CS202 (003): Operating Systems
Virtual Memory III, Weensy OS

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Most of the materials covered in this slide come from the lecture notes of Mike Walfish's CS202

Last Time

Page faults

A reference is illegal, either because it's not mapped in the page tables or because there is a protection violation.

This is a quite powerful mechanism!
(It turns out you can build interesting functionalities by triggering page faults)

How does OS get involved in page fault (in x86)?

Process constructs a trap frame and transfer execution to an interrupt/trap handler

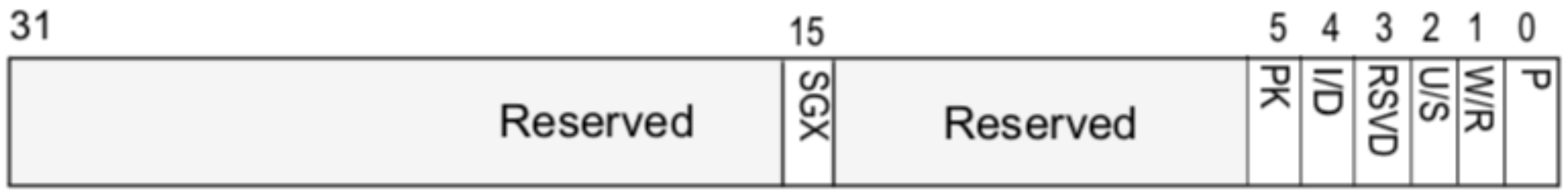
	ss	stack segment (ignore)
	%rsp	former value of stack pointer
	rflags	former value of rflags
	cs	code segment (ignore)
	%rip	Instruction that caused the trap
%rsp	error code	[................................ U/S | W/R | P]

When page fault happens, the **kernel** sets up the process's page entries properly, or terminates the process

%rip now points to the code handle the trap
(using Interrupt Descriptor Table)

%cr2 holds the faulting virtual address

U/S: user mode fault / supervisor mode fault
R/W: access was read / access was write
P: not-present page / protection violation



P	0	The fault was caused by a non-present page.
	1	The fault was caused by a page-level protection violation.
W/R	0	The access causing the fault was a read.
	1	The access causing the fault was a write.
U/S	0	A supervisor-mode access caused the fault.
	1	A user-mode access caused the fault.
RSVD	0	The fault was not caused by reserved bit violation.
	1	The fault was caused by a reserved bit set to 1 in some paging-structure entry.
I/D	0	The fault was not caused by an instruction fetch.
	1	The fault was caused by an instruction fetch.
PK	0	The fault was not caused by protection keys.
	1	There was a protection-key violation.
SGX	0	The fault is not related to SGX.
	1	The fault resulted from violation of SGX-specific access-control requirements.

Figure 4-12. Page-Fault Error Code

When does page fault occur?

Overcommitting physical memory

"Your program thinks it has 64GB of memory, but your hardware has 16 GB of physical memory"

How does this work?

Disk was (is) used to store memory pages

Advantages: address space looks huge

Disadvantages: access to "paged" memory (as disk pages that live on the disk are known) are **slow**

Rough Implementation

On a page fault, the kernel reads in the faulting page. It may need to send a page to disk (when satisfy the following TWO):

1. kernel is out of memory
2. the page that it selects to write out is dirty)

What are some other use cases of page fault?

Store memory pages across the network (Distributed Shared Memory)

On a page fault, the page fault handler went and retrieved the needed page from some other machine

Copy-on-write
(fork, mmap, …)

When creating a copy of another process, don't copy its memory. Just copy its page tables, mark the pages as read-only

When a write happens, a page fault results. at that point, the kernel allocates a new page, copies the memory over, and restarts the user program to do a write Then, only do copies of memory when there is a fault as a result of a write

Accounting

Good way to sample what percentage of the memory pages are written to in any time slice: mark a fraction of them not present, see how often you get faults

Paging in day-to-day use

Demand paging	Program code is loaded into memory only when it's needed, not all at once
Growing the stack	The seemingly contiguous virtual memory can scatter across different locations in physical memory
BSS page allocation (Block Started by Symbol)	The OS can save memory by not allocating physical pages for the BSS until the program actually tries to use variables in this segment.
Shared text	Sharing the read-only parts of a program between multiple processes running the same program
Shared libraries	Multiple programs can use the same library code in memory, saving space
Shared libraries	Allowing multiple processes to access the same memory region

Costs of page faults

What does paging from the disk cost?

