Introduction to Linux,
for Embedded Engineers

Tutorial on Virtual Memory

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[translated by ikoma]

Target Audience of this Presentation

- People who have been engaged in projects on embedded devices, and who are now using Linux as operating system

Goals of this Presentation

- To understand the mechanism of virtual memory in Linux, and to make use of it for the current project
  - Although programs work without understanding the mechanism, it is important to understand the mechanism to extract sufficient performance

Basic Concepts, First of All

- Virtual ..., Logical ...
  - Virtual addresses, logical devices, logical sectors, virtual machines
  - To handle as if it is ...
- Real ..., Physical ...
  - Real addresses, physical devices, phisical sectors
  - Itself, as it is

Virtualization: As if ... but ...

- As if it is large, but it actually small
- As if it is flat, but it actually uneven
- As if there are many, but there is actually one
- As if exclusively usable, actually shared

Virtualization is magic to hide complexity or individual depedency;
as it is magic, there is a trick
= Mapping between the real and the virtual
Translating so that it looks as if ...

Cost of Virtualization

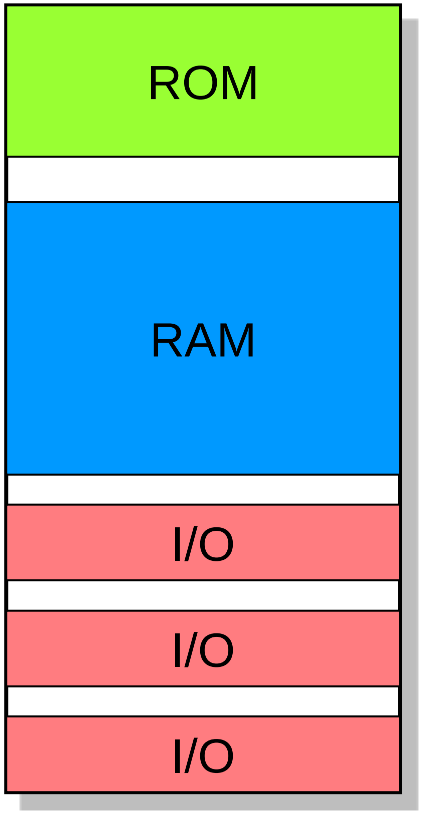
- We do virtualize as its merits are greater than its demerts, but virtualization does not always mean positive results

Phisical Memory and Virtual Memory

- Most of ordinary embedded device projects so far have handled only physical memory
- Recently, as the size of embedded systems grow, PC-oriented OSes such as Linux and WIndowsCE are getting widely used; these operating systems provide virtual memory systems
- This presentation explains Linux

Physical Memory

- Single memory space
- As each device is implemented with different addresses for ROM, RAM and I/O, programmers should code accordingly



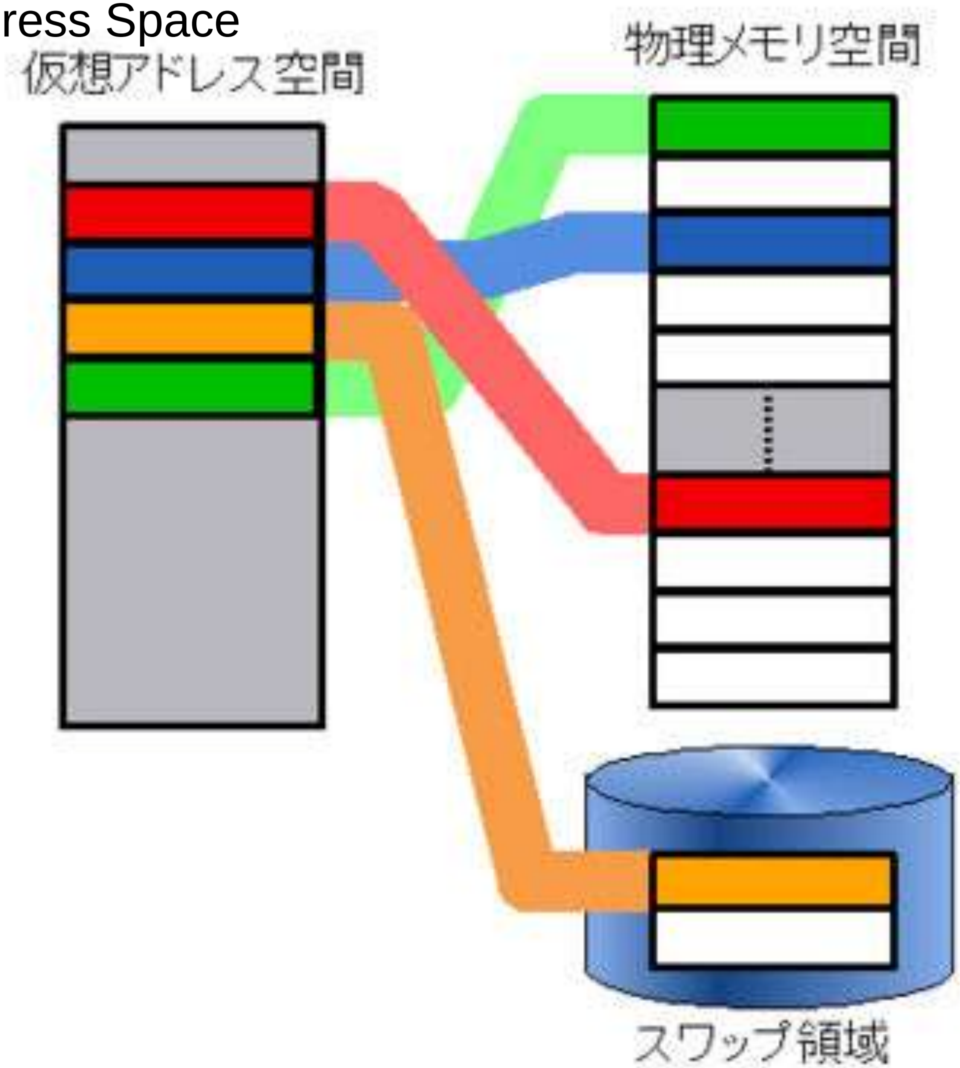
Virtual Memory

- Merits
  - User programs do not depned on actual memory map (implementation address, implementation size) any more
  - Can use non-contiguous physical memory fragments as contiguous virtual memory
  - Memory protection: Can prevent irrelevant memory from being destroyed by bugs
- Introducing new concepts
  - Address translation
  - Multiple memory spaces
  - Demand paging

