The Evolution of Microsoft's Exploit Mitigations

Past, Present, and Future

Matt Miller, Tim Burrell
<mamill,timb>@microsoft.com
Microsoft Security Engineering Center (MSEC)
Security Science

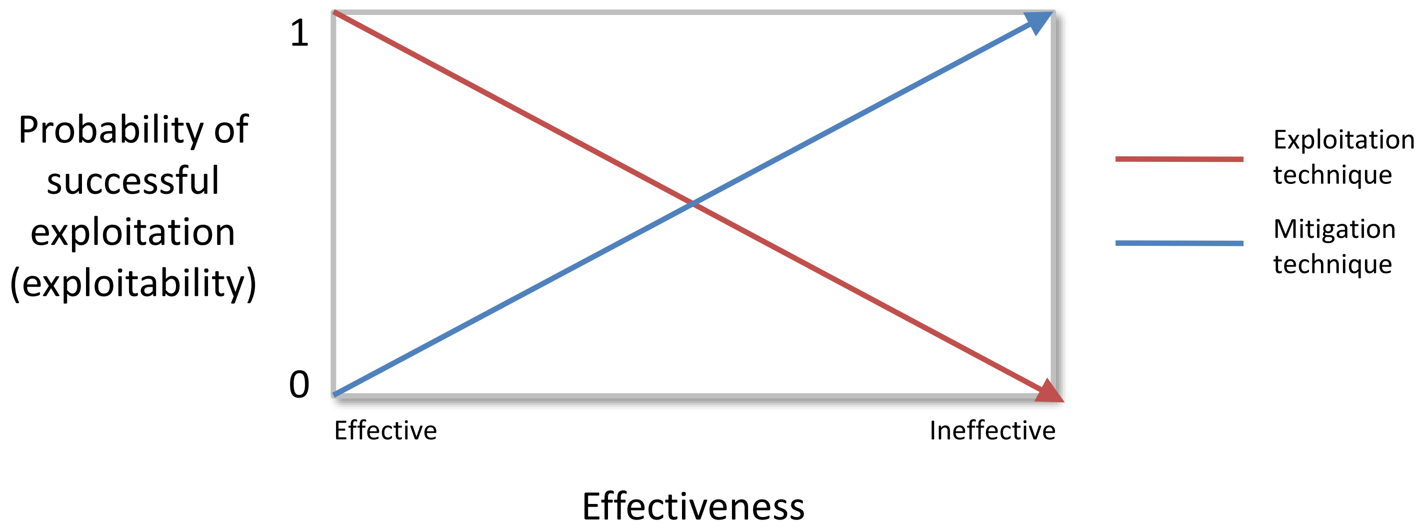
Agenda

- Defining the purpose of exploit mitigations

- Microsoft’s exploit mitigation evolution
  - The past
  - The present
  - The future

- Open problems facing exploit mitigation

The purpose of exploit mitigations



- Goal: decrease the probability of successful exploitation
  - Prevent the use of specific exploitation techniques
  - Reduce the reliability of exploitation techniques
- Generic protection for known & unknown vulnerabilities in all products, not just Microsoft products!

ACT I

THE PAST AND THE PRESENT

Exploitation

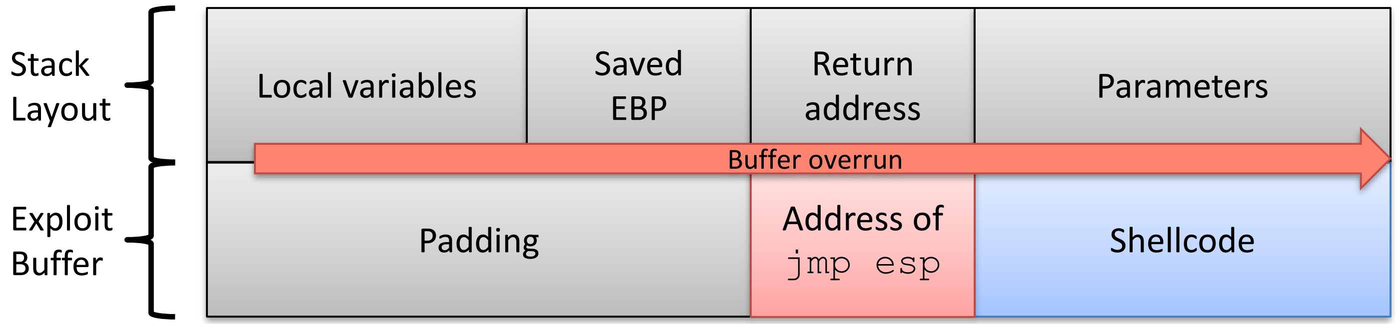
Pre-XP SP2: The era of uninhibited worms

- Reliable exploitation techniques already existed
  - And they affected Windows, too!
- Exploits were developed, worms raged
  - Jul, 2000: IIS Code Red (MS01-033)
  - Jan, 2003: SQL Slammer (MS02-039)
  - Aug, 2003: Blaster (MS03-026)
  - May, 2004: Sasser (MS04-011)
- No platform exploit mitigations existed
  - Attack surface was very big
  - Exploitation techniques were uninhibited

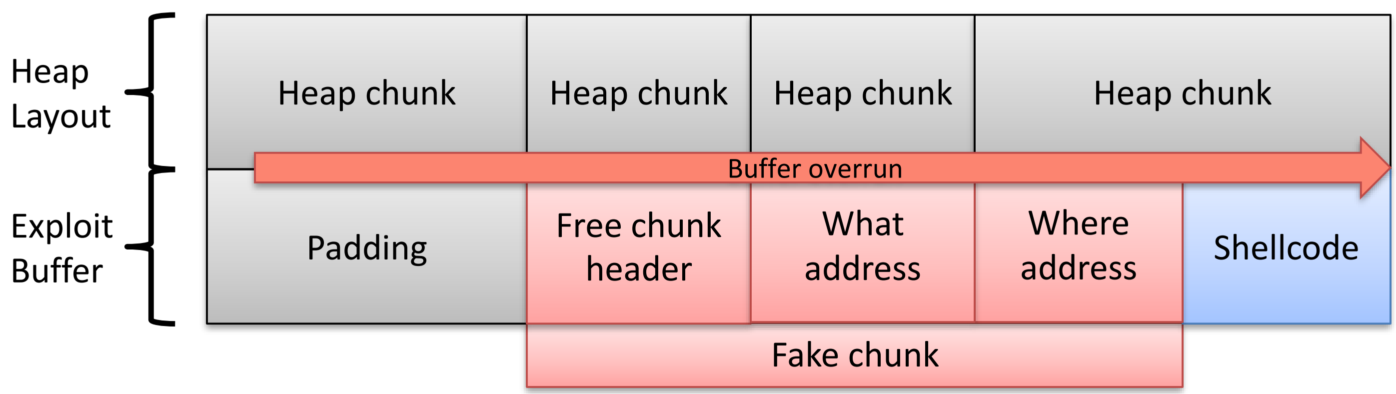
Exploitation

Same techniques, different OS

- Stack: return address overwrite [Aleph96]



