Operating Systems

Memory Allocators

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In this episode

We will see two types of allocators that can be used to manage a buffer of memory

They are extensively used within the kernel of the operating system, to manage the small objects required to implement data structures

Issues in managing memory

- fragmentation:

  when we would have enough memory to satisfy a request, but the scattered allocations in the buffer make it impossible to find a contiguous chunk that is large enough

- time:

  how long do i need to wait to get/release a memory block?

To manage memory we have to waste a little (for storing structures describing the memory layout)

SLAB allocator

Use it when

- you have a bunch of objects of fixed size (item_size)
- you know how many of these objects you can have (in the worst case)

A slab allocator divides the a memory in chunks of size item_size.

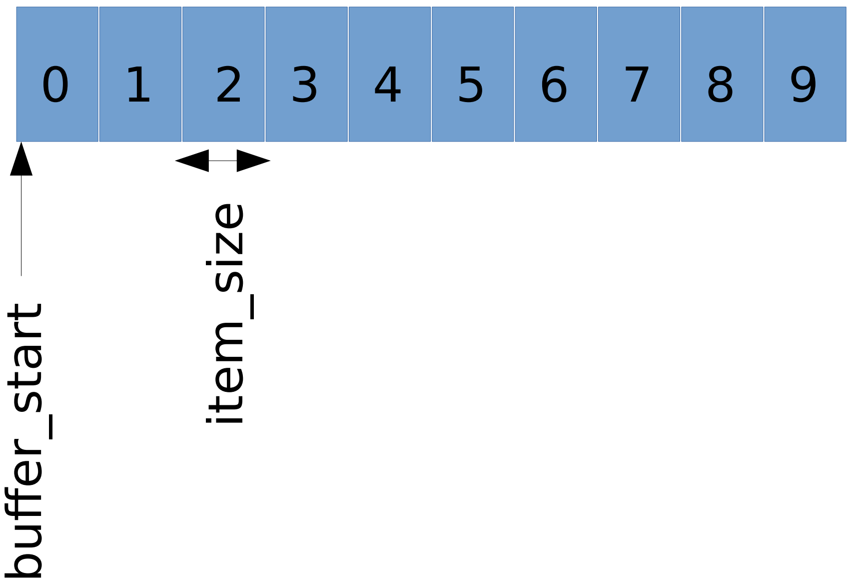
- If the memory starts at address buffer_start, the address of the idx block is

  ptr_block=buffer_start+idx *item_size

- If i know an address how to get the index? (1st order equation: resolve the above by idx)

  idx=(ptr_block-buffer_start)/item_size

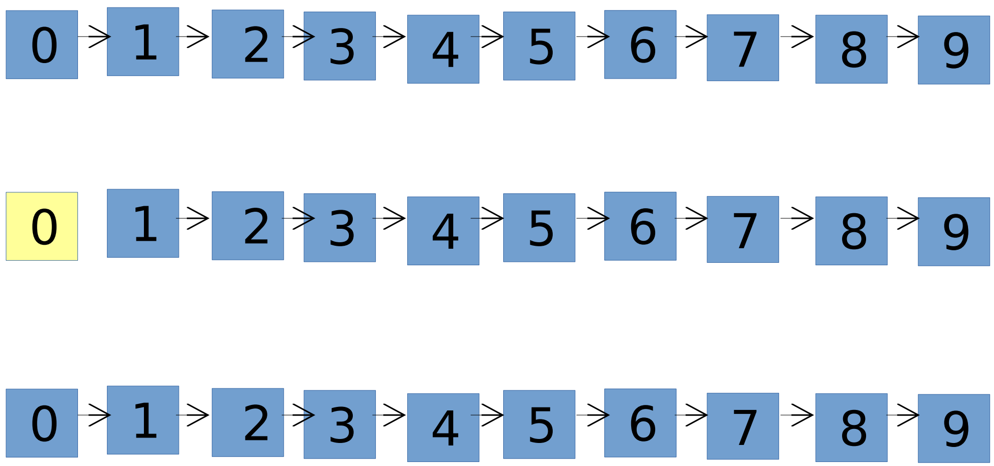
  Not all addresses are good, only those aligned with the item size boundaries



SLAB aux structures

We can have a SLAB allocator capable of satisfying the requests in O(1) by just keeping a list of structures representing free blocks

- At the beginning the list is populated with all blocks
- When a request comes, we return the block at the beginning of the list, and we remove it from the list
- When a block is deleted, we create the corresponding item and we put it back in the list.

