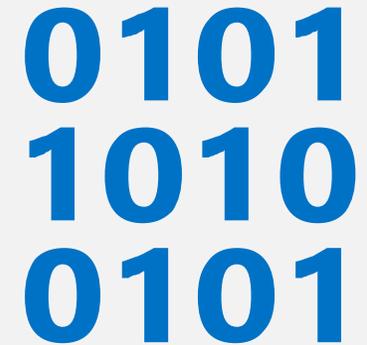
Analyze

Analyze comprehensive set of real world data
Identify opportunities for tactical attack disruption and future strategic hardening



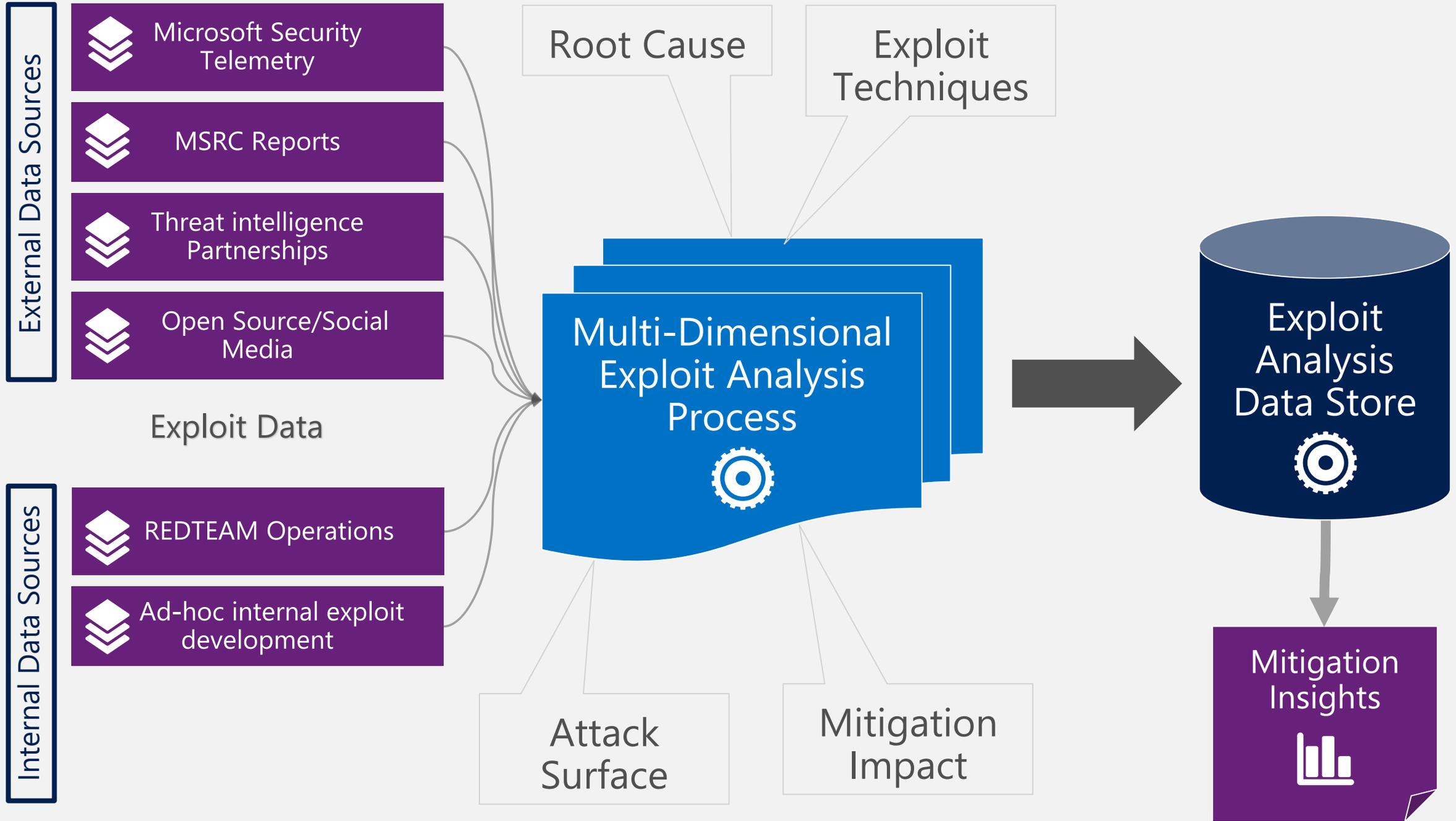
Build

Security engineers explore mitigation concepts with product owners
Security engineers prototype or productize mitigation design



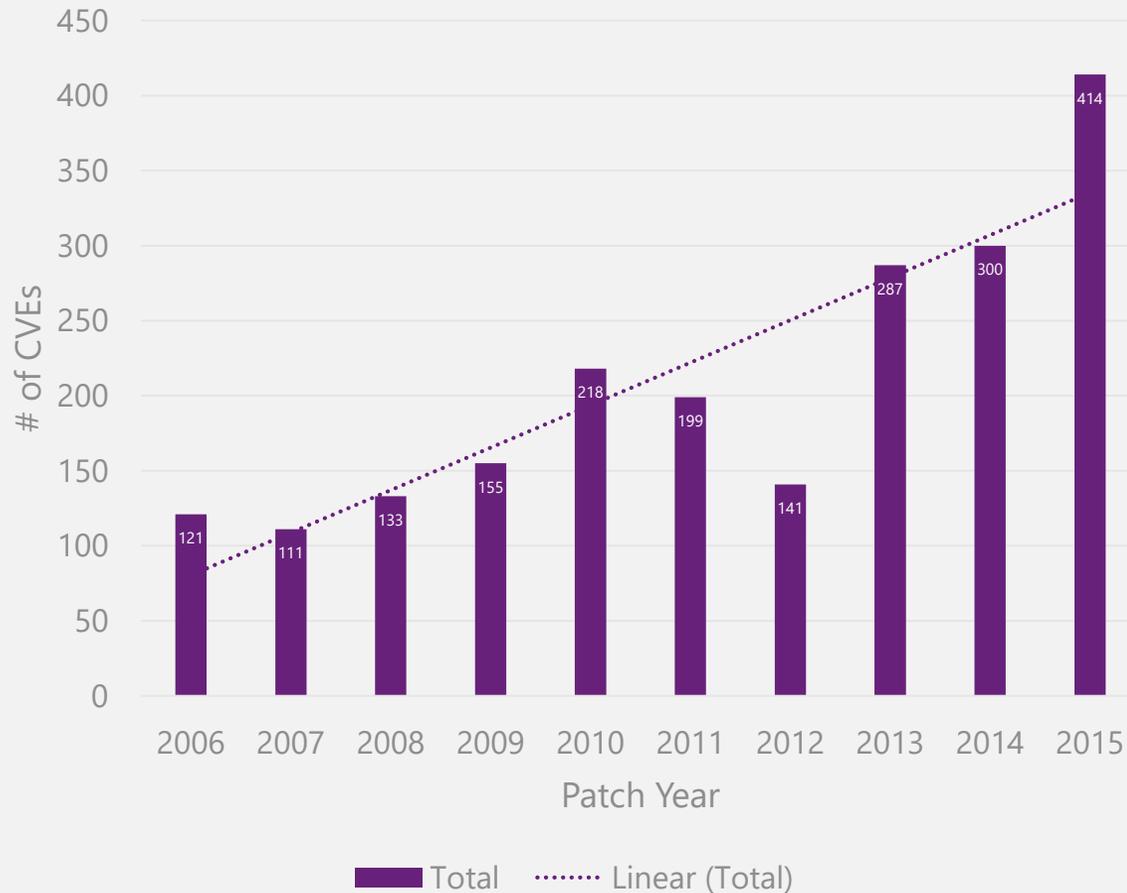
Evaluate

Windows Offensive Security Research Team (OSR) evaluates mitigations and attempts to identify bypasses
Mitigation flaws are addressed



