

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));
```

Failure to test upper bound of 32b arithmetic

Overview

- Zero allocations are featured in POSIX C, this is not a new class of vulnerability.
- We consider it more of an analysis technique for finding 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 instances automatically in 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

c:\win7rtm>alloc0-user.exe

Malloc returns : 000818F8 00081908 00081918 00081928 00081938 00081948 00081958
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HeapAlloc returns : 00163FD8 00163FE8 00163FF8 00164008 00164018 00164028 00164038
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 0x10 (vulnerable to NULL ptr deref unless using sysctl mmap protection). PaX returns 0xFFFFF000 which is unmapped.

(**) 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 deref 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 IParam)
{
    PSETTING psetting;
    PLARGE_STRING pls;
    if (IParam) {
        try {
            psetting = (PSETTING)IParam;
            // No validation on count (can be 0!)
            count = ProbeAndReadUlong(&(psetting->DataLength)) + 1;
            pls = UserAllocPoolWithQuota(count, USERTAG_FLAGS); // Zero allocation
            RtlCopyMemory(pls, (PBYTE) IParam, 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.

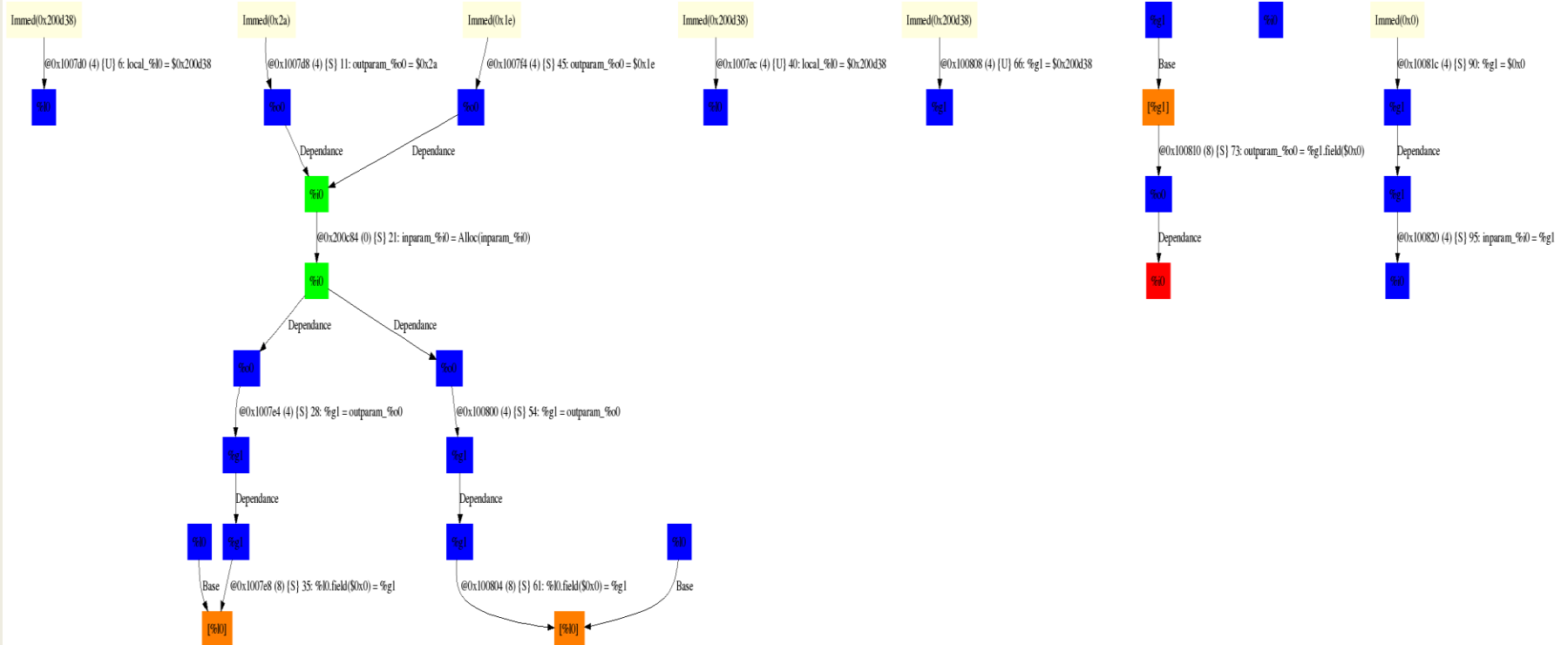
- Most compilers (GCC, LLVM, Phoenix, etc) use dataflow analysis techniques and intermediate language representation during code translation. (Ex: Static Single Assignment – SSA – form)
- With some implementation effort, an analyst can build a program analyzer within the compiler.
- Many security bugs 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: **$G (\text{Alloc}(x) \Rightarrow x \neq 0)$** 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 $\text{Alloc}(x)$ 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)

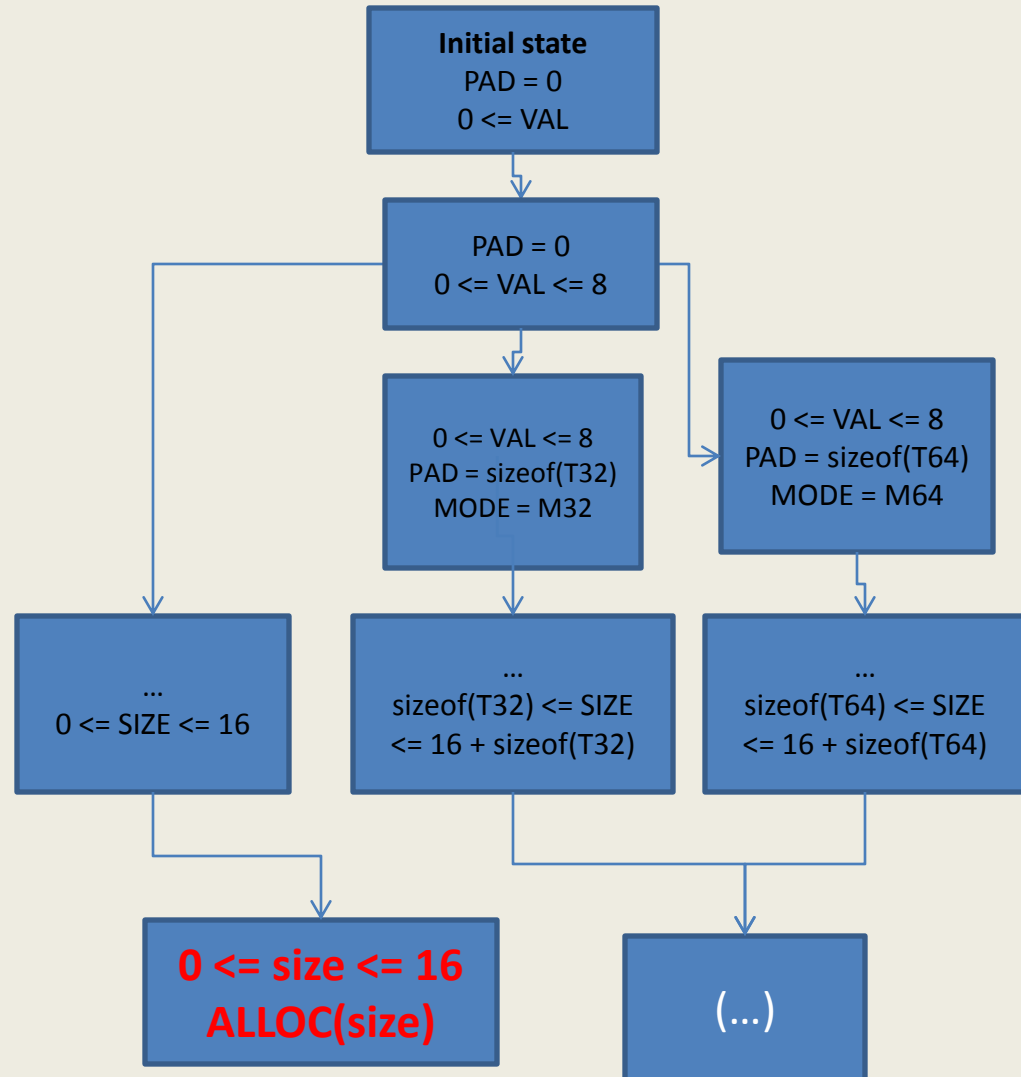
Bad: make state space explicit (combinatorial explosion)

- *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
 $G(\text{Alloc}(x) \Rightarrow (x \neq 0))$ 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) **Inferred formula**

