Virtual Memory

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Slides adapted from Dr. B. Fraser

Topics

1) How can each process have its own memory space?
2) How can the OS allocate memory to processes?
3) What if we run out of memory?

Context:

What is the problem we are trying to solve?

Details

- Virtual memory is one of the most important OS concepts.
  - It is also a good example that shows
    - the power of abstraction.
- Can find more info in OSTEP book (more depth than we require)
  - Chapter 13 The Abstraction: Address Spaces https://pages.cs.wisc.edu/~remzi/OSTEP/vm-intro.pdf
  - Chapter 15 Mechanism: Address Translation https://pages.cs.wisc.edu/~remzi/OSTEP/vm-mechanism.pdf
  - Chapter 18 Paging: Introduction https://pages.cs.wisc.edu/~remzi/OSTEP/vm-paging.pdf
  - Chapter 16 Segmentation https://pages.cs.wisc.edu/~remzi/OSTEP/vm-segmentation.pdf

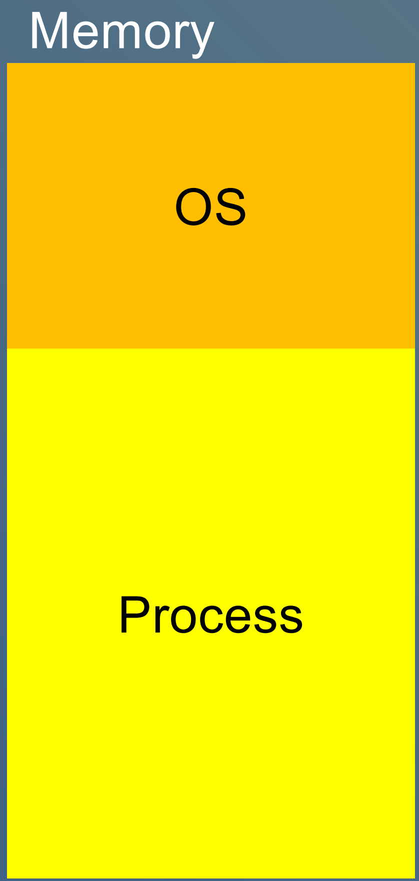
Memory Layout in the Early Days

- The entire memory was divided into two: OS and program.

  – Could run only a single program.

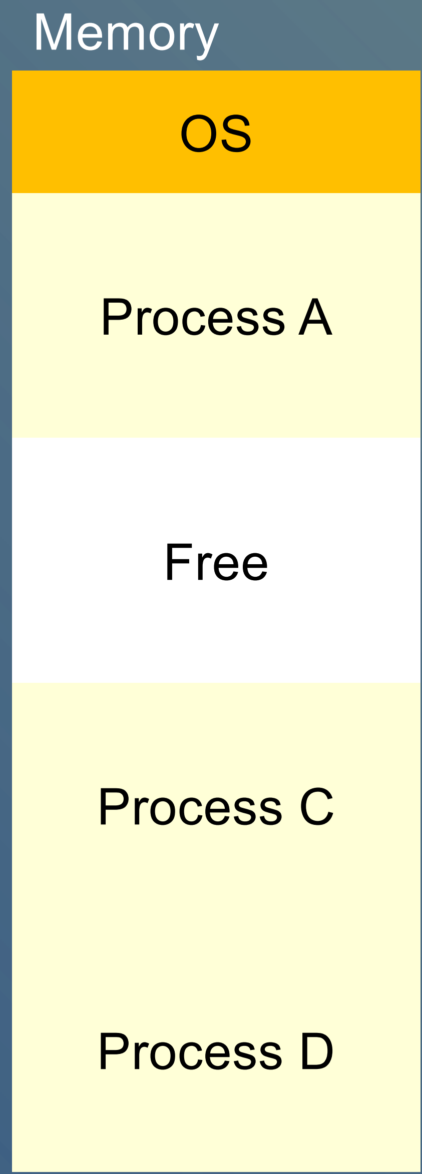
  – However, there were many users who wanted to run their own programs!

  – Users could not share the machine, lead to low utilization.



Early Memory Sharing Attempt

- Memory was divided into
  .. fixed-size regions.
- Could run multiple processes:
  ..each process used a fixed range of memory.
- Problems
  - Each process could only use a fixed (small) size memory region.
  - .. No protection/isolation across processes: a “bad” pointer in one process could access another process's memory.



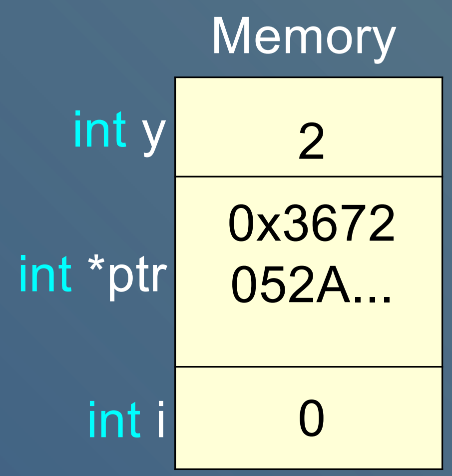
Understanding Memory

Address-Based Memory Operations

- Variables are a convenience for programmers:
  - .. The computer really works on the memory.
  - Most instruction reads from or write to memory.
- Random Access Memory (RAM)
  - .. All addresses are equally fast to access.
  - Unlike a hard-drive (disk) which spins like a record / CD / DVD:
    Disks cannot access all data equally fast, but are bigger!

