LF *live*

MENTORSHIP SERIES

LF Live MENTORSHIP SERIES

Linux
Huge Page Concepts

Mike Kravetz, SW Engineer, Oracle

LF live MENTORSHIP SERIES

Introduction and Agenda

- Basics of Virtual Memory
- Huge Pages in the Virtual Memory Model
- Huge Pages in Linux
- Hugetlbfs Specifics

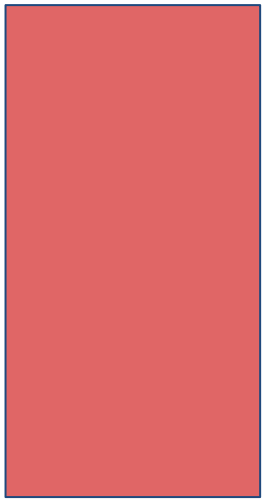
Scope and Expectations

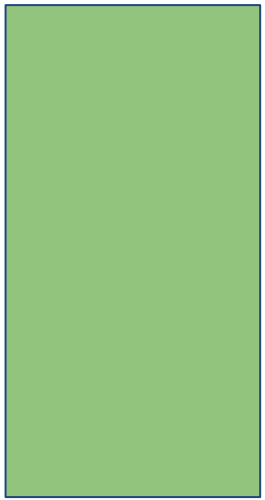
- High level description of Virtual Memory
- Intel Architecture in examples
- Expertise only in hugetlbfs

