HITB SECCONF SIN-2021

Automated 0-day discovery in 2021: Squashing the low-hanging fruit in widespread embedded software

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TRACK 1

About us

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- Experience in security research, development and pentesting
- PhD in Computer Science, 30+ academic publications
- Speaker at Black Hat, x33fcon and others

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- Experienced security researcher and architect
- BSc in Computer Science & Electrical Engineering
- Currently leading the security research teams @ JFrog

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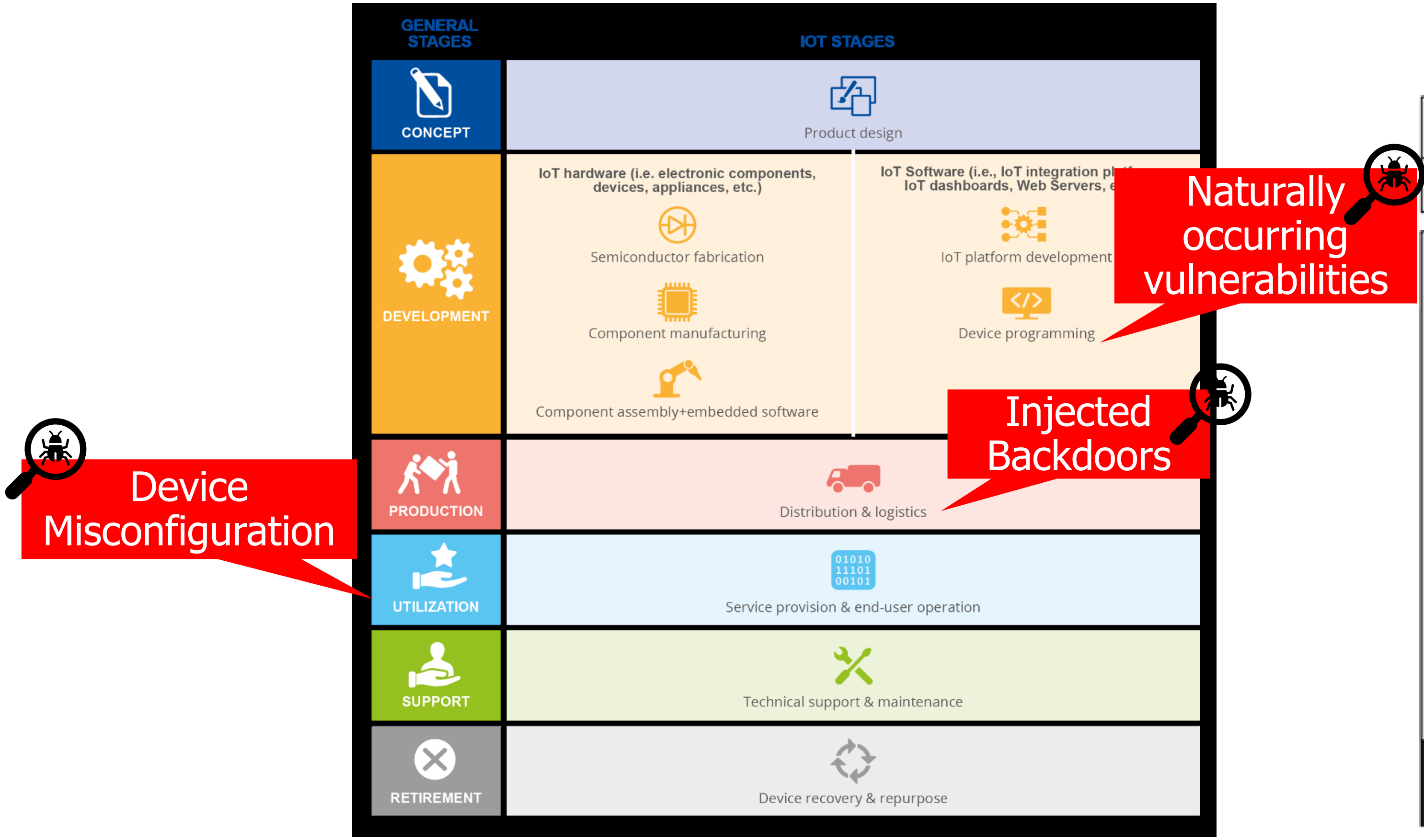
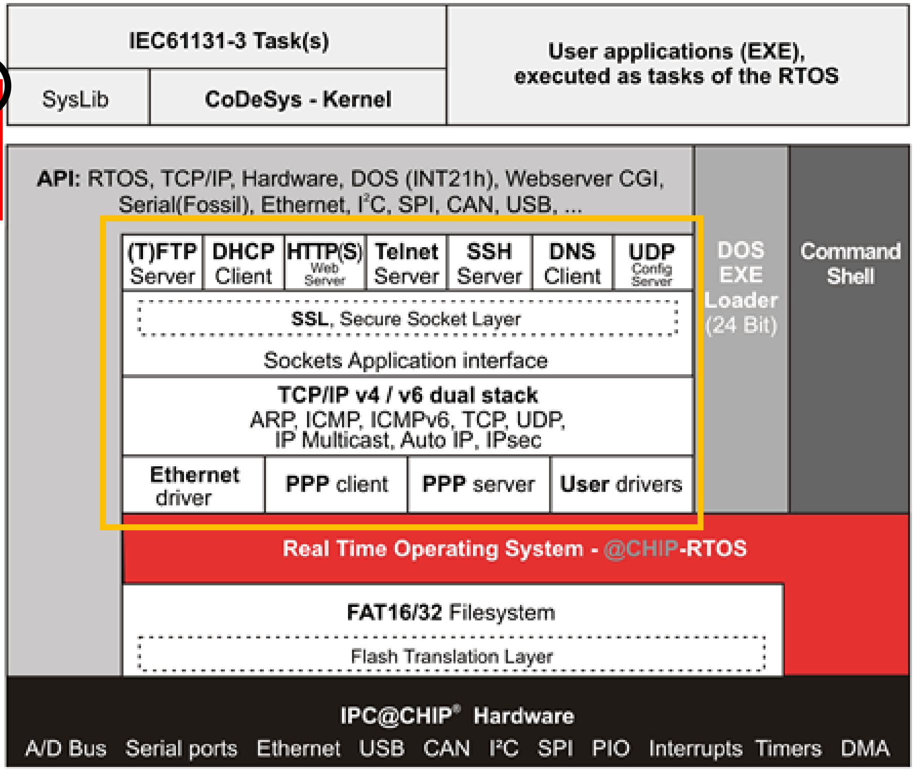
Outline

