Reverse Engineering RGB Keyboard Backlights

Rishit Bansal

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👤 Hi, I’m Rishit Bansal!

- From Bangalore, India
- Software Developer @ Dyte (https://dyte.io)
- I play CTFs with csictf, dytesec
- 2nd time at Nullcon, participant last year
    - Placed 1st along with dytesec at hardware CTF

https://www.linkedin.com/in/bansal-rishit/

🎯 What will we cover in this talk?

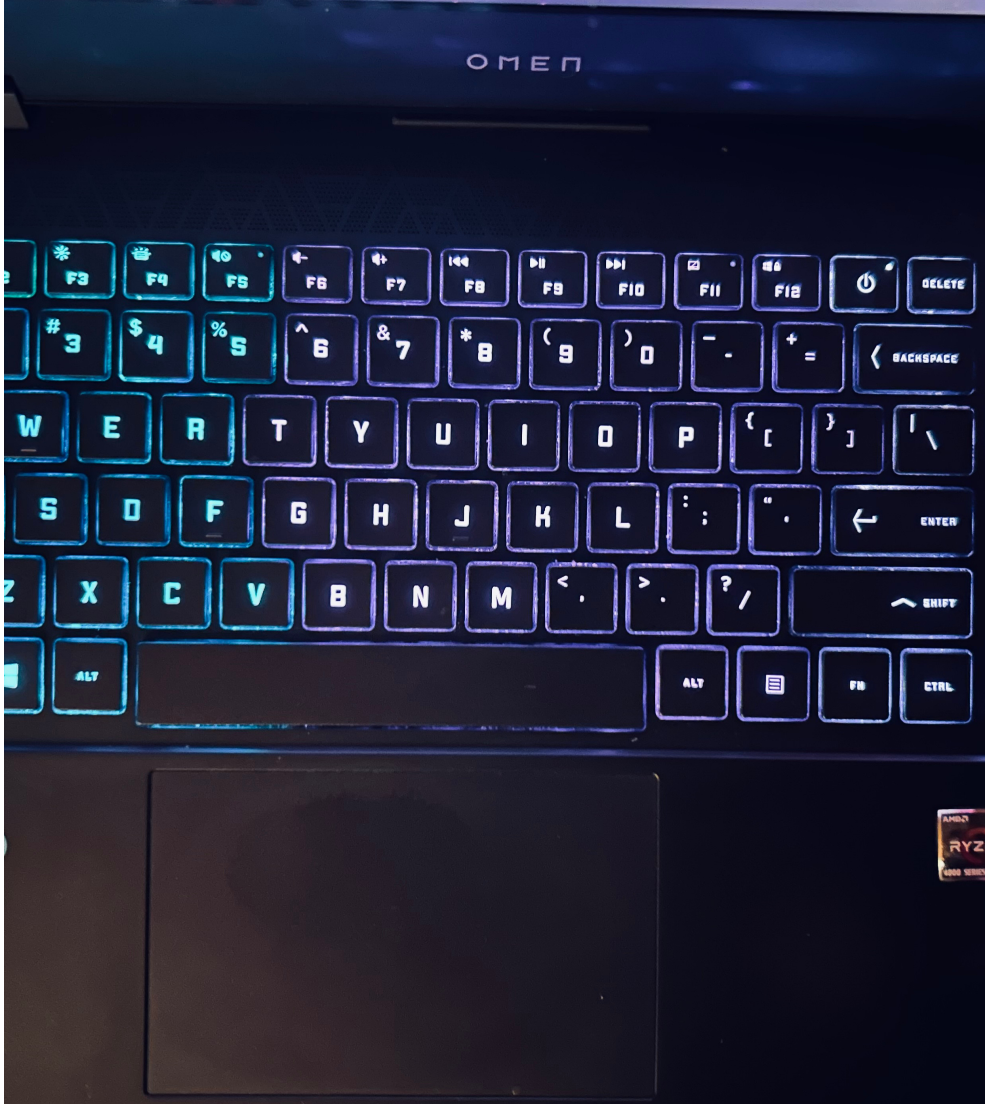
- Chapter 1: Reverse Engineer a Windows Service which interacts with keyboard backlight firmware
- Chapter 2: Understand the system protocols involved in interacting with device firmware
- Chapter 3: Re-implement the same functionality on the Linux Kernel
- Bonus: Discover new functionality possible in hardware!

Chapter 1

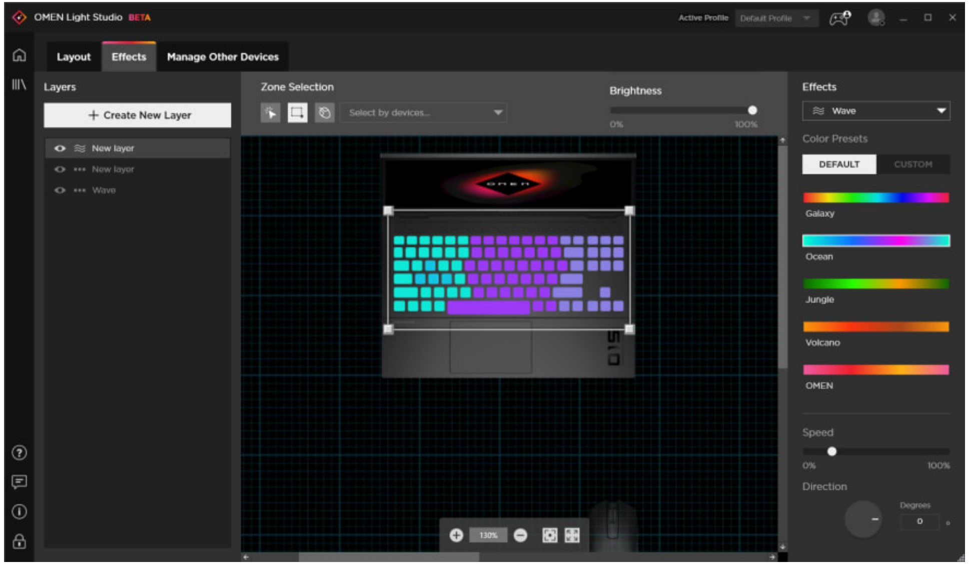
Reverse Engineering the HP Light Studio Application

The Laptop

- Laptop: HP Omen 15
- Four zones of configurable backlights
- Can set colors at a really fast rate to simulate animations.
- Hardware Key to toggle the backlight on and off.

