Google Native Client

Analysis Of A Secure Browser Plugin Sandbox

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Google Native Client

browsers are the new platform for applications

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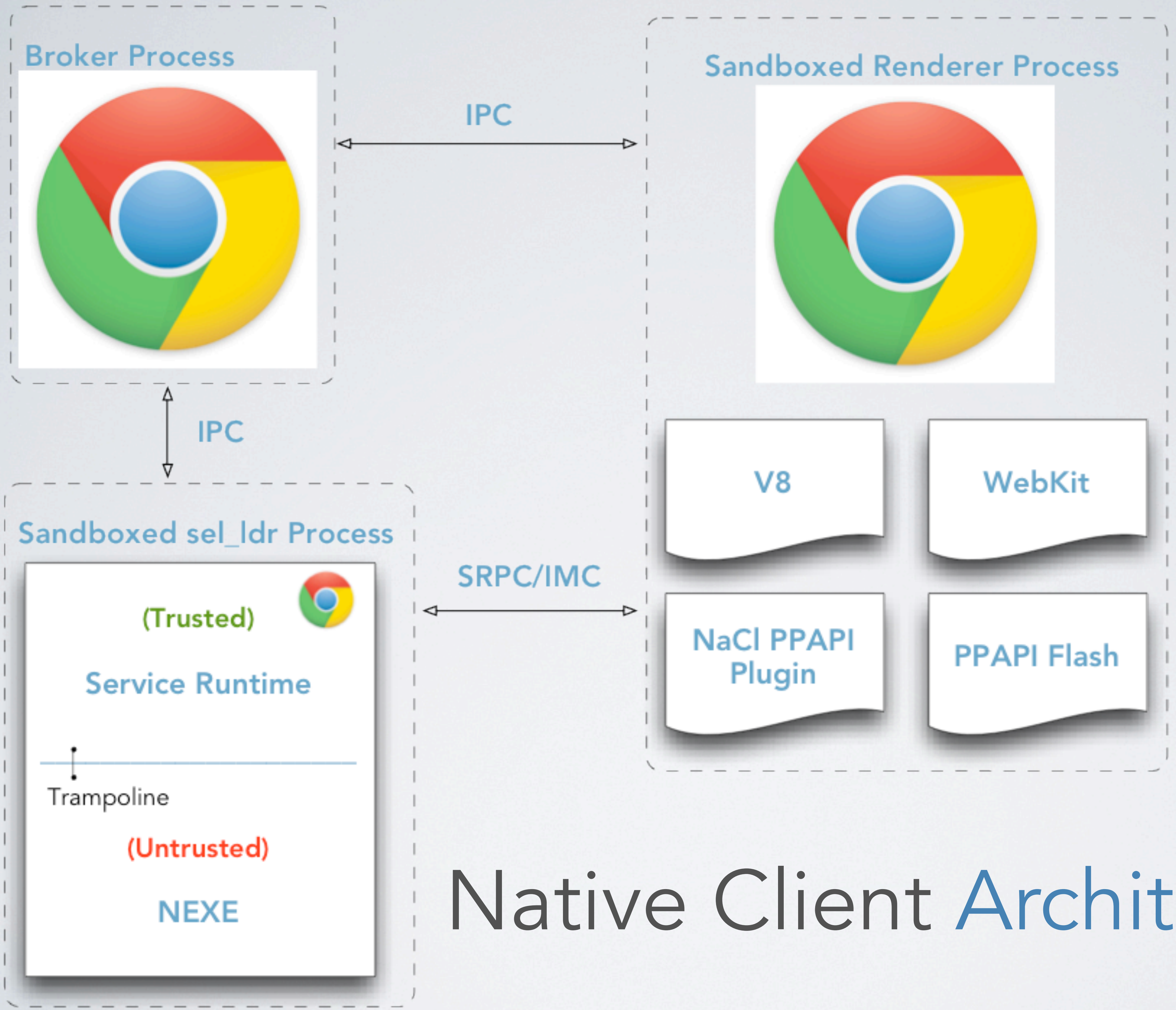
sandboxes are the future of application security

breaking easy targets is boring!

Google Native Client

- A Chrome plugin that allows the execution of native untrusted code in your browser (Win32, OS X, Linux)
- Chrome 14 shipped with NaCl by default
- Large and complex architecture
  - Modified Compiler Toolchain
  - Secure ELF loader
  - Disassembler and Code Validator
  - Service Runtime
  - Inner and Outer Sandbox
  - SRPC (Simple Remote Procedure Call)
  - IMC (Inter-Module Communication)
  - PPAPI (Pepper)



Native Client Architecture

NaCl Security

If a NaCl module can execute instructions that were not validated by the service runtime then the security provided by Native Client is broken

Modified Compiler Toolchain

- Modified GCC toolchain ships with NaCl SDK
- Only the SDK compiler can be used to produce a NEXE
- SDK can produce code for:
  - 32-bit x86
  - 64-bit x86_64

Modified Compiler Toolchain

- NEXE modules are compiled and linked as ELF
  - All of the typical structures are present
    - ELF Header, Program Headers, Dynamic Segment, Section Headers, Symbol Tables, Relocation Entries
  - readelf can be used to examine NEXE ELF structures
  - IDA Pro can be used to disassemble the NEXE .text

Modified Compiler Toolchain

- NEXE instructions must be aligned to 32 byte boundary
  - This is required by the inner sandbox
- Blacklisted instructions are never emitted

```
01000ac0 <PpapiPluginStart>:   ; 32 byte aligned
 1000ac0:       53                   push   %ebx
 1000ac1:       83 ec 28             sub    $0x28,%esp
 1000ac4:       a1 00 00 02 11       mov    0x11020000,%eax
 1000ac9:       8b 08                mov    (%eax),%ecx
 1000acb:       85 c9                test   %ecx,%ecx
 1000acd:       74 31                je     1000b00 <PpapiPluginStart+0x40>
 1000acf:       eb 0f                jmp    1000ae0 <PpapiPluginStart+0x20>
 1000ad1:       90                   nop
 1000ad2:       90                   nop
```

Modified Compiler Toolchain

- No instructions can straddle the 32 byte boundary
- Branches are used to transfer control across boundaries
- No *ret* instructions, the stack is manually modified

```
01000ac0 <PpapiPluginStart>:  ; 32 byte aligned
 1000ac0:       53                  push   %ebx
 1000ac1:       83 ec 28            sub    $0x28,%esp
 1000ac4:       a1 00 00 02 11      mov    0x11020000,%eax
 1000ac9:       8b 08               mov    (%eax),%ecx
 1000acb:       85 c9               test   %ecx,%ecx
 1000acd:       74 31               je     1000b00 <PpapiPluginStart+0x40>
 1000acf:       eb 0f               jmp    1000ae0 <PpapiPluginStart+0x20>
 1000ad1:       90                  nop
 1000ad2:       90                  nop
```

