Lecture 27: Virtual memory and paging in xv6

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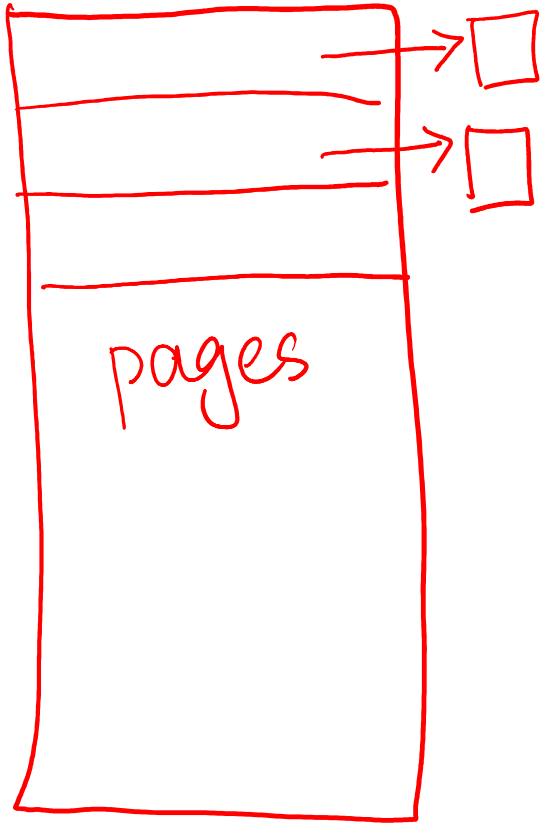
Virtual address space in xv6

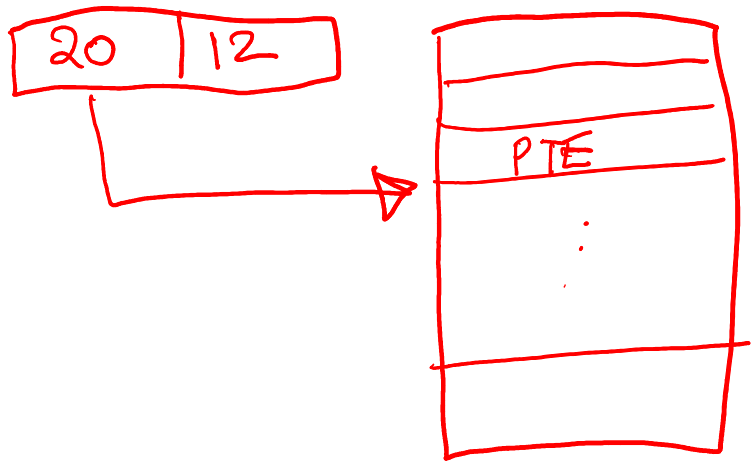
- 32-bit OS, so 2^32=4GB virtual address space for every process
- Process address space divided into pages (4KB by default), and every valid logical page used by the process is mapped to a physical frame by the OS (no demand paging)
- Page table of a process maps virtual addresses to physical addresses
  - One page table entry per page, which contains the physical frame number (PFN) and various flags/permissions for the page

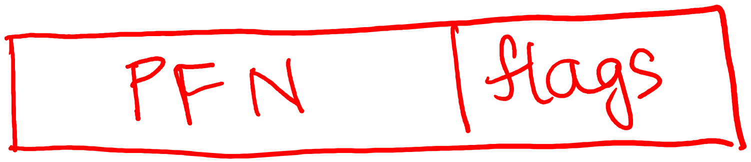


Page table in xv6

- Virtual address space = 2^32 bytes, page size = 4KB = 2^12 bytes
  – Up to 2^20 pages per process
- Page table is a logical array of 2^20 page table entries (PTE)
  – 20 bit page number is used to index into page table to locate PTE
- Each PTE has 20 bit physical frame number, and some flags
  – PTE_P indicates if page is present (if not set, access will cause page fault)
  – PTE_W indicates if writeable (if not set, only reading is permitted)
  – PTE_U indicates if user page (if not set, only kernel can access the page)
- Address translation: use page number (top 20 bits of virtual address) to index into page table, find physical frame number, add 12-bit offset