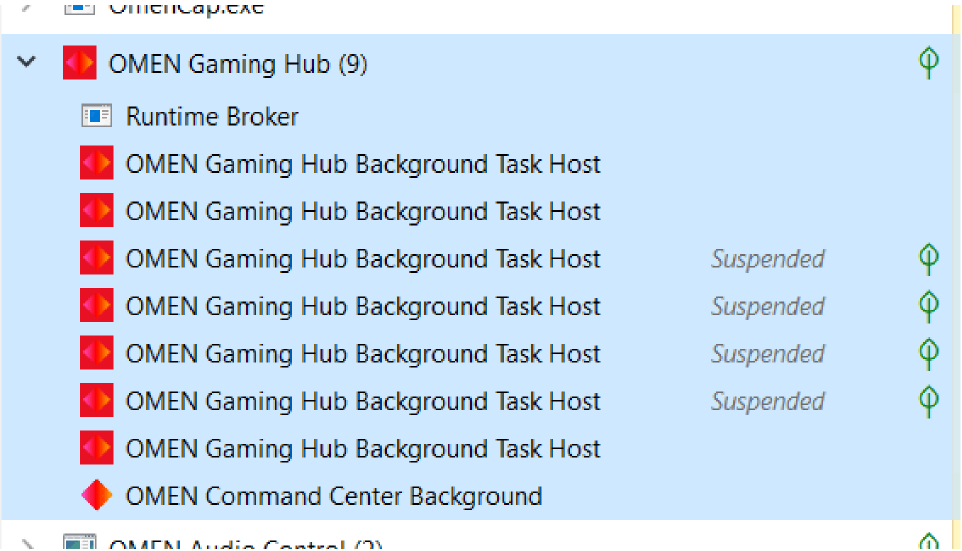


HP Omen Light Studio Application



- Windows Desktop Application
- Allows you to choose between template/custom animations
- Closed source, 0 documentation
- Animations only work when Windows boots, otherwise just static colors

Where is the service?



OmenCap.exe

OMEN Gaming Hub (9)

Runtime Broker

OMEN Gaming Hub Background Task Host

OMEN Gaming Hub Background Task Host

OMEN Gaming Hub Background Task Host *Suspended*

OMEN Gaming Hub Background Task Host *Suspended*

OMEN Gaming Hub Background Task Host *Suspended*

OMEN Gaming Hub Background Task Host *Suspended*

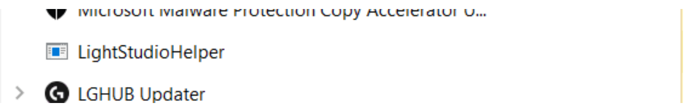
OMEN Gaming Hub Background Task Host

OMEN Command Center Background

OMEN Audio Control (2)

Omen Gaming Hub on Task Manager

`C:\Program Files\WindowsApps\AD2F1837.OMENLightStudio_1.0.37.0_x64__v10z8vjag6ke6`



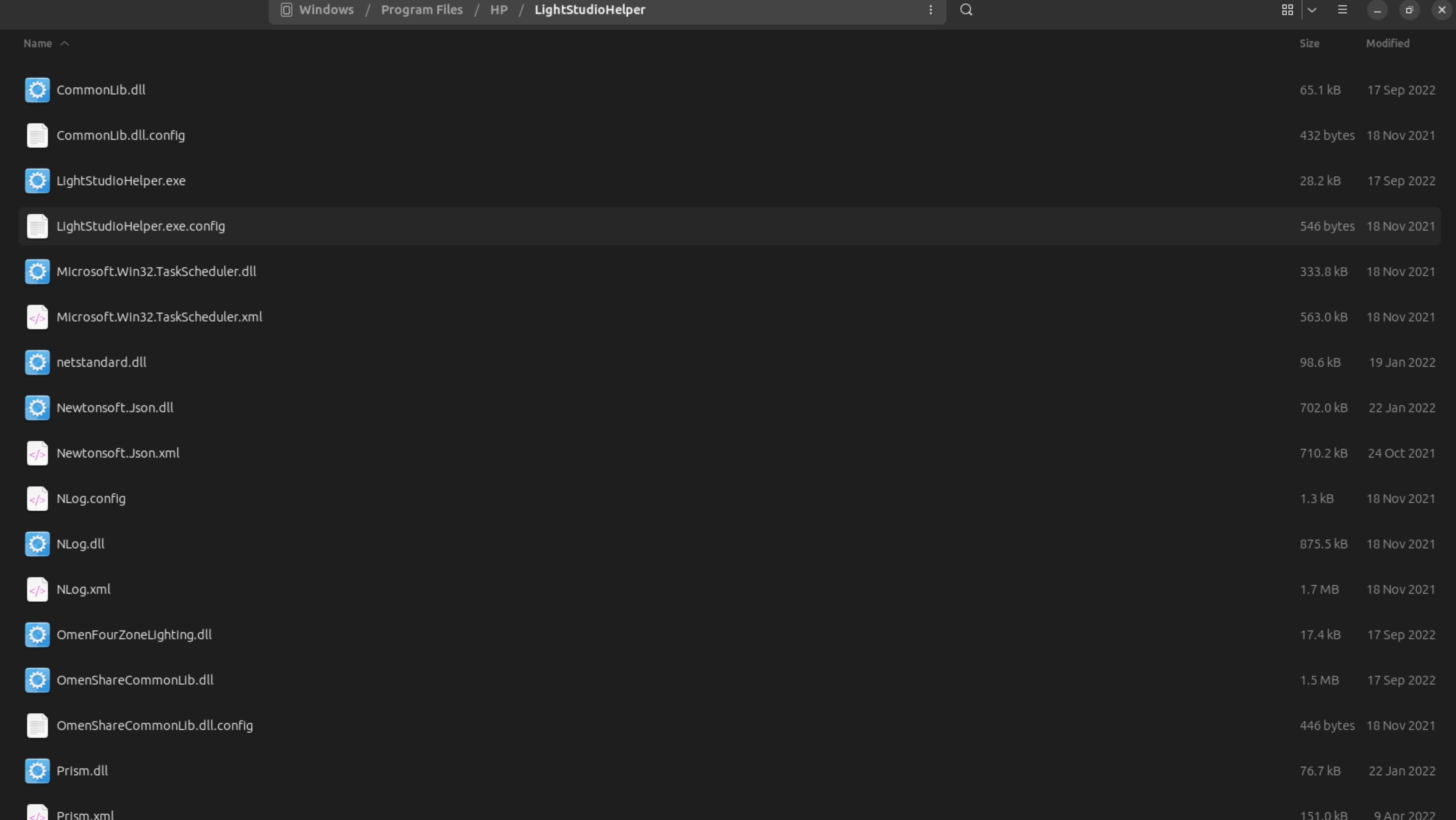
Microsoft Malware Protection Copy Accelerator U...

