# CMSC421: Principles of Operating Systems

**Nilanjan Banerjee**

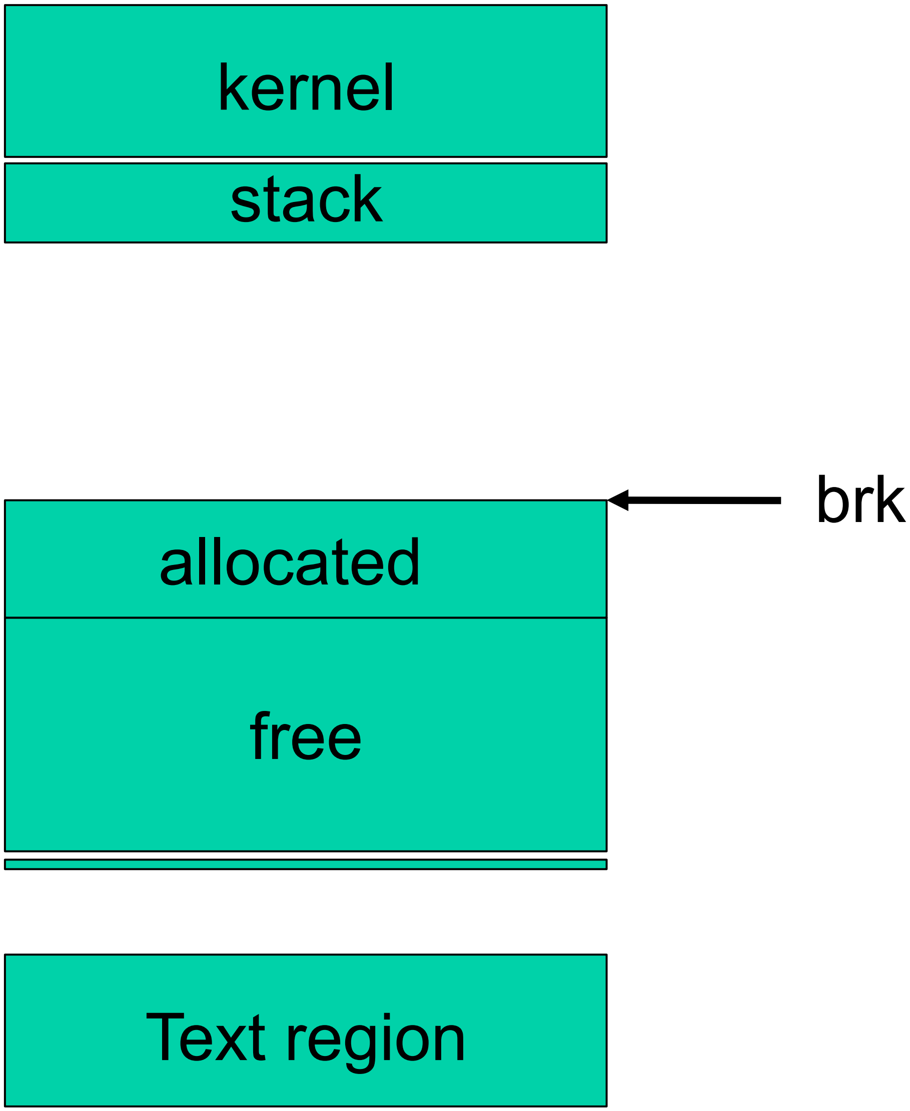
*Assistant Professor, University of Maryland*
Baltimore County
nilanb@umbc.edu
http://www.csee.umbc.edu/~nilanb/teaching/421/


**Acknowledgments: Some of the slides are adapted from Prof. Mark Corner and Prof. Emery Berger's OS course at Umass Amherst**

# Announcements

- Project 2 progress report due one week from Nov. 9th

# Coalescing

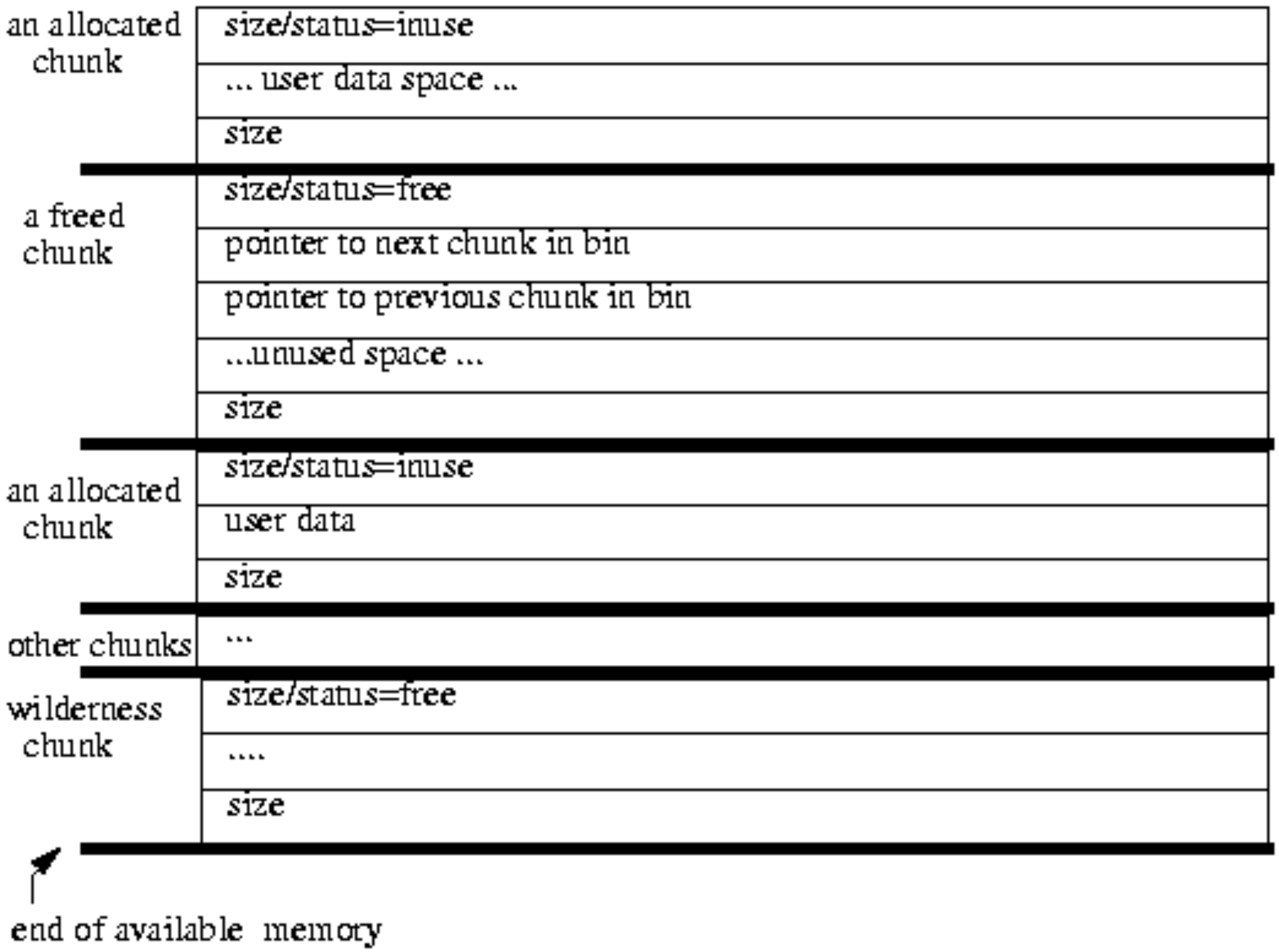



malloc(200)