Code

```c
int i = 0;
int *ptr = &i;
int y = i + 2;
```



Locality

- At any given moment, a program is likely to be accessing
  ..only a small part of its memory.
- Code:
  - Mostly accessed sequentially
  - Loops and 'if' (branches) jump around only a little usually.
- Data: Access small parts of data at once
  - Variables are often accessed repeatedly (a loop), or same data structure accessed over and over.
- ..Temporal Locality:
  - recently used data is likely to be reused (i.e., loops)
- ..Spatial Locality:
  - the next data you need is likely nearby previous data you used. (e.g., an array / struct)

Understanding Memory Solutions

- Fundamental Properties of Memory Use
  - Programs really work on memory.
  - Programs access the same data over and over again (temporal locality)
  - Programs access data nearby to previously accessed data (spacial locality)
- Can we use these to design how to share memory?

ABCD: Locality

- Assume a program has just accessed memory locations 6 and 12.
  - Spacial locality suggests we might soon access?
    (a) 0, 3, 9
    (b) 6, 12
    (c) 5, 7, 11, 13
    (d) 4, 8, 10, 14
  - Temporal locality suggests we might soon access?
    (a) 0, 3, 9
    (b) 6, 12
    (c) 5, 7, 11, 13
    (d) 4, 8, 10, 14

14
13
12
11
10
9
8
7
6
5
4
3
2
1
0

Solution:

Virtual Memory

Memory Abstraction

"All problems in computer science can be solved by another level of indirection, except for the problem of too many levels of indirection."
-- David Wheeler

- Virtual memory is a mechanism to enable:

(i).. physical memory sharing for multiple processes

(ii).. isolation of each process's memory access

- Simply put,.. a process uses virtual memory instead of physical memory.

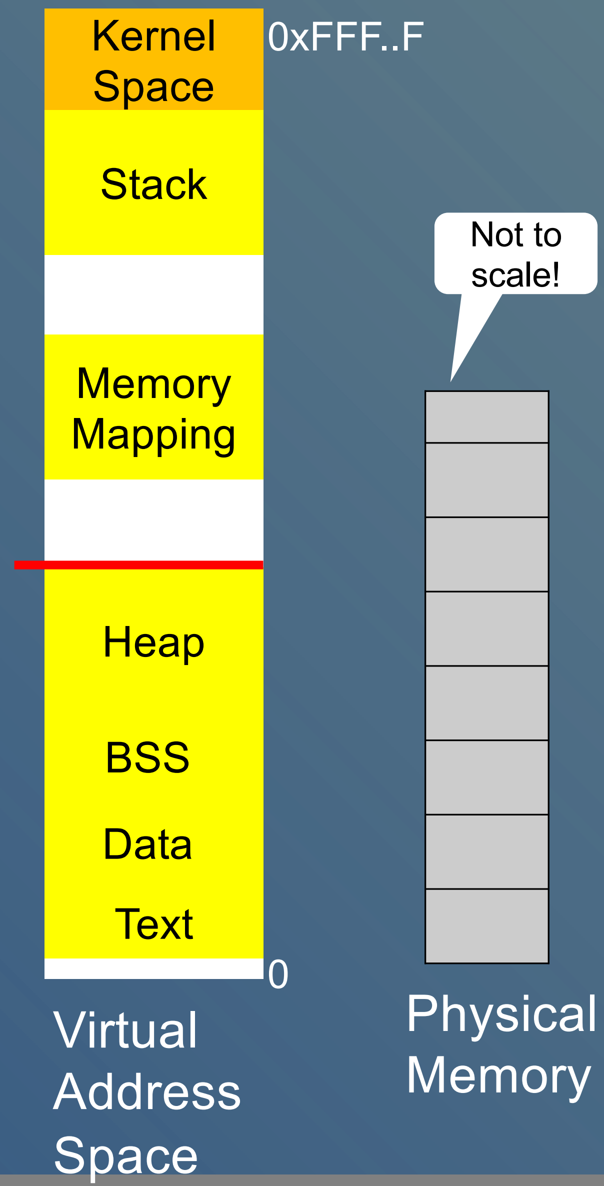
- Virtual memory consists of:

  – virtual address space and address translation.

  – Virtual memory is a good example that demonstrates the power of abstractions.

