COMP 737011 - Memory Safety and Programming Language Design

Lecture 2: Allocator Design

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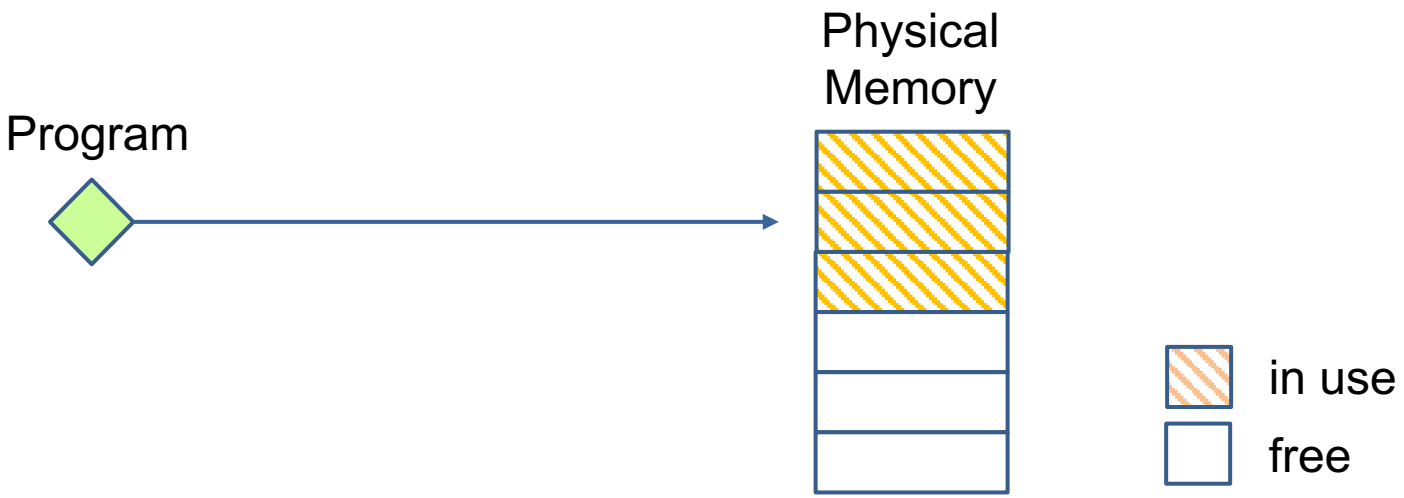
Outline

- 1. Memory Management Overview
- 2. Kernel Space Allocator
- 3. User Space Allocator

1. Memory Management Overview

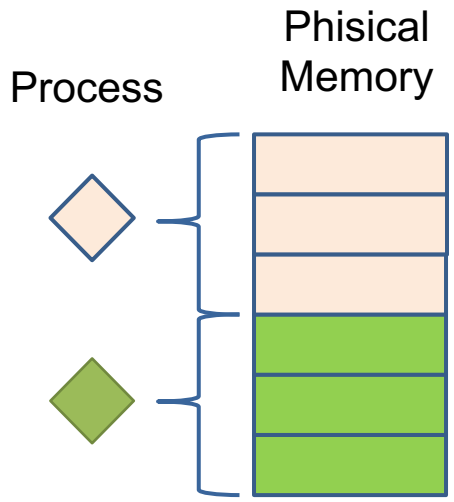
Memory Access

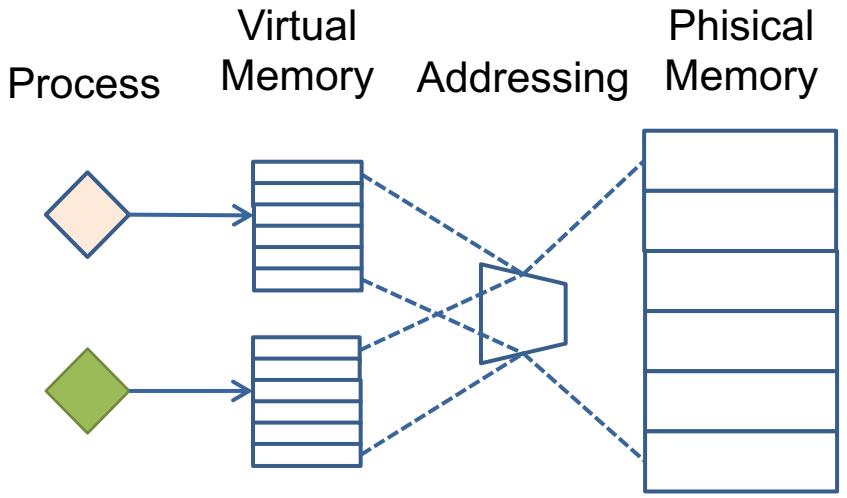
- Consider the scenarios: BIOS, embedded systems, OS kernel
- Access memory via physical addresses
  - Direct mapping: physical addr = virtual addr + offset
- How to manage allocated and freed memory blocks?
  - Buddy system



How to Support Multi-tasking OS?

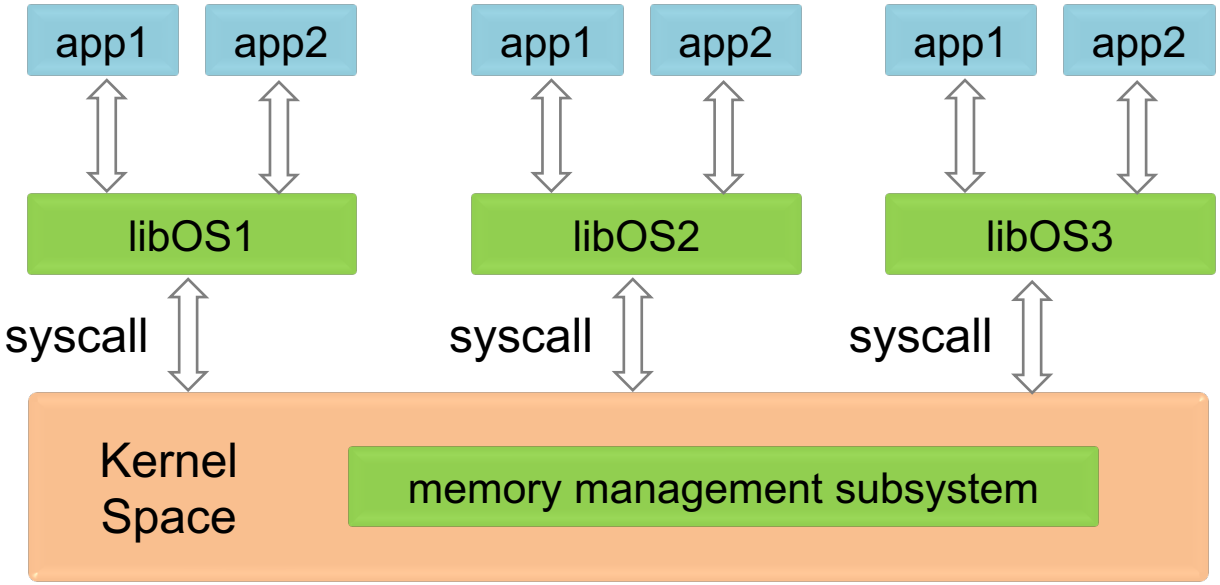
- All processes share the same memory space?
  - Each process uses an exclusive memory region
  - *e.g.,* unikernel or library OS
- Each process uses a distinct memory space
  - Virtual memory addressing
  - Both Linux and Windows use VM





