Automated vulnerability analysis of zero sized heap allocations

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Zero alloc: what is it ?

Scenario 1:

```
UINT size = readfromuntrusted();
PCHAR ptr = malloc(size);

if (ptr == NULL) return -ERR;
memcpy(ptr, data, size-1);
```

Test for NULL does not replace a 0-size check!

Zero alloc (2)

Scenario 2:

```
PSTRUCT data = readfromuntrusted();
if (data->nbr > MAXSHORT) return -ERR;
UINT size = data->nbr * sizeof(TYPE);

PSTRUCT2 ptr = Alloc(size);
if (ptr == NULL) return -ERR;
ptr->field = data->field;
```

Failure to test lower bound of allocated size

Zero alloc (3)

Scenario 3:

```
UINT size;
UCHAR *ptr;

size = readuntrusted() + sizeof(TYPE);
ptr = Alloc(size);
if (ptr == NULL) return -ERR;
memcpy(ptr, (TYPE*)buf, sizeof(TYPE));
```

Fail to test upper bound of modulo arithmetic

Overview

- ISO C99: *"If the size of the space requested is zero, the behavuior is implementation defined : either a null pointer is returned, or the behaviour is as if the size were some nonzero value, except that the returned pointer shall not be used to access an object."*
- Similar characterization are given in ANSI and earlier ISO C standards : the allocator can choose to return NULL or a "valid" pointer. Most allocators return the address of a valid heap chunk.
- This is not a class of vulnerability, more of an analysis technique to find new buffer overflows when the size of a heap memory chunk fails to follow certain constraints.
- We have an internal tool (Havoc/0-Alloc) that finds all such code occurrences automatically in large depots of C source code.

Presentation outline

1. Vulnerability assessment
   - Zero allocations tests
   - Ex1: A first historical zero allocation kernel bug
   - Ex2: Local escalation of privilege kernel bug due to a zero allocation

2. Static analysis of zero allocations
   - Automated deduction tools and techniques
   - HAVOC: a heap-aware verifier for C programs
   - Ex3: finding complex bugs with HAVOC

3. Generalization: near-zero allocation analysis
   - Ex4: Remote user-land heap overflow vulnerability

Part I

Vulnerability assessment

A. Testing: is your environment exposed?

Windows kernel zero allocation

Dummy kernel driver

```
DriverEntry()
{
(…)
for (i = 0; i < 5; i++)
{
    //Main kernel memory allocator
    char *ptr = (char *)
    ExAllocatePoolWithTag(0, 0, 0);
    KdPrint(("A: %08p \n", ptr));
}
(…)
```

Result when loaded as testdrv

testdrv: A: 89DC61B8

testdrv: A: 8980E328

testdrv: A: 89DA11A8

testdrv: A: 8976E7B8

testdrv: A: 89963E08

Root cause: ExAllocatePoolWithTag(0) returns a valid chunk

```
POOLCODE _ExAllocatePoolWithTag@12 proc
(…)
  mov    edi, [ebp+NumberOfBytes]
(…)
   test   edi, edi            ; if (NumberOfBytes == 0)
   jnz    short loc_4E4132
   inc    edi                 ; NumberOfBytes = 1;
POOLCODE:004E4132:
   add    edi, 0Fh            ; ROUNDUP(NumberOfBytes);
(…)
```

User-land tests

Compiled with: cl alloc0-user.c /link /dynamicbase as to enable ASLR

c:\win7rtm>alloc0-user.exe
Malloc returns : 000518F8 00051908 00051918 00051928 00051938 00051948 00051958
HeapAlloc returns : 00263FD8 00263FE8 00263FF8 00264008 00264018 00264028 00264038
VirtualAlloc returns : NULL NULL NULL NULL NULL NULL NULL

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VirtualAlloc returns : NULL NULL NULL NULL NULL NULL NULL

Zero allocs on UNIX

	User-land exposed	Kernel-land exposed
Linux (Debian / 2.6)	Yes	Yes (*)
Linux (Debian / 2.6 / PaX)	Yes	No (*)
FreeBSD (5.5)	No (**)	Yes
NetBSD (3.0.1)	Yes	Yes
OpenBSD (4.4)	Yes	Yes
Solaris (10)	Yes	Yes (***)
MacOsX (Leopard)	Yes	Yes

(*) Default linux kmalloc returns constant 0x10 (vulnerable to NULL ptr dereference unless mmap protection). PaX returns 0xFFFFF000 which is unmapped memory.
(**) Userland FreeBSD allocator returns a constant 0x800 on malloc(0). We suppose this is not exploitable (unless someone can exploit userland NULL derefs..)
(***) Solaris kernel allocator returns NULL on zero size. Checking the return of such function is necessary, else NULL dereference happens.

