Pintos/Tacos Lab3 Overview

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Adapted from Spring'25 slides made by Yuxing Xiang

Today

- Lab 3 overview
- Lab 3a/3b tasks
- Bitmap and hash
- Tips
- Q&A

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- **Lab 3 overview**
- Lab 3a/3b tasks
- Bitmap and hash
- Tips
- Q&A

Virtual Memory in General

- a *memory management* technique
- *an idealized abstraction of the storage resources*
- address translation using a combination of hardware and software
- easy-to-implement linking
- easy-to-implement loading
- easy-to-implement sharing
- increased security due to memory isolation
- …

Virtual Memory in Pintos/Tacos

- a *memory management* technique
- *an idealized abstraction of the storage resources*

Not your focus

- address translation using a combination of hardware and software

Your Task in Lab3

- easy-to-implement linking
- easy-to-implement loading
- easy-to-implement sharing

Bonus Goal :D

- increased security due to memory isolation
- …

Much of our focus

- **Virtual memory management**
  - Virtual pages & Segments
- **Physical memory management**
  - Physical frames
  - Replacement policy
- **Page table**
  - Address translation
  - Page fault
- **Swap Space**

Before we dive in …

- A good design goes a long way towards accomplishing your tasks and has a long way to go.
  - Alternatively, view this as the greatest creative freedom – you could make your virtual memory system truly unique.
- Questions in the design doc might help you recognize flaws in your design.
- Get your hands on **early**.

> **This assignment is an open-ended design problem.**
>
> - We are going to say as little as possible about how to do things. Instead we will focus on what functionality we require your OS to support.
> - We will expect you to come up with a design that makes sense. You will have the freedom to choose how to handle page faults, how to organize the swap partition, how to implement paging, etc.

Today

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- **Lab 3a/3b tasks**
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A brief look at lab 3a tasks

Exercise 1.1

Implement paging for segments loaded from executables.

- All of these pages should be loaded **lazily**, that is, only as the kernel intercepts page faults for them.
- Upon eviction:
  - Pages **modified** since load (e.g. as indicated by the "dirty bit") should **be written to swap**.
  - **Unmodified** pages, including read-only pages, should **never be written to swap** because they can always be read back from the executable.

Exercise 1.2

Implement a global page replacement algorithm that approximates LRU.

- Your algorithm should perform **at least as well as** the simple variant of the "second chance" or "clock" algorithm.

Exercise 2.1

Adjust user memory access code in *system call handling* to deal with potential page faults.

- **a.1**
  - load an executable
  - lazy loading
  - write back
  - swap space
- **a.2**
  - replacement policy
- **a.3**
  - modify previous implementation

A brief look at lab 3b tasks

Exercise 1.1

Implement stack growth.

- In project 2, the stack was **a single page** at the top of the user virtual address space, and programs were limited to that much stack.
- Now, **if the stack grows past its current size, allocate additional pages as necessary**.

Exercise 2.1

Implement memory mapped files, including the following system calls.

- mapid_t **mmap** (int fd, void *addr)
- void **munmap** (mapid_t mapping)

- **b.1**
  - allocate a new page when stack grows past current page
- **b.2**
  - mmap, munmap
  - can map many kinds of files

Suggestion

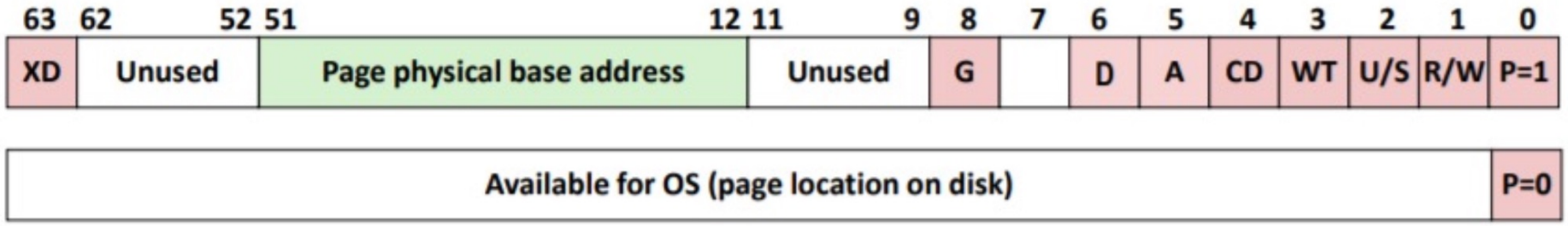
All these tasks are really the result of a complete VM system.
Read through Lab3a and 3b (Pintos) or Lab3 (Tacos) documentation; come up with a complete **design** first.

