Operating Systems

Assignment 2

Daniel Gruss

2023-11-21

Topics

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Presented Today:

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- **Mandatory:** Virtual Memory (Copy On Write, Swapping)

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Other Topics:

- You can do basically anything OS related

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- **Mandatory:** Virtual Memory (Copy On Write, Swapping)
- Shared Memory
- Memory Mapped I/O
- Dynamic Memory in the userspace

Other Topics:

- You can do basically anything OS related
- Just ask your Tutor how many points it brings

Page Replacement

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- Swap pages to the swap device (from RAM to HDD)

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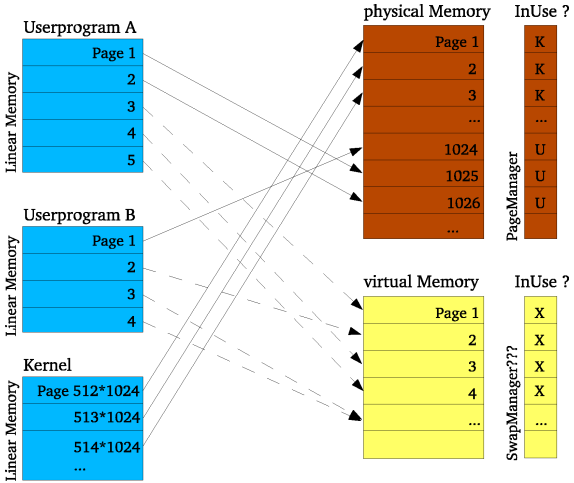
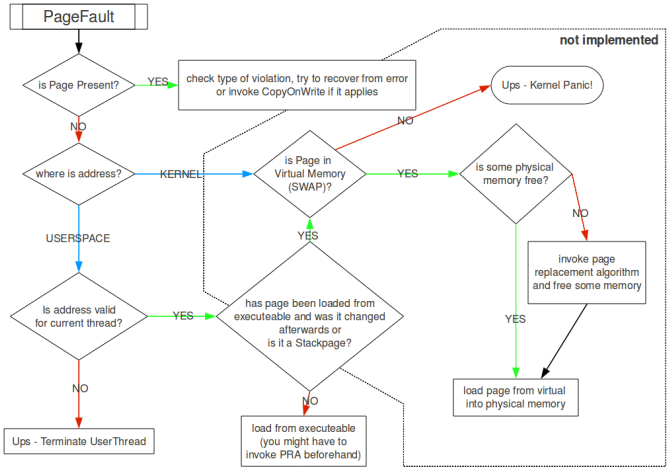
- Swap pages to the swap device (from RAM to HDD)
- Don't forget to lock shared resources!

What does the OS need to know?

What does the OS need to know?

- Where is the swap device located?
- Where to find free space within the swap device?
- Has a page been swapped out, or is it within RAM?
- Where has a page been swapped to (target address)?


Userprogram A
Linear Memory
Page 1
2
3
4
5
Userprogram B
Linear Memory
Page 1
2
3
4
Kernel
Linear Memory
Page 512*1024
513*1024
514*1024
...
physical Memory
InUse ?
Page 1
2
3
...
1024
1025
1026
...
K
K
K
...
U
U
U
PageManager
virtual Memory
InUse ?
Page 1
2
3
4
...
X
X
X
X
...
SwapManager???


PageFault
is Page Present?
YES
check type of violation, try to recover from error or invoke CopyOnWrite if it applies
not implemented
Ups - Kernel Panic!
NO
where is address?
KERNEL
is Page in Virtual Memory (SWAP)?
NO
YES
is some physical memory free?
NO
USERSPACE
YES
invoke page replacement algorithm and free some memory
Is address valid for current thread?
YES
has page been loaded from executeable and was it changed afterwards or is it a Stackpage?
YES
NO
load page from virtual into physical memory
NO
Ups - Terminate UserThread
load from executeable (you might have to invoke PRA beforehand)

Access the HDD in SWEB

- Virtual Memory is located at the third partition of the first HDD
  - (BD device number 3)
- Responsible Code: `arch_bd_*`

Example (Write to BD (Pseudocode))

```
size_t block = target block number;
pointer page_data = pointer to source data;

BDVirtualDevice* bd_device = BDManager::getInstance()->getDeviceByNumber(3);
bd_device->writeData(block*bd_device->getBlockSize(), PAGE_SIZE, page_data);
```

Do not use `BDRequest` directly unless you asked a Tutor!

Using `BDRequest` directly is unsafe!

Which pages are swappable?

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- User space pages (where does it make sense?)
- Mark PTs/PDs/PDPTs as non-present and swapped out
- Kernel pages (has not been done before)

Page Table Usage (x86_64)

present == 0: entry invalid, all bits ignored by MMU
→ pagefault on access

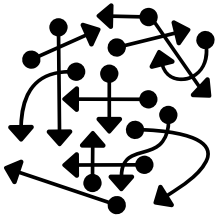
writeable == 0: write protected

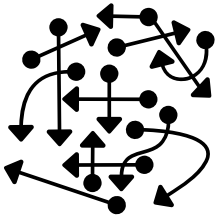
accessed, dirty == 1: has been accessed/modified

ignored_x : unused bits

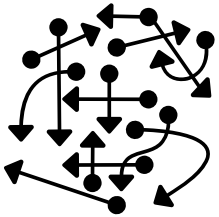
page_ppn : physical page number

```
typedef struct
{
  uint64 present            :1;
  uint64 writeable          :1;
  uint64 user_access        :1;
  uint64 write_through      :1;
  uint64 cache_disabled     :1;
  uint64 accessed           :1;
  uint64 dirty              :1;
  uint64 size               :1;
  uint64 global             :1;
  uint64 ignored_2          :3;
  uint64 page_ppn           :28;
  uint64 reserved_1         :12;
  uint64 ignored_1          :11;
  uint64 execution_disabled :1;
} PageTableEntry;
```





Testing / How to use lots of RAM



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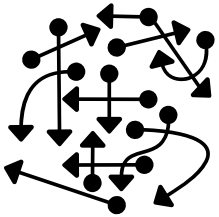

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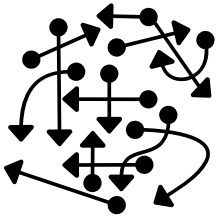

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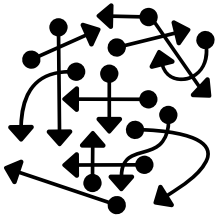
- ..., without running into the limits of the kernel heap.



- Use tests which use big arrays
  (e.g. size_t array[BIG_NUMBER];)
- Test **all** swapping-situations
- ..., without running into the limits of the kernel heap.
- Free memory can exhaust soon (even with a good PRA)!

Page Replacement Algorithms

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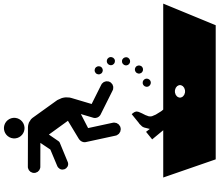

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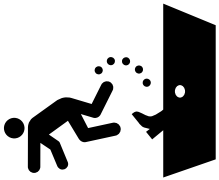

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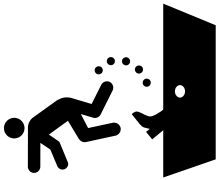

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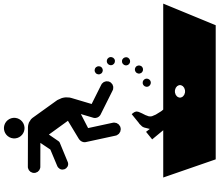

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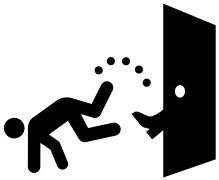

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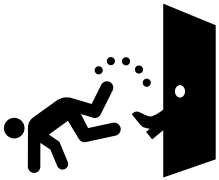

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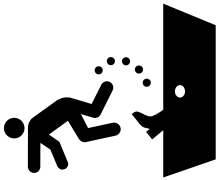

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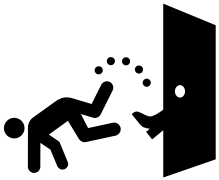

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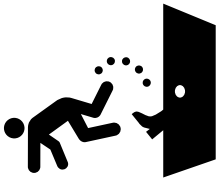

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- Create your own PRA (why is it better than other PRAs?)
- Bonus Points: User can switch PRAs

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- Hint: `InterruptUtils.cpp`

Inverted Page Table (IPT)

Shared Pages

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- Aka: Page table entries of different user spaces point to the same physical page

Where can pages be shared?

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- RAM

Where can pages be shared?

