SYNACKTIV

Attacking Safari in 2022

HEXACON

Who am I?

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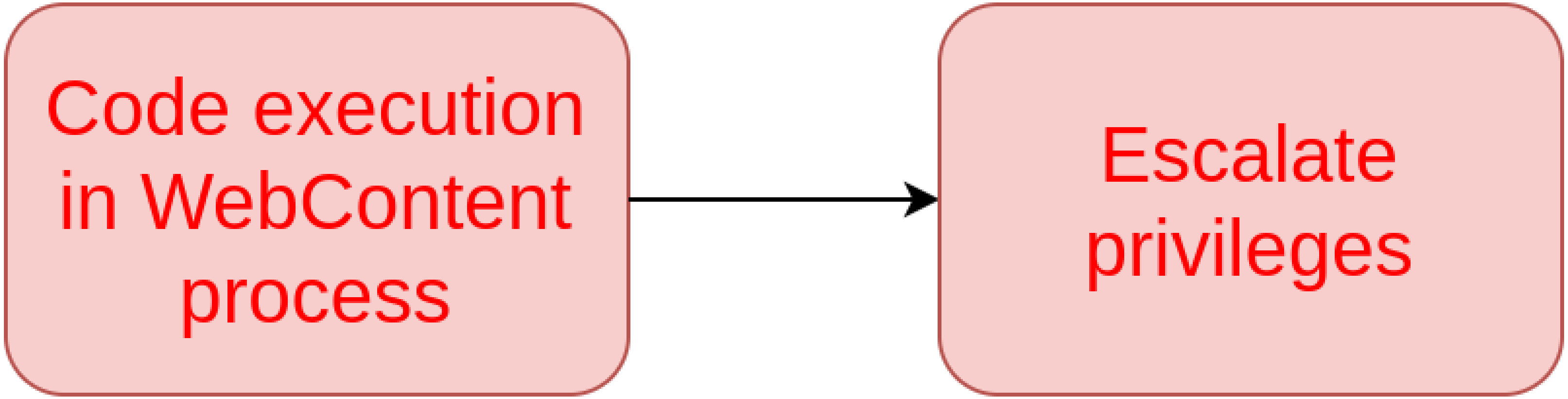
- **Synacktiv**
  - Offensive security company
  - +100 ninjas
  - We are hiring!