Analysis: High-level vulnerability & exploit trends

of Microsoft RCE/EOP CVEs by patch year



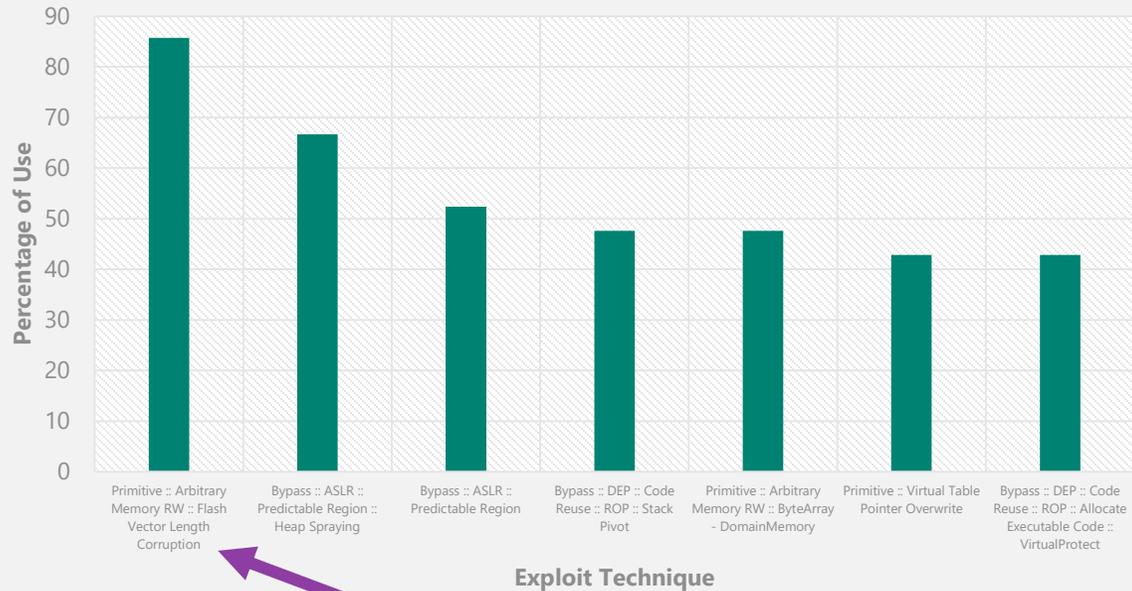
% of Microsoft RCE & EOP CVEs exploited within 30 days of patch



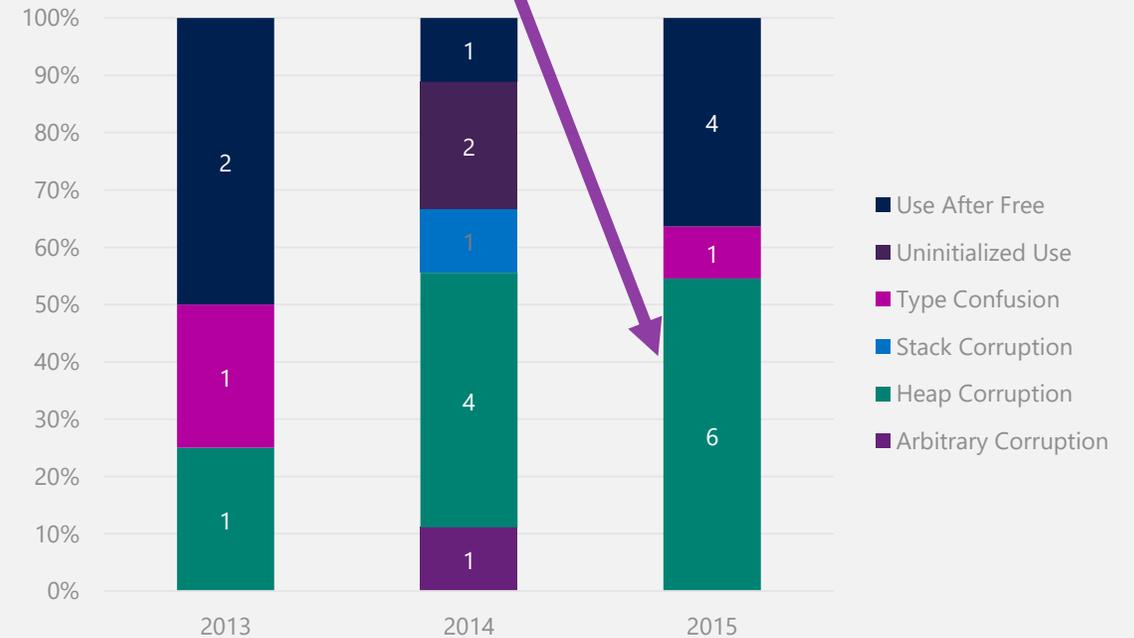
Vulnerabilities are increasing while evidence of actual exploits is decreasing due to mitigation investments

Analysis: Flash Exploit Technique Trends

Exploit Techniques used in Public Flash Exploits (2013-2015)



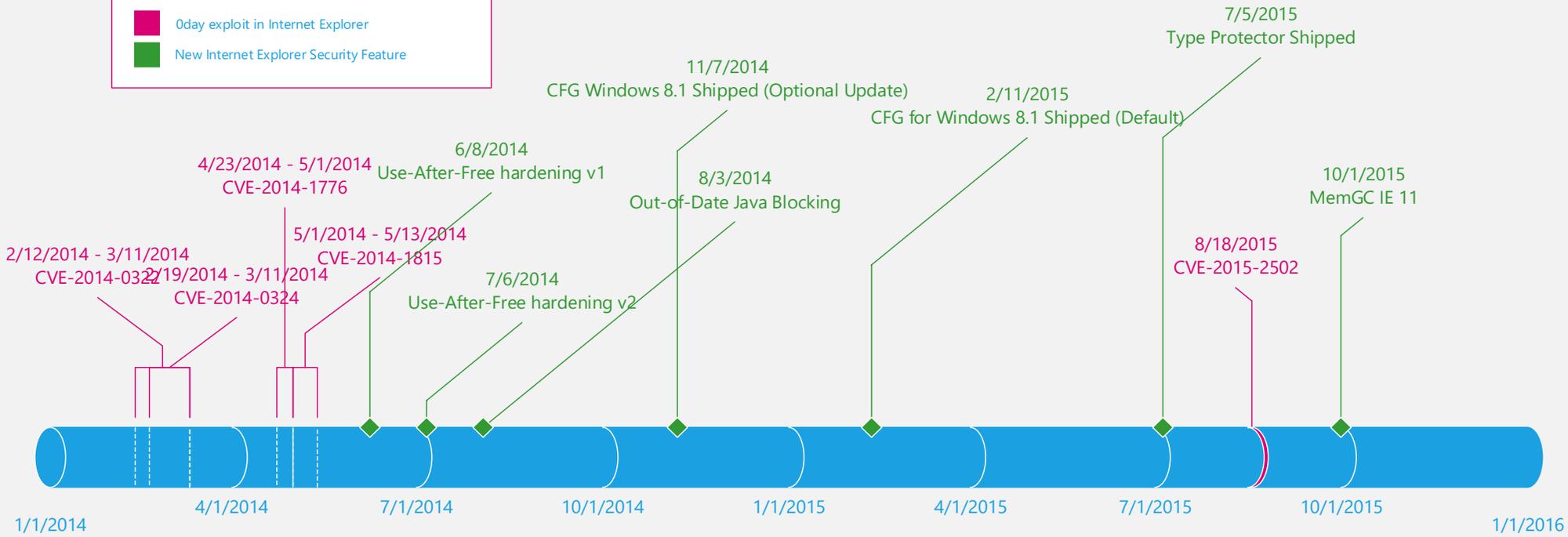
Prevalence of linear heap corruption drove adoption of Heap randomization for Flash on Windows