1. Introduction
   - Research Background
   - INFRA:HALT
   - Finding Vulnerabilities
2. Automated Vulnerability Discovery
3. Mitigation
   - Device vendors
   - Network operators
4. Conclusion

Embedded Systems Supply Chain



https://www.enisa.europa.eu/publications/guidelines-for-securing-the-internet-of-things



http://smartbox.jinr.ru/doc/chip-rtos/software.htm

Why target protocol stacks

- Wide deployment – vulnerabilities **trickle down** the supply-chain to many vendors
- Absence of *Software Bill of Materials (SBOM)* - fixes in core stack **might never make it** to all OEM firmware
- Ancient code – good chance of finding exploitable bugs
- Externally exposed, often run as privileged, low-level component
- Patching issues + Long lifespans + Broad trickle-down = **High vulnerability lifespan = High attacker ROI**

Previous work on TCP/IP stacks

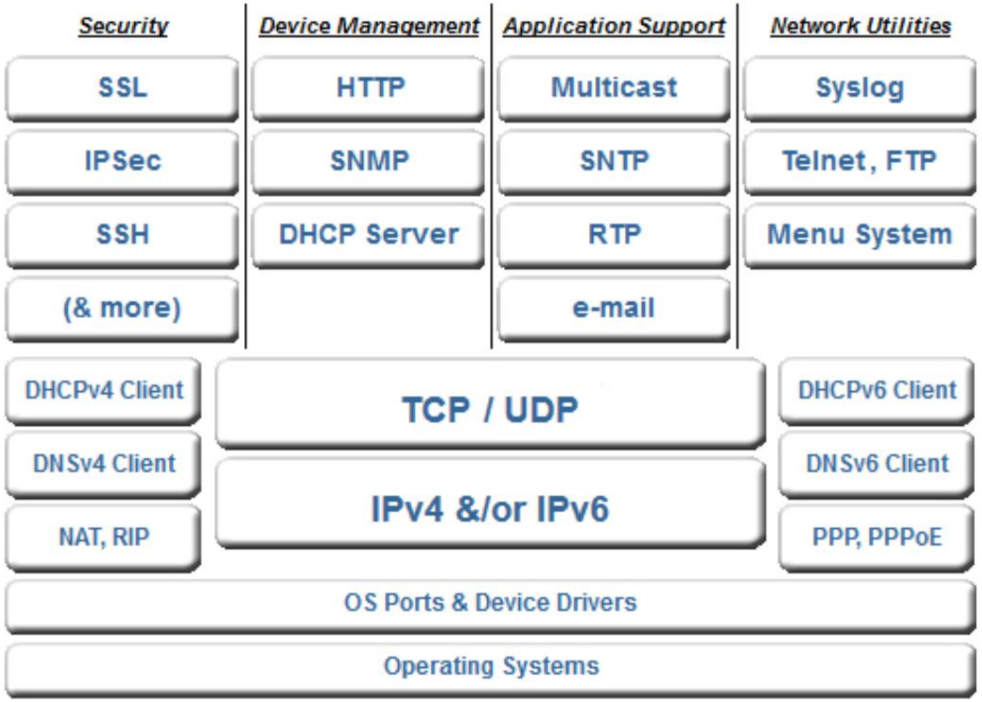
Year	Research	Description
2019	**URGENT/11**	11 CVEs on VxWorks' IPnet
2020	**Ripple20**	19 CVEs on Treck TCP/IP
2020	**AMNESIA:33**	33 CVEs in 4 open-source stacks
2021	**NUMBER:JACK**	Predictable TCP ISN in 9 stacks (open and closed)
2021	**NAME:WRECK**	9 DNS client vulnerabilities in 4 stacks
2021	**INFRA:HALT**	14 CVEs on InterNiche stack

INFRA:HALT

Vulnerabilities in the InterNiche embedded TCP/IP stack

The target: What is NicheStack?

- Developed by InterNiche in the '90s, acquired by HCC Embedded in 2016
- Distributed in several flavors (IPv4, v6, dual, lite)
- Served as basis for other stacks (e.g., emNet)
- Popular in OT devices – previous research:
  - Siemens: CVE-2019-9300, SegmentSmack variant affecting several devices
  - Abbasi et al.: looking at S7 PLCs, found and compiled stack source-code leaked via OEM



https://ww1.microchip.com/downloads/en/Site_Resource/NicheStack%20IPv4-ProductBrief.pdf

The vulnerabilities found

- 14 CVEs
- 5 components affected
  - DNS client
  - HTTP server
  - ICMP
  - TCP
  - TFTP server
- 2 RCEs
  - CVE-2020-25928 (DNS)
  - CVE-2021-31226 (HTTP)
- Found *manually* and/or *automatically*

