NEU CY 5770 Software Vulnerabilities and Security

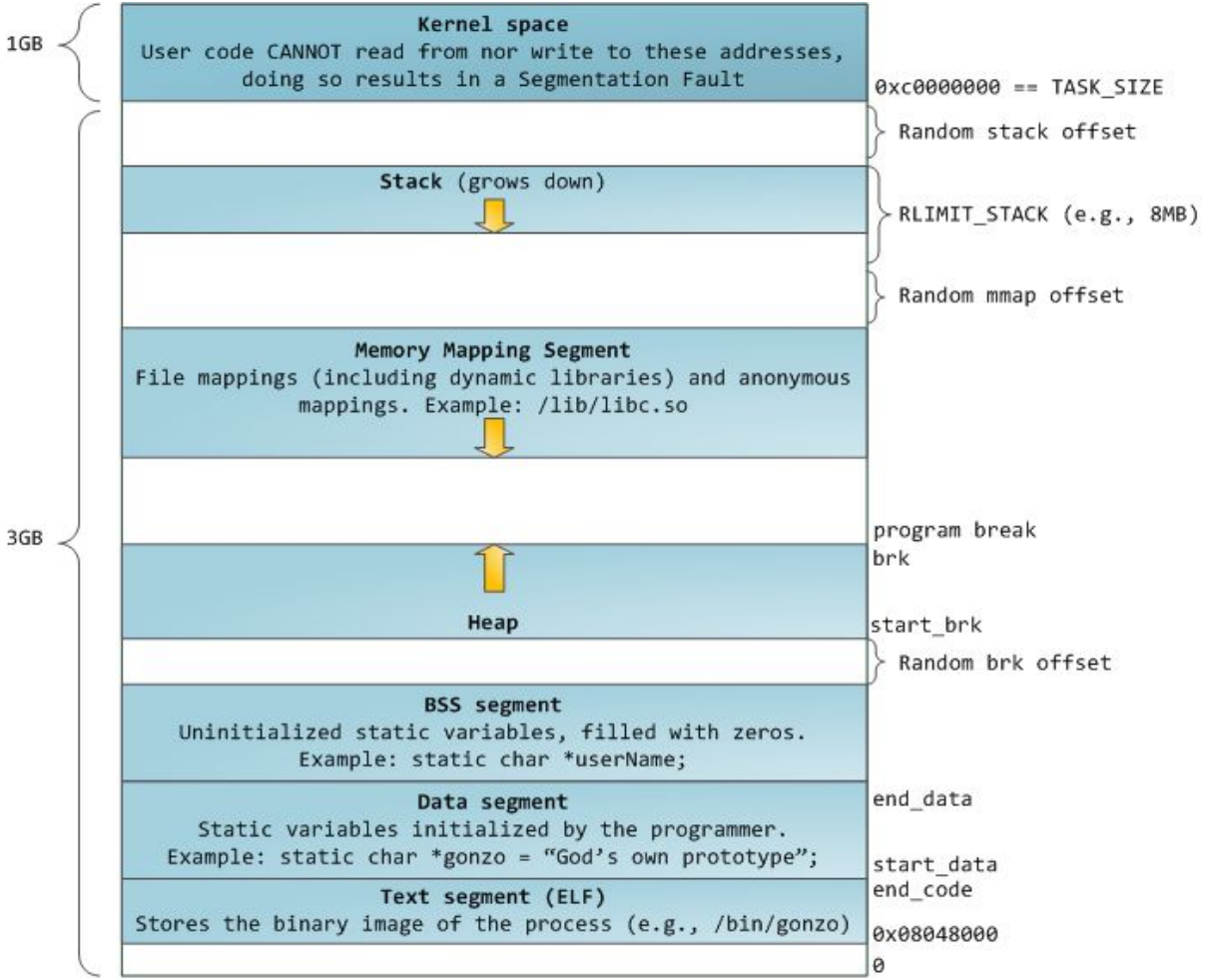
Instructor: Dr. Ziming Zhao

Today

1. Heap exploitation
    a. What is heap and dynamic memory allocator?
    b. Malloc and free interfaces
    c. Ptmalloc and tcache

Some slides are from Yan Shoshitaishvili, Arizona State University

Memory Map of Linux Process (32 bit system)



https://manybutfinite.com/post/anatomy-of-a-program-in-memory/

The Heap

The heap is *pool of memory* used for **dynamic** allocations at runtime.

Heap memory is different from stack memory in that it is ***persistent between functions***.

– **malloc**() grabs memory on the heap; keyword ***new*** in C++
– **free**() releases memory on the heap; keyword ***delete*** in C++

Both are standard C library interfaces. Neither of them directly mapps to a system call.

Why not mmap()?

Mmap()

- Mmap() is a system call. So kernel is involved, which means slow.
- Can only allocate multiples of pages (4KB).

Hence, the idea of ***dynamic memory allocator***

Dynamic memory allocators

Doug Lea malloc or **dlmalloc**: Release to public in 1987. Native version of malloc in some old distributions of Linux (http://gee.cs.oswego.edu/dl/html/malloc.html)

ptmalloc: ptmalloc is based on dlmalloc and was extended for use with multiple threads. On Linux systems, ptmalloc has been put to work for years as part of the GNU C library.

tcmalloc: Google's customized implementation of C's malloc() and C++'s operator new (https://github.com/google/tcmalloc)

jemalloc: jemalloc is a general purpose malloc(3) implementation that emphasizes fragmentation avoidance and scalable concurrency support. Used in FreeBSD, firefox, Android.

Hoard memory allocator: UMass Amherst CS Professor Emery Berger

Kmalloc: Linux kernel memory allocator

Kalloc: iOS kernel memory allocator

Segment Heap, NT Heap: Windows implementations.

malloc() and free()

stdlib.h provides with standard library functions to access, modify and manage dynamic memory.

```
void* malloc(size_t size);

Allocates size bytes of uninitialized storage. If allocation
succeeds, returns a pointer that is suitably aligned for any
object type with fundamental alignment.

void free(void* ptr);

Deallocates the space previously allocated by malloc(), etc.
```

calloc() and realloc()

```
void *calloc(size_t nitems, size_t size)
```

The difference in malloc and calloc is that malloc does not set the memory to zero whereas calloc sets allocated memory to zero.

```
void *realloc(void *ptr, size_t size)
```

Resize the memory block pointed to by ptr that was previously allocated with a call to malloc or calloc.

How to use malloc() and free()

```
int main()
{
        char * buffer = NULL;

        /* allocate a 0x100 byte buffer */
        buffer = malloc(0x100);

        /* read input and print it */
        fgets(stdin, buffer, 0x100);
        printf("Hello %s!\n", buffer);

        /* destroy our dynamically allocated buffer */
        free(buffer);
        return 0;
}
```

Heap vs. Stack

Heap

- Dynamic memory allocations at runtime
- Objects, big buffers, structs, persistence, larger things

Slower, Manual
– Done by the programmer
– malloc/calloc/recalloc/free
– new/delete

Stack

- Fixed memory allocations known at compile time
- Local variables, return addresses, function args

Fast, Automatic; Done by the compiler
– Abstracts away any concept of allocating/de-allocating

Which implementation on our server?

ldd --version

GLIBC 2.31, Ptmalloc2

https://elixir.bootlin.com/glibc/glibc-2.31/source/malloc/malloc.c

```
ctf@heapexploitation_heapchunks_32:/$ ldd --version
ldd (Ubuntu GLIBC 2.31-0ubuntu9.16) 2.31
Copyright (C) 2020 Free Software Foundation, Inc.
This is free software; see the source for copying conditions.  There is NO
warranty; not even for MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE.
Written by Roland McGrath and Ulrich Drepper.
```

Disclaimer: Ptmalloc is very complex, and its implementation is constantly changing. This is an approximation to glibc 2.31

How does ptmalloc get memory?

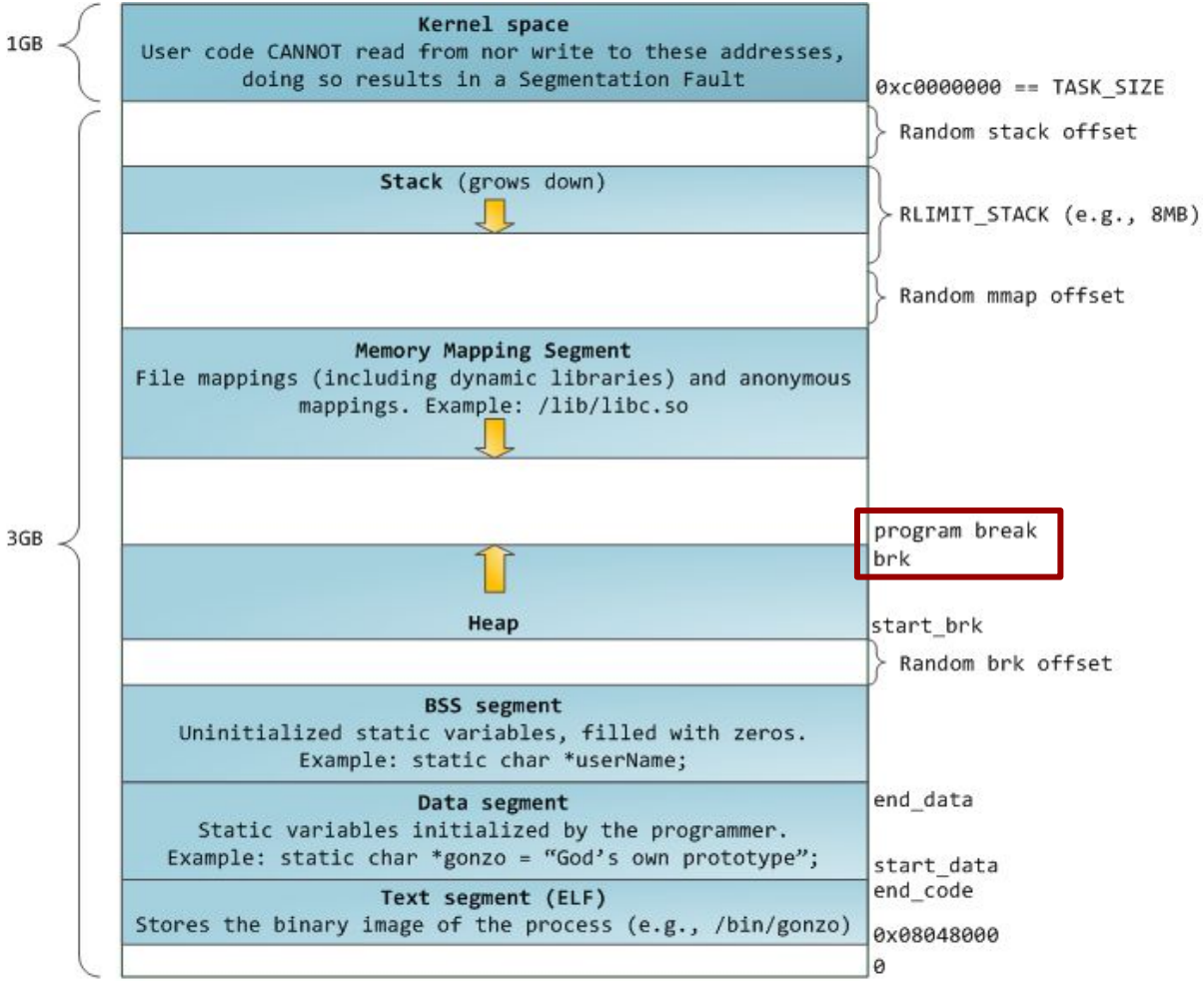
- Use the mmap() system call for large memory request
- Use brk() and sbrk() system calls
  - sbrk(NULL) returns the current program break
  - sbrk(200) expands program break by 200 bytes
  - brk(addr) expands the program break to address

```
DESCRIPTION
       brk()  and sbrk() change the location of the program break, which defines the end of the process's data segment (i.e., the pro-
       gram break is the first location after the end of the uninitialized data segment).  Increasing the program break has the effect
       of allocating memory to the process; decreasing the break deallocates memory.

       brk()  sets  the  end  of the data segment to the value specified by addr, when that value is reasonable, the system has enough
       memory, and the process does not exceed its maximum data size (see setrlimit(2)).

       sbrk() increments the program's data space by increment bytes.  Calling sbrk() with an increment of 0 can be used to  find  the
       current location of the program break.
```