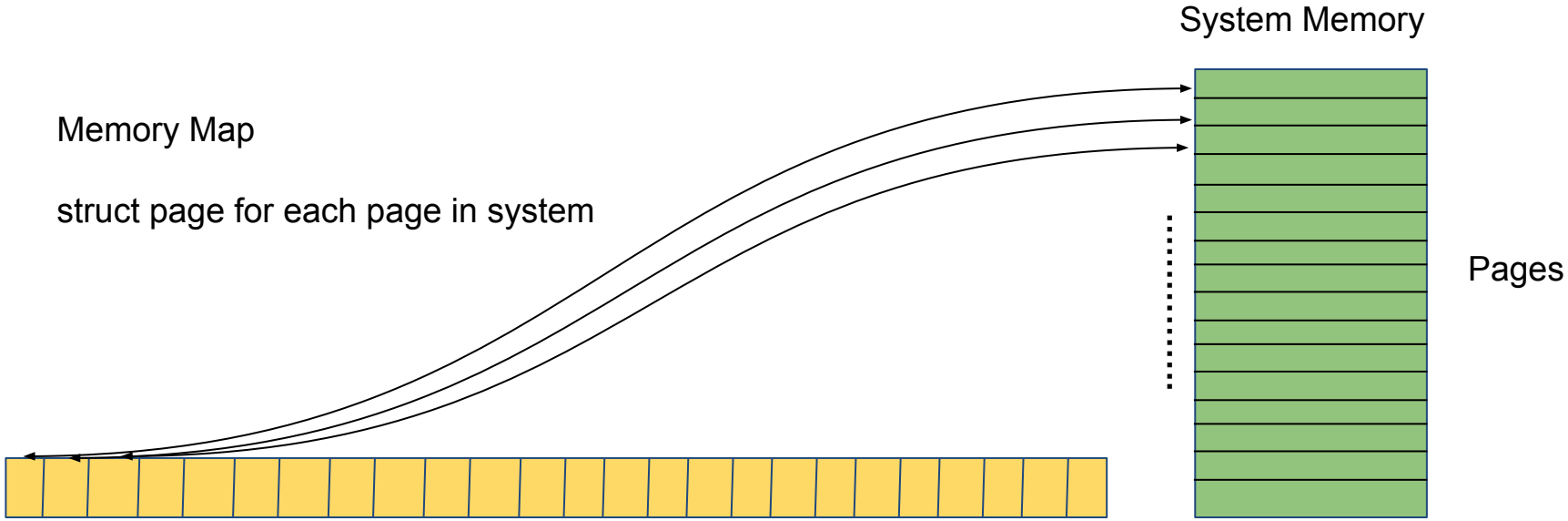
Virtual Memory Basics

Process

System Memory





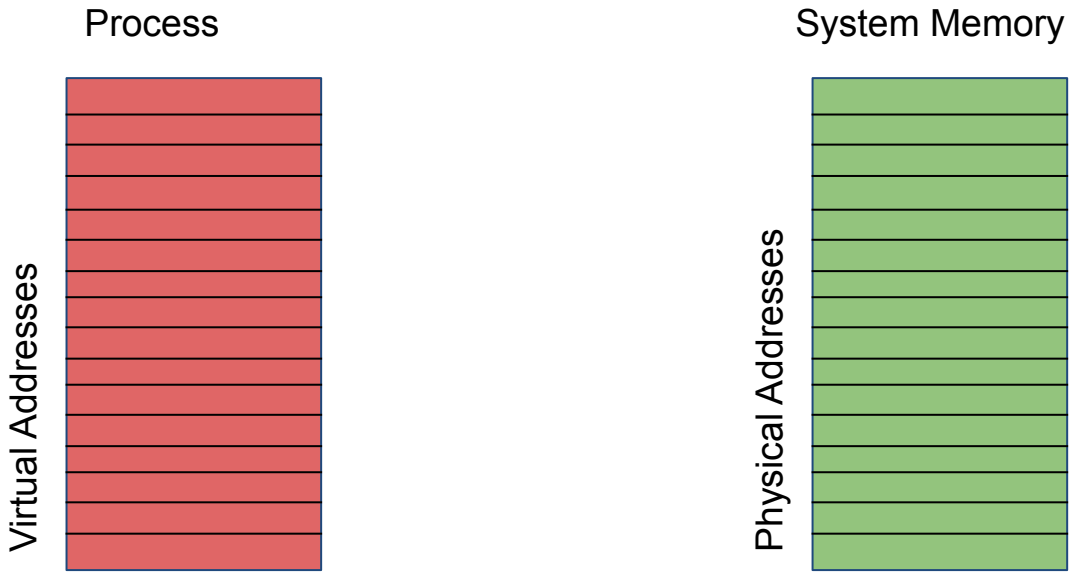

System Memory
Memory Map
struct page for each page in system
Pages