B. Examples of fixed problems

Disclaimer: The names have changed to protect the guilty.

Kernel bug due to a zero allocation

```
__kernel_entry BOOL MyNTSyscallEntryPoint(HANDLE h, PSTRUCT1 pData)
{
   PSTRUCT1       safedata = Handle2Ptr(h);
   DWORD          count;
   try {
      PSTRUCT2 curData = ProbeAndRead(pData);      // user-controlled data
      if (curData.flags & COND_FLAG)               // user-controlled test
         count = (curData.field1 * sizeof(HANDLE)) +   // count can be 0
                 (curData.field2 * sizeof(HDRTYPE)) +
                 (curData.field3 * sizeof(DWORD));
   (…)
   retval = _SetData(safedata, curData, count);    // calling internal function
   (…)
```

Kernel bug continued

```
// Precondition: count can be 0
BOOL _SetData(PSTRUCT1 safedata, PSTRUCT2 curData, DWORD count)
{
   PSTRUCT2 tmparray;
   if (pcur->flags & FLAG_ENABLED) {                    // we will enter here
      tmparray = UserAllocPool(count, USERTAG_POOL);  // zero-allocation happens!
      if (temp == NULL) return –ERR;                    // The check is bypassed
      safedata->array = tmparray + sizeof(BIGSTRUCT);   // Dangling ptr arithmetic
       // Copying 0 bytes: nothing happens ! (but see next slide)
       try {  RtlCopyMemory(safedata->array, curData->array, count); }
      except { return –ERR; }
    }
    return ESUCCESS;
}
```

Kernel bug continued (2)

```
__kernel_entry NTSTATUS NtOtherRelatedSyscall(HANDLE h)
{
   PSTRUCT1 p1;
   PSTRUCT2 p2;
   (…)
   p1 = Handle2Ptr(h);                    // We look up the same kernel structure
   if (p1->flags & FLAG_ENABLE) {   // this is the previous corruption condition!
        if (p1->array == NULL) return –ERR;
         // p1->field2 is 0 but p1->array is dangling!
         // Invalid array lookup (but no escalation of privilege, crash only)
         p2 = p1->array[p1->field2];
      }
(…)
```

Early conclusions

- A zero allocation does not lead to a systematic problem (copying few bytes of memory in a zero allocated chunk is generally safe)
- When a real problem shows up, it is not always a severe security threat (sometimes only a crash)
- A local check is not enough to assess the severity of a bug (dangling kernel pointers can be reused across system calls)

A zero allocation can also lead to a real security vulnerability. We now give such example…

Ex2: zero alloc leads to heap overflow

```
__kernel_entry NtSomeNewSyscall(PVOID lParam)
{
 PSETTING psetting;
 PLARGE_STRING pls;
 if (lParam) {
    try {
    psetting = (PSETTING)lParam;
    // No validation on count (can be 0!)
    count = ProbeAndReadUlong(&(psetting->DataLength)) + 1;
    pls = UserAllocPoolWithQuota(count, USERTAG_FLAGS); // Zero allocation
    RtlCopyMemory(pls, (PBYTE) lParam, count);     // Nothing happens as count = 0
    }
   retval = _NewInternalFunction(NULL, pls);    // Internal function is called
 (…)
```

EoP bug explained (continued)

```
Void _OtherInternalFunction(PVOID p, PLARGE_STRING lparam)
{
    LARGE_UNICODE_STRING str;
    PLARGE_STRING pstr;
    if (p == NULL)  {                          // we satisfy this condition (first param)
      pstr = lParam;                           // Remember lParam is dangling
      cbAlloc = pstr->Length + sizeof(WCHAR); // Alloc size set from uninitialized data
      // Another uncontrolled allocation happens
      str.Buffer = UserAllocPoolWithQuota(cbAlloc, USERTAG_FLAG);
      try {
          str.Length = pstr->Length;                    // Uninitialized length is used
          memcpy(str.Buffer, pstr->Buffer, str.Length); // The worse can happen…
          str.Buffer[str.Length / sizeof(WCHAR)] = 0;   // … twice.
      }
  (…)
```

Part II

Automated analysis

The need for automated analysis

- Even though we do a lot of code review, human error can lead to missing bugs.
- Important is not how many vulnerabilities you find, but how many you miss.
- Some particular classes are recurrent. We want to fix those and prove the absence of bug with higher assurance before shipping (for older products: before customers hit them).
- We introduce the use of HAVOC for property-based security assessment of C source code.