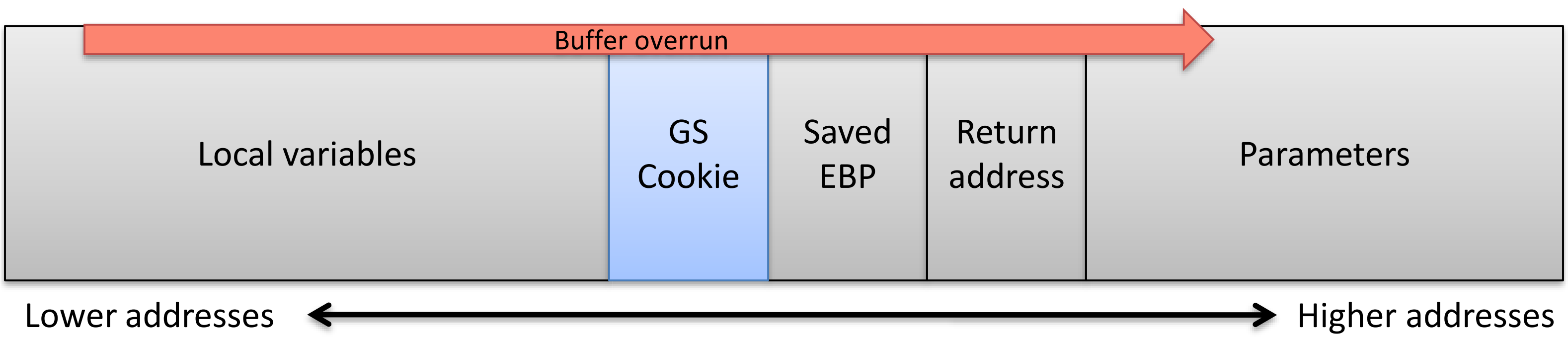
- Heap: free chunk unlink [Solar00,Maxx01,Anon01]



Mitigation

Visual Studio 2002

- GS v1 released



- Behavior
  – Compiler heuristics identify at-risk functions
  – Prologue inserts cookie into stack frame
  – Epilogue checks cookie & terminates on mismatch

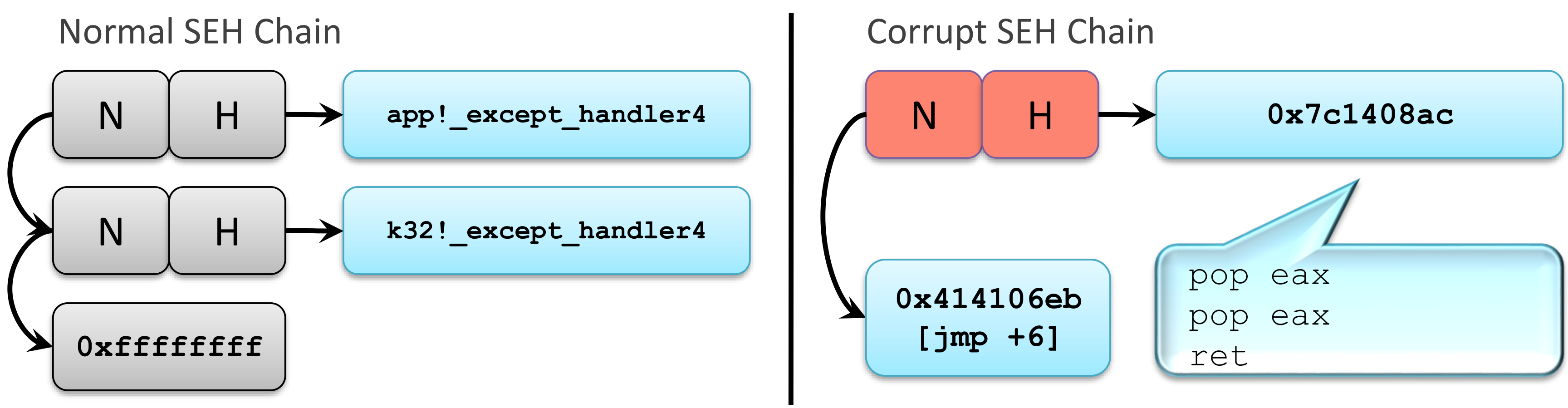
Exploitation

GS v1 weaknesses

- Adjacent local/parameter overwrite [Ren02]

```
void vulnerable(char *in) {
   int unsafe = 0; char buf[256];
   strcpy(buf, in);                             ← overflow!
   if (unsafe != 0) DoSomethingUnsafe();        ← unsafe is corrupt
   return;                                      ← GS cookie checked
}
```

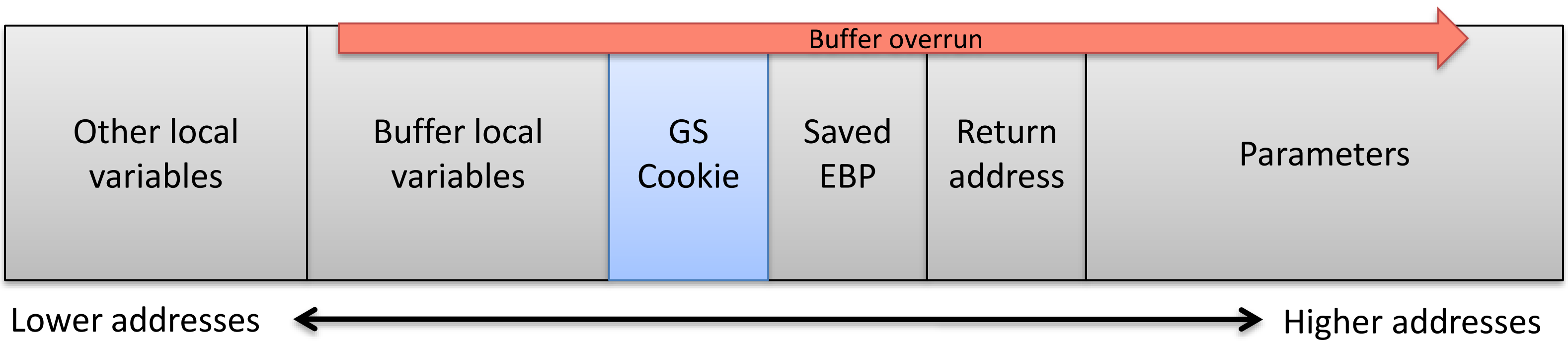
- SEH overwrite bypass [Litchfield03]