```
{
UINT size, pad = 0;          f1: 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 2)

int f(UINT val, bool mode) **Inferred formula**

{

UINT size, pad = 0; f1: pad=0

if (val > 8) return ERR;

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

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 3)

int f(UINT val, bool mode) **Inferred formula**

{

UINT size, pad = 0; f1: pad=0

if (val > 8) return ERR;

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

if (mode == M32)

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

else if (mode == M64)

 pad = sizeof(T64);

size += pad;

PTYPE ptr = Alloc(size);

__requires(size != 0)

Dummy example (step 4)

```
int f(UINT val, bool mode) Inferred formula
{
  UINT size, pad = 0;           f1: pad=0
  if (val > 8) return ERR;
  size = val*2;                 f2: f1 && (size == val*2) && (val <= 8)
  if (mode == M32)
    pad = sizeof(T32);         f3: pad=sizeof(T32) && (size == val*2) && (val <= 8)
  else if (mode == M64)
    pad = sizeof(T64);         f4: pad=sizeof(T64) && (size == val*2) && (val <= 8)
  size += pad;
  PTYPE ptr = Alloc(size);

  __requires(size != 0)
```

Dummy example (step 5)

```
int f(UINT val, bool mode) Inferred formula
{
  UINT size, pad = 0;          f1: pad=0
  if (val > 8) return ERR;
  size = val*2;                f2: f1 && (size == val*2) && (val <= 8)
  if (mode == M32)
    pad = sizeof(T32);         f3: pad=sizeof(T32) && (size == val*2) && (val <= 8)
  else if (mode == M64)
    pad = sizeof(T64);         f4: pad=sizeof(T64) && (size == val*2) && (val <= 8)
  size += pad;                 f5: (size == val*2 + pad) && (val<=8) &&
                               (pad=0 || pad=sizeof(T32) || pad=sizeof(T64))
  PTYPE ptr = Alloc(size);

  __requires(size != 0)
```