Conceptual Schema of Virtual Memory

Virtual Address Space

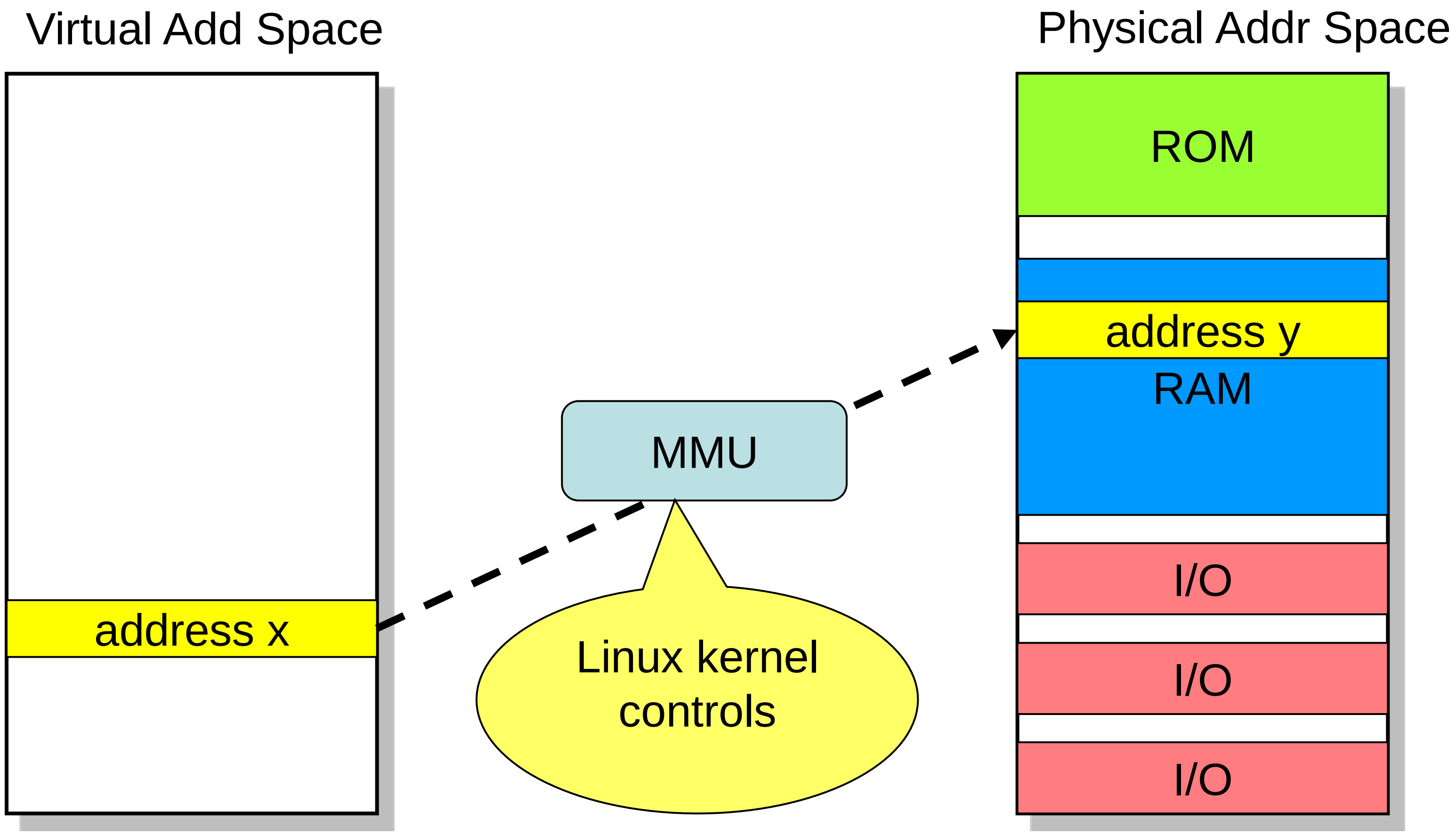
Physical Memory Space



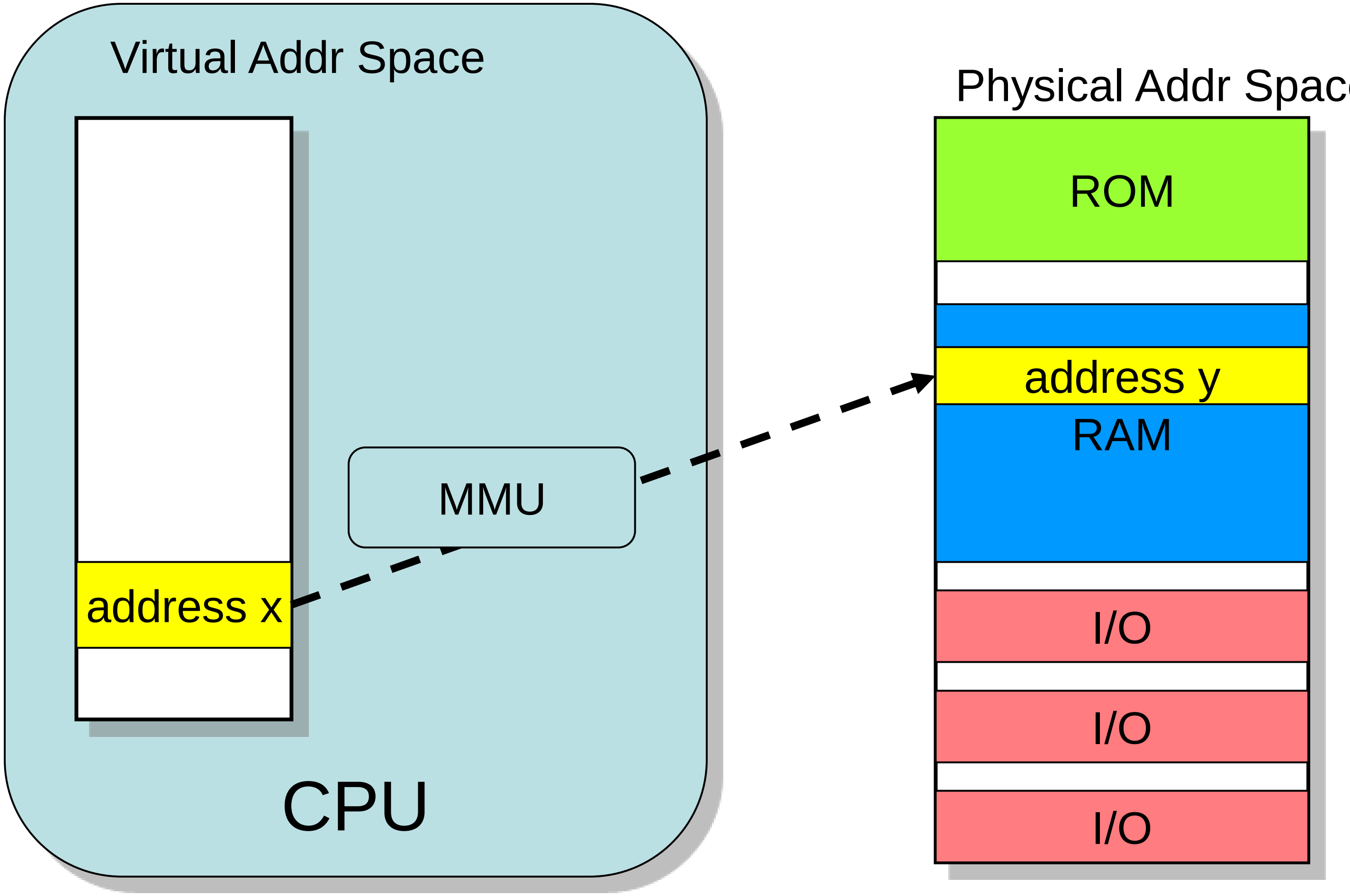
Swapping Area

Source: Wikipedia

Address Translation

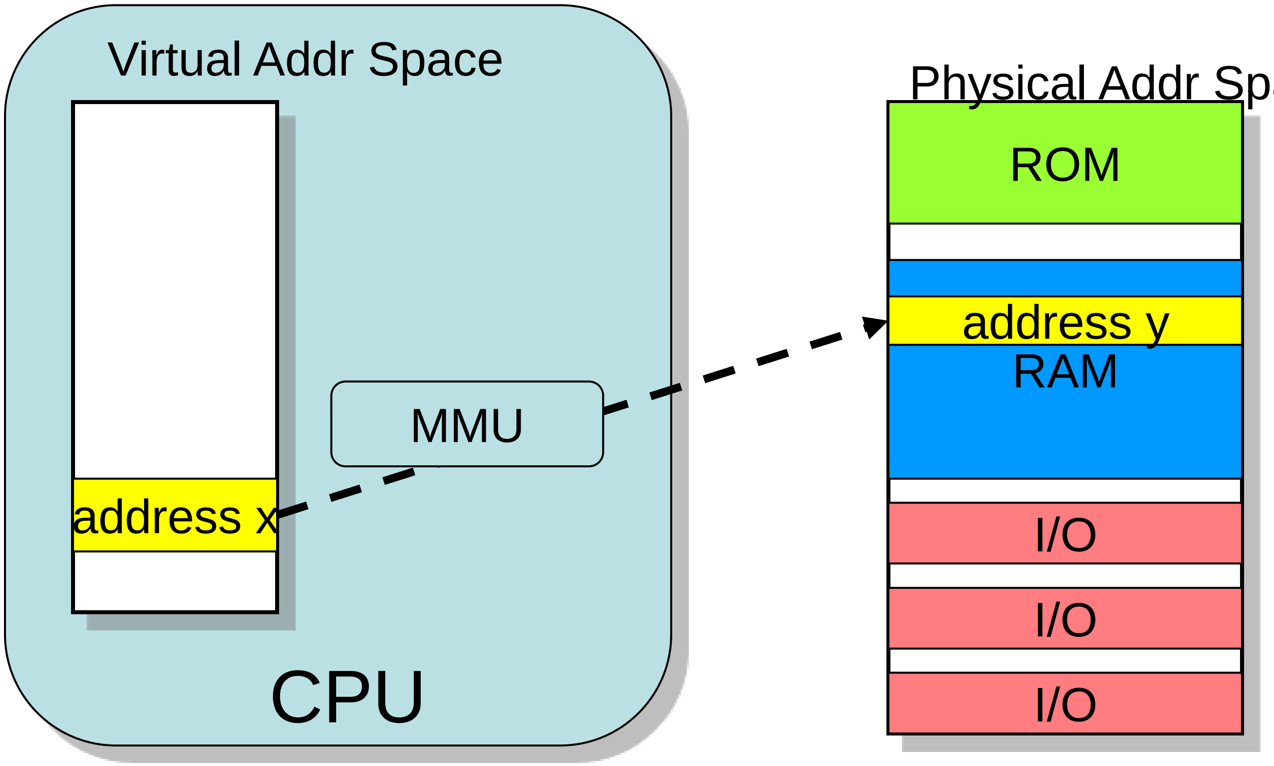


Virtual Memory is only in CPU