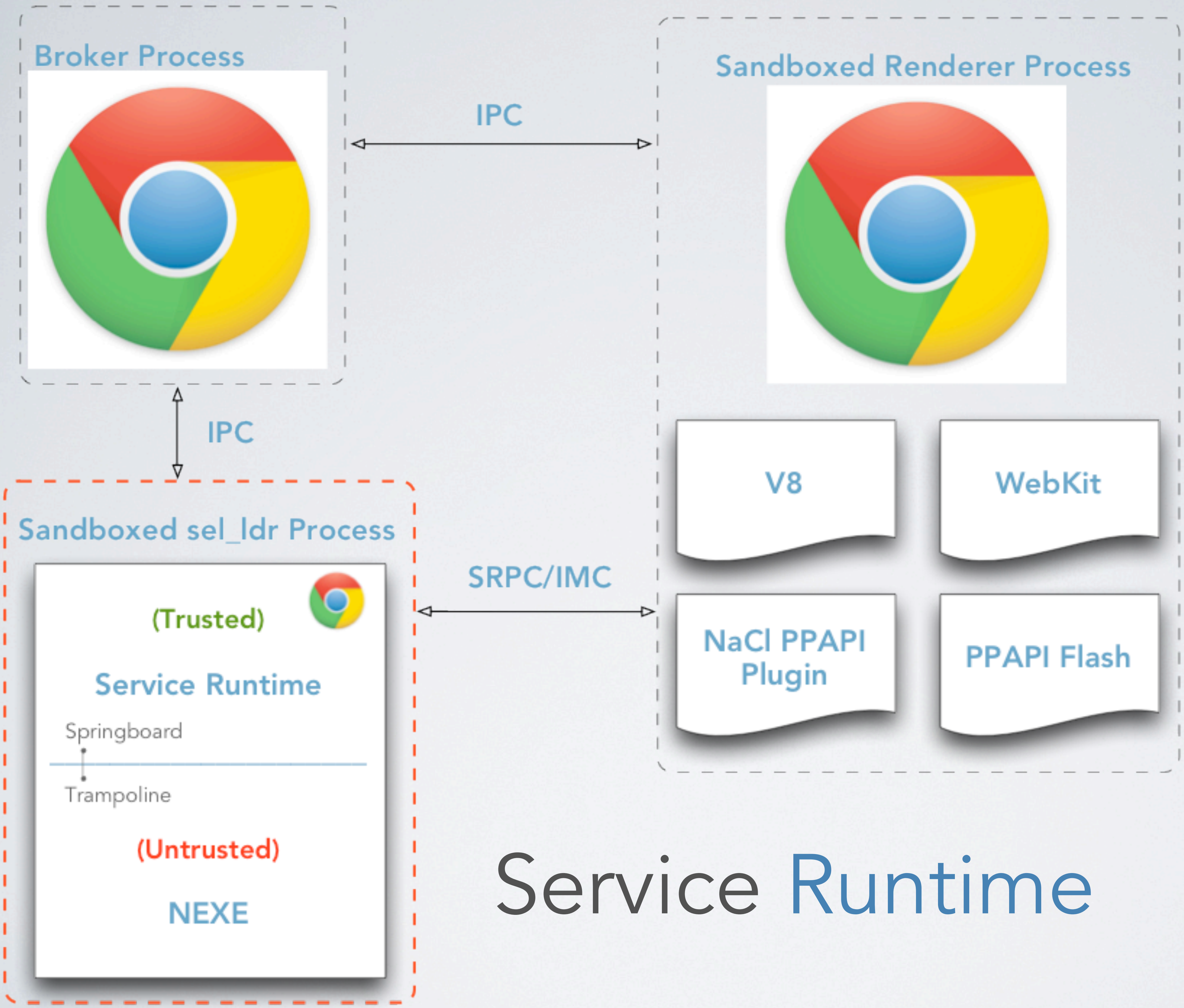
Modified Compiler Toolchain

- Branch instructions are properly aligned to validated code
- call instructions are subject to a simple AND operation
  - Alignment masking on the destination register ensures a 32 byte alignment which guarantees the destination has been run through the validator
- Prevents over written NEXE function pointers and modified registers from resulting in arbitrary code execution

```
0x100057b:   83 e0 e0   and    $0xffffffe0,%eax ; eax = 0x100057a
0x100057e:   ff d0      call   *%eax             ; eax = 0x1000560
```

Modified Compiler Toolchain

- NaCl toolchain
  - Ensures all ELF structures are properly formed
  - Only safe instructions are emitted
  - All branch instructions are preceded by alignment mask
- But an attacker can modify the NEXE binary...



Service Runtime

Service Runtime

- Stand alone process, launched from Chrome
- Runs in the same sandbox as Chrome renderer
  - 'Outer Sandbox'
- Shares its virtual address space with a NEXE module
  - Service Runtime memory is <u>trusted</u>
  - NEXE memory is <u>untrusted</u>
  - Separation between the two is the 'Inner Sandbox'

Instruction Validator

- Found in the Service Runtime
- Disassembles all NEXE instructions after ELF parsing
- Starts at trusted 32 byte aligned entry point
- Exits on any blacklisted instructions
    - Privileged instructions
    - Instructions that modify segment registers
    - ret
    - sysenter
    - prefix bytes

Instruction Validator

- The validator only performs static analysis on the code
- Static analysis will not know register values at runtime
- As long as the branch target is mod 32 aligned it knows whatever the target is it has been validated
- Example:
  - 0x1000560 not known when the validator runs
    - Guaranteed to have been properly validated due to proper 32 byte alignment

```
0x100057b:   83 e0 e0   and    $0xffffffe0,%eax ; eax = 0x100057a
0x100057e:   ff d0      call   *%eax            ; eax = 0x1000560
```