Introduction

- **Full chain on iPhone using the browser as entry point**



Introduction

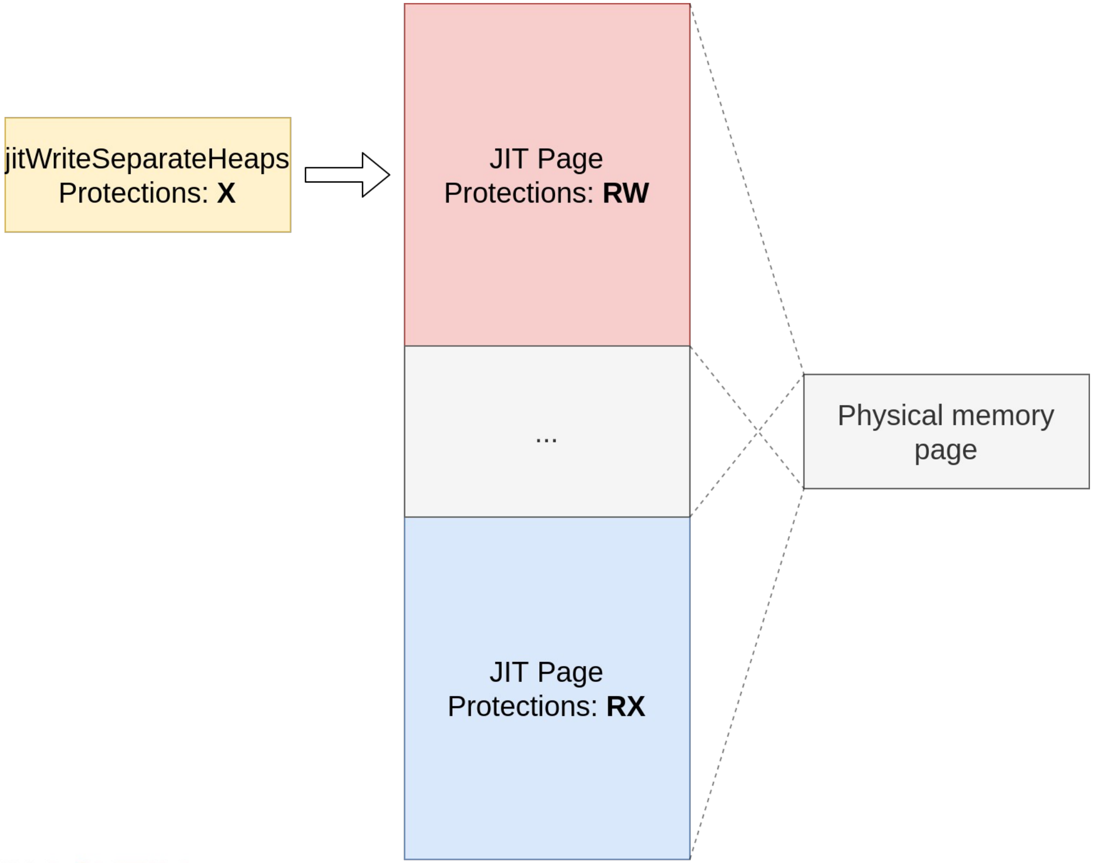
- **Steps to compromise Safari on the iPhone**
  - addrOf/fakeObj
  - Arbitrary R/W
  - Bypass PAC/APRR
  - Overwrite JIT page code
  - Arbitrary code execution!
- **Apple hardened each step of a Safari exploit...**

History of Safari mitigations

SEPARATED_WX_HEAP	APRR	GigaCage	StructureID randomization	PAC	JIT code signature	JIT Cage
2016	2017	2017	2019	2018-2022	2018-2022	2022

SEPARATED_WX_HEAP

- **The JIT page is mapped twice**
  - One has protections RX
  - Second has protections RW
- **A function is jitted to copy data in the JIT page**
  - The function is on a page with X only protection
  - The address of the RW JIT page is inlined in this function



SEPARATED_WX_HEAP

- **Public bypass still works with this mitigation[1]**
  - Build an arbitrary call primitive
    - ROP/JOP
  - Call the jitWriteSeparateHeaps function
  - Write arbitrary code in the JIT page
  - Profit!

1: https://www.sstic.org/media/SSTIC2019/SSTIC-actes/WEN_ETA_JB/SSTIC2019-Article-WEN_ETA_JB-benoist-vanderbeken_perigaud.pdf

APRR

- Hardware mitigation
- SEPARATED_WX_HEAP is replaced by APRR on supported hardware
- Atomically switches the JIT page protections using a System Register
  - RX → RW → RX

```
MOVK    X0, #0xC110
MOVK    X0, #0xFFFF,LSL#16
MOVK    X0, #0xF,LSL#32
MOVK    X0, #0,LSL#48
LDR     X0, [X0]
MSR     #6, c15, c1, #5, X0
ISB
```