Dummy example (step 6)

```
int f(UINT val, bool mode) Inferred formula
{
  UINT size, pad = 0;          f1: pad=0
  if (val > 8) return ERR;
  size = val*2;                f2: f1 && (size == val*2) && (val <= 8)
  if (mode == M32)
    pad = sizeof(T32);        f3: pad=sizeof(T32) && (size == val*2) && (val <= 8)
  else if (mode == M64)
    pad = sizeof(T64);        f4: pad=sizeof(T64) && (size == val*2) && (val <= 8)
  size += pad;                 f5: (size == val*2 + pad) && (val<=8) &&
                               (pad=0 || pad=sizeof(T32) || pad=sizeof(T64))
  PTYPE ptr = Alloc(size);    f6: 0 <= size <= 16 + MAX(0, sizeof(T32), sizeof(T64))

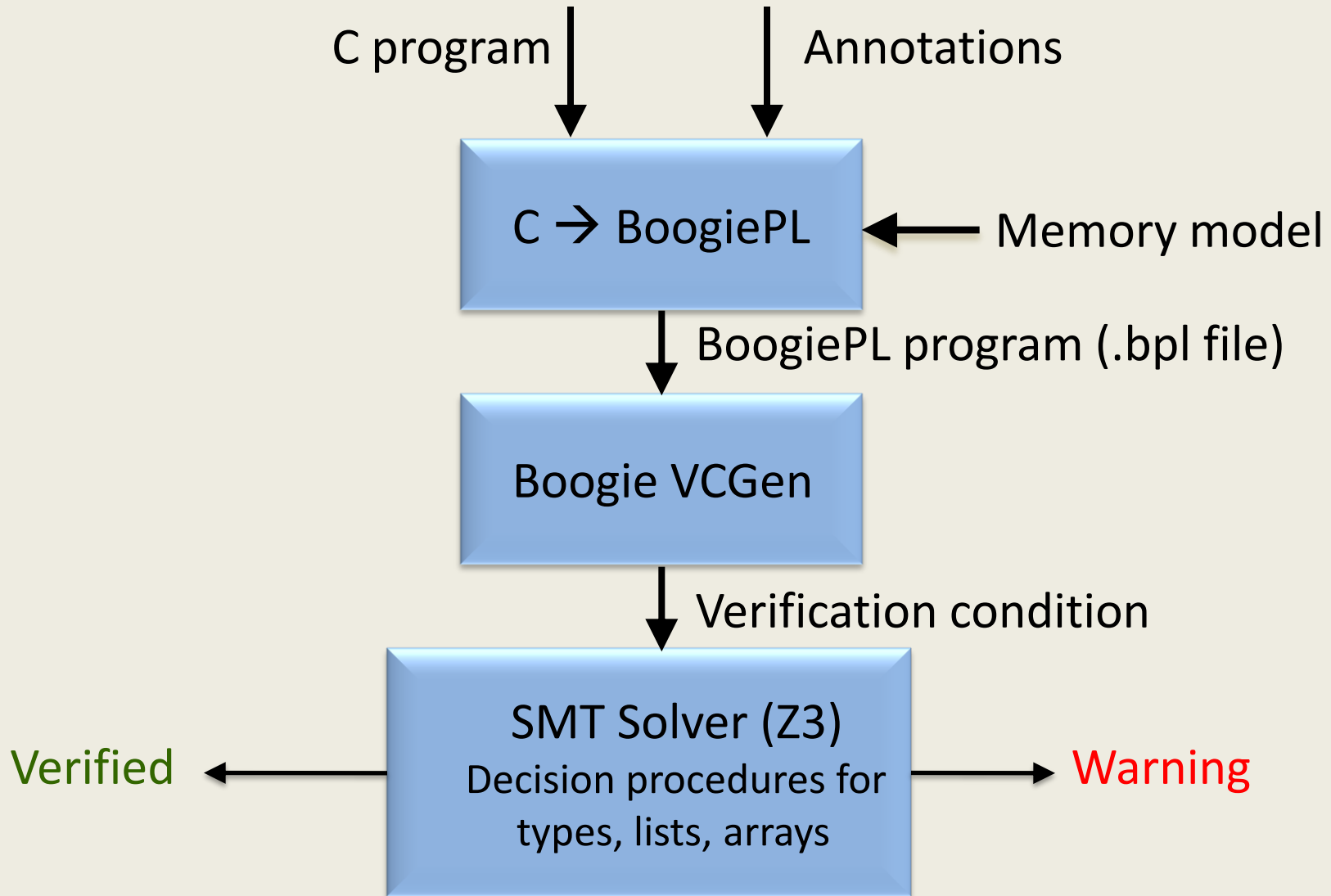
  __requires(size != 0) Precondition violation!
}
```

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

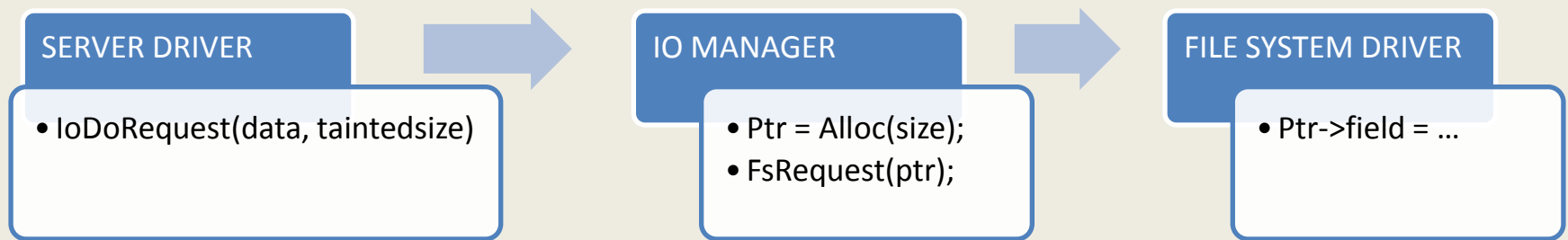
- **Our property of interest is very easily expressible using preconditions over the allocation API.**

```
__requires(Size != 0)
```

```
PVOID ExAllocatePool(PPOOL_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!) [see CsW'05: [memory_vulns_delalleau.pdf](#)]

Questions?

- Thanks for attending.
- Greetings:
 - 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

MALLOC returns : 000518F8 00051908 00051918 00051928 00051938 00051948 00051958

HeapAlloc returns : 00263FD8 00263FE8 00263FF8 00264008 00264018 00264028 00264038

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