Average memory access time

(AMAT)

$$(1-p) * \texttt{memory\_access\_time} + \texttt{p} * \texttt{page\_fault\_time}$$

where p is the prob of a page fault

$\texttt{memeory\_access\_time}(\texttt{t}_\texttt{M}) \approx \texttt{100ns}$ $\texttt{disk\_access\_time}(\texttt{t}_\texttt{D}) \approx \texttt{10ms} = \texttt{10}^7\texttt{ns}$

What does p need to be to ensure that paging hurts performance by less than 10%?

$$1.1 * t_M > (1-p) * t_M + p * t_D$$

$$p = 0.1 * \frac{t_M}{t_D - t_M} \approx \frac{10^1 ns}{10^7 ns} = 10^{-6}$$

Page faults are **super-expensive**!

"need to pay attention to the slow case if it's really slow and common enough to matter."

Lab 4: Weensy OS
(Yes, it is released today)

In Lab 4, you will write a mini OS, WeensyOS, that implements the virtual memory architecture and a few important system calls.

Weensy OS structure

Processes

*Files with p-**

Kernel Code

*Files with k-**

look at process.h for

`sys_page_alloc()` for process allocating memory

(`sys_page_alloc` is analogous to `brk()` or `mmap()` in POSIX)

`exception_return()` for when returning back into user space

`%rax` is what the application return value is

look at kernel.h for

process control block (PCB): `struct proc`

* Process registers, process state

* Process page table - a pointer (kernel virtual address, which is the identical physical address)

* to an L1 page table L1 page table's first entry points to a page table, and so on...

`virtual_memory_lookup()`:

lookup a physical page using pagetable and virtual memory.

`virtual_memory_map()`:

map virtual address -> physical address

```
typedef struct physical_pageinfo {
    int8_t owner;  //kernel, reserved, free, pid
    int8_t refcount;
} physical_pageinfo;

static physical_pageinfo pageinfo
      [PAGENUMBER(MEMSIZE_PHYSICAL)];
// one physical_pageinfo struct per _physical_ page
```