Let’s look at the tasks in another way…

What are we trying to design for?

When we execute a program…

- **When we load an executable…**
  - Only build the mappings
    - map user pages to file content
    - ***Q: How to maintain the mappings?***
      - first access will trigger page fault and then load the page
      - Store disk address in PTE like we have already known? (e.g., from ICS?)



When we execute a program…

- What do we know about Pintos/Tacos PTE?
  - Check lab document

```
 31                                  12 11 9      6 5     2 1 0
+--------------------------------------+----+----+-+-+---+-+-+-+
|           Physical Address             | AVL|    |D|A|   |U|W|P|
+--------------------------------------+----+----+-+-+---+-+-+-+
```

- **Macro: PTE_P**
  - **Bit 0, the "present" bit.**
  - When this bit is 1, the other bits are interpreted as described below. When this bit is 0, any attempt to access the page will page fault. The remaining bits are then not used by the CPU and may be used by the OS for any purpose.

  - OK! It is designed as we expected.
  - Do you think storing information in PTE is ***possible*** and ***worth the trouble to implement*** in THIS LAB?
    - 31-bit might be a challenge?
    - You decide.

When we execute a program…

- **When we load an executable…**
  - Only build the mappings
    - map user pages to file content
    - ***Q: How to maintain the mappings?***
      - first access will trigger page fault
      - **Idea 1:** Store disk address in PTE like we have already known?
      - **Idea 2:** You can design other data structures and store them in *thread*
        - Use these newly designed data structures when handling page faults

When we execute a program…

- **When we access it…**
  - Trigger page fault on first access
  - Turn to page fault handler to load the page
    - ***Q: How can we know it's time to load the page instead of other cases?***
    - ***Q: How to load the page?***
      - Read the page into memory
        - **Replacement policy**
      - Update PTE, etc.
        - Interfaces in ***threads/pte.h, userprog/pagedir.h, userprog/pagedir.c …***

Replacement policy

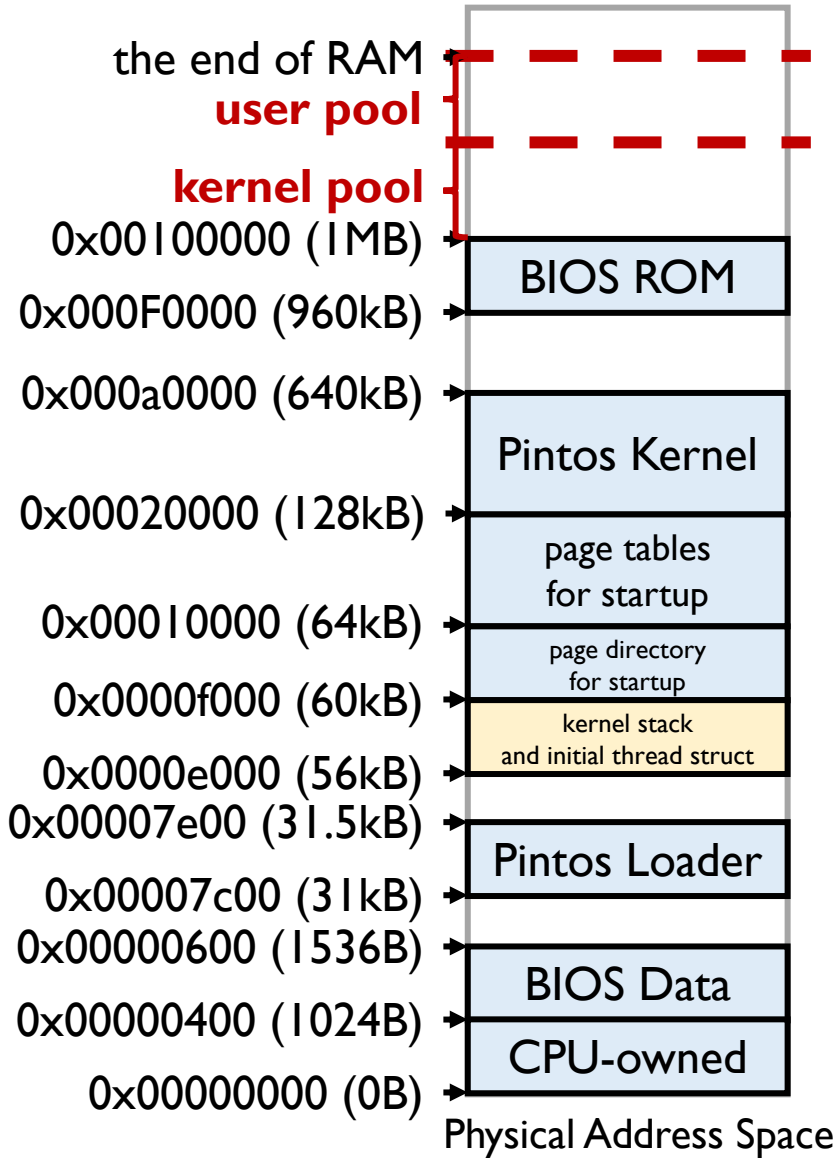
- Require one that approximates LRU
  - second chance, clock, …
  - some interfaces may be useful: ***userprog/pagedir.h***

```
bool pagedir_is_dirty (uint32_t *pd, const void *upage);
void pagedir_set_dirty (uint32_t *pd, const void *upage, bool dirty);
bool pagedir_is_accessed (uint32_t *pd, const void *upage);
void pagedir_set_accessed (uint32_t *pd, const void *upage, bool accessed);
```