# Jobs of a memory allocator like malloc

- Manage heap space in virtual memory
  - Use sbrk to ask for more memory from OS
- Coalescing
  - Keep track of free blocks
  - Merge them together when adjacent blocks are free
- Malloc needs to be really fast
  - Decide which free block to allocate
  - Lets take a look at the data structure that is used for implementing malloc and free

## Memory layout of the heap




**this linked list can be ordered in different ways**

**http://gee.cs.oswego.edu/dl/html/malloc.html**

# Selecting the free block to allocate: Fragmentation

- Intuitively, fragmentation stems from “breaking” up heap into unusable spaces
  - More fragmentation = worse utilization
- External fragmentation
  - Wasted space outside allocated objects
- Internal fragmentation
  - Wasted space inside an object

## Classical Algorithms

- First-fit
  - find first chunk of desired size

# Classical Algorithms

- Best-fit
  - find chunk that fits best
    - Minimizes wasted space

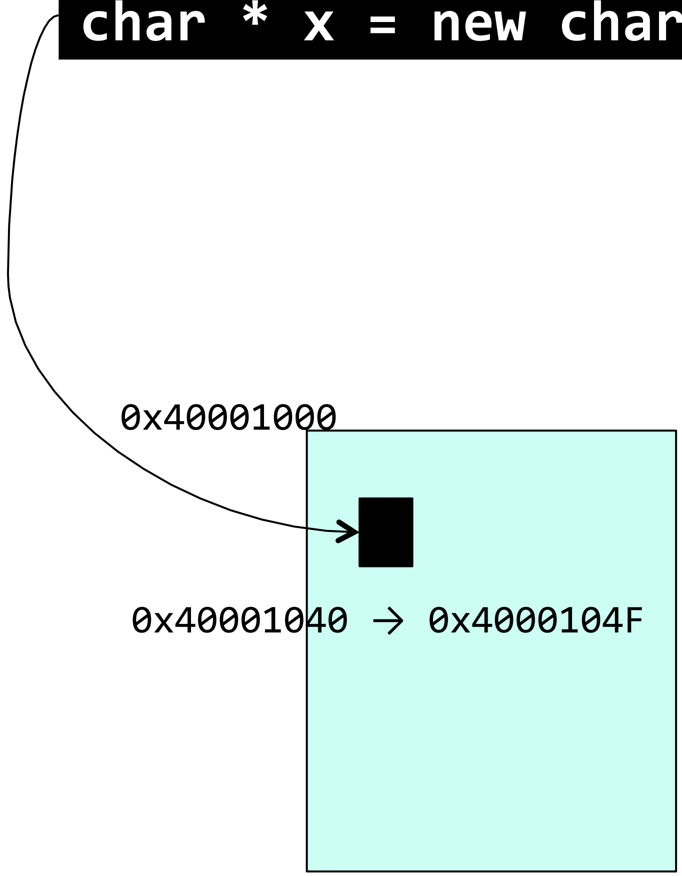
# Classical Algorithms

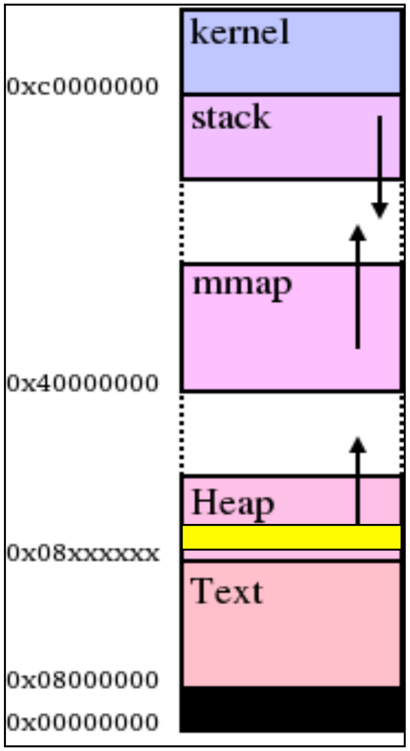
- Worst-fit
  - find chunk that fits worst
  - name is a misnomer!
  - keeps large holes around
- Reclaim space: coalesce free adjacent objects into one big object