Automated techniques
Dataflow analysis (DFA)

DFA helps to find approximate conservative solution to hard problems.

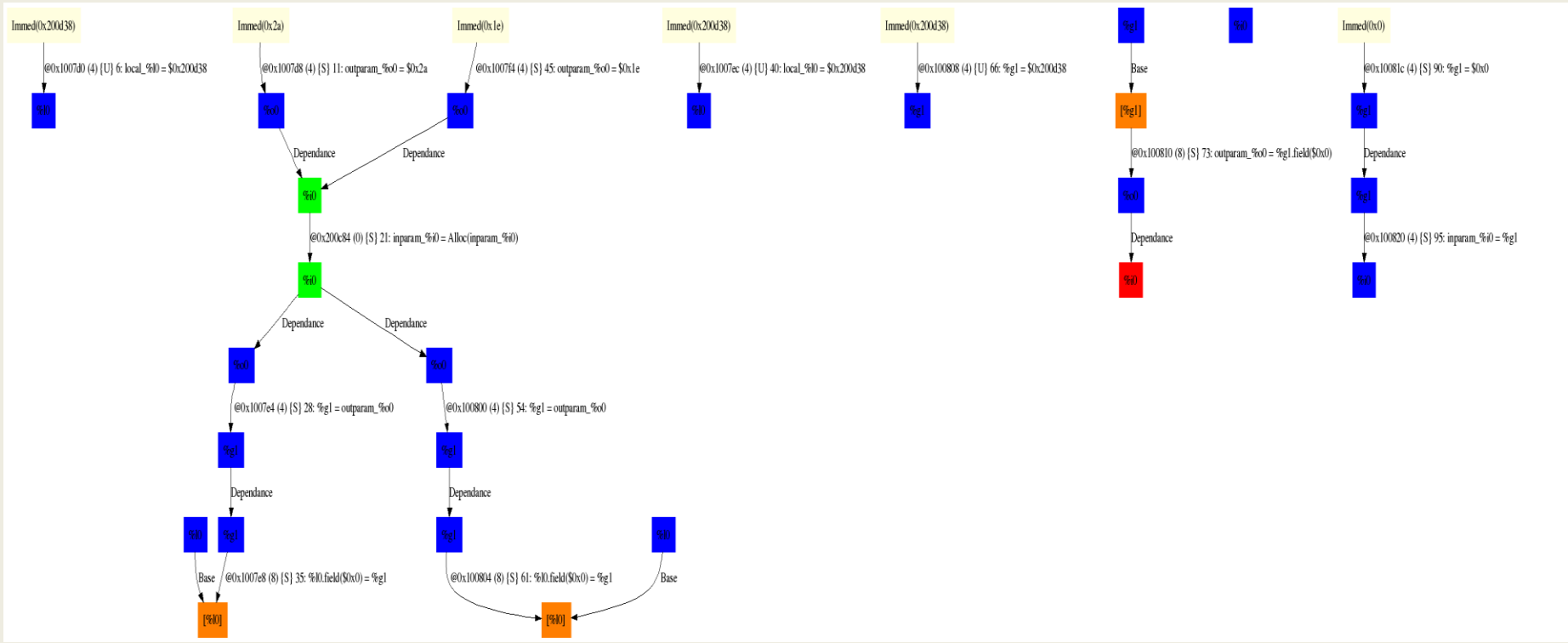
- Most compilers (GCC, LLVM, Phoenix, etc) use dataflow analysis techniques and intermediate language representation during code translation. (Ex: Static Single Assignment – SSA – form)
- With some implementation effort, an analyst can build a program analyzer within the compiler.
- Many security bugs can already be detected with such technique (ex: memory leaks, double free, uninitialized vars, etc)

Good: fast, scalable, conservative (no forgotten behaviour)

Bad: hardcoded algorithms, *too conservative (false positives)*

A data dependence graph

- Data dependence graphs (DDG) are built first based on use-def chains. In below graph, nodes are variables, green are malloc nodes while red are free nodes. Arrows are dependences between variables.
- Reachability, liveness or value flow analysis can be performed on top of DDG.
- Analysis is more refined when control predicates are retained in the IR.