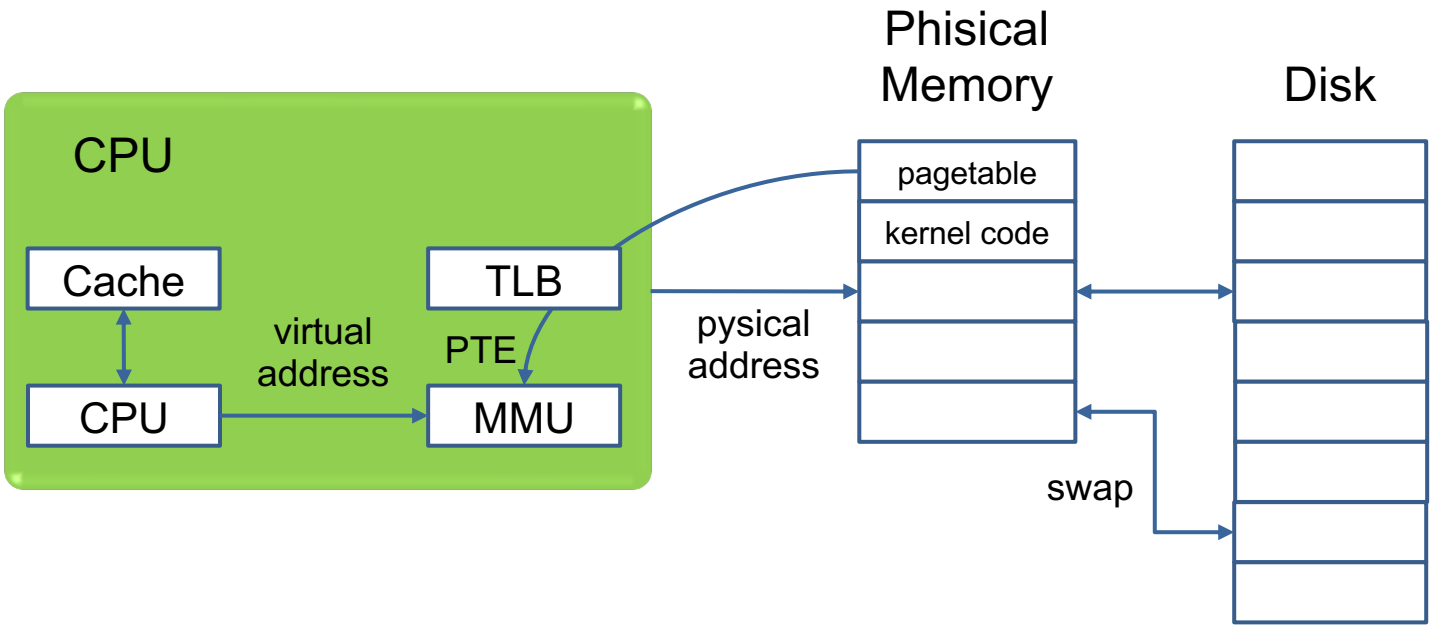
Unikernel

- Fault isolation for processes is difficult
  - Require instruction-level boudary checking
- Mainly used in embedded systems and libOSes
  - libOS: easy for code instrumentation and deployment



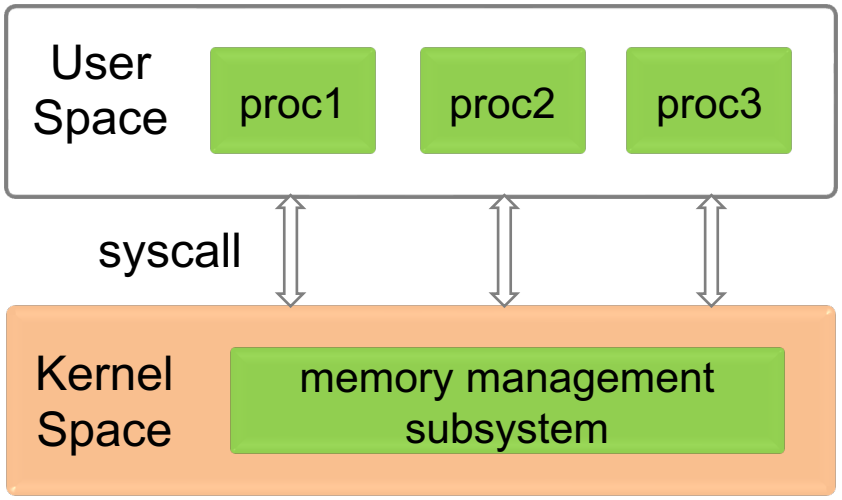
Virtual Memory Addressing

- MMU translates each virtual address to corresponding physical address by looking up the page table
- Cache page table entries with TLB
- Trigger page fault if the page is unavailable in DRAM