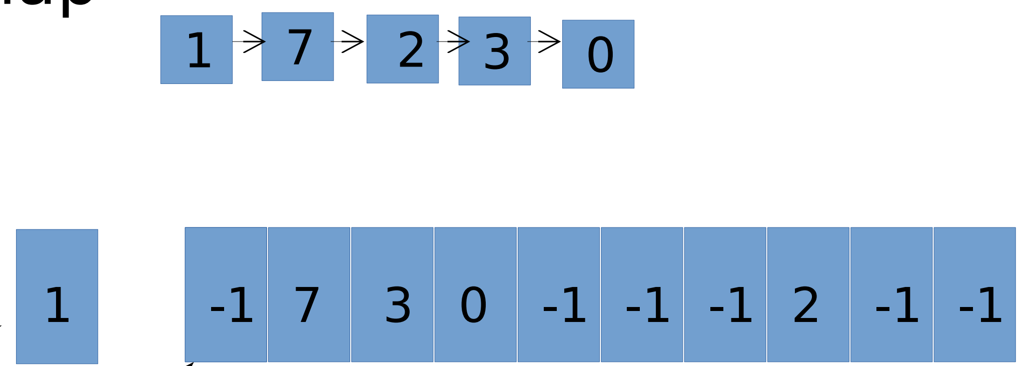


Issues:

- To implement a SLAB we need a list.
- To implement a list we need some sort of malloc
- how do we do without malloc?

Array Lists

If we know the maximum size of an list, we can map a list on an array of max_size elements.



We need

- a start position

  int start_pos;

- an array of int

  int array_list[max_size];

- The cell at position i stores
  - the index of the successor element
  - -1 if not in the list, or null

SLAB interface

To manage a memory with a slab we need

- N_max*item_size elements
- an array list of size N_max

```
typedef enum {
  Success=0x0,
  NotEnoughMemory=-1,
  UnalignedFree=-2,
  OutOfRange=-3,
  DoubleFree=-4
} PoolAllocatorResult;

typedef struct PoolAllocator{

  //contiguous buffer managed by the system
  char* buffer;
  //list of linked objects
  int*  free_list;
  //size of the buffer in bytes
  int buffer_size;

  //number of free blocks
  int size;
  //maximum number of blocks
  int size_max;
  //size of a block
  int item_size;
  //pointer to the first bucket
  int first_idx;
  // size of a bucket
  int bucket_size;
} PoolAllocator;
```

SLAB interface

To initialize a SLAB, we need to provide an external memory buffer

The buffer should have enough room to hold the enough elements and the array list.

Once initialized we can request a block to the slab, or return an already allocated block.

```
PoolAllocatorResult
  PoolAllocator_init(PoolAllocator* allocator,
                     int item_size,
                     int num_items,
                     char* memory_block,
                     int memory_size);

void* PoolAllocator_getBlock(
      PoolAllocator* allocator);

PoolAllocatorResult
      PoolAllocator_releaseBlock(
       PoolAllocator* allocator,
       void* block);

// helper function that returns a string
// from an error message
const char* PoolAllocator_strerror
           (PoolAllocatorResult result);
```

SLAB testing

```
// object size=4K
# define item_size 4096

// 16 blocks
#define num_items 16

// buffer should contain also bookkeeping information
#define buffer_size num_items*(item_size+sizeof(int))

// we allocate buffer in .bss
char buffer[buffer_size];

PoolAllocator allocator;

int main(int argc, char** argv) {
  printf("initializing... ");
  PoolAllocatorResult init_result=PoolAllocator_init(&allocator,
                                  item_size,
                                  num_items,
                                  buffer,
                                  buffer_size);
  printf("%s\n",PoolAllocator_strerror(init_result));

  // we allocate_all memory, and a bit more

  void* blocks[num_items+10];
  for (int i=0; i<num_items+10; ++i){
    void* block=PoolAllocator_getBlock(&allocator);
    blocks[i]=block;
    printf("allocation %d, block %p, size%d\n", i, block, allocator.size);
  }
```