#	CVE	Impact	CVSS	Component Affected
1	CVE-2020-25928	Remote Code Execution	9.8	DNS client
2	CVE-2021-31226	Remote Code Execution	9.1	HTTP server
3	CVE-2020-25767	Denial of Service	7.5	DNS client
4	CVE-2020-25927	Denial of Service	7.5	DNS client
5	CVE-2021-31227	Denial of Service	7.5	HTTP server
6	CVE-2021-27565	Denial of Service	7.5	HTTP server
7	CVE-2020-35683	Denial of Service	7.5	ICMP
8	CVE-2020-35684	Denial of Service	7.5	TCP
9	CVE-2021-31400	Denial of Service	7.5	TCP
10	CVE-2021-31401	Denial of Service	7.5	TCP
11	CVE-2021-36762	Denial of Service	7.5	TFTP server
12	CVE-2020-35685	TCP spoofing	7.5	TCP
13	CVE-2020-25926	DNS cache poisoning	4	DNS client
14	CVE-2021-31228	DNS cache poisoning	4	DNS client

RCE1: CVE-2020-25928 (DNS)

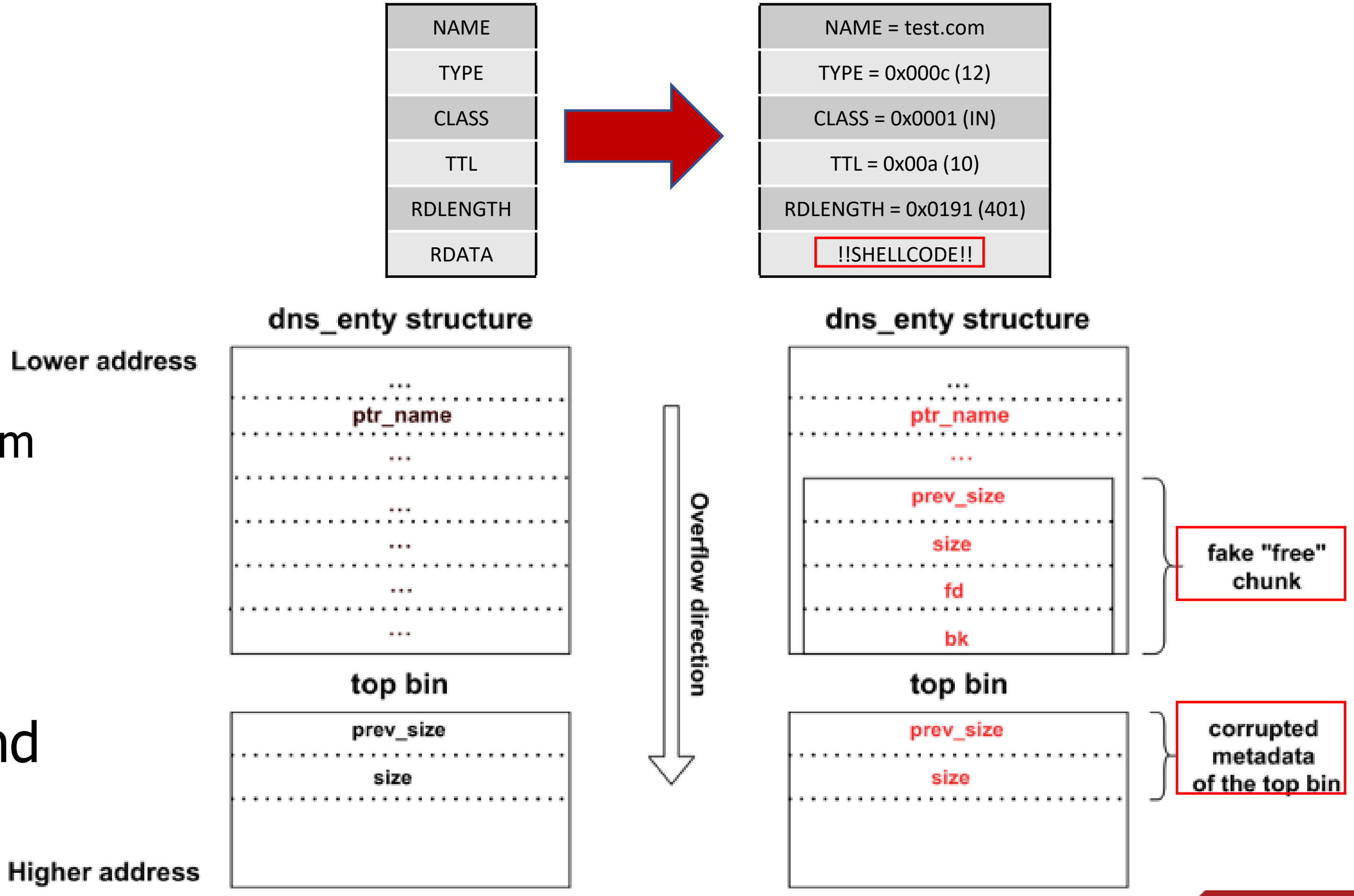
- Found manually, based on anti-pattern from NAME:WRECK
  - Similar to CVE-2020-27009 on Nucleus NET
- Resource Record length (RDLENGTH) of DNS responses is not checked
  - Attackers can specify arbitrary RDLENGTH and overflow next field (RDATA)
  - A buffer for RDATA is allocated on the heap
  - There are usually no exploit mitigations

```
typedef struct _dns_querys {
  ...
  char dns_names[256];
  char ptr_name[128];       // +128
  void *auths_ip;           // +4
  void *alist[3];           // +12
  int protocol;             // +4
  hostent he;               // +32
  int type;                 // +4
  uint8_t opcode[3];        // +3
  void *h_TXT_list;         // +4
  int h_TXT_listCount;      // +4
} dns_querys;               // distance from start of ptr_name to end of struct is 195 bytes
```

```
void dnc_set_answer(dns_querys *dns_entry, unshort type, uint8_t *cp, int rdlen)
{
  // ...
  switch ( type )
  {
    // ...
    case 0x0c:
      memcpy(dns_entry->ptr_name, cp + 1, rdlen - 1);
      // ...
      break;
    // ...
  }
}
```