OS for VM

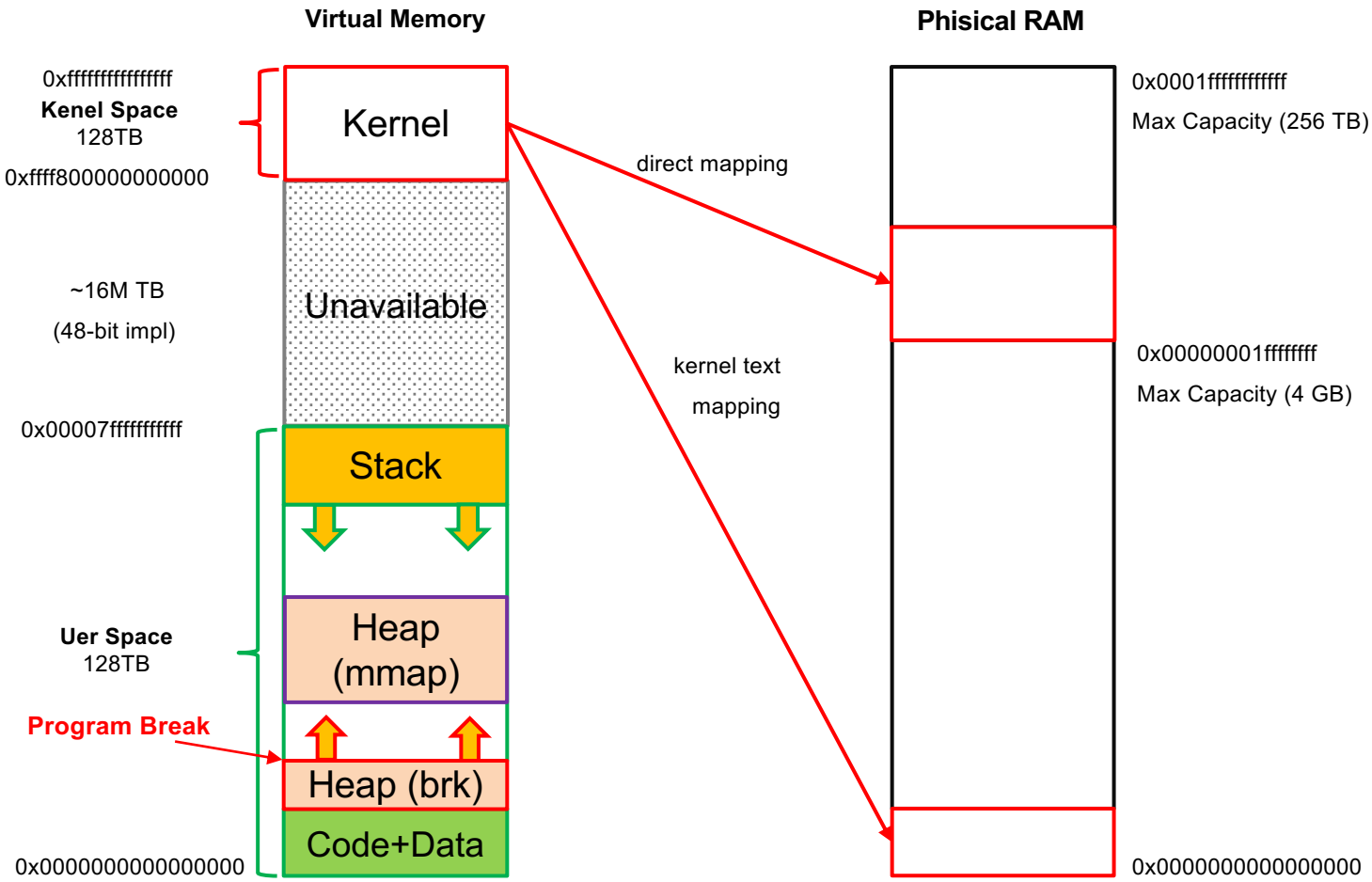
- Each process has a unique memory space
- Kernel responses for memory management
  - Map of memory space
  - Addressing
  - Handling page faults
- User space interacts with kernel via syscall



Memory Allocation in Linux

- Static allocation: code and static data
  - Compile-time constant
- Automatic allocation: stack
  - Each function has a stack frame
  - Multithreading program has multiple independent stacks
  - Compile-time constant
- Dynamic allocation: heap
  - More flexible

Virtual Address vs Phsical RAM



https://www.kernel.org/doc/Documentation/x86/x86_64/mm.txt

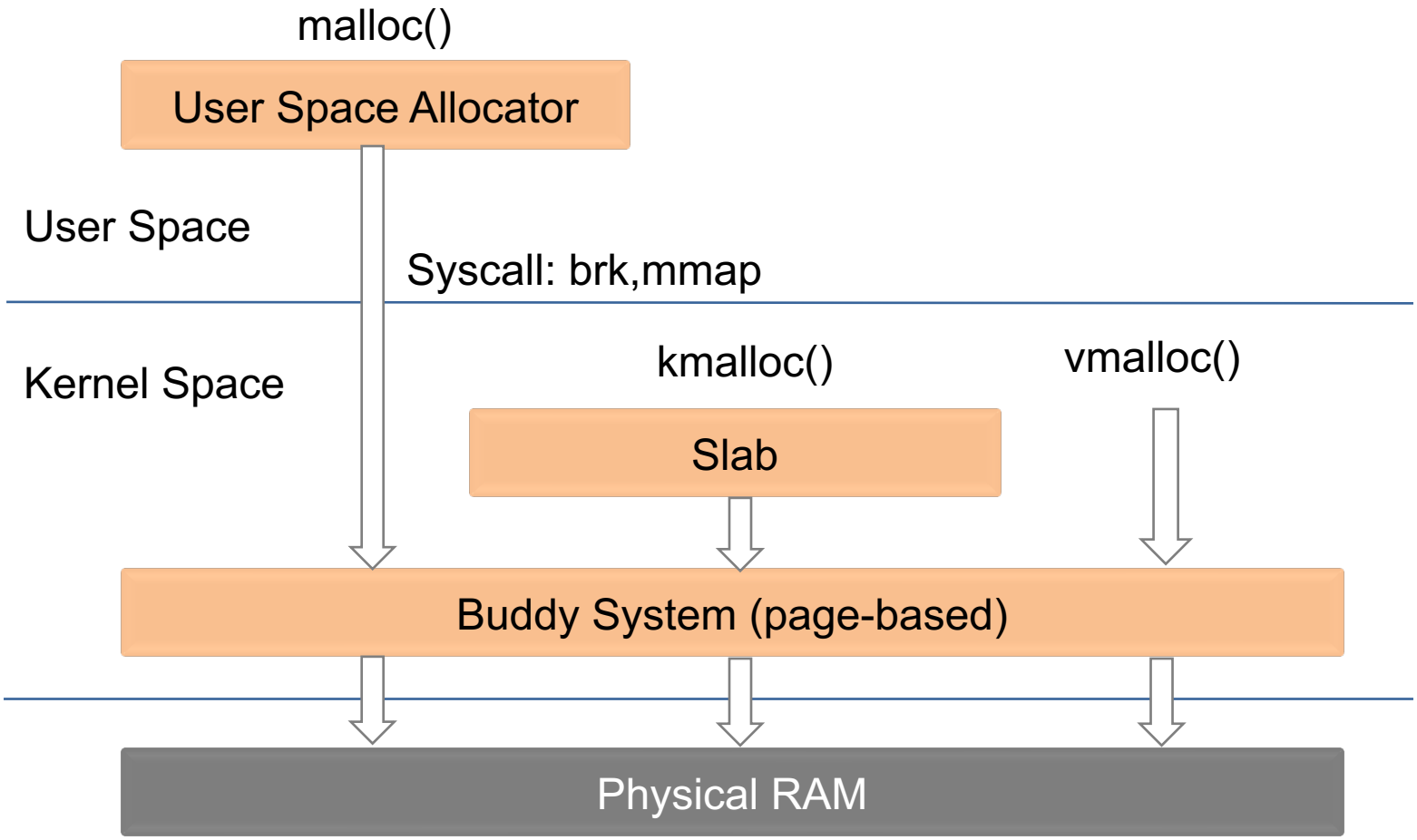
Demo: /proc/pid/maps

```
#: cat /proc/213694/maps
00400000-00401000 r--p 00000000 103:02 10223789                          ./hello
00401000-00402000 r-xp 00001000 103:02 10223789                          ./hello
00402000-00403000 r--p 00002000 103:02 10223789                          ./hello
00403000-00404000 r--p 00002000 103:02 10223789                          ./hello
00404000-00405000 rw-p 00003000 103:02 10223789                          ./hello
01b4f000-01b70000 rw-p 00000000 00:00 0                                  [heap]
7f6c23b29000-7f6c23b4b000 r--p 00000000 103:02 9963653                   libc-2.31.so
7f6c23b4b000-7f6c23cc3000 r-xp 00022000 103:02 9963653                   libc-2.31.so
7f6c23cc3000-7f6c23d11000 r--p 0019a000 103:02 9963653                   libc-2.31.so
7f6c23d11000-7f6c23d15000 r--p 001e7000 103:02 9963653                   libc-2.31.so
7f6c23d15000-7f6c23d17000 rw-p 001eb000 103:02 9963653                   libc-2.31.so
7f6c23d17000-7f6c23d1d000 rw-p 00000000 00:00 0
7f6c23d30000-7f6c23d31000 r--p 00000000 103:02 9963648                   ld-2.31.so
7f6c23d31000-7f6c23d54000 r-xp 00001000 103:02 9963648                   ld-2.31.so
7f6c23d54000-7f6c23d5c000 r--p 00024000 103:02 9963648                   ld-2.31.so
7f6c23d5d000-7f6c23d5e000 r--p 0002c000 103:02 9963648                   ld-2.31.so
7f6c23d5e000-7f6c23d5f000 rw-p 0002d000 103:02 9963648                   ld-2.31.so
7f6c23d5f000-7f6c23d60000 rw-p 00000000 00:00 0
7ffdf802d000-7ffdf804e000 rw-p 00000000 00:00 0                          [stack]
7ffdf80c7000-7ffdf80cb000 r--p 00000000 00:00 0                          [vvar]
7ffdf80cb000-7ffdf80cd000 r-xp 00000000 00:00 0                          [vdso]
ffffffffff600000-ffffffffff601000 --xp 00000000 00:00 0                  [vsyscall]
```