SLAB testing

```
// we release all memory
for (int i=0; i<num_items+10; ++i){
  void* block=blocks[i];
  if (block){
    printf("releasing... idx: %d, block %p, free %d ... ",
        i, block, allocator.size);
    PoolAllocatorResult release_result=PoolAllocator_releaseBlock(&allocator, block);
    printf("%s\n", PoolAllocator_strerror(release_result));
  }
}

// we release all memory again (should get a bunch of errors)
for (int i=0; i<num_items+10; ++i){
  void* block=blocks[i];
  if (block){
    printf("releasing... idx: %d, block %p, free %d ... ",
        i, block, allocator.size);
    PoolAllocatorResult release_result=PoolAllocator_releaseBlock(&allocator, block);
    printf("%s\n", PoolAllocator_strerror(release_result));
  }
}

// we allocate half of the memory, and release it in reverse order
for (int i=0; i<num_items-5; ++i){
  void* block=PoolAllocator_getBlock(&allocator);
  blocks[i]=block;
  printf("allocation %d, block %p, size%d\n", i, block, allocator.size);
}
```

SLAB testing

```
  for (int i=num_items-1; i>=0; --i){
  void* block=blocks[i];
  if (block){
    printf("releasing... idx: %d, block %p, free %d ... ",
        i, block, allocator.size);
    PoolAllocatorResult release_result=PoolAllocator_releaseBlock(&allocator, block);
    printf("%s\n", PoolAllocator_strerror(release_result));
  }
}

// we allocate all  memory,
// and release only even blocks, in reverse order
// release odd blocks in reverse order
for (int i=0; i<num_items; ++i){
  void* block=PoolAllocator_getBlock(&allocator);
  blocks[i]=block;
  printf("allocation %d, block %p, size%d\n", i, block, allocator.size);
}

for (int i=num_items-1; i>=0; i-=2){
  void* block=blocks[i];
  if (block){
    printf("releasing... idx: %d, block %p, free %d ... ",
        i, block, allocator.size);
    PoolAllocatorResult release_result=PoolAllocator_releaseBlock(&allocator, block);
    printf("%s\n", PoolAllocator_strerror(release_result));
  }
}
```

SLAB testing

```
  for (int i=num_items-1; i>=0; --i){
    void* block=blocks[i];
    if (block){
      printf("releasing... idx: %d, block %p, free %d ... ",
          i, block, allocator.size);
      PoolAllocatorResult release_result=PoolAllocator_releaseBlock(&allocator, block);
      printf("%s\n", PoolAllocator_strerror(release_result));
    }
  }

  // we allocate all  memory,and release only even blocks, in reverse order
  // release odd blocks in reverse order
  for (int i=0; i<num_items; ++i){
    void* block=PoolAllocator_getBlock(&allocator);
    blocks[i]=block;
    printf("allocation %d, block %p, size%d\n", i, block, allocator.size);
  }
  for (int i=num_items-1; i>=0; i-=2){
    void* block=blocks[i];
    if (block){
      printf("releasing... idx: %d, block %p, free %d ... ",
          i, block, allocator.size);
      PoolAllocatorResult release_result=PoolAllocator_releaseBlock(&allocator, block);
      printf("%s\n", PoolAllocator_strerror(release_result));
    }
  }
  for (int i=num_items-2; i>=0; i-=2){
    void* block=blocks[i];
    if (block){
      printf("releasing... idx: %d, block %p, free %d ... ",
          i, block, allocator.size);
      PoolAllocatorResult release_result=PoolAllocator_releaseBlock(&allocator, block);
      printf("%s\n", PoolAllocator_strerror(release_result));
    }
  }
```