- RAM
- Swap

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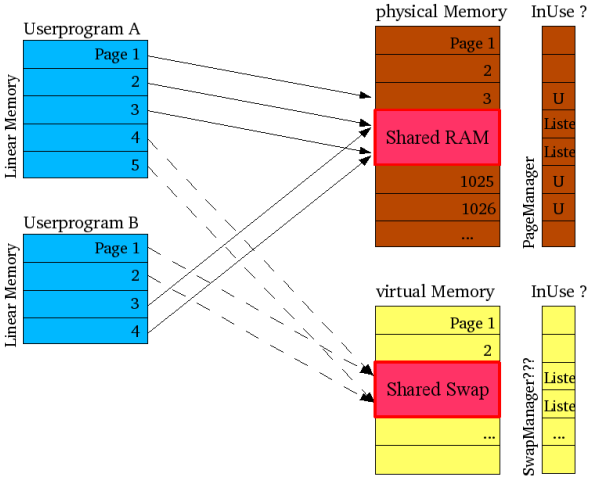
And what's with copy-on-write?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Page 1
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Page 1
2
3
4
physical Memory
InUse ?
Page 1
2
3
Shared RAM
1025
1026
...
PageManager
U
Liste
Liste
U
U
virtual Memory
InUse ?
Page 1
2
Shared Swap
...
SwapManager???
Liste
Liste
...

Virtual Memory and Shared Pages

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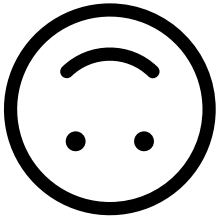

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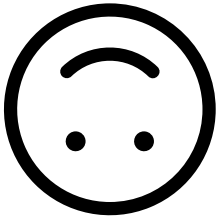
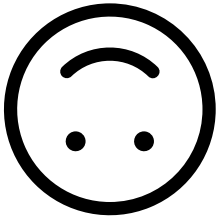
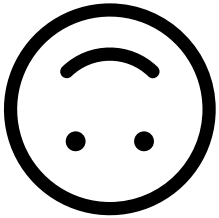




Inverted Page Table connects a physical page/swapped page to all virtual page usages



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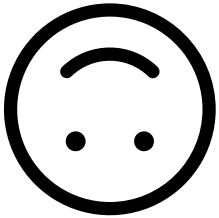

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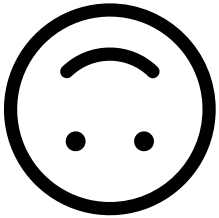

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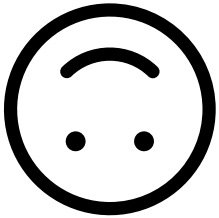

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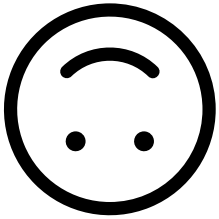

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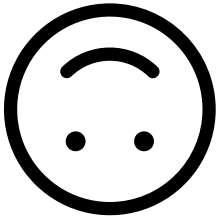

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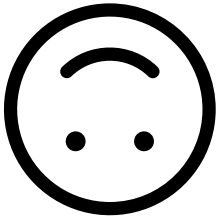

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- But what if a process terminates?

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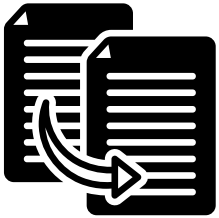

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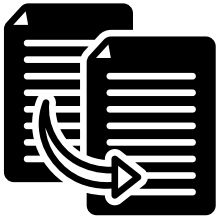

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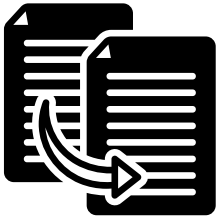

- Usage of `fork`():

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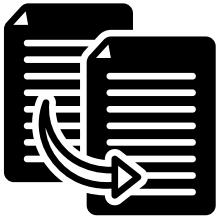

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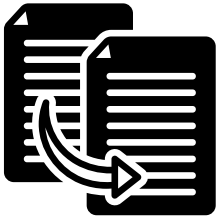

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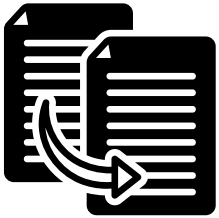

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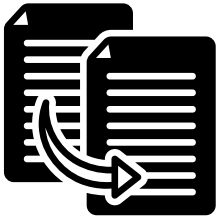

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- Do we really have to copy all the stuff?

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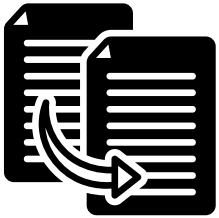

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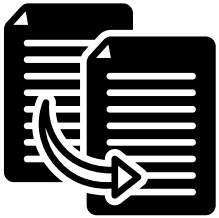
- Do we really have to copy all the stuff?
  - Both processes use the same physical and swapped pages

Copy on Write



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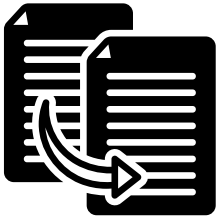

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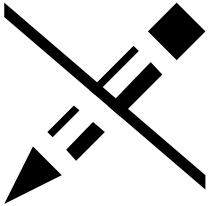
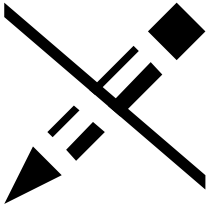
  - Works as long as no one is writing onto them

Read-Only Pages and Pagefaults

Read-Only Pages and Pagefaults



Read-Only Pages and Pagefaults



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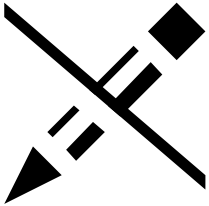
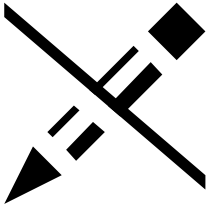


- How do we realize that someone wants to write onto a page

Read-Only Pages and Pagefaults



- How do we realize that someone wants to write onto a page
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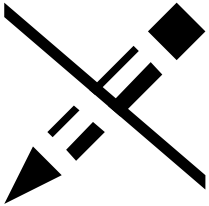
Read-Only Pages and Pagefaults



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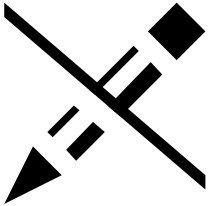

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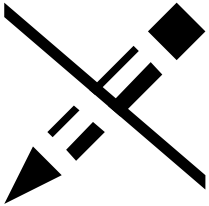
Read-Only Pages and Pagefaults



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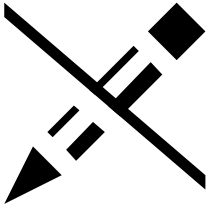
Read-Only Pages and Pagefaults



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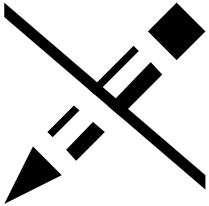
Read-Only Pages and Pagefaults



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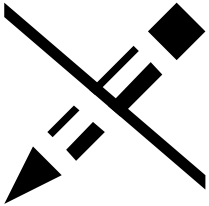
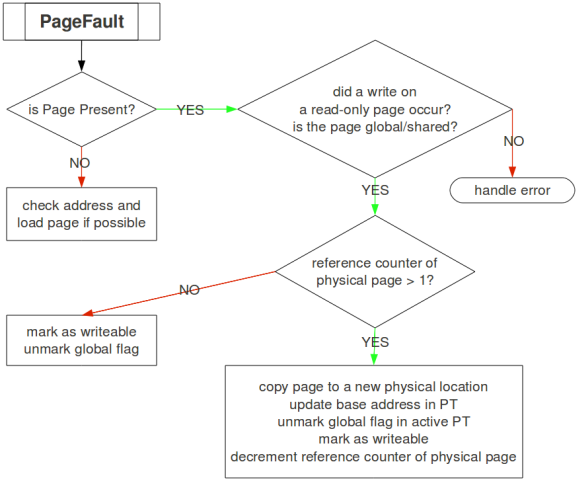
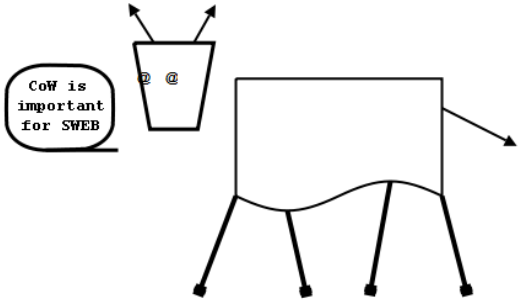
Read-Only Pages and Pagefaults



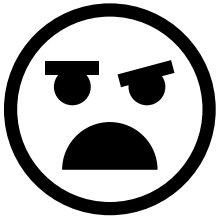
- How do we realize that someone wants to write onto a page
  - Usually we can't
  - The writeable-flag has to be zero
- Process tries to write onto a read-only page
  $\rightarrow$ PageFault
- What now?
  - $\rightarrow$ Is it a shared page?
  - $\rightarrow$ Copy page and link to the new one
  - $\rightarrow$ If only one process is left $\rightarrow$ no shared pages!


PageFault
is Page Present?
YES
NO
check address and
load page if possible
did a write on
a read-only page occur?
is the page global/shared?
NO
handle error
YES
reference counter of
physical page > 1?
NO
mark as writeable
unmark global flag
YES
copy page to a new physical location
update base address in PT
unmark global flag in active PT
mark as writeable
decrement reference counter of physical page


CoW is
important
for SWEB
@ @

What about the global flag?