pageinfo array

Weensy OS Memory Related

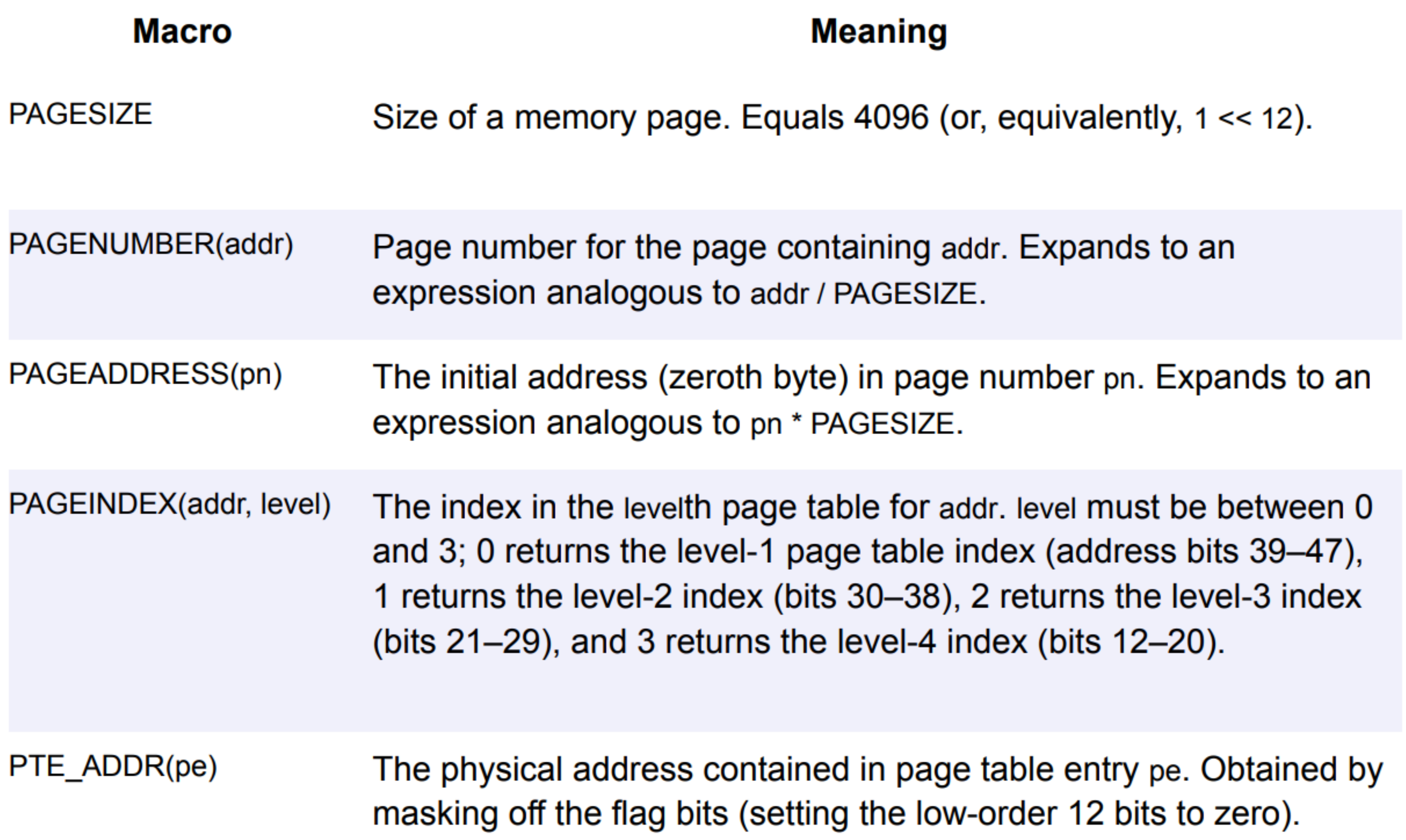
WeensyOS begins with the kernel and all processes sharing a single address space.
This is defined by the kernel_pagetable.

Kernel's pagetable is identity-mapped: Virtual address X maps to physical address X.
As you work through the project, you will shift processes to use independent address space
where each process can access only a subset of physical memory.