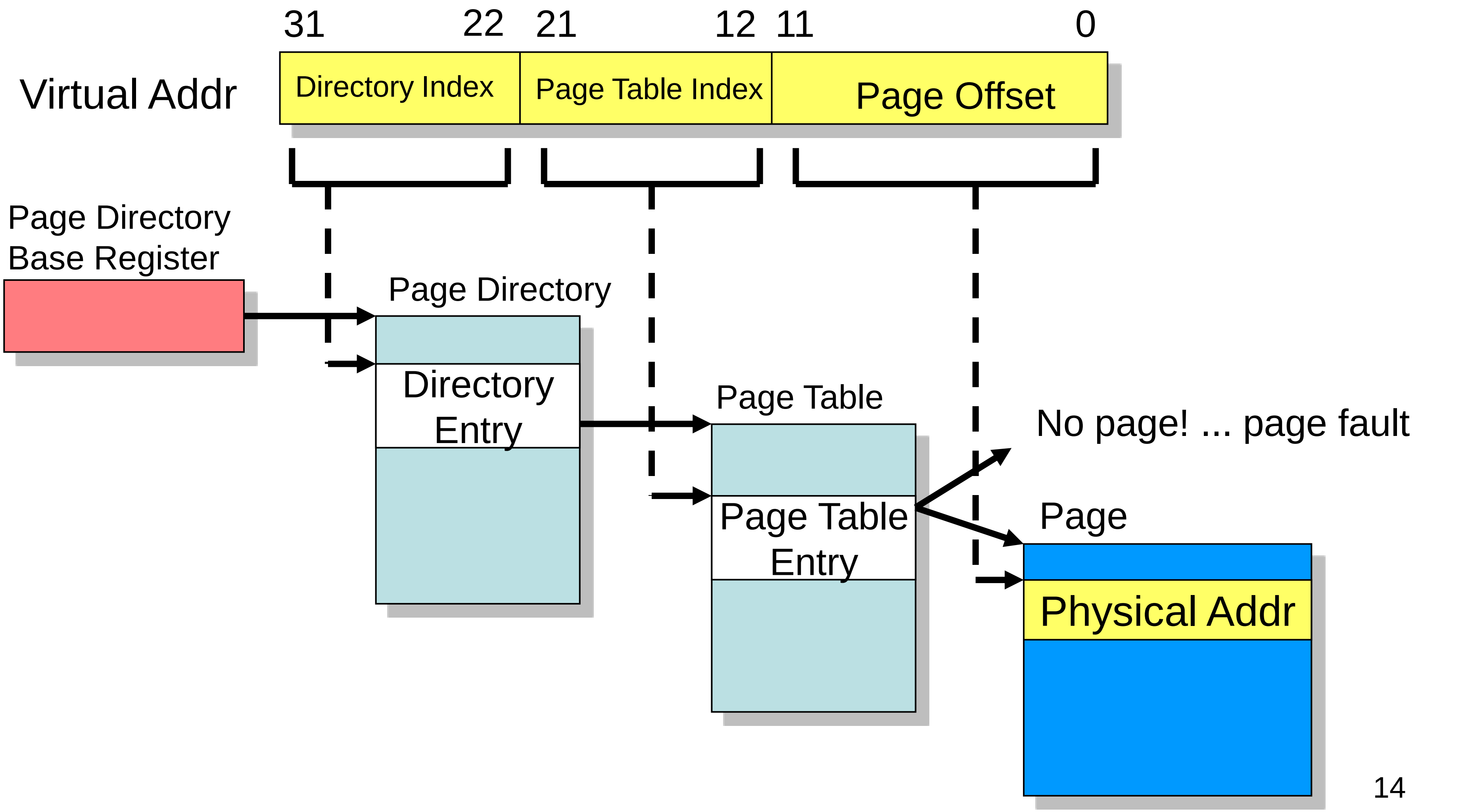
Only physical addresses come out of CPU onto address bus.
Virtual addresses can not be observed with the logic analyzer

User Program Handles only Virtual Addresses



Physical addresses are handled only in kernel mode, i.e. kernel itself and device drivers