What about the global flag?



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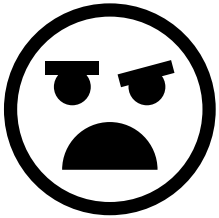

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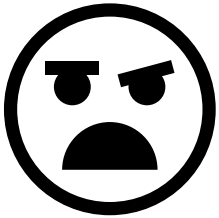

- Don't use it!

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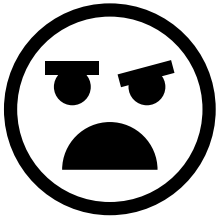

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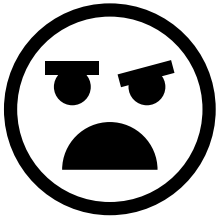

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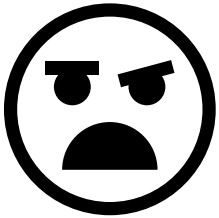

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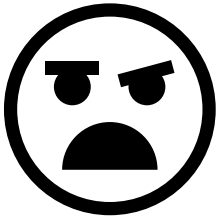
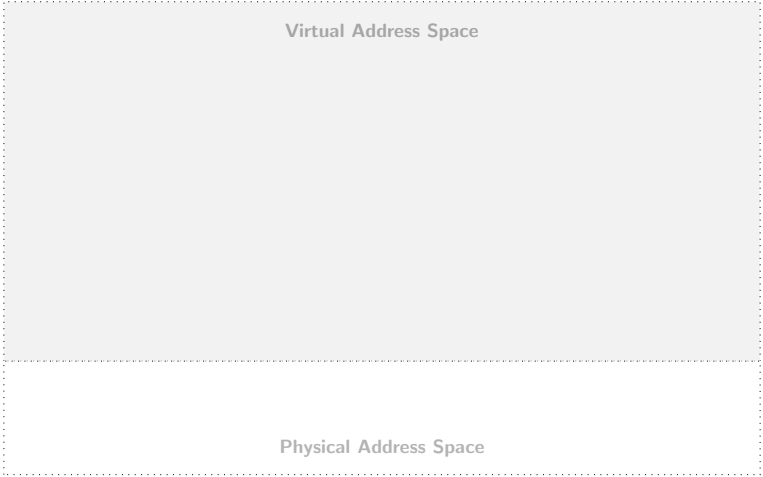


- Don't use it!
- "global" means "keep over next context switch"
- This is not what you want
- Will cause almost untraceable bugs!
- Use and rename an unused bit as "shared" flag instead

Copy-on-Write



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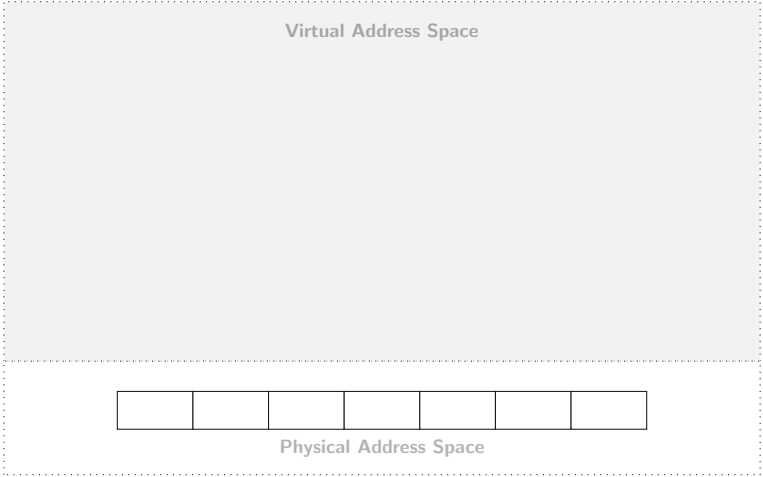

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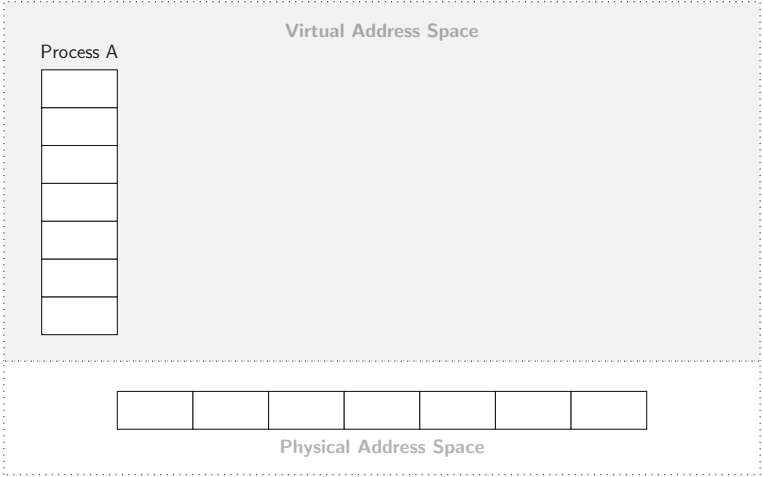

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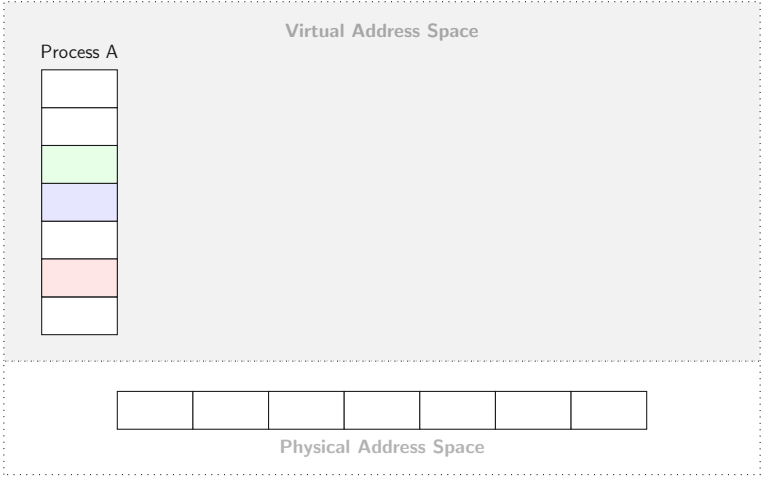

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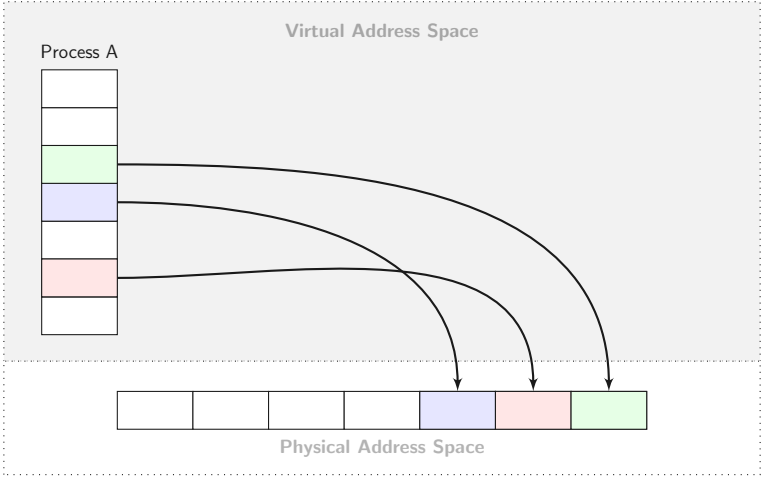

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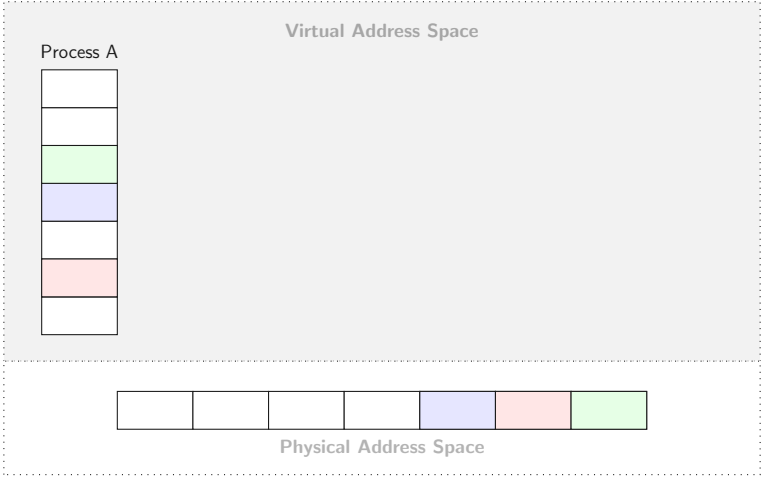