Memory Map of Linux Process (32 bit system)



https://manybutfinite.com/post/anatomy-of-a-program-in-memory/

Heap chunk: malloc_chunk (ptmalloc2 in glibc2.31; *no tcache*)

Two states: in-use and freed

```
struct malloc_chunk {

  INTERNAL_SIZE_T      mchunk_prev_size;  /* Size of previous chunk (if free).  */
  INTERNAL_SIZE_T      mchunk_size;       /* Size in bytes, including overhead. */

  struct malloc_chunk* fd;         /* double links -- used only if free. */
  struct malloc_chunk* bk;

  /* Only used for large blocks: pointer to next larger size.  */
  struct malloc_chunk* fd_nextsize; /* double links -- used only if free. */
  struct malloc_chunk* bk_nextsize;
};
```

Both in-use and freed

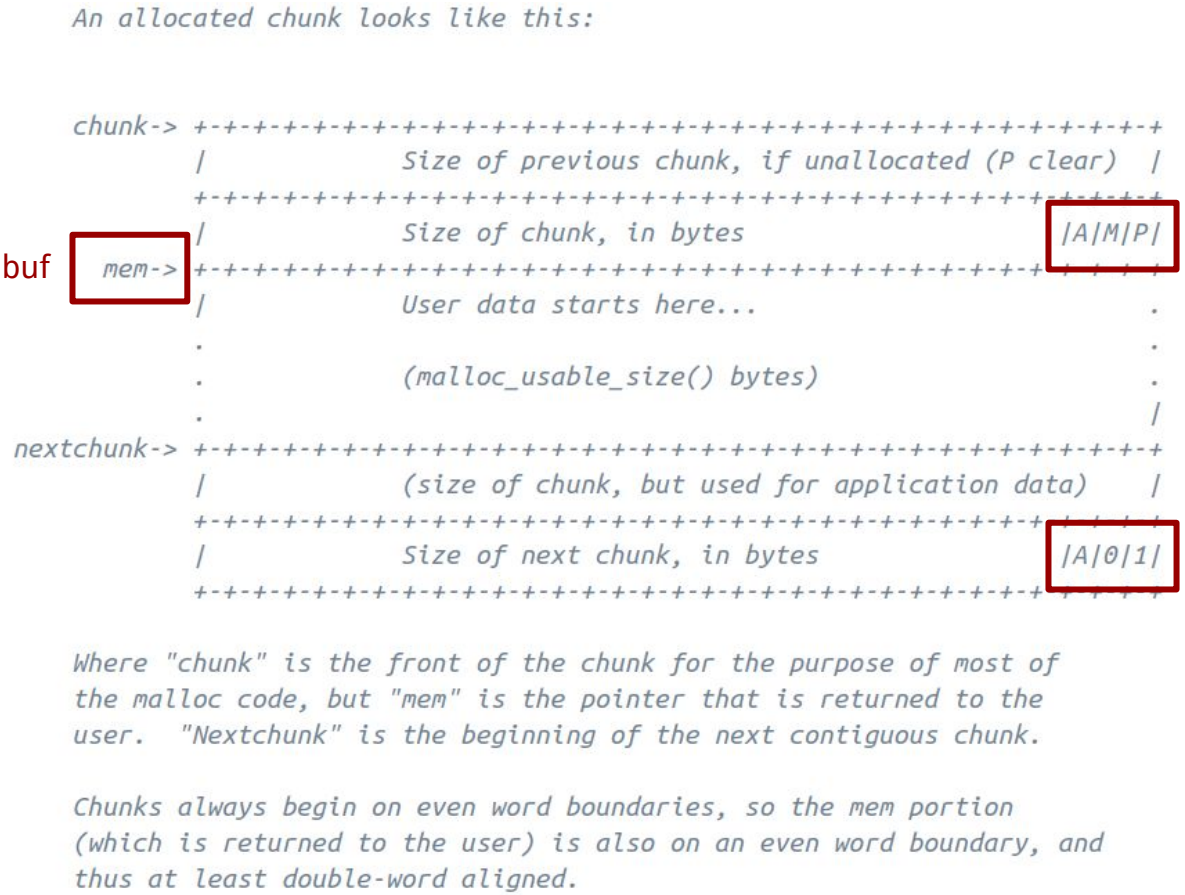
Only for freed

INTERNAL_SIZE_T is the same as size_t. 8 bytes in 64 bit;
4 bytes in 32 bits machine.
Pointer is 8/4 bytes on a 64/32 bit machine, respectively.

Alignment is defined as 2 * (sizeof(size_t))

https://elixir.bootlin.com/glibc/glibc-2.31/source/malloc/malloc.c

Heap chunk: malloc_chunk (ptmalloc2 in glibc2.31; *no tcache*)



Chunk Size: Size of entire chunk including overhead

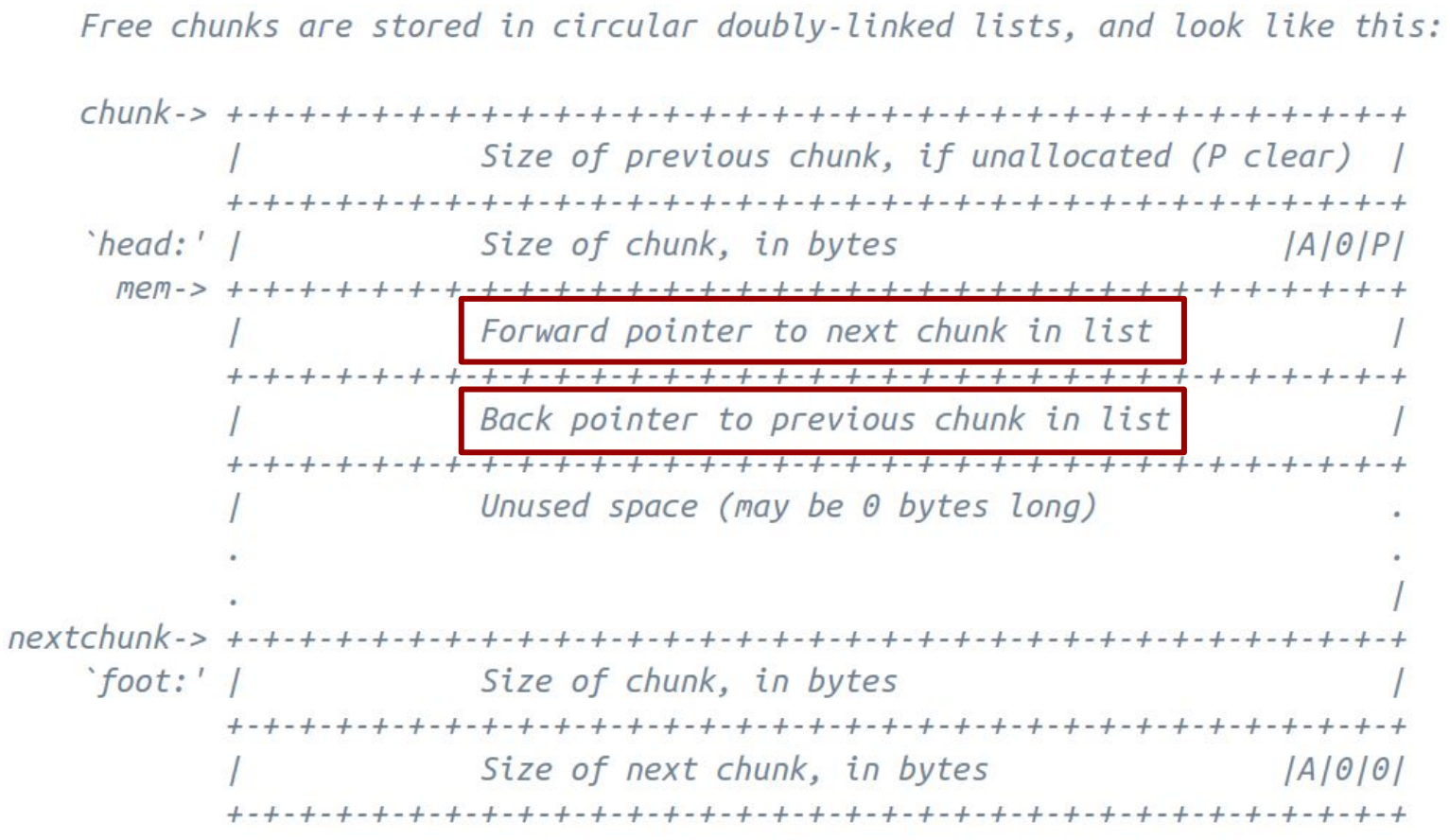
Flags: Because of byte alignment, the lower 3 bits of the chunk size field would always be zero. Instead they are used for flag bits.

0x01 **P**REV_INUSE – set when previous chunk is in use

0x02 IS_**M**MAPPED – set if chunk was obtained with mmap()

0x04 NON_MAIN_**A**RENA – set if chunk belongs to a thread arena

Heap chunk: malloc_chunk (ptmalloc2 in glibc2.31; *no tcache*)



Tcache Design

"Thread Local Caching" in ptmalloc, to speed up repeated (small) allocations in a single thread.

Implemented as a **singly-linked** list, with each thread having a list header for different-sized allocations.

```
/* There is one of these for each thread, which contains the
   per-thread cache (hence "tcache_perthread_struct").  Keeping
   overall size low is mildly important.  Note that COUNTS and ENTRIES
   are redundant (we could have just counted the linked list each
   time), this is for performance reasons.  */
typedef struct tcache_perthread_struct
{
  uint16_t counts[TCACHE_MAX_BINS];
  tcache_entry *entries[TCACHE_MAX_BINS];
} tcache_perthread_struct;
```

https://elixir.bootlin.com/glibc/glibc-2.31.9000/source/malloc/malloc.c#L2906

Bins

A bin is a list (doubly or singly linked list) of free (non-allocated) chunks.
Bins are differentiated based on the size of chunks they contain:

- Fast bin
- Unsorted bin
- Small bin
- Large bin

ptmalloc2 in glibc2.31; tcache design

1. 64 singly-linked tcache **bins** for allocations of size 16 to 1032 (functionally "covers" **fastbins** and **smallbins**)
2. 10 singly-linked **"fast" bins** for allocations of size up to 160 bytes
3. 1 doubly-linked "unsorted" bin to quickly stash free()d chunks that don't fit into tcache or fastbins
4. 64 doubly-linked **"small" bins** for allocations up to 512 bytes
5. doubly-linked **"large" bins** (anything over 512 bytes) that contain different-sized chunks

Heap chunk: malloc_chunk (ptmalloc2 in glibc2.31; tcache)

Two states: in-use and freed

fastbin/smallbin

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};
```

Not used in tcache. Can be used by the previous chunk

Both in-use and freed

https://elixir.bootlin.com/glibc/glibc-2.31.9000/source/malloc/malloc.c#L2890

Heap chunk: malloc_chunk (ptmalloc2 in glibc2.31; tcache)

Two states: in-use and freed

fastbin/smallbin

```
struct malloc_chunk {

  INTERNAL_SIZE_T      mchunk_prev_size;  /* Size of previous chunk (if free).  */
  INTERNAL_SIZE_T      mchunk_size;       /* Size in bytes, including overhead. */

  CACHE-SPECIFIC METADATA
};
```

Not used in tcache. Can be used by the previous chunk

Both in-use and freed

https://elixir.bootlin.com/glibc/glibc-2.31.9000/source/malloc/malloc.c#L2890

ptmalloc2 in glibc2.31; tcache design

fastbin/smallbin

```
#if USE_TCACHE

/* We overlay this structure on the user-data portion of a chunk when
   the chunk is stored in the per-thread cache.  */
typedef struct tcache_entry
{
  struct tcache_entry *next;
  /* This field exists to detect double frees.  */
  struct tcache_perthread_struct *key;
} tcache_entry;
```

Interlude: what is a linked list?