# A Day in the Life of a Page

- Allocate some memory

```
char * x = new char[16];
```



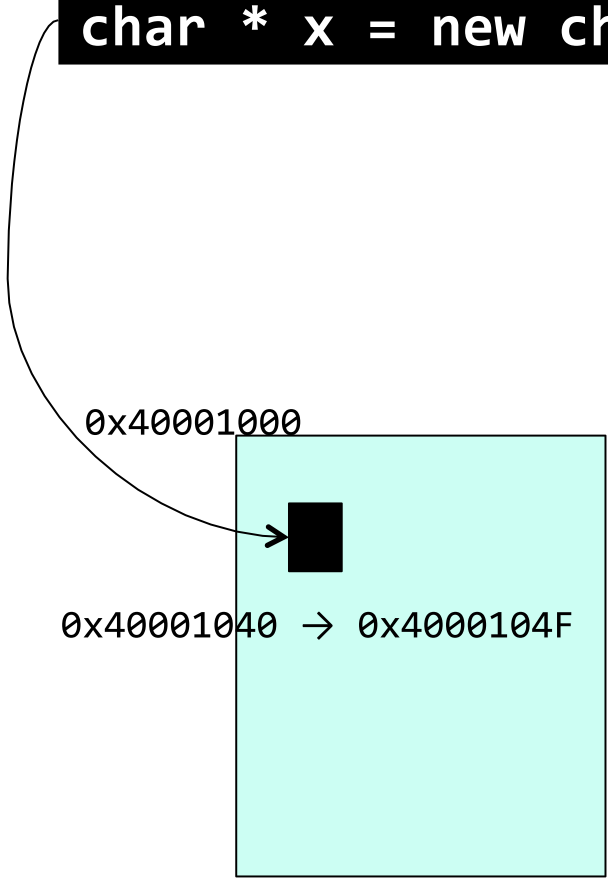



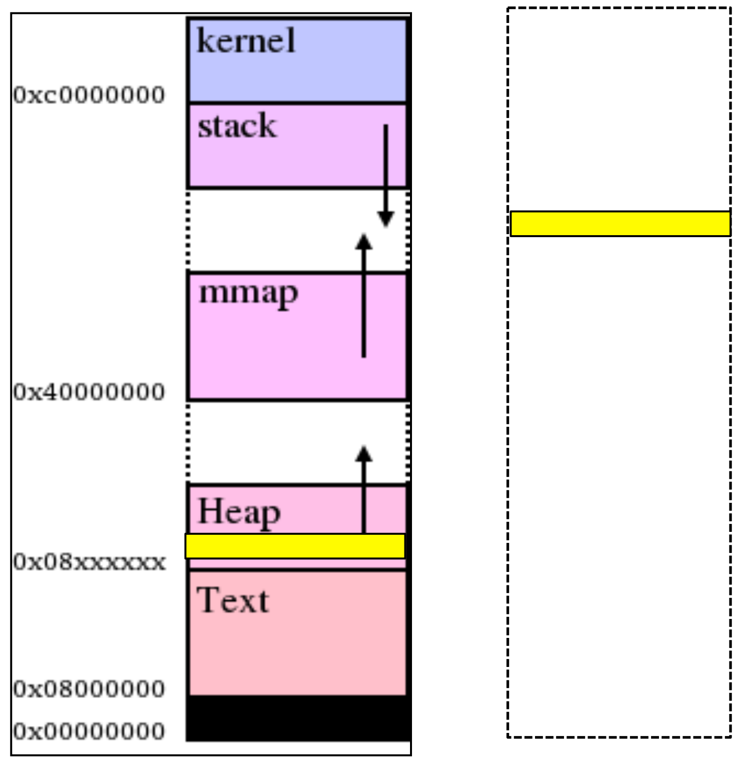

*virtual memory layout*

# A Day in the Life of a Page

- Update page tables

```
char * x = new char[16];
```



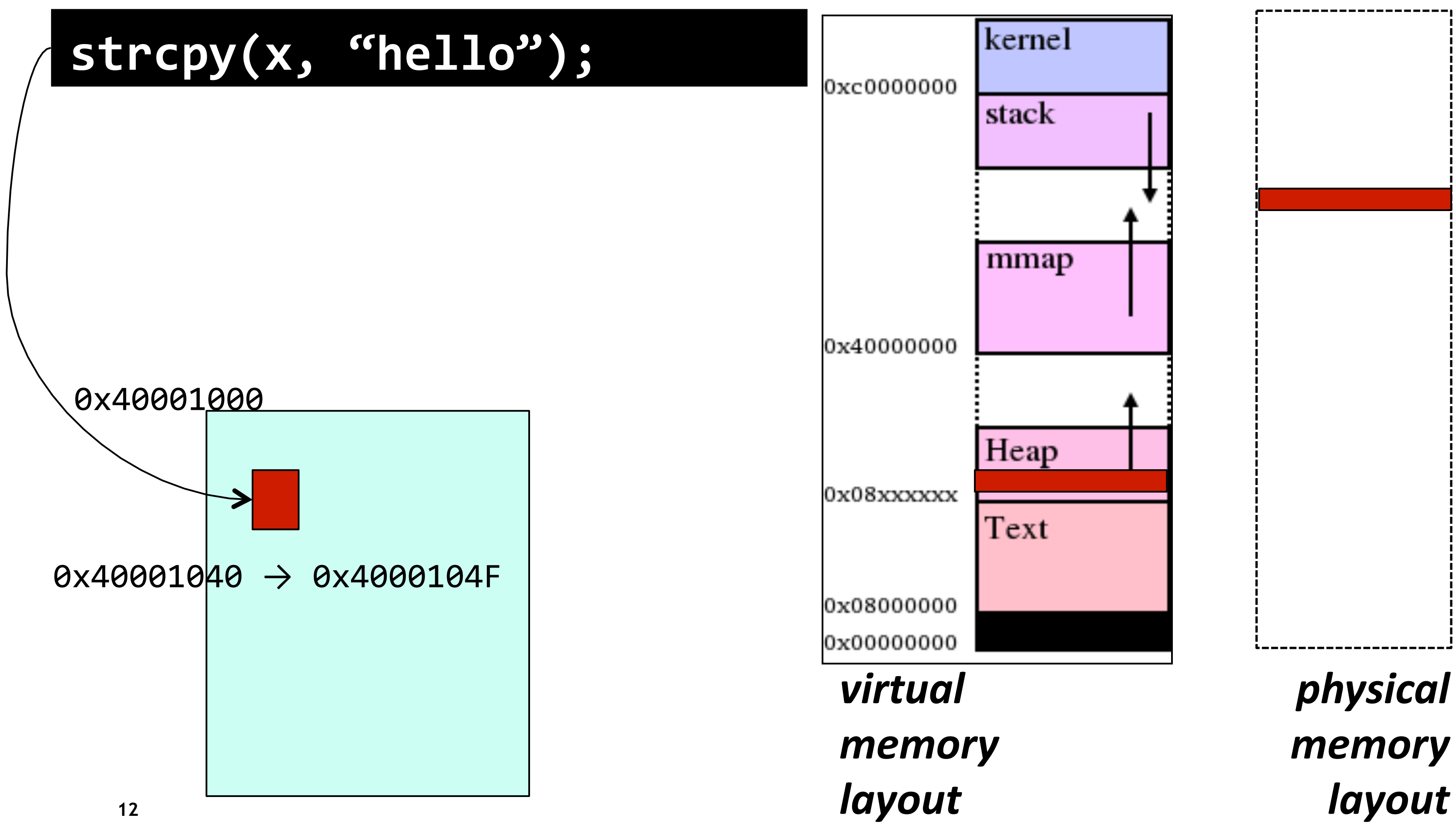




*virtual memory layout*