APRR

- **Hard jump in the middle of the function**[1]
  - The System Register value comes from a R only page shared with the kernel
  - The system register value and the value from the R only page are compared
    - Difference → crash
- **Without CFI can be bypassed like SEPARATED_WX_HEAP**

```
MOVK    X0, #0xC110
MOVK    X0, #0xFFFF,LSL#16
MOVK    X0, #0xF,LSL#32
MOVK    X0, #0,LSL#48
LDR     X0, [X0]
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ISB
MOVK    X1, #0xC110
MOVK    X1, #0xFFFF,LSL#16
MOVK    X1, #0xF,LSL#32
MOVK    X1, #0,LSL#48
LDR     X8, [X1]
MRS     X10, #6, c15, c1, #5


CMP     X8, X10
B.NE    loc_18BA4E060
```
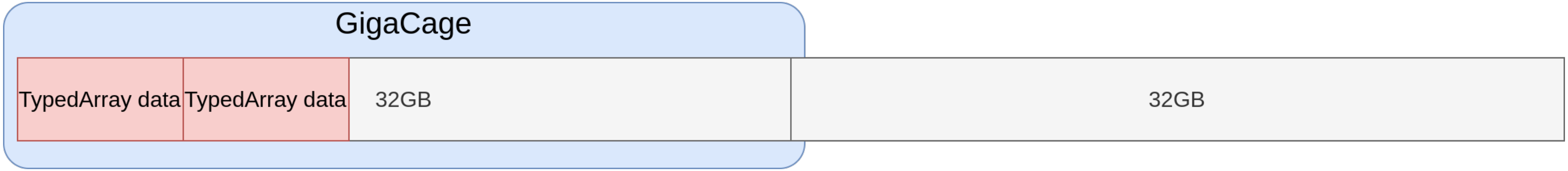

1: https://github.com/phoenhex/files/blob/master/exploits/ios-11.3.1/pwn_i8.js

GigaCage

- **TypedArray are JavaScript objects**
  - Often used to build arbitrary R/W
- **TypedArray are allocated in a 32GB zone**
  - Followed by another 32G zone allocated with PROT_NONE
- **The data buffer is now an offset to the cage and no more an address**



- **Cannot R/W outside of the cage anymore...**

GigaCage bypass

- **Many public documentation about the GigaCage[1]**
  - Some public bypasses still work…
- **One known bypass is to use other objects**
  - More on this later in this presentation
- ***GigaCage* is not enabled anymore on latest iOS versions**
  - But attackers still can’t use TypedArray to build arbitrary R/W…

1: https://googleprojectzero.blogspot.com/2020/09/jitsploitation-two.html

StructureID randomization

- **JSObject inherits from the JSCell object**

m_cellState 1 byte	m_flags 1 byte	m_type 1 byte	m_indexingType 1 byte	m_structureID 4 bytes

- **The StructureID is an index**
  - Used to get the *Structure* of a JSObject
- **Invalid StructureID → crash**
- **Before randomization the StructureID was incremental**
  - Easy to guess a valid *StructureID*
  - Build fake objects without crashing

After StructureID randomization

- **Randomization is added to the StructureID**

```
-----------------------------------------------------------------
| 1 Nuke Bit | 26 StructureIDTable index bits | 5 entropy bits |
-----------------------------------------------------------------
```

- **Signature is checked every time a JSObject property is accessed...**
  - ... but sometimes it is not![1]
  - Leads to StructureID randomization bypass
- **StructureID randomization has been removed**
  - StructureID uses low 32 bits of Structure address

1: https://i.blackhat.com/eu-19/Thursday/eu-19-Wang-Thinking-Outside-The-JIT-Compiler-Understanding-And-Bypassing-StructureID-Randomization-With-Generic-And-Old-School-Methods.pdf

PAC

- **Pointer Authentication Code**
- **Hardware mitigation**
- **Introduced in ARMv8.3-A**
- **Prevents an attacker from corrupting sensitive pointers**
  - Signature is added to some pointers
  - Corrupting a pointer without signing it correctly often leads to a crash

PAC

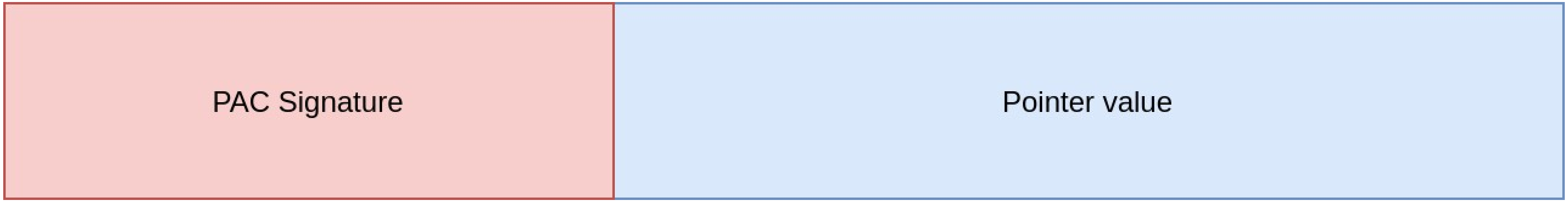
- **New ARM instructions used in Safari**
  - PAC*: Add signature to a pointer
  - AUT*: Check and remove signature from a pointer
  - XPAC*: Remove signature from a pointer
  - RETA*: Check X30 with context SP and return to X30 if the signature is correct
  - BRA* / BLRA*: Check signature and branch