Demo: dmesg

```
#: dmesg
[    0.000000] BIOS-provided physical RAM map:
[    0.000000] BIOS-e820: [mem 0x0000000000000000-0x000000000009efff] usable
[    0.000000] BIOS-e820: [mem 0x000000000009f000-0x000000000000ffff] reserved
[    0.000000] BIOS-e820: [mem 0x0000000000100000-0x00000003ffffffff] usable
[    0.000000] BIOS-e820: [mem 0x0000000040000000-0x00000000403fffff] reserved
[    0.000000] BIOS-e820: [mem 0x0000000040400000-0x0000000062588fff] usable
[    0.000000] BIOS-e820: [mem 0x0000000062589000-0x0000000062589fff] ACPI NVS
[    0.000000] BIOS-e820: [mem 0x000000006258a000-0x000000006258afff] reserved
[    0.000000] BIOS-e820: [mem 0x000000006258b000-0x0000000076252fff] usable
[    0.000000] BIOS-e820: [mem 0x0000000076253000-0x000000007907cfff] reserved
[    0.000000] BIOS-e820: [mem 0x000000007907d000-0x00000000790f9fff] ACPI data
[    0.000000] BIOS-e820: [mem 0x00000000790fa000-0x00000000795d1fff] ACPI NVS
[    0.000000] BIOS-e820: [mem 0x00000000795d2000-0x000000007acfdfff] reserved
[    0.000000] BIOS-e820: [mem 0x000000007acfe000-0x000000007acfefff] usable
[    0.000000] BIOS-e820: [mem 0x000000007acff000-0x000000007f7fffff] reserved
[    0.000000] BIOS-e820: [mem 0x00000000f0000000-0x00000000f7ffffff] reserved
[    0.000000] BIOS-e820: [mem 0x00000000fe000000-0x00000000fe010fff] reserved
[    0.000000] BIOS-e820: [mem 0x00000000fec00000-0x00000000fec00fff] reserved
[    0.000000] BIOS-e820: [mem 0x00000000fee00000-0x00000000fee00fff] reserved
[    0.000000] BIOS-e820: [mem 0x00000000ff000000-0x00000000ffffffff] reserved
[    0.000000] BIOS-e820: [mem 0x0000000100000000-0x000000027c7fffff] usable
...
[    0.073219] Memory: 7783832K/8165312K available (16393K kernel code, 4373K
rwdata, 10784K rodata, 3228K init, 6580K bss, 381220K reserved, 0K cma-reserved)
```