*physical memory layout*

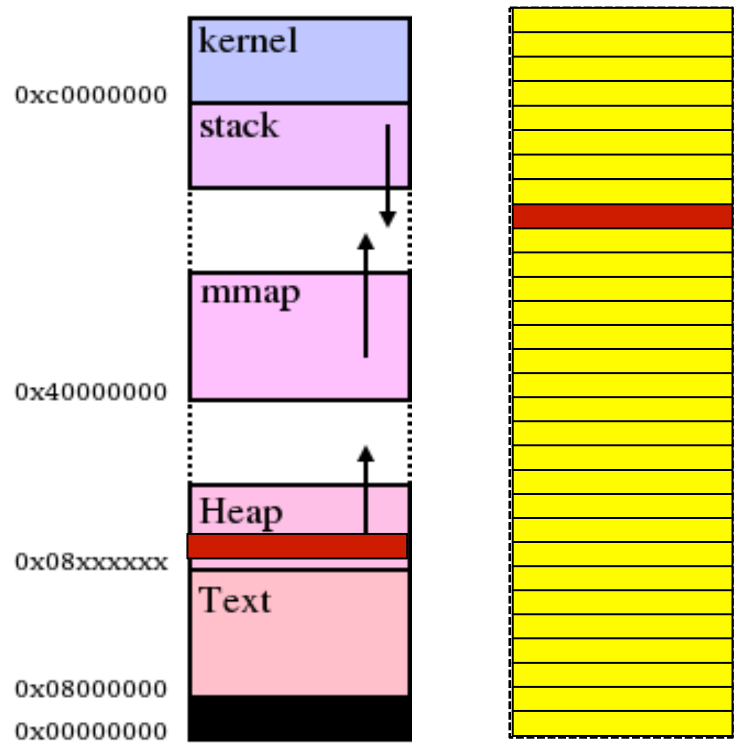
# A Day in the Life of a Page

- Write contents – *dirty* page



# A Day in the Life of a Page

- Other processes fill up memory…

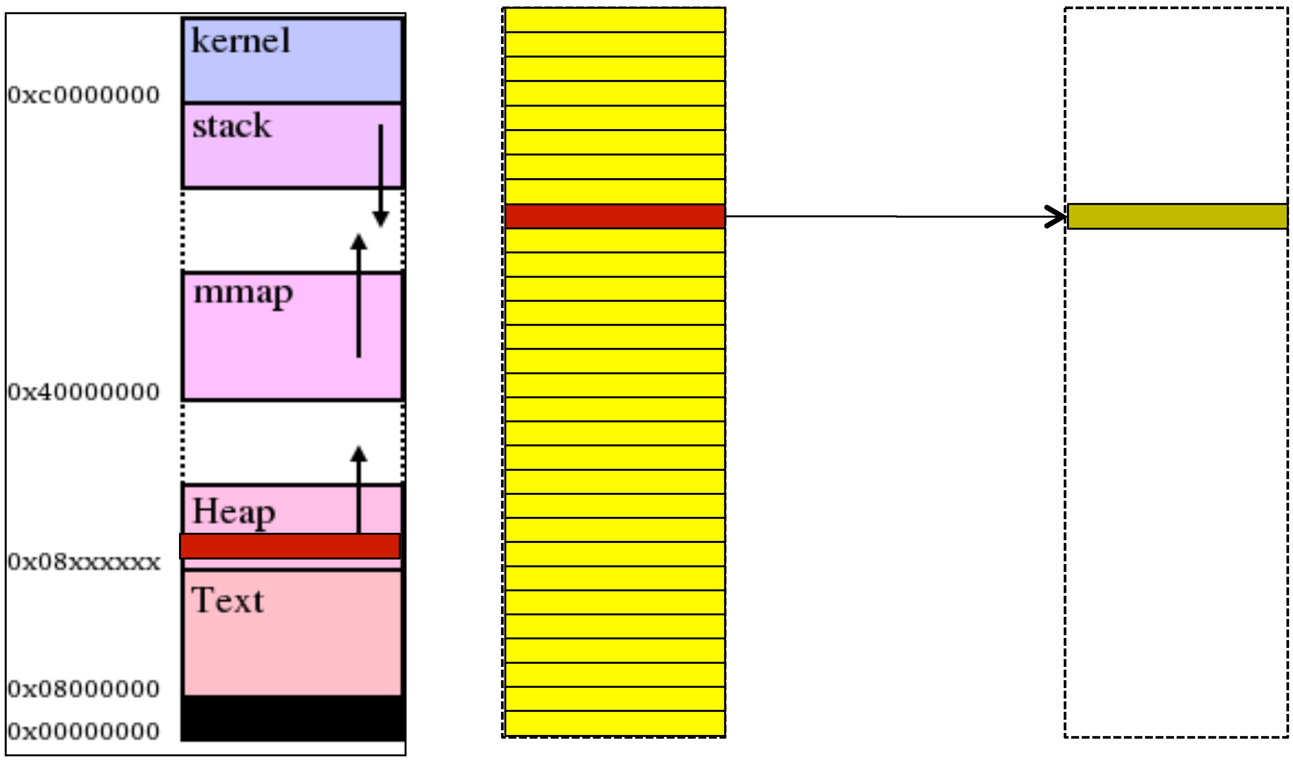



***virtual memory layout***

***physical memory layout***

# A Day in the Life of a Page

- Forcing our page to be *evicted* (*paged out*)