Address Translation with MMU

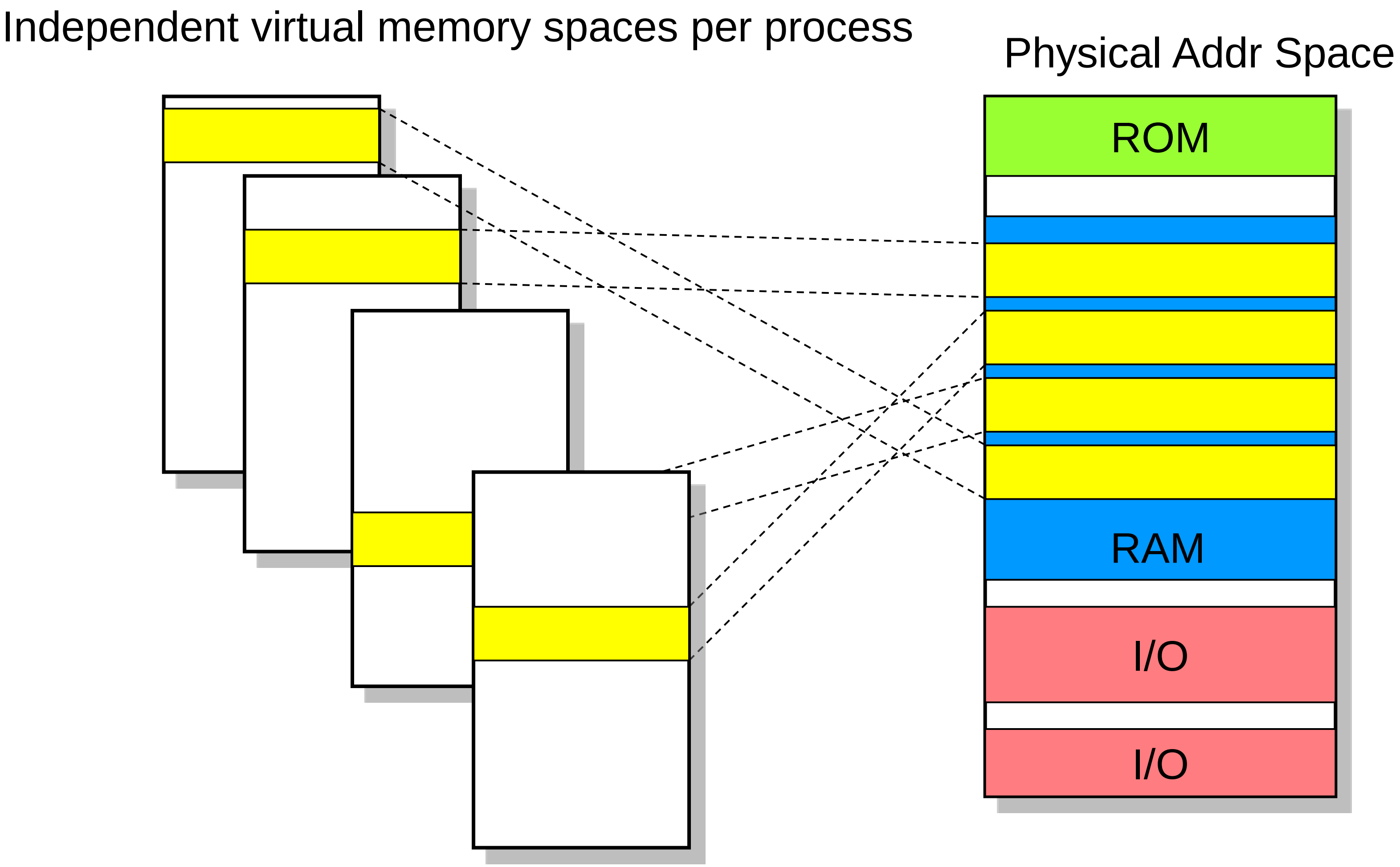


TLB

Virtual Address Pages	Physical Address Pages
...	

- Translation Lookaside Buffers
- Something like hashtable getting a physical address by a using virtual address as a key
- In most address translation, page is found in TLB, so there is no need to access page directory or page table

Multiple Memory Spaces



Demand Paging

- Mapped per page
  - Page size is usually 4Kbytes
- Two phase execution

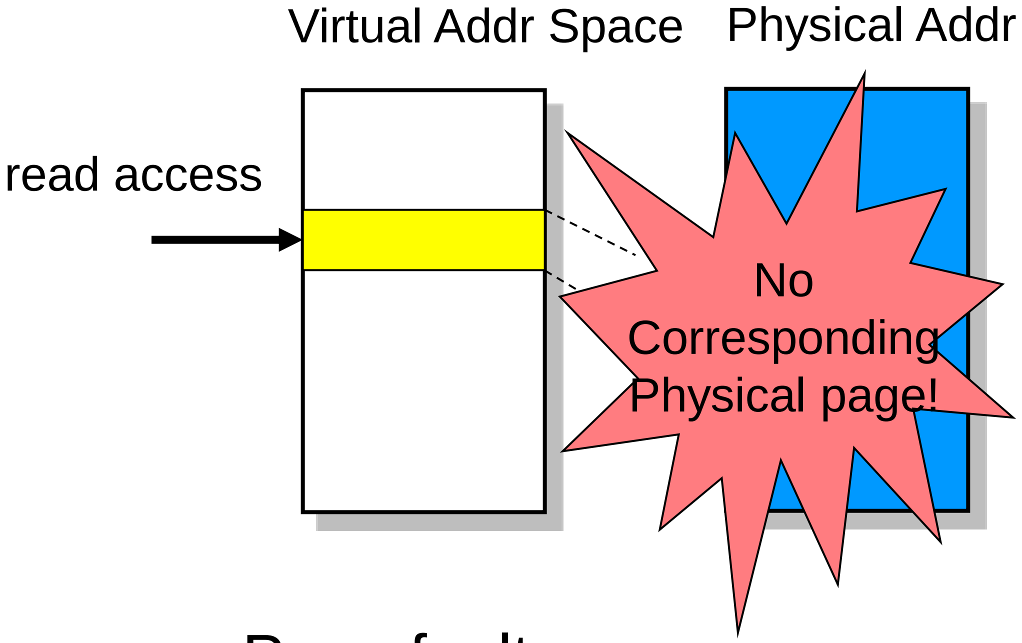
1. Virtual memory is allocated(mmap); just registered in management table
2. At actual access, physical momory is allocated for the page

As no physcal page is allocated unless the page is accessed

Virtual memory size >= Actually required physical memory size

Example of Demand Paging Behavior

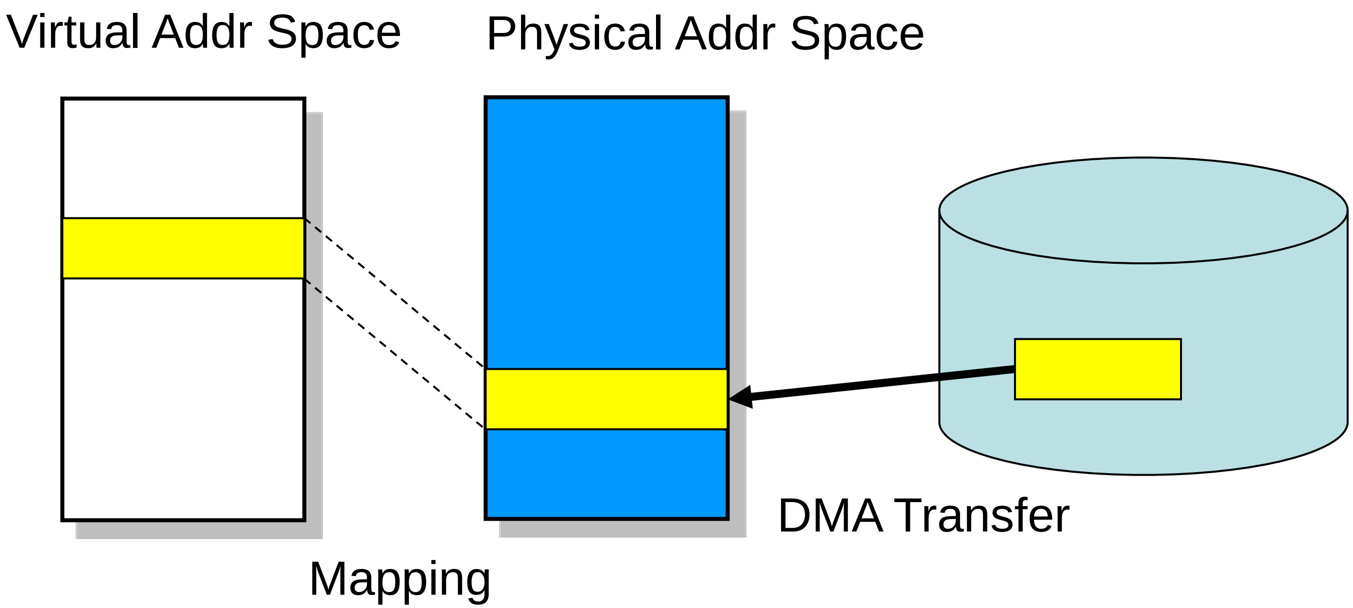
(1)



Page fault occurs;
Transits into kernel mode

Example of Demand Paging Behavior (cont.)