Automated technique 2: Model checking

- **Model checking is an implementation of formal verification of programs that operates at a higher level than data-flow analysis. MC is suitable to resolve more complex properties in big systems such as concurrent hardware and programs.**

1. A specification formula F is written in a chosen formal logic
   ex: Linear Temporal Logic (LTL), but there are many others…
   ex: **G (Alloc(x) => x != 0)** stands for: *Always (**G**) if Alloc(x) is true then x is not 0*

2. The program to analyze is represented as a state-transition system
   - Nodes are states of the analyzed program.
   - Transitions represent changes in the values of system variables.
   - Our example introduces a predicate Alloc(x) that is only true on allocation sites

See next slide..

Model checking (cont)

3. The algorithm checks statically if the formula is satisfied at runtime:
   - Check exhaustively all sequence of transitions in the system.
   - If any system path makes the formula false, there is a state where program specification is violated (e.g. we found a bug)

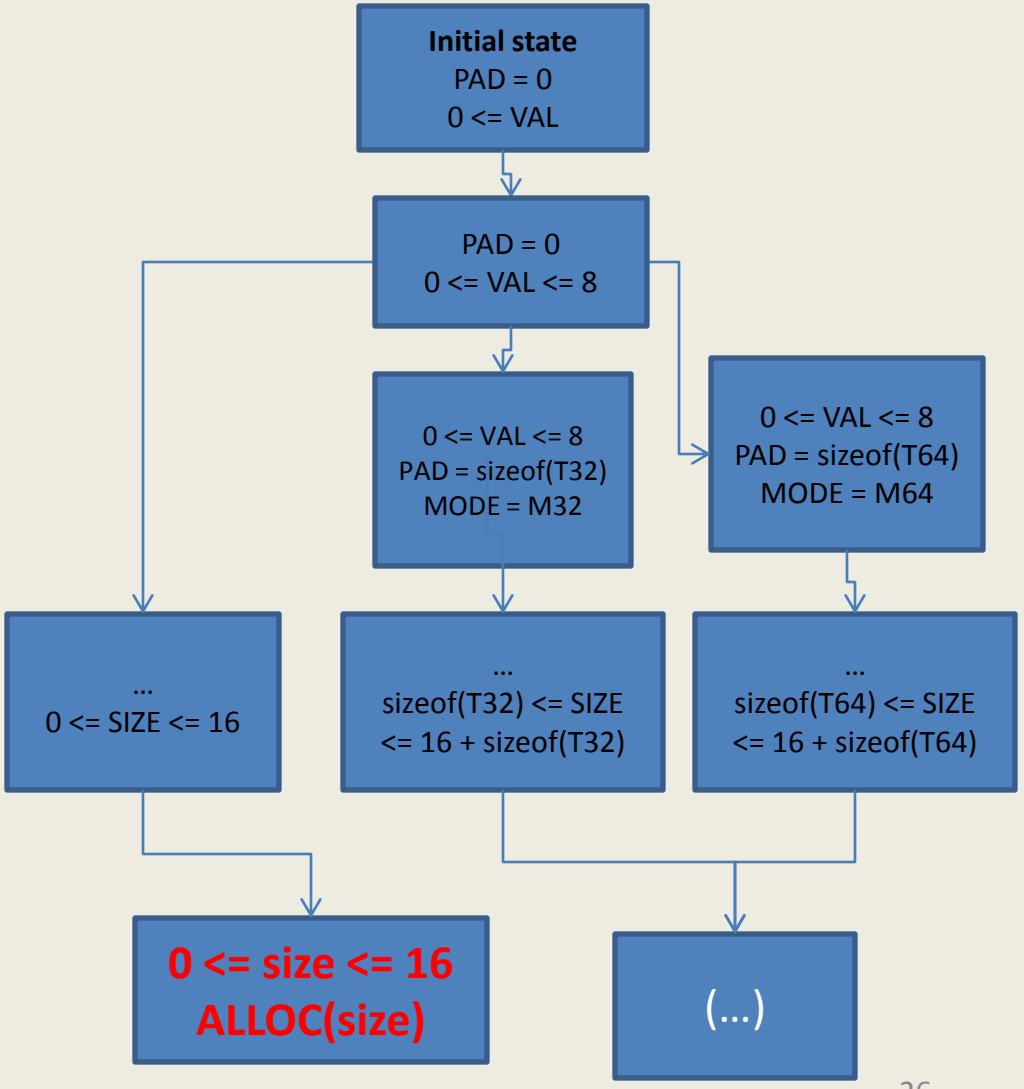
Good: Universal technique, completely automated.
Many existing tools (SPIN, SLAM, BLAST, SPOT, etc)