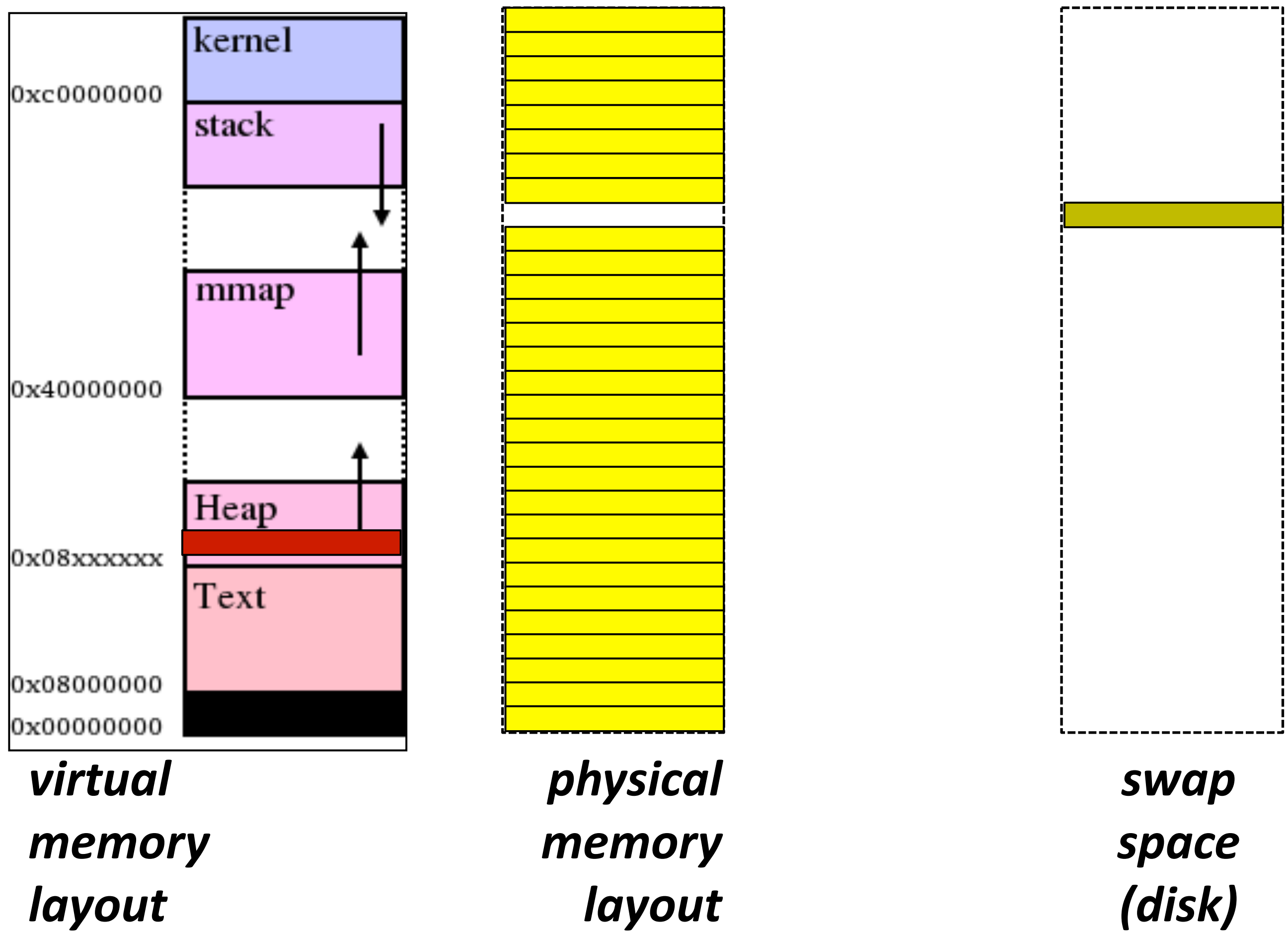

***virtual memory layout***

***physical memory layout***

***swap space (disk)***

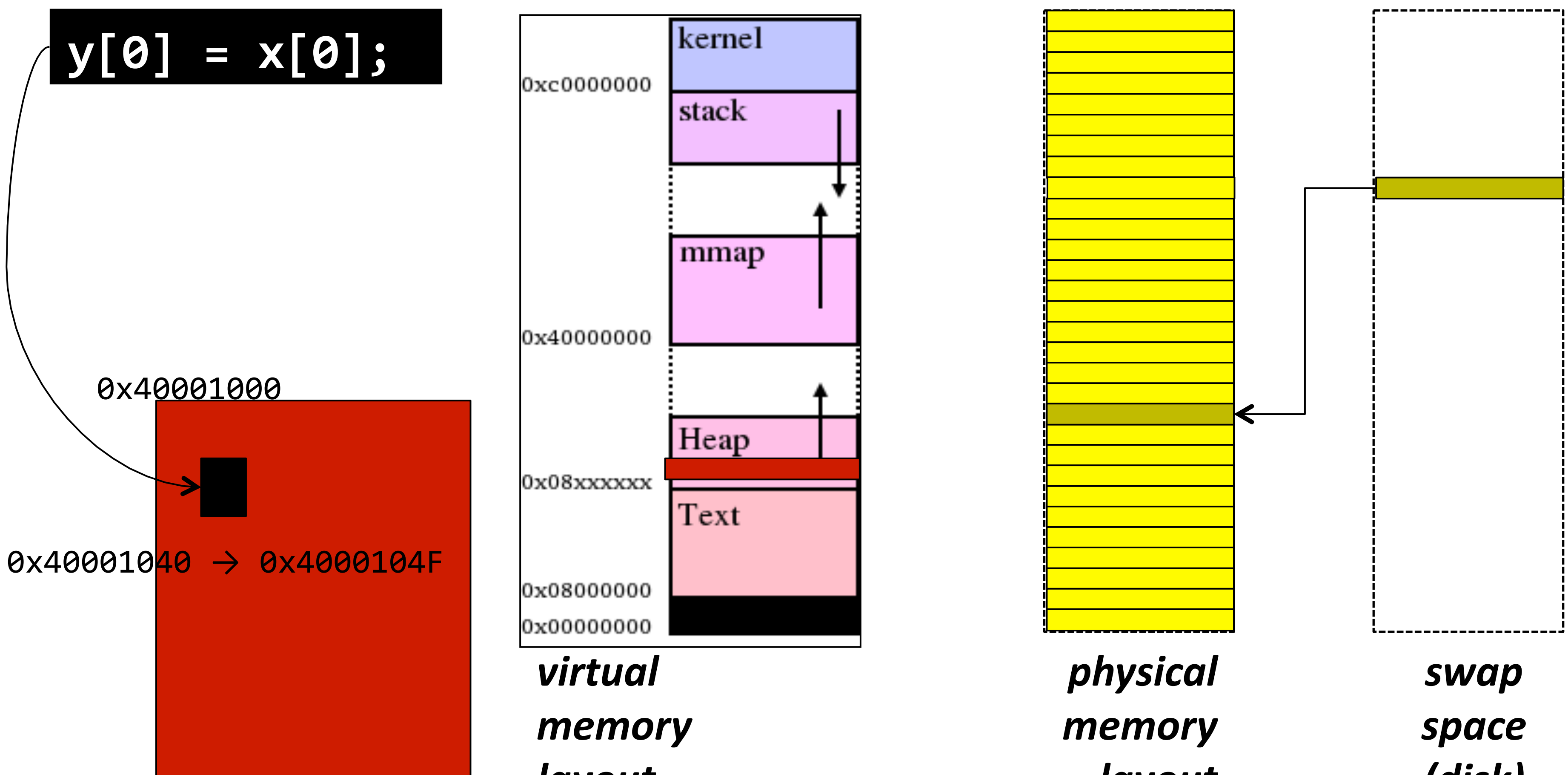
# A Day in the Life of a Page

- Now page *nonresident & protected*



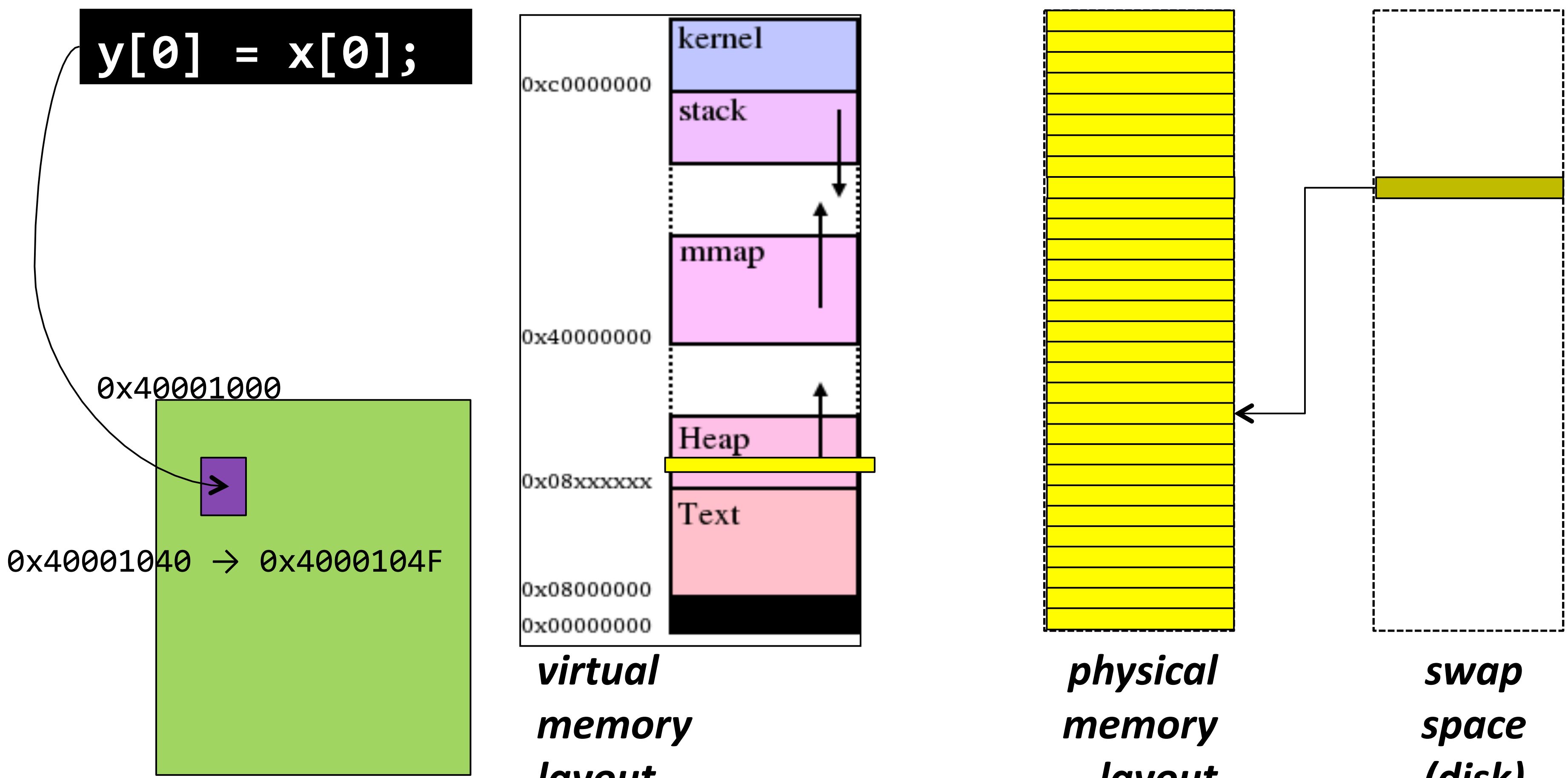
# A Day in the Life of a Page

- *Touch* page – *swap* it in



# A Day in the Life of a Page

- *Touch* page – *swap* it in



## Talked about malloc? What about physical frame mgmt?

- **malloc** works in virtual memory (works in user space)
  - Manages free blocks
  - Allocates virtual address on the heap
- Remember the OS still has to manage physical frames
  - The problem that the OS faces with physical frame allocation is the similar to malloc
  - Manage physical frames that all processes in the system requests.
- Difference with malloc
  - Has to work across all processes
    - Each process perceives 4GB of space, but in actuality there is only 4GB of physical memory space