Take home message

BE EVIL WHEN TESTING

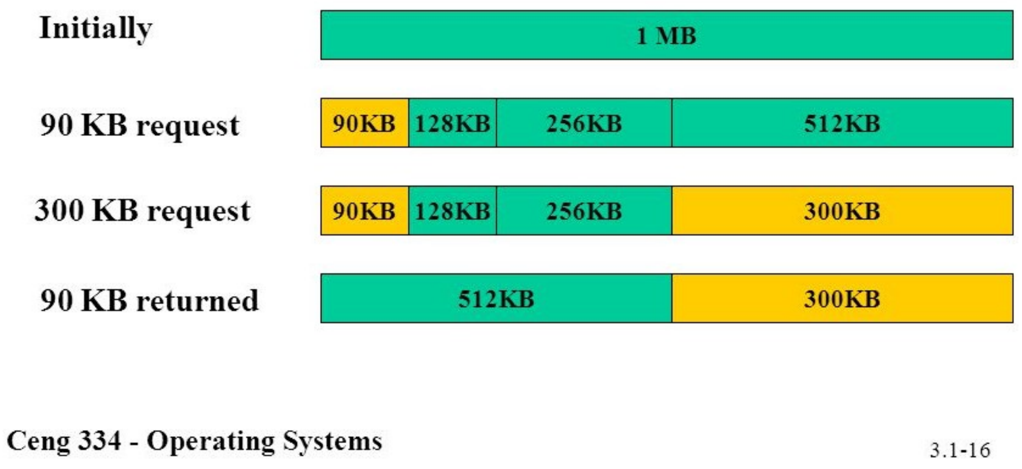
Buddy Allocator

When we have objects of arbitrary size

We recursively partition the memory in two, a maximum number of times.

A "buddy" of a memory block is the other region that is obtained by partitioning the "parent" region

Allocating a block that is smaller than the smaller partition, wastes memory



Funny Binary Trees

Enumerating the nodes of a binary tree has some funny properties:

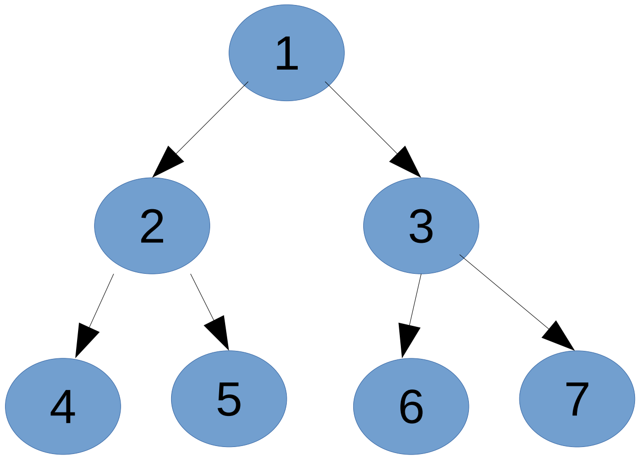
- level of node i
  - **`level(idx)=floor(log2(idx));`**
- idx of 1st node of a level i

  `firstIdx(i)=1<<i;` /*{2^i}*/
- offset of node idx in his level

  `idx-firstIdx(level(idx))`
- index of the buddy of node i

  `buddyIdx(idx)=(i%2)?idx-1:idx+1`;
- parent of the node idx

  `parentIdx(idx)=floor(idx/2)`;
- each possible allocation in our system can be given an index in a binary tree
- from this index we can recover useful information, without storing anything else




```
int levelIdx(size_t idx){
  return (int)floor(log2(idx));
};

int buddyIdx(int idx){
  if (idx&0x1){
    return idx-1;
  }
  return idx+1;
}

int parentIdx(int idx){
  return idx/2;
}

int startIdx(int idx){
  return (idx-(1<<levelIdx(idx)));
}
```

Buddy Allocator

A block of memory is associated with a BuddyListItem, that stores also the tree structure.

In the allocator, we keep free lists for each level of the buddy system.