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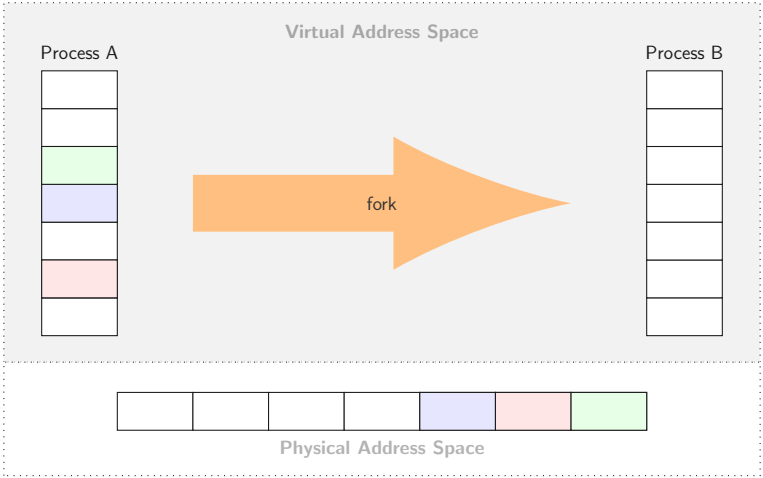

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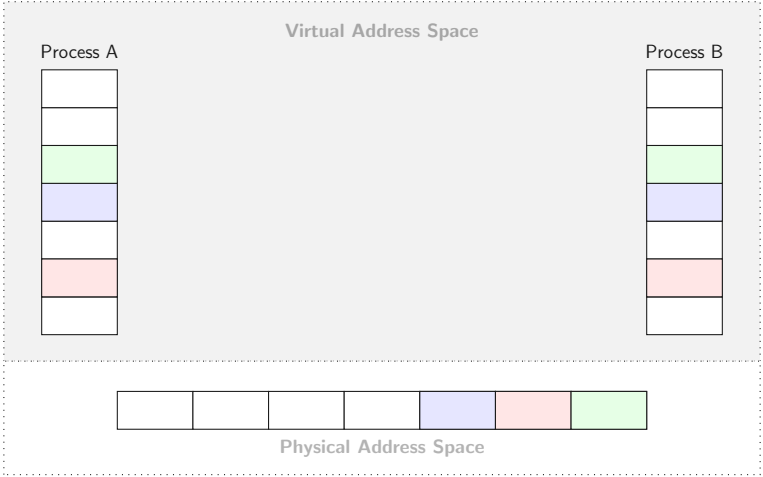

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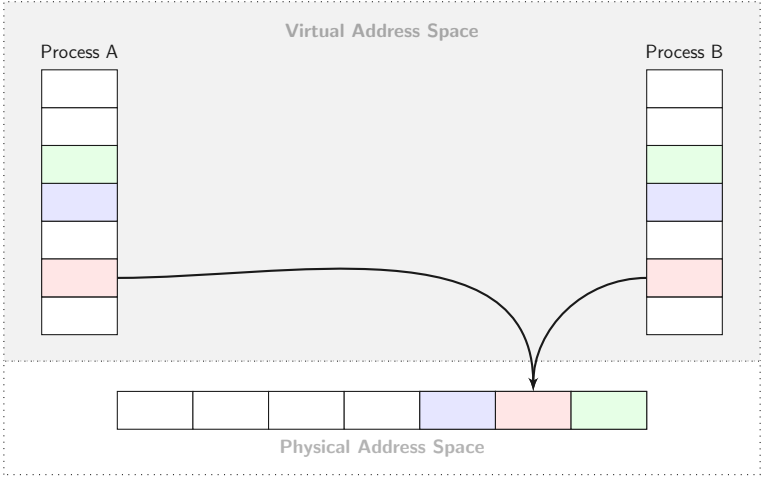

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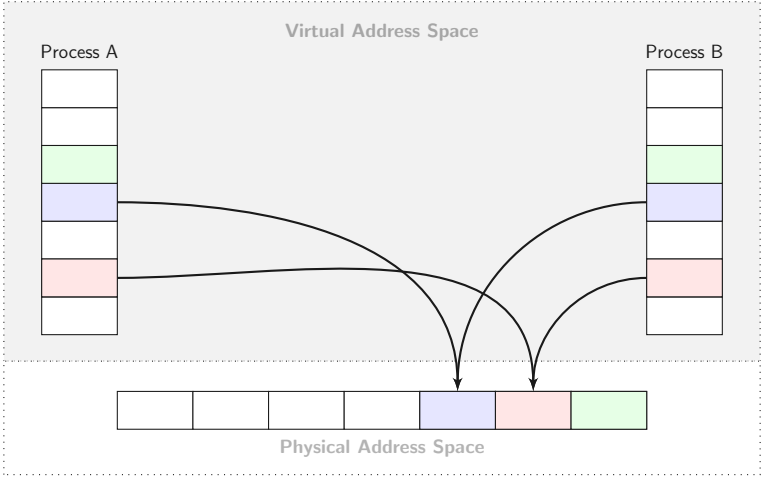

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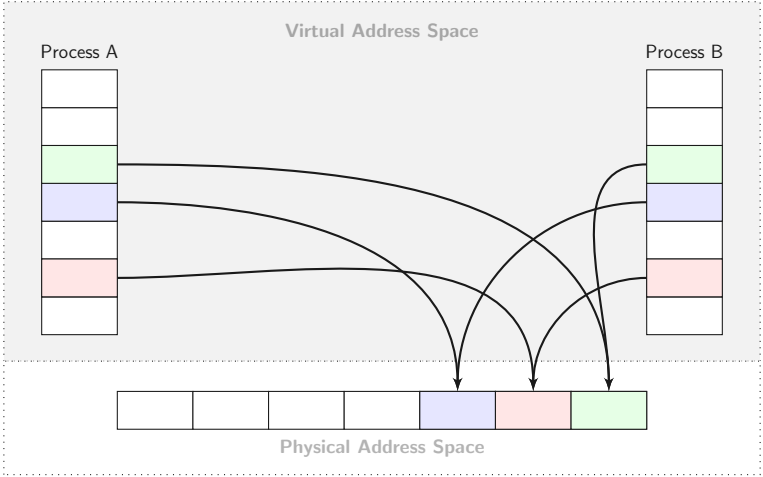

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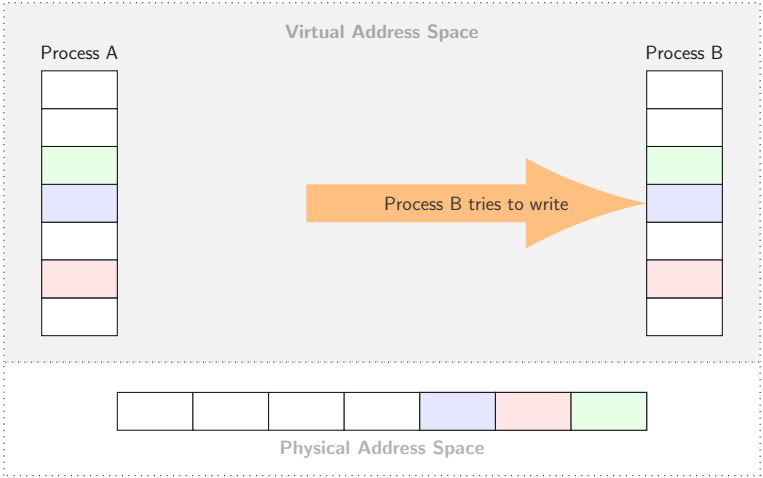

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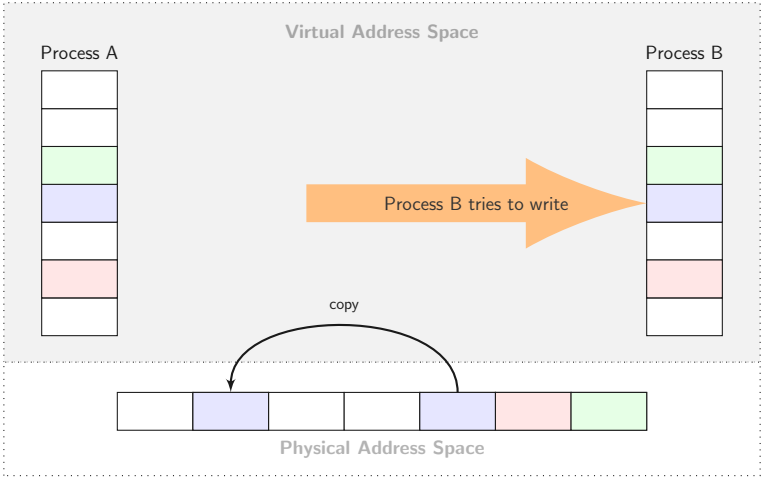