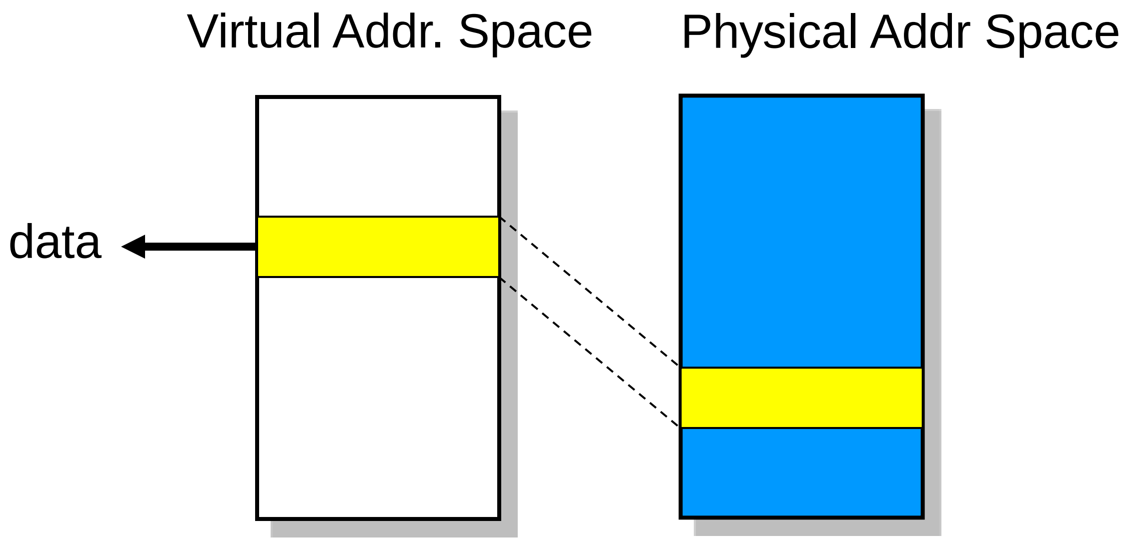
(2)



Kernel loads the data and maps physical address

Example of Demand Paging Behavior (cont.)

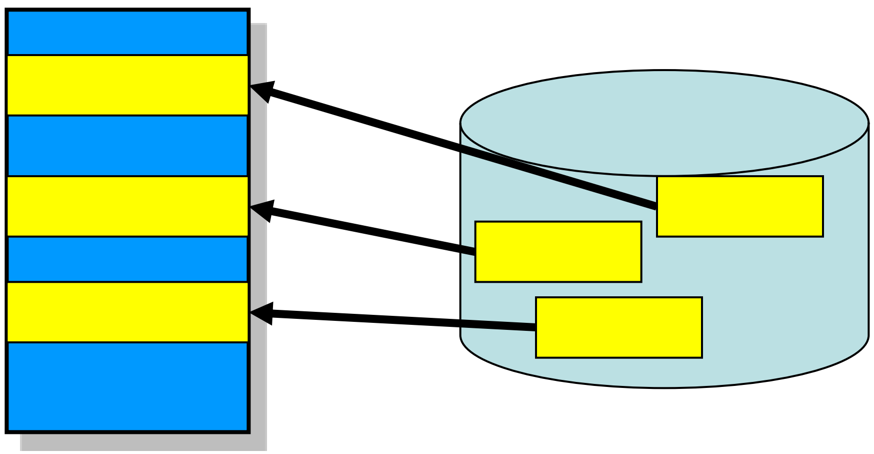
(3)



Return to user mode;
User program can read the data as if nothing happened
(but time has elapsed actually)

Page Cache

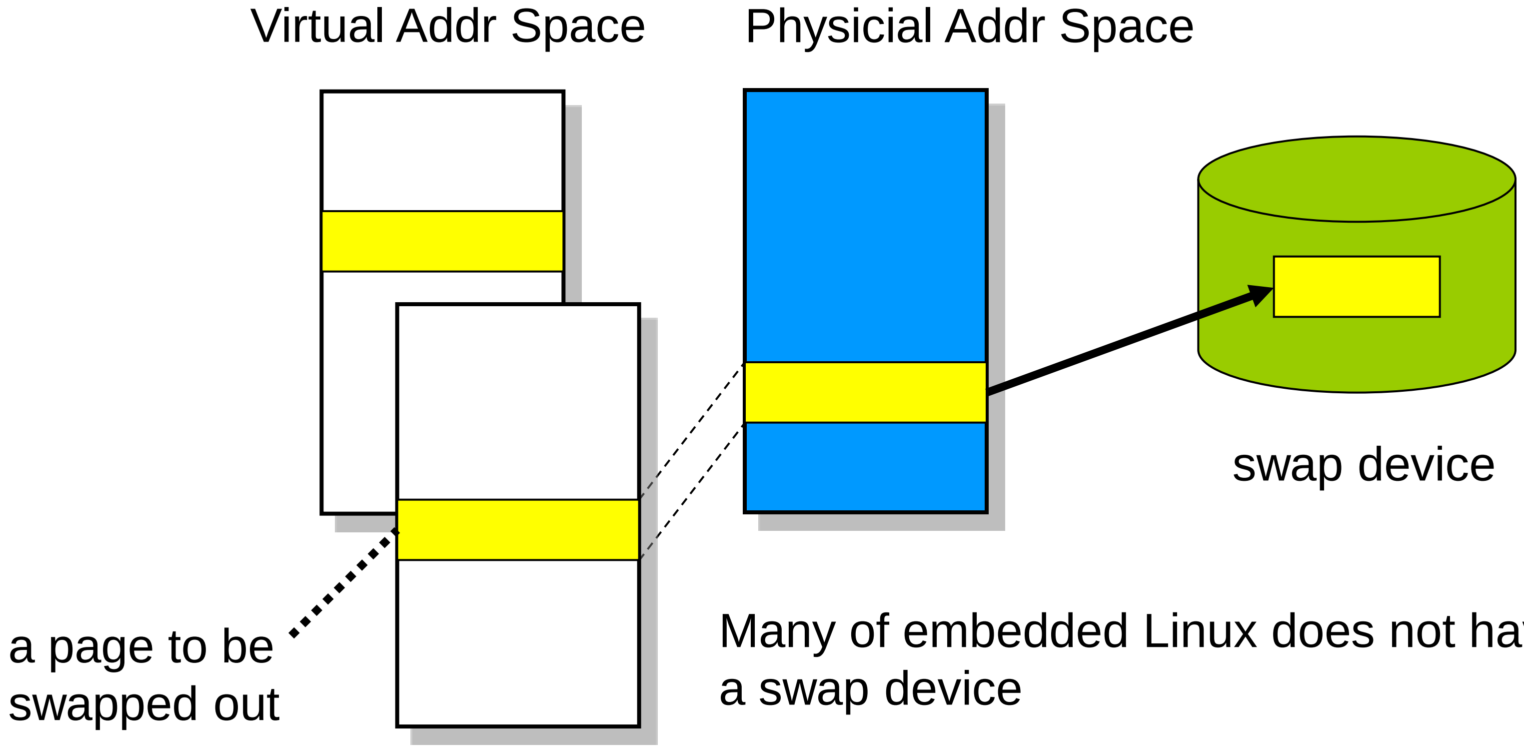
Physical Addr Space



Data read from disk are kept on memory as far as space allows.
Access tends to be sequential, so several pages are read at a time in advance;
Thus disk access does not occur every time in (2)