LightStudioHelper

LGHUB Updater

Light Studio Service on Task Manager

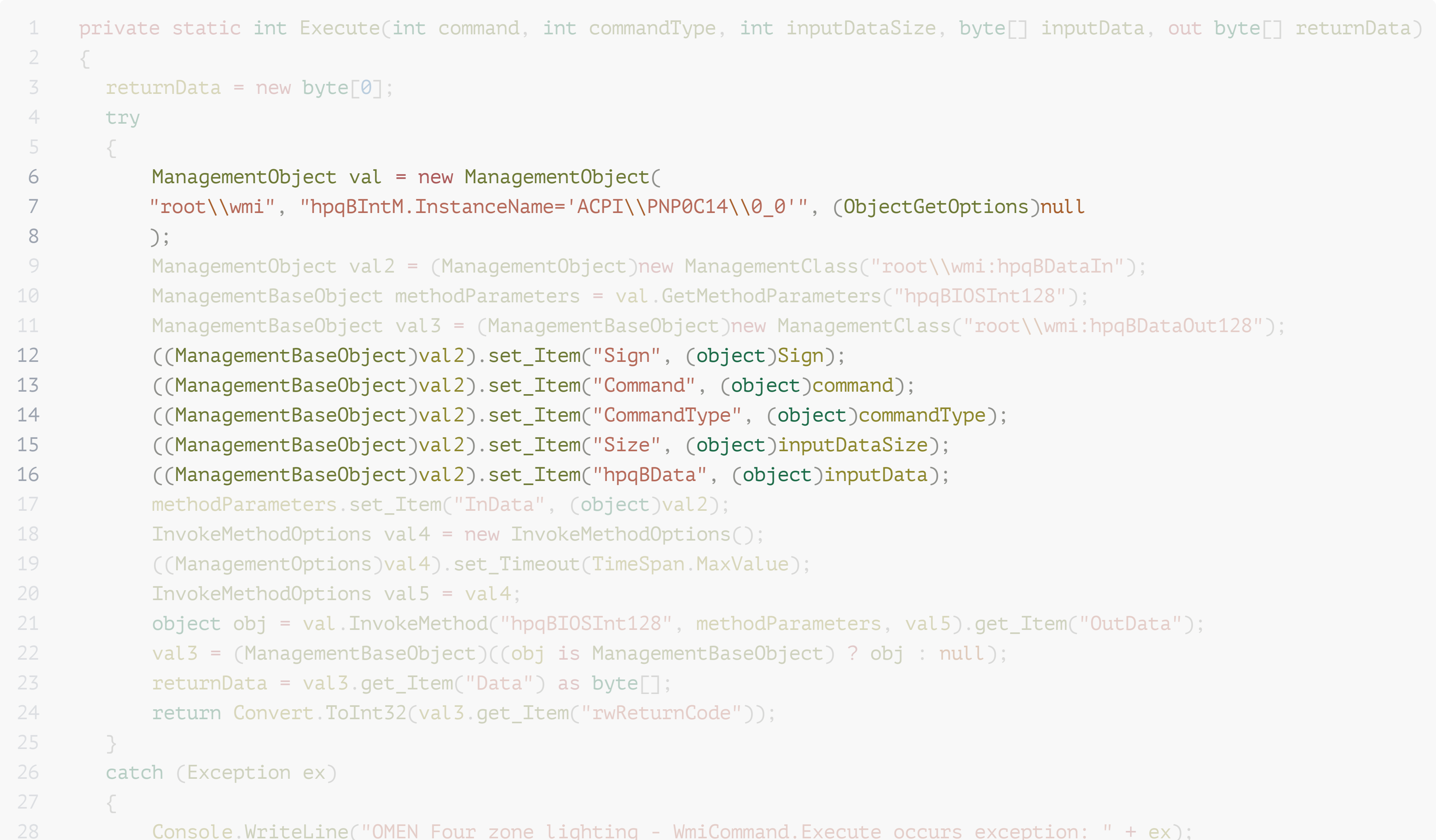
`C:\Program Files\HP\LightStudioHelper`



Windows / Program Files / HP / LightStudioHelper

Name	Size	Modified
CommonLib.dll	65.1 kB	17 Sep 2022
CommonLib.dll.config	432 bytes	18 Nov 2021
LightStudioHelper.exe	28.2 kB	17 Sep 2022
LightStudioHelper.exe.config	546 bytes	18 Nov 2021
Microsoft.Win32.TaskScheduler.dll	333.8 kB	18 Nov 2021
Microsoft.Win32.TaskScheduler.xml	563.0 kB	18 Nov 2021
netstandard.dll	98.6 kB	19 Jan 2022
Newtonsoft.Json.dll	702.0 kB	22 Jan 2022
Newtonsoft.Json.xml	710.2 kB	24 Oct 2021
NLog.config	1.3 kB	18 Nov 2021
NLog.dll	875.5 kB	18 Nov 2021
NLog.xml	1.7 MB	18 Nov 2021
OmenFourZoneLighting.dll	17.4 kB	17 Sep 2022
OmenShareCommonLib.dll	1.5 MB	17 Sep 2022
OmenShareCommonLib.dll.config	446 bytes	18 Nov 2021
Prism.dll	76.7 kB	22 Jan 2022
Prism.xml	151.0 kB	9 Apr 2022

Decompiling the Executable and DLL Files (Ilspy Demo)



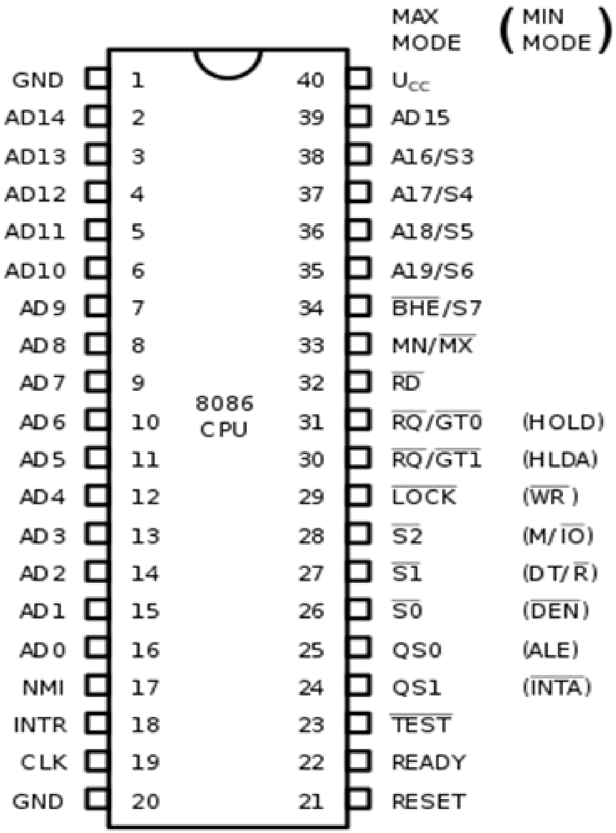
```
private static int Execute(int command, int commandType, int inputDataSize, byte[] inputData, out byte[] returnData)
{
  returnData = new byte[0];
  try
  {
      ManagementObject val = new ManagementObject(
      "root\\wmi", "hpqBIntM.InstanceName='ACPI\\PNP0C14\\0_0'", (ObjectGetOptions)null
      );
      ManagementObject val2 = (ManagementObject)new ManagementClass("root\\wmi:hpqBDataIn");
      ManagementBaseObject methodParameters = val.GetMethodParameters("hpqBIOSInt128");
      ManagementBaseObject val3 = (ManagementBaseObject)new ManagementClass("root\\wmi:hpqBDataOut128");
      ((ManagementBaseObject)val2).set_Item("Sign", (object)Sign);
      ((ManagementBaseObject)val2).set_Item("Command", (object)command);