Worked with Adobe to mitigation via Vector Length and ByteArray Mitigations

Exploit technique trend analysis drives new or improved mitigations

Success Story: Internet Explorer



Year	Patched RCE CVE	Zero Day RCE CVE
2013	116	8
2014	226	4
2015	188	1

- A focus on mitigations for disruption of invariant techniques used in exploits (ROP, Heap Spraying, UAF)
- In 2015 only 6 days with a known zero day Internet Explorer RCE exploit in-the-wild (down from 45, 135)
- Vulnerability volume has increased but number of zero day exploits has decreased

Mitigations were a key factor in zero day reduction trends

Microsoft Services Security: Assume Breach

- Azure, O365 and other have evolved the “assume breach” security methodology
- Focus on what happens after a “security boundary” is assumed breached
- **Detection, Containment, Response, and Recover**
- Services “Redteams” used to model breaches, evaluate detection, and simulate response process



Prevent Breach

Threat model

Code review

Security testing

Security development lifecycle (SDL)



Assume Breach

War game exercises

Central security monitors

Live site penetration test

Hypothesis: We can use the assume breach approach to model exploitation and drive mitigations

Challenges with Adapting “*Assume Breach*”

- Mitigations are primarily reactive if driven by ITW data
- Reactive mitigations take time to develop
- New products do not get appropriate mitigations – until they are attacked
- We do not get accurate metrics on exploit and attack development

PWN2OWN & Data Influenced Mitigations

CFG: suppress sensitive APIs

Flash: Eliminate RWX ATL thunks

Junctions: Prevent sandbox processes from creating NTFS junctions – TH1

Fonts: Move font parsing to user mode sandbox

Edge: Prevent content processes from creating child processes

Edge: Enable win32k system call restrictions

How do we design effective mitigations proactively?

REDTEAM: Windows and Devices

Model real-world attacks

- Model attacks based on ecosystem analysis and threat intelligence
- Evaluate the customer-promises from an attack perspective
- Provide data sets of detection-and-response
- Attack the full stack in production configuration (software, configuration, hardware, OEMs)

Identify security gaps

- Measure Time-to-Compromise (MTTC) / Pwnage (MTTP)
- Identify invariant techniques for mitigation
- Simulate a real-world incident response before it occurs (process, owners, messaging)
- Provide detection guidance for Defenders

Demonstrate impact

- Break-it-you-bought-it work with teams to address issues
- Design mitigations to drive up MTTC/MTTP metrics
- Enumerate business and legal risk
- Show business value, priorities, and investments needs with demonstrable attacks

REDTEAM Offensive Modeling Outcomes

- The Offensive Security Research team (OSR) operating for over a year in the Windows and Devices group
- Focused on end-to-end exploitation of common software/hardware scenarios – most without a prior known public attack
- Proactively discovered many new exploit techniques – drove mitigations into new versions of Windows prior to public use of technique
- Exploit invariants shared with Defender/ATP ([BLUETEAM](#)) to drive detection in-the-wild
- Demonstrated fundamental new memory corruption techniques and designed new general RCE mitigation for future version of Windows

Offensive security modeling is now a core pillar of Microsoft security strategy

Mitigation Improvements in Windows 10

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

Acknowledgements

Many teams and individuals worked very hard on what we are about to talk about

Internet Explorer, Edge, & Chakra	Dave Buchthal, Shubham Chopra, Crispin Cowan, Bo Cupp, Mike Decker, Jim Fox, Matt Gradwohl, John Hazen, C.J. Hebert, Forbes Higman, Michael Howell, Sermet Iskin, Rick James, Riff Jiang, Venkat Kudallur, Louis Lafreniere, Curtis Man, Ed Maurer, Bruce Morgan, Kamen Moutafov, Zach Murphy, Vidya Nallathimmayyagari, Justin Rogers, Todd Sahl, Saranya Kalpathy Seshadri, Bob Schroder, Kirk Sykora, Jason Weber
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Microsoft Research (MSR)	Richard Black, Miguel Castro, Manuel Costa, Austin Donnelly

We would also like to thank our Mitigation Bypass & Defense Bounty participants for helping us improve our defenses!

Our sincere apologies to anyone who we have unintentionally failed to list – so many people have contributed!