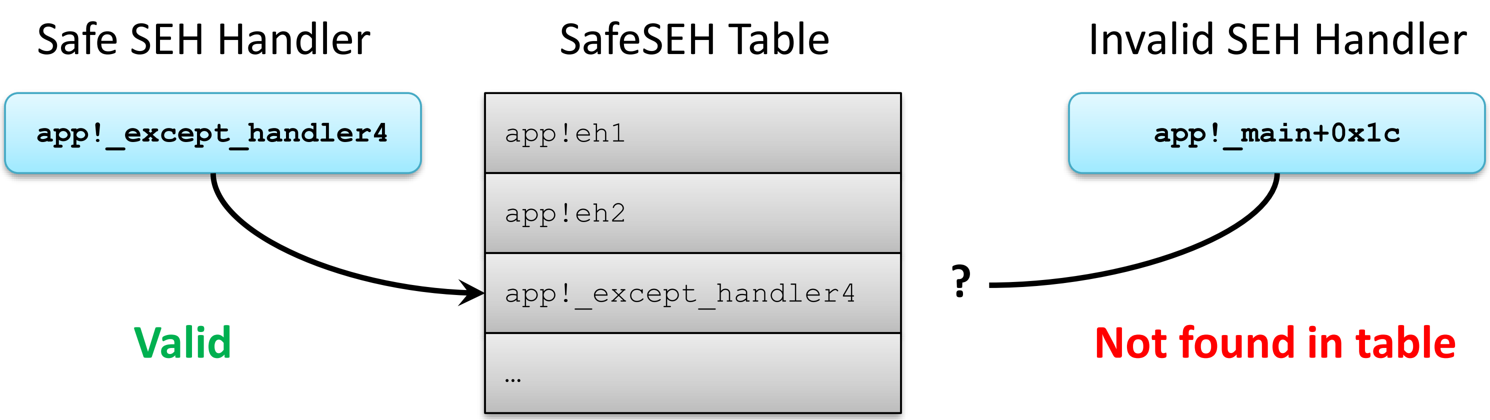
Mitigation

Visual Studio 2003

- GS v1.1 released with VS2003



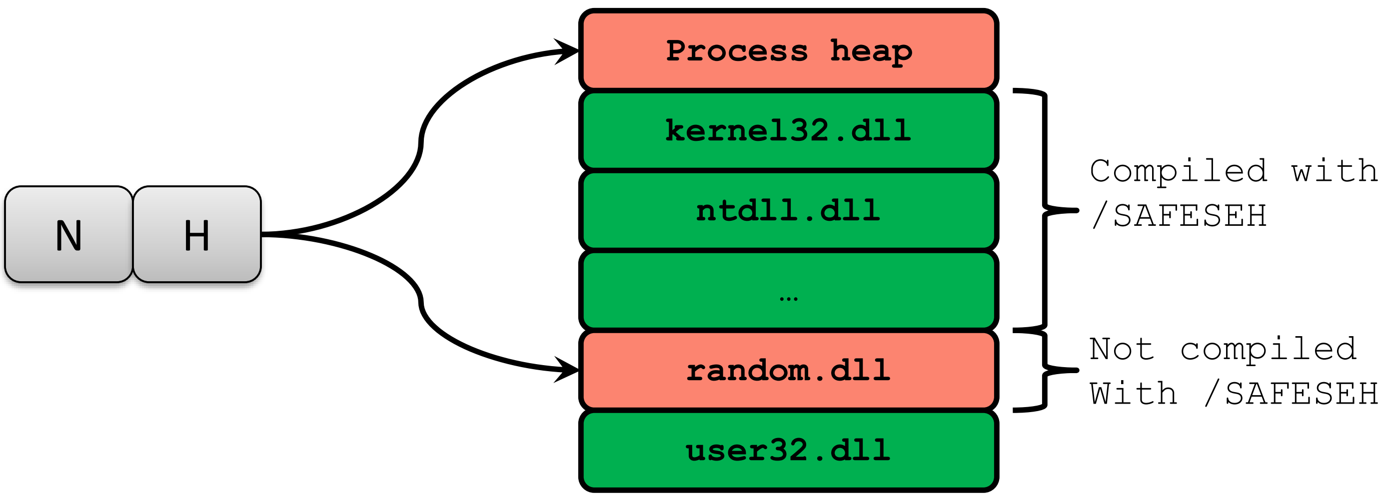
- SafeSEH added, reliant on XP+ & recompile



Exploitation

SafeSEH evasions

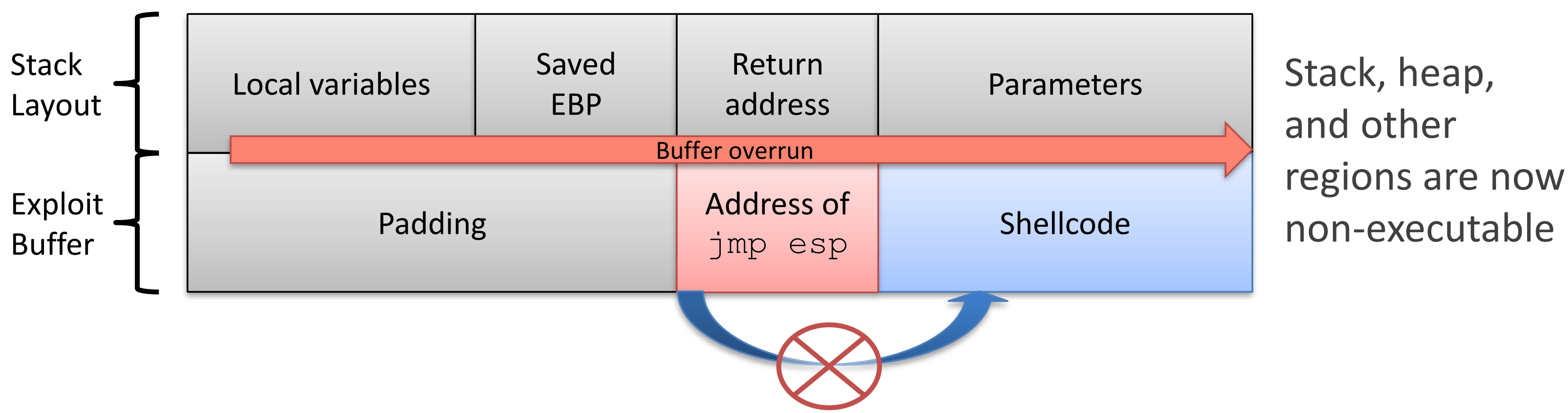
- Limitations of SafeSEH
  - Handler can be in an executable non-image region
  - Handler can be inside a binary lacking SafeSEH



Mitigation

Windows XP SP2 arrives

- System binaries built with GS v1.1 & SafeSEH
- Data Execution Prevention (DEP)
  - Hardware-enforced non-executable pages
  - Software-enforced SEH handler validation



Mitigation

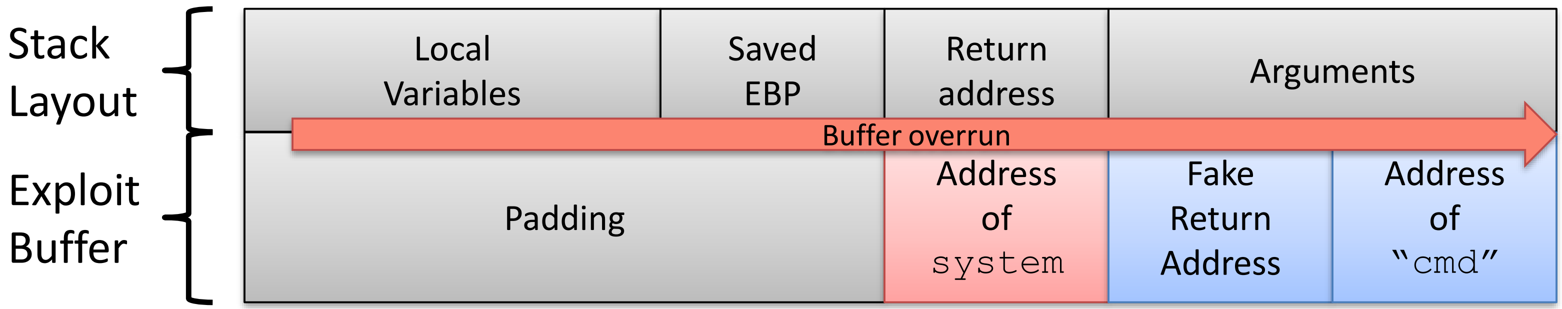
Windows XP SP2 arrives

- First round of heap mitigations
  - Safe unlinking `(E->B->F == E->F->B == E)`
  - Heap header cookie validation
- Limited randomization of PEB/TEB
  - Reduces the reliability of certain techniques
- Pointer encoding
  - Protect UEF, VEH, and others via EncodeSystemPointer

Exploitation

Same NX bypass, new OS

- Return to libc [Solar97,Nergal01]



- Many variations
  - Return into VirtualProtect/VirtualAlloc
  - Disable DEP via ProcessExecuteFlags [Skape05]
  - Create executable heap & migrate to it
  - Return-oriented programming [Shacham08]