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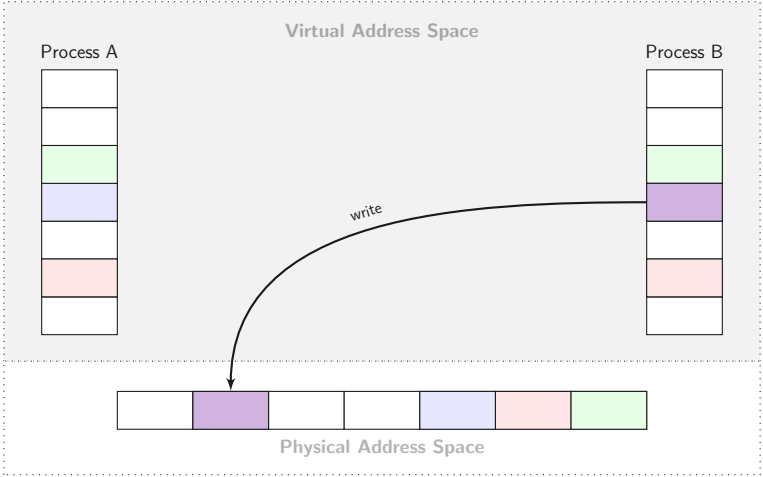

Copy On Write Without Fork

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Copy On Write Without Fork

- Starting `/usr/shell.sweb` twice, without fork

Copy On Write Without Fork

- Starting `/usr/shell.sweb` twice, without fork
- Loading the same image in different programs

Copy On Write Without Fork

- Starting `/usr/shell.sweb` twice, without fork
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- Generating the same data in different programs

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- Starting `/usr/shell.sweb` twice, without fork
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- → Page Deduplication

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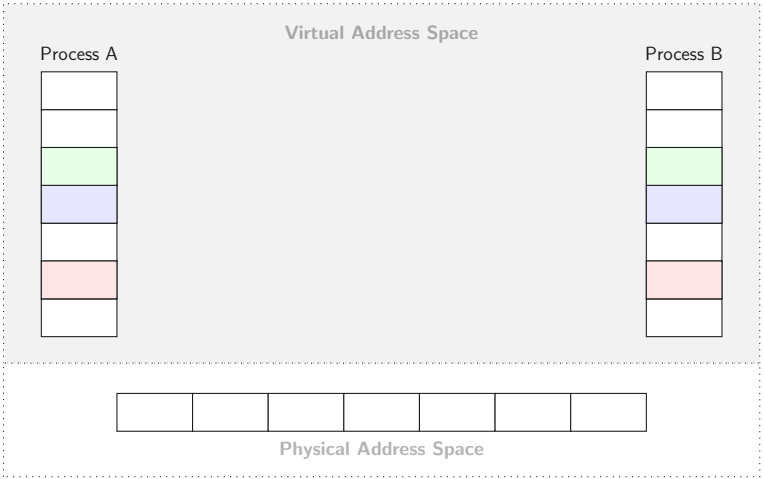

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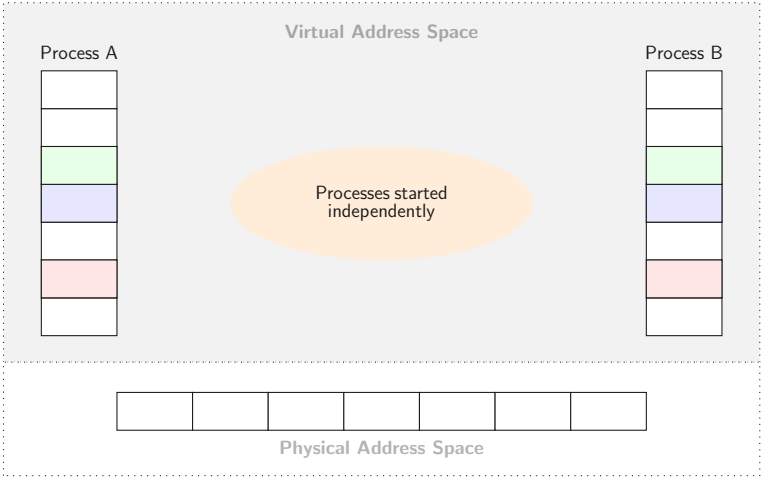

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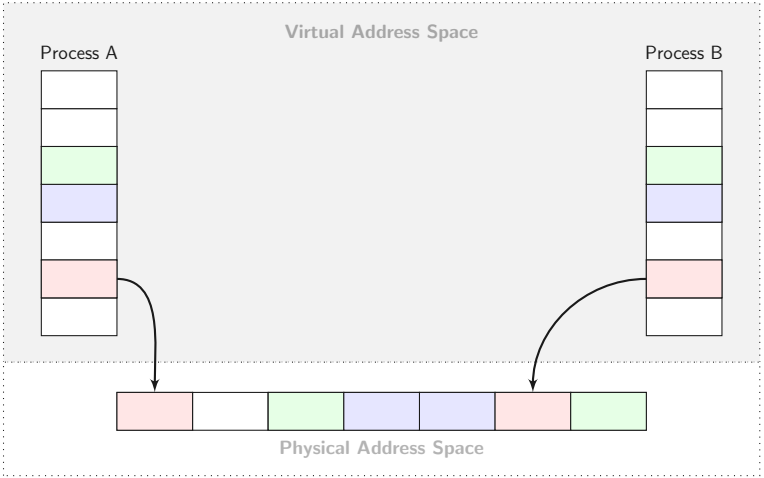

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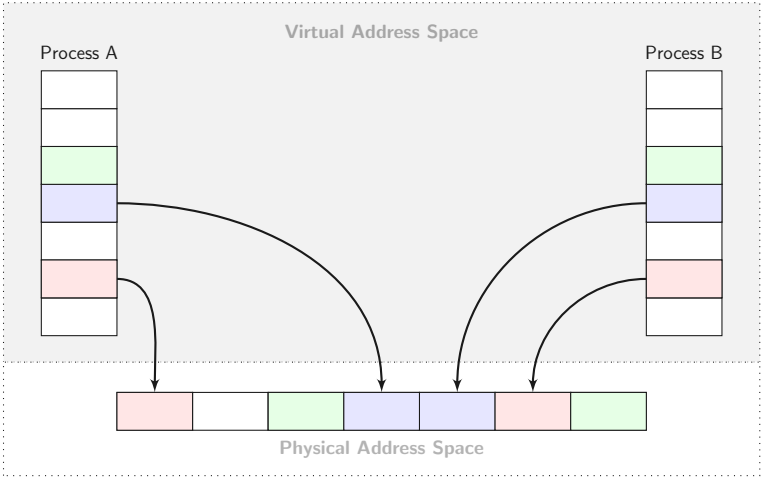

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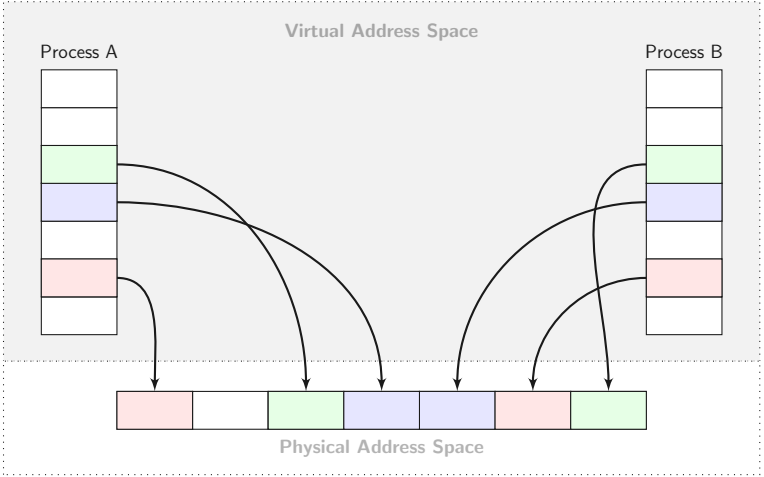

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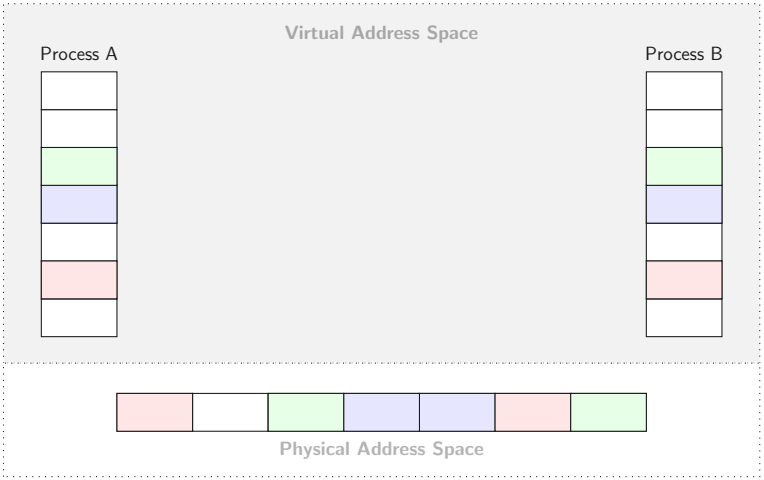

