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Draw me a Local Kernel Debugger

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Where does this talk come from?

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Branch Trace Flag

- Single step on branches
- IA32_DEBUGCTL_MSR, Eflags
- `nt!KiSaveProcessorControlState`
- This feature seems not supported anymore on new CPU
- We wanted to be able to use this feature on our new CPU (not amd64)

Where does this talk come from?

Branch Trace Store (BTS)

- Store all the branches (src and dst) taken on a CPU to a buffer
- `nt!VfInitializeBranchTracing`
- Partially implemented, could be nice to have a working POC

Where does this talk come from?

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- We looked at the options to achieve that
- We started looking at WinDbg
- We wanted easier scriptability
- We looked at how WinDbg works
- So ...

Let's draw a Local Kernel Debugger

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- Windows local kernel debugging
- DbgEngine for dummys
- Python kungfu
- Demo

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1. Introduction

Draw me a Local Kernel Debugger

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Use case of kernel debugging

- Reverse engineering
  - Understand (hidden) features
  - Study patch Tuesday
  - Hunt vulnerabilities
- Exploit development
- Driver development
- Low level interaction

Draw me a Local Kernel Debugger

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Debug settings

- Network cable
- USB (3.0 / 2.0)
- Serial cable
- Serial over USB
- **Locally**

Draw me a **L**ocal **K**ernel **D**ebugger

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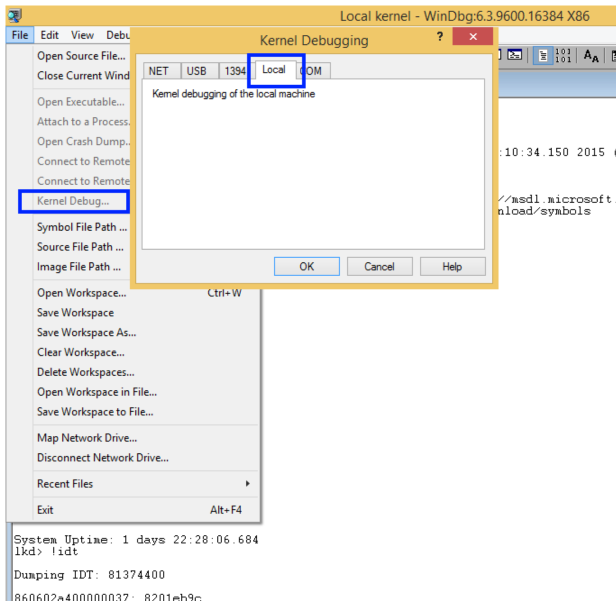
Locally?

- "Debugger" runs on the same computer
- Dump memory
  - Data structure used by processor (GDT, IDT, . . .)
  - Windows internal structures
  - Process list, handles, . . .
- Modify memory, I/O, MSRs
  - Enable hidden features
  - Fix bugs ☺

Windows local kernel debugging

WinDbg allows to perform local kernel debugging



Windows **local** kernel debugging

Prerequisite

- Boot start options must be modified
- nt!KdDebuggerEnabled must be equal to 1
- "DEBUG" in `HKLM\System\CurrentControlSet\Control\SystemStartOptions`
- `bcdedit /debug on` || `msconfig.exe`

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2 DBGEngine

DBGEngine

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- `WinDbg` uses `dbgEng.dll` : Debugger Engine
- Provides interfaces for examining and manipulating targets
- Can acquire targets, set breakpoints, monitor events, . . .

Can we write our standalone Local Kernel Debugger?

Dissecting dbgeng.dll

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dbgeng.dll

- Few exported functions (only one interesting)

```
HRESULT DebugCreate(__in REFIID InterfaceId, __out PVOID* Interface);
```

Creates a new **C**omponent **O**bject **M**odel (COM) interface of type `IDebugClient`

IDebugClient

Main object, queries other COM interfaces

- `IDebugControl`: Controls the debugger
- `IDebugSymbols`: Symbols stuff (`dbghelp.dll`, `symsrv.dll`)
- `IDebugDataSpaces`: Read / Write operations

Dissecting dbgeng.dll


```
HRESULT AttachKernel(
  [in]             ULONG Flags,
  [in, optional]  PCSTR ConnectOptions
);
```

IDebugClient (debugger.chm)

```
// Attach to the local machine.  If this flag is not set
// a connection is made to a separate target machine using
// the given connection options.
#define DEBUG_ATTACH_LOCAL_KERNEL      0x00000001
```

dbgeng.h

Not documented inside MSDN nor debugger.chm

Dissecting dbgeng.dll

- If we try to call the method, we end up in `dbgeng!LocalLiveKernelTargetInfo::InitDriver`
- This function checks if the current process name is `WinDbg` / `kd`
- If TRUE, it extracts a signed driver (`kldbgdrv.sys`) from the binary's resources
  - `lpName` = 0x7777
  - `lpType` = 0x4444