Exploitation

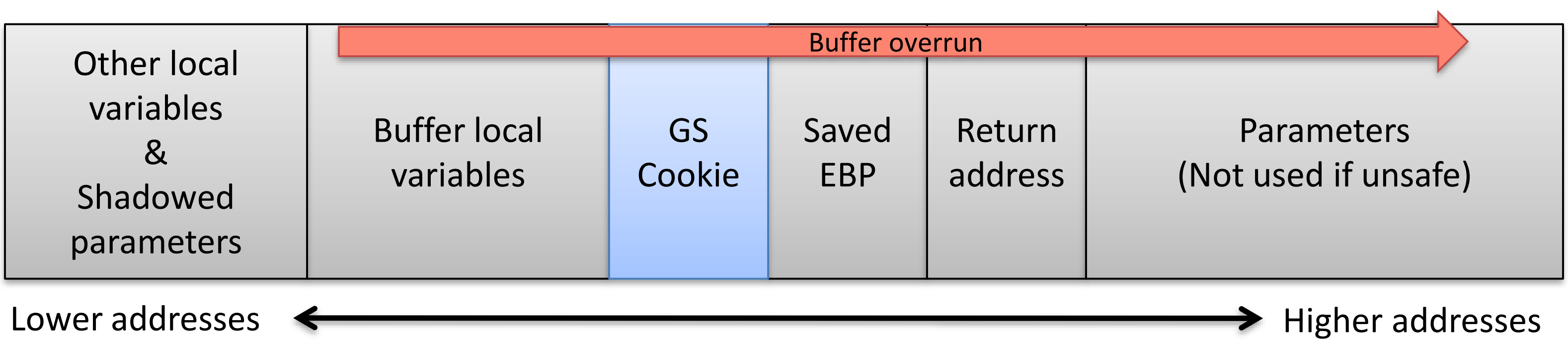
New heap techniques, less universal

- Unsafe lookaside list allocations [Anisimov04,Conover04-2]
  - Overwrite free chunk on lookaside list & then cause allocation
- Unsafe unlinking of free chunks [Conover04-2]
  - Overwrite free chunk with specific Flink and Blink values
- Unsafe unlink via `RtlDeleteCriticalSection` [Falliere05]
  - Overwrite critical section structure on heap & delete it
- Exploiting `FreeList[0]` [Moore05]
  - Overwrite free chunk stored at FreeList[0] with specific data

Mitigation

Visual Studio 2005

- GS v2 released with VS2005
  - Shadow copy of parameters is made
  - Strict GS pragma

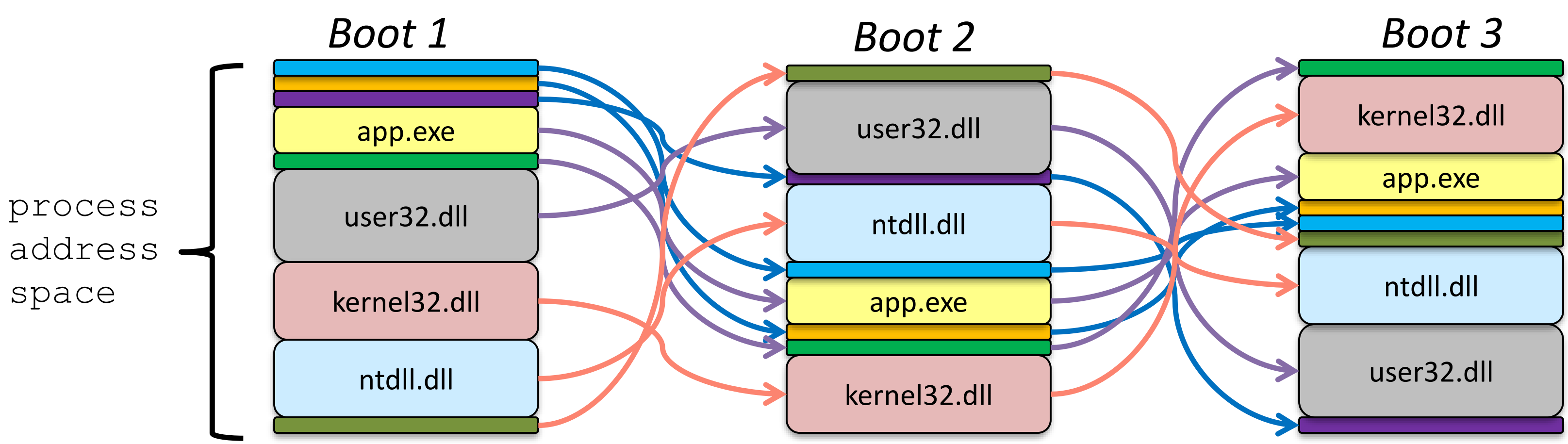


- C++ `operator::new` integer overflow detection [Howard07]

Mitigation

Windows Vista arrives

- Address Space Layout Randomization (ASLR) [PaX02]
  - Make the address space unpredictable



Region	Entropy
Image	8 bits
Heap	5 bits
Stack	14 bits

Mitigation

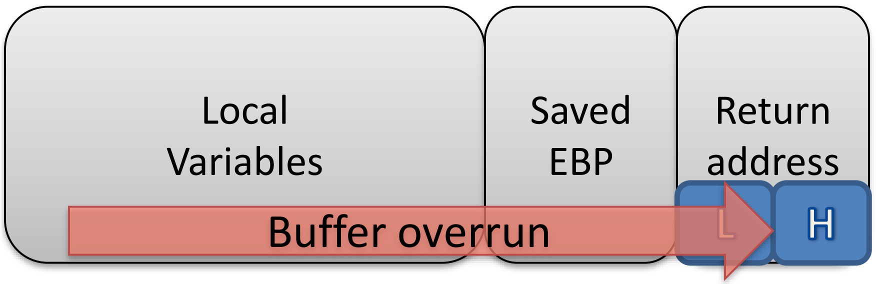
Windows Vista arrives

- Second round of heap mitigations [Marinescu06]
  - Removal of lookaside lists and array lists
  - Block metadata encryption
  - Header cookie scope extended, validated in more places
  - Dynamic change of heap allocation algorithms (LFH)
  - Terminate on heap corruption (default for system apps)
  - `RtlDeleteCriticalSection` technique mitigated by `RtlSafeRemoveEntryList`

Exploitation

Same ASLR evasions, new OS

- Partial address overwrite [Durden02]




```
memcpy(
   dest,      ← Stack buf
   src,       ← Controlled
   length);   ← Controlled
```

- Address information disclosure [Soeder06]
- Reduced entropy on some platforms [Whitehouse07]
- Brute forcing [Nergal01, Durden02, Shacham04]
- Non-relocateable/predictable addresses [Sotirov08]

Exploitation

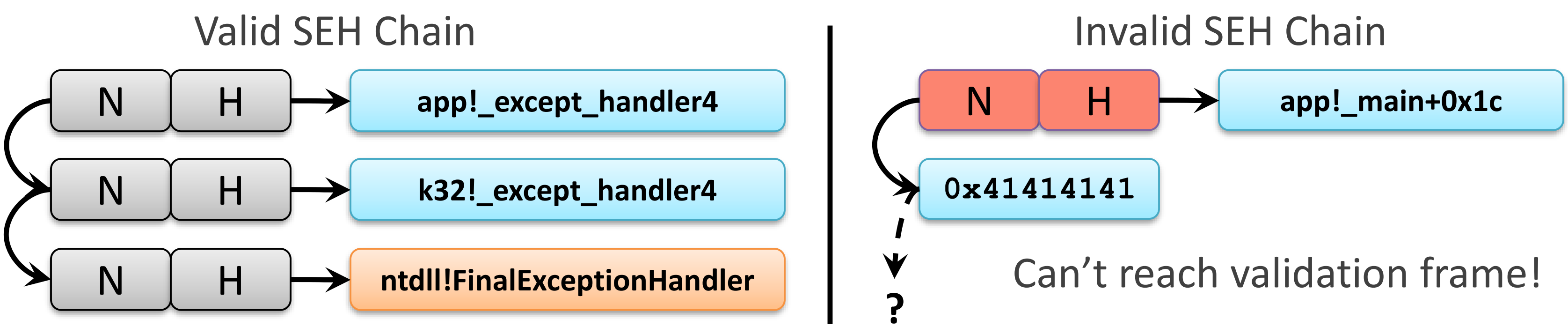
Newer heap techniques, partial & still less universal

- `HEAP` structure overwrite [Hawkes08]
  - Overwrite pointer in alloc'd chunk with heap base
  - Cause pointer to be freed & then re-allocated
  - Overwrite with specially crafted `HEAP` structure
- LFH bucket/header overflow [Hawkes08]
- Still need to evade DEP and ASLR if enabled