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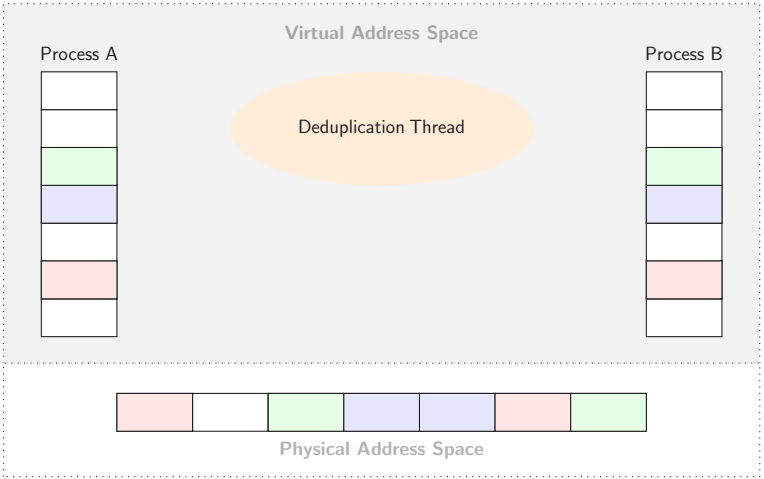

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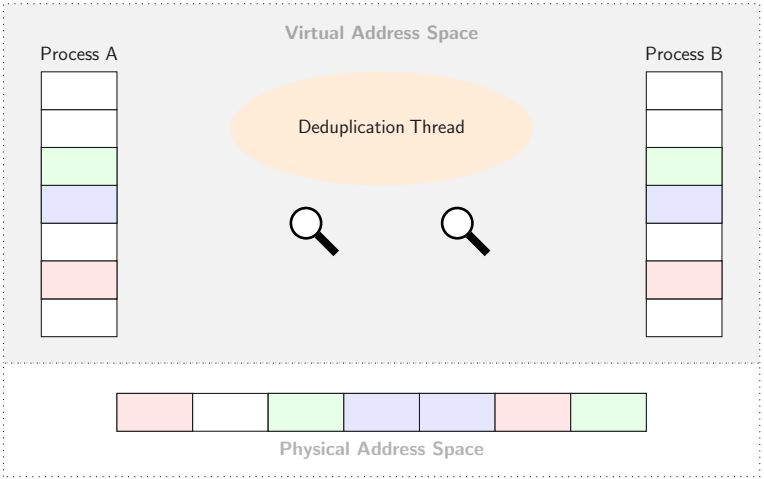

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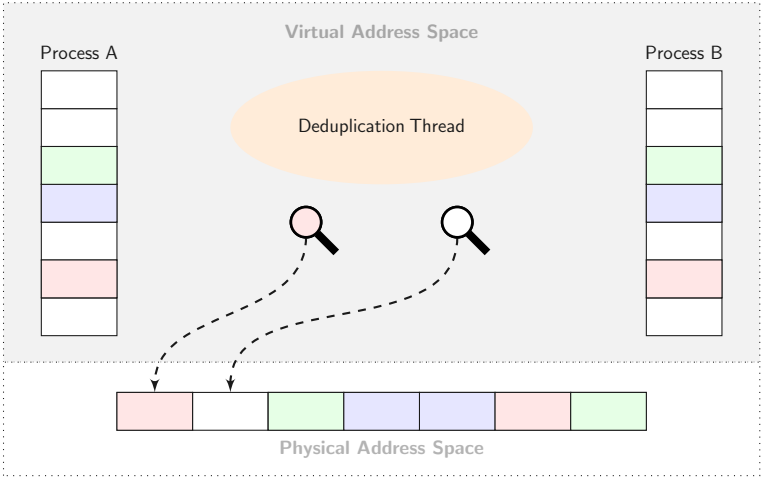

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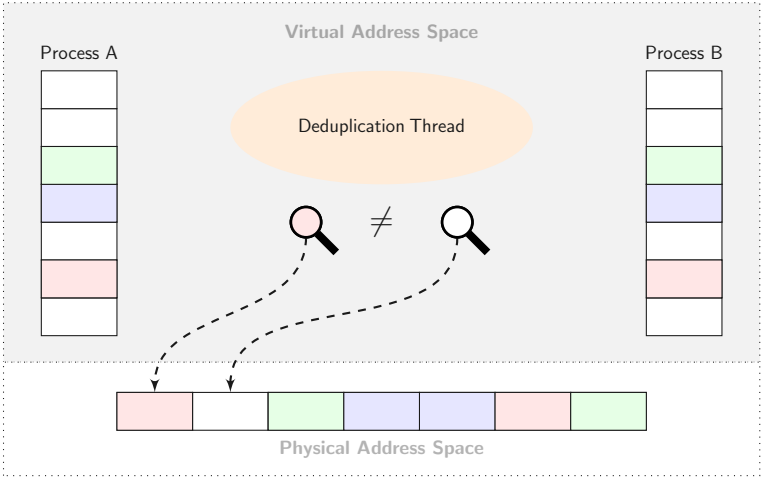

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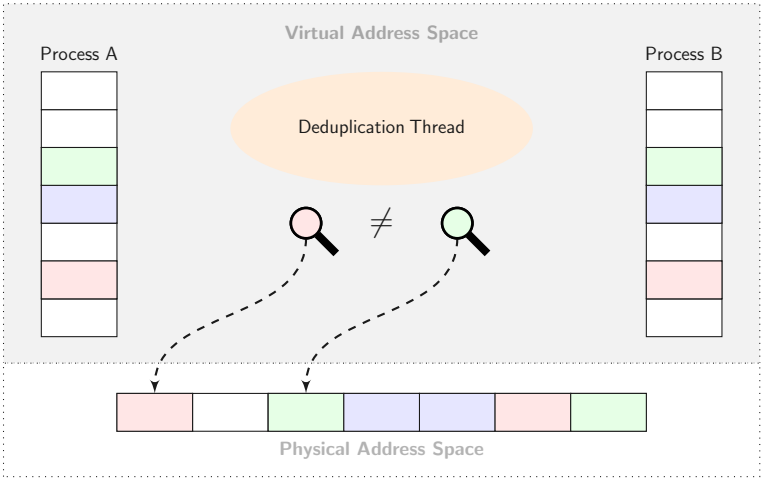

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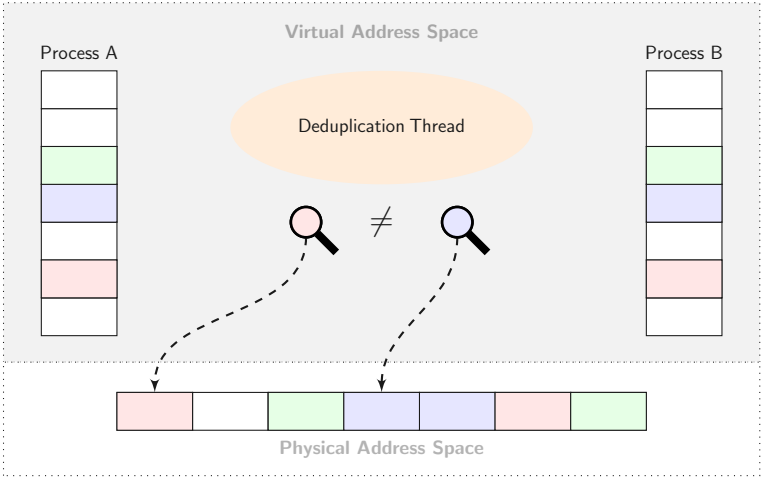

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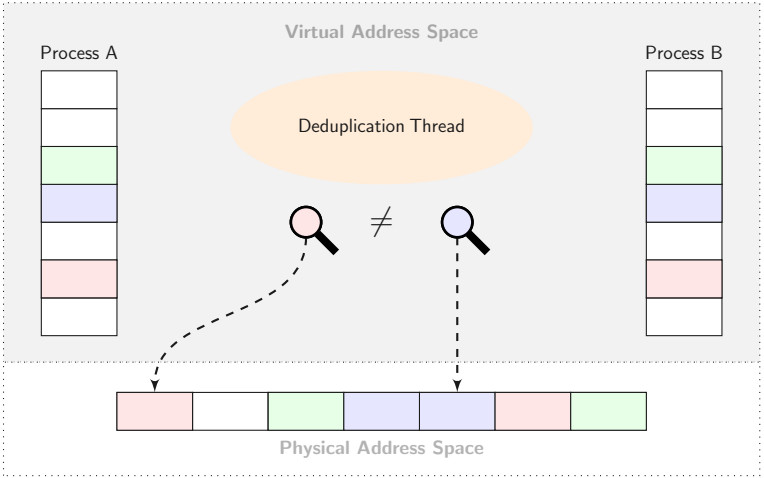

