CSCE 313-200
Introduction to Computer Systems
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Memory II
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Chapter 7: Roadmap

7.1 Requirements
7.2 Partitioning
7.3 Paging
7.4 Segmentation
7.5 Security
Paging

- Paging allows the OS to allocate non-contiguous chunks of space to application requests
  - Hardware finds the page in RAM by transparently mapping from logical to physical addresses
- Logical address consists of two parts
  - Page number
  - Offset within that page
- **Example**: 32 bit address, 4 KB pages

```
char *ptr = 0x33567
```

<table>
<thead>
<tr>
<th>Logical page number</th>
<th>Offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x33</td>
<td>0x567</td>
</tr>
</tbody>
</table>

= 0x33567
Paging

- Conversion of page numbers is done using the TLB (Translation Lookaside Buffer):

  char *ptr = 0x33 0x567

- Each process owns a page table controlled by OS
**Paging**

- **Example:** write 5000 bytes to array `ptr[]`

```c
char *ptr = 0x33567;
for (int i = 0; i < 5000; i++)
    ptr [i] = i;
```

- `Ptr + i = 0x33567-0x33FFF`
  - `i = 0-2712 (2713 iterations)`
  - Physical address range 0x453567-0x453FFF
- `Ptr + i = 0x34000-0x348EE`
  - `i = 2713-4999 (2287 iterations)`
  - Physical address range 0x621000-0x6218EE
Paging

• To avoid doubling RAM latency on random access, TLB is kept in dedicated cache memory
  – CPU performs a lookup before sending address to RAM
• Within a given page, no control of address validity
  – However, if a process goes far enough to hit next page, the TLB must have an entry for that page with correct permissions
  – If not, a page fault is thrown and the process is killed
• These concept allow allocation of pages beyond physical RAM, swapping to disk, loading to new addr
• Example: computer with 8 GB of RAM
  – Process requests 7 GB, but all other resident software and kernel occupy 2.5 GB
Paging

• Whatever pages aren’t being used are swapped to disk
  – Special pagefile provides space for this operation
  – Usually, pagefile.sys is twice the size of RAM

• Memory classification
  – Non-pageable memory: special types of pages that cannot be swapped to disk (e.g., parts of OS, locked pages, AWE segments, large-page allocations)
  – Commit set: all pageable memory of the process (i.e., allocated in the page file)
  – Working set: touched (accessed) pages in RAM
  – Private working set: a subset of the working set (e.g., heap-allocated) that is not shared with other processes

• The last three can be seen in Task Manager
Paging

- Access to page outside working set causes a **page fault**
- **Types of page faults**
  - **Hard**: requires the page to be read from disk
  - **Soft**: can be resolved with remapping (e.g., pages exists in working set of another process or first-time access)
  - **Violation**: access outside virtual space of this process or using incompatible permissions (e.g., writing to read-only page)
- **Hard/soft faults are handled transparently by OS**
- **Example**: allocate 1 GB of committed memory

```c
char *buf = (char *) VirtualAlloc(NULL, 1 << 30, MEM_COMMIT|MEM_RESERVE, PAGE_READWRITE);
```

- **Commit size, working set size, and private set size?**
Examine Task Manager:

- Commit size is 1 GB as expected, but none of that memory has been allocated in physical RAM yet
  - OS doesn’t know which pages we’ll need and in what order
  - Conserves physical RAM as much as possible
- Write something into each page: \[\text{memset}(\text{buf}, 0x55, 1 \ll 30);\]
Working with Buffers

- Suppose we intend to dynamically expand the region of allocated memory
  - But don’t want to copy data over to the new area each time
  - Similar to HeapReAlloc

- Would like to ask the kernel to map the continuation of the previous buffer to some additional physical pages:

```c
// allocation of initial 128 KB succeeds
int size = 1 << 17;
char *buf = (char *) VirtualAlloc (NULL, size, MEM_COMMIT|MEM_RESERVE, PAGE_READWRITE);
// attempt to add 16 MB to this buffer may fail
char *result = (char *) VirtualAlloc (buf + size, 1 << 24,
                                      MEM_COMMIT|MEM_RESERVE, PAGE_READWRITE);
```
The problem is that the virtual space beyond buf + size might have already been assigned
- Allocation in this case fails

Idea: reserve a huge amount of virtual space so that the heap can’t use it

Reserved memory is not mapped to pagefile until explicitly committed
- Reservation simply makes sure this address space is not used in other allocation requests
- In Server 2016, max reservation is 128 TB
Working with Buffers

• Can now commit memory in our reserved space

```c
// reserve 1 TB
char *bufMain = (char *) VirtualAlloc(NULL, (uint64) 1<<40,
    MEM_RESERVE, PAGE_READWRITE);
// allocate 128 KB
int size0 = 1 << 17;
char *buf0 = (char *) VirtualAlloc(bufMain, size0,
    MEM_COMMIT, PAGE_READWRITE);
// now add 16 MB to this buffer
int size1 = 1 << 24;
char *buf1 = (char *) VirtualAlloc(buf0 + size0, size1,
    MEM_COMMIT, PAGE_READWRITE);
// now add 1 GB
int size2 = 1 << 30;
char *buf2 = (char *) VirtualAlloc(buf1 + size1, size2,
    MEM_COMMIT, PAGE_READWRITE);
```

• Memory may be decommitted as needed

```c
// decommit 4KB from the middle of committed space
char *result = (char*) VirtualFree(buf1, 1 << 12, MEM_DECOMMIT);
```
Queue Example