Page Out

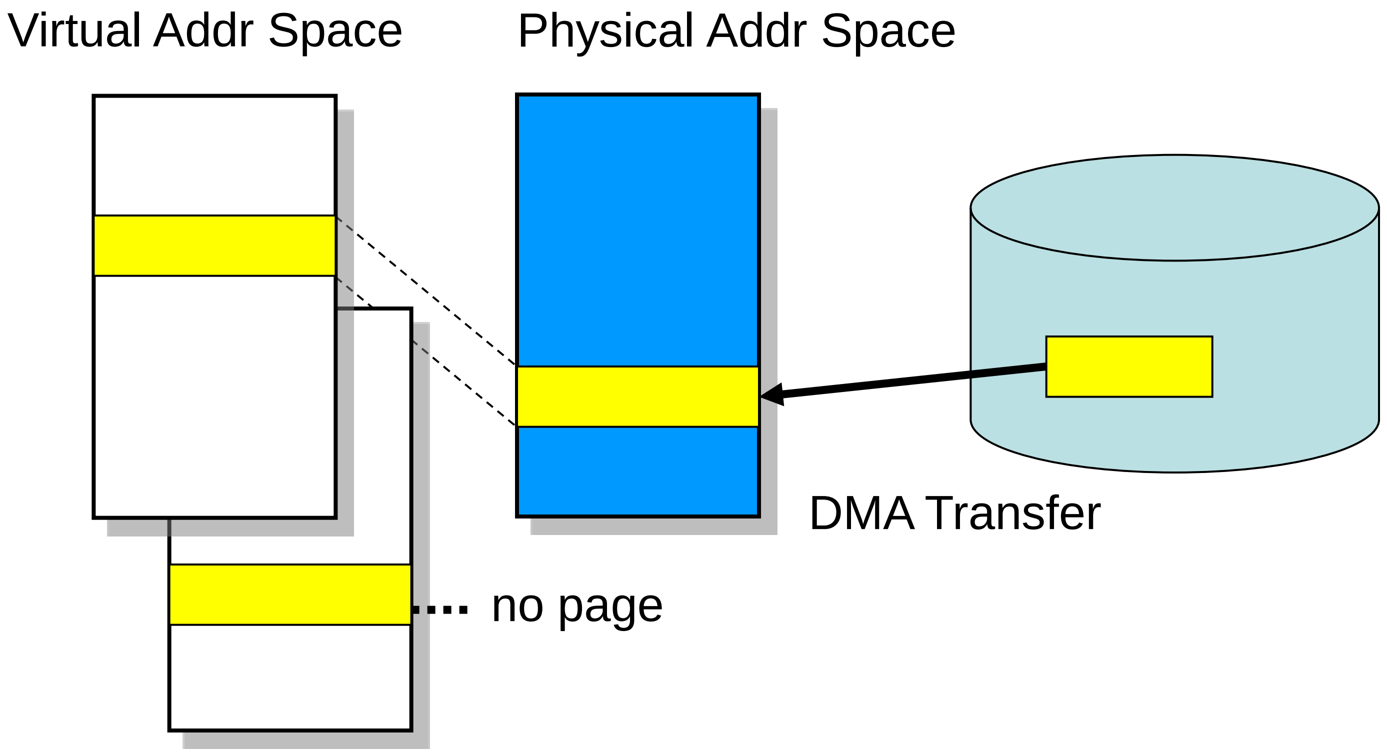
If no physical memory is available in (2), a page assumed to be least used is released. If the contents of this page is not modified, it is just discarded; otherwise, the page is swapped out onto swap device.



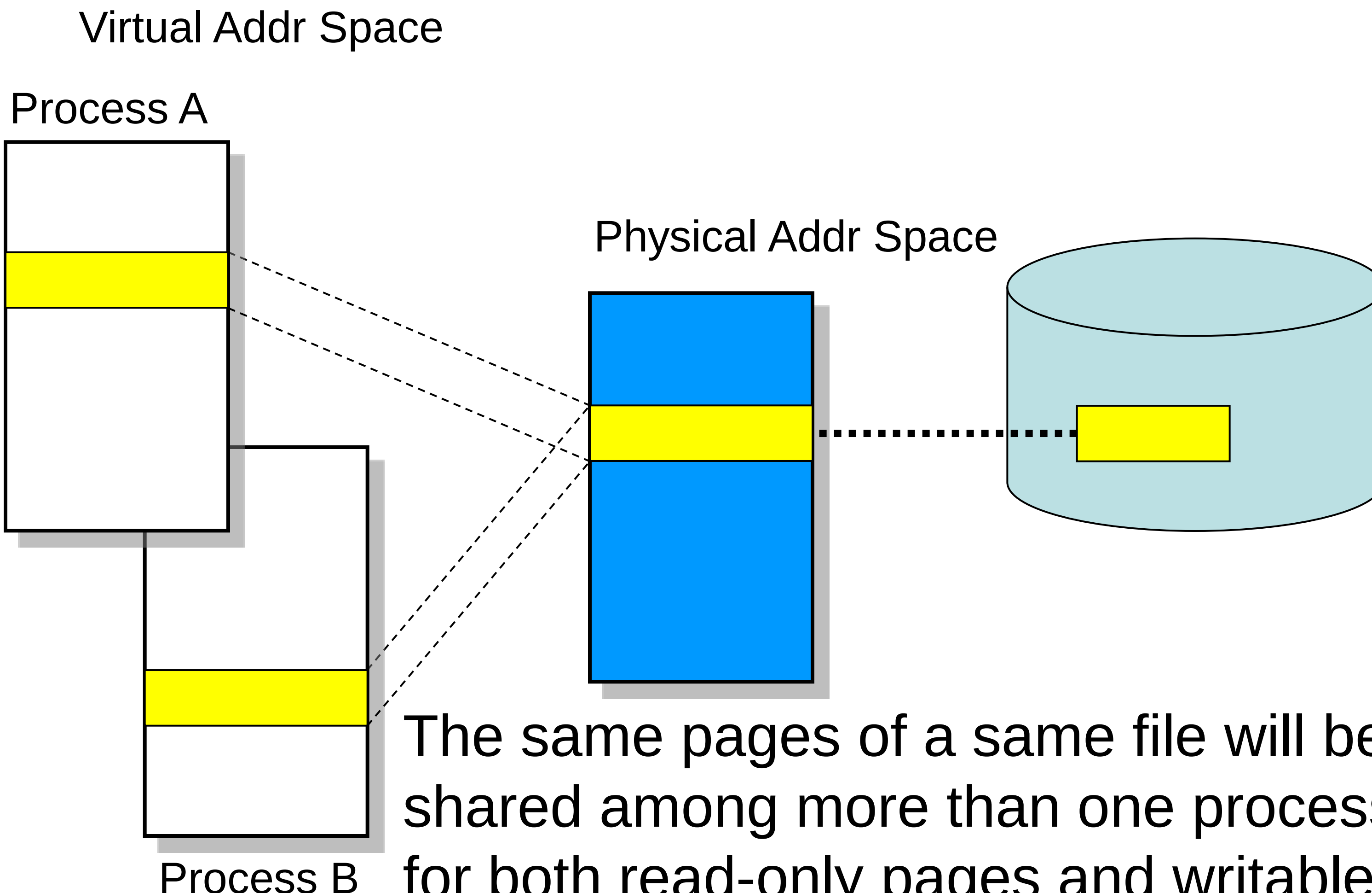
Many of embedded Linux does not have a swap device

Page Out (cont.)

A requested page is allocated using area of a page released. This “juggling” enables to larger size of virtual memory than physical memory size actually installed