Exploiting CVE-2020-25928

- Achieved RCE with the classical "unlink" technique
  - No safe unlinking
- Easy for attackers to spoof DNS records
  - Source port and TXID aren't random
    - CVE-2020-25926, CVE-2021-31228
  - responses from any IP address are accepted
- Shellcode uses the stack API to perform TCP handshake and send further malicious packets

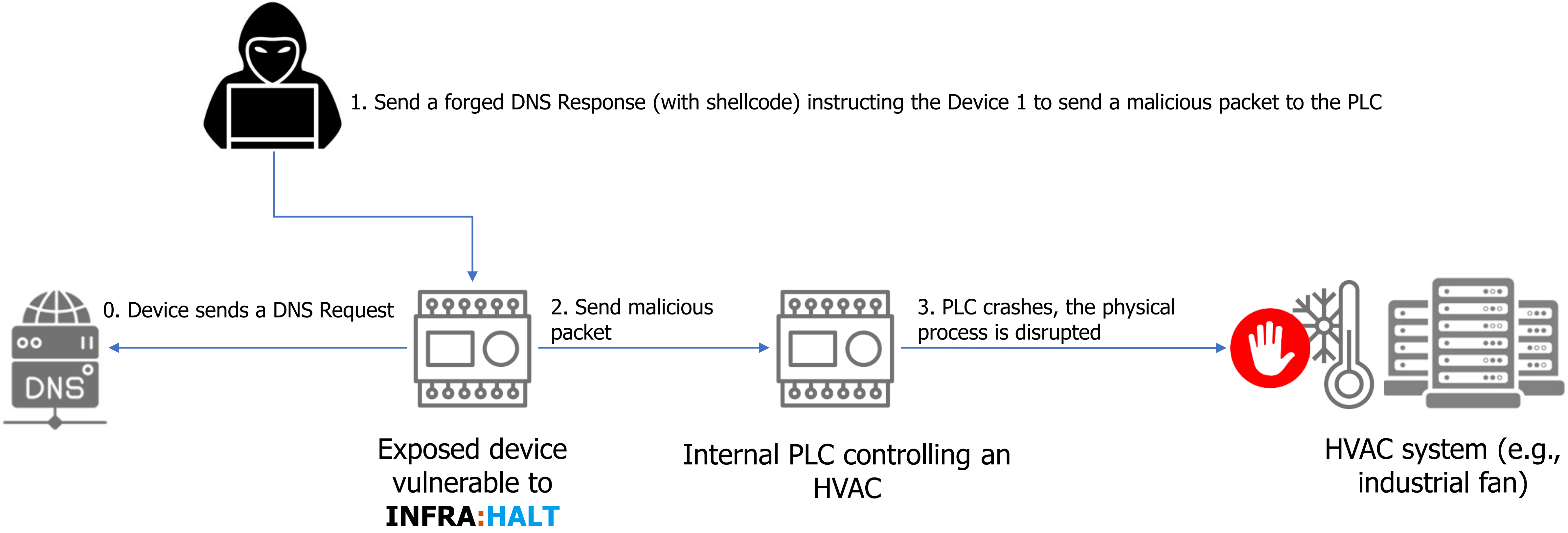


RCE2: CVE-2021-31226 (HTTP)

- Found automatically – *more details later*
- Occurs when parsing the HTTP POST Request URI field: http://example.org/path/to/file?param42
- A request string of more than 52 bytes may cause a (heap) buffer overflow
- RCE can be achieved similar to CVE-2020-25928 (more careful heap shaping required)

```
Hypertext Transfer Protocol
  POST /AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAzzzz HTTP/1.1\r\n
    [Expert Info (Chat/Sequence): POST /AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAzzzz HTTP/1.1\r\n]
    Request Method: POST
    Request URI: /AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAzzzz
    Request Version: HTTP/1.1
  Host: 192.168.100.2\r\n
  Content-Type: multipart/form-data;boundary=xxxxxx\r\n
  Content-Length: 0\r\n
    [Content length: 0]
  Connection: close\r\n
  \r\n
  [Full request URI: http://192.168.100.2/AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAzzzz]
  [HTTP request 1/1]
```

Attack scenario



https://www.youtube.com/watch?v=plgtt1BD-nI

Supply Chain Impact

NicheStack Products

IPv6	IPv4	v4/v6	Lite	
	✓	✓		Auto-IP
✓	✓	✓	✓	DDNS
	✓	✓	✓	DHCP Server
✓	✓	✓	✓	DNS Client
	✓	✓		DNS Server
✓	✓	✓	✓	Email Alerter
✓	✓	✓	✓	FTP Server + Client
	✓	✓		IP Multicast
✓	✓	✓		IPSec/IKE
	✓	✓		NAT
✓	✓	✓		NAT-PT
✓	✓	✓	✓	POP3
✓	✓	✓	✓	PPP
✓	✓	✓	✓	▪ MS-CHAP
✓	✓	✓		▪ MultiLink
✓	✓	✓		▪ PPPoE
	✓	✓		RIP
	✓	✓		SSL/TLS
✓	✓	✓	✓	SNMPv1
✓	✓	✓	✓	SNMPv2(c)
✓	✓	✓	✓	SNMPv3
✓	✓	✓	✓	Telnet Server
✓	✓	✓	✓	TFTP Client+Server
✓	✓	✓	✓	Web Server
✓	✓	✓	✓	▪ HTML Compiler
	✓	✓		▪ Web Server-SSL
✓	✓	✓	✓	NicheTool