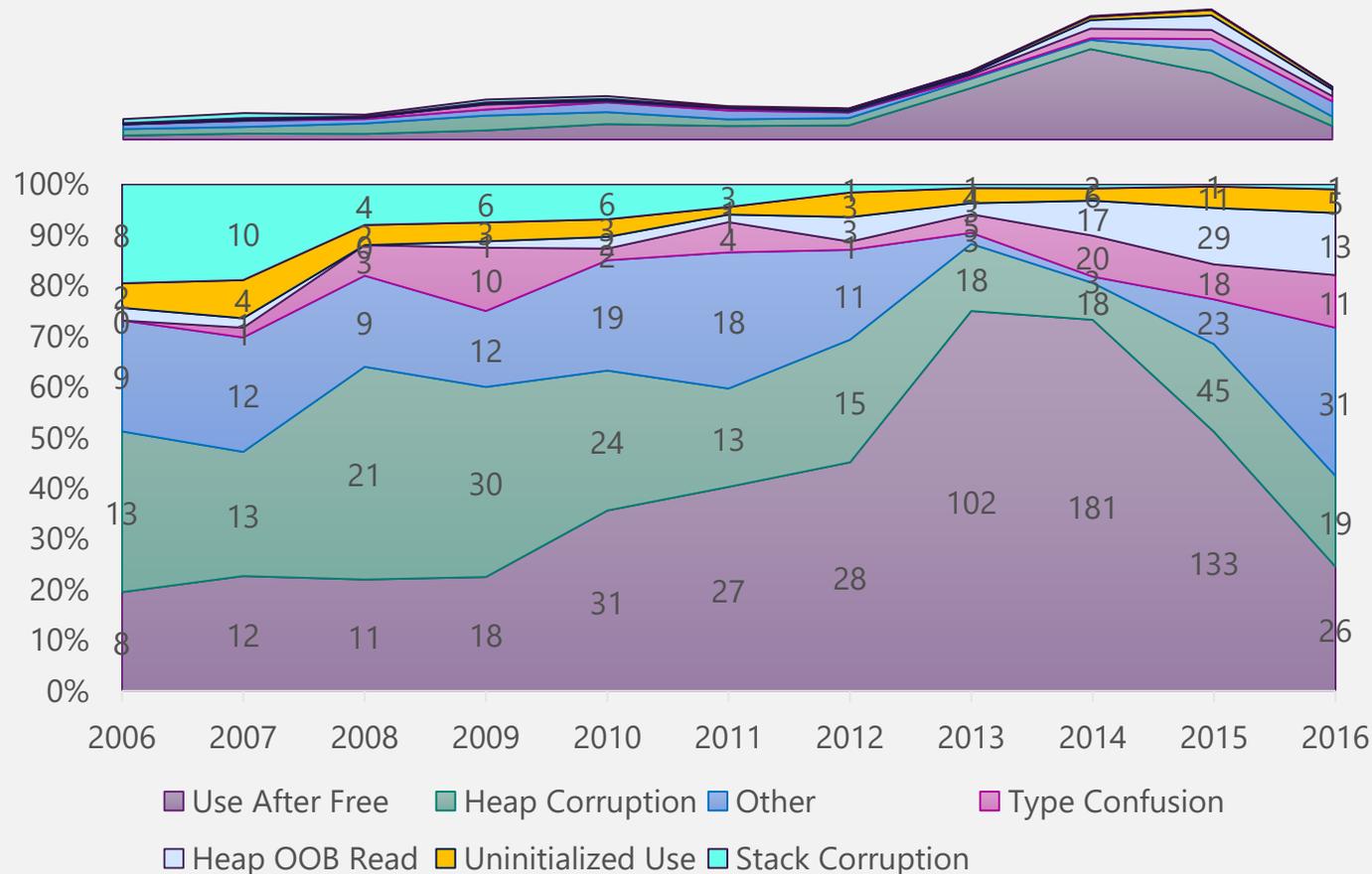
Eliminating classes of vulnerabilities

We move beyond the “hand-to-hand combat” of finding and fixing individual issues by identifying ways to eliminate entire classes of vulnerabilities

Goal: Increase attacker cost of finding exploitable vulnerabilities

We closely study vulnerability root cause trends

Microsoft security engineers categorize the root cause of every vulnerability and look for patterns



Root causes of Windows, Internet Explorer, and Edge Remote Code Execution (RCE) CVEs by patch year

Stack corruption issues have been essentially eliminated

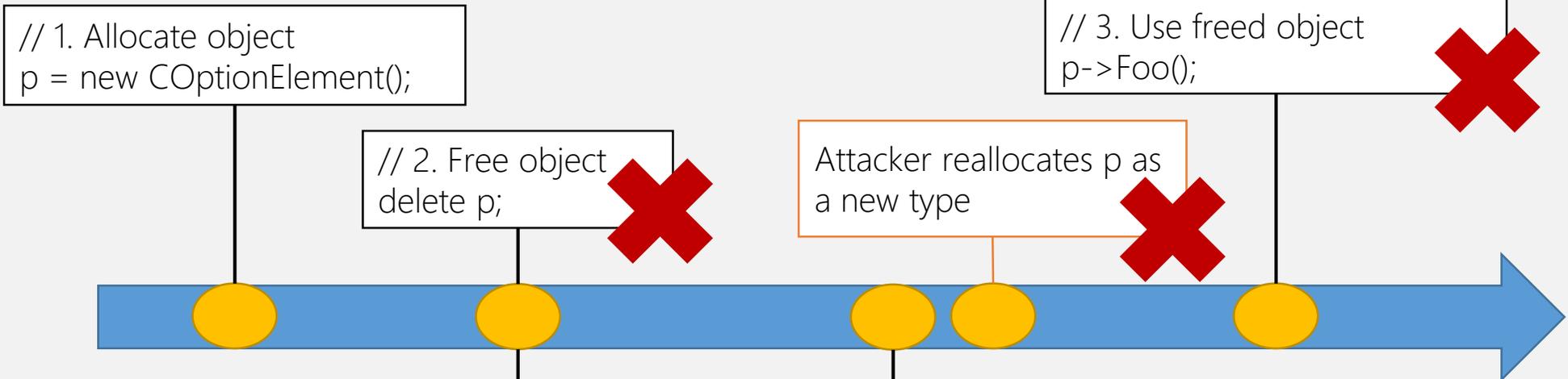
Use after free issues rose dramatically in 2013 & 2014 but have since decreased

Heap out-of-bounds read, type confusion, and DLL planting have increased

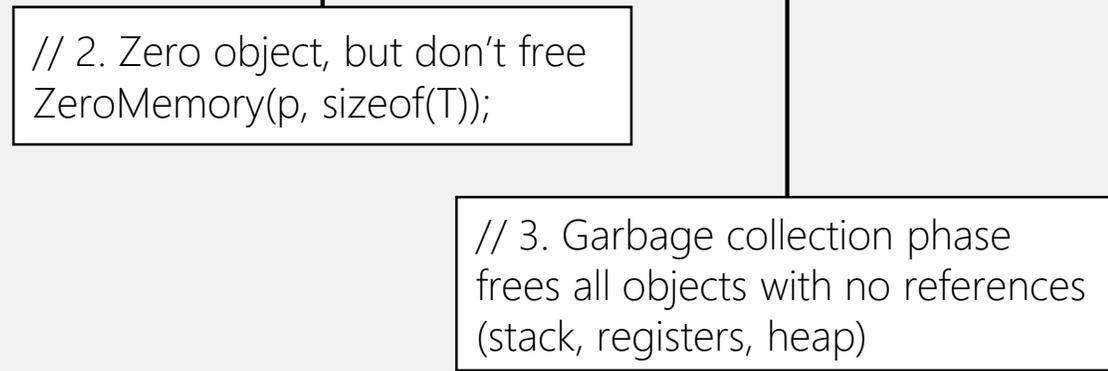
Memory Garbage Collection (MemGC)

The vast majority of the use after free issues we observed were in our DOM engine in Internet Explorer

Without MemGC



With MemGC



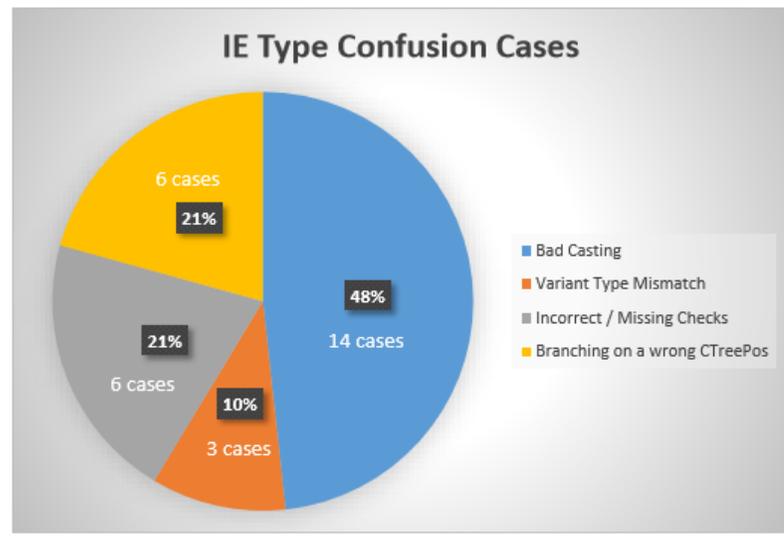
MemGC is a conservative garbage collector (GC) for our DOM engine that makes DOM use after free issues non-exploitable