- All algorithms have a common thing to do…
- ***Q: How to manage the frames and their related information?***
  - **Frame management**

Frame management

- *Q: What frames do we need to manage?*
- ***Claim: In lab3, you only need to manage frames in user pool.***
  - Why?
  - Let's look at the definitions of the two pools again.



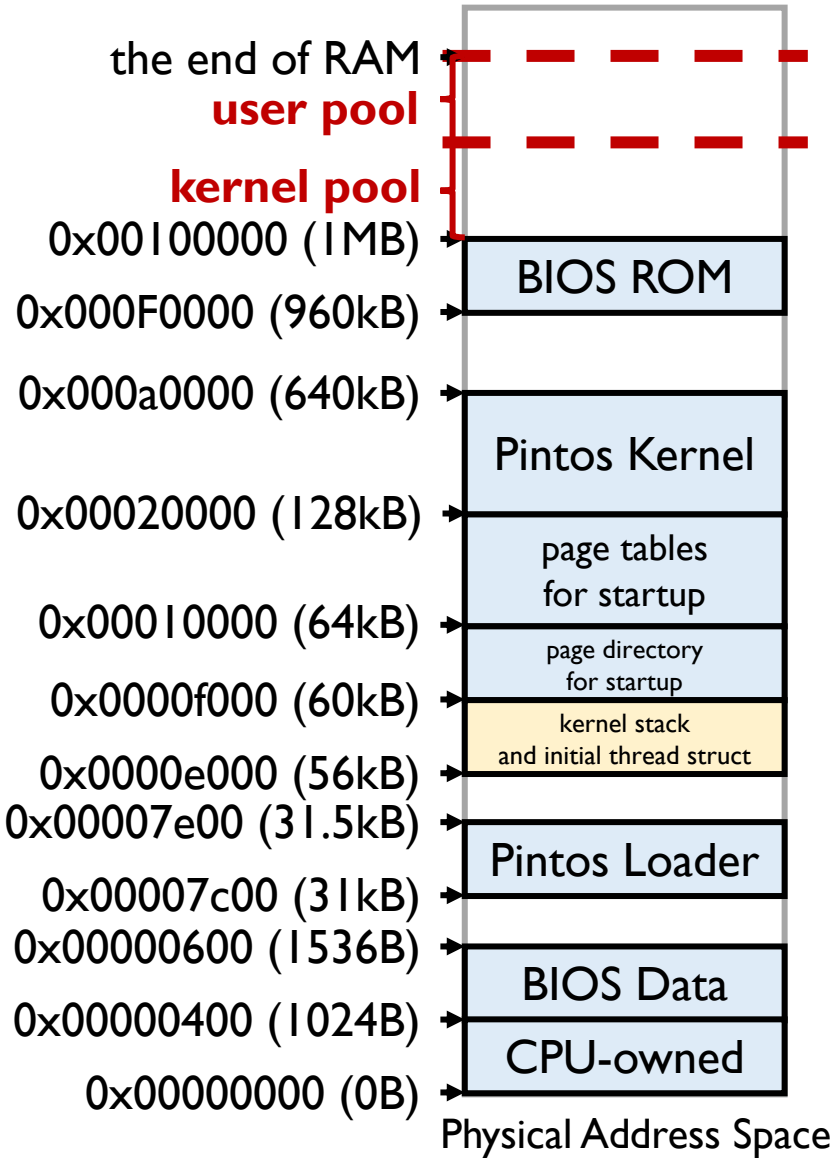
Frame management

> ***The user pool*** **should be used for allocating memory for user processes and** ***the kernel pool*** **for all other allocations. This will only become important starting with project 3. Until then, all allocations should be made from** ***the kernel pool*****.**