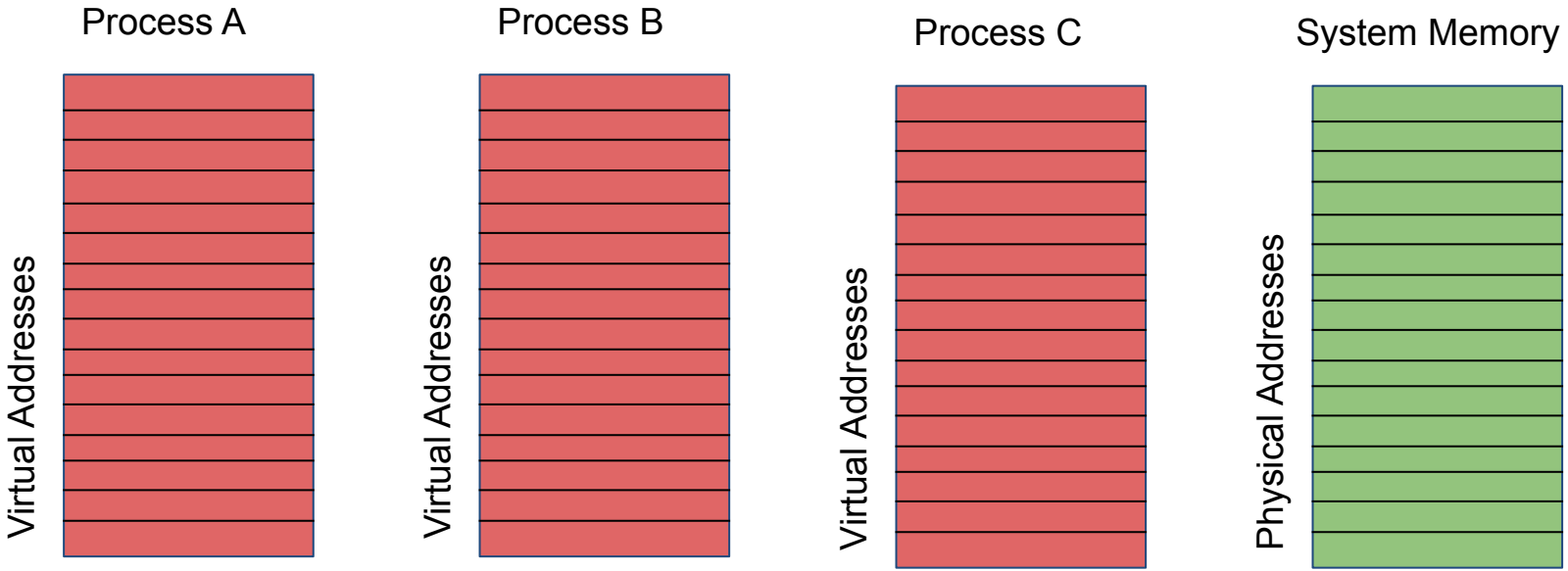
Memory Map

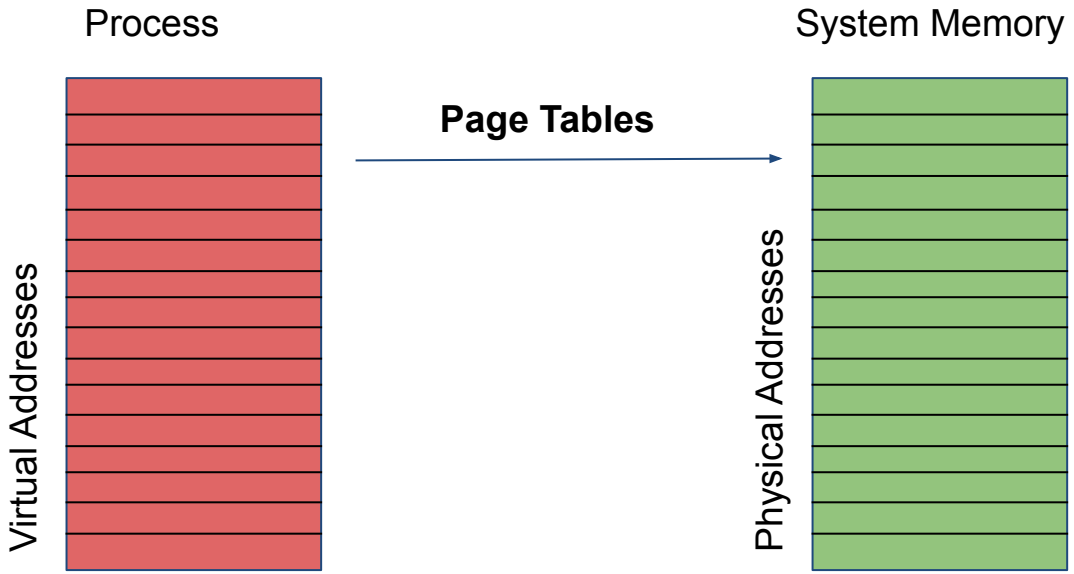
Struct Page Key Fields

- Page Flags
  - PG_locked, PG_dirty, PG_active, PG_uptodate, PG_head, PG_hwpoison …
- Reference Count
- Map Count