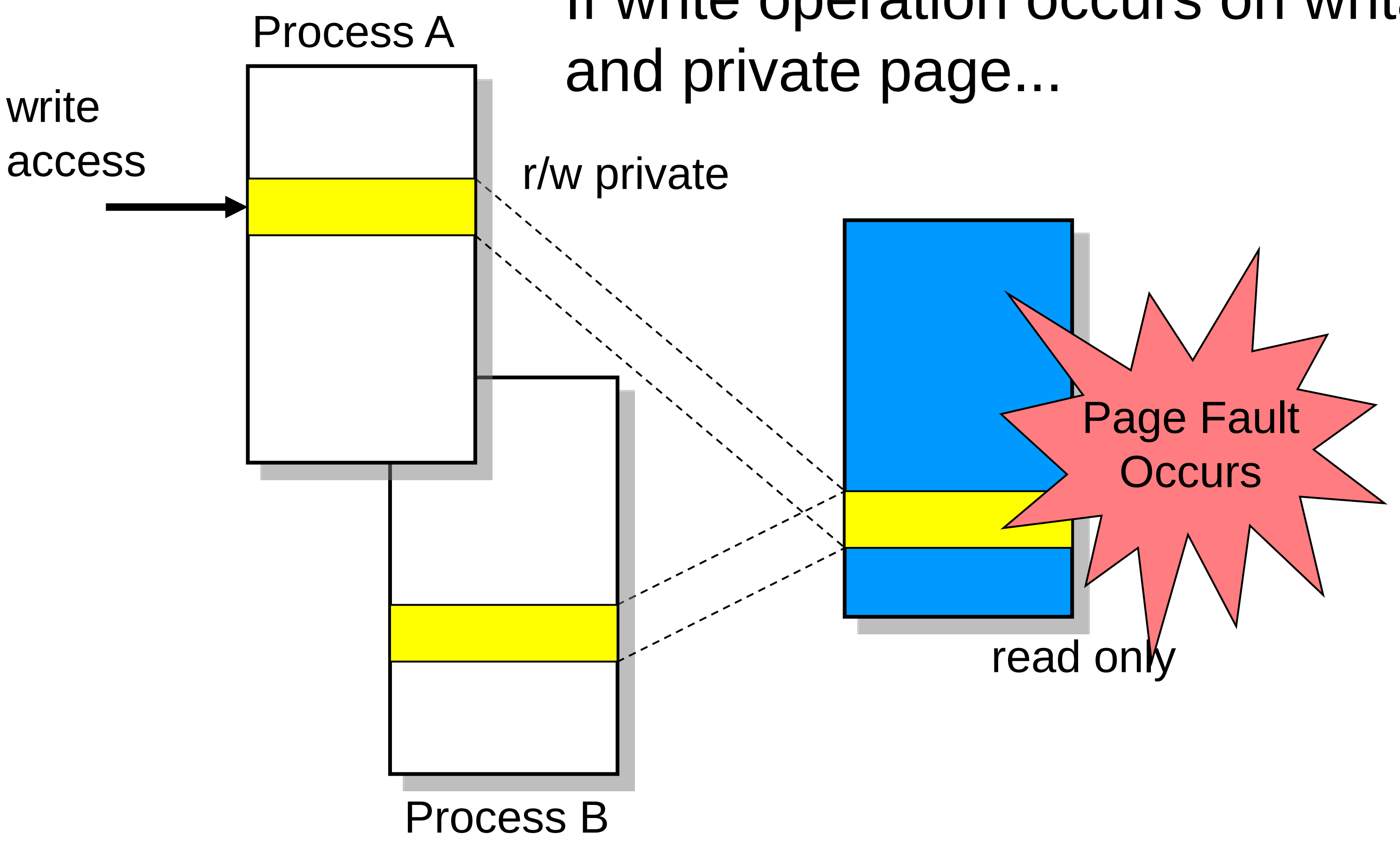
Page Sharing



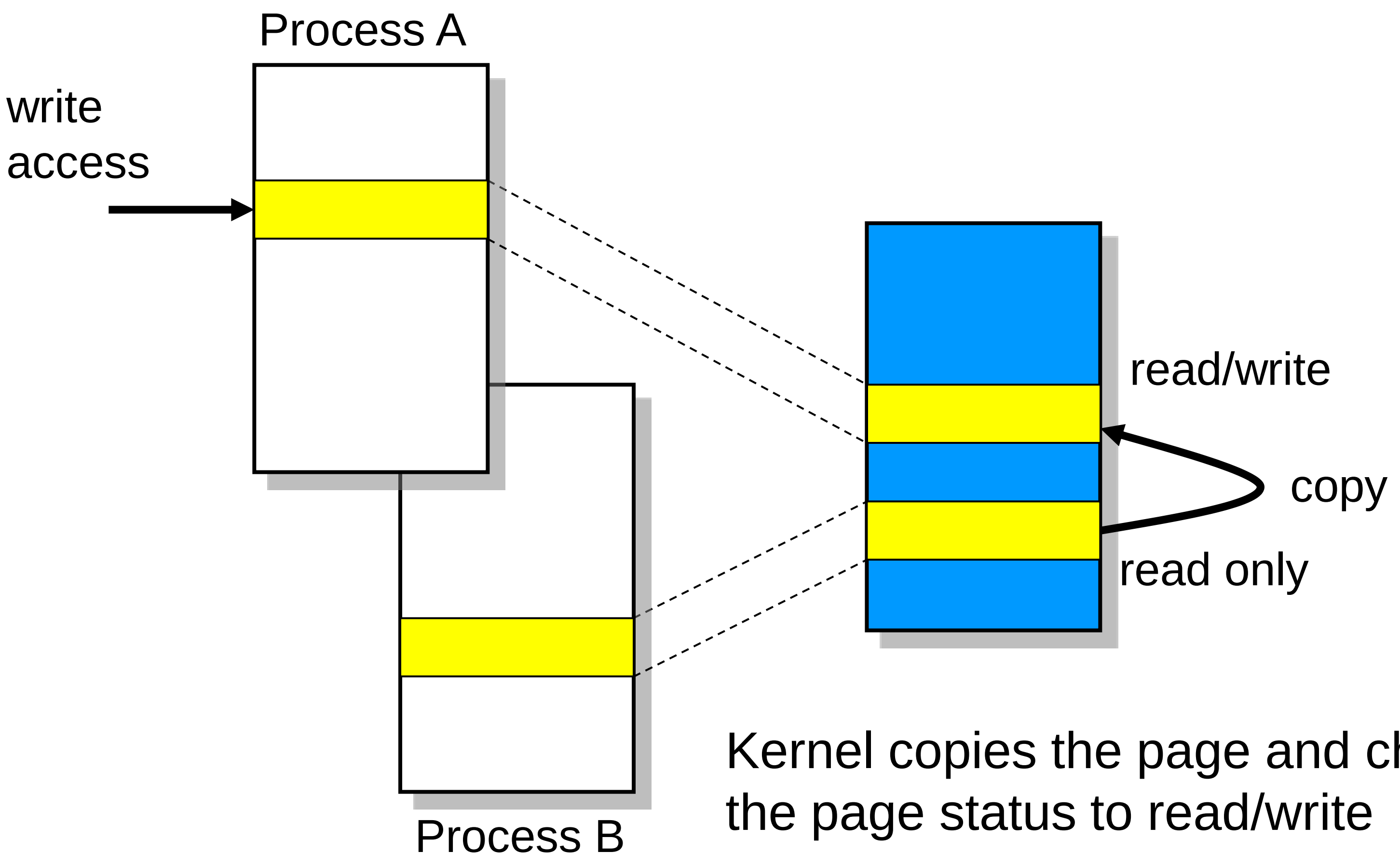
The same pages of a same file will be shared among more than one processes; for both read-only pages and writable pages

Copy on Write

If write operation occurs on writable and private page...