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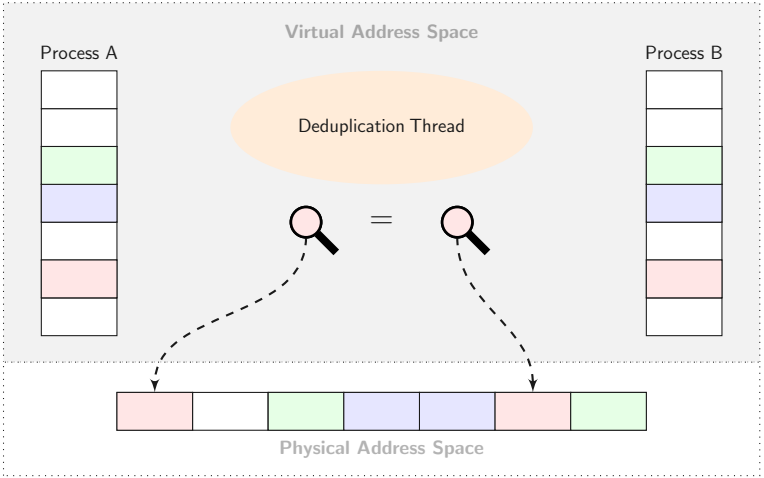

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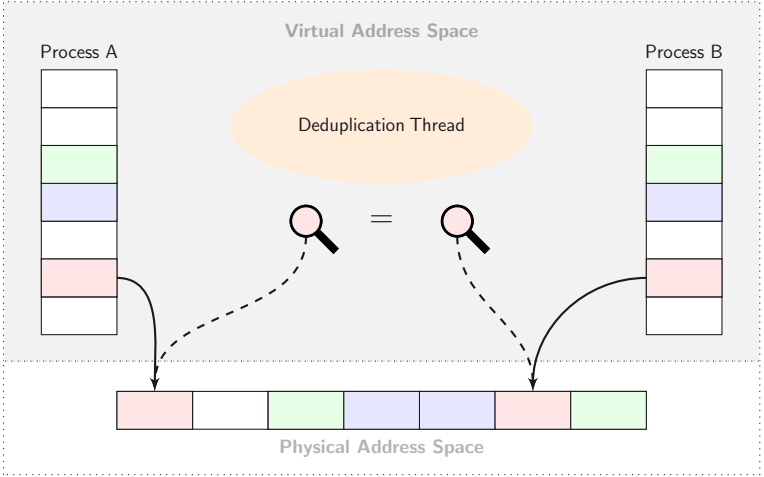
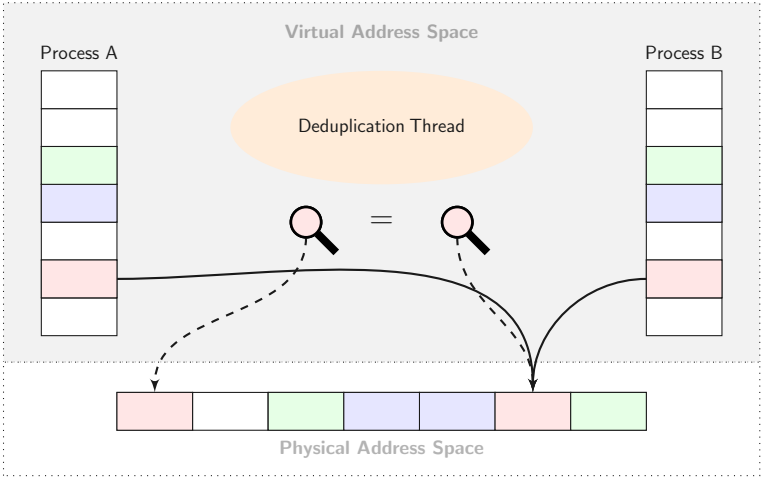


Page Deduplication



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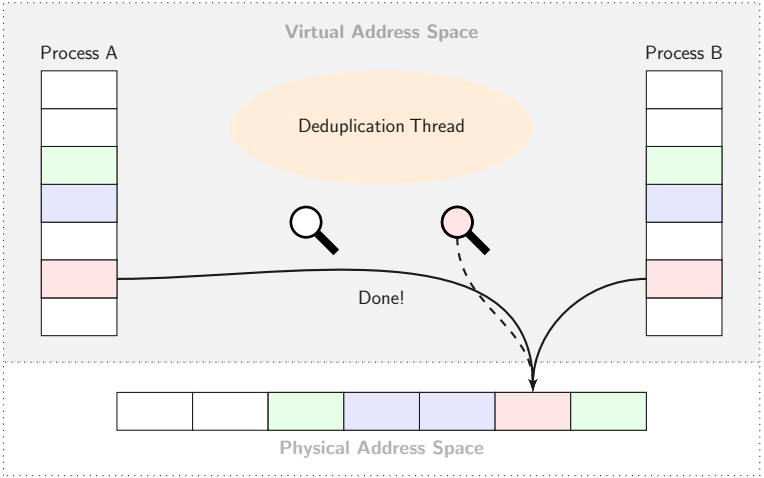

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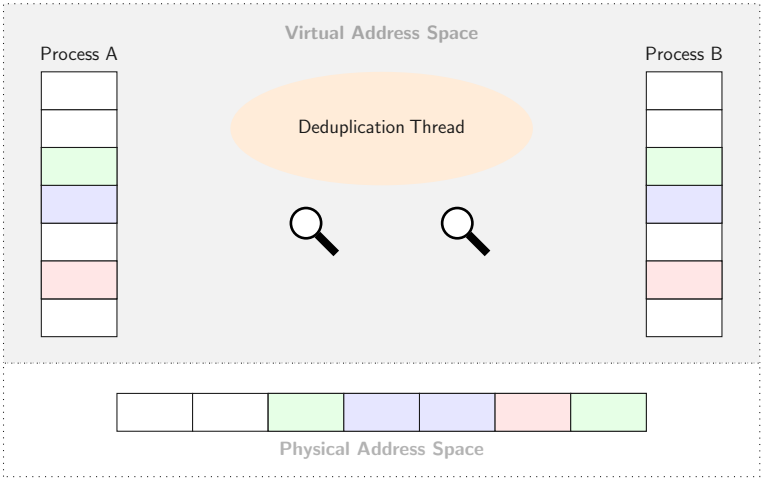

Additional Tasks

Shared Memory

Shared Memory

Shared Memory

Shared Memory

1. Process A wants to share 3 pages with process B

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6. $\rightarrow$ A and B now share 3 pages

Shared Memory: How To Implement

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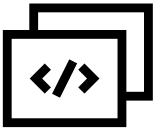

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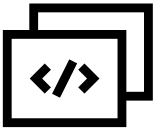

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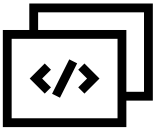

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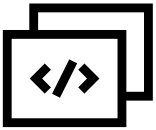

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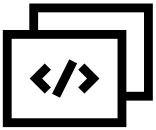

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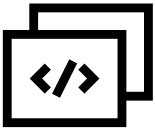

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- Manages IDs (pseudo file-descriptor) and users of the shared regions
- `munmap` and `close` when the process ends or manually
- No reference to the shared memory object $\rightarrow$ destroy it

Memory Mapped File I/O

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  - Depends on the flags set when being mapped
- If several processes have the same file mapped $\rightarrow$ Shared Memory

mmap / munmap

- `void *mmap(void *addr, size_t len, int prot, int flags, int fildes, off_t off);`
- `int munmap(void *addr, size_t len);`

fildes
- `shm_open` or `open`
- Which processes opened the same file?

len
- Only multiples of `PAGE_SIZE`
- File size usually not `PAGE_SIZE`-aligned

mmap / munmap

- `void *mmap(void *addr, size_t len, int prot, int flags, int fildes, off_t off);`
- `int munmap(void *addr, size_t len);`

protection : Access rights for the mapped areas

- `PROT_READ`: How to prevent write accesses?
- `PROT_WRITE`: flags relevant!

mmap / munmap

- `void *mmap(void *addr, size_t len, int prot, int flags, int fildes, off_t off);`
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flags :

- MAP_PRIVATE:
  - Copy-on-write
  - No write-back
- MAP_SHARED:
  - Write-back to file on `munmap`
  - Changes visible to other processes immediately!

mmap / munmap

- `void *mmap(void *addr, size_t len, int prot, int flags, int fildes, off_t off);`
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... easy to combine with shared memory syscalls

Userspace Dynamic Memory

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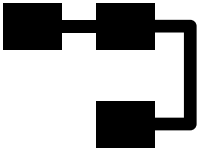