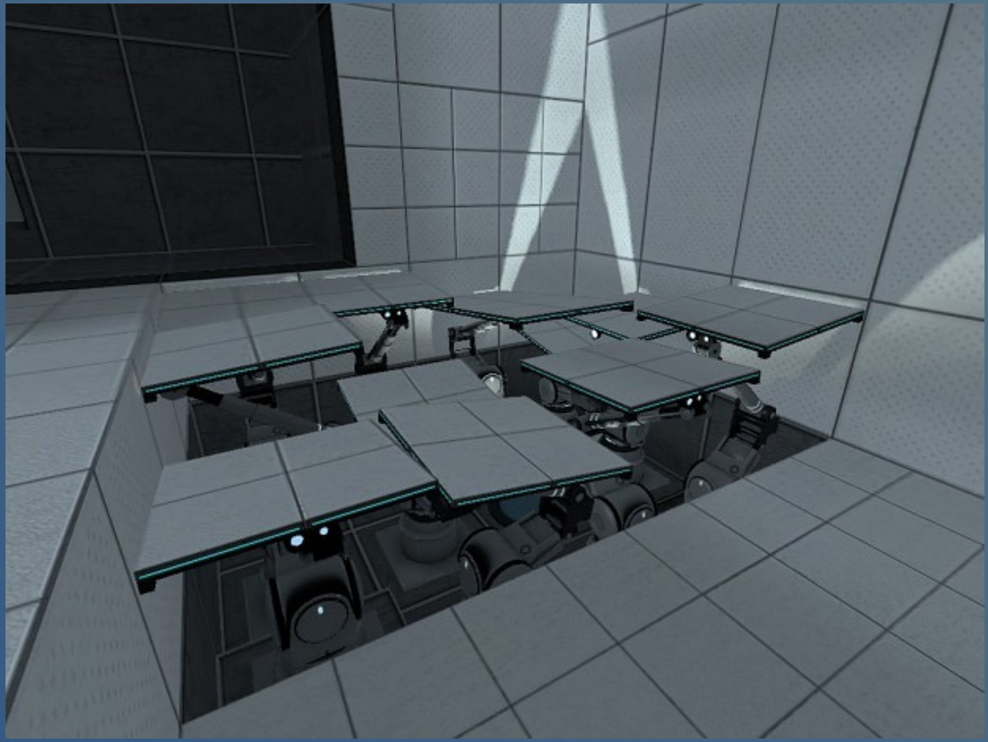
Virtual Address Space

- All memory discussed so far
  ..has been virtual memory!
  - Virtual memory size is
    - determined by the pointer size: 0 to 2^{64}-1
  - Virtual memory is a memory abstraction (imaginary space) that the program & programmer operates in.
  - The OS + hardware build us this imaginary space.
- Virtual vs Physical
  - User-level processes works with virtual addresses.
  - Kernel-level components can deal with both virtual and physical addresses.



Room Analogy

- Imagine a process as a room
  - It’s virtual memory space is the surface of the walls.
  - There are no ***real*** walls; they are an illusion:
    - Wall panels are moved into place as needed to make the room.

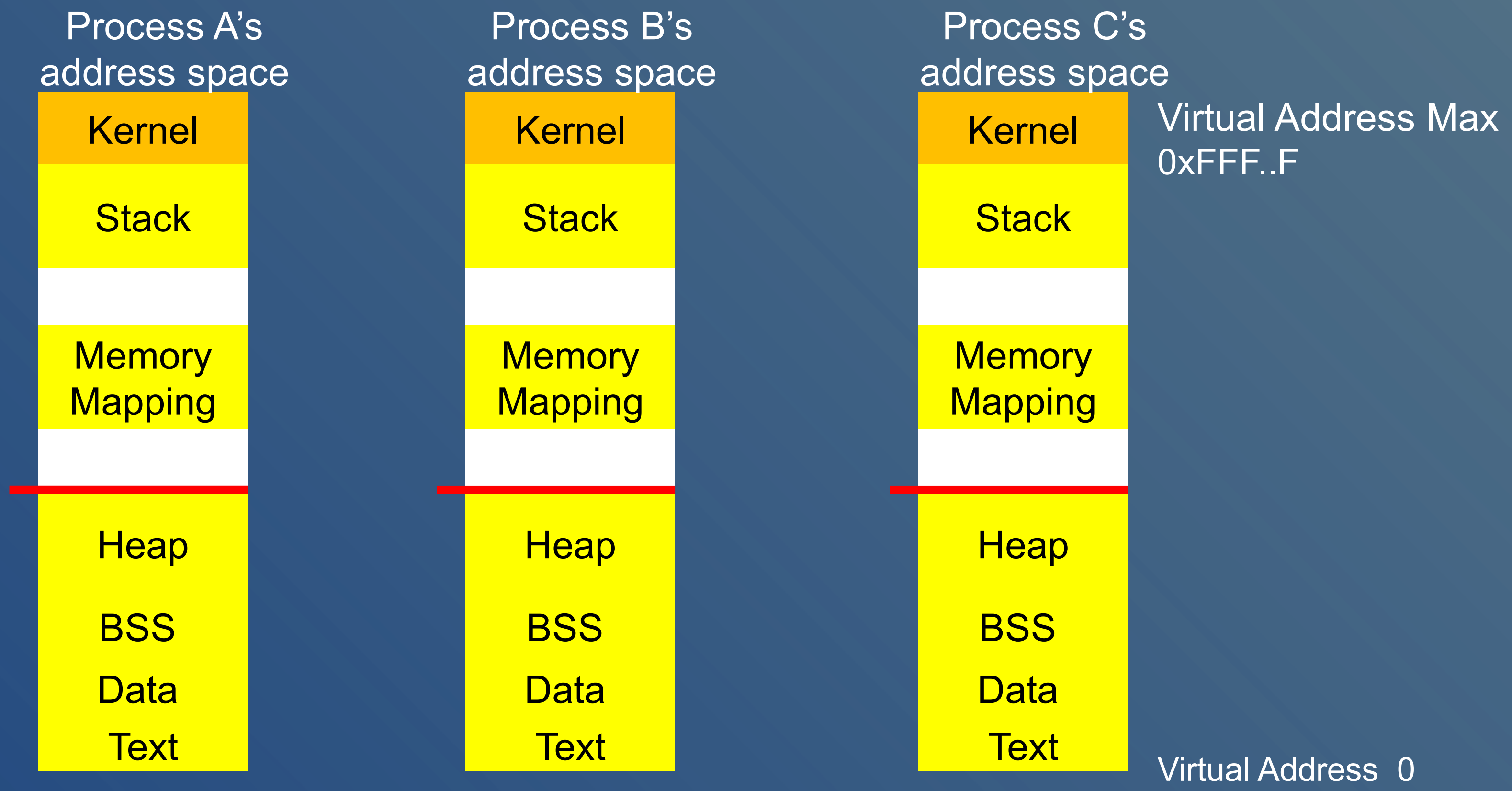


Room Analogy (cont)