      ((ManagementBaseObject)val2).set_Item("CommandType", (object)commandType);
      ((ManagementBaseObject)val2).set_Item("Size", (object)inputDataSize);
      ((ManagementBaseObject)val2).set_Item("hpqBData", (object)inputData);
      methodParameters.set_Item("InData", (object)val2);
      InvokeMethodOptions val4 = new InvokeMethodOptions();
      ((ManagementOptions)val4).set_Timeout(TimeSpan.MaxValue);
      InvokeMethodOptions val5 = val4;
      object obj = val.InvokeMethod("hpqBIOSInt128", methodParameters, val5).get_Item("OutData");
      val3 = (ManagementBaseObject)((obj is ManagementBaseObject) ? obj : null);
      returnData = val3.get_Item("Data") as byte[];
      return Convert.ToInt32(val3.get_Item("rwReturnCode"));
  }
  catch (Exception ex)
  {
      Console.WriteLine("OMEN Four zone lighting - WmiCommand.Execute occurs exception: " + ex);
```

Chapter 1 Summary

- Used ILSpy to decompile a .NET Windows Service, identified how the Light Studio Helper Service Works
- Mysterious References to other protocols and Windows APIs
    - Windows C# API: `` `ManagementObject` ``
    - References to `` `root\\wmi` ``
    - `` `ACPI\\PNP0C14\\0_0` ``
- "Command" parameter is passed `` `131081` ``
    - Type `` `1` ``: Checks if lighting is supported
    - Type `` `2` ``: Getting the colors of each zone on the keyboard
    - Type `` `3` ``: Setting the colors of each zone on the keyboard
    - Type `` `4` ``: Checks if backlight is on or off
    - Type `` `5` ``: Sets brightness for each of the 4 zones

Chapter 2: Understanding ACPI and WMI

History of I/O device interop



- On the 8086, I/O devices sent interrupts are sent by:
  - Sending a pulse on `` `INTR` `` pin
  - Receives interrupt vector on Data pins, and jumps to interrupt execution