Dissecting `kldbgdrv.sys`

`kldbgdrv.sys`

- Create a device `\\.\kldbgdrv`
- Wrapper around `nt!KdSystemDebugControl` via DeviceIoControl (`dwIoControlCode = 0x22C007`)

`nt!KdSystemDebugControl`

- Check the value of nt!KdDebuggerEnabled (set during system startup)
- Read/Write: I/O, Memory, MSR, Data Bus, KPCR, ...
- `nt!KdpSysReadIoSpace` & `nt!KdpSysWriteIoSpace` broken, allows only aligned I/O

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Stand-Alone application

Custom LKD

- Use dbgeng.dll like WinDbg
- Put kldbgdrv.sys inside our own resources

```
> type poc.rc
0x7777        0x4444      "dep\\kldbgdrv_64.sys"
> rc.exe /nologo poc.rc
```

- Add 3 others resources
  - dbgeng.dll
  - dbghelp.dll
  - symsrv.dll

No need to install anything ☺

Stand-Alone application

- Name our executable `WinDbg.exe` / `kd.exe` or hook `kernel32!GetModuleFileNameW`
- Enable SeDebugPrivilege / SeLoadDriverPrivilege
- Check if `debug` mode is enable
- Load `dbgeng.dll` (from extracted resources)
- Create an `IDebugClient` and `IDebugControl` interface with `DebugCreate`
- Call `AttachKernel` with DEBUG_ATTACH_LOCAL_KERNEL
- Call `WaitForEvent` until debugger is attached

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3 Python

What we need

Problems

- Call COM interface in Python
- `kernel32!GetModuleFileNameW` must return `windbg.exe`
- Embed `kldbgdrv.sys` as a resource

What we need

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Problems

- Call COM interface in Python
- `kernel32!GetModuleFileNameW` must return `windbg.exe`
- Embed `kldbgdrv.sys` as a resource

Solutions

- `ctypes` module
- Import Address Table (IAT) hooks

COM with ctypes

```
/* The SetSymbolPath method sets the symbol path. */
HRESULT SetSymbolPath(
  [in] PCSTR Path
);
```

```
int __stdcall IDebugSymbols::SetSymbolPath(PVOID, LPCSTR)
```

HOWTO

```
# SetSymbolPath is the 42nd entry in IDebugSymbols's vtable
SetSymbolPathFunction = WINFUNCTYPE(HRESULT, c_char_p)(41, "SetSymbolPath")
SetSymbolPathFunction(DebugSymbolsObject, "C:\\whatever")
# Abstract stuffs
kdbg.DebugSymbols.SetSymbolPath("C:\\symbols")
```

IAT hooks in Python

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Steps

- Find the IAT entry (PEB + PE Parsing)
- Hook it with a stub able to call our Python function

What we need

- Python $\rightarrow$ native execution
- native execution $\rightarrow$ Python

ctypes magic once again


```
def get_peb_addr():
    # mov    rax,QWORD PTR gs:0x60; ret
    get_peb_64_code = "65488B042560000000C3".decode("hex")
    # Declare a function type that takes 0 arg and returns a PVOID
    func_type = ctypes.CFUNCTYPE([PVOID])
    addr = write_code(get_peb_64_code)
    # Create a function of type ‘func_type‘ at addr
    get_peb = func_type(addr)
    # Call it
    return get_peb()
```

Python $\rightarrow$ Native execution

ctypes magic once again


```
def my_callback(x, y):
    "Do whatever you want"
    return 0

# Create the type of the function
func_type = WINFUNCTYPE(c_uint, c_uint, c_uint)
# c_callable contains a native stub able to transform
# the arguments to Python object and call Python code
c_callable = func_type(my_callback)
```

Native execution → Python

- This stub is not enough for our IAT hook as we need to prepare threads to call Python code
- *Manually* create another stub that will call the `ctypes` stub

Additional work

Make threads able to execute Python code

- Need to call `PyGILState_Ensure` before the `ctypes` stub and `PyGILState_Release` after
- Need to leave registers and stack untouched for proper arguments parsing
  - Poping and saving the return address elsewhere
  - Need to save registers (not on the stack)