Many offerings

COLDFIRE_TCPIP: InterNiche's ColdFire TCP/IP Stack

NicheStack TCP/IP Network Stack - Nios II Edition

NicheStack TCP/IP Network Stack - Nios II Edition is a software suite of networking protocols designed from the ground u… designing network-connected embedded devices with the Nios II processor. Product highlights include the following:

AVAILABLE THROUGH MICROCHIP www.microchip.com/harmony

NicheStack IPv4 - The Standard For Embedded TCP/IP for PIC32 MX and MZ Available From microchipDIRECT

…via many distributors…

Networking Protocol Software for Embedded Processors

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Networking Stacks — TCP/IP, IPv6, 6LoWPAN, PPP | Embedded Security — SSL, IPSec, etc. | Apps & Device Management — HTTP, SNMP, DHCPv6 & more | Device Support — File Systems, RTOS, USB, Ports | Demos & Other Formats — Pre-Compiled Libs, Free Demos

Just Some Customers of InterNiche's Networking Source Code

…end up in many ways in many products from many vendors

https://web.archive.org/web/20170213060851/http://www.iniche.com:80/company/manylogos.php

Finding the vulnerabilities

- Input
  - Leaked source code of v3.1 (as mentioned in previous research)
  - Binary demo of more recent version (previously available on vendor's website)

- Manual analysis based on known anti-patterns
  - AMNESIA:33 – integer overflows, lack of bounds checks
  - NUMBER:JACK – weak ISN
  - NAME:WRECK – DNS compression and several others – see https://github.com/Forescout/namewreck

- The stack matched almost all the known anti-patterns
  - Didn't analyze IPv6 – not available in the source
  - Great result, but ***lots of work*** **and** ***potentially missed issues…***

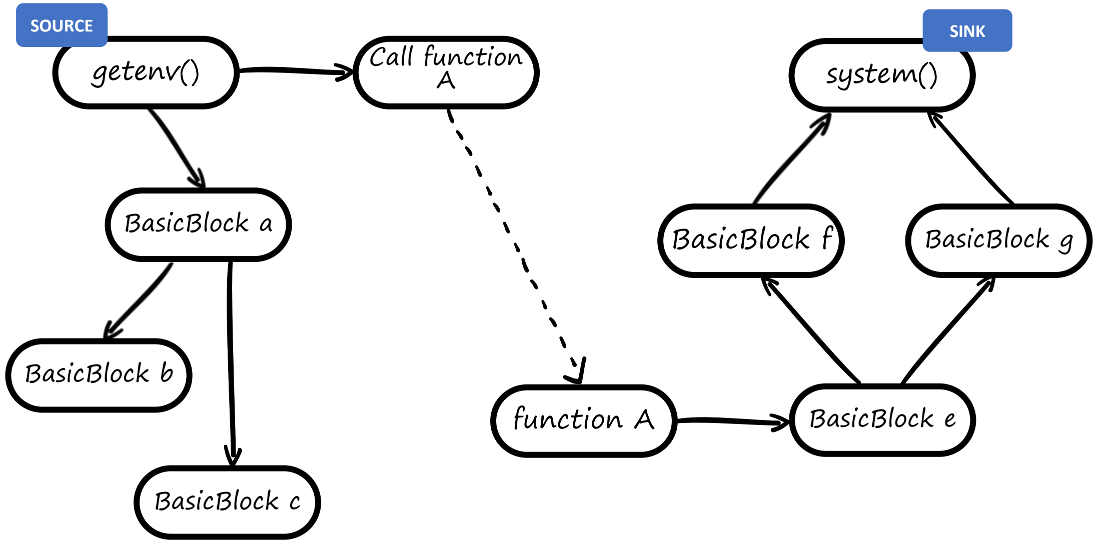
- **…enter automated Vulnerability Discovery**

Automated Vulnerability Discovery

Overcoming the limitations of manual research

Method of operation – high level

- #1 – Map possible user input **sources**
- #2 – Map possible dangerous **sinks**
- #3 – Find **unfiltered** data flow between #1 & #2



Method of operation - detailed

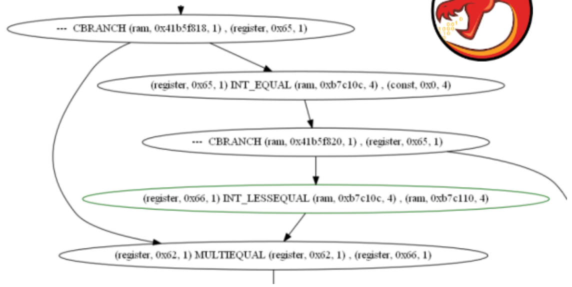
Level

Example

Code

```
ldr r12,[sp,#local_240]
and this,this,#0x1f8
cpy param_3,r7
cpy param_2,r8
add this,r9,this
```

Intermediate representation



Interfaces of code blocks
Influence maps of interfaces

`f:a -> b`
`b` is a buffer accumulated in a loop
Loop condition depends on `a`

Information flow

Argument of `system()` in `f` is calculated from output of `recv()` in `g`

Level

Example

Correspondence between inputs and outputs

`f("Hello") = 5`

Known functions

`f` is `strcpy`
`g` is `malloc`

Higher level analysis – Ghidra P-Code

- Ghidra's decompiler lifts ASM to high-level IR
- This allows for easier, cross-architecture analysis

```
memset(&rcvdq,0,0x14);
void *to_netmain = NULL;
void *to_nettick = NULL;
cli_install_menu(&netmain_nt);
```