PAC

- **Two kinds of pointers can be signed**
  - Data
  - Instruction
- **Two keys can be used for each kind**
  - Key A
  - Key B
- **A context is often used to avoid pointer substitution**
  - A pointer can also be signed with a null context...

PAC

- **The signature is stored in the top bits of a pointer**
- **The signature length depends on the key/pointer kind**
  - 16 bits
  - 24 bits



PAC

- **Instruction pointers**
  - VTable function pointer => PACIA
  - Return value stored on the stack => PACIB
  - JIT Code pointer => PACIB
- **Data pointers**
  - VTable pointer => PACDA
  - Sensitive data pointer (TypedArray data pointer…) => PACDB
  - JIT instructions => PACDB

PAC

- **What is not signed in Safari?**

PAC bypass

- **Bypassing PAC is a security issue in itself**
  - Apple takes PAC bypasses very seriously
- **Many PAC bypasses have been disclosed since PAC introduction**
  - Apple fixes each of them
    - Hardware improvement
    - Software improvement

PAC bypass: design issue

- **If a pointer authentication fails**
  - Signature is removed and one of the top bits is flipped
  - Does not raise an exception
- **If the pointer is signed again after the failed AUT***
  - Correct signature is added, with a flipped bit
  - PAC bypass: flip the bit again to get the correct signature
- **EnhancedPAC is implemented first on A14 SoC**
  - Signing invalid pointers will discard the signature
  - Can’t leak the signature anymore…

PAC bypass: bruteforce

- **The signature can still be bruteforced...**
- **...but Apple killed this bypass again**
- **The compiler option -fptrauth-auth-traps is used**
  - Adds a check after all AUT* instructions
  - If the signature given to the AUT* instruction is invalid → ABORT

```
AUTIB    X16, X17
MOV      X17, X16
XPACI    X17
CMP      X16, X17
B.EQ     loc_18BA4ABD8
BRK      #0xC471
```

PAC bypass: bruteforce

- **Apple added a new feature in the A15 SoC**
  - ARMv8.6-A FPAC extension
  - If an AUT* instruction fails, an exception is now raised
- **Apple killed this exploitation method with this feature**

PAC bypass: null context chained

- **Initially, many pointers were signed with a null context**
- **A potential bypass could be to use null signed pointers in a JOP chain**
  - Build powerful primitives
- **Never seen publicly**
- **Since iOS 15 this attack has been almost killed**
  - Very few pointers are still signed with a null context

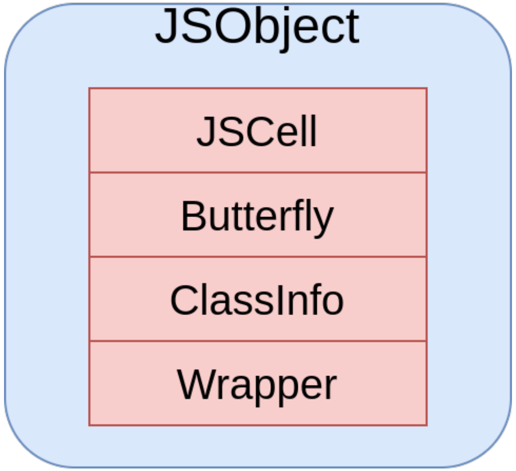
PAC bypass

- **More bypasses[1]**
  - Unprotected code pointers
  - Race condition with the JIT thread
  - Blocking the JIT thread while copying data on the JIT page
  - Signal handlers corruption
- **All of these bypasses have been fixed**