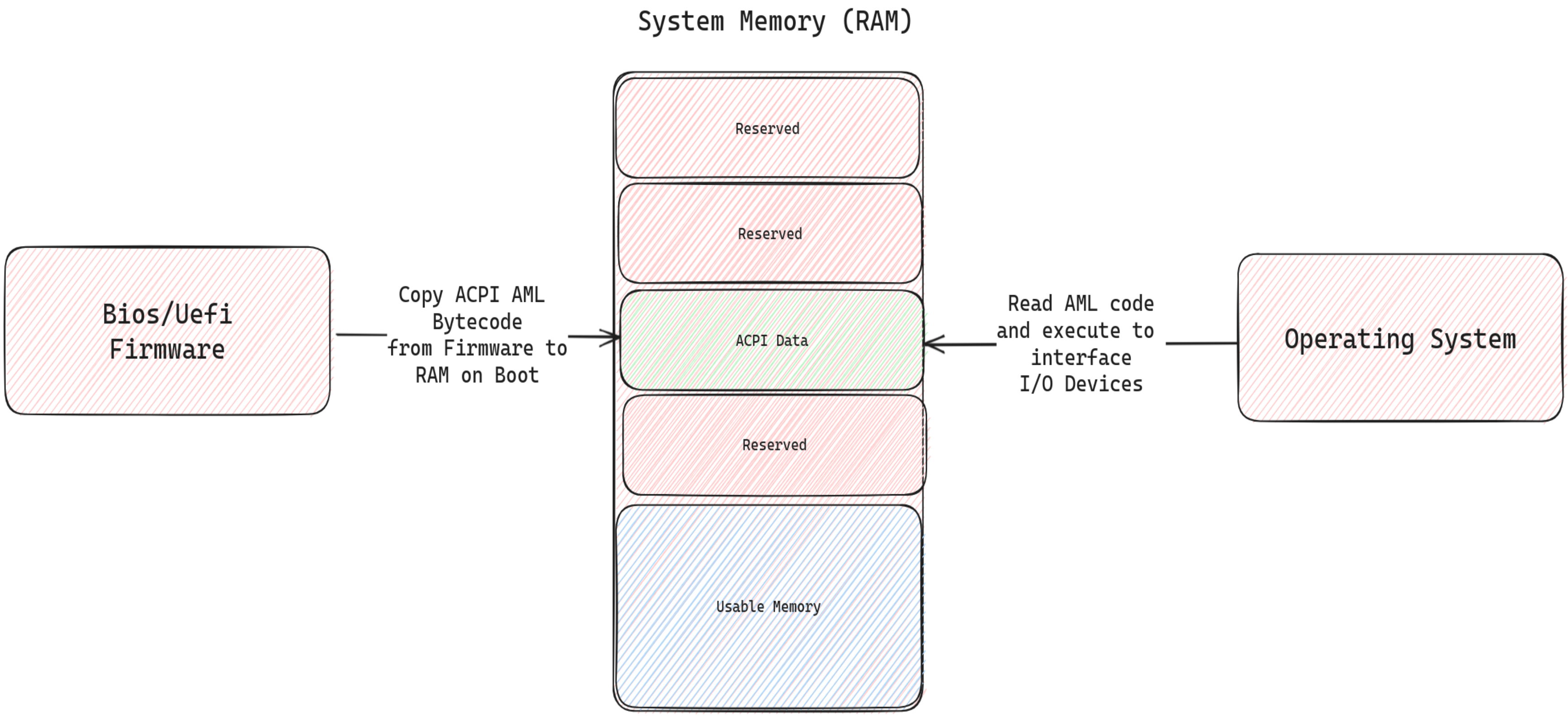
Disadvantages:

- No standardization on interrupt numbers, vectors
- I/O Device API handlers were hardcoded in Bios Firmware
- OS/Kernel space software has no direct I/O accees, functionality hardcoded in Bios
  - Needed in modern systems (read temp sensors, power management, etc.)

ACPI (Advanced Configuration and Power Interface)

- Introduced to move I/O API interfaces out of firmware to operating system
- A new language to write I/O related code
  - AML (ACPI Machine Language Bytecode)
  - Interpreted and executed on the operating system!
- ASL code is stored in firmware on "ACPI tables"
  - Loaded into main memory during boot time for OS access

ACPI Architecture


System Memory (RAM)
Reserved
Reserved
ACPI Data
Reserved
Usable Memory
Bios/Uefi Firmware
Copy ACPI AML Bytecode from Firmware to RAM on Boot
Read AML code and execute to interface I/O Devices
Operating System

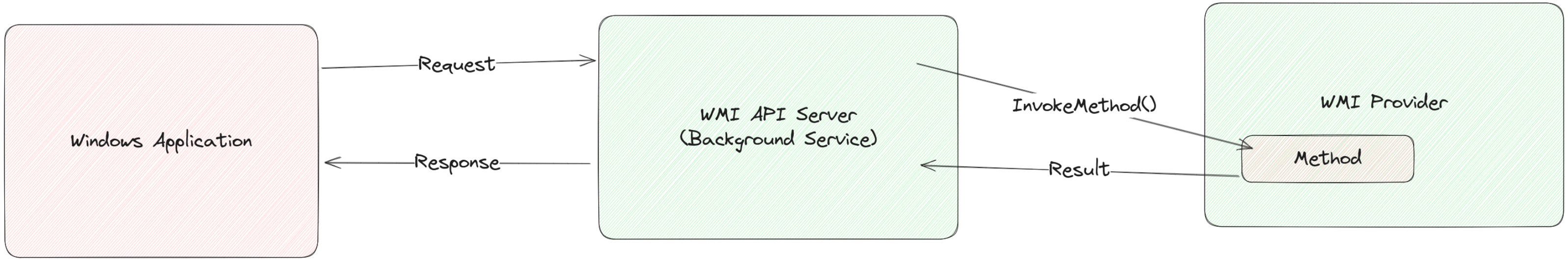
Reading/Decompiling AML code on Linux

- AML Code is loaded into main memory on boot by firmware
  - Linux ACPI Driver mounts this at `/sys/firmware/acpi/tables/DSDT`
- `iasl -d <dsdt_dump>` CLI tool can be used to decompile AML bytecode