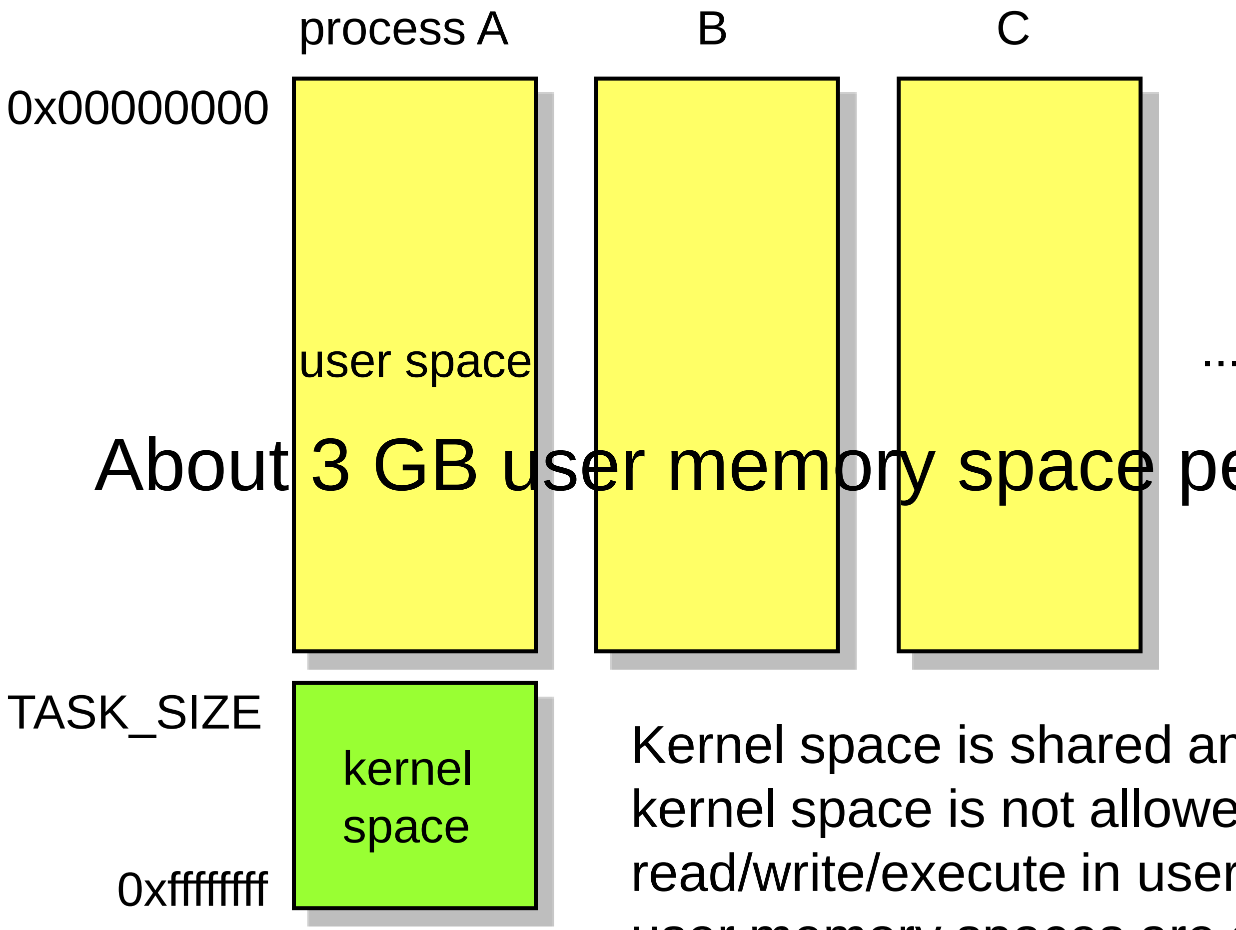


Copy on Write (cont.)



Kernel copies the page and changes the page status to read/write

Memory Spaces of Processes



About 3 GB user memory space per process

Kernel space is shared among processes;
kernel space is not allowed to
read/write/execute in user mode;
user memory spaces are switched
when processes switched

TASK_SIZE is 0xc0000000 for i386;
0xbf000000 for ARM

Example of Memory Space of a User Process

cat /proc/<PROCESS_ID>/maps

```
00101000-0011a000 r-xp 00000000 fd:00 15172739   /lib/ld-2.4.so
0011a000-0011b000 r-xp 00018000 fd:00 15172739   /lib/ld-2.4.so
0011b000-0011c000 rwxp 00019000 fd:00 15172739   /lib/ld-2.4.so
0011e000-0024a000 r-xp 00000000 fd:00 15172740   /lib/libc-2.4.so
0024a000-0024d000 r-xp 0012b000 fd:00 15172740   /lib/libc-2.4.so
0024d000-0024e000 rwxp 0012e000 fd:00 15172740   /lib/libc-2.4.so
0024e000-00251000 rwxp 0024e000 00:00 0
08048000-08049000 r-xp 00000000 fd:00 11666681   /home/koba/lab/loop/a.out
08049000-0804a000 rw-p 00000000 fd:00 11666681   /home/koba/lab/loop/a.out
b7fef000-b7ff1000 rw-p b7fef000 00:00 0
b7fff000-b8000000 rw-p b7fff000 00:00 0
bffeb000-c0000000 rw-p bffeb000 00:00 0          [stack]
```

Address Range

file offset

inode

file name

r: read
w: write
x: execute
s: shared
p: private (copy on write)

device
major:minor

Example of Memory Space of a User Process (Detail)

cat /proc/<PROCESS_ID>/smaps

```
      ....
0011e000-0024a000 r-xp 00000000 fd:00 15172740   /lib/libc-2.4.so
Size:                 1200 kB
Rss:                   136 kB
Shared_Clean:          136 kB
Shared_Dirty:            0 kB
Private_Clean:           0 kB
Private_Dirty:           0 kB
0024a000-0024d000 r-xp 0012b000 fd:00 15172740   /lib/libc-2.4.so
Size:                   12 kB
Rss:                     8 kB
Shared_Clean:            0 kB
Shared_Dirty:            0 kB
Private_Clean:           0 kB
Private_Dirty:           8 kB
0024d000-0024e000 rwxp 0012e000 fd:00 15172740   /lib/libc-2.4.so
Size:                    4 kB
Rss:                     4 kB
Shared_Clean:            0 kB
Shared_Dirty:            0 kB
Private_Clean:           0 kB
Private_Dirty:           4 kB
      ....
```

RSS = Physical Memory Size

mmap System Call

```
#include <sys/mman.h>

void *mmap(void *start, size_t length, int prot, int flags,
        int fd, off_t offset);

int munmap(void *start, sizt_t length);
```

- Map/Unmap files or devices onto memory
- Argument *prot*
  - PROT_NONE, or OR operation of PROT_EXEC, PROT_READ, and PROT_WRITE
- Argument *flags*
  - MAP_FIXED, MAP_SHARED, MAP_PRIVATE, MAP_ANONYMOUS, ...

mmap tips

- Unless specified as MAP_FIXED, kernel searches available pages
- If MAP_FIXED is specified and it overlaps existing pages, the pages are *mumpap*ped internally
  - Thus this option is usually not used
- File offset must be multiple of page size
- Addresses and sizes of *mmap* and *munmap* need not be identical

Usage of mmap (1)

- As substitute of *malloc* for large size
  - No data copy, such as compaction, occurs
  - Unlike *malloc/free*, addr and size at *munmap* can be different than those at *mmap*
    - It is possible to allocate a large chunk with a single *mmap*, and to release piecemeal with multiple *munmap*s
  - In *malloc* of glibc implementation, *mmap* is called for a certain size or larger
    - DEFAULT_MMAP_THRESHOLD = (128*1024)

Usage of mmap (2)

- Fast file access
  - In system calls *read* and *write*, data is internally buffered in physical pages; from there data is copied to array specified by user
  - Using *mmap* enables to access page directly, thus number data copies can be reduced
  - java.nio.MappedByteBuffer in Java1.4

Usage of mmap (3)

- Shared memory among processes
  - Map the same file as readable/writable and shared from more than one processes
  - IPC shared memory system calls (*shmget*, *shmat*, ...) does above internally

Usage of mmap (4)

- Access to physical memory, I/O ports
  - By mapping device file /dev/mem, it becomes possible to read/write physical memory space in user mode
  - To access /dev/mem, root privilege is required

Summary

- Virtual memory usage and physical memory usage are not same. Physical one matters in practice
- Be careful when overhead of virtual memory occurs.
  - TLB miss
  - Page fault
- Make use of system call mmap

References

- Linux kernel source code
  http://www.kernel.org/
- GNU C library source code
  http://www.gnu.org/software/libc/
- **“Understanding the Linux Kernel (2nd Edition)”**
  by Daniel P. Bovet (O’Reilly) [Japanese translation; 3rd Edition available in English]
- “Linux kernel 2.6 Kaidokushitsu”, by Hirokazu Takahashi et. al. (SoftBank Creative) [in Japanese]
- Linux man command
- And other search results on web

One more thing: hot topics

- From CELF BootTimeResources
  - KernelXIP
  - ApplicationXIP
  - (DataReadInPlace)
- From CELF MemoryManagementResouces
  - Huge/large/superpages
  - Page cache compression