- Imagine a process as a room
  - Virtual memory space is the walls:
  Pointers can point to the wall, can read/write on wall.
  - Walls have 2^{64} locations; much bigger than physical memory
- OS + hardware only put "physical" memory panels behind a few areas of the wall.
  - Operations on areas with physical panels work;
  - Operations outside of those areas fail: page-faults
  - E.g., reading from address 0x100 is virtual memory address.
    - Program doesn't know (or care) which physical "panel" of memory we are writing to.
- A physical "panel" is called either a page frame or segment

Process Virtual Memory

- Each process..gets its own (virtual) address space:
  - 0 to 2^{64}-1 (or 2^{32}-1).
- Each address in a virtual address space is a virtual address (physical address points to a physical memory location)



Benefits of Virtual Memory

- A process only sees its own address space,
  - i.e., .. memory isolation between processes.
- Temporal & spacial locality mean
  ..a process likely does not need all its data at once.
  - Don't have 16EB per process of physical memory!
  - OS can swap to a file on disk areas that have not recently been used
    - Makes physical memory available for other processes.

This file is called the.. Swap Space

Room Analogy

- Out of Memory
  - We can run out of physical memory panels for our room
  - So take an "older" panel, save it to disk, and then re-use it in a new place.
- If Needed Again
  - If needed later, we take another physical memory panel and reload the swapped out data from disk
  - Map virtual memory to the correct physical memory location.
  - Program never knows the difference!
- Works across multiple processes
  - OS manages mapping virtual address to physical memory panels
  - Panels are shared across all processes

Address Translation

Address Translation

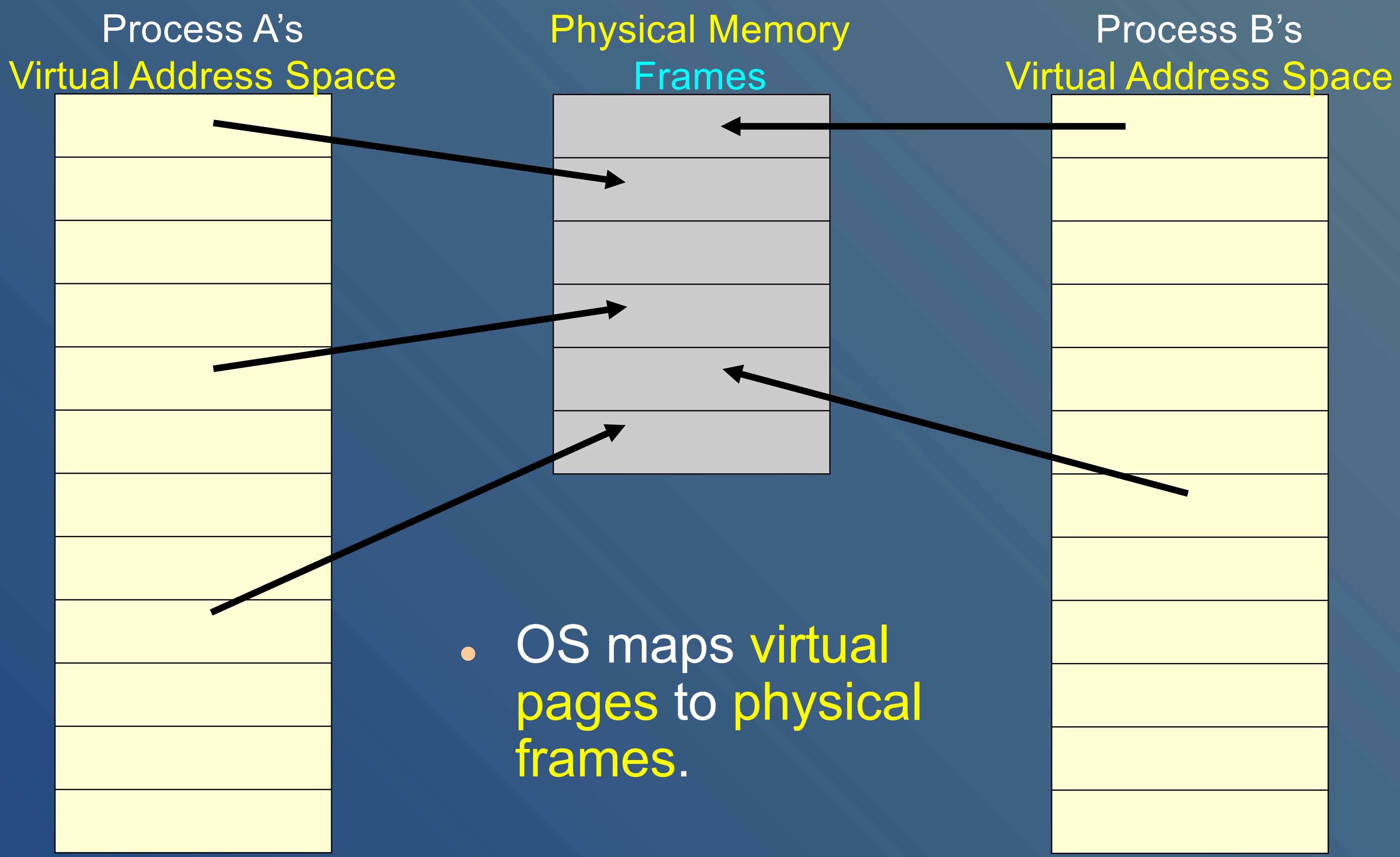
- Process knows virtual addresses; hardware needs physical address
  - Must translate between them!
- Virtual Memory is.. divided into regions called pages
  - Each page is
  .. mapped to a physical memory "page frame" or just "frame"
  - Kernel controls the mapping
  - Kernel configures hardware to translate virtual addresses into physical addresses