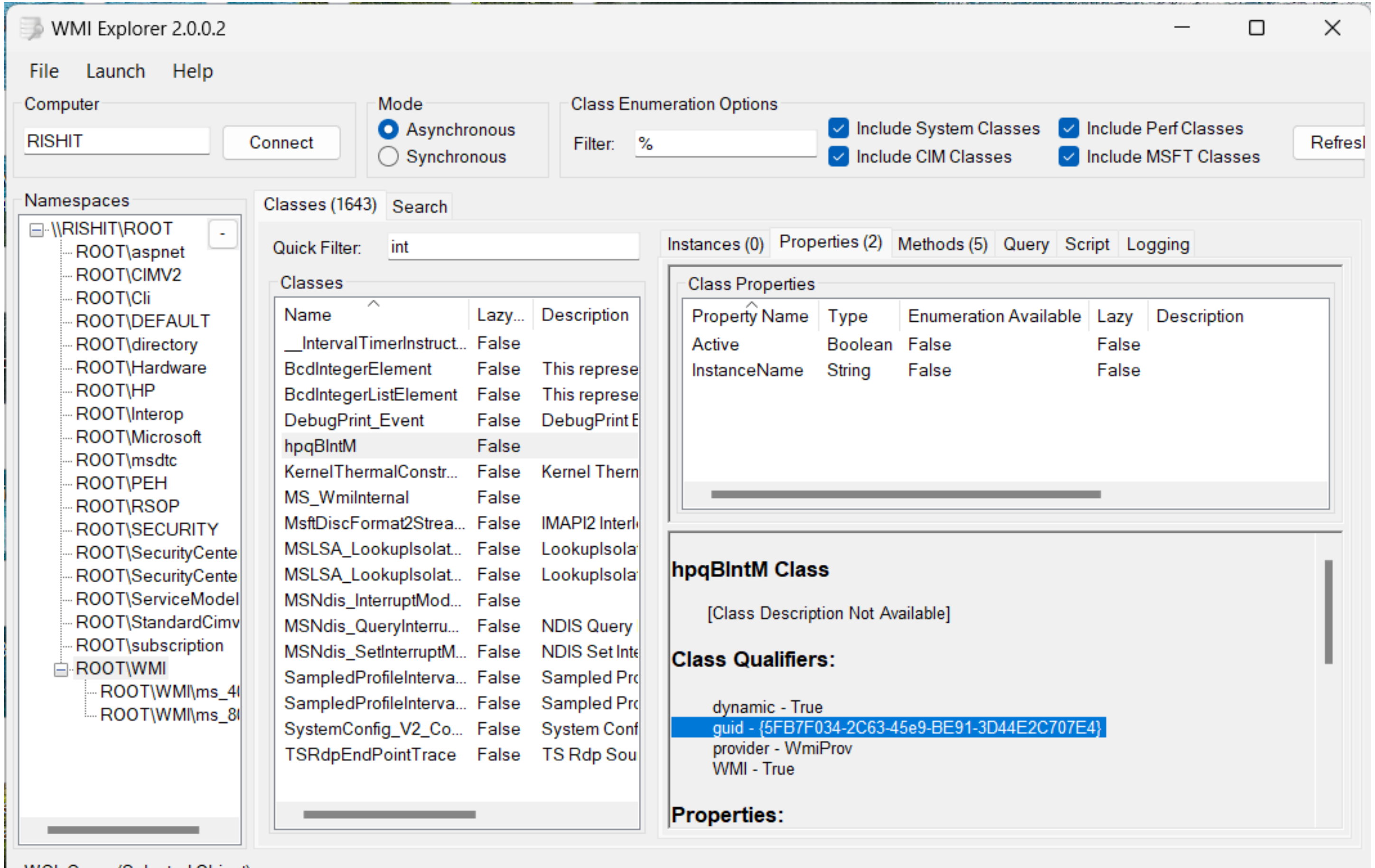
```
  Scope (_SB)
    {
        Device (ACAD)
        {
            Name (_HID, "ACPI0003" /* Power Source Device */)  // _HID: Hardware ID
            Name (_PCL, Package (0x01)  // _PCL: Power Consumer List
            {
                _SB
            })
            Name (XX00, Buffer (0x03) {})
            Name (ACSB, One)
            Name (ACDC, 0xFF)
            Method (_STA, 0, NotSerialized)  // _STA: Status
            {
                Return (0x0F)
            }
...
```

WMI (Windows Management Instrumentation)

- A protocol to help sysadmins manage distributed network of windows machines.
  - Execute management scripts/retreieve information from machines.
- Runs a simple server which accepts requests from clients, and executes them on "WMI Providers"
  - Providers expose classes and methods, each class has a unique "GUID"
- Simply put, just a way to do RPC between applications on windows machines.



WMI Explorer



Computer: RISHIT

Mode: ● Asynchronous ○ Synchronous

Class Enumeration Options

Filter: %

☑ Include System Classes ☑ Include Perf Classes
☑ Include CIM Classes ☑ Include MSFT Classes

Namespaces

```
\\RISHIT\ROOT
  ROOT\aspnet
  ROOT\CIMV2
  ROOT\Cli
  ROOT\DEFAULT
  ROOT\directory
  ROOT\Hardware
  ROOT\HP
  ROOT\Interop
  ROOT\Microsoft
  ROOT\msdtc
  ROOT\PEH
  ROOT\RSOP
  ROOT\SECURITY
  ROOT\SecurityCente
  ROOT\SecurityCente
  ROOT\ServiceModel
  ROOT\StandardCimv
  ROOT\subscription
  ROOT\WMI
    ROOT\WMI\ms_4(
    ROOT\WMI\ms_8(
```