Instruction Validator

- The NaCl SDK contains a standalone NEXE validator

```
$ ./ncval_x86_32 ../examples/hello_world_glibc/hw.nexe
segment[0] p_type 3 p_offset ee0 vaddr 11000ee0 paddr 11000ee0 align 1 filesz 19 memsz 19 flags 4
segment[1] p_type 1 p_offset 140 vaddr 1000140 paddr 1000140 align 65536 filesz da0 memsz da0 flags 5
parsing segment 1
VALIDATOR: 10008e6: ret instruction (not allowed)
VALIDATOR: 10008e6: Illegal instruction
segment[2] p_type 1 p_offset ee0 vaddr 11000ee0 paddr 11000ee0 align 65536 filesz 478 memsz 478 flags 4
segment[3] p_type 1 p_offset 1358 vaddr 11011358 paddr 11011358 align 65536 filesz 13c memsz 13c flags 6
segment[4] p_type 1 p_offset 10000 vaddr 11020000 paddr 11020000 align 65536 filesz 0 memsz 2c flags 6
segment[5] p_type 2 p_offset 136c vaddr 1101136c paddr 1101136c align 4 filesz d8 memsz d8 flags 6
segment[6] p_type 1685382481 p_offset 0 vaddr 0 paddr 0 align 4 filesz 0 memsz 0 flags 6
segment[7] p_type 7 p_offset 0 vaddr 0 paddr 0 align 4 filesz 0 memsz 0 flags 4
*** ../examples/hello_world_glibc/hw.nexe IS UNSAFE ***
Validated ../examples/hello_world_glibc/hw.nexe
*** ../examples/hello_world_glibc/hw.nexe IS UNSAFE ***
```

Service Runtime

- Inner Sandbox
  - Required because the untrusted NEXE shares virtual address space with the trusted service runtime
- Separating untrusted code and data
  - x86 memory segmentation model
  - x86_64 mov/branch alignment, guard pages
  - ARM load/store/branch alignment, guard pages
  - TLS segments store data/registers between context switches

Service Runtime

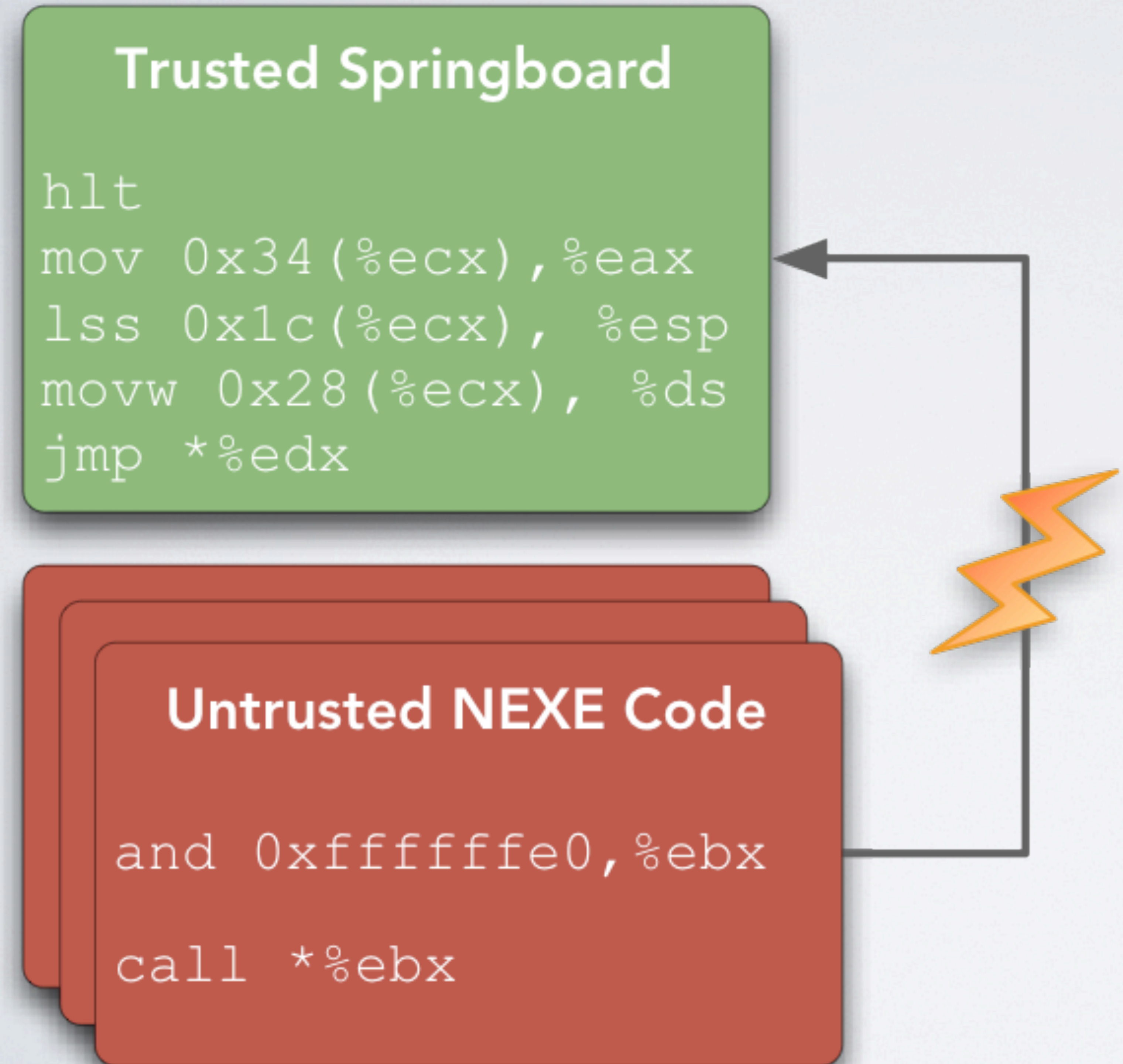
- Trusted instruction blocks are mapped at runtime to enable a context switch between trusted and untrusted
  - Springboard enable trusted to untrusted
  - Trampolines enable untrusted to trusted
  - Each contain privileged instructions that manipulate the segment registers

- x86 Segment Registers
  - Used to separate trusted from untrusted code/data
  - Modified when switching between trusted/untrusted
  - %cs code
  - %ds data
  - %gs thread local storage
  - %ss %es %fs

Service Runtime

- Memory may not be marked executable at runtime
- New executable code pages may not be created at runtime
- This guarantees only validated code pages are set executable

Service Runtime



The untrusted NEXE code is unable to transfer control to an arbitrary location in the trusted Springboard due to the alignment mask before the call. It may only execute the first instruction, which is a *hlt*