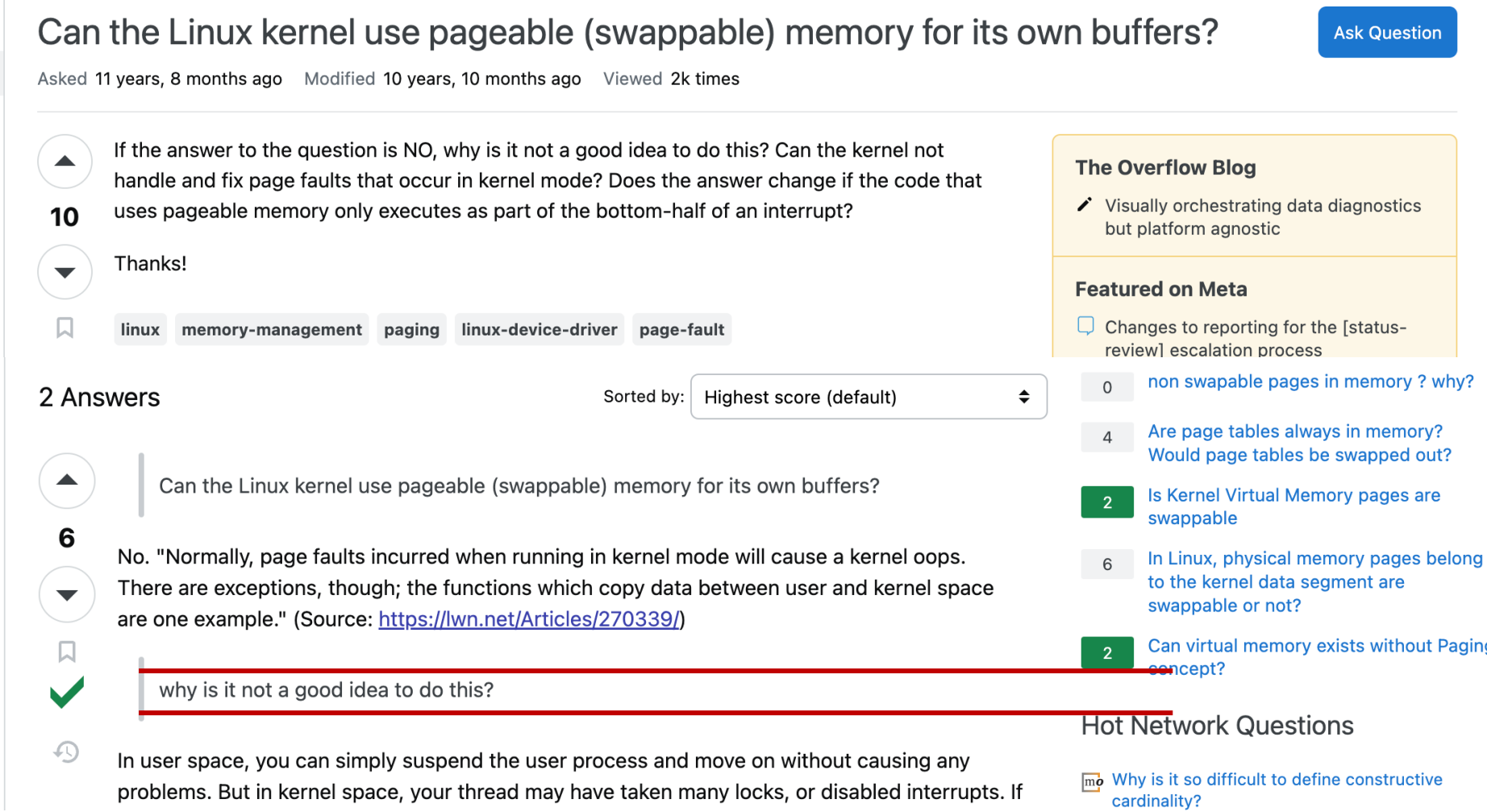
- The fact that an executable or another kind of file is mapped to user space indicates that ***you can only load it or reload it into user pool***.
- No allocation in user pool before Lab3 means that if you manage all frames in user pool you don't need to worry about evicting a frame **for your own kernel code**.