Bad: make state space explicit (combinatorial explosion)

- ***Model checkers can be used in conjunction with flow analyzers to verify complex program properties expressed in a formal logic.***

State-transition graph

```
Int func(UINT val, int mode)
{
1. UINT size, pad = 0;
2. if (val > 8) return ERR;
3. if (mode == M32)
4.  pad = sizeof(T32);
5. else if (mode == M64)
6.   pad = sizeof(T64);
7. size = val*2 + pad;
8. PTYPE ptr = Alloc(size);
(…)
```



We can reach a state where
G (Alloc(x)=> (x != 0)) is false

Automated techniques (3) Theorem Proving (TP)

- TP is a mathematical technique of logical proof checking that can reason precisely about call-free/loop-free programs.
- A verification condition (VC) is constructed that captures all paths within each procedure of the analyzed program.
- Pre-conditions and post-conditions (e.g. assert(F)) are enforced/checked at specific program points.
  - Pre/post-conditions can be written manually, prover will check them.
  - We can write a wrapper tool that will also generate pre/post-conditions automatically when the program locations of interest can be easily guessed.

Theorem proving

- Checking a formula F can have two results:
  - For program points of interest, no scenario can violate the requested pre/post condition. The program is free of such mistakes at checked program points. Or..
  - We cannot prove F at some program point P, the verifier emits a warning and provide the counter-example (faulty) trace ending at P.

Good: Precise technique (no approximation), scales well (modular analysis).

Bad: May require users to specify procedure contracts manually

We have applied TP on many kernel components (some of 1 million LOC)

Dummy example reloaded
Logical inference

```
int f(UINT val, bool mode)
{
UINT size, pad = 0;
if (val > 8) return ERR;
size = val * 2;
if (mode == M32)
  pad = sizeof(T32);
else if (mode == M64)
   pad = sizeof(T64);
size += pad;
PTYPE ptr = Alloc(size);
                                    __requires(size != 0)
(…)
```

Dummy example (step 1)

```
int f(UINT val, bool mode)
{
UINT size, pad = 0;
if (val > 8) return ERR;
size = val * 2;
if (mode == M32)
  pad = sizeof(T32);
else if (mode == M64)
   pad = sizeof(T64);
size += pad;
PTYPE ptr = Alloc(size);
```

Inferred formula

f1: pad=0

__requires(size != 0)

Dummy example (step 2)

```
int f(UINT val, bool mode)
{
UINT size, pad = 0;
if (val > 8) return ERR;
size = val * 2;
if (mode == M32)
  pad = sizeof(T32);
else if (mode == M64)
   pad = sizeof(T64);
size += pad;
PTYPE ptr = Alloc(size);
```

Inferred formula

f1: pad=0

f2: f1 && (size == val*2) && (val <= 8)

__requires(size != 0)

Dummy example (step 3)

```
int f(UINT val, bool mode)
{
UINT size, pad = 0;
if (val > 8) return ERR;
size = val*2;
if (mode == M32)
  pad = sizeof(T32);
else if (mode == M64)
   pad = sizeof(T64);
size += pad;
PTYPE ptr = Alloc(size);
```

Inferred formula

f1: pad=0

f2: f1 && (size == val*2) && (val <= 8)

f3: pad=sizeof(T32) && (size == val*2) && (val <= 8)

__requires(size != 0)

Dummy example (step 4)

```
int f(UINT val, bool mode)
{
UINT size, pad = 0;
if (val > 8) return ERR;
size = val*2;
if (mode == M32)
  pad = sizeof(T32);
else if (mode == M64)
   pad = sizeof(T64);
size += pad;
PTYPE ptr = Alloc(size);
```

Inferred formula

f1: pad=0

f2: f1 && (size == val*2) && (val <= 8)

f3: pad=sizeof(T32) && (size == val*2) && (val <= 8)

f4: pad=sizeof(T64) && (size == val*2) && (val <= 8)

__requires(size != 0)

Dummy example (step 5)

```
int f(UINT val, bool mode)
{
UINT size, pad = 0;
if (val > 8) return ERR;
size = val*2;
if (mode == M32)
  pad = sizeof(T32);
else if (mode == M64)
   pad = sizeof(T64);
size += pad;


PTYPE ptr = Alloc(size);
```