NACL Syscalls

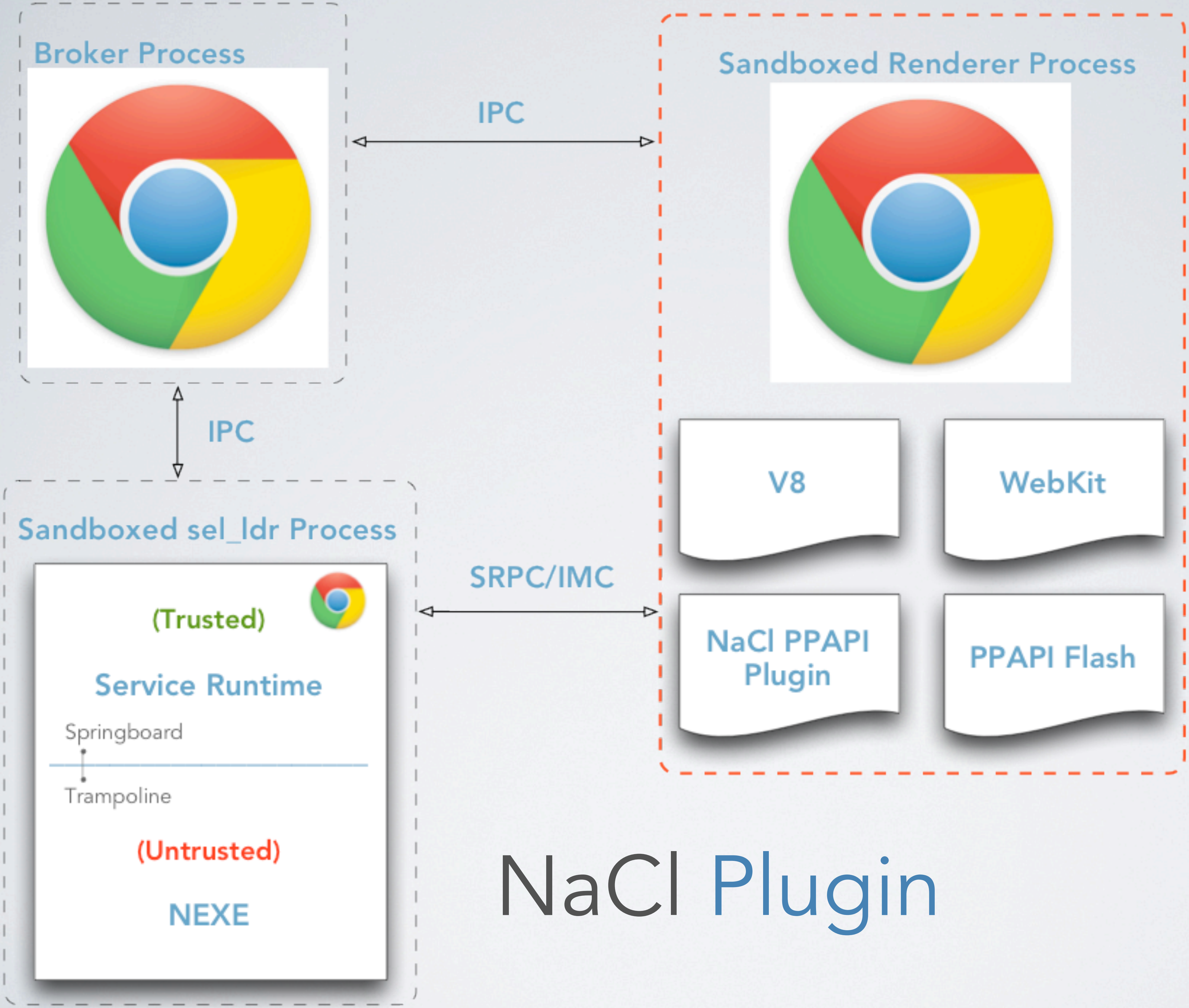
- A NEXE cannot make normal syscalls
  - sysenter / int 0x80 not allowed by the validator
- 30~ NACL_SYSCALLS
- Basic operations such as open, close, read, write, ioctl, mmap, munmap, stat, _exit and a few others
  - NACL specific IMC accept, connect, send, recv
- These are dispatched via Springboard/Trampoline code

Service Runtime IMC

- Inter-Module Communication (IMC) is the core protocol all NEXE data to the NaCl plugin rides on
- IMC uses basic socket types that initialized by the imc_makeboundsock and imc_socketpair NACL_SYSCALL's
- IMC is built on top of platform supplied UNIX sockets, named pipes and shared memory
- IMC is too low level to be used by application developers

Service Runtime SRPC

- Simple Remote Procedure Call (SRPC)
- Rides on top of IMC
- SRPC allows for the encapsulation of serialized data between NEXE modules and the NaCl plugin
- SRPC endpoints are invoked via SRPC signatures
  - NaClSrpcInvokeBySignature(channel, “MyMethod:i:i”, resource, bool)
- Although SRPC is at a higher level than IMC its not intended to be used by application developers directly


Broker Process
IPC
Sandboxed Renderer Process
IPC
V8
WebKit
Sandboxed sel_ldr Process
SRPC/IMC
(Trusted)
Service Runtime
Springboard
Trampoline
(Untrusted)
NEXE
NaCl PPAPI Plugin
PPAPI Flash

NaCl Plugin

NaCl Plugin

- The NaCl plugin itself is a trusted PPAPI plugin
- It lives inside the Chrome renderer process as a .DLL
- Invoked by HTML ‘embed’ tag

```
<embed name="NaCl_module"
     id="hello_world"
     width=200 height=200
     src="hello_world.nmf"
     type="application/x-NaCl" />
```

NaCl Plugin

- The .nmf file is a ‘NaCl Manifest File’
- JSON that specifies NEXE and .so libraries

```
{ "files": {
  "libgcc_s.so.1": { "x86-32": { "url": "lib32/libgcc_s.so.1" } },

  "main.nexe": { "x86-32": { "url": "hw.nexe" } },

  "libc.so.3c8d1f2e": { "x86-32": { "url": "lib32/libc.so.3c8d1f2e" } },

  "libpthread.so.3c8d1f2e": { "x86-32": { "url": "lib32/libpthread.so.3c8d1f2e" } } },

  "program": { "x86-32": { "url": "lib32/runnable-ld.so" } }

}
```

- The plugin is responsible for parsing this JSON using a third party package named ‘jsoncpp’
- NaCl downloads the NEXE using the PPAPI URLLoader and FileIO interfaces

NaCl Plugin

- NaCl asks the Chrome browser process to start the service runtime process
- Once the service runtime has started they establish an SRPC connection with each other
  - This is known as an administrative channel
  - Once the NEXE has been started a new SRPC channel is created specifically for communication with untrusted code

