CSCE 313-201
Introduction to Computer Systems
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Memory
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Chapter 7: Roadmap

7.1 Requirements
7.2 Partitioning
7.3 Paging
7.4 Segmentation
7.5 Security
Main memory services of the OS:

- 1) Dynamic allocation/deletion
- 2) Process & data relocation
  - Transparent fragmentation of process data/code within RAM and swapping to disk as needed
- 3) Protection
  - No unauthorized access to space of other processes
- 4) Sharing
  - Ability to map portions of RAM between different processes

Requirements

Memory manager, hardware paging, and address virtualization
Chapter 7: Roadmap

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Memory Management

- Memory allocation is a complex problem
  - We examine only the most basic approaches
- Partitioning: type of RAM segmentation into blocks
- Placement: actual block allocation algorithms

Note: memory heaps have nothing to do with priority queues
Static partitioning defines block boundaries a-priori
- Process may hold any number of blocks, which may appear to it as contiguous space
- Mapping done in hardware

Suffers from internal fragmentation

Blocks may be of constant or variable size
- For simplicity, most kernels have constant-size blocks called pages

Each page must be a power of 2 (usually 4 KB)
Tweaking virtual-page tables is slow and a privileged operation; allocation rounded to nearest page size.

Idea: add memory management to user space that can satisfy small buffer request with less overhead.

Dynamic partitioning (heap) grabs pages from the OS, then splits them into smaller chunks in user space. Much faster, but leads to external fragmentation.

More difficult to manage due to variable-size blocks.
Heap Allocation

• Memory is typically allocated from:
  – Stack (local variables)
  – Heap (new/malloc)
  – OS (VirtualAlloc)

• We are now concerned with heap
  – OS issues covered during next class

• Scanning
  – Linearly search through RAM (or list of empty blocks) to find empty blocks to allocate

• Search types:
  – First fit: scans from start
  – Best fit: finds the smallest free block that satisfies the request
  – Next fit: searches from the last allocation forward

• E.g., Unix SLOB allocator for simple (embedded) devices

```c
void f (void) {
    int a; // on the stack
    // ptr on the stack, buffer on the heap
    char *buf = new char [100];
    // ptr on the stack, buffer from the kernel
    char *OSbuf = VirtualAlloc (...);
}
```
Heap Allocation

- **Buddy System**
  - Organizes OS chunk into blocks that are powers of 2
  - Smallest block has size $2^L$, largest $2^U$

- **Request of size $R$ arrives**
  - Find a block with size that’s nearest power of 2
  - If no such block exists, split larger free blocks in half until a block of correct size is available

- **Example:** $U = 20$, $L = 12$
  - First request is $R_1 = 90K$
  - Then requests $R_2 = 150K$, $R_3 = 200K$ arrive in that order
Heap Allocation

• To free a block, check if the matching buddy is free
  – If so, combine and free the larger block
  – Process repeats until we can’t go further

• Example:
  – Release order: R2, R1, R3
  – Which nodes are combined?

• Method drawbacks?
  – Both internal and external fragmentation, constant splitting & merging

• How to implement this scheme efficiently?
  – First problem is finding free blocks in U-L time
  – Second problem is merging buddies in U-L time
Heap Allocation

- Given R, first determine the size of target block
  - Needs to be the nearest power of 2 above or equal to R
  - Use _BitScanReverse to get the highest bit set in DWORD
- Free blocks are kept in queues, one for each level
  - Try popping a block from the needed level, if nothing there, go hunting for a larger block up the tree

```c
int levels = U - L + 1;
// queue of free blocks
Queue *fb = new Queue [levels];
char* Alloc (int R) {
    if (R == 0)
        return NULL;
    // index of the queue in [0, levels-1]
    DWORD qIdx = GetIndex (R);
    // search for the nearest empty block
    int i = qIdx;
    while (i >= 0 && fb[i].size() == 0)
        i--;
    // anything available?
    if (i < 0) return NULL;
    // if so, split them down
    for ( ; i < qIdx; i++) {
        ptr = fb[i].pop();
        fb[i+1].push (ptr);
        fb[i+1].push (ptr + 2^(i+1));
    }
    // pop our block
    ptr = fb[qIdx].pop();
    return ptr;
}
```

