

## Escaping the Safari Sandbox: A tour of WebKit IPC OFFENSIVE CON

## Who am I?

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- Vulnerability research & Exploitation

## Synacktiv

- Offensive security company
- +170 ninjas
- We are hiring!



## Introduction

An analysis of an in-the-wild iOS Safari WebContent to GPU Process exploit

By Ian Beer







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#### Browser engine

- Developed by Apple
- Mainly used by Safari
- Initial release in 2005

## Ships everything to build a browser

- JavaScript engine
- DOM/rendering engine
- Web APIs
- User Interface API
- Etc.



## Architecture

### Initial architecture

- Single process
- Too much privileges

## Bad from a security point of view

• Compromise the process  $\rightarrow$  Game Over





## Architecture

#### WebKit2!

## Multi-process

- UIProcess
  - Most privileged
- WebContent
  - Less privileged...
  - ...still too much











## WebContent

### Most exposed process

- DOM rendering
- JavaScript engine
- Web APIs implementation
- Almost no privileges
  - Hardened sandbox profile
- Can use sandbox extensions...
  - ...require user permission
- WebKit processes expose a large surface

IOKit	0
Unix syscalls	~90
Mach traps	~30
MIG routines	~20
Userland services	0
WebKit process	3



## NetworkProcess

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### Network-related process

- Loading remote/local resources
- Web APIs implementation
  - CacheAPI
  - SharedWorker
  - etc.

### Larger kernel and userland surface

- Few network-related syscalls
- Access to 1 IOKit
- Communicates with some services



## **GPUProcess**

## Video and graphics processing

- Communicates with GPU (via ANGLE)
- Web APIs implementation
  - WebGL
  - WebGPU!
    - Not reachable anymore
  - Etc.
- Data parsing
  - Font, WebRTC

### Almost same sandbox as WebContent

Few IOKits and services



## **UIProcess**

### Main Safari process

### Most privileged WebKit process

- Display on screen
- User interaction
- Process management
- User permissions management
  - Camera
  - Microphone
  - etc.

### No specific sandbox

### WebKit processes are extensions<sup>1</sup>

Services before iOS 17.4

#### Communicate through Mach messages

UIProcess starts every WebKit process



1: https://developer.apple.com/documentation/extensionkit?language=objc

#### 

#### UIProcess allows WebContent to communicate with other processes



#### Processes have their own dedicated connection

Messages are filtered based on connection type



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- Message starts with a mach\_msg\_header\_t
- Followed by a message header
- Custom encoder/decoder
  - Integer, string, floating number
  - Memory entry, Objective-C object



#### 

#### WebKit2 can send Objective-C objects

- Based on NSKeyedArchiver and NSKeyedUnarchiver
  - Objects are serialized as BPlist



## Very powerful

- Lots of objects can be encoded/decoded
- Supports cyclic decoding
- Historically lots of exploits abused the Objective-C deserializer<sup>123</sup>
- Apple starts killing exploitation methods...

1: https://googleprojectzero.blogspot.com/2020/01/remote-iphone-exploitation-part-1.html 2: https://googleprojectzero.blogspot.com/2022/03/forcedentry-sandbox-escape.html 3: https://googleprojectzero.blogspot.com/2023/10/an-analysis-of-an-in-the-wild-ios-safari-sandbox-escape.html



## NSSecureCoding

- Must specify decoded type
- Raise exception if decoded object type != specified type
- Allows to decode subclasses of the specified type!
  - If **NSObject** is in the allowed list  $\rightarrow$  arbitrary deserialization!
    - (id)decodeObjectForKey:(NSString\*);

With Secure Coding

- (id)decodeObjectOfClass:(Class) ForKey:(NSString\*);

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### Trust restrictions

- Applied to Platform Binary and Apple applications
  - Raises an exception if **NSObject** is in the allowed list
  - Collection classes must explicitly be in the allowed list
    - NSArray
    - NSSet
    - etc.
  - Disable many features of NSPredicate
  - Disable cyclic decoding
  - Decoding must use NSSecureCoding

#### Can't easily trigger arbitrary Objective-C deserialization anymore #SYNACKTIV

#### Strict mode

- Applied to WebKit processes
  - (void)\_enableStrictSecureDecodingMode;
- Even more restrictive than Secure Coding mode
  - Can't decode subclasses anymore
  - Stops attacker from decoding some sensitive object fields
- Breaks some exploitations methods
- Very few Objective-C objects can still be decoded in WebKit



#### WebKit has its own heap allocator

- "Libpas is a beast of a malloc, designed for speed, memory efficiency, and type safety.", Filip Pizlo
- Exposes API
  - FastMalloc
  - ISOHeap
    - Still documented
    - Few WebKit objects uses this API
  - GigaCage, JITHeap
    - Not relevant for this talk