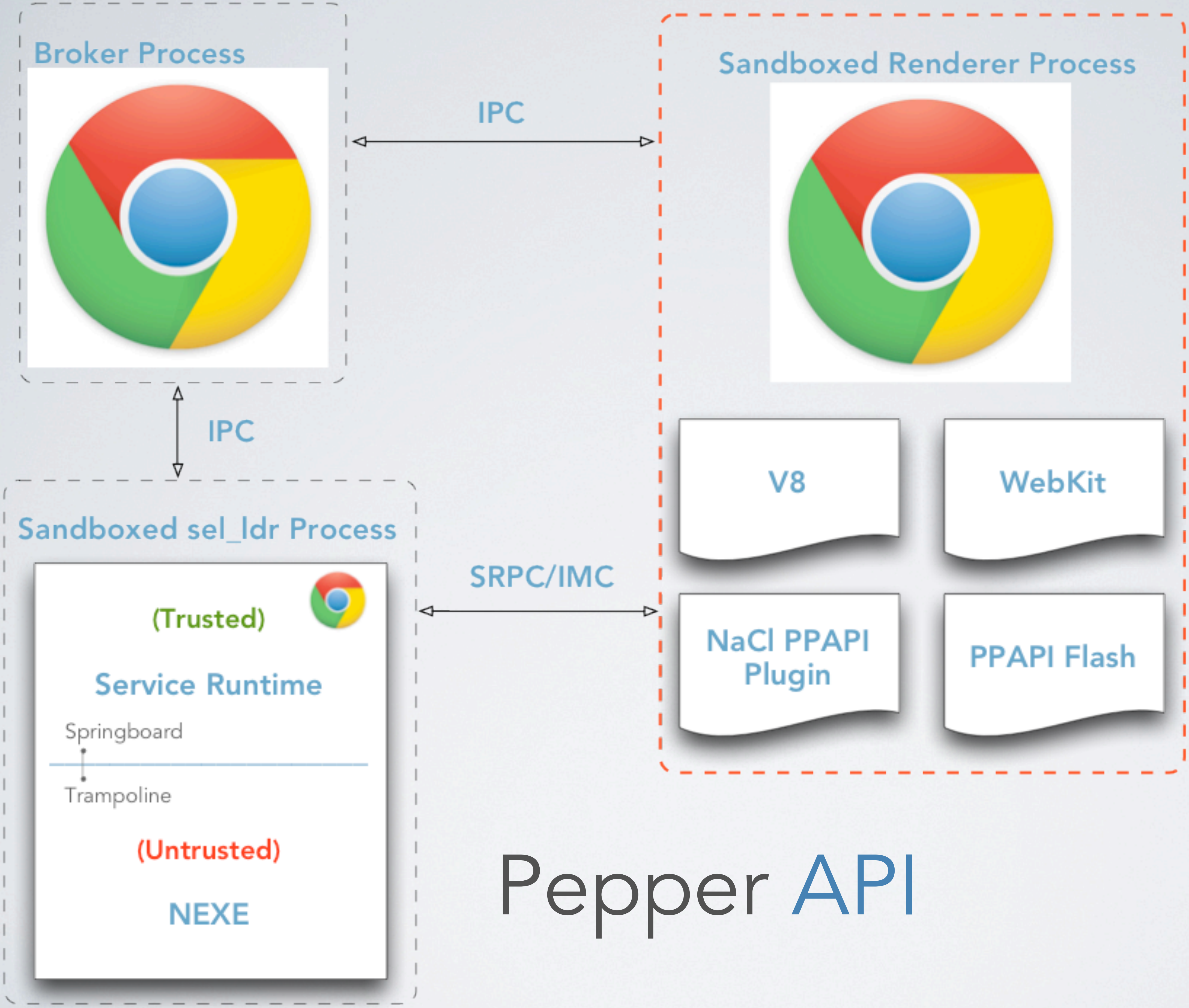
NaCl Plugin

- NaCl must expose part of itself to the browser DOM
- However PPAPI is not scriptable like NPAPI
- Only a few properties and functions are exposed
  - readyState, lastError, exitStatus
  - postMessage

NaCl Plugin

- PostMessage is how JavaScript talks to the NEXE module
- The NEXE must implement pp::Instance::HandleMessage to receive these messages
  - The PPB_Messaging::PostMessage C++ interface is used to send messages back to JavaScript
  - JavaScript gets alerted to new messages using an event listener and a callback
  - These messages have no format and can be binary or ASCII

Pepper API



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PPAPI Flash

Pepper API

- NPAPI (Netscape Plugin Application Programming Interface)
  - Designed for browser plugins written 10 years ago
- PPAPI (Pepper Plugin Application Programming Interface)
  - Designed for modern browser plugins
  - New APIs for Audio, FileIO, 3D and a lot more
  - Chrome is the only browser shipping support for PPAPI

Pepper API

- Major differences between PPAPI and NPAPI
  - PPAPI plugins are not scriptable via JavaScript
    - Only PostMessage is used to transfer data
  - PPAPI supports out of process plugins from the start
    - NPAPI had to bolt this on many years later
  - PPAPI provides interfaces for privileged actions
    - FileIO is a good example
    - In Chrome this is handled by the broker

PPAPI Plugins

- Trusted PPAPI plugins run in a sandboxed Chrome renderer process or a separate sandboxed plugin process
  - The Native Client plugin itself is a PPAPI plugin that lives in the sandboxed Chrome renderer process
  - Adobe Pepper Flash is an out of process PPAPI plugin
- Untrusted PPAPI plugins in Chrome run as a NEXE module
  - NEXE's communicate with PPAPI layer using a proxy