Quick Filter: int

Classes

Name	Lazy...	Description
__IntervalTimerInstruct...	False	
BcdIntegerElement	False	This represe
BcdIntegerListElement	False	This represe
DebugPrint_Event	False	DebugPrint E
hpqBIntM	False	
KernelThermalConstr...	False	Kernel Therm
MS_WmiInternal	False	
MsftDiscFormat2Strea...	False	IMAPI2 Interl
MSLSA_LookupIsolat...	False	LookupIsola
MSLSA_LookupIsolat...	False	LookupIsola
MSNdis_InterruptMod...	False	
MSNdis_QueryInterru...	False	NDIS Query
MSNdis_SetInterruptM...	False	NDIS Set Inte
SampledProfileInterva...	False	Sampled Pro
SampledProfileInterva...	False	Sampled Pro
SystemConfig_V2_Co...	False	System Conf
TSRdpEndPointTrace	False	TS Rdp Sou

Class Properties

Property Name	Type	Enumeration Available	Lazy	Description
Active	Boolean	False	False	
InstanceName	String	False	False	

hpqBIntM Class

[Class Description Not Available]

Class Qualifiers:

dynamic - True
guid - {5FB7F034-2C63-45e9-BE91-3D44E2C707E4}
provider - WmiProv
WMI - True

Properties:

How it all links together: WMI-ACPI!

- Microsoft’s proprietary extenstion to the ACPI specification
- Allows you to expose ACPI Methods, as WMI Methods on Windows.
- Developer must create a custom ACPI device with ID `` `PNP0C14` `` in AML.
    - Must have a field called `` `_WDG` ``
    - `` `_WDG` `` stores metadata for links between WMI Class GUIDs and ACPI Functions (Wmxx)

```
Device (WMID)
        {
            Name (_HID, "PNP0C14" /* Windows Management Instrumentation Device */)  // _HID: Hardware ID
            Name (_WDG, Buffer (0x0118)
            {
                /* 0000 */  0x34, 0xF0, 0xB7, 0x5F, 0x63, 0x2C, 0xE9, 0x45,  // 4.._c,.E
                /* 0008 */  0xBE, 0x91, 0x3D, 0x44, 0xE2, 0xC7, 0x07, 0xE4,  // ..=D....
                /* 0010 */  0x41, 0x41, 0x01, 0x02, 0x79, 0x42, 0xF2, 0x95,  // AA..yB..
                /* 0018 */  0x7B, 0x4D, 0x34, 0x43, 0x93, 0x87, 0xAC, 0xCD,  // {M4C....
                /* 0020 */  0xC6, 0x7E, 0xF6, 0x1C, 0x80, 0x00, 0x01, 0x08,  // .~......
```

Using wmidump to read WDG buffers

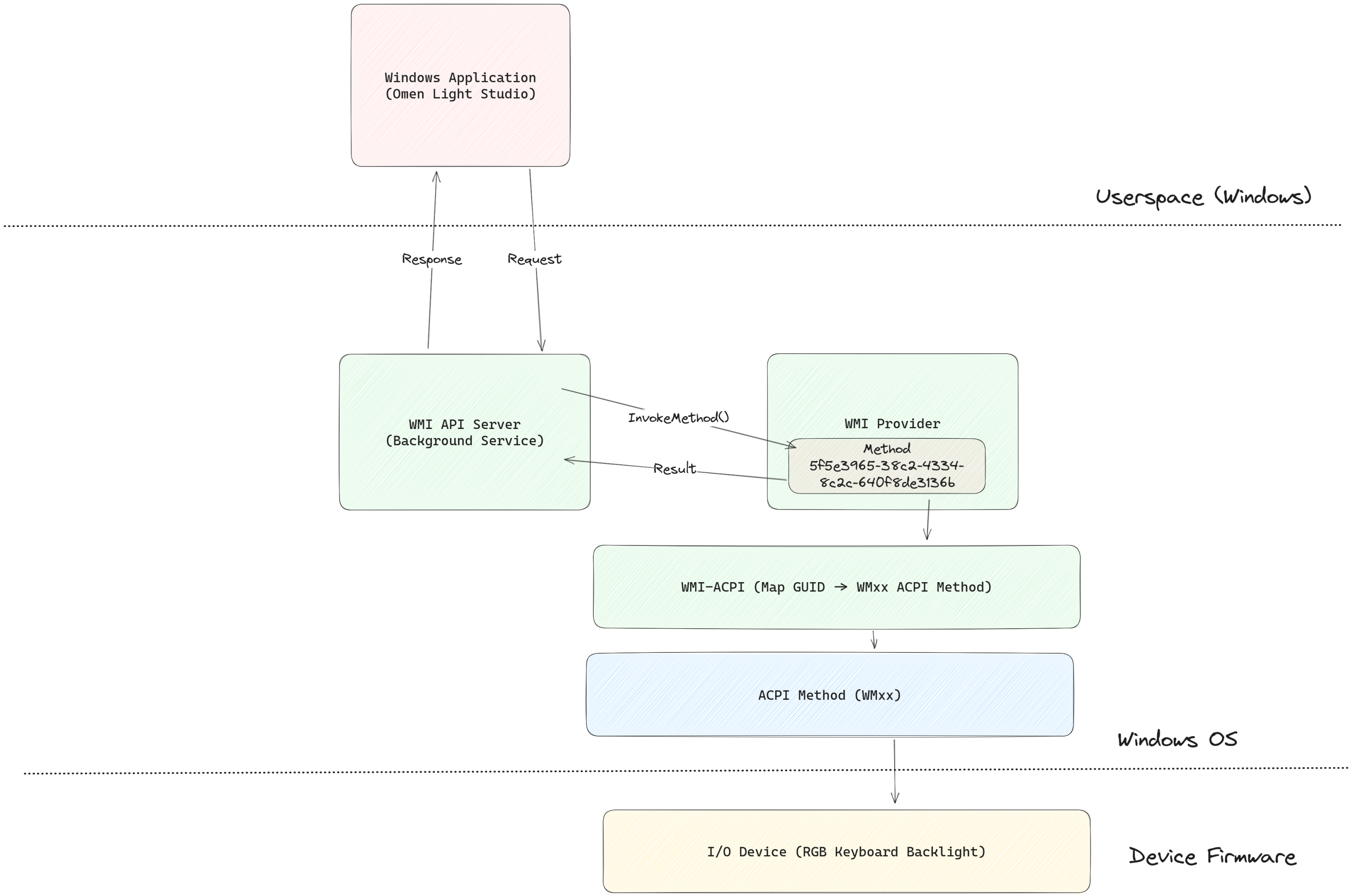
- `` `$ wmidump < file_with_wdg_buffer` ``
- Extracts out the WMI method GUIDs and ACPI function mappings

```
5FB7F034-2C63-45E9-BE91-3D44E2C707E4:
    object_id: AA
    instance_count: 1
    flags: 0x2 ACPI_WMI_METHOD
95F24279-4D7B-4334-9387-ACCDC67EF61C:
    notify_id: 0x80
    instance_count: 1
    flags: 0x8 ACPI_WMI_EVENT
....
```