```
typedef struct tcache_perthread_struct
{
  char counts[TCACHE_MAX_BINS];
  tcache_entry *entries[TCACHE_MAX_BINS];
} tcache_perthread_struct;

typedef struct tcache_entry
{
  struct tcache_entry *next;
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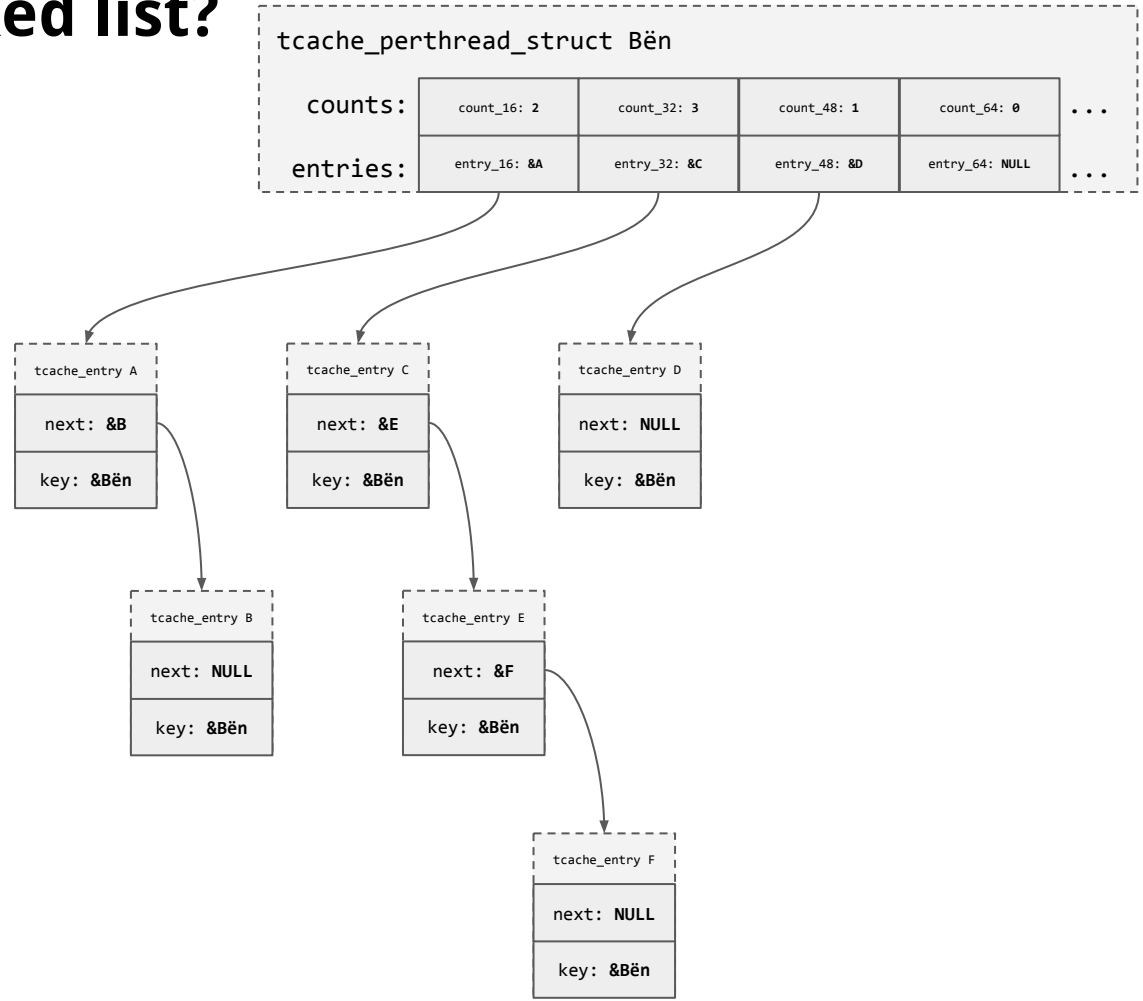