Mitigation

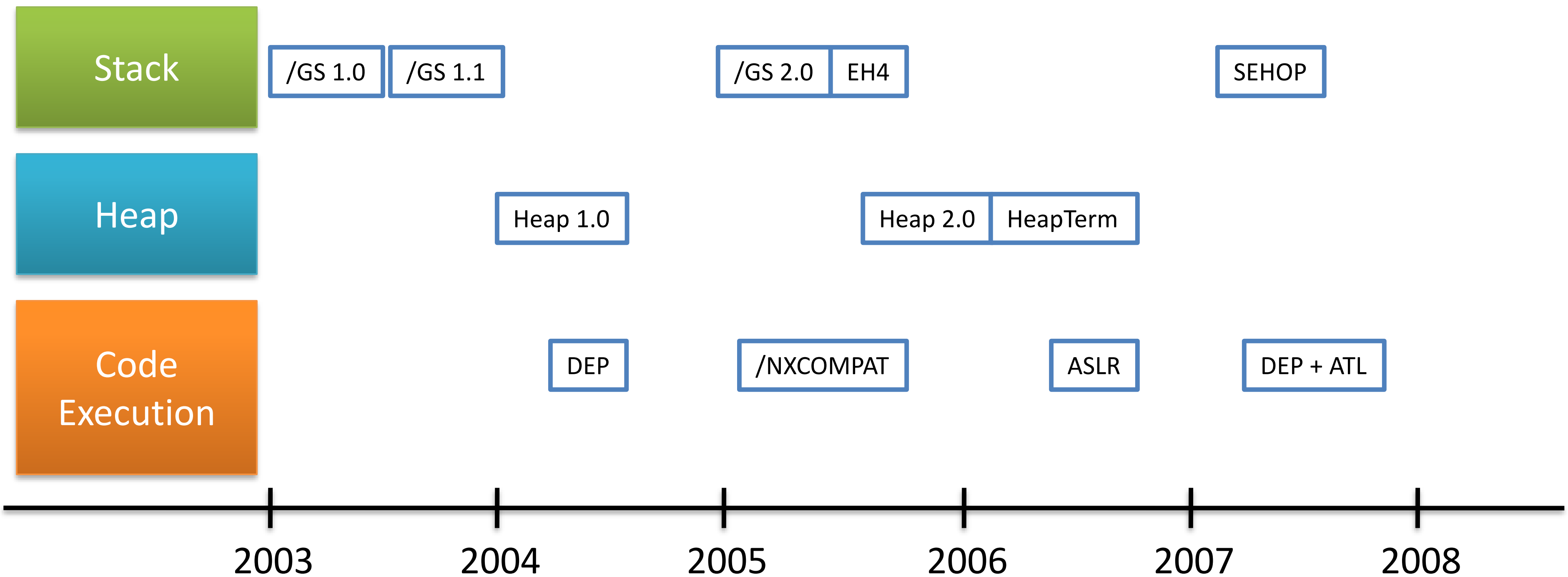
Windows Vista SP1 and Windows Server 2008 RTM

- SEH Overwrite Protection (SEHOP)
  - Dynamic SEH chain validation
  - GS+SEHOP = robust mitigation for most stack buffer overruns!



- Kernel mode ASLR
  - NT/HAL (5 bits of entropy)
  - Drivers (4 bits of entropy)

Exploit Mitigations Timeline



ACT II

FUTURE MITIGATIONS & OPEN PROBLEMS

Mitigation

GS – effective or not?

- Vista
  - GS fundamentally the same
  - Many bypasses closed off via OS improvements
    - EH abuse
    - NX/DEP
    - ASLR
- Vista released worldwide 30^{th} January 2007
- MS07-017 security bulletin 10^{th} April 2007
  - Trivially exploitable stack overflow in ANI file parsing

Mitigation

The GS heuristic

- Not all functions GS-protected
  - Obvious and less obvious performance cost
- Insert cookie for
  - arrays of size>4 with element size <= 2 (char/wchar)
  - Structures containing arrays with element size <=2
- Originally designed to mitigate overflows arising from untrusted **string** data

Mitigation

MS07-017 – ANI stack overflow

- The target of the overflow was a ANIHEADER structure on the stack:

```
typedef struct _ANIHEADER {
  DWORD cbSizeof;
  DWORD cFrames;
  DWORD cSteps;
  DWORD cx, cy;
  DWORD cBitCount, cPlanes;
  DWORD jifRate;
  DWORD fl; } ANIHEADER, *PANIHEADER;
```

Mitigation

MS07-017 – ANI stack overflow

- The ANIHEADER overflow equivalent to:

```
ANIHEADER   myANIheader;
memcpy(&myANIheader,
    untrustedFileData->headerdata,
    untrustedFileData->headerlength);
```

- No character buffers on the stack

  ⇒No GS protection

  ⇒myANIheader is being *treated* like a character buffer

Mitigation

Target buffer mitigated by GS?

Security bulletin	GS?	
MS03-026 (Blaster)	**Yes**	
MS06-040	**Yes**	
MS07-029	**Yes**	
MS04-035 (Exchange)	**No**	DWORD array
MS06-054 (.PUB)	**No**	structure populated from file
MS07-017 (.ANI)	**No**	structure populated from file

Mitigation

Vista SP1

- In development at time of ANI vulnerability
- #pragma strict_gs_check?
- More aggressive GS heuristic
- Much more aggressive GS heuristic
- Any address-taken local variable is considered a potential target!

Mitigation

strict GS

Target buffer mitigated by GS?

Security bulletin	Legacy GS		Strict GS
MS03-026 (Blaster)	Yes		Yes
MS06-040	Yes		Yes
MS07-029	Yes		Yes
MS04-035 (Exchange)	No	DWORD array	Yes
MS06-054 (.PUB)	No	Data structure	Yes
MS07-017 (.ANI)	No	Data structure	Yes

Mitigation

strict GS

```
#pragma strict_gs_check(on)
void main()
{
   int i;

   printf("%d", (int) &i); // address-taken
}
```

Mitigation

strict GS

- Applied in a very targeted way for Vista SP1

Binary	Functions in DLL	OS	Number of cookies	% protected functions	Factor increase
qasf.dll	1526	**Vista RTM (GS)**	58	3.80%	3.5
		Vista SP1 (strict GS)	202	13%	
avifil32.dll	494	**Vista RTM (GS)**	40	8.10%	3.4
		Vista SP1 (strict GS)	134	27%	
WMASF.dll	1484	**Vista RTM (GS)**	40	2.70%	13.1
		Vista SP1 (strict GS)	524	35%	

- But not suitable for system-wide deployment

  ⇒GS++

Mitigation

GS++ heuristic ?

- All arrays?
- All structures?

Performance concerns!

What subset is most likely to contain untrusted data?