Inferred formula

f1: pad=0

f2: f1 && (size == val*2) && (val <= 8)

f3: pad=sizeof(T32) && (size == val*2) && (val <= 8)

f4: pad=sizeof(T64) && (size == val*2) && (val <= 8)

f5: (size == val*2 + pad) && (val<=8) &&
(pad=0 || pad=sizeof(T32) || pad=sizeof(T64))

__requires(size != 0)

Dummy example (step 6)

```
int f(UINT val, bool mode)
{
UINT size, pad = 0;
if (val > 8) return ERR;
size = val*2;
if (mode == M32)
  pad = sizeof(T32);
else if (mode == M64)
   pad = sizeof(T64);
size += pad;


PTYPE ptr = Alloc(size);
```

Inferred formula

f1: pad=0

f2: f1 && (size == val*2) && (val <= 8)

f3: pad=sizeof(T32) && (size == val*2) && (val <= 8)

f4: pad=sizeof(T64) && (size == val*2) && (val <= 8)

f5: (size == val*2 + pad) && (val<=8) &&
(pad=0 || pad=sizeof(T32) || pad=sizeof(T64))

f6: 0 <= size <= 16 + MAX(0, sizeof(T32), sizeof(T64))

__requires(size != 0) **Precondition violation!**

In practice, we analyze each path separately to avoid approx. at merge points.