How did we get here?

```
a = malloc(16);
b = malloc(16);
c = malloc(32);
d = malloc(48);
e = malloc(32);
f = malloc(32);

// allocations that are not freed
// don't show up in the tcache!
x = malloc(64);
y = malloc(64);
z = malloc(64);

// later freed allocations show up
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free(b);
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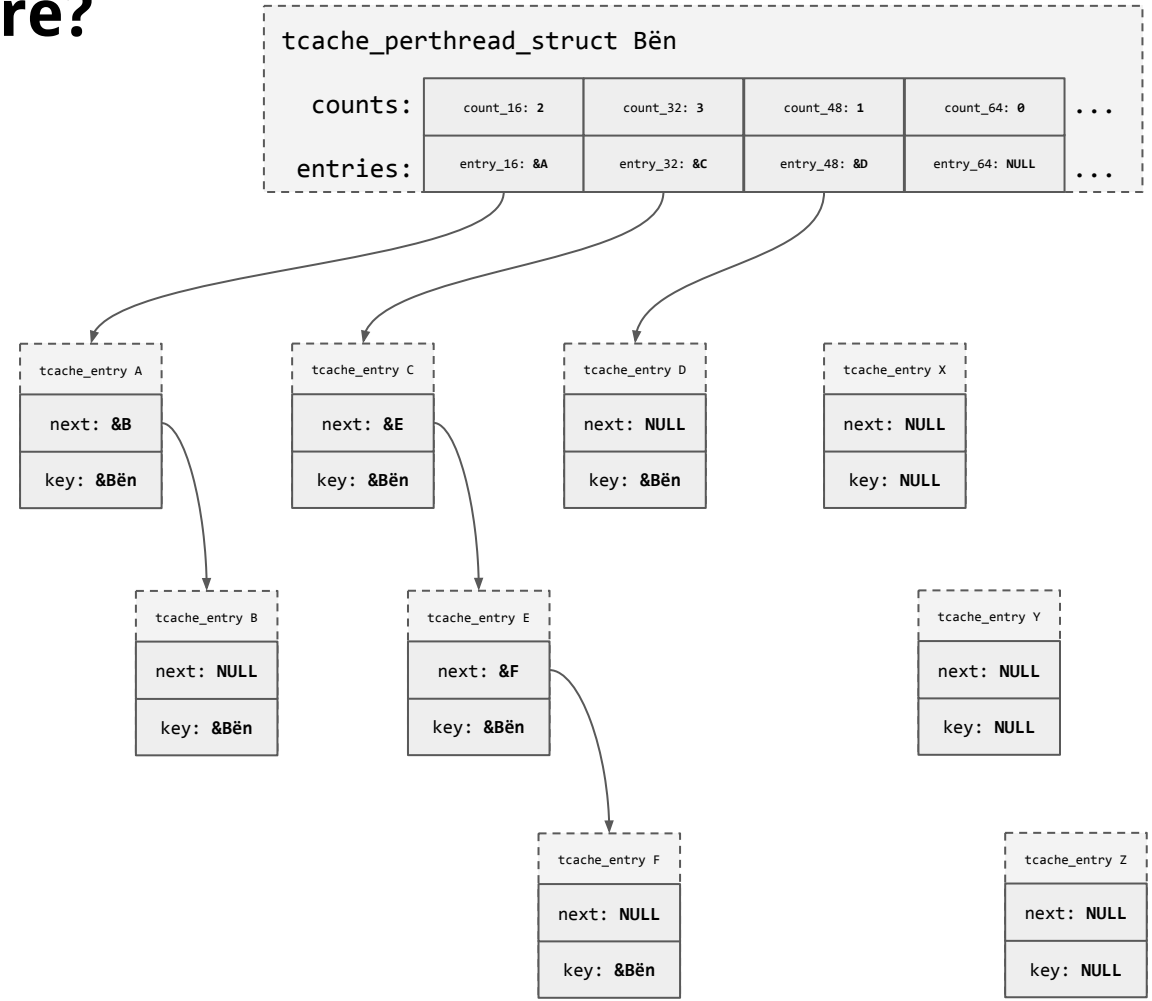

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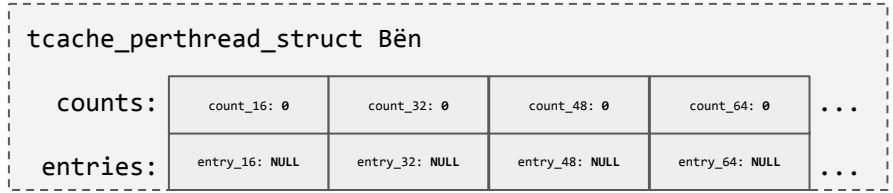

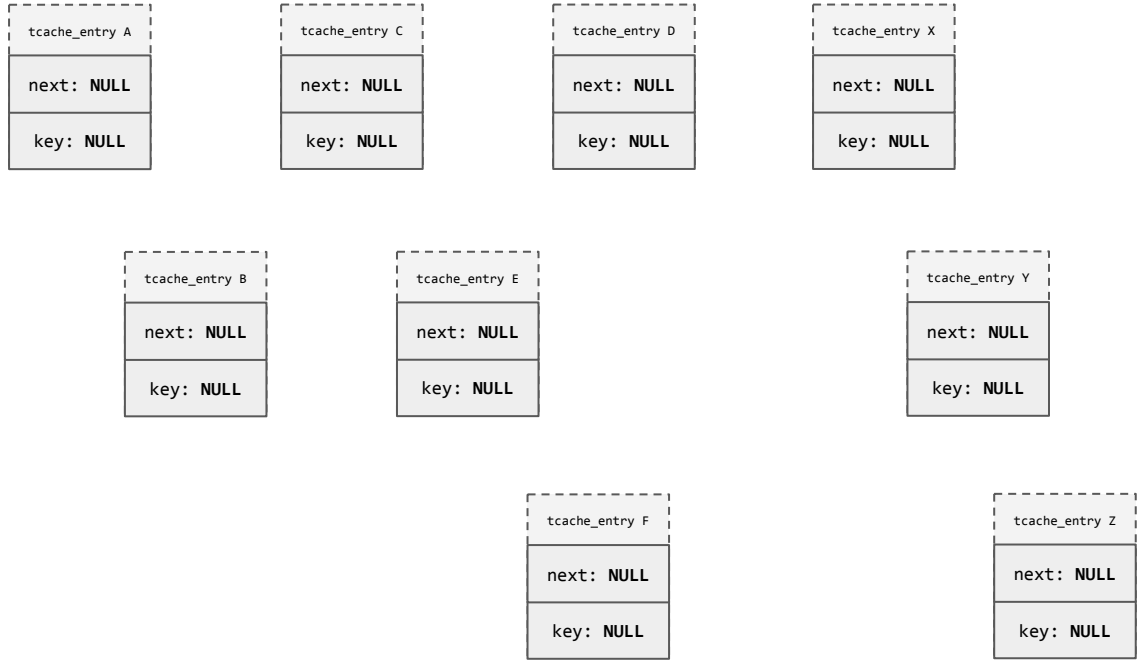

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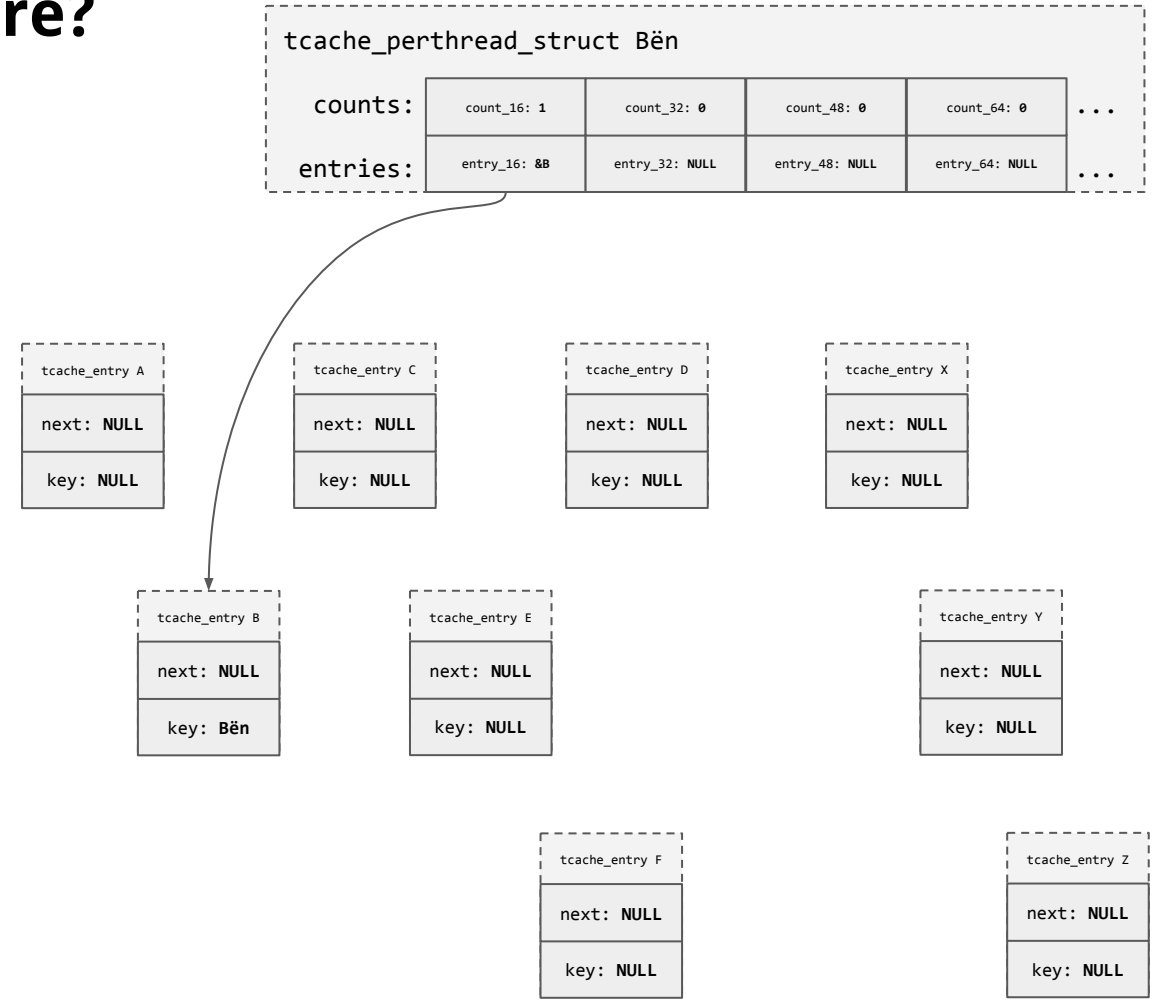

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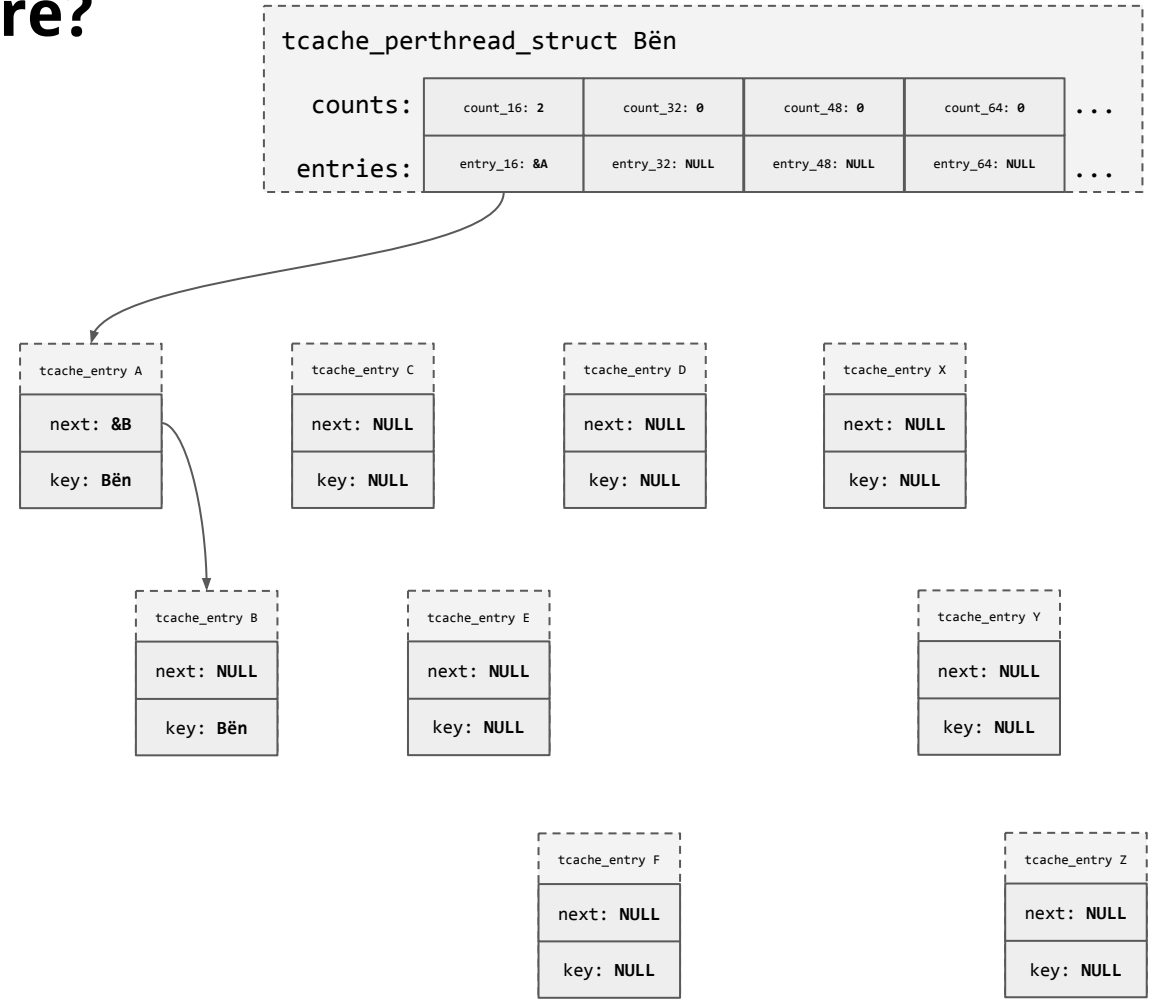

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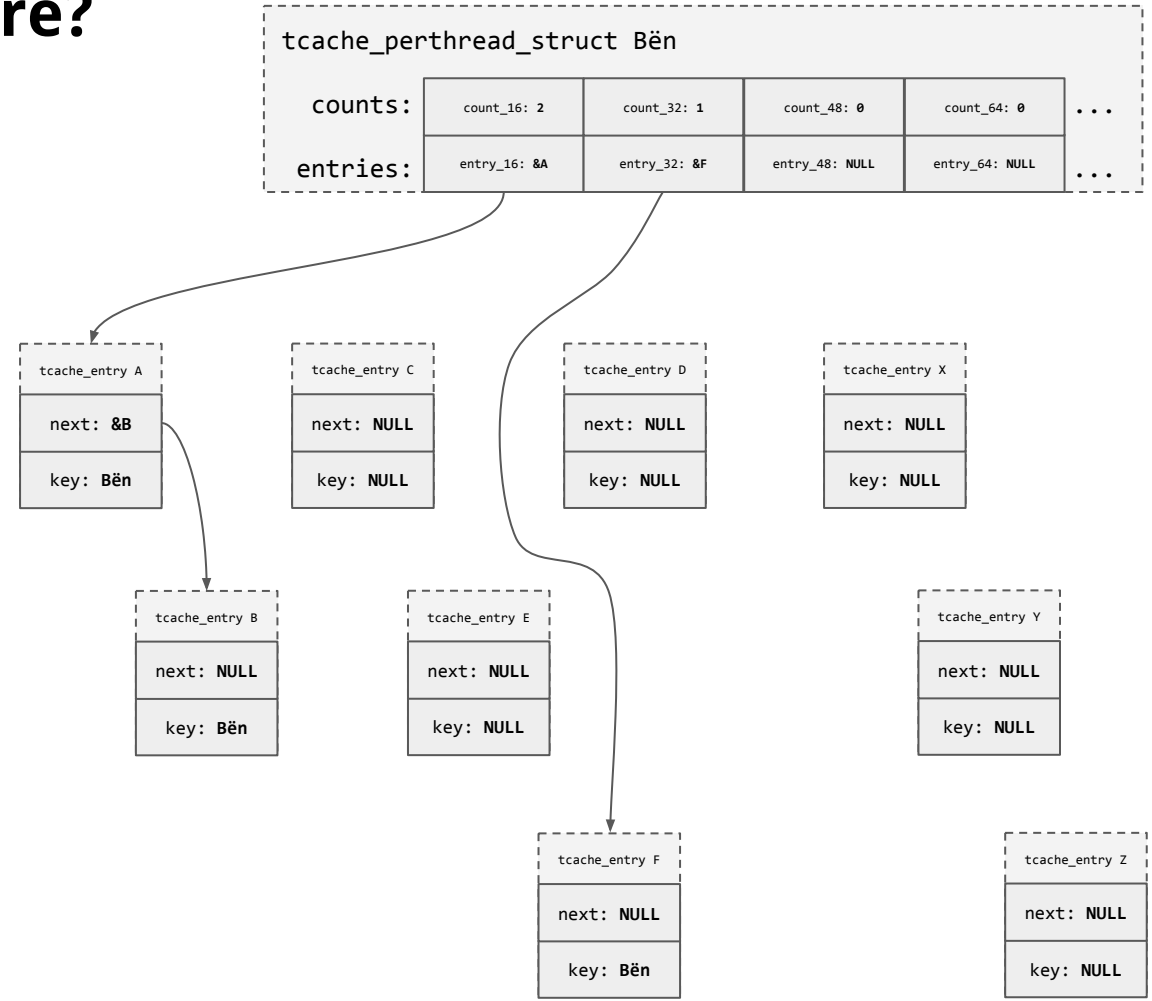

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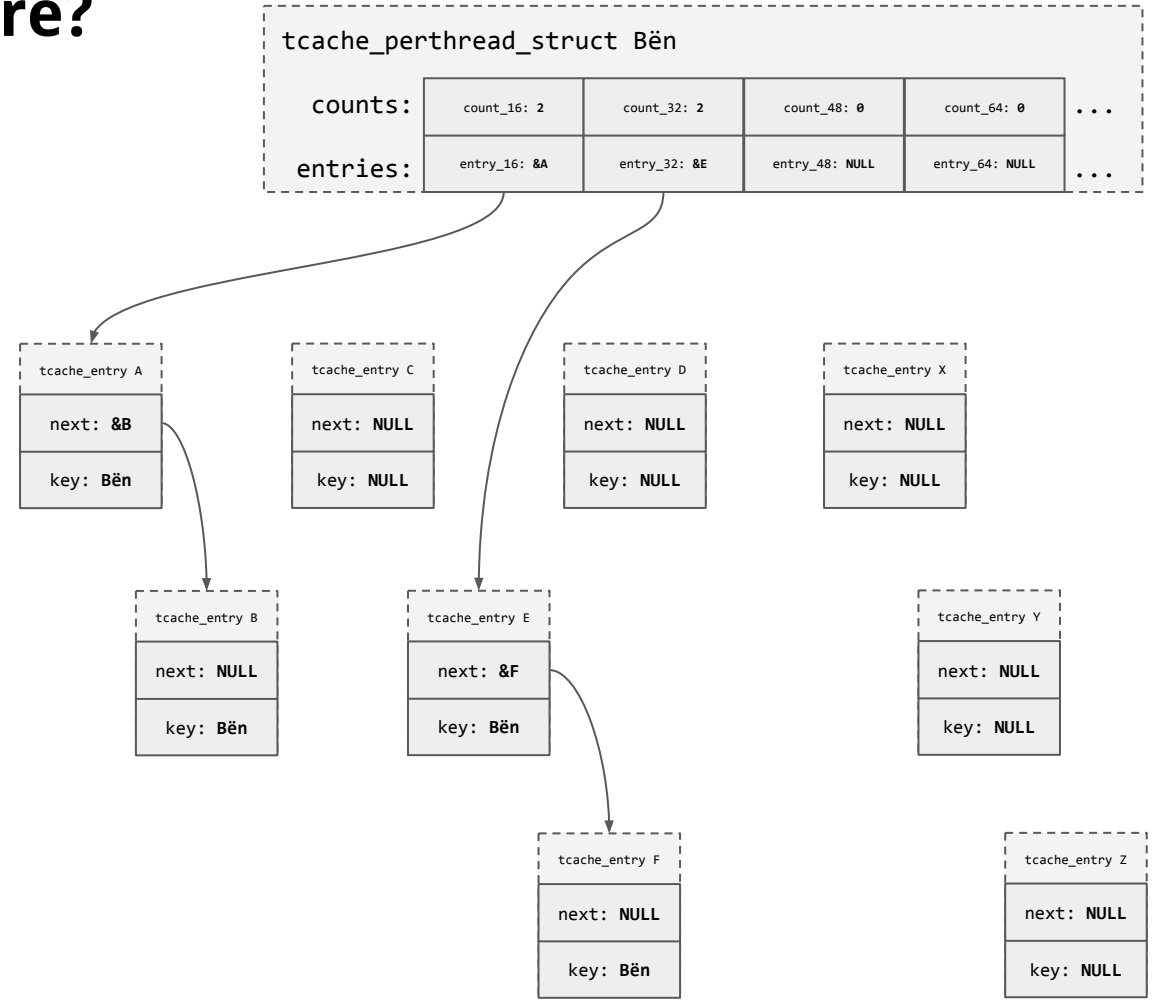

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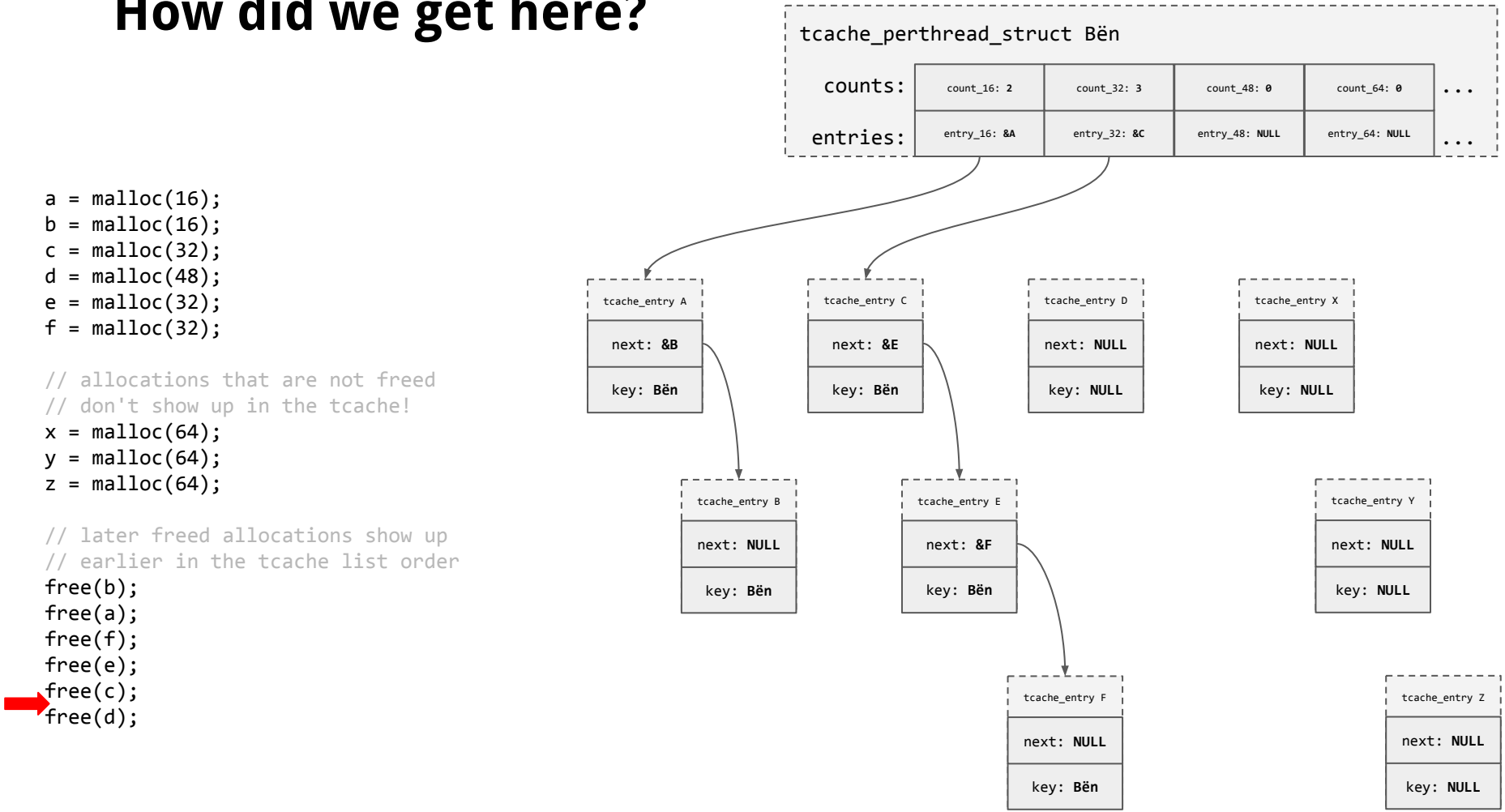

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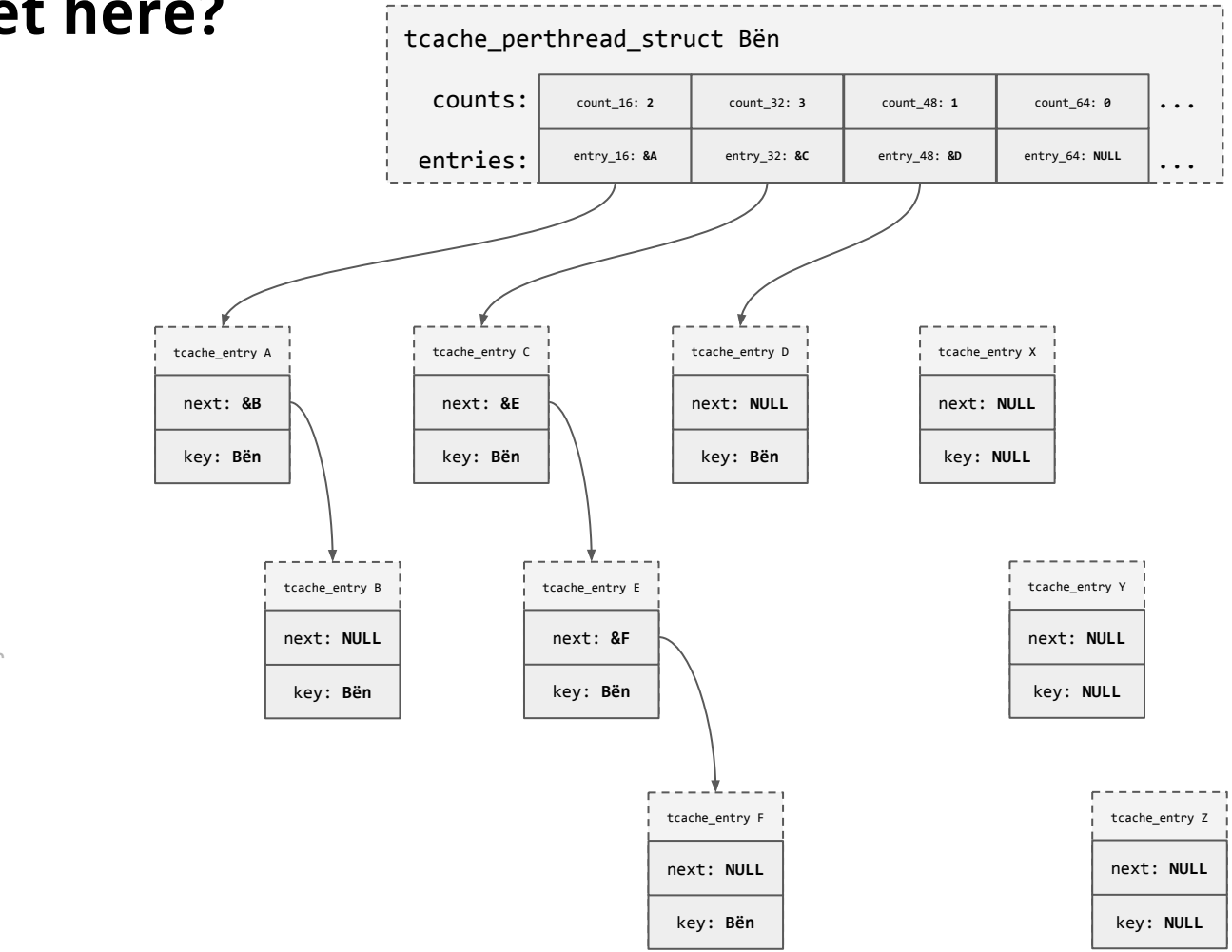


tcache - freeing

Each `tcache_entry` is actually the exact allocation that was freed! On `free()`, the following happens:

Select the right "bin" based on the size:

```
idx = (freed_allocation_size - 1) / 16;
```

Check to make sure the entry hasn't already been freed (double-free):

```
((unsigned long*)freed_allocation)[1] == &our_tcache_perthread_struct;
```

Push the freed allocation to the front of the list!

```
((unsigned long*)freed_allocation)[0] = our_tcache_perthread_struct.entries[idx];
our_tcache_perthread_struct.entries[idx] = freed_allocation;
our_tcache_perthread_struct.count[idx]++;
```

Record the tcache_perthread_struct associated with the freed allocation (for checking against double-frees)

```
((unsigned long*)freed_allocation)[1] = &our_tcache_perthread_struct
```

tcache - allocation

On allocation, the following happens:

Select the bin number based on the requested size:

```
idx = (requested_size - 1) / 16;
```

Check the appropriate cache for available entries:

```
if our_tcache_perthread_struct.count[idx] > 0;
```

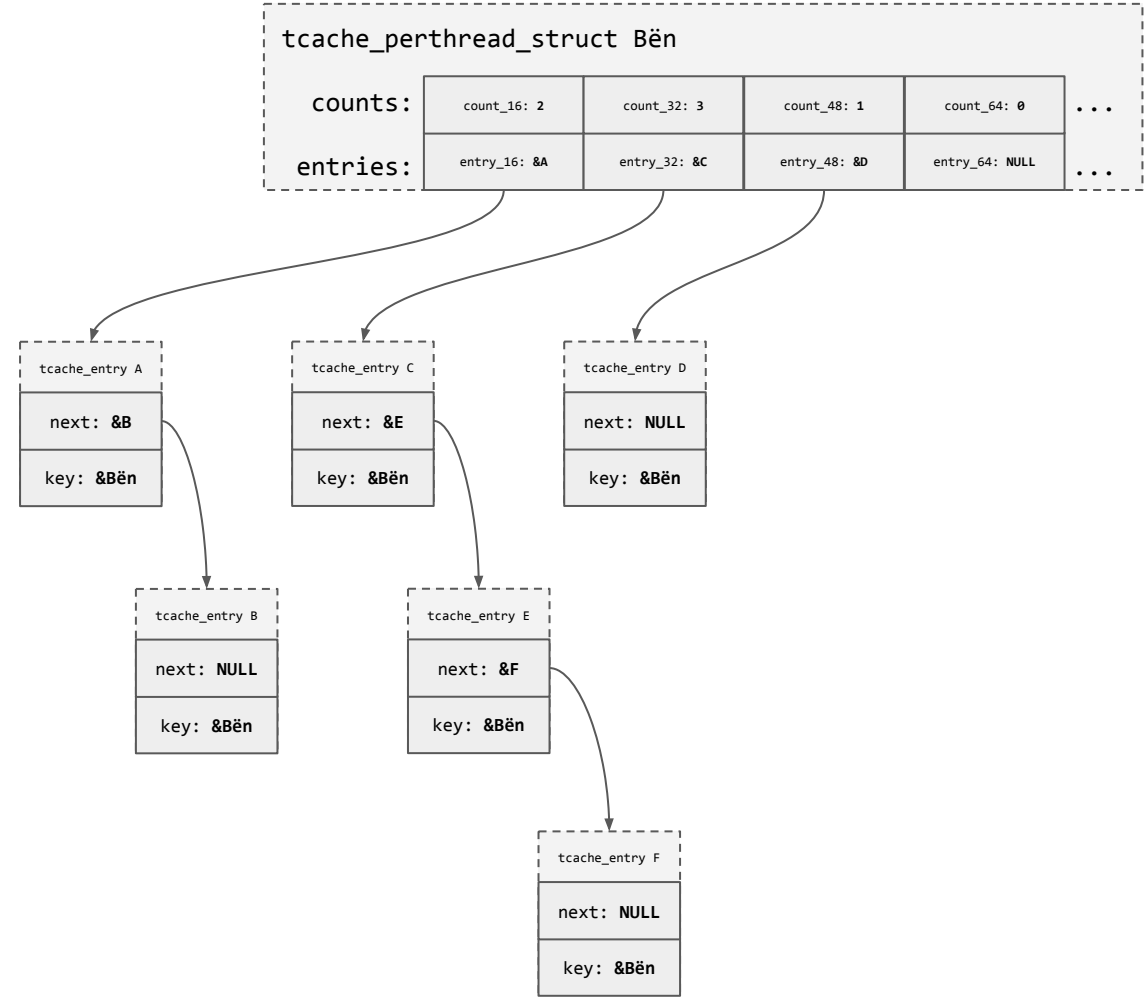
Reuse the allocation in the front of the list if available:

```
unsigned long *to_return = our_tcache_perthread_struct.entries[idx];
tcache_perthread_struct.entries[idx] = to_return[0];
tcache_perthread_struct.count[idx]--;
return to_return;
```

Things that are **not** done:

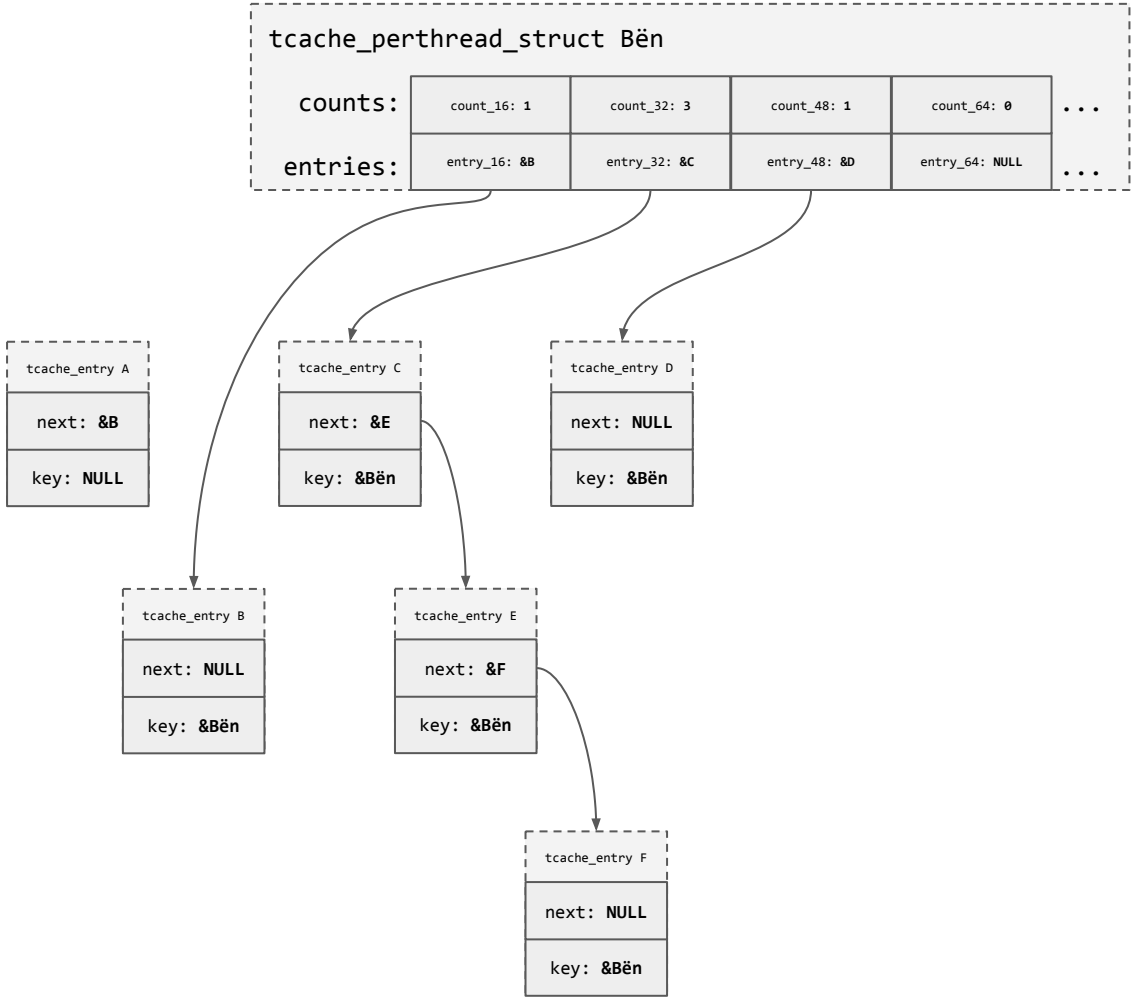
- clearing all sensitive pointers (only `key` is cleared for some reason).
- checking if the `next` (`return[0]`) address makes sense

Onward!


tcache_perthread_struct Bën
counts:
count_16: 2
count_32: 3
count_48: 1
count_64: 0
...
entries:
entry_16: &A
entry_32: &C
entry_48: &D
entry_64: NULL
...
tcache_entry A
next: &B
key: &Bën
tcache_entry C
next: &E
key: &Bën
tcache_entry D
next: NULL
key: &Bën
tcache_entry B
next: NULL
key: &Bën
tcache_entry E
next: &F
key: &Bën
tcache_entry F
next: NULL
key: &Bën

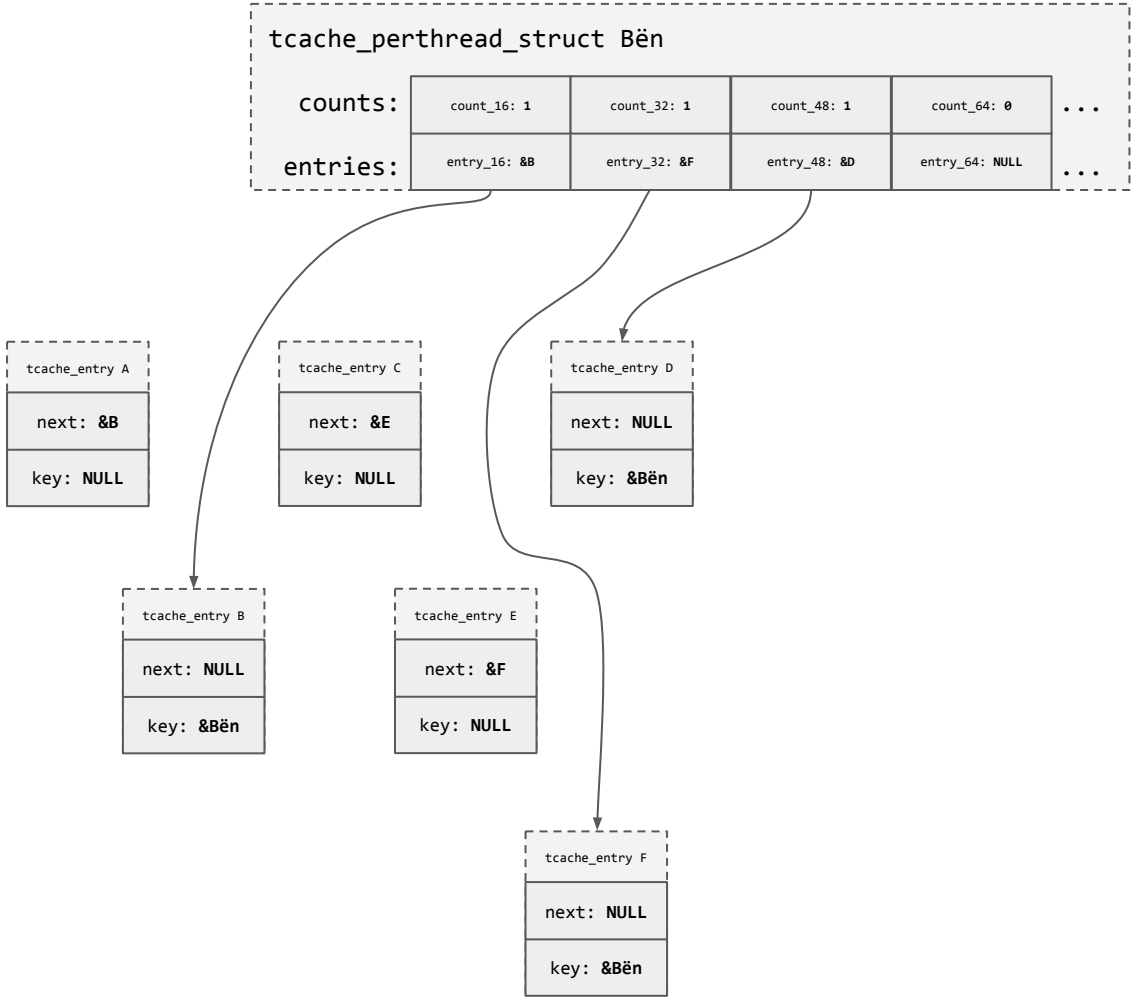
Onward!

```
malloc(16) == a
```



Onward!

```
malloc(16) == a
malloc(32) == c
malloc(32) == e
```



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```
malloc(16) == a
malloc(32) == c
malloc(32) == e
malloc(48) == d
malloc(16) == b
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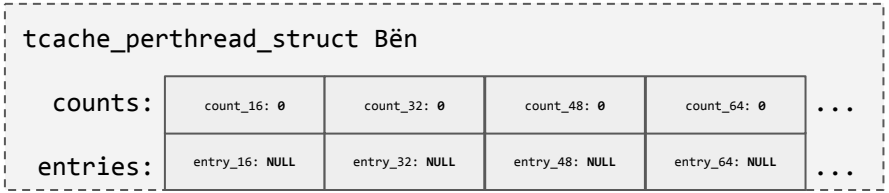
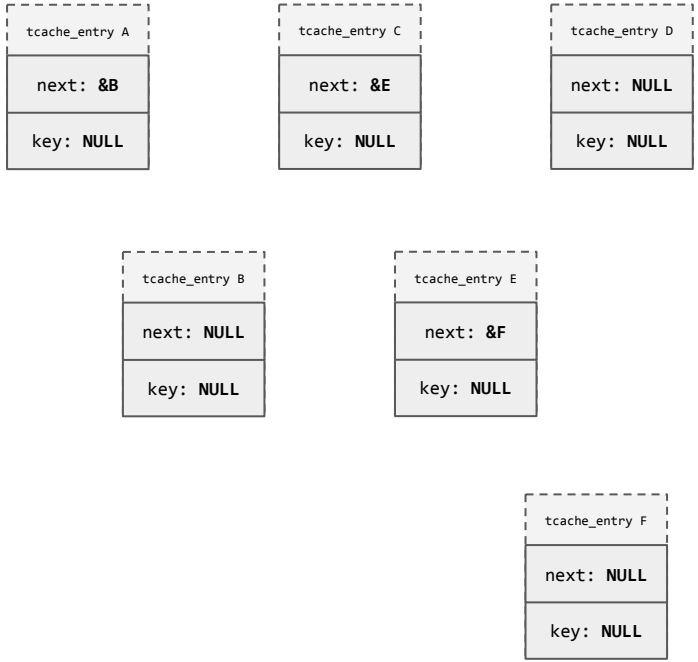
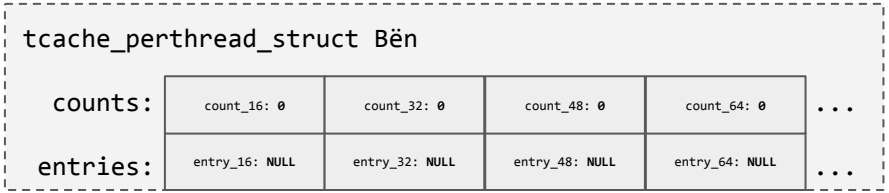
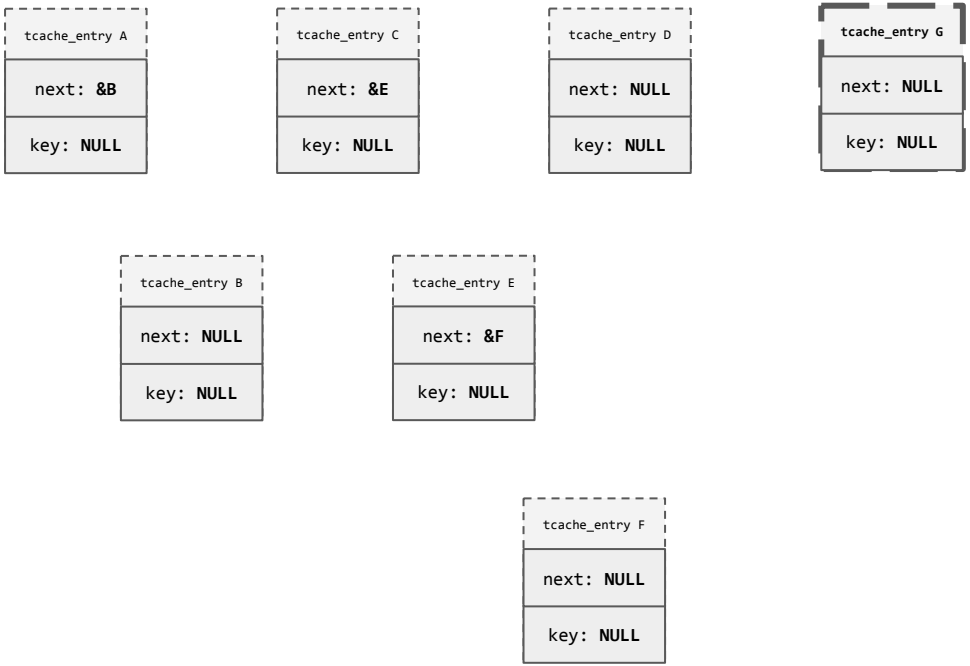




Onward!