Pepper Proxy

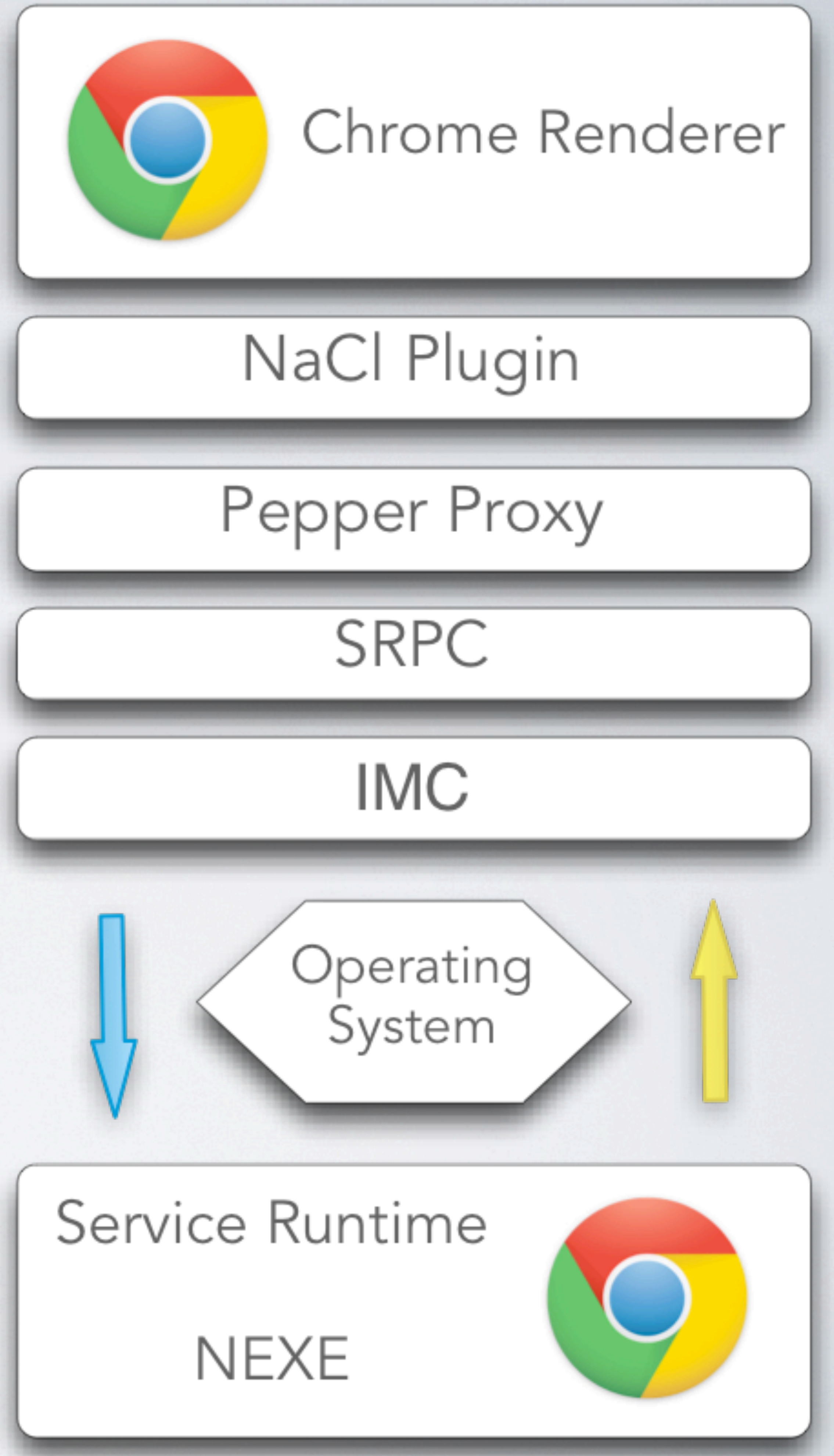
- NEXE modules need to talk to the browser to provide any useful functionality
- PPAPI provides plugins the ability to access privileged browser resources
- The NaCl plugin implements the pepper proxy
- The proxy contains SRPC server and client code

Pepper Proxy

- Server code hands off data from the client to thunks which then direct it to the proper PPAPI backend in Chrome
- Client code makes requests back to the untrusted NEXE
- NaCl uses IDL files to describe these interfaces
  - C++ code is often auto generated using them

Pepper Proxy

- The protocol stack allows untrusted NEXE modules to invoke trusted PPAPI interfaces
- Serialized PPAPI arguments, over SRPC, over IMC
- Most of this is binary data packaged up as PP_Var or basic data types