Original source

```
mov.w      r1,#0x0
mov.w      r2,#0x14
bl         memset
movw       r3,#0x3a38
movt       r3,#0x2000
mov.w      r2,#0x0
tr        r2,[r3,#0x0 ]=>to_netmain
movw       r3,#0x3a3c
movt       r3,#0x2000
mov.w      r2,#0x0
tr        r2,[r3,#0x0 ]=>to_nettick
movw       r0,#0xc4c
movt       r0=>netmain_nt ,#0x2000
bl         cli_install_menu
```

Disassembly

OUTPUT P-CODE INPUT 1 INPUT 2

```
(unique, 0x1000004c, 4) PTRSUB (const, 0x0, 4) , (const, 0x20003f0c, 4) // &rcvdq
--- CALL (ram, memset, 8) , (unique, 0x1000004c, 4) , (const, 0x0, 4) , (const, 0x14, 4)
(ram, 0x20003a38, 4) COPY (const, 0x0, 4) // *to_netmain = NULL
(ram, 0x20003a3c, 4) COPY (const, 0x0, 4) // *to_nettick = NULL
(unique, 0x10000030, 4) PTRSUB (const, 0x0, 4) , (const, 0x20000c4c, 4) // &netmain_nt
---  CALL (ram, cli_install_menu, 8) , (unique, 0x10000030, 4)
```

Decompilation

Mapping user input sources

- Usually harder than mapping sinks
- High-accuracy sources
  - Syscalls – *recv* (network), *getenv* (local), *fread* (local)
  - Reading from well-known input MMIO (ex. UART, BLE)
    - See [Ghidra SVD-Loader]

- Score-based sources
  - *ntohs* / *ntohl* (assumes this converts network integers)
    - Note these can often be inlined!
  - Functions that reference well-known protocol strings
    - In this case, return value and all arguments and will be treated as sources

Example of protocol excerpts

HTTP

```
pcVar6 = stristr(pcp,"Content-Length:");
if (pcVar6 == (char *)0x0) {
  ht_senderr(hp,400,"Content-length required");
  hp->state = 8;
  return;
}
lVar7 = atol(pcVar6 + 0xf);
hp->contentlen = lVar7;
if ((hp->rxsize - (int)(pcVar4 + -(int)pcVar9) < hp-
>contentlen) &&
    (pcVar5 = stristr(pcVar5,"multipart/form-
data"), pcVar5 == (char *)0x0)) {
```

FTP

```
v10 = command(L"USER %s");
v11 = GetProcessHeap();
...
v10 = command(L"PASS %s");
v14 = GetProcessHeap();
...
v10 = command(L"ACCT %s");
```

- More encountered strings = higher confidence score

Mapping sinks

- Basic sinks
  - Command injection – *system* / *popen* etc.
  - Buffer overflow – *memcpy* / *strcpy* etc.
    - In memcpy case, check that both source and length are user-controlled

- Advanced sinks
  - Inline copy operations / copy loops
  - Integer overflow leading to buffer overflow

```
while ( 1 )
{
    cur = src + 1;
    if ( cur2 == '@' )
        break;
    ++src;
    dst[v3] = cur2;
    cur2 = (unsigned __int8)*cur;
    ++v3;
    if ( !*cur )
        goto exit_loop;
}
```

libc detection via emulation

- libc might be statically linked (ex. RTOS binary blob)
- This means – no function symbols!
- But we need function names such as “strcpy” for our sinks
- Our solution – function divination via emulation
- Inputs
  - Expected function prototype
  - Set of matching inputs & outputs
- Outputs
  - All functions with matching behavior

```python
class TestStrcat(Function):
    NAME = "strcat"
    PARAM_DEREFS = [1, 1]

    STRING = b"Hello,"
    STRING2 = b" world !"

    def probe(self):
        ptr = self.alloc_mem(len(self.STRING) + len(self.STRING2) + 1, write=True)
        self.write_string(ptr, self.STRING)
        ptr2 = self.alloc_string(self.STRING2)

        result = self.call(ptr, ptr2)

        return (
            result == ptr
            and self.memcmp(ptr, self.STRING + self.STRING2)
            and self.memcmp(ptr2, self.STRING2)
        )

    PROBES = Probe(probe)
```

Data flow analysis – Ghidra's API

- Ghidra provides basic **intra-function** DFA
- ex. [getForwardSlice / getForwardSliceToPCodeOps]

```
phVar2 = hp->upload;
iVar3 = phVar2->curlen;
n = phVar2->boundarylen;
if (iVar3 + inlen < (int)n) {
  memcpy(phVar2->pbuf + iVar3,start,inlen);
  iVar1 = strncmp(phVar2->pbuf,phVar2->boundary,iVar3 + inlen);
  if (iVar1 == 0) {
    phVar2->curlen = iVar3 + inlen;
    return (char *)0x0;
  }
}
```