- Design self-resizing Q that keeps data contiguous and never has to memcpy
  - Code below does not handle errors, nor does it compute how much to expand or shrink by

```cpp
Q::Q () {
    reserveSize = (uint64) 1<<40;
    char *bufMain = (char *) VirtualAlloc (NULL, reserveSize,
                                           MEM_RESERVE, PAGE_READWRITE);
    head = tail = (Item*) (next = last = bufMain);
}

void Q::push (Item x) {
    // overflow of current commit section?
    if (tail + sizeof(x) >= next) {
        // add some commit space in front of the tail
        VirtualAlloc (next, expandSize, MEM_COMMIT, PAGE_READWRITE);
        next += expandSize;
    }
    *tail++ = item;
}
```
Queue Example

- Shrink the committed region during pop

```c
Item Q::pop (void) {
    if (head > last + shrinkSize) {
        // decommit old memory behind the head
        VirtualFree (last, shrinkSize, MEM_DECOMMIT);
        last += shrinkSize;
    }
    return *head++;  
}
```

- **Problem #1**: cannot commit/decommit too fast
  - Keep expandSize and shrinkSize around 1 MB
- **Problem #2**: queue eventually overflows when reserveSize is exceeded
  - If 128 TB of virtual space is not enough, memcpy or linked lists of buffers cannot be avoided
• Assume there exists some complex data processing library whose APIs only work with contiguous buffers
  – Can the library be hacked to work with shadow buffers?
• If so, what if some records do not fit in shadow buffer?
  – Recall that shadow buffers must be at least the size of the longest record (e.g., word) in the file
• Some files may have extremely long records
  – E.g., each record in a graph contains a node ID and a list of its neighbors; for 300M neighbors, 2.4 GB per record
• Worse yet, what if individual records do not fit in RAM?
  – E.g., search engine index contains a keyword hash and a list of pages where the keyword appears; for a popular keyword found in 5B pages, this requires 40 GB
Suppose the library is a streaming data processor
- Operates on data only sequentially and going forward
- Never returns by more than X bytes, where X is small

**Goal**: use virtual memory to create an illusion of a continuous file in RAM for this library

**Idea**: let the library run into page faults
- Which we catch, commit the next chunk of virtual memory, read the next file block into it, and return control to the API
- Blocks of memory that are 2 buffers behind are decommitted assuming buffer size is no smaller than X

**Performance (AMD Phenom II)**: page-fault rate is ~900K/sec
Disk I/O Example

- What’s a good reserve size?
  - Length of file

- This is how memory-mapped files work
  - Slightly more general as they allow random access
  - Read small buffer surrounding the page fault
  - Decommit old pages using LRU or some other technique
  - See CreateFileMapping and MapViewOfFile

- Problem: this method can only do single-buffering
  - Stalls processing while the next buffer is being read
  - Only solution is to read ahead into other RAM locations, then memcpy into buf_{i+2} during page faults
Disk I/O Example

- Using AWE (Address Windowing Extensions)
  - Six physical buffers allocated by disk thread, into which it reads the file, wrapping back to \( B_0 \) after \( B_5 \)
  - Two green buffers are mapped to virtual addresses currently being processed by the library; \( B_2-B_5 \) are used for read-ahead
  - On page fault, the oldest buffer \( B_0 \) is unmapped, the next buffer \( B_2 \) is mapped where the page fault occurred
Disk I/O Example

- Writing-to-buffer benchmark
  - 1) No remapping or page-fault processing

  ```c
  char *buf = VirtualAlloc (NULL, 1e9, MEM_COMMIT|MEM_RESERVE, ...);
  ```

  - 2) Reserve virtual memory, catch page faults, commit new chunks of size 1 MB, decommit old chunks

  ```c
  char *buf = VirtualAlloc (NULL, 1e9, MEM_RESERVE, ...);
  __try {
    writeToPtr (buf, 1e9);
  }
  __except ( ... ) {
  }
  ```

  - 3) Reserve physical memory (AWE), catch page faults, remap chunks of size 1MB, unmap old chunks
Disk I/O Example

- Two versions of `writeToPtr()`:

```
writeToPtrA (char *buf, int size) {
    for (int i=0; i < size; i++)
        buf[i] = 55;
}
```

```
writeToPtrB (char *buf, int size) {
    memset (buf, 55, size);
}
```

- Benchmark results:

<table>
<thead>
<tr>
<th>Mapping</th>
<th>writeToPtr</th>
<th>Working set</th>
<th>Page faults</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) None</td>
<td>loop</td>
<td>1 GB</td>
<td>245,493</td>
<td>3.4 sec</td>
</tr>
<tr>
<td></td>
<td>memset</td>
<td>same</td>
<td>same</td>
<td>343 ms</td>
</tr>
<tr>
<td>2) Commit</td>
<td>loop</td>
<td>5.3 MB</td>
<td>245,327</td>
<td>3.2 sec</td>
</tr>
<tr>
<td></td>
<td>memset</td>
<td>same</td>
<td>same</td>
<td>499 ms</td>
</tr>
<tr>
<td>3) Physical</td>
<td>loop</td>
<td>5.3 MB</td>
<td>1,361</td>
<td>3.1 sec</td>
</tr>
<tr>
<td></td>
<td>memset</td>
<td>same</td>
<td>same</td>
<td>156 ms</td>
</tr>
</tbody>
</table>