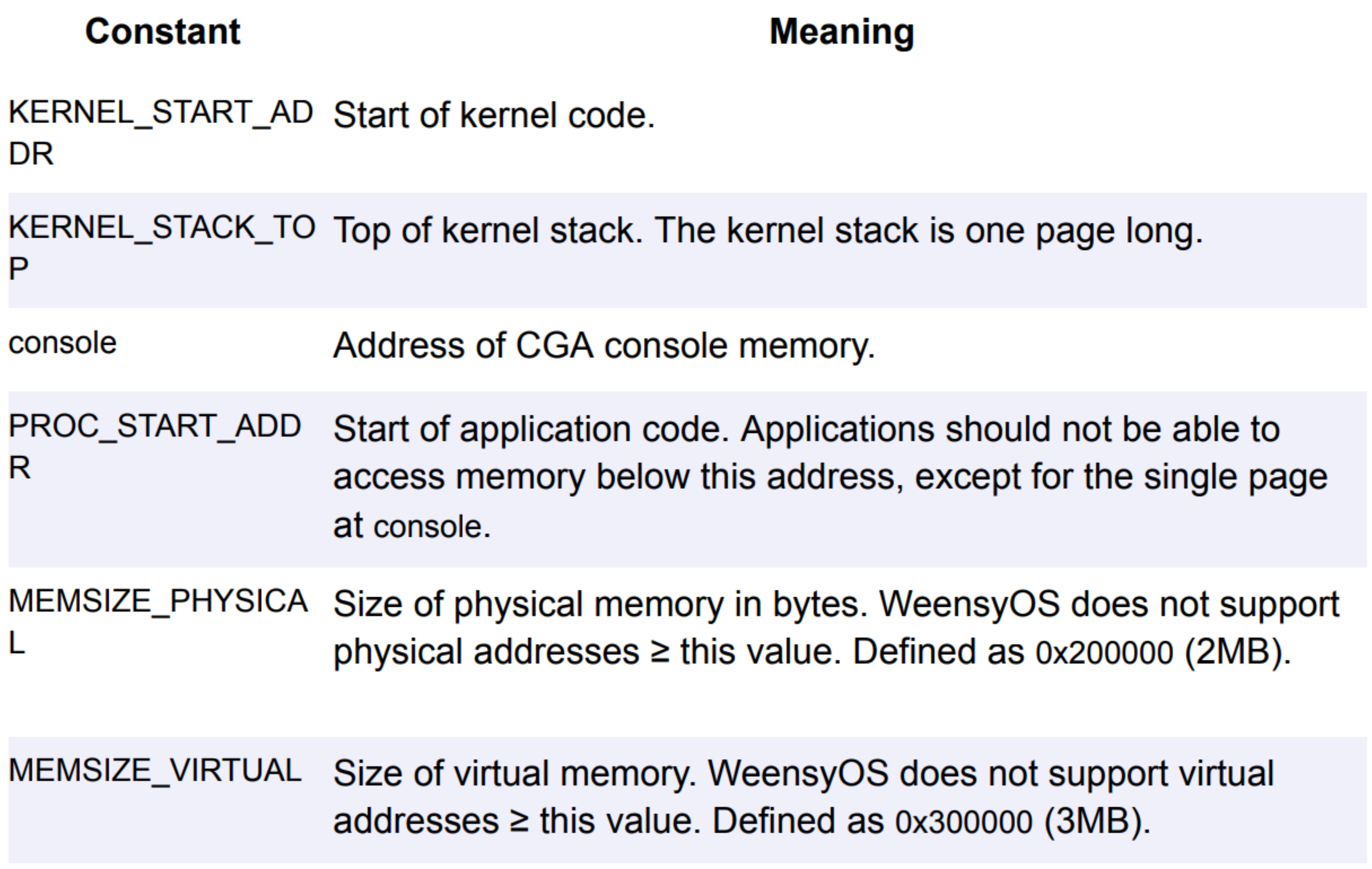
The OS supports 3MB of virtual memory on top of 2MB of physical memory.
(Recall the point of virtualization, from the perspective of the process, it thinks it has 3MB of memory. But in reality, it doesn't.)

Assume page size to be 4KB, each entry in the page table is 64 bit.
How to we support 3MB of virtual memory? How many L4 pagetable do we need?
(2 L4 page tables)

Weensy OS Macros and Constants



Macro	Meaning
PAGESIZE	Size of a memory page. Equals 4096 (or, equivalently, 1 << 12).
PAGENUMBER(addr)	Page number for the page containing addr. Expands to an expression analogous to addr / PAGESIZE.
PAGEADDRESS(pn)	The initial address (zeroth byte) in page number pn. Expands to an expression analogous to pn * PAGESIZE.
PAGEINDEX(addr, level)	The index in the levelth page table for addr. level must be between 0 and 3; 0 returns the level-1 page table index (address bits 39–47), 1 returns the level-2 index (bits 30–38), 2 returns the level-3 index (bits 21–29), and 3 returns the level-4 index (bits 12–20).
PTE_ADDR(pe)	The physical address contained in page table entry pe. Obtained by masking off the flag bits (setting the low-order 12 bits to zero).



Constant	Meaning
KERNEL_START_ADDR	Start of kernel code.
KERNEL_STACK_TOP	Top of kernel stack. The kernel stack is one page long.
console	Address of CGA console memory.
PROC_START_ADDR	Start of application code. Applications should not be able to access memory below this address, except for the single page at console.
MEMSIZE_PHYSICAL	Size of physical memory in bytes. WeensyOS does not support physical addresses ≥ this value. Defined as 0x200000 (2MB).
MEMSIZE_VIRTUAL	Size of virtual memory. WeensyOS does not support virtual addresses ≥ this value. Defined as 0x300000 (3MB).

Lab 3 is Due Tomorrow!