Commonly 64 Bytes in Size

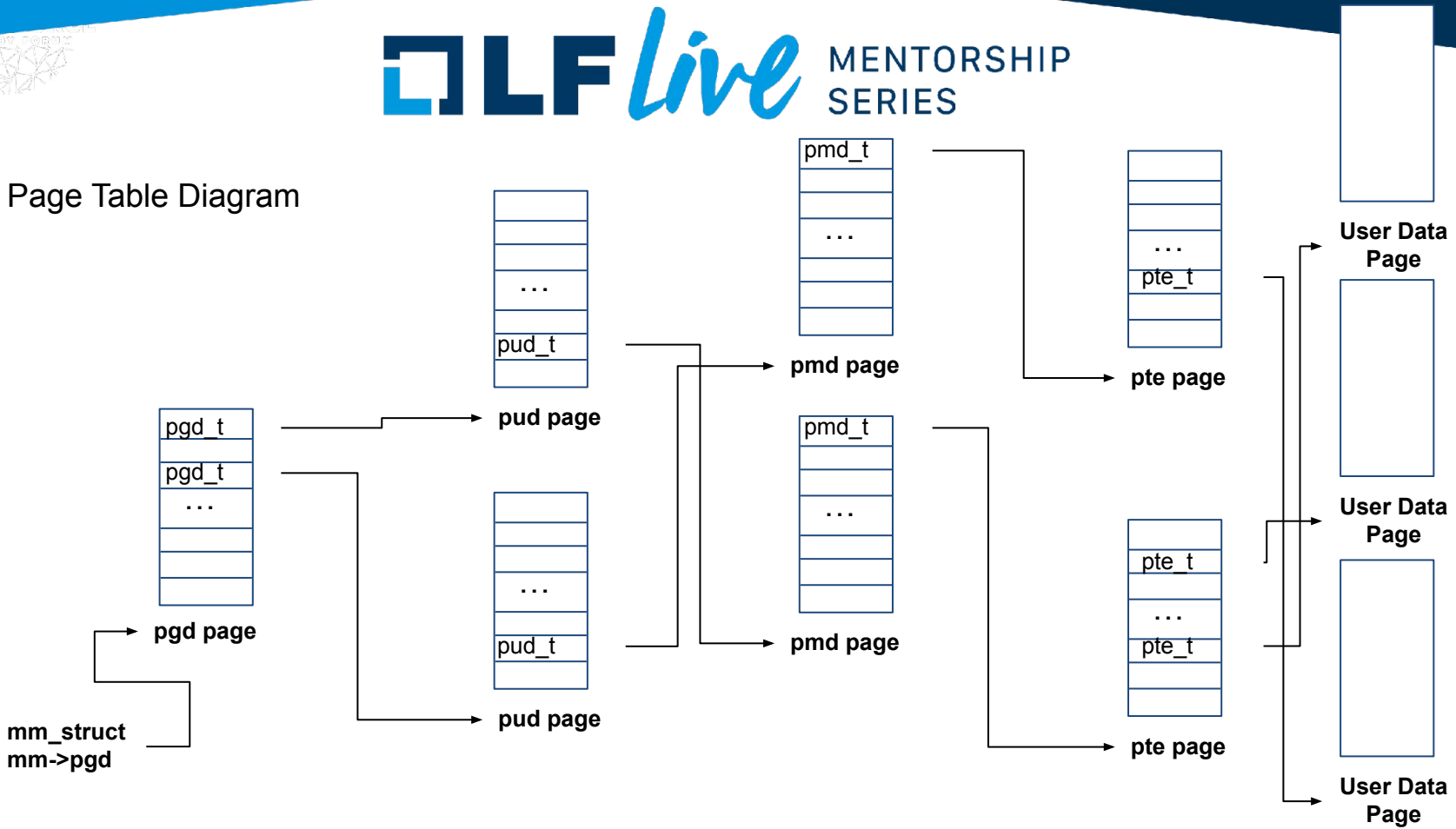

Process
Virtual Addresses
System Memory
Physical Addresses


Process A
Process B
Process C
System Memory
Virtual Addresses
Virtual Addresses
Virtual Addresses
Physical Addresses