Frame management

- ***Q: What frames do we need to manage?***
- ***Claim: In lab3, you only need to manage frames in user pool.***
- So there will be no replacement in kernel pool?
  - We use *palloc* to allocate memory in kernel pool.
  - Our tests (and hopefully your code) will not ask for that much memory allocation in kernel pool. **So you don't need to consider that.**
  - **BUT IS THIS ACTUALLY A PROBLEM IN REAL-WORLD KERNELS?**



Aside: The Linux kernel is *completely* not pageable



Can the Linux kernel use pageable (swappable) memory for its own buffers?

Ask Question

Asked 11 years, 8 months ago Modified 10 years, 10 months ago Viewed 2k times

10

If the answer to the question is NO, why is it not a good idea to do this? Can the kernel not handle and fix page faults that occur in kernel mode? Does the answer change if the code that uses pageable memory only executes as part of the bottom-half of an interrupt?

Thanks!

linux memory-management paging linux-device-driver page-fault

2 Answers Sorted by: Highest score (default)

6

> Can the Linux kernel use pageable (swappable) memory for its own buffers?

No. "Normally, page faults incurred when running in kernel mode will cause a kernel oops. There are exceptions, though; the functions which copy data between user and kernel space are one example." (Source: https://lwn.net/Articles/270339/)

> why is it not a good idea to do this?

In user space, you can simply suspend the user process and move on without causing any problems. But in kernel space, your thread may have taken many locks, or disabled interrupts. If

The Overflow Blog

Visually orchestrating data diagnostics but platform agnostic

Featured on Meta

Changes to reporting for the [status-review] escalation process

0 non swapable pages in memory ? why?

4 Are page tables always in memory? Would page tables be swapped out?

2 Is Kernel Virtual Memory pages are swappable

6 In Linux, physical memory pages belong to the kernel data segment are swappable or not?

2 Can virtual memory exists without Paging concept?

Hot Network Questions

Why is it so difficult to define constructive cardinality?

Moral: *Pageable kernels aren't that popular/useful.*

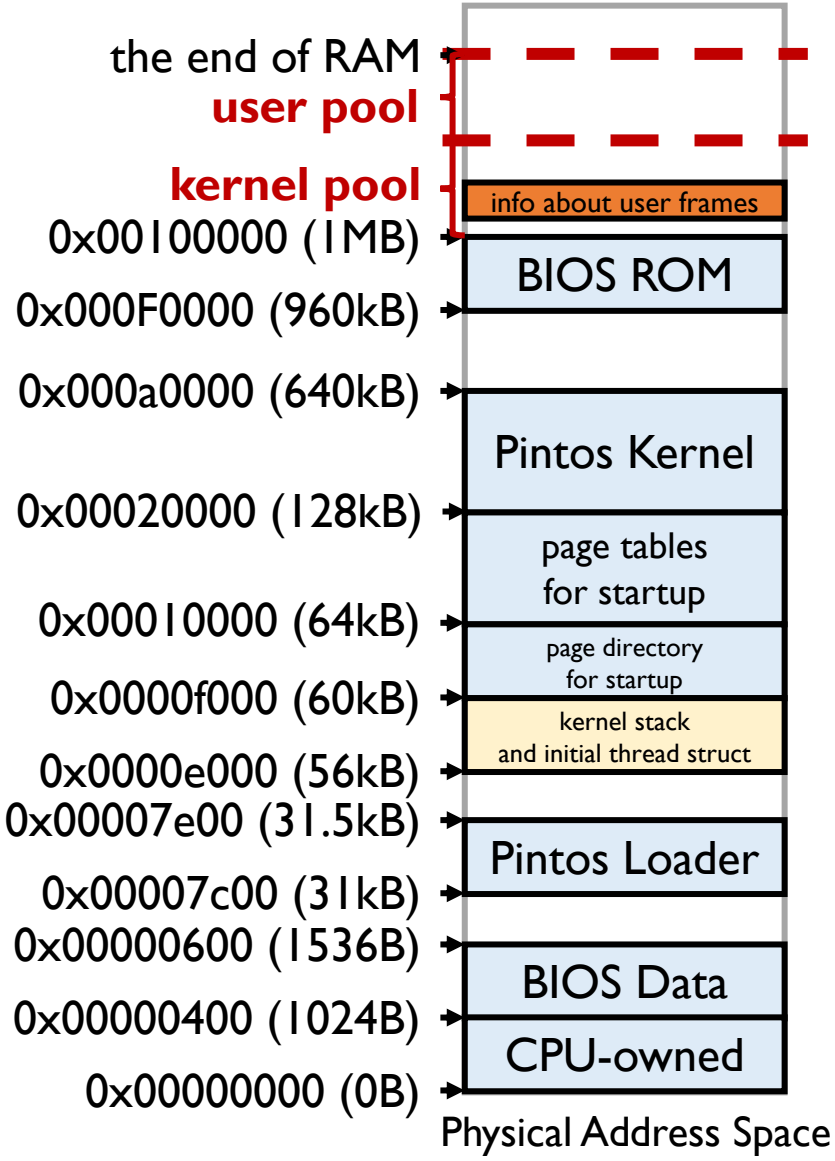
You are certainly not required to implement that in Pintos/Tacos.