Tactic	Applies to	First shipped
Eliminate entire classes of vulnerabilities	Edge on Windows 10 and backported to IE9+ on Windows Vista+	July, 2015 (Windows 10 RTM)

Type confusion protection

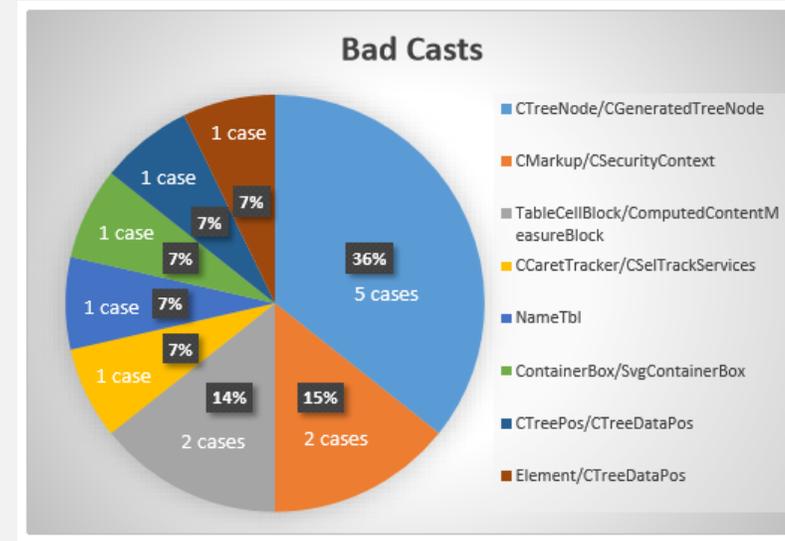
In late 2014, we began investigating ways to eliminate type confusion issues as these were being increasingly reported

We found that ~50% were due to bad casts



Categories of type confusion issues observed from 2012 through 2014

Of which ~50% appeared to be recurring patterns



Classes that were involved in type confusions resulting from bad casts

We introduced additional checks to eliminate ~50% of type confusions (recurring bad casts and branching on wrong CTreePos)

Tactic	Applies to	First shipped
Eliminate entire classes of vulnerabilities	Edge and IE11 on Windows 10 and backported to IE10+ on Windows 7+	July, 2015 (Windows 10 RTM)

Edge attack surface reduction

With the Edge browser, we also seized the opportunity to drastically reduce the attack surface exposed to the web

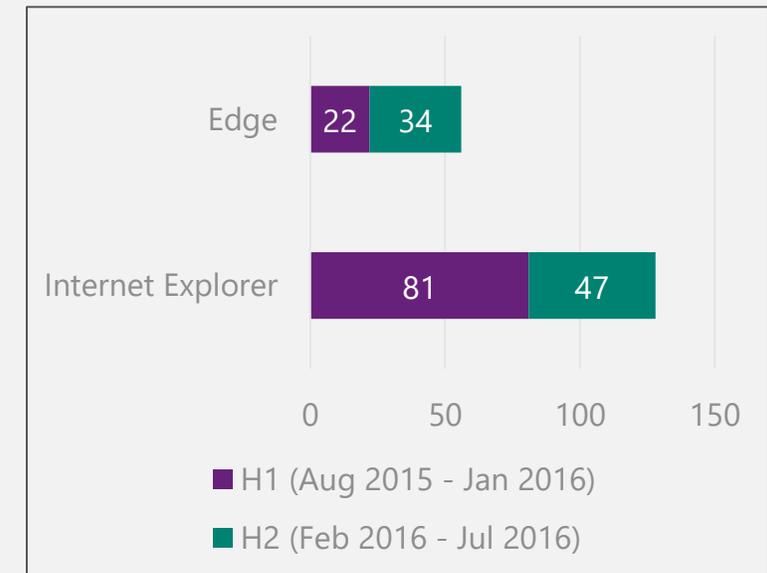
- ✓ No legacy document modes
- ✓ No legacy script engines (VBScript, JScript)
- ✓ No Vector Markup Language (VML)
- ✓ No Toolbars
- ✓ No Browser Helper Objects (BHOs)
- ✓ No ActiveX controls

Tons of code was removed as a result!

In the past year

Edge had 56% fewer RCE CVEs compared to Internet Explorer

Internet Explorer RCE CVEs decreased 40% H/H



Tactic	Applies to	First shipped
Eliminate entire classes of vulnerabilities	Edge on Windows 10	July, 2015 (Windows 10 RTM)

Breaking exploitation techniques

We assume that we won't be able to eliminate all vulnerabilities, so we look for ways to break the techniques that attackers can use to exploit them

Goal: Increase attacker cost of developing a reliable exploit for a vulnerability

Exploiting vulnerabilities has become increasingly difficult

Exploitation used to be simple

Circa 2003; exploit steps for CVE-2003-0344

- ✓ Trigger stack buffer overrun
- ✓ Overwrite return address with ~~predictable address of a "JMP ESP"~~
- ✓ ~~Execute shellcode from the stack~~
- ✓ Arbitrary native code execution ☹️

Now, it is much more involved

- ✓ Place array length at a predictable location (via heap spray/massage)
- ✓ Modify array length via memory corruption, enabling arbitrary read/write
- ✓ Use arbitrary read/write to discover DLL base address
- ✓ Construct ROP payload by searching for code sequences in the DLL
- ✓ Corrupt C++ virtual table pointer and trigger virtual method call to first gadget
- ✓ Execute ROP payload (typically to make shellcode executable)
- ✓ Execute arbitrary native code
- ✓ Escape the sandbox (or operate inside it)

The Info leak era of software exploitation

Fermin Serna, Black Hat 2012

Exploits start relying on ~~non-ASLR DLLs~~ to bypass ASLR and ROP to bypass DEP

Exploits start relying on address space information disclosures

Windows Vista enables ASLR

Kills (most) predictable images

Internet Explorer 8 enables DEP

Kills heap spraying of code

Windows 8 adds Force ASLR; IE10 enables it

Kills all predictable images

2006

2007

2008

2009

2010

2011

2012

2013

2014

2015

2016

Code heap spraying era

Non-ASLR DLL era

Arbitrary read/write era

User mode exploit mitigations

64-bit browsing by default

~~Place array length at a predictable location (via heap spray/message)~~

Heap spraying has been a standard technique used by nearly every browser exploit

Heap spraying example from Metasploit [1]

```
var memory = new Array();
function sprayHeap(shellcode, heapSprayAddr, heapBlockSize) {
  var index;
  var heapSprayAddr_hi = (heapSprayAddr >> 16).toString(16);
  var heapSprayAddr_lo = (heapSprayAddr & 0xffff).toString(16);
  while (heapSprayAddr_hi.length < 4) { heapSprayAddr_hi = "0" + heapSprayAddr_hi; }
  while (heapSprayAddr_lo.length < 4) { heapSprayAddr_lo = "0" + heapSprayAddr_lo; }

  var retSlide = unescape("%u" + heapSprayAddr_hi + "%u" + heapSprayAddr_lo);
  while (retSlide.length < heapBlockSize) { retSlide += retSlide; }
  retSlide = retSlide.substring(0, heapBlockSize - shellcode.length);

  var heapBlockCnt = (heapSprayAddr - heapBlockSize) / heapBlockSize;
  for (index = 0; index < heapBlockCnt; index++) {
    memory[index] = retSlide + shellcode;
  }
}
```