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Callback decorator

- Create a wrapper function that:
  - Handle all the low level magic
  - Create a Python function calling the real API
  - Call our hook with original arguments

```
@Callback(ctypes.c_void_p, ctypes.c_ulong)
def exit_callback(x, real_function):
    print("Try to quit with {0}".format(x))
    if x == 42:
        print("TRYING TO REAL EXIT")
        return real_function(1234)
    return 0x4242424243444546

exit_process_iat.set_hook(exit_callback)
```

Bonus

We can generate specialized Callback decorators for functions with known arguments

Application to dbgeng.dll

- `dbgeng!LocalLiveKernelTargetInfo::InitDriver` checks the name of the current process

```
@windows.hooks.GetModuleFileNameWCallback
def EmulateWinDbgName(hModule, lpFilename, nSize, real_function):
    if hModule is not None:
        return real_function()
    ptr_addr = ctypes.cast(lpFilename, ctypes.c_void_p).value
    v  = (c_char * 100).from_address(ptr_addr)
    path = "C:\\windbg.exe"
    path_wchar = "\x00".join(path) + "\x00\x00\x00"
    v[0:len(path_wchar)] = path_wchar
    return len(path_wchar)
```

Hook for `kernel32!GetModuleFileNameW`

Application to dbgeng.dll

- Embed `kldbgdrv.sys` as a resource (0x7777, 0x4444)

```
DRIVER_RESOURCE = Resource(DRIVER_FILENAME, 0x7777, 0x4444)

@windows.hooks.LoadResourceCallback
def LoadResourceHook(hModule, hResInfo, real_function):
    if hResInfo in HRSRC_dict:
        return HRSRC_dict[hResInfo].load_resource()
    return real_function()

# Simplified implementation of Ressource.load_resource
# Real implementation must keep driver_data alive so it's
# not garbage collected
def load_resource(self):
    driver_data = open(self.filename, 'rb').read()
    char_p = ctypes.c_char_p(driver_data)
    real_addr = ctypes.cast(char_p, ctypes.c_void_p).value
    return real_addr
```

Hook for `kernel32!LoadResource`

Results

```
from dbginterface import LocalKernelDebugger

kdbg = LocalKernelDebugger()
addr = kdbg.get_symbol_offset("nt!KiSystemStartup")
print("nt!KiSystemStartup -> " + hex(addr))
data =  kdbg.read_virtual_memory(addr, 0x10)
print("Read 0x10 at symbol :\n" + repr(data))
```

Python LKD in action

```
> python64 test.py
nt!KiSystemStartup -> 0xfffffff81081310L
Read 0x10 at symbol :
'U\x8b\xec\x83\xec \x8b]\x08\x89\x1dhD\x07\x81\x8b'
```

Output

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Limitations

- Impossible to perform non-aligned I/O using (`nt!KdpSysReadIoSpace` & `nt!KdpSysWriteIoSpace`)
- Unable to allocate kernel memory
- Unable to call custom kernel functions

Upgrade

- We didn’t want to disable Secure Boot
- We didn’t want to rely on compilation step

Upgrade

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- We didn't want to disable Secure Boot
- We didn't want to rely on compilation step

Solution

- Use `kldbgdrv` driver features to upgrade it
- Add new execution path during IOCTL handling

Upgrade

- We can now "register" custom code execution to custom IOCTL code

Features

- Perform non-aligned I/O
- Call custom kernel functions with arguments
- Allocate kernel memory (and map it to user-land)

Upgrade Example

```
self.upgrade_driver_add_new_ioctl_handler(DU_MEMALLOC_IOCTL,
        Alloc_IOCTL.get_code())


# Wrapper in LocalKernelDebugger
@require_upgraded_driver
def alloc_memory(self, size=0x1000, type=0, tag=0x45544942):
    buffer = struct.pack("<QQQ", type, size, tag)
    res = c_uint64(0x44444444)
    DeviceIoControl(handle, DU_MEMALLOC_IOCTL, buffer,
                    len(buffer),  byref(res), sizeof(res))
    return res.value
```

Memory allocation upgrade

Upgrade Example


```
>>> hex(kdbg.alloc_memory(0x42000, type=0, tag=0x21444b4c))
'0xffffe001572b2000L'
```

Kernel memory allocation from Python

```
lkd> !pool 0xffffe001572b2000
Pool page ffffe001572b2000 region is Unkno...
*ffffe001572b2000 : large page allocation, Tag is LKD!, size is 0x42000 bytes
        Owning component : Unknown (up...
```