Memory Management Framework



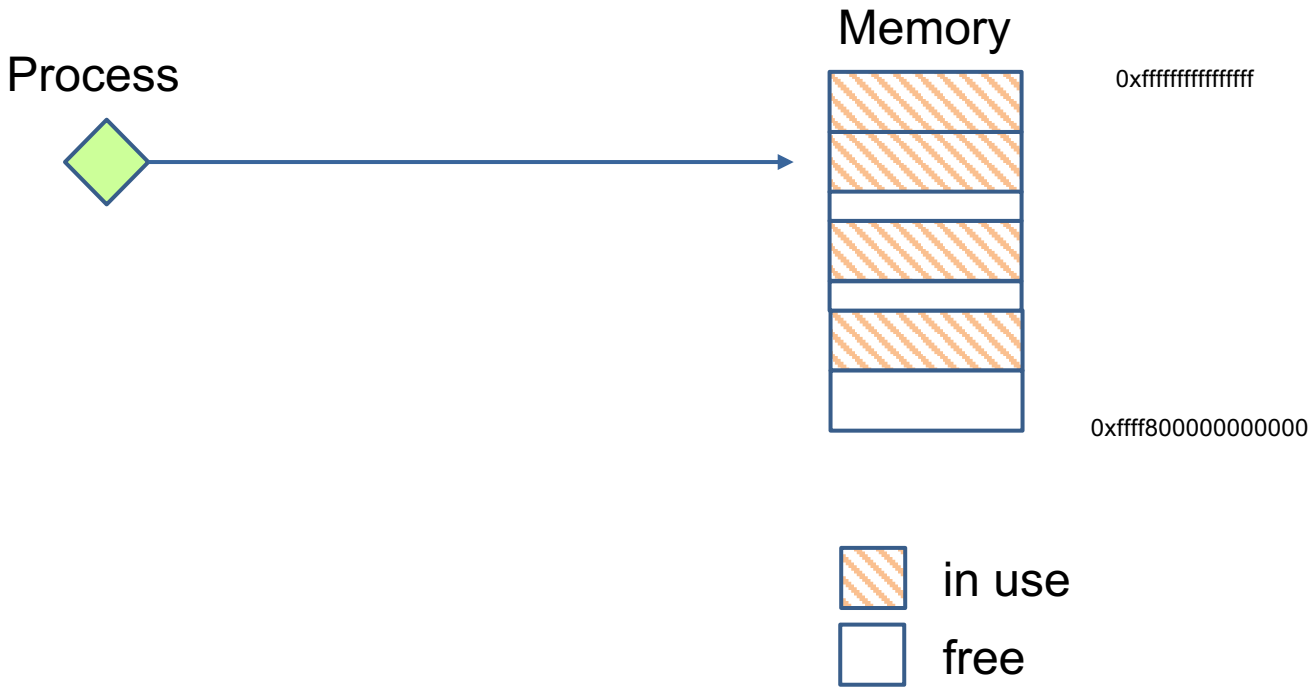
2. Kernel Space Allocator

Buddy Allocator

Slab

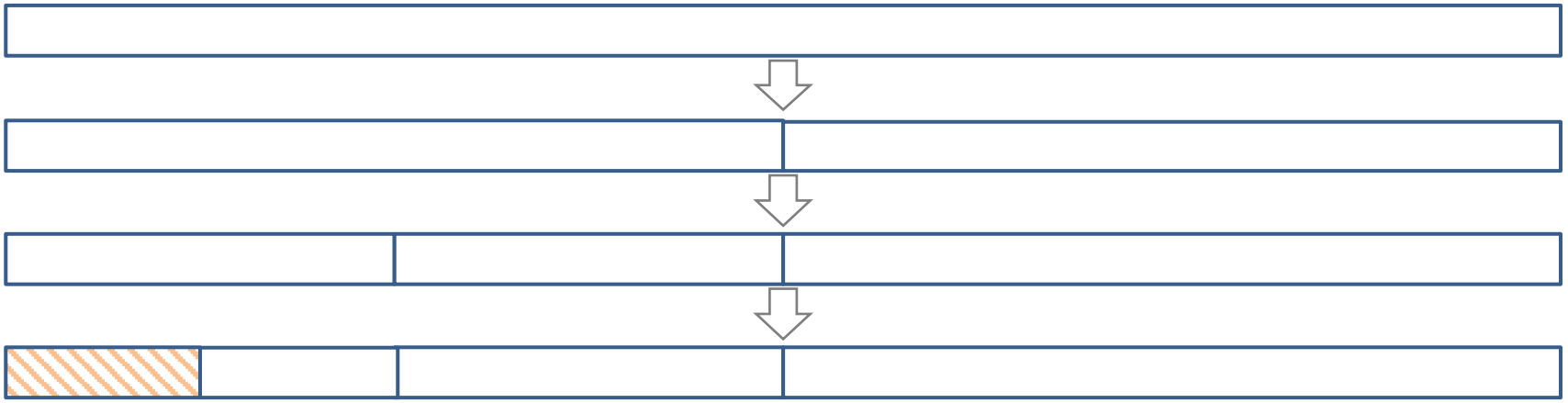
Problem Analysis

- How to manage allocated and freed memory blocks?
- Challenges:
  - May suffer fragementation issues;
  - Slowdown when colasing neighbor chunks.



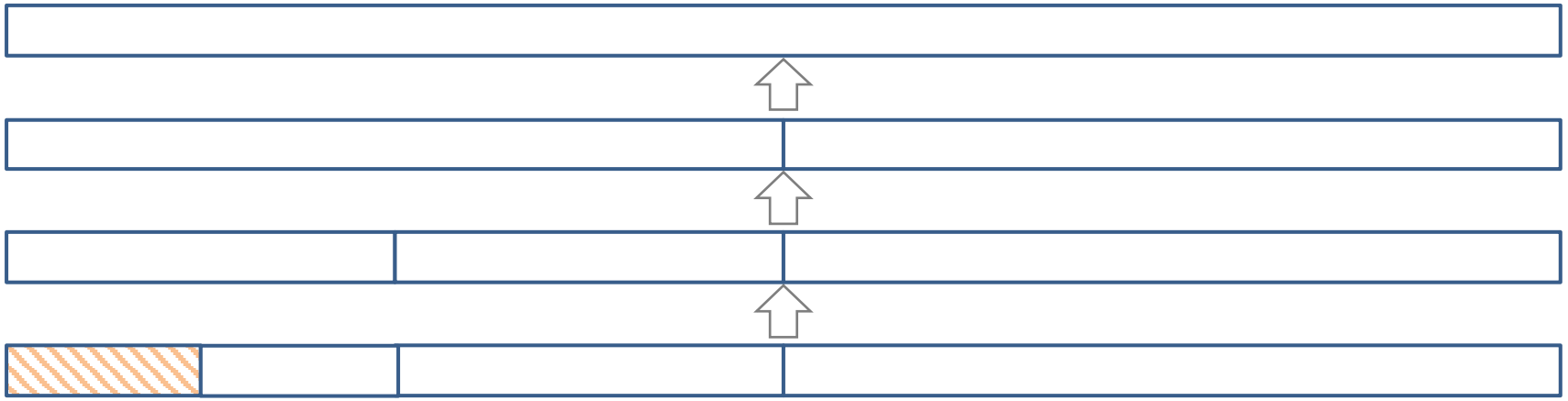
Buddy Algorithm

- Memory spaces are managed as blocks of pages.
  - Block size: 2^m pages
  - E.g., m = 10, block size = 1024 * 4K
- Supposing requesting k byte memory, $k < 2^{m-1}$
  - Segment the blocks n times until $k > 2^{m-n-1}$



Buddy Algorithm: Deallocation

- Repeatedly merge with adjacent blocks if they are free.
- Condition of merge:
  - The adjacent blocks are equal size.
  - The address after merging should always be aligned to the block size.



Buddy Structure

TAG (1 bit): allocated or free

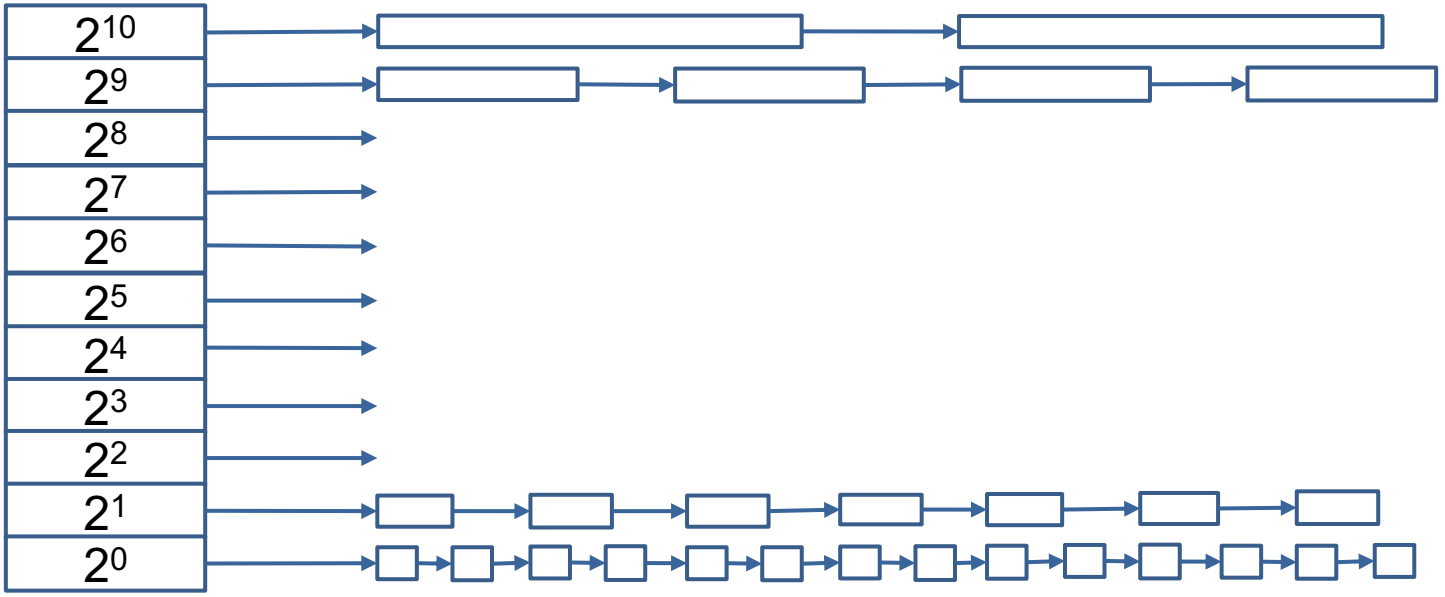
TYPE (2 bits):