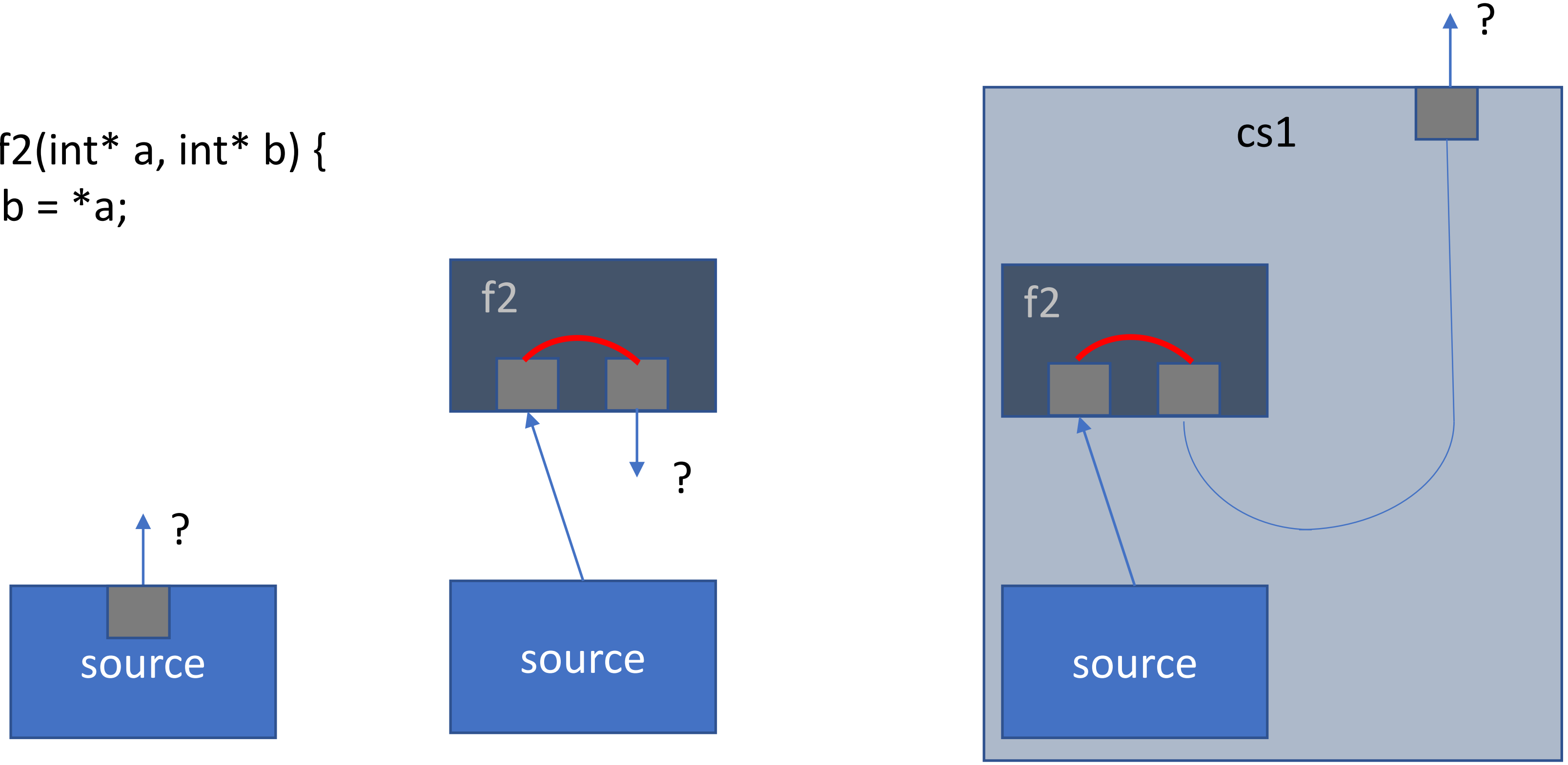
- Doesn't handle stack variables
- Does not propagate outside of function or into child functions

Data flow analysis – expanding on Ghidra

- Do any of the defined source variables "reach" a sink function?

```
int cs1(int* a) {
  int d;
  source(&d);
  f2(&d, a);
}
```

```
int f2(int* a, int* b) {
    *b = *a;
}
```



Data flow analysis – basic filtering

- Specific operations in the data flow path can make the vulnerability unexploitable
- Classic examples of these can be statically detected
  - Buffer overflow – size checks
  - Command injection – shell metacharacter filtering
  - General – data anchoring

```c
char buf[50];
if (strlen(userinput) >= 50) {
    return ERR;
}
strcpy(buf, userinput);
```

```c
char *res = strpbrk(userinput, "*;`${}|&<>");
if (NULL != res) {
    // Shell metacharacter detected!
    return ERR;
}
```

```c
char buf[50];
if (strcmp(userinput, "fixed_input")) {
    return ERR;
}
// userinput == “fixed_input”
strcpy(buf, userinput);
```

Advanced filtering with symbolic execution

- Filtering may be too exotic to detect via a fixed list of static cases

```c
unsigned int a = read_int();
unsigned int b = read_int();
if( a > 1 ){
    if( b < 20) {
        if( a * b > 30){
            func_one();
        } else {
            func_two();
        }

    } else {
        func_three();
    }

} else {
    func_four();
}
```

X > 1 and Y < 20

X > 1 and Y < 20
and
X * Y > 30

X > 1 and Y < 20
and
X * Y < 30

Advanced filtering with symbolic execution

- Very compute intensive, must be restricted to pre-observed code blocks from static analysis

```
char *userinput = getenv("UNSAFE_VAR"); // No constraints on userinput
... // A lot of processing on userinput
system(userinput); // Many constraints on userinput
```

- Last line might have many constraints
  - strlen(userinput) == 3 && userinput[1] = 'A' etc.
- Add a custom constraint and check for satisfiability
  - userinput[i] = '`' for i in strlen(userinput)

Detecting CVE-2021-31228

- HTTP server DoS
- Signed comparison leading to (huge) overflow

```
char * getbndsrch(htupload *htup,char *cp,int len,int *err)
{
  if (len < htup->boundarylen) { // Signed comparison!
    memcpy(htup->pbuf,cp,len);
    ...
```