VA



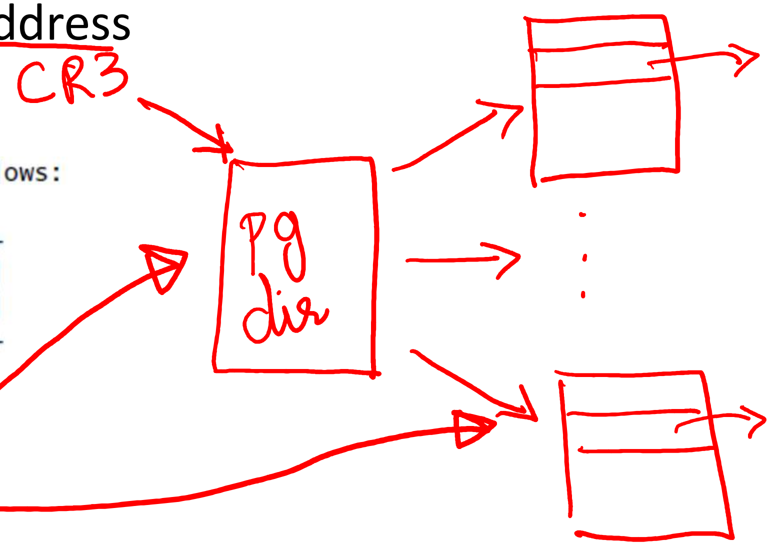


PFN + offset = PA

Two level page table

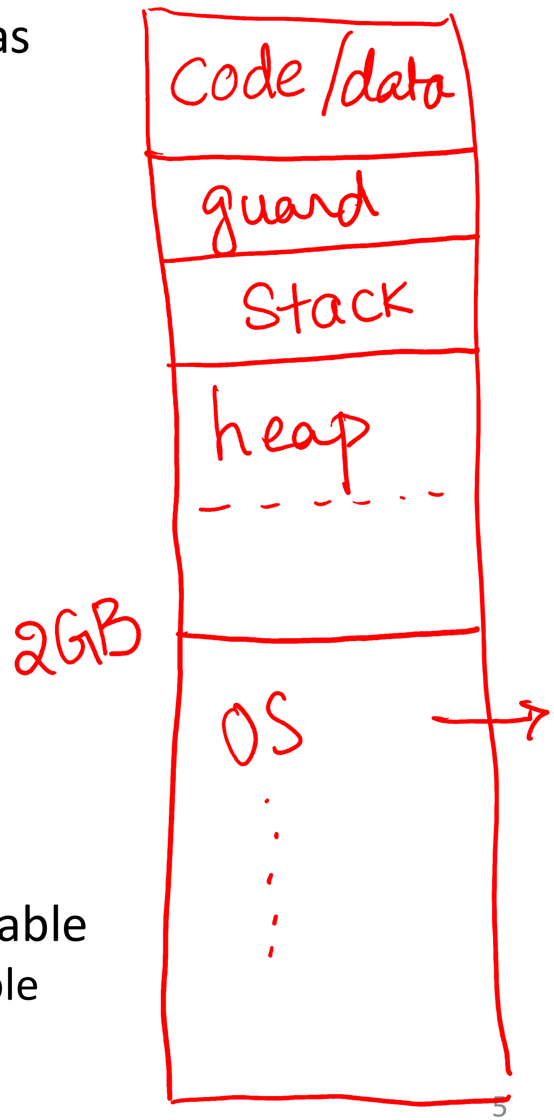
- 2^20 PTEs cannot be stored contiguously, page table has two levels
  - 2^10 “inner” page table pages, each with 2^10 PTEs
  - Outer page directory stores PTE-like references to the 2^10 inner page table pages
  - Physical address of outer page directory is stored in CPU’s cr3 register, used by MMU during address translation
- 32 bit virtual address = 10 bits index into page directory, next 10 bits index into inner page table, last 12 bits are offset within page
  - PFN from PTE + offset = physical address

```
// A virtual address 'la' has a three-part structure as follows:
//
// +--------10------+-------10-------+---------12----------+
// | Page Directory |   Page Table   | Offset within Page  |
// |      Index     |      Index     |                     |
// +----------------+----------------+---------------------+
//  \--- PDX(va) --/ \--- PTX(va) --/
```