Proof of work

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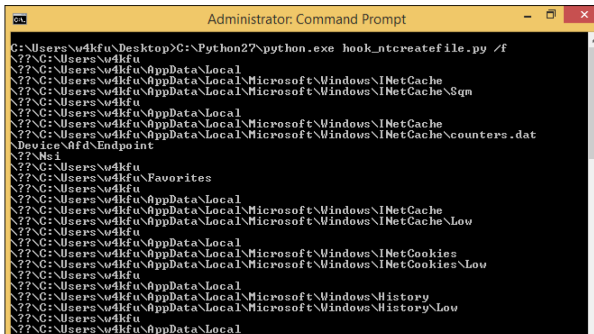
Demo

- Setup Inline hook on `nt!NtCreateFile`



Demo

- Display devices attached to PCI bus
- `DebugDataSpaces::ReadBusData`

Demo

- Display the interrupt dispatch table and `KINTERRUPT` associated

Administrator: Command Prompt

```
C:\Users\w4kfou\Desktop\LocalKernelDebug>C:\Python27x64\python.exe example\idt.py
0x00 0xfffff803171e6900L nt!KiDivideErrorFault
0x01 0xfffff803171e6a00L nt!KiDebugTrapOrFault
0x02 0xfffff803171e6bc0L nt!KiNmiInterrupt
0x03 0xfffff803171e6f40L nt!KiBreakpointTrap
0x04 0xfffff803171e7040L nt!KiOverflowTrap
0x05 0xfffff803171e7140L nt!KiBoundFault
0x06 0xfffff803171e7240L nt!KiInvalidOpcodeFault
0x07 0xfffff803171e7480L nt!KiNpxNotAvailableFault
0x08 0xfffff803171e7540L nt!KiDoubleFaultAbort
0x09 0xfffff803171e7600L nt!KiNpxSegmentOverrunAbort
0x0A 0xfffff803171e76c0L nt!KiInvalidTssFault
0x0B 0xfffff803171e7780L nt!KiSegmentNotPresentFault
0x0C 0xfffff803171e78c0L nt!KiStackFault
0x0D 0xfffff803171e7a00L nt!KiGeneralProtectionFault
0x0E 0xfffff803171e7b00L nt!KiPageFault
0x10 0xfffff803171e7e80L nt!KiFloatingErrorFault
0x11 0xfffff803171e8000L nt!KiAlignmentFault
0x12 0xfffff803171e8100L nt!KiMcheckAbort
0x13 0xfffff803171e8780L nt!KiXmmException
0x1F 0xfffff803171e2660L nt!KiApcInterrupt
0x29 0xfffff803171e8940L nt!KiRaiseSecurityCheckFailure
0x2C 0xfffff803171e8a40L nt!KiRaiseAssertion
0x2D 0xfffff803171e8b40L nt!KiDebugServiceTrap
0x2F 0xfffff803171e2930L nt!KiDpcInterrupt
0x30 0xfffff803171e2b60L nt!KiHvInterrupt
0x31 0xfffff803171e2ec0L nt!KiVmbusInterrupt0
0x32 0xfffff803171e3210L nt!KiVmbusInterrupt1
0x33 0xfffff803171e3560L nt!KiVmbusInterrupt2
0x34 0xfffff803171e38b0L nt!KiVmbusInterrupt3
0x37 0xfffff80317072790L <KINTERRUPT 0xfffff80317072700L>
```

Demo

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Branch Trace Store (BTS)

- Store all the branches (src and dst) taken on a CPU to a buffer
- IA32_DEBUGCTL_MSR, MSR_IA32_DS_AREA
- ...

HowTo

- Setup the Debug Store (DS) Area
- Setup the BTS related fields in DS
- Activate BTS (bit 6 & 7 IA32_DEBUGCTL_MSR)