Detecting CVE-2021-31228 (2)

- Source detection – through dynamic stdlib mapping (atol)
- Source function “ht_readmsg” also flagged due to HTTP strings

```
void ht_readmsg(httpd *hp)
{
    ...
    pcVar6 = stristr(pcp,"Content-Length:");
    ...
    lVar7 = unknown_func(pcVar6 + 0xf); // Actually "atol". Parse "Content-Length"
    hp->source_field = lVar7; // Mark the field as having user input
    if ((hp->rxsize - (int)(pcVar4 + -(int)pcVar9) < hp->contentlen) &&
        (pcVar5 = stristr(pcVar5,"multipart/form-data"), pcVar5 == (char *)0x0)) {
    ...
}
```

Advantage of dynamic divination

```
long unknown_func(_reent *rptr,char *nptr,char **endptr,int base)
{
  pbVar5 = (byte *)nptr;
  do {
    pbVar2 = pbVar5;
    pbVar5 = pbVar2 + 1;
    uVar7 = (uint)*pbVar2;
    bVar9 = __ctype_ptr__[uVar7 + 1] & 8;
  } while (bVar9 != 0);
  if (uVar7 == 0x2d) {
    uVar7 = (uint)*pbVar5;
    bVar9 = 1;
    pbVar6 = pbVar2 + 2;
  }
  else {
    pbVar6 = pbVar5;
    if (uVar7 == 0x2b) {
      pbVar6 = pbVar2 + 2;
      uVar7 = (uint)*pbVar5;
    }
  }
  if (base == 0) {
    if (uVar7 != 0x30) {
      base = 10;
```

Detecting CVE-2021-31228 (3)

- "hp" struct and fields tracked via DFA through multiple functions

ht_readmsg → wbs_loop → wbs_post → wbs_multidata → getbndsrch

(Data Reference)

Detecting CVE-2021-31228 (4)

- Eventually a memcpy sink is reached (there are two)
- Vulnerability classified as signed comparison
  - Without “if” check -> classified as heap overflow
  - With unsigned “if” check -> classified as non-vuln

```
char * getbndsrch(htupload *htup,char *cp,int len,int *err)
{
  if (len < htup->boundarylen) { // Signed comparison
    memcpy(htup->pbuf,cp,len); // Buffer overflow sink
    ...
```

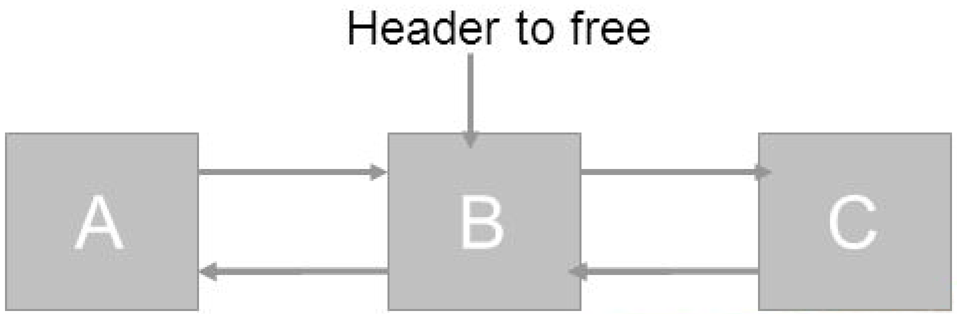
Mitigation

What can we do about these widespread vulnerabilities?

For device vendors

1. Enable common vulnerability mitigations
   - **Safe unlinking**
   - Stack canaries
   - ASLR
   - FORTIFY_SOURCE

B->Flink->Blink == B->Blink->Flink == B



2. Employ SAST and DAST scanning solutions
   - As shown, some issues can be found automatically

For network operators

1. Know what is on your network
   - Assess risk upon connect and continuously
   - Patch devices if possible

2. Segment to mitigate risk

3. Monitor the network for malicious packets
   - Vulnerabilities in TCP/IP stacks tend to be very similar

Affected component	Mitigation Recommendation
DNS client	• Disable the DNS client of the device if possible and not needed • Block DNS traffic if not needed • Using internal DNS servers is not sufficient because there are several vulnerabilities that facilitate DNS spoofing attacks
HTTP / TFTP	• Disable HTTP / TFTP server of the device if not needed • Whitelist connections and block others
TCP	• Monitor traffic for malformed IPv4/TCP packets • Drop these malformed packets at firewalls
ICMP	• Monitor traffic for malformed ICMPv4 packets • Drop these malformed packets at firewalls

Conclusion

Discussion

- Vulnerability finding today: manual + automated
  - Automated can find low-hanging fruits much easier and faster
  - Manual still useful for more complex issues
- More vulnerabilities means more *vulnerabilities to disclose*
  - INFRA:HALT took 9 months
  - Currently, there is very limited involvement of asset owners
- Identifying vulnerable devices without firmware analysis is challenging
  - Lack of SBOM, opaque documentation, few network banners, etc.
  - Some vendors still investigating impact of AMNESIA:33 almost a year after initial disclosure

Key takeaways

- TCP/IP stacks have critical vulnerabilities that trickle down the supply chain
  - Other popular software components could have similar impact
- Automated vulnerability discovery helps in identifying many of those at a large-scale
  - Turning point for the community, soon even more vulnerabilities will be found even faster
- Mitigation of these widespread issues involves both device vendors and network operators
  - Since they affect legacy but active devices, just waiting for patches is not a good solution
- Learn more at
  - Forescout's Project Memoria
  - JFrog's blog

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https://discord.gg/dXE8ZMvU9J