- first bit: left or right buddy
- second bit: whether the parent is the left or right buddy

INDEX ($\log_2 n$ bits): size

Buddy Allocator：Free Lists

- Free blocks are managed as lists.
  - Each list maintains blocks of the same size.
    - Largest block: 2^{10} pages
    - Smallest block: 2^{0} pages
- Allocation: search from the list of the best fit
  - If the list is empty, try another list with larger blocks



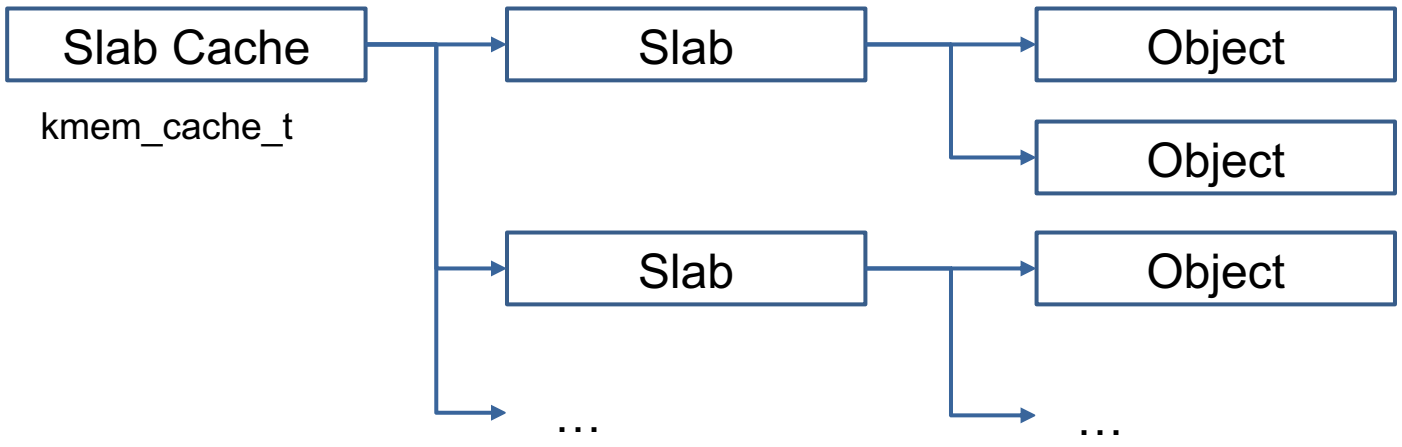
Demo: /proc/buddyinfo

```
#: cat /proc/buddyinfo
Node 0, zone      DMA      0    0    0    0    0    0    0    0    1    3
Node 0, zone    DMA32      9    6    7    6    9    5    7    7    6    5  445
Node 0, zone   Normal   1388  445  216   94   56   47   45   12    2    4  700
```

```
#: dmesg
[    0.016942] Faking a node at [mem 0x0000000000000000-0x000000027c7fffff]
[    0.016957] NODE_DATA(0) allocated [mem 0x27c7d6000-0x27c7fffff]
[    0.017361] Zone ranges:
[    0.017362]   DMA      [mem 0x0000000000001000-0x0000000000ffffff]
[    0.017366]   DMA32    [mem 0x0000000001000000-0x00000000ffffffff]
[    0.017369]   Normal   [mem 0x0000000100000000-0x000000027c7fffff]
[    0.017371]   Device   empty
```

Slab Allocation

- Byte-based allocation
- Reduce interactions with the buddy system
- Use cache to save the initialization cost of frequently used data structures (e.g., task_struct, inodes)



Demo: /proc/slabinfo

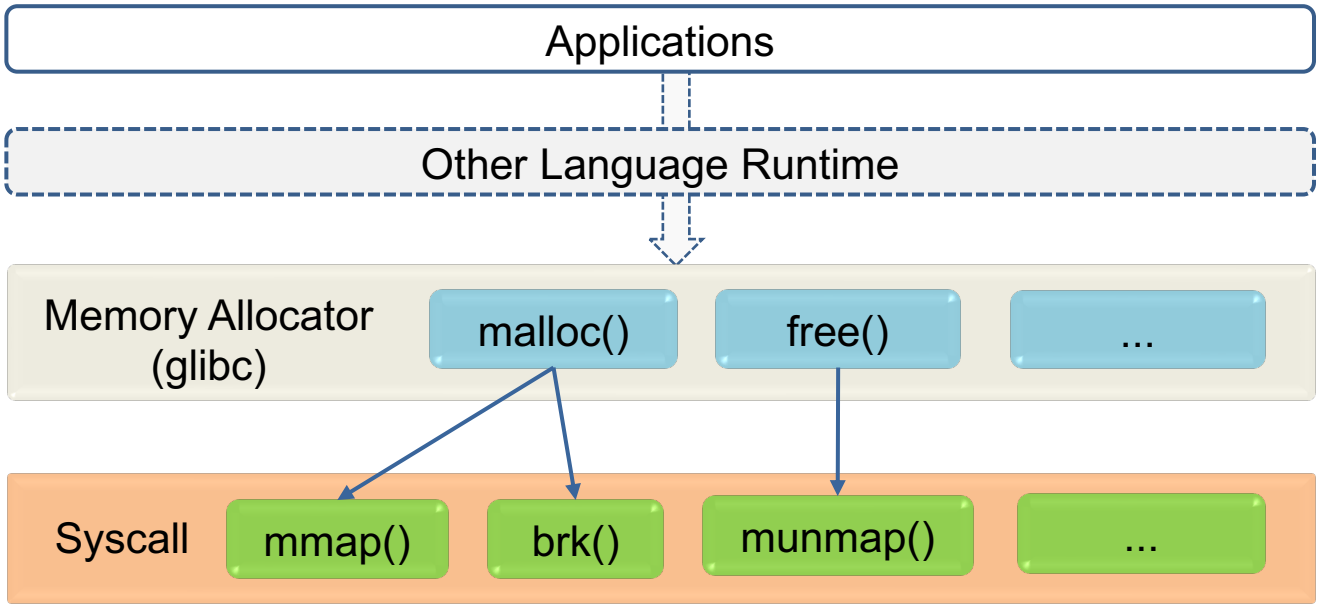
```
#: cat /proc/slabinfo
# name            <active_objs> <num_objs> <objsize> <objperslab> <pagesperslab> : tunables <limit> <batchcount>
<sharedfactor> : slabdata <active_slabs> <num_slabs> <sharedavail>

nf_conntrack        1000   1075    320   25    2 : tunables    0    0    0 : slabdata     43     43      0
au_vdir                0      0    128   32    1 : tunables    0    0    0 : slabdata      0      0      0
au_finfo               0      0    192   21    1 : tunables    0    0    0 : slabdata      0      0      0
au_icntnr              0      0    832   39    8 : tunables    0    0    0 : slabdata      0      0      0
au_dinfo               0      0    192   21    1 : tunables    0    0    0 : slabdata      0      0      0
ovl_inode             44     44    720   22    4 : tunables    0    0    0 : slabdata      2      2      0
...
```