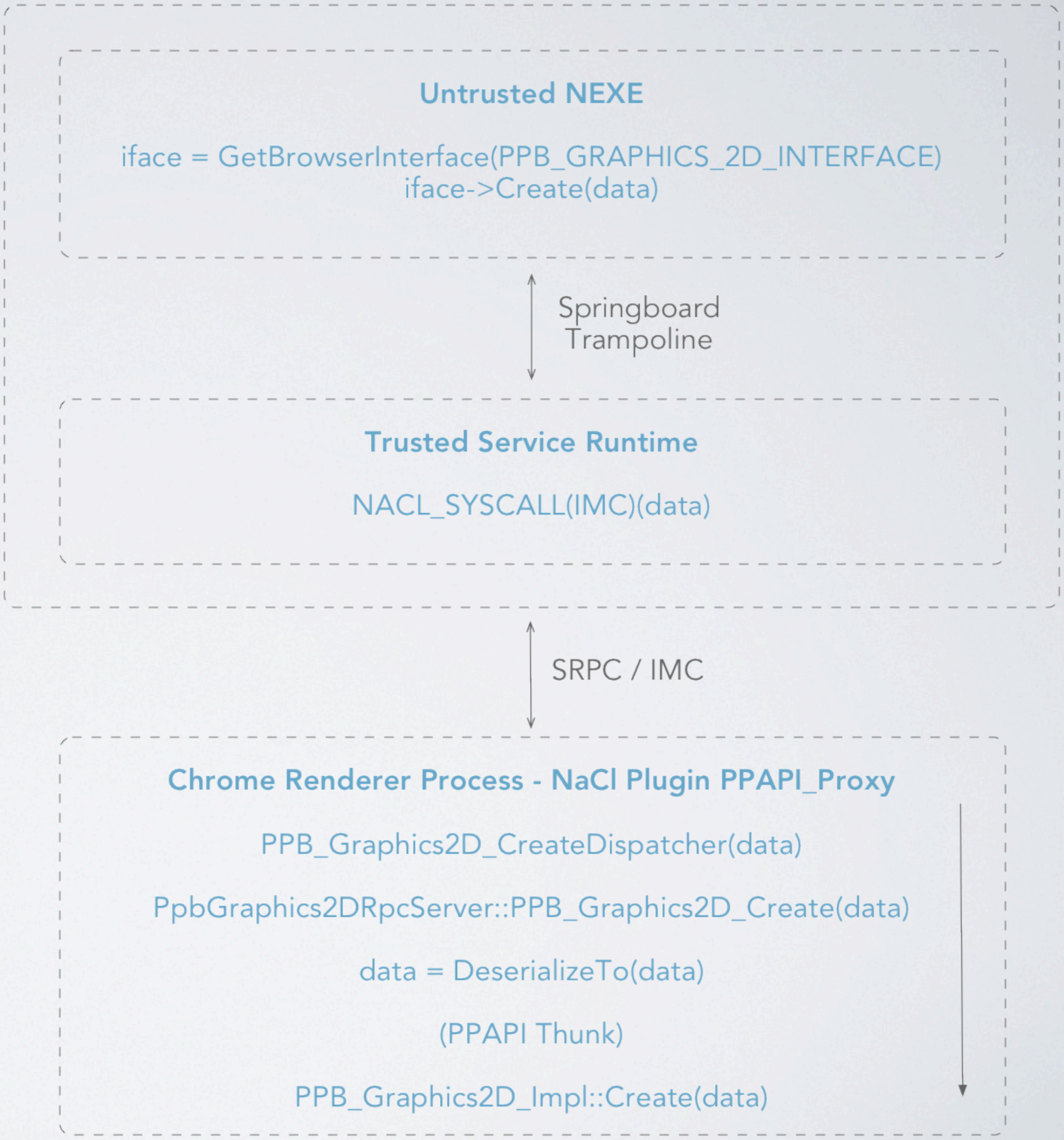


Pepper Proxy

- Data sent over the proxy is serialized
  - PP_VarType - enum specifying type of PP_Var
  - PP_VarValue - union holding simple data types
  - PP_Var - structure that holds PP_VarType and PP_VarValue

Pepper Proxy

- Creates a PP_Var and other args
- Calls a remote pepper interface
- SRPC message gets created
- SRPC message sent over IMC
- Received by remote pepper proxy
- Data deserialized
- Passed off to PPAPI



Pepper Proxy

- Lots of shared code between trusted/untrusted sides
- Both sides can act as server and/or client
- A simple rule to help differentiate the two
  - Interfaces prefixed with PPP are on the untrusted side
  - Interfaces prefixed with PPB are on the trusted side

Pepper Proxy

- Manages callbacks and related SRPC data structures
  - Callbacks exist to inform a remote NEXE when the renderer has completed an operation
  - Callbacks are bound to the SRPC channel
  - Callbacks can only be invoked on the main thread

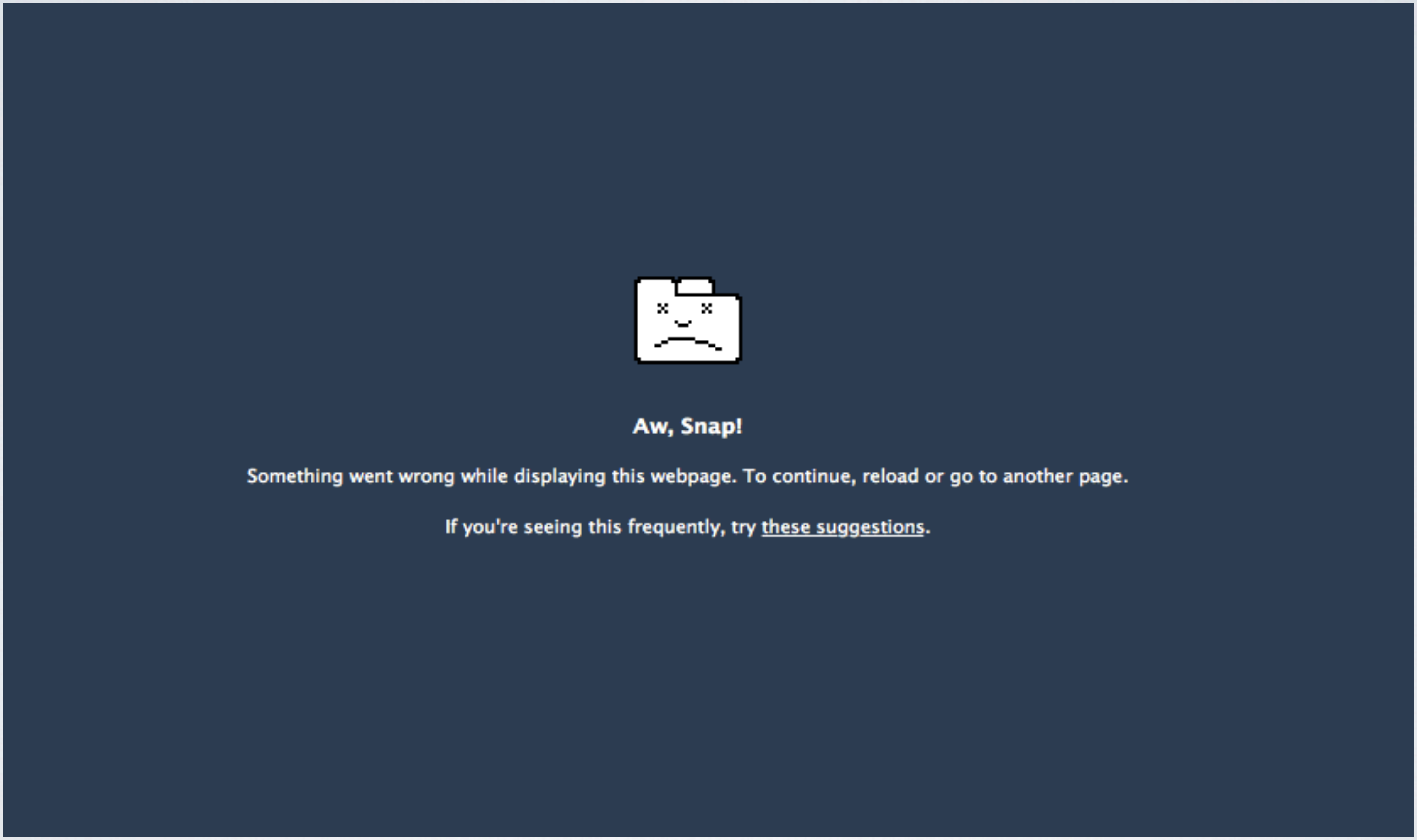
Pepper Proxy

- The pepper proxy is <u>not</u> a security boundary
- It performs little to no validation of untrusted data
- It is exists only to proxy data between an untrusted NEXE and the PPAPI implementation

Portable NaCl

- PNaCl (Pinnacle)
- Web site hosts LLVM IR produced by NaCl SDK toolchain
- PNaCl transforms LLVM IR to native code for the users architecture using AOT
- These native instructions are then put in a NEXE
- The inner sandbox and pepper proxy remain as-is
- 32-bit ARM Support
- Google has projected a 2012 release

NaCl Attack Surface



NaCl Attack Surface

- Outer (Chrome) sandbox escapes require
  - Vulnerabilities in the broker process
  - No/Weakly sandboxed processes (Flash, GPU)
  - Kernel vulnerabilities the sandbox can’t fully prevent
- Inner sandbox
  - Cannot reach the broker process directly
  - You are in a sandbox within a sandbox
  - You cannot make syscalls or talk to the kernel directly
- NaCl raises the bar for exploitation
  - Multiple sandboxes
  - Instruction validation