Address Translation

- Consider a memory operation like:
  int *ptr;
  *ptr = 10;
- Steps in translation:

1. Figure out which virtual memory page *ptr is on.
2. Figure out which physical frame it maps to
3. Redirects the access to the correct physical memory frame and address within it.

Address Translation



- OS maps virtual pages to physical frames.

Address Translation

- Approaches to Mapping "Panels' to Memory
  - How do we divide our virtual address space into smaller regions ("panels" in our analogy)?

Paging

Pages

- ..Virtual address space is divided into fixed-size pages
  - 4 KB is a popular size but modern OSs have bigger pages (e.g., 4 MB) as well.
- Example
  - If we have 16KB virtual address space and page size 4K
  - How many pages? .. We need 4 pages.
  - Here are 2 process, each with its own virtual address space. Page numbers are in binary:

Process A's Address Space
page 11
page 10
page 01
page 00

Process B's Address Space
page 11
page 10
page 01
page 00

Page Frames

- Physical memory divided into
  .. page frames (or frames)
  - Each is the same size as pages.

- Example:
  if we have 8KB of memory with 4KB page size = 2 frames
  (#'s in binary)

Physical Memory
Frames

page frame 01
page frame 00

Address Translation

- A virtual address is divided into two parts:
  - .. <page number, offset>
- Example:
  4 pages, each of 16 bytes.
  - 4 pages need.. 2-bits to pick between pages.
  - 16 bytes need.. 4-bits of offset into the page.
  - 6-bit virtual address space divided into 2-bit page numbers and 4-bit offsets
    - Address 100101 is divided into page number 10 and offset 0101.
    - Address 000010 is divided into page number 00 and offset 0010.

ABCD: Address Translation

- Consider a computer where
  - each page is 32 bytes
  - have 8 pages

What does the memory address 10011010b mean?

(a) Page 10011b, Offset 010b
(b) Page 100b, Offset 11010b
(c) Page 010b, Offset 10011b
(d) Page 11010b, Offset 100b

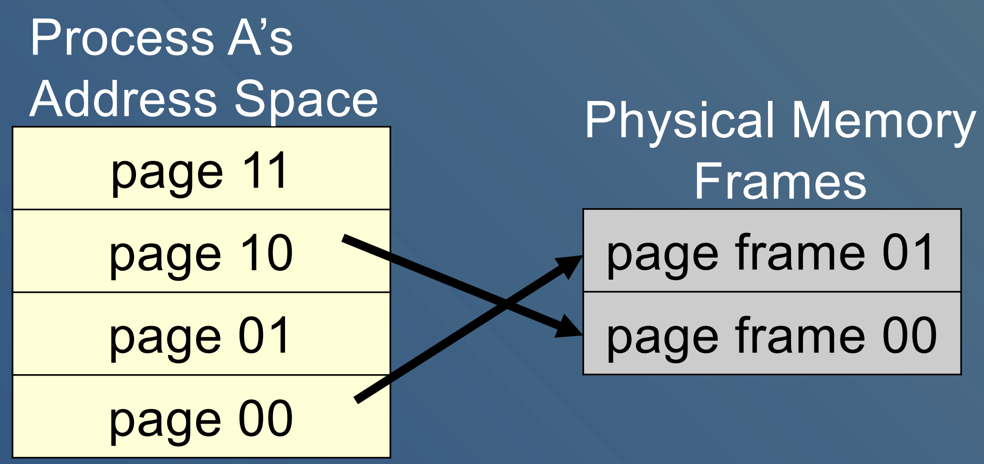
Page Table

- When a process accesses a (virtual) address,
  ..paging translates the address's page number to a page frame number.
  - The offset does not change.

- Kernel maintains a page table per process.
  - Maps page number (virtual) to a page frame number (physical).