We use a SLAB allocator to manage the lists

What is the maximum capacity of the SLAB?

```
typedef struct BuddyListItem {
  ListItem list;
  int idx;   // tree index
  int level; // level for the buddy
  char* start; // start of memory
  int size;
  struct BuddyListItem* buddy_ptr;
  struct BuddyListItem* parent_ptr;
} BuddyListItem;


typedef struct  {
  ListHead free[MAX_LEVELS];
  ListHead occupied[MAX_LEVELS];
  int num_levels;
  PoolAllocator list_allocator;
  the memory area to be managed
  char* memory; //
  // the minimum page of RAM that can be returned
  int min_bucket_size;
} BuddyAllocator;
```

Buddy Allocator

We store each level in a list of "free blocks"

When memory is requested:

- the size+8 is rounded up to the size of the smallest partition capable to contain it
- if the partition is in the free list of that level, we return the partition and we remove from the free list
- if a partition at that level is not available, we ask for a partition to the higher level and we split in two (recursively) the region returned, populating the free list accordingly

```
//allocates memory
void* BuddyAllocator_malloc(BuddyAllocator* alloc,
                            int size) {
  // calculate max mem
  int mem_size=
    (1<<alloc->num_levels)*alloc->min_bucket_size;

  //calculate level for page
  int  level=floor(log2(mem_size/(size+8)));

  // if the level is too small, we pad it to max
  if (level>alloc->num_levels)
    level=alloc->num_levels;

  printf("requested: %d bytes, level %d \n",
         size, level);

  // we get a buddy of that size;
  BuddyListItem* buddy=
    BuddyAllocator_getBuddy(alloc, level);
  if (! buddy)
    return 0;

  // we write in the memory
    region managed the buddy address
  BuddyListItem** target=
    (BuddyListItem**)(buddy->start);
  *target=buddy;
  return buddy->start+8;
}
```

note that we return the start address+8

Buddy Allocator

We store each level in a list of "free blocks"

When memory is requested:

- the size is rounded up to the size of the smallest partition capable to contain it
- if the partition is in the free list of that level, we return the partition and we remove from the free list
- if a partition at that level is not available, we ask for a partition to the higher level and we split in two (recursively) the region returned, populating the free list accordingly

```
BuddyListItem* BuddyAllocator_getBuddy(
      BuddyAllocator* alloc, int level){
  if (level<0)
    return 0;
  if (! alloc->free[level].size ) {
    // no buddies on this level
    BuddyListItem* parent_ptr=
      BuddyAllocator_getBuddy(alloc, level-1);
    if (! parent_ptr)
      return 0;

    // parent already detached from free list
    int left_idx=parent_ptr->idx<<1;
    int right_idx=left_idx+1;

    BuddyListItem* left_ptr=
     BuddyAllocator_createListItem(alloc,
                                   left_idx,
                                   parent_ptr);
    BuddyListItem* right_ptr=
      BuddyAllocator_createListItem(alloc,
                                   right_idx,
                                   parent_ptr);
    // we need to update the buddy ptrs
    left_ptr->buddy_ptr=right_ptr;
    right_ptr->buddy_ptr=left_ptr;
  }
  // we detach the first
  if(alloc->free[level].size) {
    BuddyListItem* item=
     (BuddyListItem*)
     List_popFront(alloc->free+level);
    return item;
  }
  return 0;
}
```

Buddy Allocator

When memory is released we

- identify the "region" that was associated to the released block (see how in the next slide)
- if the buddy of the region is **not** in the free list of the level, we add the element to the list and we terminate
- if the buddy is in the free list, we
  - merge the two buddies, by deleting them from the free list
  - we insert a new entry in the upper level, corresponding to the merged elements (recursively)

This mechanism is capable to handle a certain level of fragmentation

The max operations are O(levels)

```
void BuddyAllocator_releaseBuddy(
              BuddyAllocator* alloc,
              BuddyListItem* item){

  BuddyListItem* parent_ptr=item->parent_ptr;
  BuddyListItem *buddy_ptr=item->buddy_ptr;

  // buddy back in the free list of its level
  List_pushFront(&alloc->free[item->level],
               (ListItem*)item);

  // if on top of the chain, do nothing
  if (! parent_ptr)
    return;

  // if the buddy of this item is not free,
  // we do nothing
  if (buddy_ptr->list.prev==0 &&
     buddy_ptr->list.next==0)
    return;

  //join
  //1. we destroy the two buddies in the free list;
  printf("merge %d\n", item->level);
  BuddyAllocator_destroyListItem(alloc, item);
  BuddyAllocator_destroyListItem(alloc, buddy_ptr);
  //2. we release the parent
  BuddyAllocator_releaseBuddy(alloc, parent_ptr);

}
```

Buddy Allocator

How to determine the buddy of a memory area when it is freed?