https://stackoverflow.com/questions/18198059/can-the-linux-kernel-use-pageable-swappable-memory-for-its-own-buffers

https://unix.stackexchange.com/questions/531554/are-linux-kernel-modules-a-sort-of-linux-system-paged-pool

Frame management

- ***Q: What frames do we need to manage?***
- ***Claim: In lab3, you only need to manage frames in user pool.***
- So what's good about this claim?
  - The data not in user pool resides in physical memory
  - Feel free to allocate your global data structures in kernel pool and use them to manage all the user frames!
    - Initialization can be done in *pintos_init*



Replacement policy

- Require one that approximates LRU
  - second chance, clock, …
  - some interfaces may be useful: ***userprog/pagedir.h***

```
bool pagedir_is_dirty (uint32_t *pd, const void *upage);
void pagedir_set_dirty (uint32_t *pd, const void *upage, bool dirty);
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```

- All algorithms have a common thing to do…
- ***Q: How to manage the frames and their related information?***
  - Frame management
  - **Swap space management**

Swap space management

- Swap space is a space on a hard disk that is a backup for physical memory.
- In Pintos, swap space is a **block device**. In Tacos, you simply use a file in **DISKFS**.
- ***The interfaces of block device have been provided.***

```
/** A block device. */
struct block
  {
    struct list_elem list_elem;         /**< Element in all_blocks. */

    char name[16];                      /**< Block device name. */
    enum block_type type;                /**< Type of block device. */
    block_sector_t size;                 /**< Size in sectors. */

    const struct block_operations *ops;  /**< Driver operations. */
    void *aux;                          /**< Extra data owned by driver. */

    unsigned long long read_cnt;        /**< Number of sectors read. */
    unsigned long long write_cnt;       /**< Number of sectors written. */
  };
```

Swap space management

- Block device
  - *devices/block.h, devices/block.c*
  - Initialized in *pintos_init*
  - **Get a block device**
    - block_get_role
  - **Read from a block device**
    - block_read
  - **Write to a block device**
    - block_write
  - Other interfaces you may use

```
/** Finding block devices. */
struct block *block_get_role (enum block_type);
void block_set_role (enum block_type, struct block *);
struct block *block_get_by_name (const char *name);
```

```
/** Type of a block device. */
enum block_type
  {
    /* Block device types that play a role in Pintos. */
    BLOCK_KERNEL,               /**< Pintos OS kernel. */
    BLOCK_FILESYS,              /**< File system. */
    BLOCK_SCRATCH,              /**< Scratch. */
    BLOCK_SWAP,                 /**< Swap. */
    BLOCK_ROLE_CNT,
```