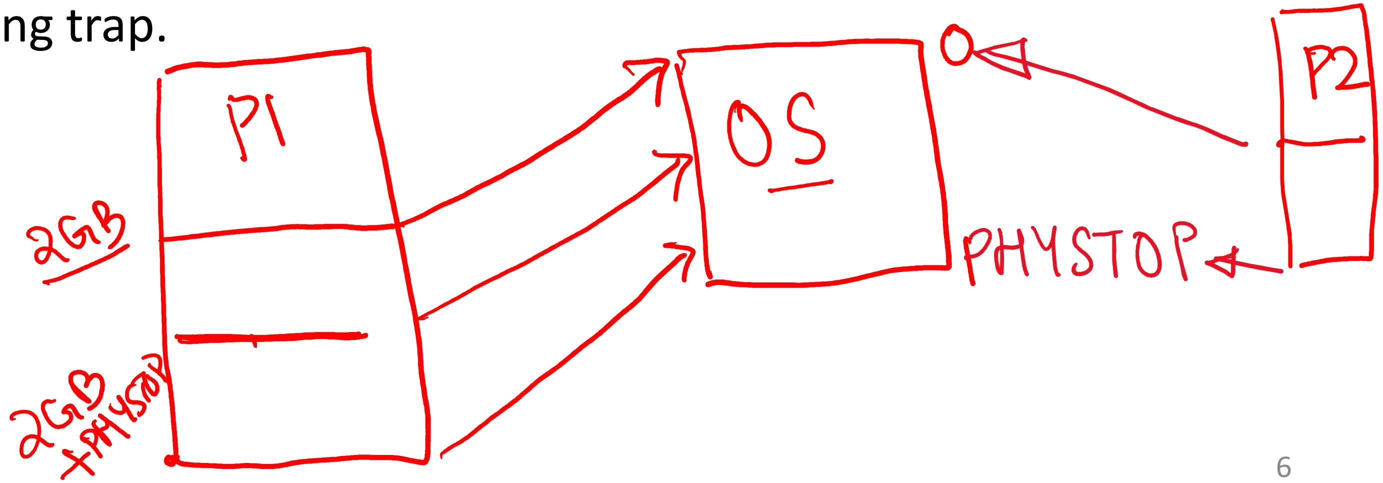
Process virtual address space in xv6

- Memory image of a process starting at address 0 has
  - Code/data from executable
  - Fixed size stack (with guard page)
  - Expandable heap
- Kernel code/data is mapped beginning at address KERNBASE (2GB)
  - Kernel code/data
  - Free pages maintained by kernel
  - Some space reserved for I/O devices
- Page table of a process contains two sets of PTEs
  - User entries map low virtual addresses to physical memory used by the process for its code/data/stack/heap
  - Kernel entries map high virtual addresses to physical memory containing OS code and data structures (identical entries in all processes)
- Process can only access memory mapped by page table
  - Access only possible via virtual addresses in page table
- Different page table for every process, page table needs to be switched during a context switch



OS page table mappings (1)

- OS code/data structures part of virtual address space of every process.
  - Page table entries map high virtual addresses (2GB to 2GB+PHYSTOP) to OS code/data located in physical memory (0 to PHYSTOP)
  - Only one copy of OS code in memory, mapped into all process page tables
  - Kernel mappings are identical in all processes
- Can't you directly access OS code using its physical address? No. With paging and MMU turned on, physical memory can only be accessed by assigning a virtual address to it, and adding a mapping from virtual to physical address in page table.
- What happens during a trap? The same page table can be used to access kernel during a trap. If OS is not part of virtual address space, will need new page table during trap.

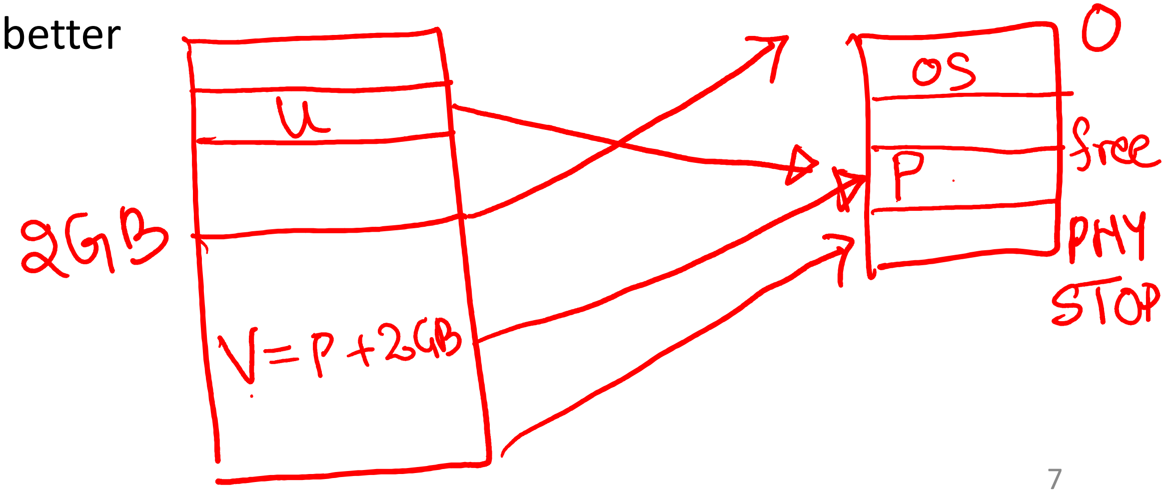


OS page table mappings (2)