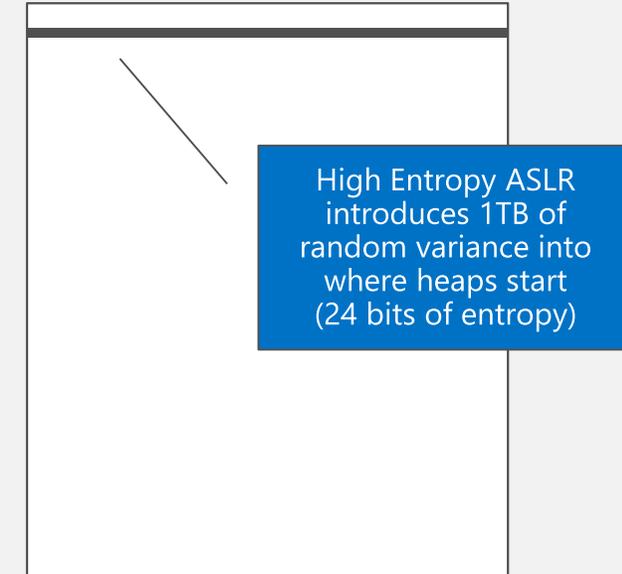
[1] https://github.com/rapid7/metasploit-framework/blob/master/data/js/memory/heap_spray.js

32-bit address space (2GB)



32-bit address space is small and easy to spray

64-bit address space (128TB)



64-bit address space with High Entropy ASLR makes traditional heap spraying impractical

Majority of Windows 10 devices are running a 64-bit version of Windows & Edge

Attackers must have an additional information disclosure

Tactic	Applies to	First shipped
Breaking exploitation techniques	Edge on Windows 10	July, 2015 (Windows 10 RTM)

Control Flow Guard

~~Corrupt a C++ virtual table pointer and trigger virtual method call to first gadget~~

Modern exploits typically rely 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