- WMAA Method in AML Code:

```
Method (WMAA, 3, Serialized)
{
    Acquire (MUTZ, 0xFFFF)
    Local0 = HWMC (Arg1, Arg2)
    Release (MUTZ)
    Return (Local0)
}
```

WMI-ACPI Flow for Omen Light Studio Application



Windows Application
(Omen Light Studio)

Userspace (Windows)

Response

Request

WMI API Server
(Background Service)

InvokeMethod()

Result

WMI Provider

Method
5f5e3965-38c2-4334-
8c2c-640f8de3136b

WMI-ACPI (Map GUID → WMxx ACPI Method)

ACPI Method (WMxx)

Windows OS

I/O Device (RGB Keyboard Backlight)

Device Firmware

Chapter 2 Summary

- Learned about the innter workings of two protocols, ACPI and WMI.
- ACPI specifies "AML" code loaded from BIOS into main memory.
  - OS (Eg: Linux) can read and execute this to interact with I/O devices.
- WMI provides a way for user-space communication between services on Windows.
- WMI-ACPI exposes ACPI methods as WMI Methods

Plan: Implement a kernel driver to interface WMI/ACPI on Linux!

Chapter 3: Developing WMI Drivers on the Linux Kernel

acpi.h in the Linux Kernel

- Implementation of the ACPI specification / AML interpretor
- `` `acpi_boot_init()` `` is called on boot to parse AML from ACPI tables in system-memory
- Provides helper functions to invoke WMI-ACPI methods using their GUID directly from a kernel driver:

```
extern acpi_status wmi_evaluate_method(const char *guid, u8 instance,
                    u32 method_id,
                    const struct acpi_buffer *in,
                    struct acpi_buffer *out);
```

Interfacing kernel APIs from userspace

- `` `sysfs` `` allows you to create custom files in the /sys/ to represent device driver APIs
  - You can write/read to these files from userspace, to trigger handlers in the kernel
- In our case, /sys/class/leds is most relevant to represent the keyboard backlight device
  - Has special handlers we have to implement for brightness control
  - Added a custom file called `` `zone_colors` `` to represent the RGB backlights

```
static DEVICE_ATTR_RW(zone_colors);
static struct attribute *omen_kbd_led_attrs[] = {
    &dev_attr_zone_colors.attr,
    NULL,
};
ATTRIBUTE_GROUPS(omen_kbd_led);

static struct led_classdev omen_kbd_led = {
    .name = "hp_omen::kbd_backlight",
    .brightness_set = set_omen_backlight_brightness,
    .brightness_get = get_omen_backlight_brightness,
    .max_brightness = 1,
    .groups = omen_kbd_led_groups,
};
```

What the new device driver file tree looks like

```
rishit@OMEN-laptop:~/Documents/kernels/staging$ ls /sys/class/leds/hp_omen\:\:kbd_backlight/
brightness  max_brightness  subsystem  uevent
device      power           trigger    zone_colors
```

- We need to write handlers to read/write `brightness` and `zone_colors`

```c
#define HPWMI_READ_ZONE 0x02
#define HPWMI_WRITE_ZONE 0x03
#define OMEN_ZONE_COLOR_LEN 0x0c // 12 bytes (3 components (R,G,B) * 4 zones)
#define OMEN_ZONE_COLOR_OFFSET 0x19 // 25
#define HPWMI_KB 0x20009 // 131081

static ssize_t zone_colors_store(struct device *dev, struct device_attribute *attr, const char *buf, size_t count)
{
    u8 val[128];
    int ret;

    ret = hp_wmi_perform_query(HPWMI_READ_ZONE, HPWMI_KB, &val, zero_if_sup(val), sizeof(val));

    if (ret)
        return ret;

    if (count != OMEN_ZONE_COLOR_LEN)
        return -1;

    memcpy(&val[OMEN_ZONE_COLOR_OFFSET], buf, count);

    ret = hp_wmi_perform_query(HPWMI_WRITE_ZONE, HPWMI_KB, &val, sizeof(val), 0);

    if (ret)
        return ret;

    return OMEN_ZONE_COLOR_LEN;
}
```

Handlers for brightness control

```
#define HPWMI_WRITE_BRIGHTNESS 0x05

#define HPWMI_KB 0x20009 // 131081

static void set_omen_backlight_brightness(struct led_classdev *cdev, enum led_brightness value)
{
    char buffer[4] = { (value == LED_OFF) ? 0x64 : 0xe4, 0, 0, 0 };

    hp_wmi_perform_query(HPWMI_WRITE_BRIGHTNESS, HPWMI_KB, &buffer,
                         sizeof(buffer), 0);
}
```

- **Bonus**: Even though this LED only supports ON and OFF state, we can *simulate* brightness using a trick
- We can use the previous zone_colors_store/read methods and "scale" the RGB components by the brightness multipler
- $R_{eff}(zone) = R(zone) * (brightness/100)$

Demo

Thank you!

Questions?