1: https://googleprojectzero.blogspot.com/2020/09/jitsploitation-three.html

PAC R/W

- **PAC doesn't sign a lot of sensitive data pointers**
- **Some object can be wrapped into a JSObject**
  - DOMRect
    - Contains 4 doubles
    - Has methods to read and write these doubles
- **Faking a wrapper to a DOMRect object**
  - Arbitrary R/W
- **Method used by a public exploit[1]**



1: https://blog.google/threat-analysis-group/analyzing-watering-hole-campaign-using-macos-exploits/

PAC kill R/W method

- **Method killed by iOS 15.4**
- **Some wrappers to sensitive wrapped objects are now signed**
  - Most of them manipulate floats/doubles
  - Killed many arbitrary R/W methods

```
commit 30199a0aff4a6eff01d9a90aa1c05aac87f1a4cd
Author: [redacted] <[redacted]@apple.com>
Date:   Thu Feb 10 14:46:18 2022 +0000

    Introduce SignedPtrTraits which enables Ref pointers to be protected with PtrTags.
```

JIT Code signature

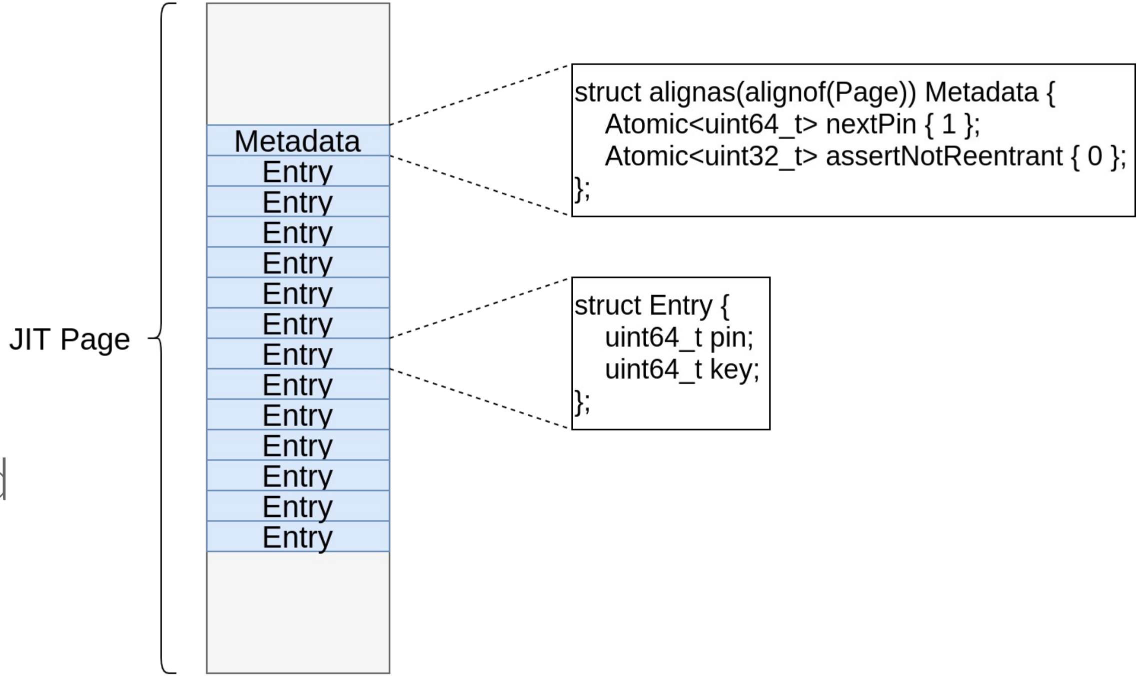
- **The JIT compilation can be done in another thread**
  - The assembly code is stored in a temporary buffer while doing compilation
  - The temporary buffer content is copied in the JIT page at the end of the compilation
- **Before JIT code signature**
  - Race the JIT thread to put arbitrary code in the temporary buffer
  - Profit!
  - But…