NaCl Attack Surface

- Native Client isolates untrusted code (inner sandbox)
- But you need trusted components to do useful things
- We find attack surface anywhere untrusted code can influence the execution of trusted code

NaCl Attack Surface

- Vulnerable NEXE modules are not an issue
  - Validation of all direct/indirect execution branches
  - Why attack a NEXE module when you can load one directly instead?
- Malicious NEXE modules
  - Attempt to find and exploit vulnerabilities in various NaCl components

NaCl Attack Surface

- Service Runtime
  - Inner Sandbox
    - ELF loader
    - Instruction validator disassembler
    - NACL_SYSCALL implementations

NaCl Attack Surface

- NaCl PPAPI Plugin
  - IMC
  - SRPC
  - DOM interfaces
  - JSON parser

NaCl Attack Surface

- PPAPI - Pepper Proxy
  - Server interfaces
  - Client interfaces
- PPAPI
  - Interface implementations reached via the proxy
- GPU
  - Direct interfaces to the GPU
  - Pinky Pie exploited an integer overflow here for Pwnium

NaCl Vulnerabilities

- Vulnerabilities discovered in Native Client
  - The first inner sandbox break out
  - 2009 Security Contest
  - Various Google discovered vulnerabilities
  - 2011 PPAPI - Pepper Proxy source audit

First Inner Sandbox Breakout

- Call instruction memory dereference

```
andl $0xffffffe0, %edx
call *(%edx)
```

- The validator and branch alignment ensure the value in the register is 32 byte aligned but not the value it references

- Results in execution of a non-validated instruction

- Discovered by Alex Radocea

2009 Security Contest

- Uncovered 20 new security vulnerabilities in NaCl
- Nothing that significantly broke the inner sandbox design
- 1st place - Mark Dowd, Ben Hawkes
  - 2nd place - Chris Rohlf, Eric Monti, Jason Carpenter
    - 3rd place - Gabriel Campana
      - 4th place - Daiki Fukumori
        - 5th place - Alex Radocea
- Some of these vulnerabilities are still relevant to NaCl

2009 Security Contest

- Two byte jmp prefix
  - Unchecked prefix bytes on branch instruction
- EFLAGS direction flag modification
  - Untrusted NEXE instructions can change the direction flag
- Validated code unmapping
  - An untrusted NEXE can unmap validated code and replace it
- Uninitialized vtable
  - A manual vtable left uninitialized can lead to code execution

2009 Security Contest

- The architecture has changed significantly since 2009
- NPAPI is gone but the same type of issues could be found in the PPAPI replacement
- Proved the inner sandbox was relatively strong
  - Provided a good look at the future of NaCl vulnerabilities
  - Trusted components that handle untrusted data are more likely to contain vulnerabilities than the inner sandbox

Google NaCl Vulnerabilities

- Win64 inner sandbox escape via KiUserExceptionDispatcher
  - Exceptions transfer execution to this function which is not aware of the trusted vs untrusted stack
- bsf Instruction inner sandbox escape
  - Cannot properly validate alignment of conditional value
- Trampoline address space leak
  - Does not use PIC code, leaks a .text instruction address
- Address space leak via JavaScript error
  - A JavaScript error message contained a memory address

Pepper Proxy Source Audit

- June 2011 Pepper Proxy Source Audit
  - Performed under contract to Google while at Matasano
- 3 week project
- 1 Person
- 10 vulnerabilities discovered
- Manual source audit of C/C++
  - Many thousands of lines
  - No scanners
  - Mostly grep and reading source

Pepper Proxy Source Audit

- Are there vulnerabilities in the pepper proxy that would allow a malicious NEXE to escape the inner sandbox?
  - Many interfaces accept and deserialize untrusted data
  - Lots of opportunity for vulnerable code

Pepper Proxy Source Audit

- PPB_Graphics2D_Create Shared Memory Integer Overflow
- PPB_Context3DTrusted_CreateTransferBuffer Shared Memory Integer Overflow
- PPB_Audio_Create SRPC Channel Use After Free
- PPB_URLLoader_Open CORS Request Allows For Header Injection
- PPB_URLLoader_ReadResponseBody Heap Overflow

Pepper Proxy Source Audit

- PPB_FileIO_Write Out Of Bounds Read Information Leak
- PPB_FileIO_Dev_Read Heap Overflow
- PPB_PDF_SearchString Potential Heap Overflow
- PPB_FileRef_Create Potential Directory Traversal
- Heap Overflow In MessageChannelEnumerate

Pepper Proxy Source Audit

- Length calculations are difficult with serialized binary data
- The pepper proxy and SRPC glue code is tricky
  - Callbacks and channel related structures need to be tracked
- Confusion over who validates data can lead to vulnerabilities
  - PPAPI implementation vs proxy receiver stub

Pepper Proxy Source Audit

- Successful exploitation of a vulnerability in the pepper proxy allows arbitrary code execution in the renderer
  - Inner sandbox has been defeated
  - Chrome renderer sandbox is still enforced
  - This is not exactly equivalent to a WebKit/V8 bug
    - The pepper proxy exposes more interfaces at a lower level

Chrome Shaker

- A pepper proxy fuzzer
- Developed under contract to Google January 2012
- Joint project with Matasano Security (Cody Brocious)
- Google deployed it in their fuzzing farm
- https://code.google.com/p/chrome-shaker/

Chrome Shaker

- Simple NEXE template in C++
  - NEXE glue code, random numbers, memory etc...
- Python tool that parses pepper proxy IDL files
  - Generates C++ into the basic template
  - Sets up each PPAPI interface in the 'C' style
  - Calls interfaces in random order with random arguments

Chrome Shaker

- Fuzzing from a NEXE is not easy
- You can’t log to disk
  - How do you write to disk from within two sandboxes?
    - Use the interface (FileIO) that you’re currently fuzzing?
    - We had to resort to STDOUT
- You need a constant source of random data
  - We cheated and call into JavaScript for window.crypto
- Some code paths require calling interfaces in order
  - We have an API dependency file in yaml for this

The Conclusion

- NaCl is trying to solve a difficult problem
- NaCl is not ActiveX or NPAPI
- NaCl research into SFI and the inner sandbox will influence future sandbox designs with similar goals
- As the attack surface grows more implementation vulnerabilities may be found in trusted code
  - The NaCl design helps to mitigate their impact
- Enable Chrome's Click-To-Play

The End

Questions?

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BlackHat Survey

Please fill out the BlackHat survey!