Demo

Administrator: Windows PowerShell

```
PS C:\Users\Hakril\Desktop\LocalKernelDebug> python64 .\example\PEBS_BTS_demo.py
BtsBufferBase = 0xffffe0015a700000L
Buffer contains 7926 entries
Dumping 20 first entries
Jump 0xfffff960000a076eL (win32k!UserSessionSwitchLeaveCrit + 0xeL) -> Jump 0xfffff960000a078cL (win32k!Use
Jump 0xfffff960000a078cL (win32k!UserSessionSwitchLeaveCrit + 0x2cL) -> Jump 0xfffff80127570a90L (nt!PsGetC
Jump 0xfffff80127570aa0L (nt!PsGetCurrentThreadWin32Thread + 0x10L) -> Jump 0xfffff960000a0792L (win32k!Use
Jump 0xfffff960000a0799L (win32k!UserSessionSwitchLeaveCrit + 0x39L) -> Jump 0xfffff960000a07ccL (win32k!Us
Jump 0xfffff960000a07e9L (win32k!UserSessionSwitchLeaveCrit + 0x89L) -> Jump 0xfffff80127528f70L (nt!ExRele
Jump 0xfffff80127528f7fL (nt!ExReleaseResourceAndLeavePriorityRegion + 0xfL) -> Jump 0xfffff80127529950L (n
Jump 0xfffff801275299d5L (nt!ExpReleaseResourceForThreadLite + 0x85L) -> Jump 0xfffff80127529ad7L (nt!ExpRe
Jump 0xfffff80127529b52L (nt!ExpReleaseResourceForThreadLite + 0x202L) -> Jump 0xfffff80127529a64L (nt!ExpR
Jump 0xfffff80127529ad6L (nt!ExpReleaseResourceForThreadLite + 0x186L) -> Jump 0xfffff80127528f84L (nt!ExRe
Jump 0xfffff80127528f98L (nt!ExReleaseResourceAndLeavePriorityRegion + 0x28L) -> Jump 0xfffff80127529000L (
Jump 0xfffff8012752909aL (nt!PsBoostThreadIoEx + 0x9aL) -> Jump 0xfffff80127528f9dL (nt!ExReleaseResourceAn
Jump 0xfffff80127528fc3L (nt!ExReleaseResourceAndLeavePriorityRegion + 0x53L) -> Jump 0xfffff9600018800bL (
Jump 0xfffff96000188017L (win32k!NtUserCallMsgFilter + 0x117L) -> Jump 0xfffff801275e91b3L (nt!KiSystemServ
Jump 0xfffff801275e920fL (nt!KiSystemServiceExit + 0x54L) -> Jump 0xfffff801275e9268L (nt!KiSystemServiceEx
Jump 0xfffff801275e9277L (nt!KiSystemServiceExit + 0xbcL) -> Jump 0xfffff801275e92a7L (nt!KiSystemServiceEx
Jump 0xfffff801275e92b6L (nt!KiSystemServiceExit + 0xfbL) -> Jump 0xfffff801275e92f9L (nt!KiSystemServiceEx
Jump 0xfffff801275e9338L (nt!KiSystemServiceExit + 0x17dL) -> Jump 0x772a5b1aL (None + None)
Jump 0x772a5b1aL (None + None) -> Jump 0x772a2073L (None + None)
Jump 0x772a2078L (None + None) -> Jump 0x772fa44bL (None + None)
Jump 0x772fa452L (None + None) -> Jump 0x772fa4b8L (None + None)
```

SOGETI

Demo

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Functions window

Function name
- __DEFAULT_CW_in_mem
- __newclmap
- __newcumap
- _WHEAErrorSourceMethods_(

Graph overview

IDA View-A | Hex View-1 | Structures | Enums | Imports | Exports

```
; Attributes: noreturn bp-based frame

; NTSTATUS __stdcall KiSystemStartup(PDRIVER_OBJECT DriverObject, PUNICO
public _KiSystemStartup@4
_KiSystemStartup@4 proc near

var_20= byte ptr -20h
var_18= byte ptr -18h
var_14= byte ptr -14h
var_10= dword ptr -10h
var_C= dword ptr -0Ch
```

100.00% (-80,-31) (685,221) 001FC608 0062A008: KiSystemStartup(x) (Synchronized with Hex View-1

Output window

```
Python kdbg.execute("lm m nt*")
start    end        module name
77130000 77294000   ntdll      (private pdb symbols)  c:
\users\w4kfu\desktop\localkerneldebug\symbols\ntdll.pdb\93706DA6AD4F4B2087941EB59B2E19231\ntdll.pdb
81868000 81e17000   nt         (pdb symbols)          c:
\users\w4kfu\desktop\localkerneldebug\symbols\ntkrpamp.pdb\D458E245FA454CC8A00EB77B09FFC26D1\ntkrpamp.pdb
8203b000 821dd000   Ntfs       (deferred)
Python kdbg.execute("dt nt!_KPCR IDT GDT 0n{0}".format(kdbg.read_processor_system_data(0, 0)))
   +0x038 IDT : 0x80f16400 _KIDTENTRY
   +0x03c GDT : 0x80f16000 _KGDTENTRY
Python kdbg.execute("dt nt!_KIDTENTRY 0x80f16400")
   +0x000 Offset           : 0xa59c
   +0x002 Selector         : 8
   +0x004 Access           : 0x8e00
   +0x006 ExtendedOffset   : 0x8197
```


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Conclusion

- Local **K**ernel **D**ebugging is a really nice feature provided by the Windows kernel
- Such scriptability in python from user-land can be interesting in many use-cases that we are still exploring
- Source code available at `https://github.com/sogeti-esec-lab/LKD`

Questions?

Thank you for your attention