# Tasks of the OS physical page management unit

- **Allocate new pages to applications**
  - OS do this lazily
  - malloc call would usually return immediately
  - OS allocates a new physical only when the process reads/writes to the page
  - Similar to the Copy-on-Write policy for fork()
- In the event that all physical frames are taken
  - OS needs to evict pages
    - Take page from main memory and store it on swap space
  - Needs a policy for evicting pages

# Page replacement policy for Demand Paging?

**What is the optimal page replacement policy?**

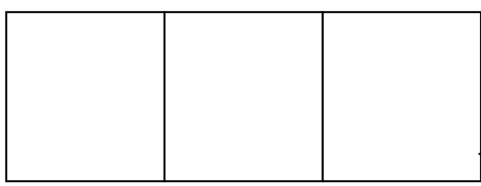
## Optimal Page Replacement policy

- **Find the page that is going to used farthest into the future**
  - Evict the page from main memory to swap space
  - Allocate the freed page to the new process
  - Problems: it is impossible to predict the future

- Approximation is LRU (least recently used page)
  - Find the page that is least recently used and evict it
  - Remember this has to be **super-fast**
  - **What would be techniques to implement this in the kernel?**

# Implementing Exact LRU

- On each reference, time stamp page
- When we need to evict: select oldest page
  = least-recently used



A, B, C, B, C, C, D

# Implementing Exact LRU

- On each reference, time stamp page
- When we need to evict: select oldest page = least-recently used

| | | |
|---|---|---|
| A<br>1 | | |

A, B, C, B, C, C, D

# Implementing Exact LRU

- On each reference, time stamp page
- When we need to evict: select oldest page = least-recently used

| | | |
|---|---|---|
| A | B | |
| 1 | 2 | |

A, B, C, B, C, C, D

# Implementing Exact LRU

- On each reference, time stamp page
- When we need to evict: select oldest page = least-recently used

| A | B | C |
|---|---|---|
| 1 | 2 | 3 |

A, B, C, B, C, C, D

# Implementing Exact LRU

- On each reference, time stamp page
- When we need to evict: select oldest page
  = least-recently used

| A | B | C |
|---|---|---|
| 1 | 4 | 3 |

A, B, C, B, C, C, D

# Implementing Exact LRU

- On each reference, time stamp page
- When we need to evict: select oldest page = least-recently used

| A | B | C |
|---|---|---|
| 1 | 4 | 5 |

A, B, C, B, C, C, D

# Implementing Exact LRU

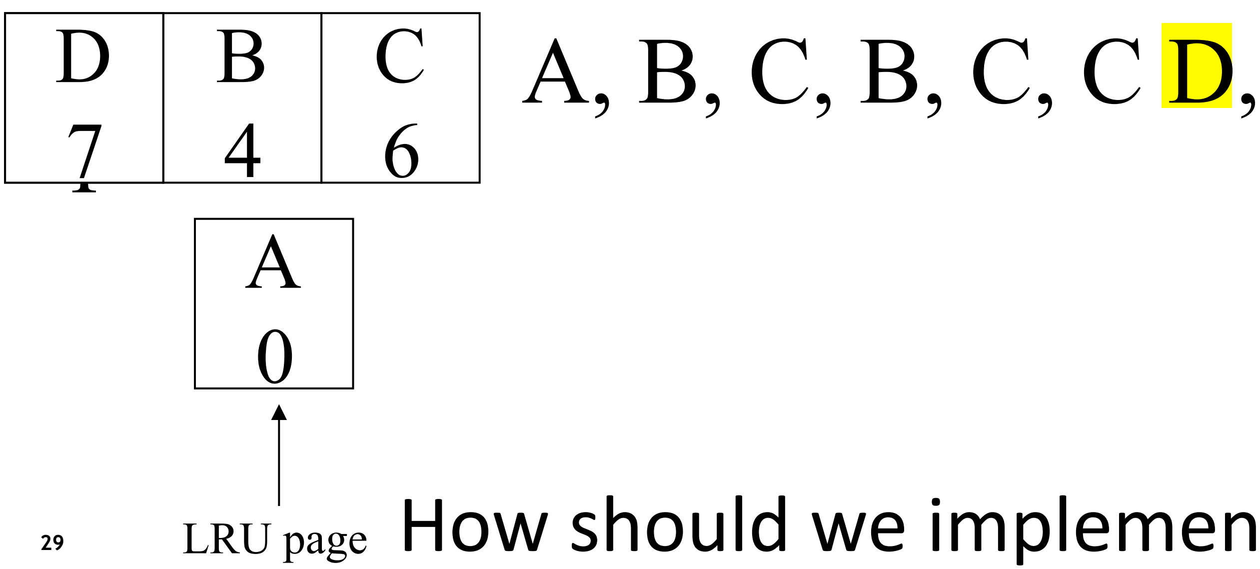
- On each reference, time stamp page
- When we need to evict: select oldest page = least-recently used

| A | B | C |
|---|---|---|
| 1 | 4 | 6 |

A, B, C, B, C, C, D

## Implementing Exact LRU

- On each reference, time stamp page
- When we need to evict: select oldest page = least-recently used




How should we implement this?

# Implementing Exact LRU

- Could keep pages in order
  – optimizes eviction
    - Priority queue:
      update = O(log n), eviction = O(log n)

- Optimize for common case!
    - Common case: hits, not misses
    - Hash table:
      update = O(1), eviction = O(n)

# Cost of Maintaining Exact LRU

- Hash tables: too expensive
  - On every reference:
    - Compute hash of page address
    - Update time stamp

# Cost of Maintaining Exact LRU

- Alternative: doubly-linked list
  - Move items to front when referenced
  - LRU items at end of list
  - Still too expensive
    - 4-6 pointer updates per reference
- Can we do better?