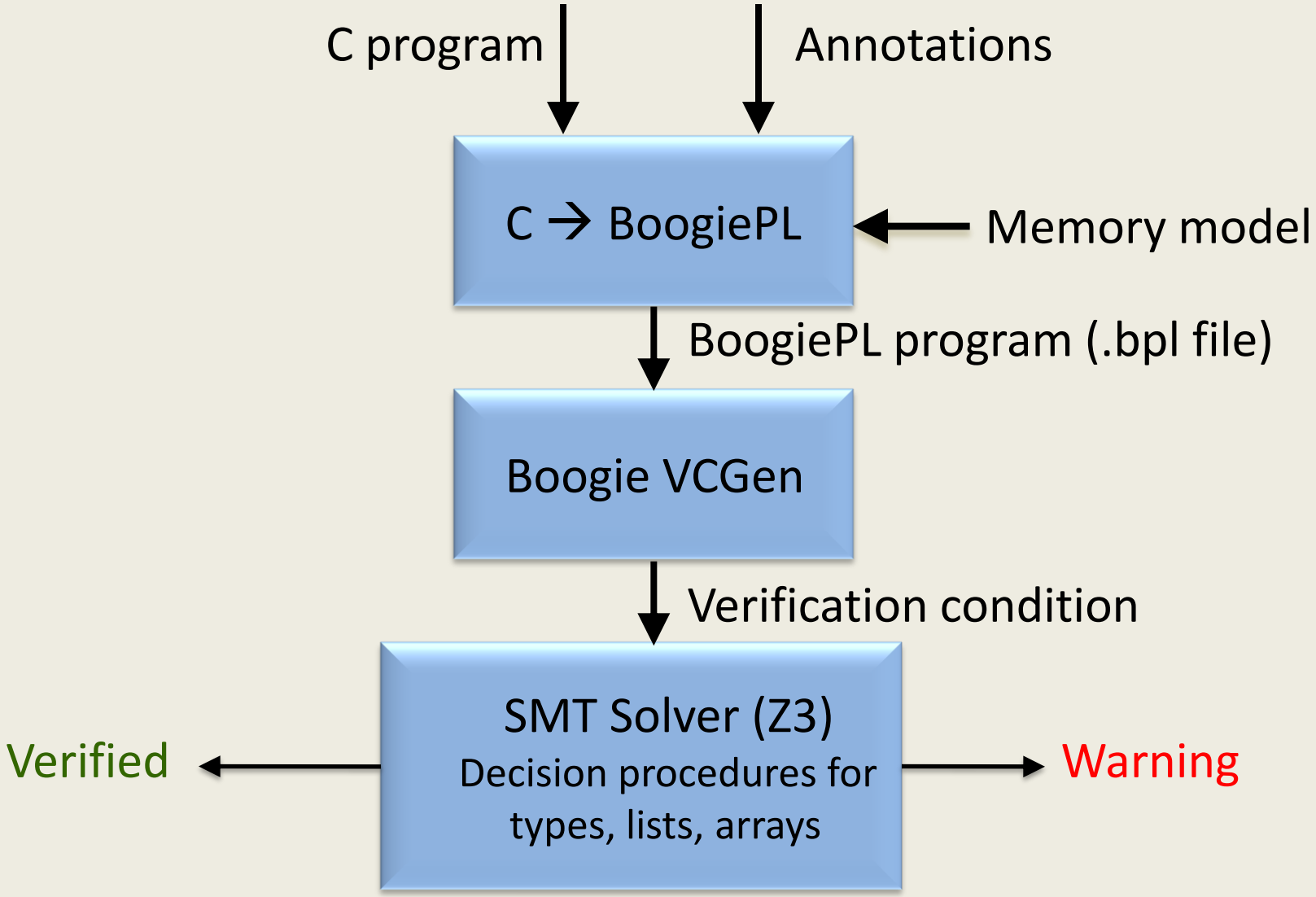
Automated analysis : HAVOC

- **HAVOC: Heap Aware Verifier for C programs**
  - **A static analysis tool for source code:**
    - **Based on the Boogie theorem prover**
    - **Uses a documented code IR : BoogiePL**
    - **Decision procedure based on constraint solving (Z3)**
    - **User can specify properties to be checked via annotations**

- **Project developed at Microsoft Research in the RiSE team**
  - *http://research.**microsoft**.com/en-us/projects/**havoc**/*
  - **Plug-in for the Microsoft C/C++ compiler**
  - **Detailed user manual**

- **MSEC use HAVOC for the assessment of software security properties:**
  - **To find new bugs.**
  - **To find variants of existing bugs.**

HAVOC: The big picture



HAVOC analysis modes

- HAVOC can run either as a local checker (intra-procedural analysis only) or a global checker (inter-procedural analysis)
  - In local checking mode, function parameters and return values of callees are always assumed untrusted.
    - Leads to more false positives.
    - Analysis converges fast.
  - In global checking mode, preconditions are propagated to called functions at call sites. Parameters and return values are no more assumed untrusted.
    - Global checking performs inter-procedural inference using a fixed-point algorithm over the call graph.

Example of HAVOC annotations

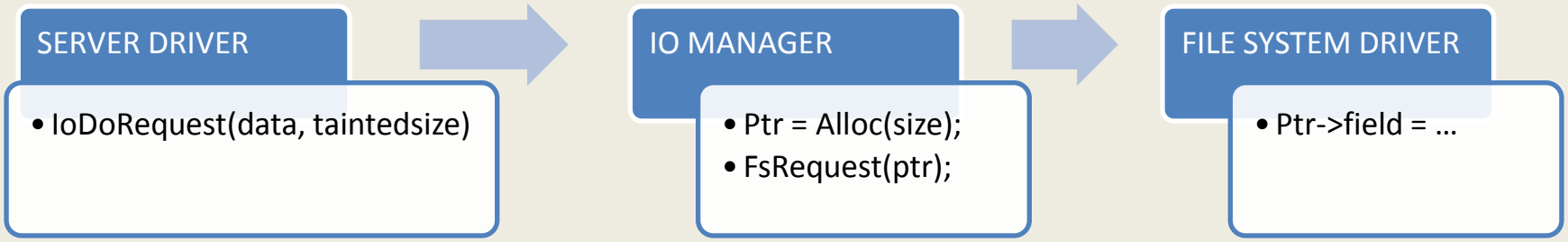
- **Our property of interest is very easily expressible using preconditions over the allocation API.**

```
__requires(Size != 0)
PVOID ExAllocatePool(POOL_TYPE PoolType, SIZE_T Size);
```

- **The analyzer can prove that 98% of allocation sites are secure wrt. zero allocations using local analysis only. The rest shows up in the warning list.**
  - 100 warnings for 1 million LOC (numbers differ for other properties).
  - Can be refined with global analysis to obtain perfect result. The analysis becomes much more expensive to resolve the remaining 2% of cases.