Mitigation

GS++ heuristic

Arrays where element type not of pointer type:

- `char myBuf[]`
- `DWORD myBuf[]`
- `HANDLE myBuf[]`

and size of array is >2 elements

Mitigation

GS++ heuristic

- Structures:
  - Containing an array where element type is not of pointer type.
  - Made up of pure data:
    - No members of pointer type
    - >8 bytes in size
    - Default constructor/destructor

```
struct _ANIHEADER{
DWORD cbSizeof;
DWORD cFrames;
DWORD cSteps;
DWORD cx, cy;
DWORD cBitCount
DWORD cPlanes;
DWORD jifRate;
DWORD fl; };
```

Mitigation

Impact on cookie count

GS-protected functions in sample code

	Original GS	VS2010 GS
User/client	9608	12846
Kernel	2361	4686
User/client (% total fns)	6.0%	8.0%
Kernel mode (% total fns)	5.2%	10.4%

⇒Cookie increase between 2% and 5%

Mitigation

GS optimization

- No GS cookies when usage is provably safe

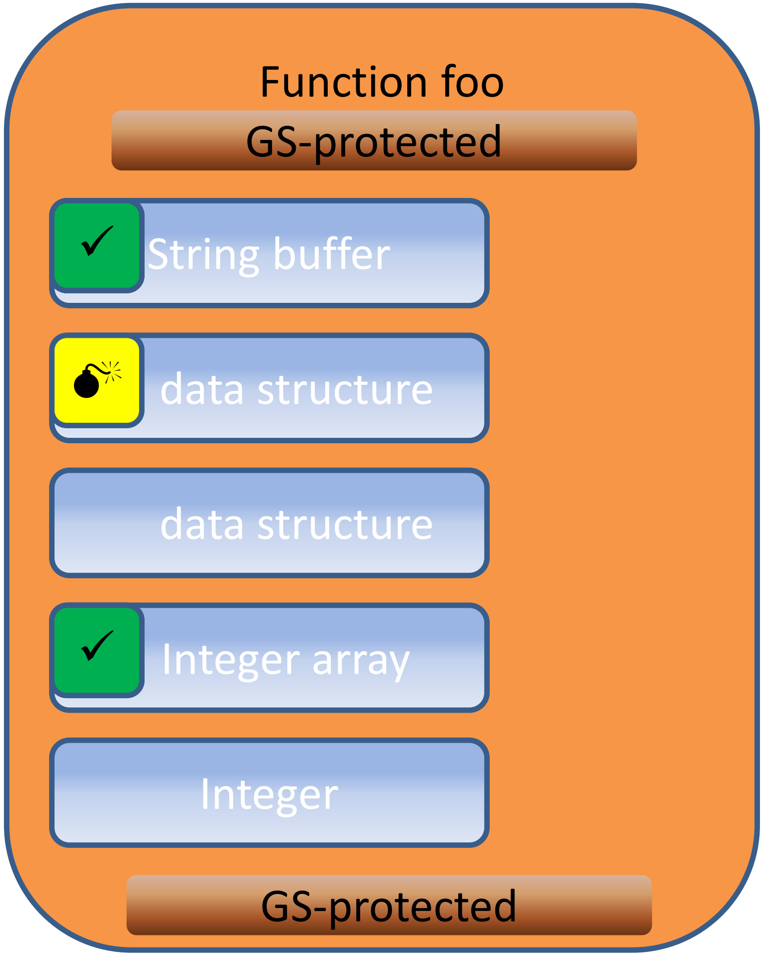
✓

```
STDAPI ConsumeData(BYTE *pbData)
{
   BYTE Temp[MAX];

   if (pbData)
   {
     ...
       memcpy (   Temp,
                  pbData,
                  ARRAYSIZE(Temp));
     ...
   }
```

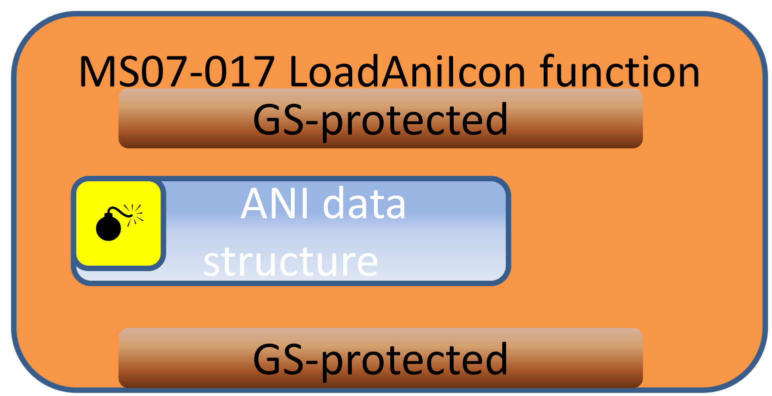
Mitigation

GS enhancements [VS2010]



- GS heuristic
  - Identify more *potential* hazards
- GS optimization
  - Some *potential* hazards turn out to be **safe**

Increased scope of heuristic:



Impact on cookie count

	Original GS	VS2010 GS	VS2010 GS [with GS opt]
User/client	9608	12846	11654
Kernel	2361	4686	3909
User/client (% total fns)	6.0%	8.0%	7.3%
Kernel mode (% total fns)	5.2%	10.4%	8.7%

Mitigation

Impact on stack overflow security bulletins

Security bulletin	Original GS	VS2010 GS	Strict GS
MS03-026 (Blaster)	Yes	Yes	Yes
MS06-040	Yes	Yes	Yes
MS07-029	Yes	Yes	Yes
MS04-035 (Exchange)	No	Yes	Yes
MS06-054 (.PUB)	No	Yes	Yes
MS07-017 (.ANI)	No	Yes	Yes

Mitigation

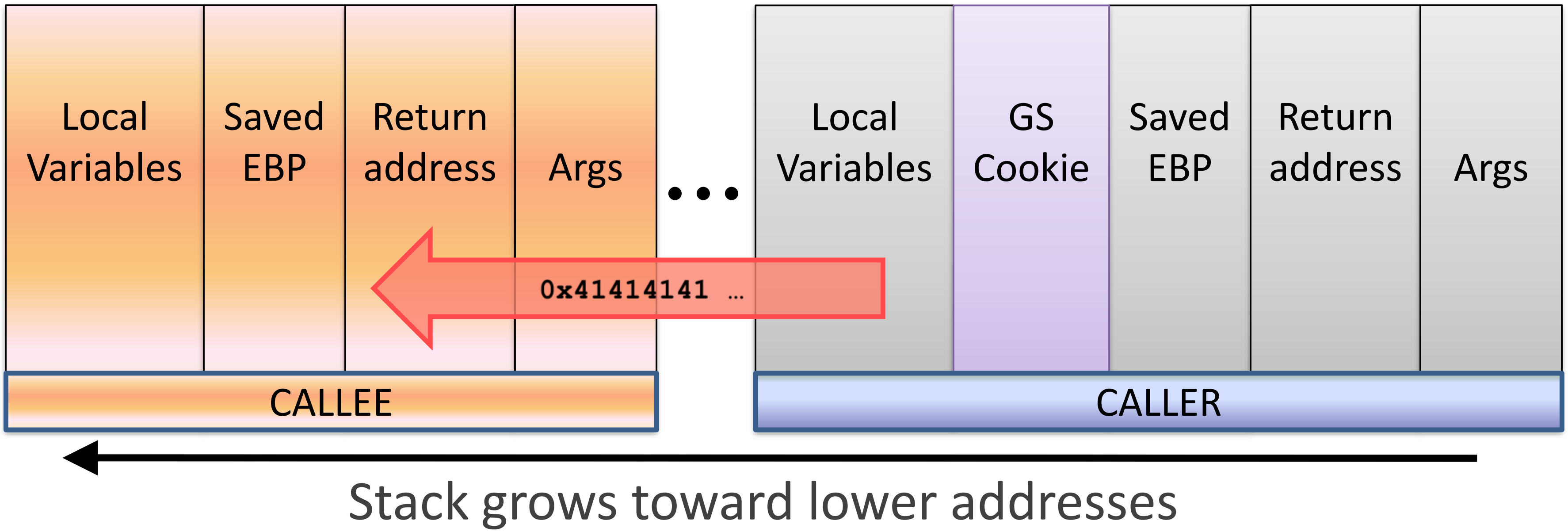
... but GS not a panacea

Security bulletin	Original GS	VS2010 GS	Strict GS
MS03-026 (Blaster)	Yes	Yes	Yes
MS06-040	Yes	Yes	Yes
MS07-029	Yes	Yes	Yes
MS04-035 (Exchange)	No	Yes	Yes
MS06-054 (.PUB)	No	Yes	Yes
MS07-017 (.ANI)	No	Yes	Yes
MS08-072	N/A	N/A	N/A
MS08-067	N/A	N/A	N/A

Mitigation

Still need to write secure code!