- Kernel page table mappings map virtual addresses 2GB: (2GB+PHYSTOP) to physical addresses 0 : PHYSTOP
  – 0 to PHYSTOP has memory for kernel code/data, I/O devices, mostly free pages
- Assigning free pages to processes
  – Suppose physical frame P is initially mapped into kernel part of address space at virtual address V (we will have V = P+2GB)
  – When assigned to a user process, P is assigned another virtual address U (<2GB)
  – Same frame P mapped twice into page table, at virtual addresses U and V
  – Kernel and user access same memory using different virtual addresses
- Every byte of RAM can consume 2 bytes of virtual address space, so xv6 cannot use more than 2GB of RAM (since max 32-bit virtual address space is 4GB)
  – Real kernels deal with this better

$U \to P$

$V \to P$

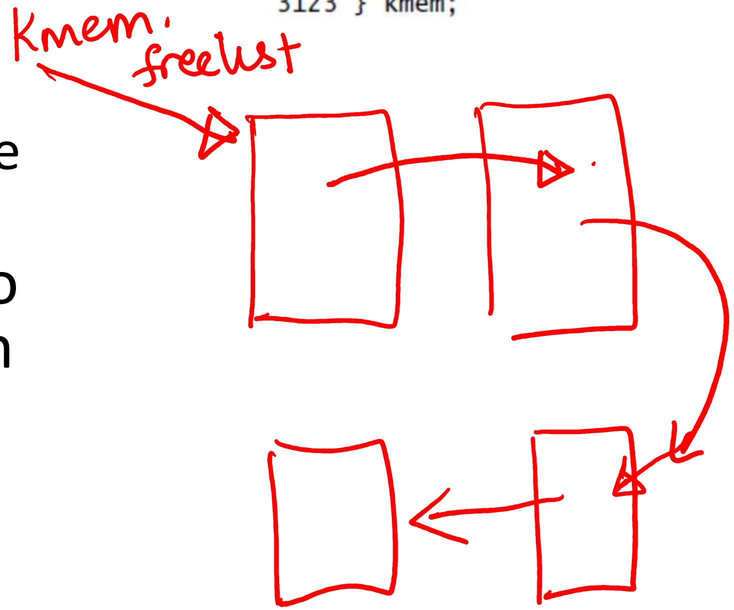


Maintaining free memory

- After boot up, RAM contains OS code/data and free pages
- OS collects all free pages into a free list, so that it can be assigned to user processes
  - Used for user memory (code/data/stack/heap) and page tables of user processes
- Free list is a linked list, pointer to next free page embedded within previous free page
  - Kernel maintains pointer to first page in the list

```
struct run {
  struct run *next;
};

struct {
  struct spinlock lock;
  int use_lock;
  struct run *freelist;
} kmem;
```

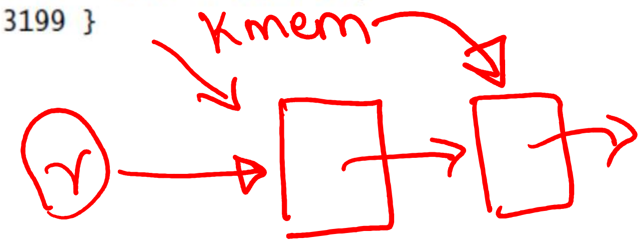


alloc and free operations

- Anyone who needs a free page calls kalloc()
  - Sets free list pointer to next page and returns first free page on list
- When memory needs to be freed up, kfree() is called
  - Add free page to head of free list, update free list pointer

```
char*
kalloc(void)
{
  struct run *r;

  if(kmem.use_lock)
    acquire(&kmem.lock);
  r = kmem.freelist;
  if(r)
    kmem.freelist = r->next;
  if(kmem.use_lock)
    release(&kmem.lock);
  return (char*)r;
}
```

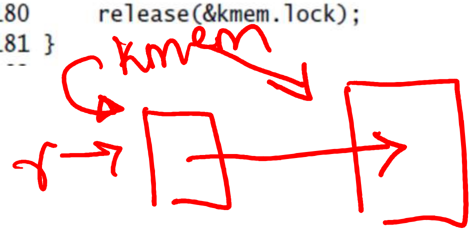



```
void
kfree(char *v)
{
  struct run *r;

  if((uint)v % PGSIZE || v < end || V2P(v) >= PHYSTOP)
    panic("kfree");

  // Fill with junk to catch dangling refs.
  memset(v, 1, PGSIZE);

  if(kmem.use_lock)
    acquire(&kmem.lock);
  r = (struct run*)v;
  r->next = kmem.freelist;
  kmem.freelist = r;
  if(kmem.use_lock)
    release(&kmem.lock);
}
```



Summary of virtual memory in xv6

- Only virtual addressing, no demand paging
- 4GB virtual address space for each process
- 2 tier page table: outer pgdir, inner page tables
- Process address space has:
  - User memory image at low virtual addresses (<2GB)
  - Kernel code/data mapped at high virtual addresses
- Kernel part of address space has OS code/data, memory for I/O devices, and free pages
  - Assigned to user processes as needed