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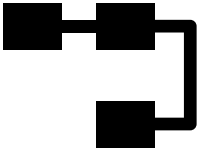
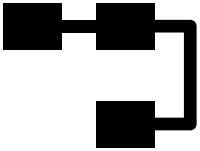


Userspace Dynamic Memory

- Memory allocation at runtime



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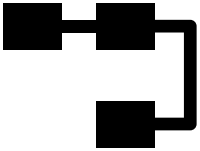

- Memory allocation at runtime
- Implement malloc/free

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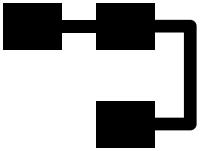

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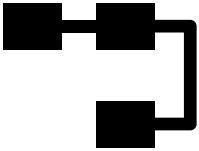

- Memory allocation at runtime
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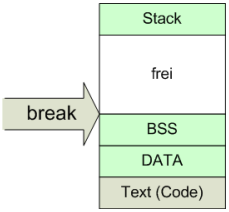
Address space of a process:



How to use brk/sbrk

- `int brk(void *end_data_segment);`
- `void *sbrk(int increment);`
- Linker symbol `_end`

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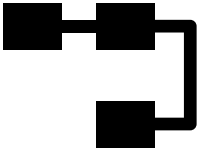
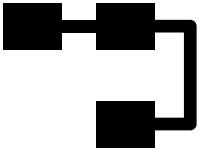
Example (sbrk/break in userspace)

```
extern _end;
//...
size_t heap_start = &_end;
size_t heap_end = heap_start + 4096;
if ( brk(heap_end) == 0)
{
  //do stuff in dynamic memory
}
```

Userspace Memory Management





`brk` and `sbrk` are complicated to use - let's implement:

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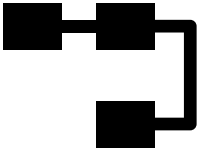

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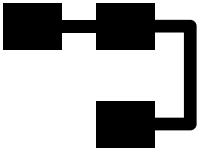

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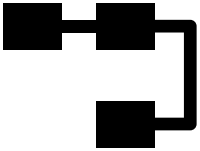

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- Manages the allocated memory regions
  - Requests pages from the kernel

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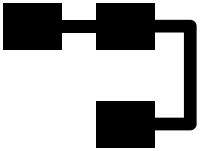

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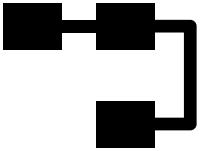

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- `malloc(size_t size)`/`free(void *p)` in libc
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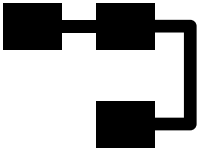
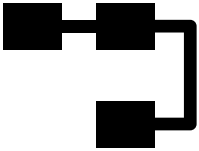
  - Frees unused pages again
  - therefore uses `brk()`/`sbrk()`

Userspace Memory Management





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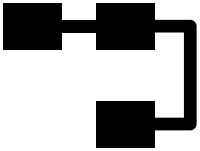

- simple implementation:
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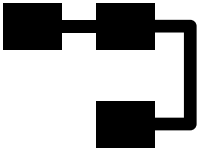
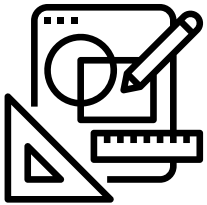


- simple implementation:
  doubly-linked list containing the memory regions
- Don't forget about locking!

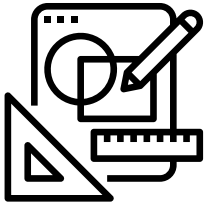
Design / Submissions

Design



Proof-of-Concept-Implementation as in Assignment 1

Design



Proof-of-Concept-Implementation as in Assignment 1

Recommendation: Start with swapping

Alternative tasks

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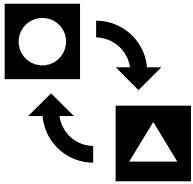

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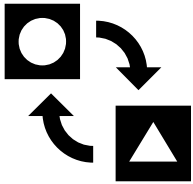

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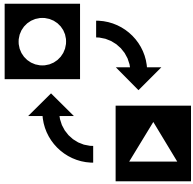
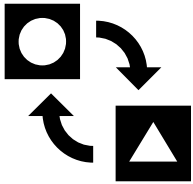


- Normal way: mandatory task virtual memory

Alternative tasks



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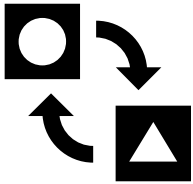

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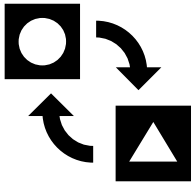

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- This is not possible without discussing it with me!

Submission

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- As in Assignment 1

Submission

- As in Assignment 1
- Tags:

Submission

- As in Assignment 1
- Tags:
  - Design/Proof-of-Concept: `SubmissionD2`

Submission

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  - Implementation: `SubmissionI2`

Deadlines

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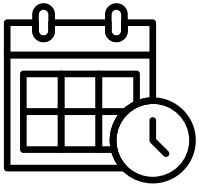

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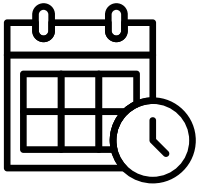

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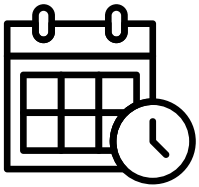
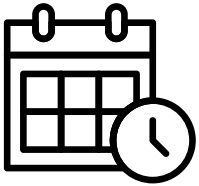


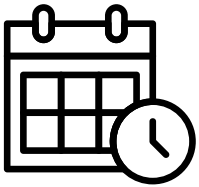
- Design-PoC: 15.12.2023, 18:00

Deadlines



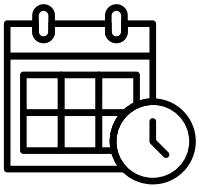
- Design-PoC: 15.12.2023, 18:00
  - Individual feedback meetings ideally between 18.-20.12.

Deadlines



- Design-PoC: 15.12.2023, 18:00
  - Individual feedback meetings ideally between 18.-20.12.
- Implementation: 19.01.2024, 18:00

Deadlines



- Design-PoC: 15.12.2023, 18:00
  - Individual feedback meetings ideally between 18.-20.12.
- Implementation: 19.01.2024, 18:00
- Since 2011 we went to a pub after the implementation deadline

Student Debates on A2 Designs

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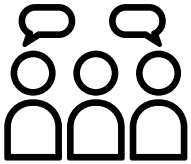
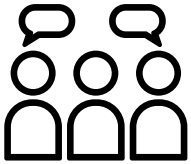
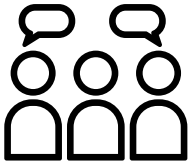


Student Debates on A2 Designs

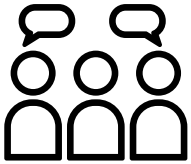


Student Debates on A2 Designs



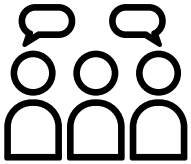
- In two weeks (04.-07.12.)

Student Debates on A2 Designs



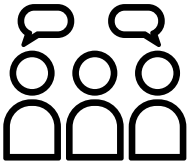
- In two weeks (04.-07.12.)
- Like the one from Assignment 1

Student Debates on A2 Designs



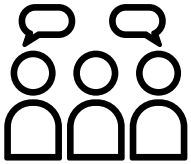
- In two weeks (04.-07.12.)
- Like the one from Assignment 1
- Compulsory attendance

Student Debates on A2 Designs



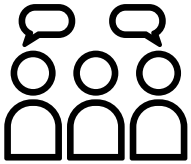
- In two weeks (04.-07.12.)
- Like the one from Assignment 1
- Compulsory attendance
- Bring 2 pieces of paper with your name

Student Debates on A2 Designs



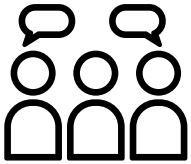
- In two weeks (04.-07.12.)
- Like the one from Assignment 1
- Compulsory attendance
- Bring 2 pieces of paper with your name
- Repeating the assignment specification is not enough!

Student Debates on A2 Designs



- In two weeks (04.-07.12.)
- Like the one from Assignment 1
- Compulsory attendance
- Bring 2 pieces of paper with your name
- Repeating the assignment specification is not enough!
- Your design should be complete by that time

Student Debates on A2 Designs



- In two weeks (04.-07.12.)
- Like the one from Assignment 1
- Compulsory attendance
- Bring 2 pieces of paper with your name
- Repeating the assignment specification is not enough!
- Your design should be complete by that time
- Instant feedback

Evaluations

Evaluations

Evaluations

Evaluations

- Tell us what was good and should remain the same

Evaluations

- Tell us what was good and should remain the same
- Tell us what was bad and should be changed

Evaluations

- Tell us what was good and should remain the same
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- Tell us what was good and should remain the same
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