```
/** Block device operations. */
block_sector_t block_size (struct block *);
void block_read (struct block *, block_sector_t, void *);
void block_write (struct block *, block_sector_t, const void *);
const char *block_name (struct block *);
enum block_type block_type (struct block *);
```

Swap space management

- Are all these interfaces enough for our task?
- How to manage swap space?
  - e.g., finding free slots for new swap-out requests? Identifying which slot to swap in in page faults?
  - What data structure should be used for managing the swap space?
  - …

When we execute a program…

- **When we read it…**
  - …
- **When we write it…**
  - write back instead of write through
  - dirty bit
  - some interfaces may be useful: ***userprog/pagedir.h***

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void pagedir_set_dirty (uint32_t *pd, const void *upage, bool dirty);
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```

- **When we extend it…**
  - Stack growth or mmap (new mapping!)

Revisit lab 3a tasks

Exercise 1.1

Implement paging for segments loaded from executables.

- All of these pages should be loaded **lazily**, that is, only as the kernel intercepts page faults for them.
- Upon eviction:
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Adjust user memory access code in *system call handling* to deal with potential page faults.

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  - swap space
- **a.2**
  - replacement policy
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Revisit lab 3b tasks

Exercise 1.1

Implement stack growth.

- In project 2, the stack was **a single page** at the top of the user virtual address space, and programs were limited to that much stack.
- Now, **if the stack grows past its current size, allocate additional pages as necessary**.

Exercise 2.1

Implement memory mapped files, including the following system calls.

- mapid_t **mmap** (int fd, void *addr)
- void **munmap** (mapid_t mapping)

- **b.1**
  - allocate a new page when stack grows past current page
- **b.2**
  - mmap, munmap
  - can map many kinds of files

Key parts

- **User pages mapping maintenance**
- **Frame management**
- **Swap space management**
- **Bonus: Implementing shared memory in Pintos/Tacos?**
  - **When:** exec() shares the same frames for identical executables, with copy-on-write (COW); mmap() can also share file-backed or anonymous pages
  - **What:** think about the mapping between virtual and physical pages - they are now many-to-many; what extra design (e.g., an extra abstraction layer?) might help you track these mappings without too much overhead?
  - **How:** Learn from the great example of Linux - not necessarily the code, but its design.
  - **Why:** If you find it cool :D …and, it is indeed possible.

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Bitmap

- *lib/kernel/bitmap.h, lib/kernel/bitmap.c*
- Bitmap is an effective way to make marks.
- Bitmap is used in memory *pool* to mark whether the pages in pool are used.

```
/** A memory pool. */
struct pool
  {
    struct lock lock;                   /**< Mutual exclusion. */
    struct bitmap *used_map;            /**< Bitmap of free pages. */
    uint8_t *base;                      /**< Base of pool. */
  };
```

```
/** Creation and destruction. */
struct bitmap *bitmap_create (size_t bit_cnt);
struct bitmap *bitmap_create_in_buf (size_t bit_cnt, void *, size_t byte_cnt);
size_t bitmap_buf_size (size_t bit_cnt);
void bitmap_destroy (struct bitmap *);

/** Bitmap size. */
size_t bitmap_size (const struct bitmap *);
```

```
/** Setting and testing single bits. */
void bitmap_set (struct bitmap *, size_t idx, bool);
void bitmap_mark (struct bitmap *, size_t idx);
void bitmap_reset (struct bitmap *, size_t idx);
void bitmap_flip (struct bitmap *, size_t idx);
bool bitmap_test (const struct bitmap *, size_t idx);

/** Setting and testing multiple bits. */
void bitmap_set_all (struct bitmap *, bool);
void bitmap_set_multiple (struct bitmap *, size_t start, size_t cnt, bool);
size_t bitmap_count (const struct bitmap *, size_t start, size_t cnt, bool);
bool bitmap_contains (const struct bitmap *, size_t start, size_t cnt, bool);
bool bitmap_any (const struct bitmap *, size_t start, size_t cnt);
bool bitmap_none (const struct bitmap *, size_t start, size_t cnt);
bool bitmap_all (const struct bitmap *, size_t start, size_t cnt);
```

Hash

- *lib/kernel/hash.h, lib/kernel/hash.c*
- The element stored in the hash table can be quickly retrieved.
- Like *list_elem* for *List*, *hash_elem* is used in *hash*.

```
/** Basic life cycle. */
bool hash_init (struct hash *, hash_hash_func *, hash_less_func *, void *aux);
void hash_clear (struct hash *, hash_action_func *);
void hash_destroy (struct hash *, hash_action_func *);

/** Search, insertion, deletion. */
struct hash_elem *hash_insert (struct hash *, struct hash_elem *);
struct hash_elem *hash_replace (struct hash *, struct hash_elem *);
struct hash_elem *hash_find (struct hash *, struct hash_elem *);
struct hash_elem *hash_delete (struct hash *, struct hash_elem *);

/** Iteration. */
void hash_apply (struct hash *, hash_action_func *);
void hash_first (struct hash_iterator *, struct hash *);
struct hash_elem *hash_next (struct hash_iterator *);
struct hash_elem *hash_cur (struct hash_iterator *);