Runtime

```
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

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>

Tactic	Applies to	First shipped
Breaking exploitation techniques	Edge on Windows 10 and IE11 on Windows 8.1+	November, 2014 (Windows 8.1 Update 3)

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 can be abused	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 Edge on Windows 10
	LoadLibrary – mitigated in latest version of Edge on Windows 10 via code integrity
	WinExec – mitigated in Edge on Windows 10 anniversary edition via child process policy
Corrupting return addresses on the stack	Known limitation that we intend to address with new technology (e.g. with Intel CET)

We are continuing to explore ways to improve CFG to more strongly prevent control-flow hijacking

Code integrity & image load restrictions

Exploits can attempt to inject and run arbitrary code by causing a malicious DLL to be loaded

Windows 10 allows processes to enable code integrity and image load restrictions to prevent malicious DLLs from being loaded

“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".



DLL loading restrictions supported by Windows 10

- ✓ Only properly signed images can be loaded (Microsoft, WHQL, Store, or DRM signed)
- ✓ Binaries on remote devices (UNC/WebDAV) cannot be loaded

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

An additional benefit: these restrictions help prevent unwanted DLLs from being injected into processes that enable them

Tactic	Applies to	First shipped
Breaking exploitation techniques	Edge on Windows 10 and opt-in for other apps	November, 2015 (Windows 10 1511 update)

Dynamic code restrictions

~~Execute arbitrary native code~~

Nearly all exploits rely on creating new executable code pages that contain their shellcode

Windows 10 allows processes to enable dynamic code generation restrictions which imposes W^X invariants

Code is immutable

Code pages cannot become writable via VirtualProtect or initially allocated as WX

Data cannot become code

Data pages cannot become executable via VirtualProtect or initially allocated as WX

Combined with image load restrictions, this prevents all forms of unsigned arbitrary code injection within a process

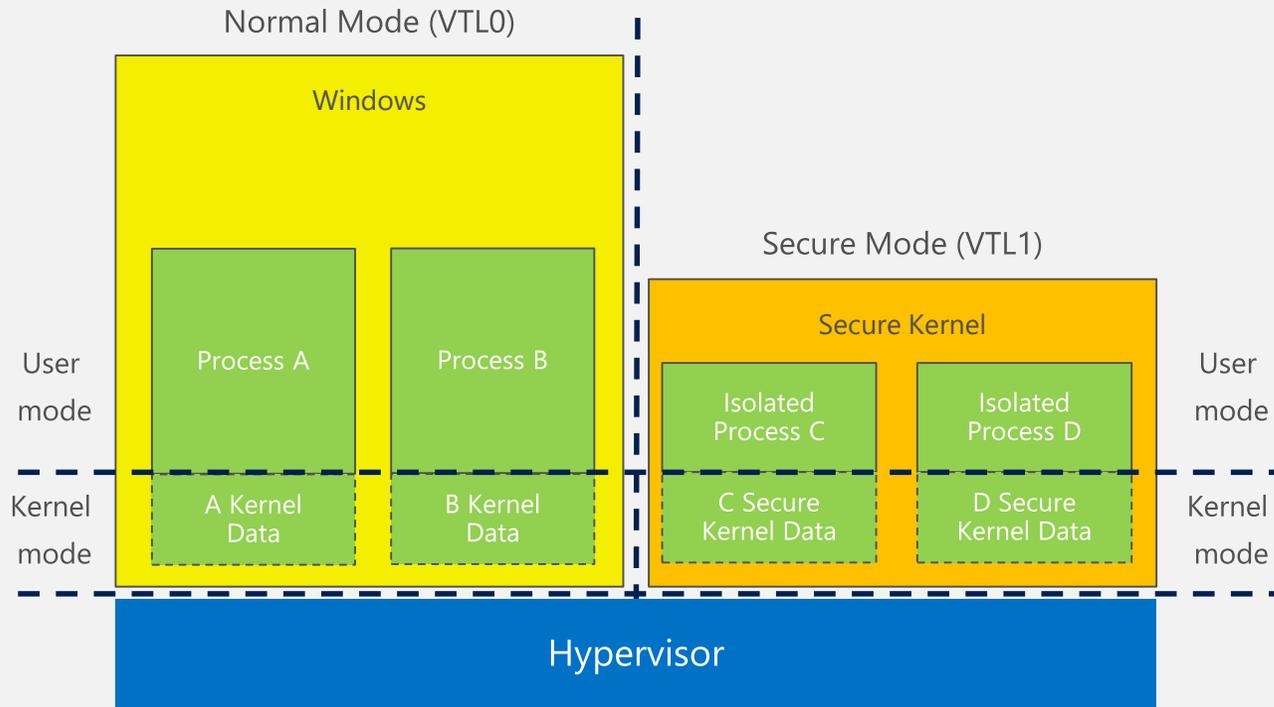
Tactic	Applies to	First shipped
Breaking exploitation techniques	Opt-in by process on Windows 8.1+	August, 2013 (Windows 8.1 RTM)

Kernel mode exploit mitigations

Windows 10 Virtualization-Based Security (VBS)

Hyper-V on Windows 10 enables a suite of robust protection features for the host and guest kernels

Virtual Secure Mode (VSM) architecture



<https://channel9.msdn.com/Blogs/Seth-Juarez/Windows-10-Virtual-Secure-Mode-with-David-Hepkin>

Mitigations enabled by Hyper-V & VSM

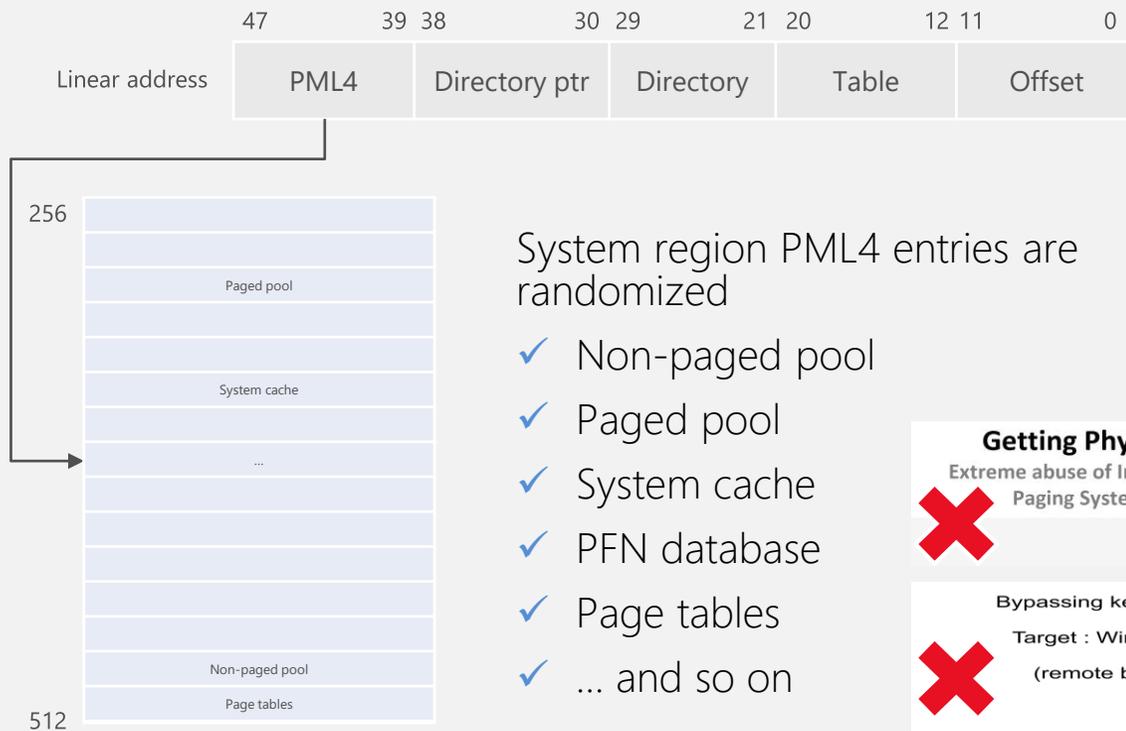
- ✓ Hyper Guard
 - Prevents modification of key MSRs, control registers, and descriptor table registers
 - Example: SMEP cannot be disabled
- ✓ Hypervisor-Enforced Code Integrity (HVCI)
 - Only properly signed kernel pages can become executable
- ✓ Robust even if an attacker can perform arbitrary read/write in VTL0 kernel

Tactic	Applies to	First shipped
Breaking exploitation techniques	Windows 10 with Hyper-V enabled	July, 2015 (Windows 10 RTM)

Windows Kernel 64-bit ASLR Improvements

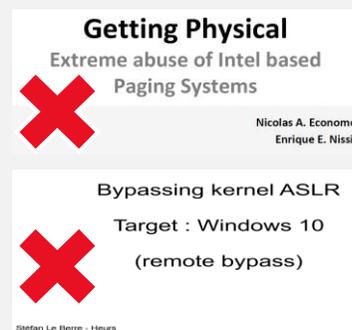
Predictable kernel address space layout has made it easier to exploit certain types of kernel vulnerabilities

64-bit kernel address space layout is now dynamic



Various address space disclosures have been fixed

- ✓ Page table self-map and PFN database are randomized
 - Dynamic value relocation fixups are used to preserve constant address references
- ✓ SIDT/SGDT kernel address disclosure is prevented when Hyper-V is enabled
 - Hypervisor traps these instructions and hides the true descriptor base from CPL>0
- ✓ GDI shared handle table no longer discloses kernel addresses



Tactic	Applies to	First shipped
Breaking exploitation techniques	Windows 10 64-bit kernel	August, 2016 (Windows 10 Anniversary Edition)

Enabling opt-in mitigations

Mitigation	How to opt-in
Control Flow Guard	Compile and link with /guard:cf (requires Visual Studio 2015 Update 2+)
Image load restrictions	<ul style="list-style-type: none">• SetProcessMitigationPolicy with ProcessImageLoadPolicy• UpdateProcThreadAttribute with PROC_THREAD_ATTRIBUTE_MITIGATION_POLICY
Code integrity restrictions	<ul style="list-style-type: none">• SetProcessMitigationPolicy with ProcessSignaturePolicy• UpdateProcThreadAttribute with PROC_THREAD_ATTRIBUTE_MITIGATION_POLICY
Dynamic code restrictions	<ul style="list-style-type: none">• SetProcessMitigationPolicy with ProcessDynamicCodePolicy• UpdateProcThreadAttribute with PROC_THREAD_ATTRIBUTE_MITIGATION_POLICY