### FastMalloc

- Based on Thread Local Cache
- Almost every WebKit object uses this API
- Sorts allocations based on their sizes
- Few security protections
  - Good control over the heap

## Probabilistic Guard Malloc

- Tries to catch memory corruption bugs in the wild
  - Adds guard pages and segregation
- 1/1000 probability to have the feature enabled
  - 1 allocation every 4000-5000 is guarded

## Not a security hardening



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#### TZone

- Disabled by default! (for now...)
- Objects information is stored in Mach-O section <u>tzone</u> descs
- Allocations are stored into buckets
  - Based on their size and alignment
  - AND a random seed
    - Generated by the kernel
  - Can't predicate which objects share the same buckets
- Tries to break heap-based exploit reliability

Bucket 1	Bucket 2
Object A	Object B
Object A	Object D
Object C	Object B
Object C	Object B
Object A	Object B

## **Default userland malloc**

#### Almost every process uses this heap allocator

- Historically hacker friendly<sup>1</sup>
- iOS 17 introduced a little change...





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## **Default userland malloc**



## malloc() is replaced by malloc\_type\_malloc()

- Second parameter is a tag generated by the compiler
- Looks like a new hardened allocator, but...

## malloc\_type\_malloc() still uses the old implementation

- The tag is never used (as of iOS 17.4)
- At least WebKit processes don't use it
- Is typed malloc coming to userland?



### Need to bypass PAC again outside of WebContent

- WebContent has its own PAC keys
- Latest PAC bypasses targeted the DYLD loader<sup>12</sup>

## Very interesting target

- Lots of optimizations
- Has to sign pointers at runtime
  - dlsym()
  - Relocation

1: https://googleprojectzero.blogspot.com/2023/10/an-analysis-of-an-in-the-wild-ios-safari-sandbox-escape.html 2: https://media.ccc.de/v/37c3-11859-operation\_triangulation\_what\_you\_get\_when\_attack\_iphones\_of\_researchers



### Structures used to keep information about loaded images

Initially not protected





## Build fake Mach-O in memory

dlsym() returns arbitrary signed pointers



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...

### DYLD now protects its internal structures

- Structures are allocated in VM\_PROT\_READ pages
- Switches to VM\_PROT\_WRITE when it needs to write
- Switches back to VM\_PROT\_READ after writing
- Attackers can't corrupt DYLD structures anymore...
  - ...but if attackers can call mprotect() they can change pages protections
    - Operation Triangulation did that



#### DYLD pages are now protected using SPRR

- Pages mapped with VM\_FLAGS\_TPR0
- Protections dynamically changed by DYLD
- Operation Triangulation PAC bypass doesn't work anymore



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## The GPU full chain exploits a race condition in dlsym()

- Corrupts the symbol name on the stack before it is used
- Sign arbitrary symbols



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### Can't map RWX pages

Only WebContent and few other processes

## Useful to have an execution context in the compromised process

- To pivot into the compromised process
- To implement the next stage
- Spawn a JavaScript engine!

### JavaScriptCore exposes an Objective-C API

- (JSValue\*)evaluateScript:(NSString\*);
- (JSValue\*)objectForKeyedSubscript:(id);
- (void)setObject:(id) forKeyedSubscript:(id);
- Corrupt JSValue inside the JavaScript engine
  - Transfer primitives
- Apple doesn't like this exploitation method...







Forbid JS execution in the GPU Process.

https://bugs.webkit.org/show\_bug.cgi?id=254101
rdar://106869810

The GPU Process does not need to execute any JS code. We should enforce this invariant.





### Can't spawn JavaScript engine in the GPU process anymore

- Opcode list is trashed at process initialization
- VM::VM initialization is forbidden
  - Or is it?



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#### Checked in the VM constructor

vmCreationDisallowed must be set to crash the process

VM::VM(VMType vmType, HeapType heapType, WTF::RunLoop\* runLoop, bool\* success)
// ...
if (UNLIKELY(vmCreationShouldCrash || g\_jscConfig.vmCreationDisallowed))
CRASH WITH EXTRA SECURITY IMPLICATION AND INFO(/\* ... \*/);





```
void GPU_SERVICE_INITIALIZER(xpc_connection_t connection, xpc_object_t initializerMessage)
{
    g_jscConfig.vmEntryDisallowed = true;
    g_wtfConfig.useSpecialAbortForExtraSecurityImplications = true;
```

WTF::initializeMainThread();





### Bypass JavaScript engine hardening

- PAC bypass is mandatory
- Restore each signed functions pointers in g\_opcodeMap



## Conclusion

Escaping the WebContent sandbox through WebKit processes looks promising...

- ... but increases full-chains complexity
- DYLD is a good PAC bypass target...
  - ... lots of PAC bypasses killed
- iOS has never had so many userland mitigations...
  - ... but in 2023 attackers were still able to build a full-chain from WebContent :-)







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