```
malloc(16) == a
malloc(32) == c
malloc(32) == e
malloc(48) == d
malloc(16) == b
malloc(32) == f
malloc(64) == g
```



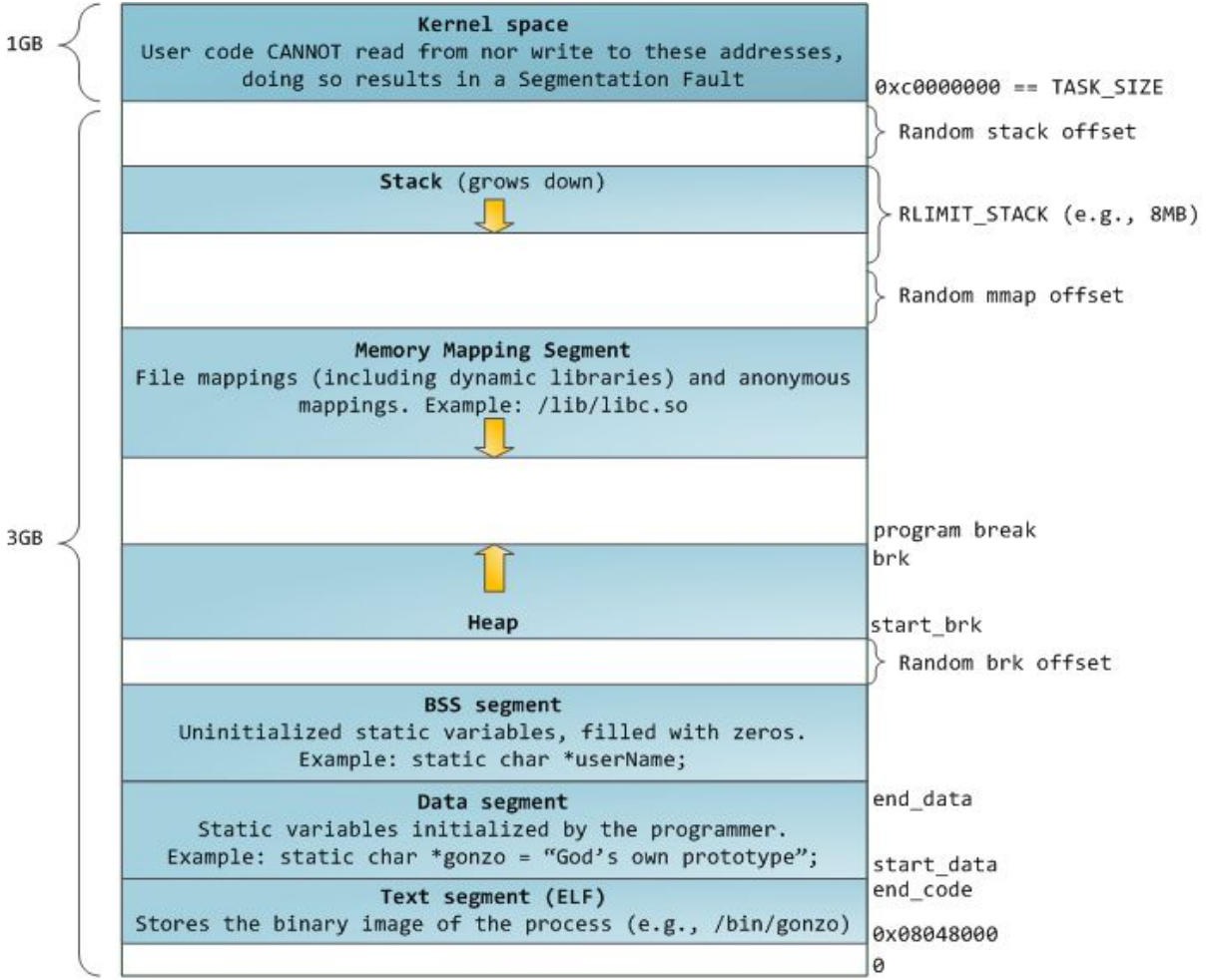


code/heapsizes

```
int main()
{
   unsigned int lengths[] = {32, 4, 20, 0, 64, 32, 32, 32, 32, 32};
   unsigned int * ptr[10];
   int i;

   for(i = 0; i < 10; i++)
      ptr[i] = malloc(lengths[i]);

   for(i = 0; i < 9; i++)
      printf("malloc(%2d) is at 0x%08x, %3d bytes to the next pointer\n",
            lengths[i],
            (unsigned int)ptr[i],
            (ptr[i+1]-ptr[i])*sizeof(unsigned int));

  return 0;}
```

https://github.com/RPISEC/MBE/blob/master/src/lecture/heap/sizes.c

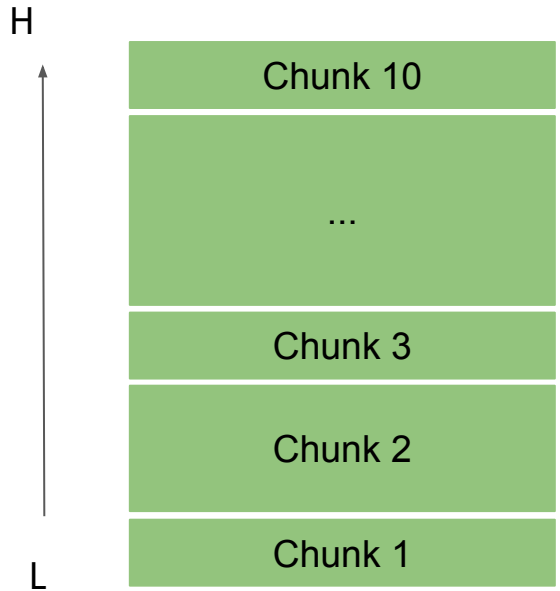
Heap goes from low address to high address



https://manybutfinite.com/post/anatomy-of-a-program-in-memory/

code/chunk_sizes

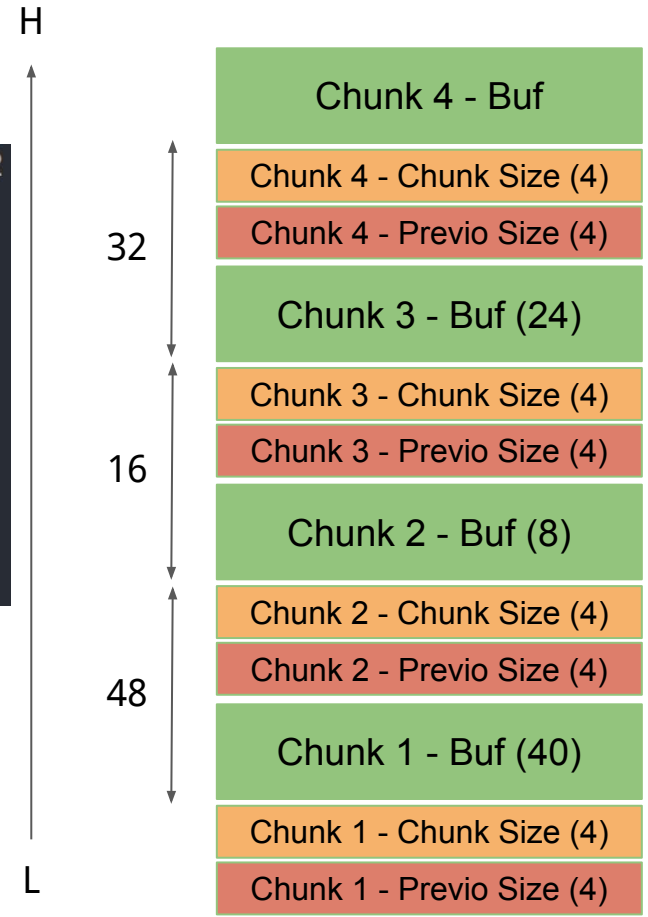
```
int main()
{
   unsigned int lengths[] = {32, 4, 20, 0, 64, 32, 32, 32, 32, 32};
   size_t * ptr[10];
   int i;

   for(i = 0; i < 10; i++)
      ptr[i] = malloc(lengths[i]);

   for(i = 0; i < 9; i++)
      printf("malloc(%2d) is at 0x%016x, %3d bytes to the next pointer\n",
            lengths[i],
            (unsigned int)ptr[i],
            (ptr[i+1]-ptr[i])*sizeof(unsigned int));

  return 0;}
```



code/chunk_sizes 32bit

```
ctf@heapexploitation_heapsizes_32:/$ ./heapexploitation_heapsizes_32
The size of size_t is 4
The size of a pointer is 4
malloc(32) is at 0x5655a5b0,  48 bytes to the next pointer
malloc( 4) is at 0x5655a5e0,  16 bytes to the next pointer
malloc(20) is at 0x5655a5f0,  32 bytes to the next pointer
malloc( 0) is at 0x5655a610,  16 bytes to the next pointer
malloc(64) is at 0x5655a620,  80 bytes to the next pointer
malloc(32) is at 0x5655a670,  48 bytes to the next pointer
malloc(32) is at 0x5655a6a0,  48 bytes to the next pointer
malloc(32) is at 0x5655a6d0,  48 bytes to the next pointer
malloc(32) is at 0x5655a700,  48 bytes to the next pointer
```

Alignment is at least defined as 2 * (sizeof(size_t)) = 16

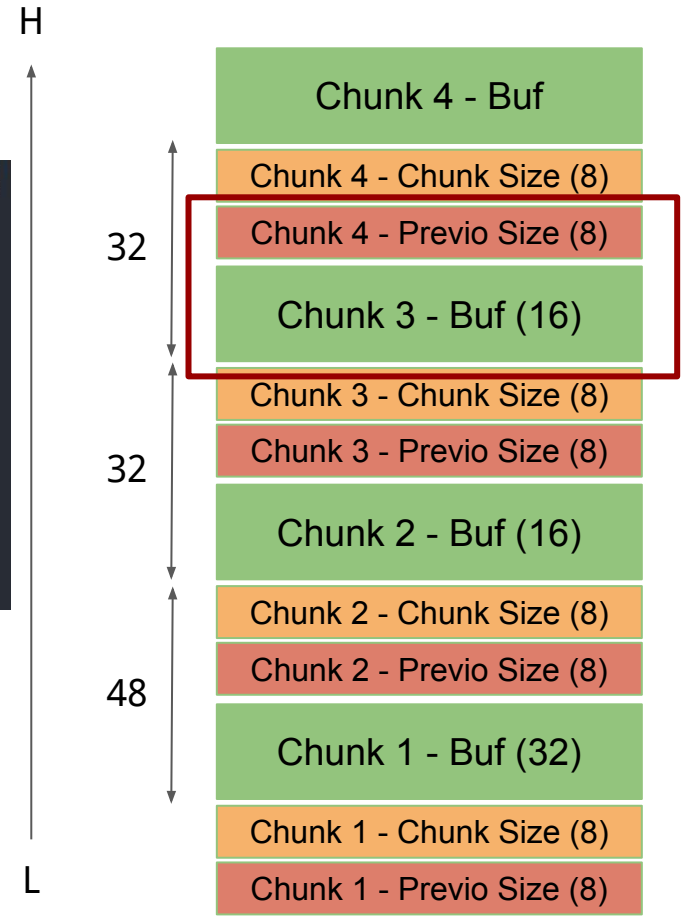


code/chunk_sizes 64bit

```
ctf@heapexploitation_heapsizes_64:/$ ./heapexploitation_heapsizes_64
The size of size_t is 8
The size of a pointer is 8
malloc(32) is at 0x555596b0,  48 bytes to the next pointer
malloc( 4) is at 0x555596e0,  32 bytes to the next pointer
malloc(20) is at 0x55559700,  32 bytes to the next pointer
malloc( 0) is at 0x55559720,  32 bytes to the next pointer
malloc(64) is at 0x55559740,  80 bytes to the next pointer
malloc(32) is at 0x55559790,  48 bytes to the next pointer
malloc(32) is at 0x555597c0,  48 bytes to the next pointer
malloc(32) is at 0x555597f0,  48 bytes to the next pointer
malloc(32) is at 0x55559820,  48 bytes to the next pointer
```

Alignment is defined as 2 * (sizeof(size_t)) = 16

Chunk4's previous size field is used by Chunk3



code/chunk_sizes

```
/*
  malloc(size_t n)
  Returns a pointer to a newly allocated chunk of at least n
  bytes, or null if no space is available. Additionally, on
  failure, errno is set to ENOMEM on ANSI C systems.