- Even the new heuristic will not cover all cases
- GS does not apply to some types of stack-based attacks (for example underflow).



Mitigation

GS++

- In forthcoming Visual Studio 2010 beta
  - Same /GS switch
  - Enhanced GS++ heuristic
- Planned for by release (no guarantees!)
  - GS optimization

Mitigation

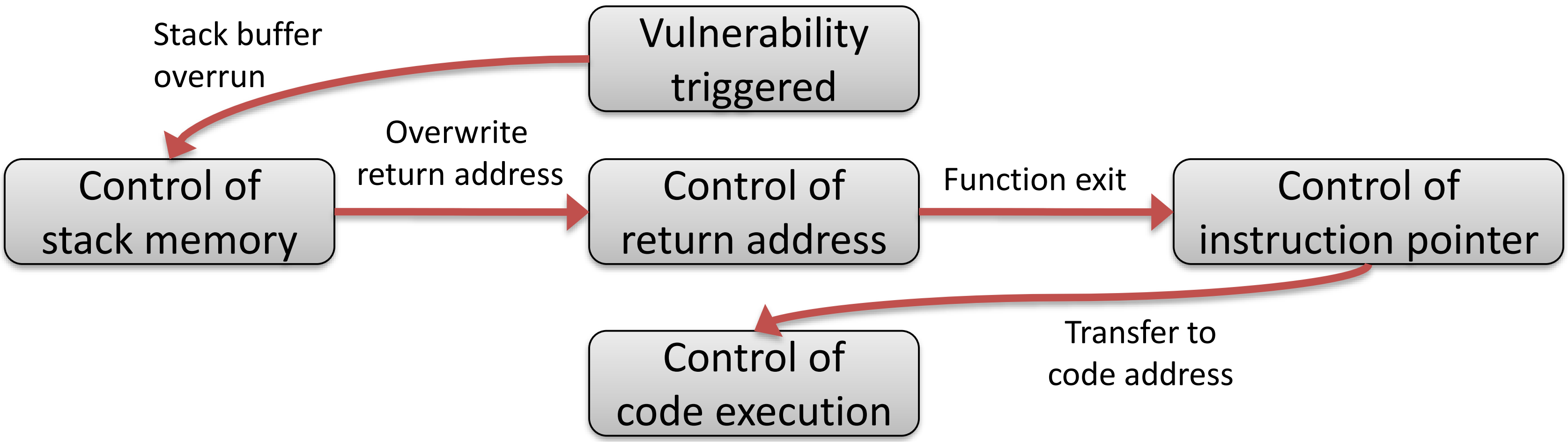
Other future enhancements

- Increased entropy for kernel mode ASLR
  - Drivers: 6 bits on x86, 8 bits on x64
- IE8 opt-in to DEP [Lawrence08]
- … and some others we can’t talk about yet ☺

Measuring exploitability

- Measuring exploitability is important [Alberts09]
  - Exploitability Index enables effective risk management
- But exploitability can be difficult to measure
  - Numerous interrelated and evolving techniques
  - Dependent upon scenario & individual expertise
- How can we objectively measure exploitability?
  - Experimental proposal: simulated exploitation

Simulated exploitation



- Abstract state-based model of *known* exploitation strategies
  - Logical exploit execution states
  - Exploitation techniques transition between states
- Exploitability derived from predicates on transitions
- **Experimental only**
  - Not used for Microsoft's Exploitability Index in bulletins
  - Provides an estimate of exploitability, not a proof

Simulated exploitation example #1

1. Input scenario configuration

Configuration	Value
hw_base_profile	p4
os_base_profile	win XP SP0
app_base_profile	default
vuln_base_profile	stack_memory_corruption
vuln_local	false
vuln_traditional	true
vuln_function_gs_enabled	false

2. Simulate

3. Output metrics

Metric	Value
Fitness	1.0
Exploitability	1.0
Desirability	1.0
Likelihood	1.0
Homogeneity	0.05
Population	0.05

```
Transitions:
   target_defined                 -> start_env_prep           -> env_prep_incomplete
   env_prep_incomplete            -> finish_env_prep          -> env_prep_complete
   env_prep_complete              -> trigger_vulnerability    -> vulnerability_triggered
   vulnerability_triggered        -> stack_buffer_overrun     -> control_of_stack_memory
   control_of_stack_memory        -> overwrite_return_address -> control_of_return_address
   control_of_return_address      -> function_exit            -> control_of_instruction_pointer
   control_of_instruction_pointer -> transfer_to_code_address -> control_of_code_exec
Assumptions:
   can_overwrite_stack_memory()   -> 1.0                 [stack_buffer_overrun]
   can_overwrite_return_address() -> 1.0                 [overwrite_return_address]
   can_control_stack_pointer()    -> 1.0                 [overwrite_return_address]
   can_find_address(code)         -> 1.0                 [transfer_to_code_address]
```

Simulated exploitation example #2

1. Input scenario configuration

Configuration	Value
hw_base_profile	p4
os_base_profile	win XP SP0
app_base_profile	default
vuln_base_profile	stack_memory_corruption
vuln_local	false
vuln_traditional	true
vuln_function_gs_enabled	true