Page Table

Page Number	Page Frame Number
00	01
10	00

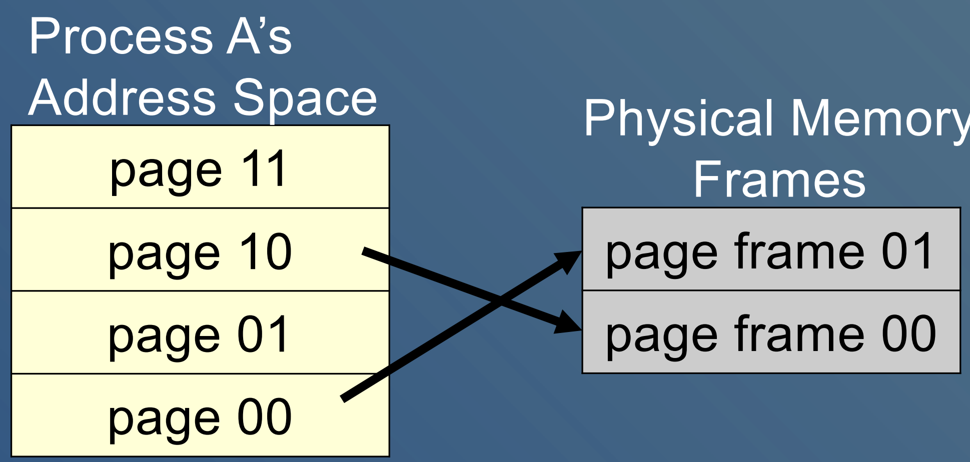


Address Translation Example

- Example:
  Convert virtual address 101011b to physical address
  - Assume 16 byte pages.
    So, offset is.. 4 bits
  - Address is 6 bits therefore
    ∴ Page is 2 bits (4 pages)
  - Page: 10b
    Offset: 1011b
    ∴ Maps to page frame 00
    (unchanged)
  - So physical memory 001011b

Page Table

Page Number	Page Frame Number
00	01
10	00



Number of Pages

- There are vastly more (virtual) pages than (physical) page frames.
  - .. Cannot map all pages to frames at once!
  - OS only maps a page to a frame when needed (more later).
- Hardware supports converting pointers from virtual to physical addresses
  - OS configures the page table
  - HW looks mappings at runtime

Page Table Size

- Page Table Size

–If page numbers use **n** bits,
the maximum possible number of pages is $\mathbf{2^n}$.

–If offsets use **m** bits,
the maximum possible page size is $\mathbf{2^m}$.

- For example,

–Page size 4 KB on a 32-bit architecture.

–m =..12 ($2^{12} = 4096$)

–n =.. 20 (32 bits - 12 for offset),

–Therefore can have 2^{20} pages.
This is 1M pages!

ABCD: Address Translation

- Given the page table below, what is the physical address for (virtual) address 0010 1011 1101 1100b?

(a)<000001, 1111011100>

(b)<001010, 1111011100>

(c)<111010, 1111011100>

(d)<000101, 1111011100>

Page Table

Page Number	Page Frame Number
000001	001010
111010	000011
101001	000111
001010	000101

Segmentation

Segmentation

- Segmentation is another solution
  .. for mapping virtual memory to physical memory
- Segmentation is similar to paging:
  – Memory is divided it sections
  – Each section is located in physical memory
  – Virtual memory addresses are translated to physical memory addresses.
- Segmentation is different because:
  – .. each memory area is not a fixed size,
    but rather a meaningful region
  – E.g., text segment, data segment, stack segment, heap segment, ...

Segmentation Address translation

- Segmentation Address translation
  - Must still translate virtual memory address to physical memory address (beyond scope of this course)
- Modern OSs typically use paging rather than segmentation.

Segmentation and External Fragmentation

- External Fragmentation (recall)
  When free space is broken up into many different places.

–Over time, with segmentation, free space gets broken up into different places.

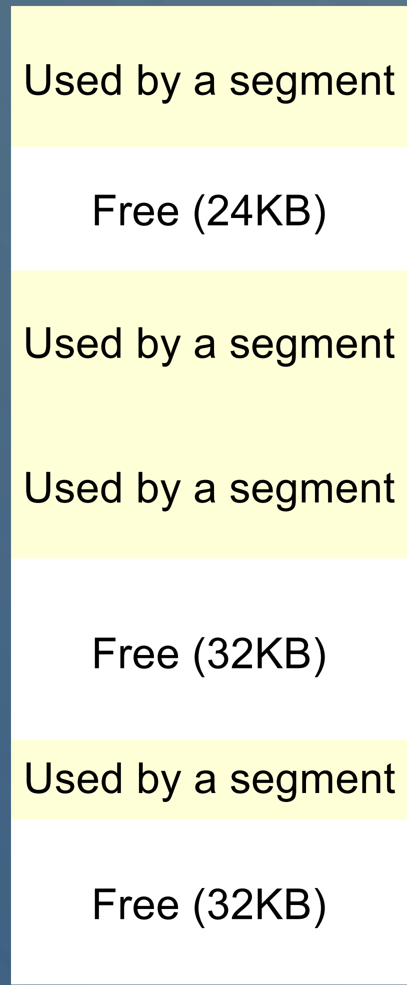
–.. When trying to allocate a new segment, we need a contiguous block of memory.

–Since segments are of different sizes, no one free block might be big enough, even if we have enough total free memory.

- Example:

–Unable to allocate 40KB segment

Physical Memory



Paging and External Fragmentation

- .. Paging cannot suffer external fragmentation since every page is of the same size:
  - We only have one page size, so when you need a page.. any page will do!
- Internal Fragmentation
  - Since pages are handed out at a fixed size, there is very likely to be wasted space at the end of a page.
  - It happens with paging.
  - Combat it by keeping page size small.