  If n is zero, malloc returns a minimum-sized chunk. (The
  minimum size is 16 bytes on most 32bit systems, and 24 or 32
  bytes on 64bit systems.)  On most systems, size_t is an unsigned
  type, so calls with negative arguments are interpreted as
  requests for huge amounts of space, which will often fail. The
  maximum supported value of n differs across systems, but is in
  all cases less than the maximum representable value of a
  size_t.
*/
```

Malloc Trivia

How many bytes on the heap are your ***malloc chunks*** really taking up?

- malloc(32); 48 bytes (32bit/64bit)
- malloc(4); 16 bytes (32bit) / 32 bytes (64bit)
- malloc(20); 32 bytes (32bit/64bit [Prev Size field reused])
- malloc(0); 16 bytes (32bit) / 32 bytes (64bit)

code/malloc_chunks

```
void print_chunk(size_t * ptr, unsigned int len)
{
   printf("[prev - 0x%016x][size - 0x%08x][buffer (0x%016x)] - from malloc(%d)\n",  *(ptr-2), *(ptr-1), (unsigned int)ptr, len); }

int main()
{
   void * ptr[LEN];
   unsigned int lengths[] = {0, 4, 8, 16, 24, 32, 64, 128, 256, 512, 1024, 2048, 4096, 8192, 16384};
   int i;

   printf("mallocing...\n");

   for(i = 0; i < LEN; i++)
      ptr[i] = malloc(lengths[i]);

   for(i = 0; i < LEN; i++)
      print_chunk(ptr[i], lengths[i]);

   return 0;}
```

Modified from https://github.com/RPISEC/MBE/blob/master/src/lecture/heap/heap_chunks.c

```
➜ malloc_chunks git:(master) ../../../software-security-course-binaries/heapexploitation/malloc_chunks_32
mallocing...
[prev - 0x0000000000000000][size - 0x00000011][buffer (0x00000000571245b0)] - from malloc(0)
[prev - 0x0000000000000000][size - 0x00000011][buffer (0x00000000571245c0)] - from malloc(4)
[prev - 0x0000000000000000][size - 0x00000011][buffer (0x00000000571245d0)] - from malloc(8)
[prev - 0x0000000000000000][size - 0x00000021][buffer (0x00000000571245e0)] - from malloc(16)
[prev - 0x0000000000000000][size - 0x00000021][buffer (0x0000000057124600)] - from malloc(24)
[prev - 0x0000000000000000][size - 0x00000031][buffer (0x0000000057124620)] - from malloc(32)
[prev - 0x0000000000000000][size - 0x00000051][buffer (0x0000000057124650)] - from malloc(64)
[prev - 0x0000000000000000][size - 0x00000091][buffer (0x00000000571246a0)] - from malloc(128)
[prev - 0x0000000000000000][size - 0x00000111][buffer (0x0000000057124730)] - from malloc(256)
[prev - 0x0000000000000000][size - 0x00000211][buffer (0x0000000057124840)] - from malloc(512)
[prev - 0x0000000000000000][size - 0x00000411][buffer (0x0000000057124a50)] - from malloc(1024)
[prev - 0x0000000000000000][size - 0x00000811][buffer (0x0000000057124e60)] - from malloc(2048)
[prev - 0x0000000000000000][size - 0x00001011][buffer (0x0000000057125670)] - from malloc(4096)
[prev - 0x0000000000000000][size - 0x00002011][buffer (0x0000000057126680)] - from malloc(8192)
[prev - 0x0000000000000000][size - 0x00004011][buffer (0x0000000057128690)] - from malloc(16384)
➜ malloc_chunks git:(master) ../../../software-security-course-binaries/heapexploitation/malloc_chunks_64
mallocing...
[prev - 0x0000000000000000][size - 0x00000021][buffer (0x00000000bc5db6b0)] - from malloc(0)
[prev - 0x0000000000000000][size - 0x00000021][buffer (0x00000000bc5db6d0)] - from malloc(4)
[prev - 0x0000000000000000][size - 0x00000021][buffer (0x00000000bc5db6f0)] - from malloc(8)
[prev - 0x0000000000000000][size - 0x00000021][buffer (0x00000000bc5db710)] - from malloc(16)
[prev - 0x0000000000000000][size - 0x00000021][buffer (0x00000000bc5db730)] - from malloc(24)
[prev - 0x0000000000000000][size - 0x00000031][buffer (0x00000000bc5db750)] - from malloc(32)
[prev - 0x0000000000000000][size - 0x00000051][buffer (0x00000000bc5db780)] - from malloc(64)
[prev - 0x0000000000000000][size - 0x00000091][buffer (0x00000000bc5db7d0)] - from malloc(128)
[prev - 0x0000000000000000][size - 0x00000111][buffer (0x00000000bc5db860)] - from malloc(256)
[prev - 0x0000000000000000][size - 0x00000211][buffer (0x00000000bc5db970)] - from malloc(512)
[prev - 0x0000000000000000][size - 0x00000411][buffer (0x00000000bc5dbb80)] - from malloc(1024)
[prev - 0x0000000000000000][size - 0x00000811][buffer (0x00000000bc5dbf90)] - from malloc(2048)
[prev - 0x0000000000000000][size - 0x00001011][buffer (0x00000000bc5dc7a0)] - from malloc(4096)
[prev - 0x0000000000000000][size - 0x00002011][buffer (0x00000000bc5dd7b0)] - from malloc(8192)
[prev - 0x0000000000000000][size - 0x00004011][buffer (0x00000000bc5df7c0)] - from malloc(16384)
```

code/tcache_smallbin_free

```
void print_inuse_chunk(size_t * ptr)
{
	printf("[prev - 0x%016x][size - 0x%016x][buffer (0x%016x)] -
Chunk 0x%016x - In use\n",
		*(ptr-2),
		*(ptr-1),
		(unsigned int)ptr,
		(unsigned int)(ptr-2));
}

void print_freed_chunk(size_t * ptr)
{
	printf("[prev - 0x%016x][size - 0x%016x][next - 0x%016x
][key - 0x%016x ] - Chunk 0x%016x - Freed\n",
		*(ptr-2),
		*(ptr-1),
		*ptr,
		*(ptr+1),
		(unsigned int)(ptr-2));
}
```

```
int main()
{
   size_t * ptr[LEN];
   unsigned int lengths[] = {32, 32, 32, 32, 32}; int i;

   printf("mallocing...\n");
   for(i = 0; i < LEN; i++)
      ptr[i] = malloc(lengths[i]);

   for(i = 0; i < LEN; i++)
      print_inuse_chunk(ptr[i]);

   printf("\nfreeing all chunks...\n");
   for(i = 0; i < LEN; i++)
      free(ptr[i]);

   for(i = 0; i < LEN; i++)
      print_freed_chunk(ptr[i]);

   return 0;}
```

```
→ software-security-course-binaries ./heapexploitation/tcache_smallbin_free_32
mallocing...
[prev - 0x0000000000000000][size - 0x0000000000000031][buffer (0x00000000571e95b0)] - Chunk 0x00000000571e95a8 - In use
[prev - 0x0000000000000000][size - 0x0000000000000031][buffer (0x00000000571e95e0)] - Chunk 0x00000000571e95d8 - In use
[prev - 0x0000000000000000][size - 0x0000000000000031][buffer (0x00000000571e9610)] - Chunk 0x00000000571e9608 - In use
[prev - 0x0000000000000000][size - 0x0000000000000031][buffer (0x00000000571e9640)] - Chunk 0x00000000571e9638 - In use
[prev - 0x0000000000000000][size - 0x0000000000000031][buffer (0x00000000571e9670)] - Chunk 0x00000000571e9668 - In use

freeing all chunks...
[prev - 0x0000000000000000][size - 0x0000000000000031][next - 0x0000000000000000 ][key - 0x00000000571e9010 ] - Chunk 0x00000000571e95a8 - Freed
[prev - 0x0000000000000000][size - 0x0000000000000031][next - 0x00000000571e95b0 ][key - 0x00000000571e9010 ] - Chunk 0x00000000571e95d8 - Freed
[prev - 0x0000000000000000][size - 0x0000000000000031][next - 0x00000000571e95e0 ][key - 0x00000000571e9010 ] - Chunk 0x00000000571e9608 - Freed
[prev - 0x0000000000000000][size - 0x0000000000000031][next - 0x00000000571e9610 ][key - 0x00000000571e9010 ] - Chunk 0x00000000571e9638 - Freed
[prev - 0x0000000000000000][size - 0x0000000000000031][next - 0x00000000571e9640 ][key - 0x00000000571e9010 ] - Chunk 0x00000000571e9668 - Freed
→ software-security-course-binaries ./heapexploitation/tcache_smallbin_free_64
mallocing...
[prev - 0x0000000000000000][size - 0x0000000000000031][buffer (0x00000000abcbc6b0)] - Chunk 0x00000000abcbc6a0 - In use
[prev - 0x0000000000000000][size - 0x0000000000000031][buffer (0x00000000abcbc6e0)] - Chunk 0x00000000abcbc6d0 - In use
[prev - 0x0000000000000000][size - 0x0000000000000031][buffer (0x00000000abcbc710)] - Chunk 0x00000000abcbc700 - In use
[prev - 0x0000000000000000][size - 0x0000000000000031][buffer (0x00000000abcbc740)] - Chunk 0x00000000abcbc730 - In use
[prev - 0x0000000000000000][size - 0x0000000000000031][buffer (0x00000000abcbc770)] - Chunk 0x00000000abcbc760 - In use

freeing all chunks...
[prev - 0x0000000000000000][size - 0x0000000000000031][next - 0x0000000000000000 ][key - 0x00000000abcbc010 ] - Chunk 0x00000000abcbc6a0 - Freed
[prev - 0x0000000000000000][size - 0x0000000000000031][next - 0x00000000abcbc6b0 ][key - 0x00000000abcbc010 ] - Chunk 0x00000000abcbc6d0 - Freed
[prev - 0x0000000000000000][size - 0x0000000000000031][next - 0x00000000abcbc6e0 ][key - 0x00000000abcbc010 ] - Chunk 0x00000000abcbc700 - Freed
[prev - 0x0000000000000000][size - 0x0000000000000031][next - 0x00000000abcbc710 ][key - 0x00000000abcbc010 ] - Chunk 0x00000000abcbc730 - Freed
[prev - 0x0000000000000000][size - 0x0000000000000031][next - 0x00000000abcbc740 ][key - 0x00000000abcbc010 ] - Chunk 0x00000000abcbc760 - Freed
```