3. User Space Allocator

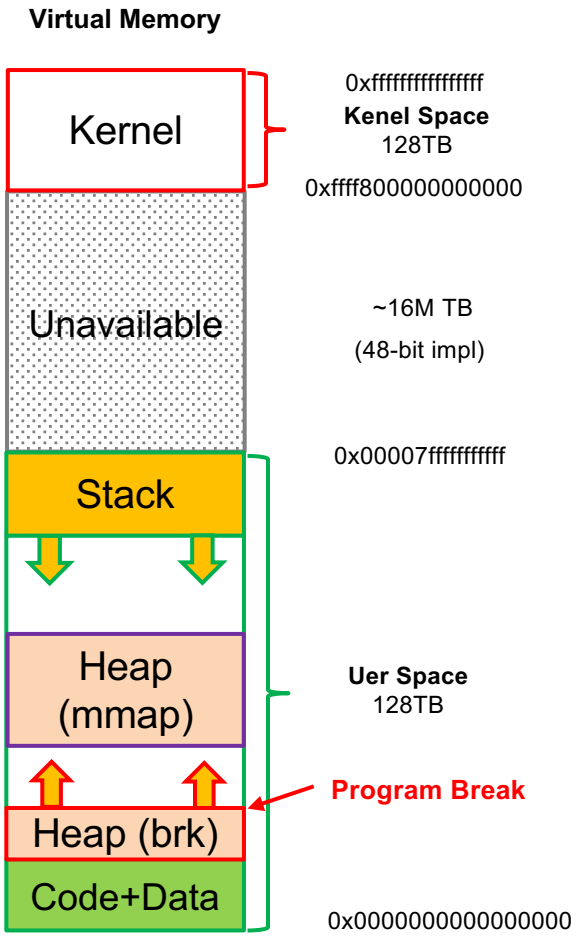
User Space Allocation APIs

- Memory allocator provides user-friendly APIs
  - e.g., malloc() and free() in glibc APIs
- Memory allocator invokes syscalls for achieving memory allocation.
  - e.g., brk() and mmap() in Linux



Heap Management in Linux

- Program break
  - Linux syscall brk()
  - For small-size memory trunks
  - Increase the brk pointer for memory allocation
  - Continuous address space
- Memory mapping:
  - Linux syscall mmap()
  - For file mapping and memory of large size (usually 256 KB)
  - Freed via munmap()



brk()/sbrk()/mmap()

```
int brk(void* end_data_segment); //Linux syscall
//change brk pointer to the specified addr value

void *sbrk(intptr_t increment); //a library API in Linux
//increase the brk pointer according to the increment

void *mmap(void *addr, // starting address
           size_t length, // byte
           int prot, // memory protection: read/write/exec
           int flags, // visibility: shared or private
           int fd, // file descriptor
           off_t offset); // offset of the file

int munmap(void *addr, size_t length);
```

https://man7.org/linux/man-pages/man2/brk.2.html
https://man7.org/linux/man-pages/man2/mmap.2.html
https://man7.org/linux/man-pages/man2/syscalls.2.html

glibc APIs for Heap Management

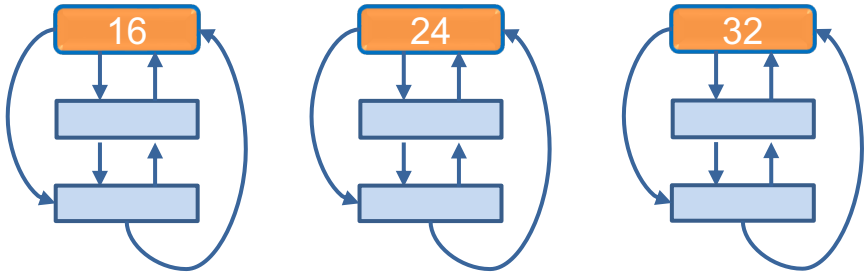
- malloc(size_t n)
  - Allocate a new memory space of size n
  - The memory is not cleared
  - Return the address pointer
- free(void * p)
  - Release the memory space pointed by p
  - Do not return to the system directly (for brk)
  - What would happen if p is null or already freed?
- calloc(size_t nmemb, size_t size)
  - Allocate an array of nmemb * size byte
  - The memory is set to zero
- realloc(void *p, size_t size)
  - Resize the memory block pointed by p to size bytes

Design Challanges for Allocator

- Each syscall costs nearly a hundred CPU cycles
  - =>An allocator should not frequently invoke syscalls
- Heap data are not compact
  - =>Decreasing brk pointer for free is almost impossible
- How to manage and reuse freed memory chunks?

Basic Idea: Doug Lea's Allocator (dlmalloc)