Running out of Memory

Out of Memory

- Out of memory
  - Limited physical memory but virtual memory space is vast!
  - Can't bring in all virtual pages to physical memory.
    What do we do?
- Demand paging & swapping
  - Demand paging:
    - a page is brought into memory only when needed
  - Swapping:
    if we don't have a free page frame, kick out a page already in memory to disk and bring in the new page.
  - Swap space:
    disk space dedicated to store swapped-out pages.
- How do we decide which memory page to swap out?
  We need a page replacement algorithm

Demand Paging

- Why does demand paging work?
  - Insight: .. A typical program only accesses a small portion of its memory space.
  - This is based on locality of access.
- Recall:
  - Temporal locality: if a program accesses a memory location, it is likely that it's going to access it again in the near future.
  - Spatial locality: if a program accesses a memory location, it is likely that it's going to access other memory locations nearby.
- .. Paging leverage spatial locality:
  - when a memory location is accessed, it brings in the region that the location belongs to, not just the specific memory location.
- Demand paging & swapping leverage temporal locality:
  - ..recently used pages are already in memory.

Page Replacement Algorithms

- Page Fault
  - when a memory location is accessed but
    - .. the corresponding page is not found in physical memory.
  - we need to bring in the page into a memory frame.
- The Question
  - When the memory is full (i.e., all page frames are used) and we need to load a new page,
    - .. which page do we swap out to disk to make space?

Optimal Page Replacement Algorithm

- Optimal page replacement algorithm

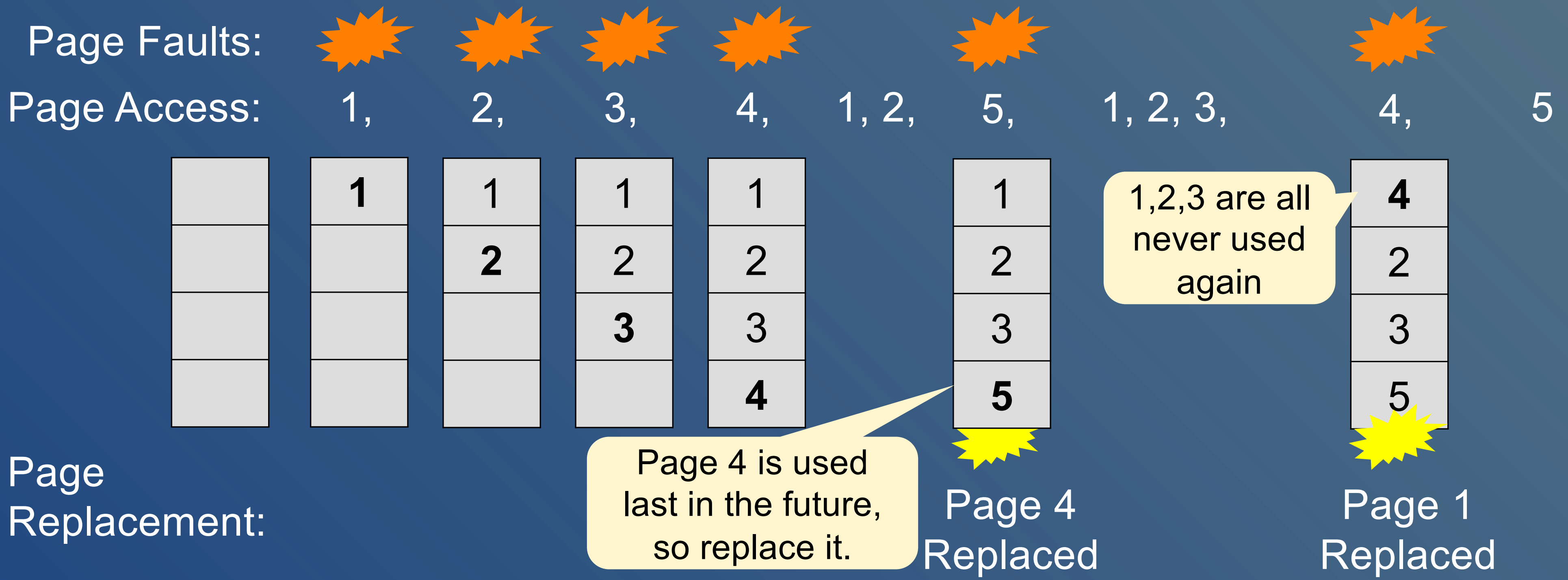
.. picks the page that will not be used for the longest time.

– This assumes that we know the future (which is impossible). Thus, this is only a theoretical exercise.

– Page replacement algorithms try to approximate this as much as possible.