2. Simulate

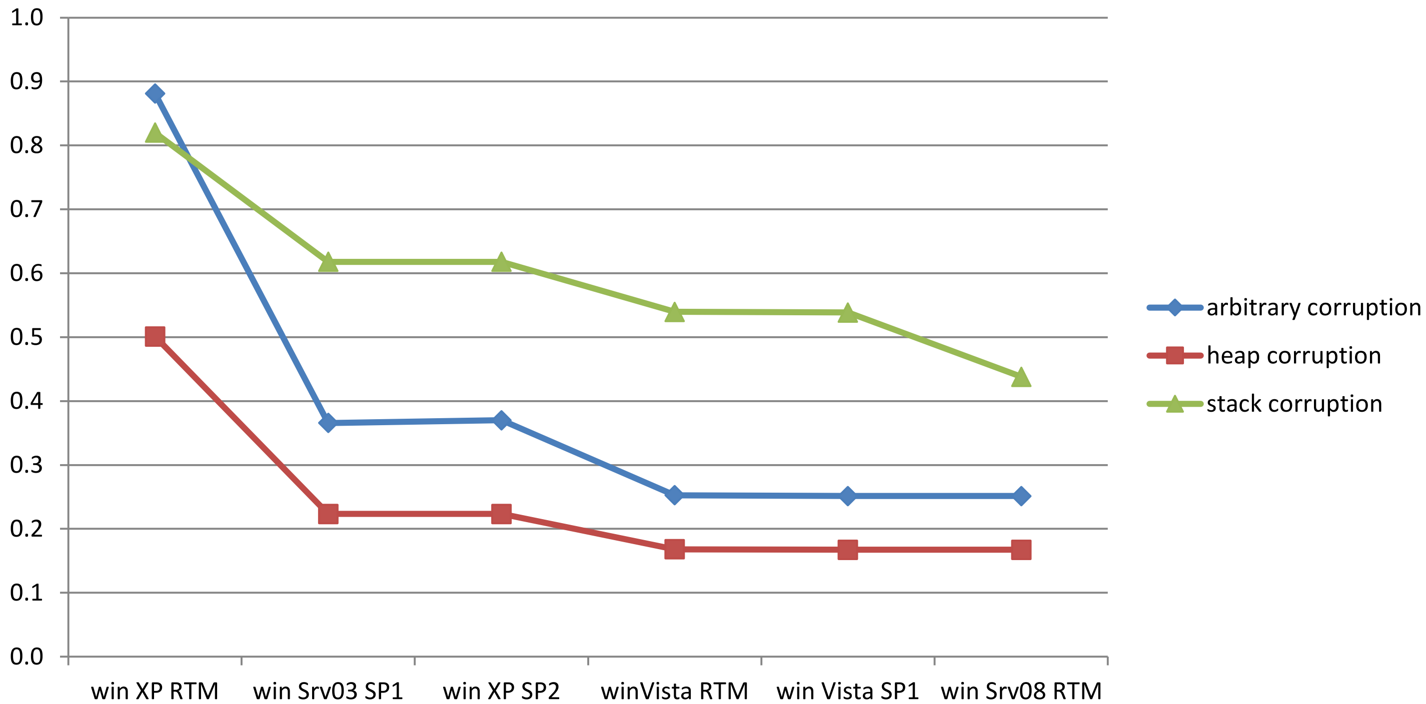
3. Output metrics

Metric	Value
Fitness	2.3283e-10
Exploitability	2.3283e-10
Desirability	1.0
Likelihood	1.0
Homogeneity	1.1642e-11
Population	0.05

```
Transitions:
   target_defined                 -> start_env_prep            -> env_prep_incomplete
   env_prep_incomplete            -> finish_env_prep           -> env_prep_complete
   env_prep_complete              -> trigger_vulnerability     -> vulnerability_triggered
   vulnerability_triggered        -> stack_buffer_overrun      -> control_of_stack_memory
   control_of_stack_memory        -> overwrite_return_address  -> control_of_return_address
   control_of_return_address      -> function_exit             -> control_of_instruction_pointer
   control_of_instruction_pointer -> transfer_to_code_address  -> control_of_code_exec
Assumptions:
   can_overwrite_stack_memory()   -> 1.0                  [stack_buffer_overrun]
   can_overwrite_return_address() -> 1.0                  [overwrite_return_address]
   can_control_stack_pointer()    -> 1.0                  [overwrite_return_address]
   can_guess_gs_cookie()          -> 2.3283064365387e-10  [function_exit]
   can_find_address(code)         -> 1.0                  [transfer_to_code_address]
```

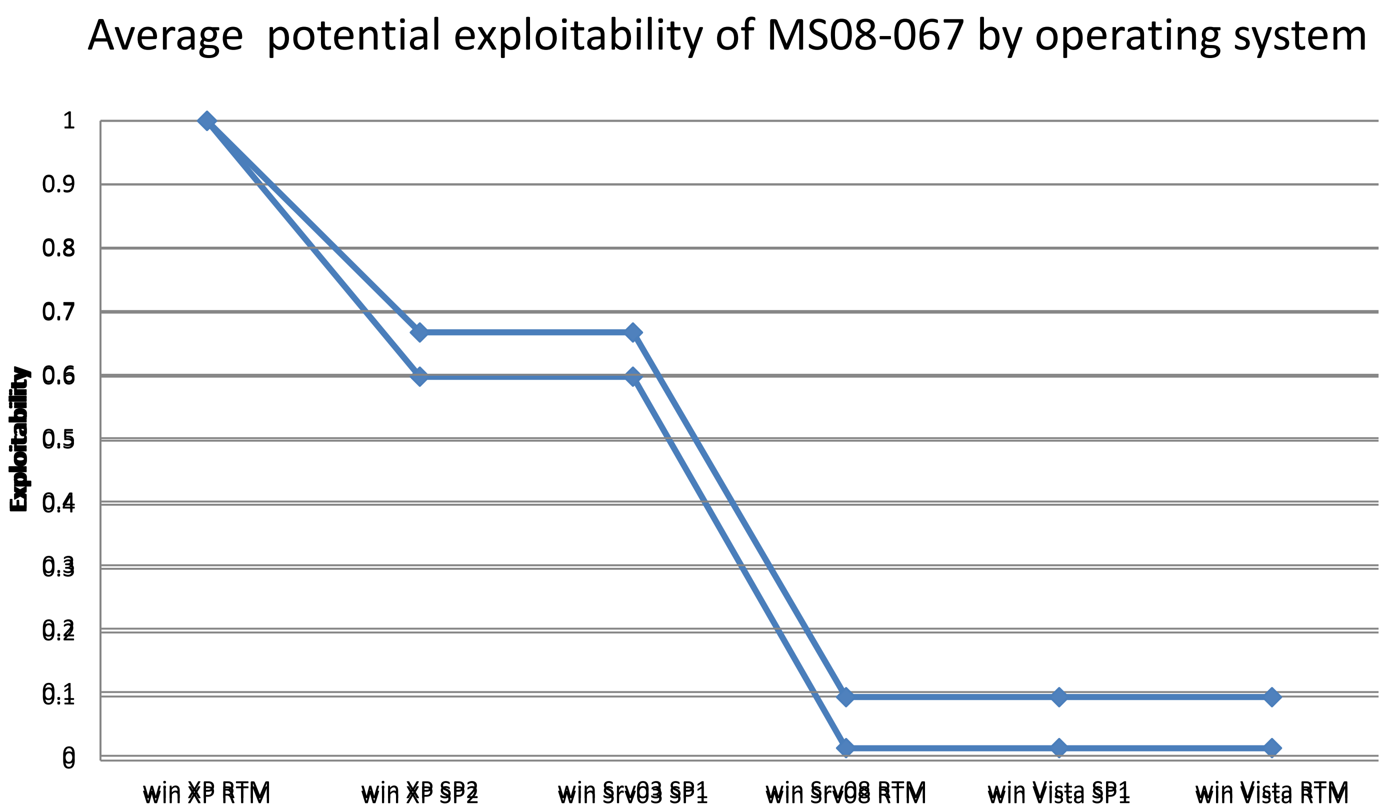
Analyzing simulation data

What if we ran the simulator across all vulnerability scenario permutations?



Average exploitability for general classes of vulnerabilities by major operating system as computed across varying hardware, OS, application, and vulnerability profiles

Analyzing simulation data



Scenario defined as:
remote, non-traditional, stack-based buffer overrun, GS not present, in the context of svchost.exe
and NX hardware present

So what good is this stuff?

- Provides a flexible understanding of exploitability
  - Effectiveness of exploitation & mitigation techniques
  - The ability to evaluate specific vulnerability scenarios
- Not dependent on individual knowledge
  - The model aggregates all domain knowledge
  - This doesn’t mean it’s perfect (exploitation is an art)
- Can be used to measure the impact of open problems
  - Intuition can do this as well, but less concretely

Open Problems

Exploitation techniques

- Non-traditional memory corruption
  - Corruption at attacker-controlled offsets
  - Examples: MS08-067, Flash NULL deref [Dowd08]
- Corruption of in use heap objects
  - Overwriting application specific data [Waisman07]

Open Problems

Mitigation weaknesses

- Address space predictability
  - Address space spraying (heap, stack, etc)
  - Fixed mappings (e.g. IL only assembly) [Sotirov08]
  - Information disclosure [Soeder06]
  - Brute forcing [Sotirov07]

- NX evasion
  - Migration to VirtualProtect/VirtualAlloc region
  - Migration to executable heap

Open Problems

Contextual weaknesses

- Kernel mode
  - Executable pool memory
  - NULL pointer dereferences (local priv escalation)
- Extensible applications [Sotirov08]
  - Significant range of control given to attacker
- Applications without mitigations enabled
  - Adoption of existing mitigations (DEP, ASLR, SEHOP)

Conclusion

- Modern exploitation is difficult & not universal
  - Techniques are tied to specific vulnerability scenarios
- Gaps do exist that can make exploitation easier
  - But these are the exception, not the rule
- We are committed to protecting our customers
  - Continued improvement of our mitigation technology
  - Providing actionable exploitability data with bulletins

Questions?

Thank you!

- Exploit mitigation feedback or ideas? Contact us!
  - switech@microsoft.com
- Security Science at Microsoft
  - http://www.microsoft.com/security/msec
- Security Research & Defense blog
  - http://blogs.technet.com/srd

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