/** Information. */
size_t hash_size (struct hash *);
bool hash_empty (struct hash *);
```

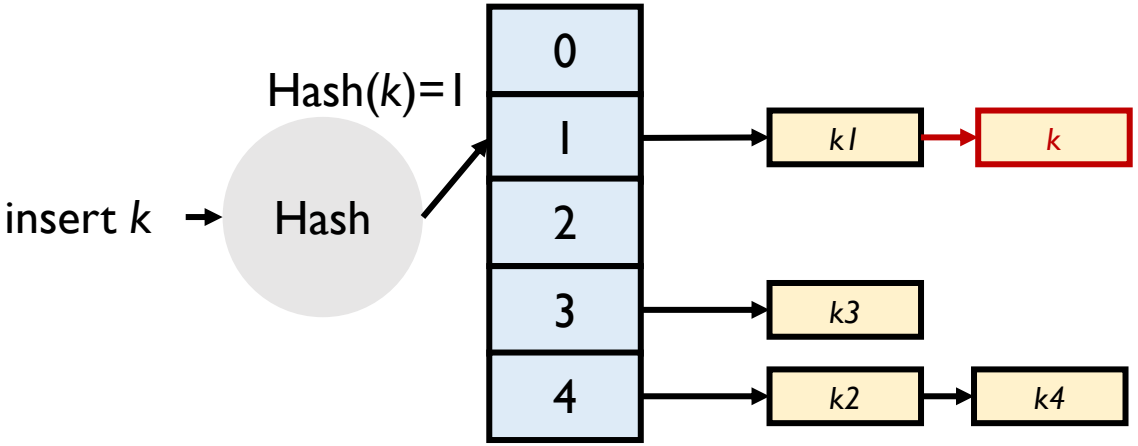
```
/** Computes and returns the hash value for hash element E, given
   auxiliary data AUX. */
typedef unsigned hash_hash_func (const struct hash_elem *e, void *aux);

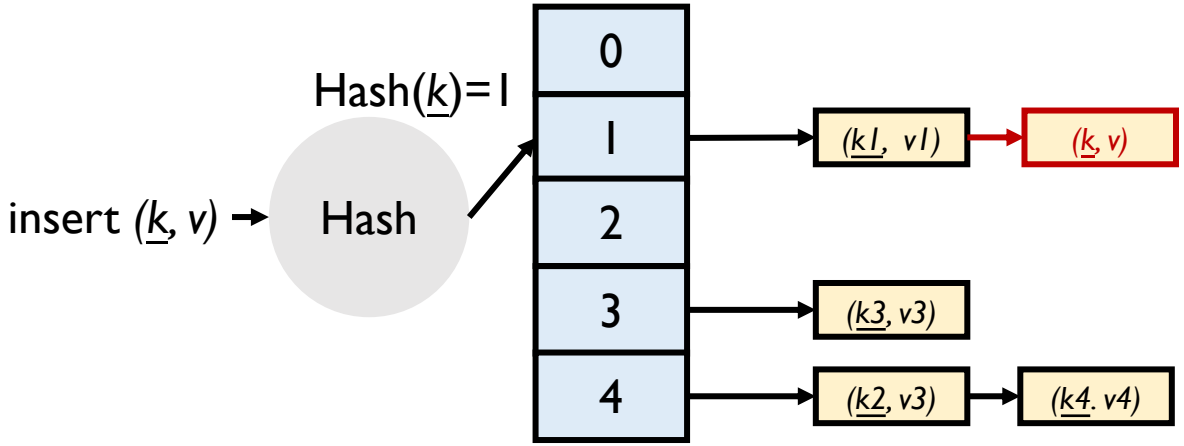
/** Compares the value of two hash elements A and B, given
   auxiliary data AUX.  Returns true if A is less than B, or
   false if A is greater than or equal to B. */
typedef bool hash_less_func (const struct hash_elem *a,
                             const struct hash_elem *b,
                             void *aux);
```

```
/** Hash element. */
struct hash_elem
  {
    struct list_elem list_elem;
  };
```

How to use hash table to implement a fast mapping (hash map)

- Given a key *k*, get its correspondent value *v* efficiently
- This is quite helpful in implementing our mapping from user pages to swap space content or file content.
- **Just use hash table to maintain keys, and combine correspondent values with keys.**
  - e.g. put key and value in a struct, and use key as the hash key





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Other things you may need to give attention to…

- **Synchronization problem**
  - especially when accessing some global variables
  - support pinned pages
- **Remember to free the resources when the process exits**
- **Note that a disk sector is *512B* while a page is *4096B***
- **Read requirements in document carefully**
- …

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Thanks for your listening.