- Option 1:

  We seek for a list item whose "start" field address matches with the returned region (slow)

- Option 2:
  - We "store" the address of the list item (that is in a "detached" status, in the first bytes of the memory partition.
  - the returned memory address will be

    beginning_of_region+address_size
  - We can retrieve the address of the list element by decrementing the address of <address_size> bytes

```
//releases allocated memory
void BuddyAllocator_free(BuddyAllocator* alloc,
                         void* mem) {
  printf("freeing %p", mem);
  // we retrieve the buddy from the system
  char* p=(char*) mem;
  p=p-8;
  BuddyListItem** buddy_ptr=(BuddyListItem**)p;
  BuddyListItem* buddy=*buddy_ptr;
  //printf("level %d", buddy->level);
  // sanity check;
  assert(buddy->start==p);
  BuddyAllocator_releaseBuddy(alloc, buddy);

}
```

Buddy Allocator Interface

- The interface is similar to the pool allocator
- need to pass two buffers:
  - one for the internal pool allocator that stores the list
  - one for the managed memory
  - the smallest leaf of the buddy
- no need to specify the block size

```
// initializes the buddy allocator,
   and checks that the buffer is large enough
void BuddyAllocator_init(BuddyAllocator* alloc,
                         int num_levels,
                         char* buffer,
                         int buffer_size,
                         char* memory,
                         int min_bucket_size);

//allocates memory
void* BuddyAllocator_malloc(BuddyAllocator* alloc,
                            int size);

//releases allocated memory
void BuddyAllocator_free(BuddyAllocator* alloc,
                         void* mem);
```

Buddy Testing

```
#include "buddy_allocator.h"
#include <stdio.h>

#define BUFFER_SIZE 102400
#define BUDDY_LEVELS 9
#define MEMORY_SIZE (1024*1024)
#define MIN_BUCKET_SIZE (MEMORY_SIZE>>(BUDDY_LEVELS))

char buffer[BUFFER_SIZE]; // 100 Kb buffer to handle memory should be enough
char memory[MEMORY_SIZE];

BuddyAllocator alloc;
int main(int argc, char** argv) {

  //1 we see if we have enough memory for the buffers
  int req_size=BuddyAllocator_calcSize(BUDDY_LEVELS);
  printf("size requested for initialization: %d/BUFFER_SIZE\n", req_size);

  //2 we initialize the allocator
  printf("init... ");
  BuddyAllocator_init(&alloc, BUDDY_LEVELS,
                      buffer,
                      BUFFER_SIZE,
                      memory,
                      MIN_BUCKET_SIZE);
  printf("DONE\n");

  void* p1=BuddyAllocator_malloc(&alloc, 100);
  void* p2=BuddyAllocator_malloc(&alloc, 100);
  void* p3=BuddyAllocator_malloc(&alloc, 100000);
  BuddyAllocator_free(&alloc, p1);
  BuddyAllocator_free(&alloc, p2);
  BuddyAllocator_free(&alloc, p3);
}
```

Buddy Issues

Issues

- Lots of space wasted to store the tree
- Recursion is good for compilers, should be avoided inside an OS
  - in this case it can easily be avoided

Solutions

- Tree is stored in a bitmap
- No free lists, the items are found through brutal bitwise checks
- Modern machines do this 64 bytes at a time
- Asymptotically worse, better in practice (cache issues etc)

Exercises

SLAB

- Implement the exercise on the polimorphic list using a SLAB allocator instead malloc/free

Buddy

- modify the init function of the buddy allocator so that it takes
  - a memory buffer
  - the size of the memory area to manage
  - the number of levels
- The internal buffer for the SLAB allocator should be "taken" from the single buffer passed, and allocated at the beginning of it