- Block with index i has size $2^{U-i}$
How to free blocks and find who their buddies are?
  - Assume both ptr to start of block and its size are known

XOR block ptr with its size
  - This gives a ptr to buddy block

One approach is to scan the queue of free blocks, if buddy is there, merge

However, this requires more overhead than we wanted (i.e., $2^{U-L+1}$ worst case)

Idea: store allocation state with the blocks
  - Reserve a shadow buffer at the start of block
Heap Allocation

- Merge happens only when our buddy is free and their size matches ours
- Example when checking only the free flag is insufficient?
  - In this tree, 4B when freed will attempt to merge with 2A since starting address of 2A and 4A is the same (i.e., 0)
- To expedite efficient removal from queues, block headers may be organized into a doubly linked list instead of using separate queues

```
class Header {
    int size;
    bool free;
}
```
Modern malloc (stdlib, glibc) are variations on buddy

Unix \textit{slab} allocator
\begin{itemize}
  \item Do not merge up when expecting new requests of similar size and always maintain a cache of small blocks
  \item Threshold size for merging may be guesstimated from prior request patterns or hardwired ahead of time
\end{itemize}

Low fragmentation heaps
\begin{itemize}
  \item When multiple options are possible, attempt to optimize continuity of space
  \item 4B might be preferred over 4D for new splits
\end{itemize}

Per-CPU heaps with better concurrency
Practical Issues

• Overhead per block
  – Release mode 16 bytes, debug 64 bytes

• Stack overflow
  – Too many local variables for default stack size or recursion too deep

• Stack corruption
  – Buffer overflow on local arrays

• Heap corruption
  – Block header wiped out or no man’s land is written to

• Heaps grab large pieces of memory from the OS
  – Since heaps are in user mode, they are quicker than asking the kernel
  – Allocation more efficient for small pieces (all kernel blocks rounded off to 4KB)

• When you run outside the heap into OS territory, hard crash on access violation

```c
void buggy (void) {
  double a [1e8];
  int b [100];
  memset (b, 0, 10000);
  char *c = new char [100];
  memset (c, 0, 10000);
}
```
Practical Issues

• Unless it’s extreme, heap corruption goes undetected
  – In debug mode, until the next new/delete operation sniffs something wrong and throws an assertion violation
  – In release mode, nothing happens until you crash

• Example: threadA corrupts the heap, threadB crashes
  – How to make these situations more suitable for debugging?

• Can ask the OS for the buffer using VirtualAlloc()
  – If writing outside page boundary, kernel does not tolerate any funny business, throws access violation immediately
Practical Issues

• Catching crash exceptions is controversial
  - Unless there are good reasons, it only obscures the cause of the crash, increases debug time

```c
// SEH-style handler
__try {
  f(x);
} __except ( MyCrashHandler ( GetExceptionCode() )) {
  // catch other exceptions here
}
```

• Writing a library that is used by someone else
  - Should you test their pointers for NULL?
  - Should you check if memory is valid using IsBadReadPtr, IsBadWritePtr, IsBadCodePtr, IsBadStringPtr?

```c
MyLibraryAPI (char *ptr) {
  // how much checking to do
  // on validity of ptr?
}
```
One school of thought is to catch crashes, return explicit errors that help understand the problem
- E.g., ReadFile returns error 998 (ERROR_NOACCESS)

Another direction is to just crash without any checks
- If someone is passing NULL or invalid handles, they’re probably not checking for return codes; bugs should be made obvious to them

Finally, your API can catch the crash, silently ignore it, and make someone’s life more difficult
- Not recommended