## Hardware Support and approximate LRU (Linux Kernel)

- Maintain reference bits for every page
  - On each access, set reference bit to 1
  - Page replacement algorithm periodically resets reference bits

| A | B | C |
|---|---|---|
| 1 | 1 | 1 |

A, B, C, B, C, C, D

## Hardware Support

- Maintain reference bits for every page
  - On each access, set reference bit to 1
  - Page replacement algorithm periodically resets reference bits

| A | B | C |
|---|---|---|
| 0 | 0 | 0 |

A, B, C, | B, C, C, D

reset reference bits

## Hardware Support

- Maintain reference bits for every page
  - On each access, set reference bit to 1
  - Page replacement algorithm periodically resets reference bits

| A | B | C |
|---|---|---|
| 0 | 1 | 0 |

A, B, C, | B, C, C, D

## Hardware Support

- Maintain reference bits for every page
  - On each access, set reference bit to 1
  - Page replacement algorithm periodically resets reference bits

| A | B | C |
|---|---|---|
| 0 | 1 | 1 |

A, B, C, | B, C, C, D

## Hardware Support

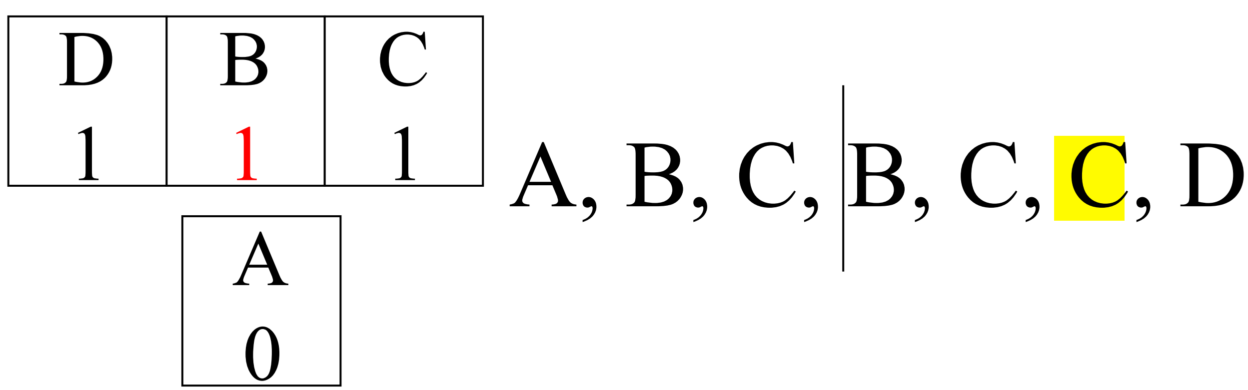
- Maintain reference bits for every page
  - On each access, set reference bit to 1
  - Page replacement algorithm periodically resets reference bits

| A | B | C |
|---|---|---|
| 0 | 1 | 1 |

A, B, C, | B, C, C, D

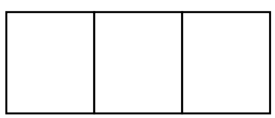
# Hardware Support

- Maintain reference bits for every page
  - On each access, set reference bit to 1
  - Page replacement algorithm periodically resets reference bits
  - Evict page with reference bit = 0
- Cost per miss = O(n)



# Most-Recently Used (MRU)

- Evict most-recently used page
- Shines for LRU's worst-case:

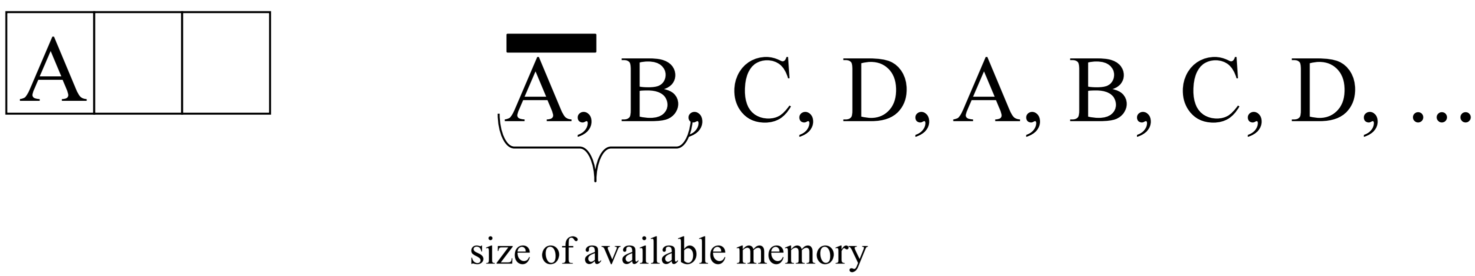


A, B, C, D, A, B, C, D, ...

size of available memory

## Most-Recently Used (MRU)

- Evict most-recently used page
- Shines for LRU's worst-case: loop that exceeds RAM size



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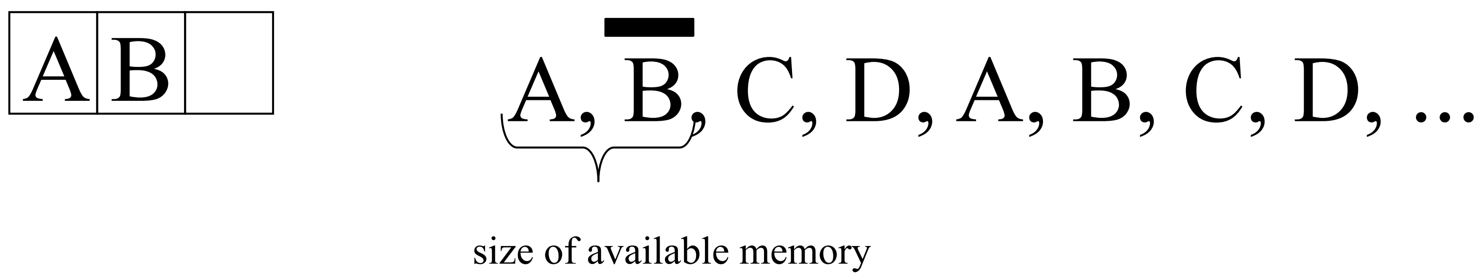

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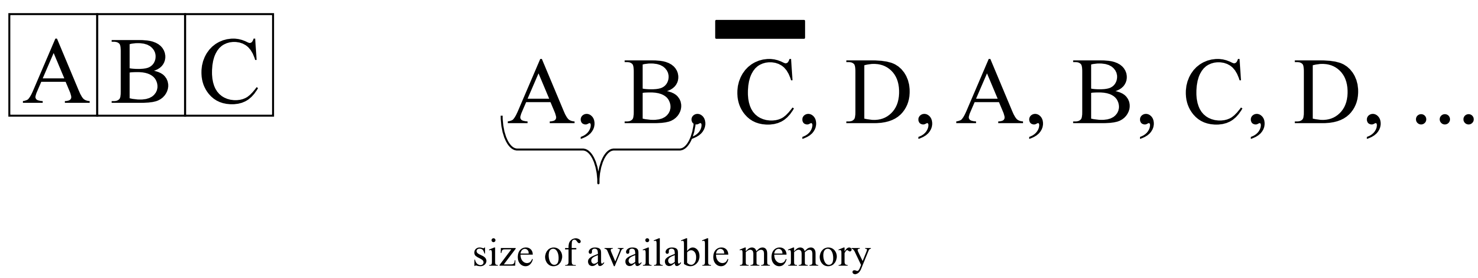