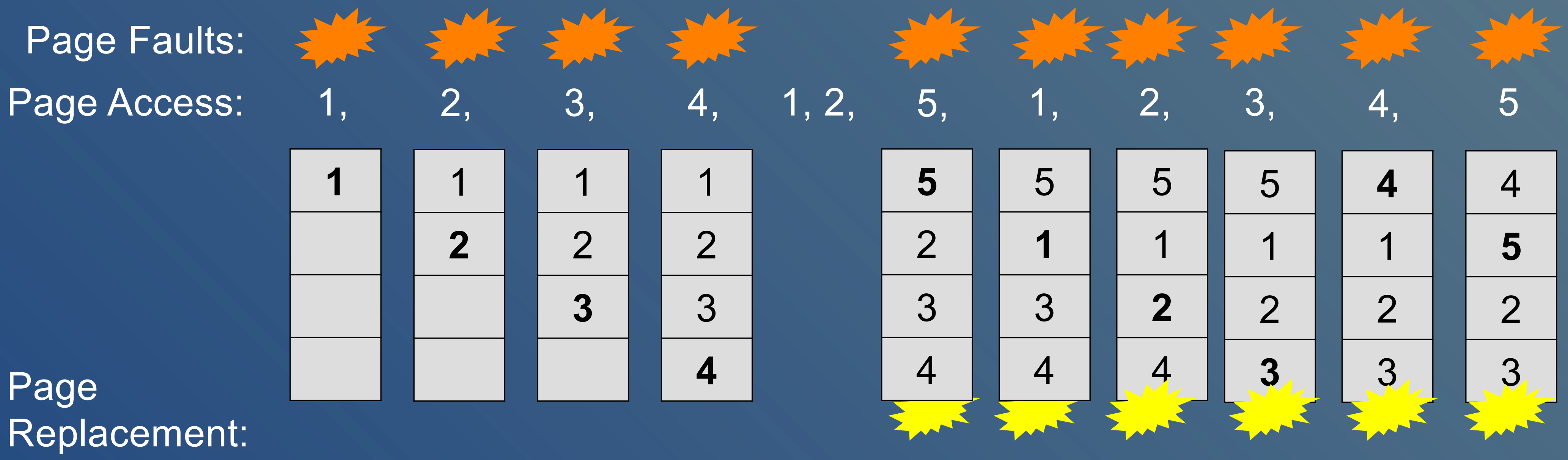
Optimal Page Replacement Example

- Example
  - Memory has 4 page frames.
  - Memory page access order (by page number):
    1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5



FIFO (First In, First Out)

- FIFO
  - Keeps track of when a page was brought in to memory.
  - .. The first one that was brought in gets swapped out first.



- 10 page faults!
- This is simple but does not consider useful properties like locality.

LRU (Least Recently Used)

- .. Replace page that has not been used for longest period.
  - It tries to approximate the optimal algorithm.
  - It tries to infer the future based on past.

Page Faults:

Page Access: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

1,	2,	3,	4,	5,	3,	4,	5
1	1	1	1	1	1	1	**5**
	2	2	2	2	2	2	2
		3	3	**5**	5	**4**	4
			4	4	**3**	3	3

Page Replacement:

- 8 page faults
- Tracking access time is not simple to implement. Approximate it?

ABCD: LRU Paging

- Consider the following computer:
  - 4 page frames
  - Uses LRU page replacement algorithm

  How many page faults are there for the following sequence of page accesses?

  - `1,   2,   3,   4,   5,   2,   4,   5,   1,   5`

`*    *    *    *    *(1)                    *(3)`

(a) 2 page faults
(b) 5 page faults
(c) 6 page faults
(d) 10 page faults

Second-Chance

- Second Chan~~g~~e is an approximation of LRU
  - Each page has a reference bit (ref_bit), initially = 0
  - .. When a page is accessed, hardware sets ref_bit to 1.
  - We maintain a moving pointer to the next (candidate) "victim".
- When choosing a page to replace,
  check ref_bit of victim:
  - .. If ref_bit == 0, replace it.
  - Else
    - Clear ref_bit to 0.
    - Leave page in memory
      .. (give it another chance).
    - Move pointer to next page (wrapping around)
    - Repeat till a victim is found.

Next Victim

Ref. Bit	Pages
0	...
1	...
1	...
0	...

Second Chance Example

- Example
  - Assume we have triggered a page fault.
  - No empty pages, so must replace.
  - Let’s find the victim page to replace.

Initial State

Ref. Bit	Pages
0	...
1	...
1	...
0	...

Next Victim

Clear flag; Move on

Ref. Bit	Pages
0	...
0	...
1	...
0	...

Clear flag; Move on

Ref. Bit	Pages
0	...
0	...
0	...
0	...

Found Victim Page!

Ref. Bit	Pages
0	...
0	...
0	...
1	changed

ABCD: Second Chance

- Using second chance page replacement algorithm, which page will be the next victim?

Next Victim

Ref. Bit	Pages
~~1~~ 0	Page 110
~~1~~ 0	Page 111
0	Page 101
~~1~~ 0	Page 001

(a) Page 110b
(b) Page 111b
(c) Page 101b
(d) Page 001b

Thrashing

Thrashing

- If a process access a large amount of memory,
  OS could keep needing to bring new pages into memory

– Example:

An process that jumps through a huge amount of memory, reading one value every 4K (once per page).

- Thrashing:

– a process is too busy swapping in and out pages and not really executing its program on the CPU.

Summary

- Virtual Memory
  - Process works only in the virtual memory space.
  - OS can flexibly share memory between processes.
  - Gives process memory isolation.
- Address Translation
  - Converting (virtual) address to physical address.
- Paging
  - Virtual memory broken up into identical size pages.
  - Physical memory broken up into page frames (“frames”).
- Segmentation
  - Like paging, but different size regions (segments).
- Page replacement algorithms:
  - Optimal, FIFO, LRU, Second Chance