JIT Code signature

- **Apple introduced the JIT code signature**
  - Stop attackers from overwriting the *JIT* code buffer
- **Software mitigation based on PAC**
- **Instructions stored in the temporary buffer are signed**
  - Each instruction signature generates a hash stored in the hash buffer
    - Signed with previous hash and PACDB
- **Signature is checked when the temporary buffer is copied in the JIT page**
  - If the signature is invalid → Crash

JIT Code signature PIN

- **The hash used to sign the next instruction was not protected**
- **It is now signed with a unique identifier (PIN)**
  - Each JIT compilation uses a different PIN
  - PIN informations are stored in the JIT page
  - An attacker can’t modify them



JITCage

- **The A15 SoC brings a new complex mitigation**
  - The JITCage!
- **The JITCage stops attackers from calling arbitrary functions from the JIT page**
- **The JIT page is now mapped with a new flag**
  - MAP_JITCAGE?
- **The XNU open-source project doesn't have references about this flag…**

JITCage

- ...but the KernelCache has references!

```
void __fastcall enable_jitbox(__int64 thread)
{
  __int64 current_thread; // x0
  __int64 v3; // x8
  unsigned __int64 StatusReg; // x9

  current_thread = get_thread_ro();
  if ( current_thread == thread )
  {
    v3 = *(_QWORD *)(current_thread + 0x358);
    StatusReg = _ReadStatusReg(ARM64_SYSREG(3, 0, 13, 0, 4));
    *(_QWORD *)(*(_QWORD *)(StatusReg + 0x158) + 0x218LL) = v3;
    *(_QWORD *)(*(_QWORD *)(StatusReg + 0x158) + 0x210LL) = *(_QWORD *)(current_thread + 0x350);
    _WriteStatusReg(ARM64_SYSREG(3, 4, 15, 15, 4), *(_QWORD *)(current_thread + 0x358));
    _WriteStatusReg(ARM64_SYSREG(3, 4, 15, 15, 1), *(_QWORD *)(current_thread + 0x350));
    __isb(0xFu);
  }
}
```

JITCage

- **The kernel sets new System Registers using**
  - The size of the JIT page
  - The address of the JIT page
  - Some unknown flags
- **The KernelCache has no other information**
- **The interesting part of the JITCage is implemented in the A15 SoC**

JITCage

- **The following instructions can’t be executed in the JITCage**
  - RET
  - BR/BLR/BL
  - SVC
  - MRS/MSR
- **If one tries to execute these instructions in the JITCage**
  - The processor raises an EXC_BAD_INSTRUCTION exception

JITCage

- **The PAC IA/IB keys are different in the JITCage**
- **Can’t sign instruction pointers in the JITCage**
  - PACIA doesn’t add signature if executed in the JITCage
  - PACIB can only sign pointer that points into the JITCage
  - PACD* seems unaffected by the JITCage

JITCage

- The JIT code has to call functions outside of the JITCage
- Setting a System Register allows changing IA key
  - Instruction pointers used by the JITCage are signed with the IA key
- Only done once when the JavaScript engine is initialized
- Can’t be done anymore after

```
MRS     X8, #4, c15, c15, #6
ORR     X8, X8, #0x8000
MSR     #4, c15, c15, #6, X8
```

- An attacker can’t easily call functions outside of the JITCage

Conclusion 1/2

- **Getting arbitrary code on latest iPhone involves finding:**
  - A vulnerability
  - A new method to build arbitrary R/W
  - A PAC bypass
  - An APRR bypass
  - A JITCage bypass
- **One solution for attackers could be to implement the next stage using JavaScript only...**

Conclusion 2/2

- **2022 in short**
  - Yet another mitigation
  - Yet other exploitation methods killed
- **What to expect in the next years?**
  - Same as above?
- **Maybe it's time for attackers to find another entry point than the browser…**
  - …or maybe not? :-)
  - JavaScript is a powerful engine to attack all those mitigations

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