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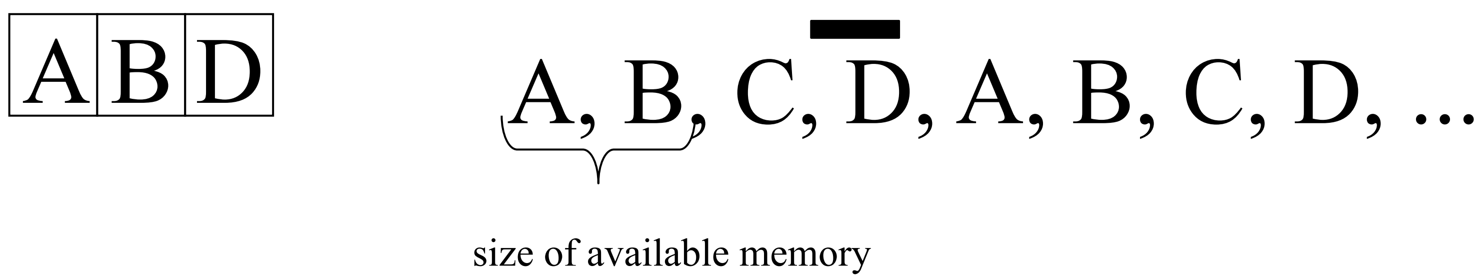

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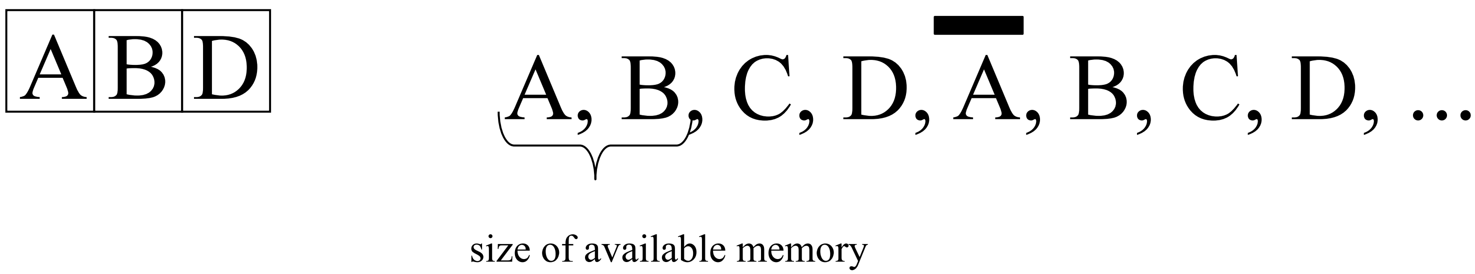

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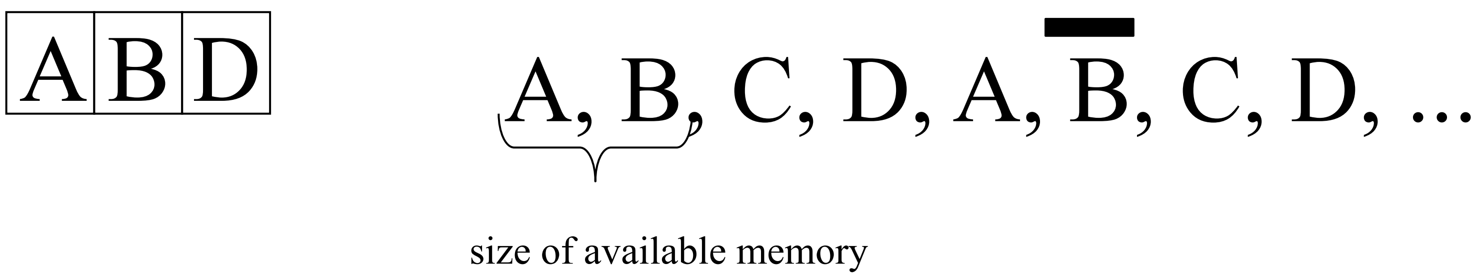

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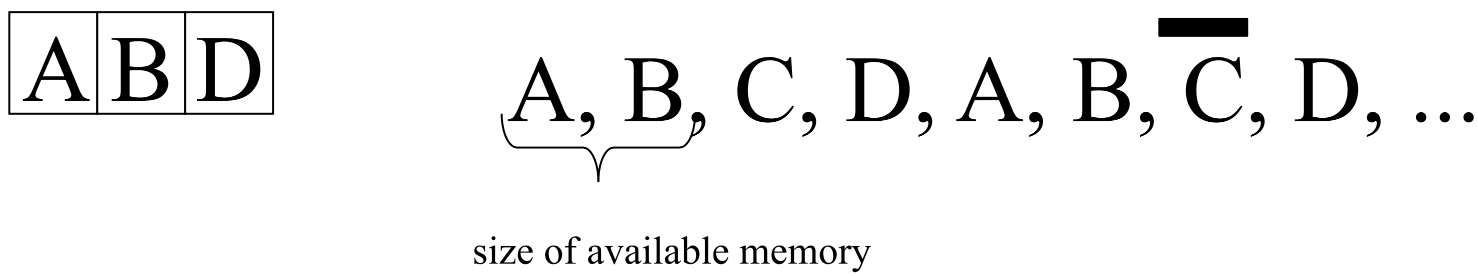
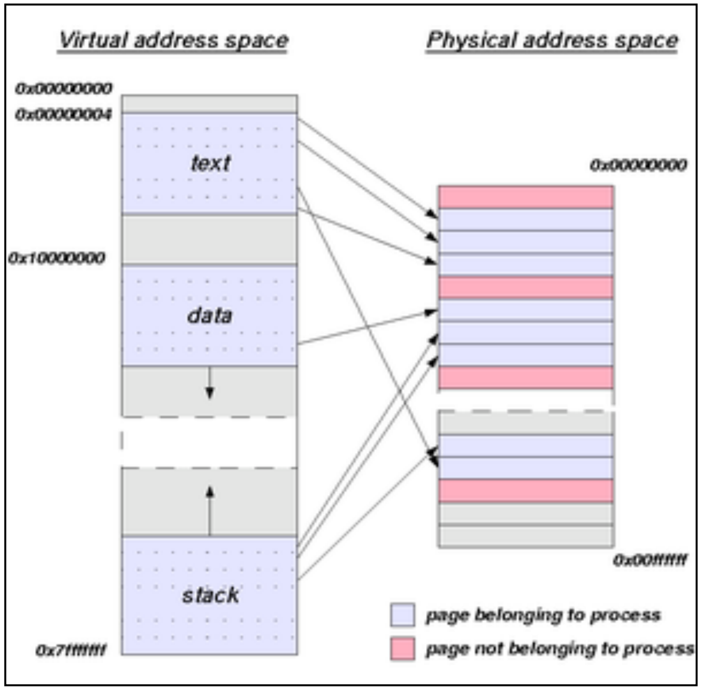


# FIFO

- First-in, first-out: evict oldest page
- As competitive as LRU, but performs miserably in practice!
  - Ignores locality
  - Suffers from Belady's anomaly:
    - More memory can mean more paging!
  - LRU & similar algs. do not
    - Stack algorithms – more memory means ≥ hits

# Tricks with Page Tables: Sharing

- Paging allows sharing of memory across processes
  - Reduces memory requirements
- Shared stuff includes code, data
  - Code typically R/O



# Tricks with Page Tables: COW

- Copy on write (COW)
  - Just copy page tables
  - Make all pages read-only
- What if process changes mem?

- All processes are created this way!

# In-class Discussion