Child process restrictions	<ul style="list-style-type: none">• UpdateProcThreadAttribute with PROC_THREAD_ATTRIBUTE_CHILD_PROCESS_POLICY
HVCI	<ul style="list-style-type: none">• Set HypervisorEnforcedCodeIntegrity (REG_DWORD) to 1 in HKLM\SYSTEM\CurrentControlSet\Control\DeviceGuard

For more information: <https://aka.ms/setprocessmitigationpolicy>

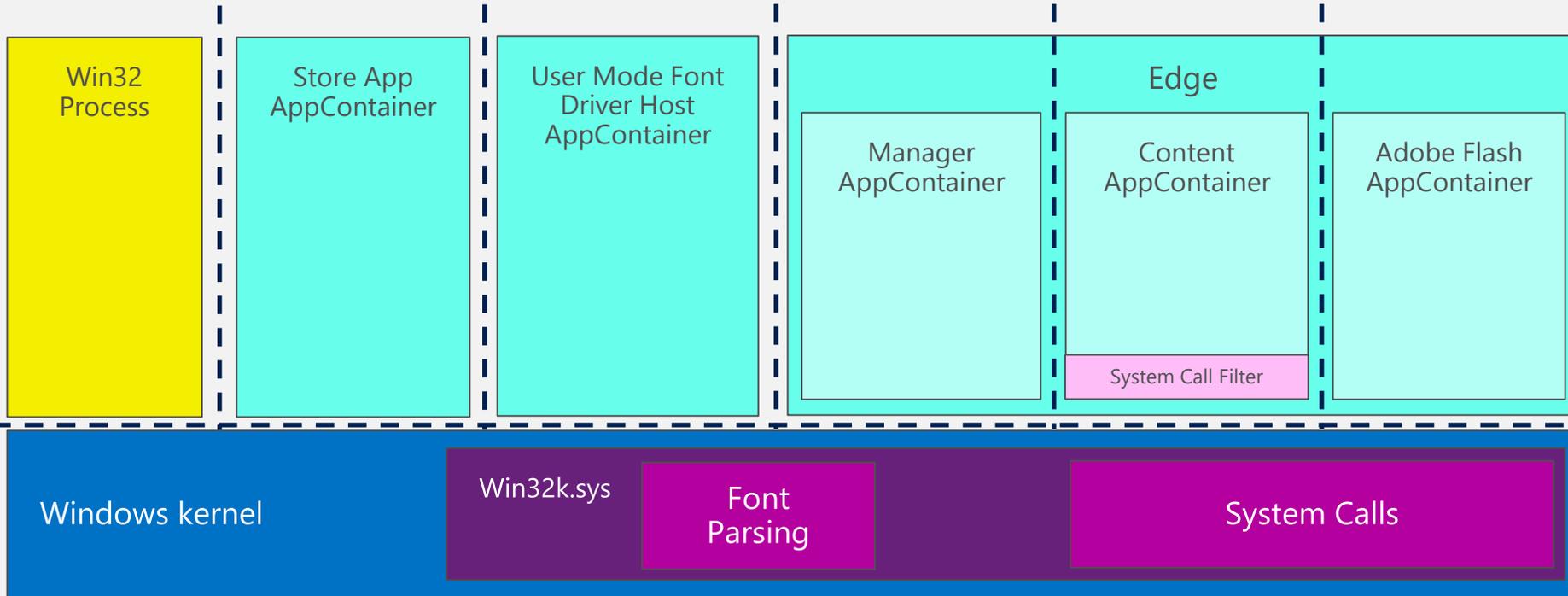
Containing damage & preventing persistence

We assume that we won't be able to prevent exploitation in all cases, so we look for ways to effectively isolate and contain the damage if a vulnerability is successfully exploited

Goal: Increase attacker cost of effectively leveraging an exploit for a vulnerability

AppContainer (AC)

AppContainer provides strong sandboxing and isolation for applications on Windows



- ✓ Store apps all run within an AC
- ✓ Font parsing is now done in user mode within an AC
- ✓ Edge uses a multi-AC design for isolation

New in Windows 10 Anniversary Edition

- ✓ Adobe Flash has now been moved to its own AC
- ✓ Win32k system call filtering is enabled for Edge

AppContainer Properties	Security boundary	Microsoft will address vulnerabilities that can violate AC security boundary
	Capability-based resource access	Network, file, registry, and device access are restricted (both read and write)
	Locked down process	No symbolic links, reduced attack surface, and various mitigations on by default

Tactic	Applies to	First shipped
Containing damage & preventing persistence	Multiple applications	August, 2012 (Windows 8)

Limiting the window of opportunity to exploit

Assuming all else fails, we look to have effective tools and processes to limit the scope and window of opportunity for attackers to leverage an exploit for a vulnerability

Goal: Minimize an attacker's return on investment from the use of an exploit for a vulnerability

Reducing the attacker's window of opportunity

Rapidly Respond

- Mobilize engineering teams to quickly understand and develop a fix for a vulnerability

Rapidly Protect

- Use SmartScreen and other technologies to protect customers from in-the-wild attacks
- Enable Microsoft Active Protection Program (MAPP) partners to protect the broader ecosystem

Rapidly Update

- Broadly deploy and install security updates to quickly minimize the affected population size

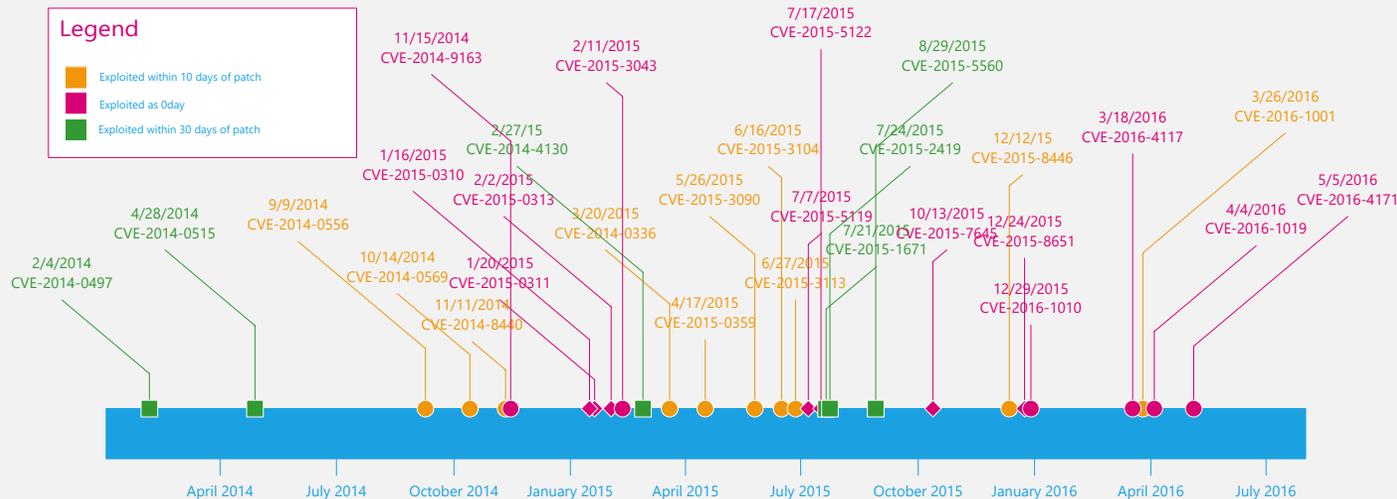
Conclusion

Security is more than just the code you write

We apply our strategy beyond Microsoft by working with our partners to help improve Windows platform security

We've worked closely with Adobe to help harden Flash Player

We've worked with Intel to help design CET



✓ Control-flow Enforcement Technology (CET)

- Indirect branch tracking via ENDBRANCH
 - Return address protection via shadow stack
- ✓ Hardware-assists for helping to mitigate control-flow hijacking & ROP

Array Length Hardening

ByteArray Isolation

Flash out-of-process

CFG/JIT hardening

Heap Hardening

UAF Hardening

Preview specification:

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

Measuring the impact of our strategy so far

We've made measurable progress on improving customer safety

- ✓ The number of Microsoft vulnerabilities exploited within 30 days of a patch has continued to decline Y/Y despite increases in the number of vulnerabilities being addressed each year
- ✓ In the last two years, no zero day exploits for Microsoft RCE vulnerabilities have been found in-the-wild that work against Internet Explorer 11 on Windows 8.1+
- ✓ Since releasing Edge one year ago, there have been no zero day exploits found in-the-wild targeting Edge

Windows 10 and Edge are always up-to-date and offer strong defenses against modern threats

Our data-driven and red team assisted approach strongly positions us to identify & deliver impactful mitigations

Microsoft Edge RCE on WIP Bounty Program

- Submit a **remote code execution (RCE)** vulnerability for Microsoft Edge
- The bugs reported should be on the **most recent Windows Insider Preview slow build**
- Program duration is **August 4 2016 to May 15 2017**

Only eligible reported on the latest WIP slow builds will be paid a bounty

- This continues our effort in finding bugs in the earlier stages of development
- Microsoft will pay up to \$1,500 for the first external report received on an internally known issue
- Microsoft will pay up to \$15,000 on a previously unknown RCE on Edge

Vulnerability type	Functioning Exploit	Proof of concept	Report Quality	Payout range (USD) *
Remote Code Execution in Microsoft Edge on recent builds of WIP slow	Required	Required	High	Up to \$15,000
	No	Required	High	Up to \$6,000
	No	Required	Low	Up to \$1,500