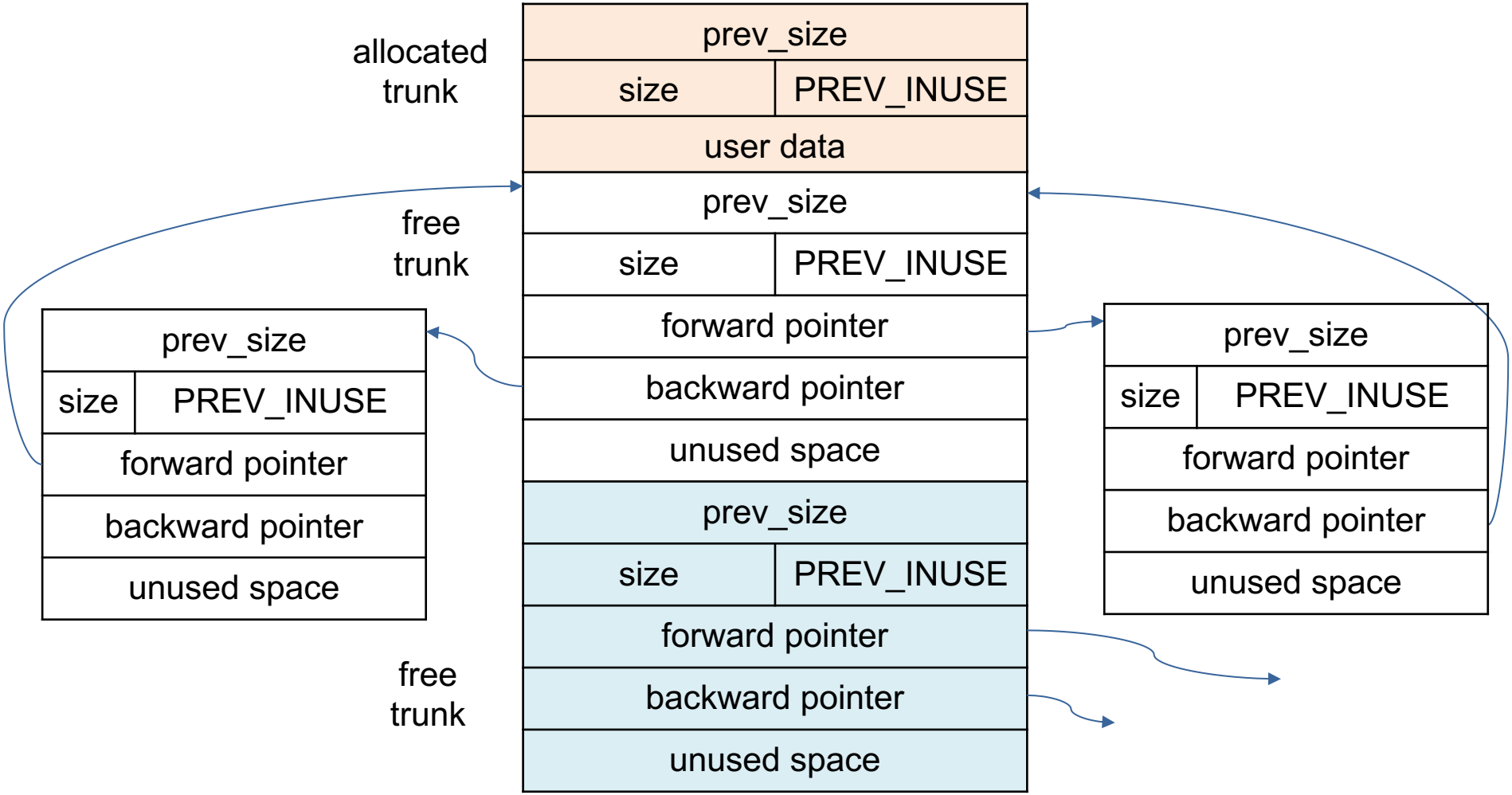
- Freed memory chunks are managed as bins
  - Each bin is a double-lined list of freed chunks of “fixed” size
  - How to determine the size of each bin?
    - Bins for sizes < 512 bytes are spaced 8 bytes apart
    - Larger bins are approximately logarithmically spaced
- malloc() finds the corresponding bin for allocation
  - index is computed by logical shift
  - first-in-first-out



https://github.com/ennorehling/dlmalloc/blob/master/malloc.c

Structure of Chunks: Boundary Tag

- Sizes information is stored both in the front of each chunk
- To facilitate consolidating fragmented chunks



Fastbins and Unsorted Bins

- Design consideration for consolidation is expensive
- Fastbins: light-weight bins in single-linked list
  - cannot be coalesced with adjacent chunks automatically
- Unsorted bins: free chunks are first put into unsorted bins before adding to lists

	list	**coalesce**	**data**
Fast bin	single-linked	no	small
Regular bin	double-linked	may	could be large

https://github.com/ennorehling/dlmalloc/blob/master/malloc.c

More Allocators

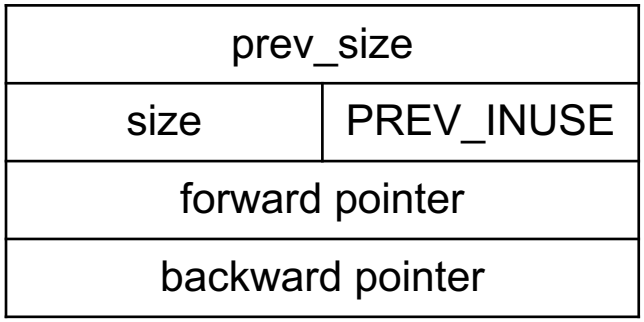
- ptmalloc (pthreads malloc): used in glibc
  - a fork of dlmalloc with threading-related improvements
  - https://sourceware.org/glibc/wiki/MallocInternals
- tcmalloc (thread-caching malloc) by Google
  - https://google.github.io/tcmalloc/
- jemalloc
  - http://jemalloc.net/

Coding Practice: A Toy Allocator

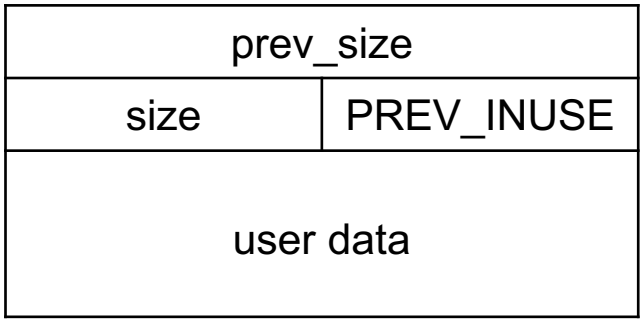
Practice

- Write a user space allocator based on a code template.
- The template contains one free list.

```
struct chunk{
    unsigned long prev_size;
    unsigned long size; //use the last bit for prev_inuse
    struct chunk* fd;
    struct chunk* bk;
};
```



structure of a free trunk



structure of an allocated trunk

Tasks

- We have initialized the list with a trunk of 320 bytes memory

```
void *p0 = sbrk(0);
brk(p0 + 320);
ty_chunk_ptr p = (ty_chunk_ptr) p0;
p->size = (unsigned long) 320 | PREV_INUSE;
head = p;
p->bk = NULL;
p->fd = NULL;
```

- Implement the malloc_new() and free() function
  - malloc_new(): find a trunk in the list for allocation:
    - trunk size > required size => split it into two chunks
  - free_new(): add the trunk back to the list
    - do consolidations if possible

```
void *malloc_new(unsigned long n);
void free_new(void *p);
```

Check The Correctness of Your Program

```
void *x1 = malloc_new(8);
void *x2 = malloc_new(16);
...//more malloc
free_new(x1);
free_new(x2);
... //more free
ty_chunk_ptr p = head;
printf("usable:%ld, occupied:%ld\n", p->size-17, p->size);
while(p->fd!=NULL){
    p = p->fd;
    printf("usable:%ld, occupied:%ld\n", p->size-17, p->size);
}
```