- **A simple local check found multiple escalation of privilege bugs in the windows kernel.**

Using HAVOC to find complex bugs in the remote kernel attack surface



- Inter-modules bugs are hard to find with static analysis as they involves multiple interfaced components implemented in many millions of LOC.
- How to find all such bugs quickly?
  - Restrict the analysis to the server driver.
  - Understand what happens behind interface calls (ex: IoDoRequest())
  - We enforce post-conditions on the parameters of the interface API

```
__requires(size != 0)
BOOL IoDoRequest(PVOID data, UINT size);
```

Part III: generalization

Near-zero allocation analysis

Near-zero allocation analysis

- Sometimes zero allocations are correctly filtered by wrapper macros that ensures NULL is returned if 0 is passed as a size. Those API are obviously not vulnerable to zero allocations.
- Dangerous behaviour can still happen if the size variable is not properly handled. We give an example of such remote overflow bug.
- We currently have no automated analysis for finding those bugs (beside existing generic and noisy buffer overflow finders) but we found some by code review.

Remote heap overflow due to near-zero allocation bug

```
STATUS DecodeTextString(PBYTE inputdata, DWORD aSize, PSTATUSINFO status)
{
  //status->integercount is read on the wire (remotely controlled) and can be 0.
  eStatus = PKT_GetValueLength(inputdata, aSize, &status->integerCount, status);
 // Could allocate only 2 bytes
 status->tmpbuf =  malloc (status->integerCount + 2);
 if (NULL == status->tmpbuf)
   return EOOMEM;
 // nothing happens as we copy 0 byte
 memcpy(status->tmpbuf, inputdata, status->integerCount);
 // byteCpd stays  0!
 status->bytesCpd += status->integerCount;
 // tmpbuff is 2 bytes and non initialized!
 bool res = HeaderFieldStringConvert(status);
 (…)
```

Remote near-zero alloc bug (2)

```
Bool HeaderFieldStringConvert(PSTATUSINFO status)
{
   if (NULL == status->finalbuf)   {
        // We will enter here when the first header string entry is sent.
       // The first string has to be non-empty as byteCpd is well checked for 0 here
        if (0 == status->bytesCpd) return(-EINCOMPLETE);
         status->finalbuf = calloc(status->bytesCpd);
         if (NULL == status->finalbuf) return (EOOMEM);
    }
   else { // We enter here for next strings
     newlen = strlen(status->finalbuf);
     // No test if byteCpd is 0. The buffer will only grow of one byte
     status->finalbuf = realloc(status->finalbuf, (status->bytesCpd + newlen + 1) ;
     if (NULL == status->finalbuf) return (-EOOMEM);
     // Each entry is concatenated (separated by a coma)
     *(status->finalbuf + newlen)= HEADER_COMMA_CHAR;
     newlen++;
   }
(…)
```

Remote near-0 alloc bug (3)

Next in HeaderFieldStringConvert() :

```
(…)
PCHAR charSet = (status->tmpbuff[0] & 07F) // Use of uninitialized data
status->bytesCpd--; // BUG: if byteCpd was 0, bytecpd becomes very big!
 switch (charSet)     // We  might enter in any of the switch branch due to uninit charSet
   {
     (…)
      default:
      // "finalbuf" overflow will happen in ConvertFromASCII()
      eStatus = ConvertFromASCII(status->tmpbuff+1, status->bytesCpd,
                                                 status->finalbuf + newlen));
(…)
```

A regular string copy then happens with big size in ConvertFromASCII (heap overflow)

Conclusion

- We approach the complex problem of finding subclasses of buffer overflows automatically.
- Boundary values are generally more problematic for developers.
- We reduced the problem space to understand what happens when allocation size is zero or in the neighbourhood of zero.
- This restriction leads to the construction of a precise analyzer with very small false positive rate that scales to millions of LOC (need source code)

Related work

- Related people:
  - TWC MSEC Science UK team.
  - Microsoft Prefast/CSE team (Windows static analysis team).

- Related properties:
  - Forgetting to test NULL after allocation is a different problem. We don't need a complex analysis to find such errors.
  - Analysis of large allocations leading to the NULL page being mapped is a different property. Zero allocations generally don't lead to memory leaks (hint: find unbounded allocation sites!)

Questions?

- Thanks for attending.

- Greets:
  - Josh Lackey, Damian Hasse & Alex Lucas for their experienced feedback on the presented material.
  - Shuvendu Lahiri, Mark Wodrich, Matt Miller, Peter Beck, Thomas Garnier for their support in security vulnerability research in Microsoft.
  - Enrico Perla and the PaX team for their assistance on UNIX testing.

- For any enquiry: jvanegue@microsoft.com

Bonus slide: Exploitability / Mitigations Windows Kernel Heap ASLR

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Heap ASLR on the windows kernel uses 5 bits of entropy (Windows 7 / Vista)