Process
System Memory
Page Tables
Virtual Addresses
Physical Addresses

LF Live MENTORSHIP SERIES

Page Table Diagram



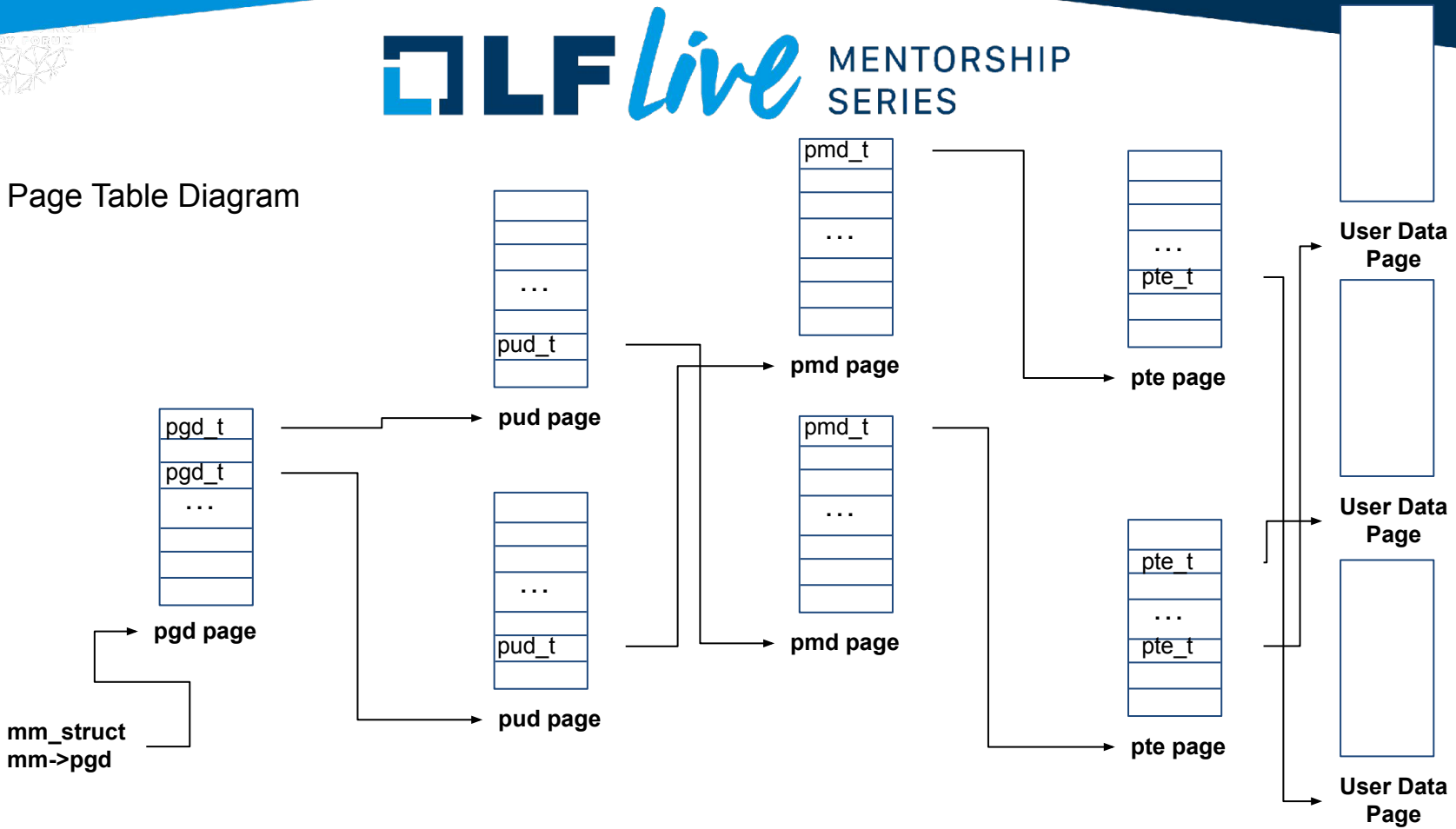
LF live MENTORSHIP SERIES

Page Table Specifics

- Each PGD, PUD, PMD or PTE table is one Page in size
- Table is an array of entries, each a word in size
- X86_64 example
  - Page - 4K
  - Word - 8bytes
  - 512 entries per page
    - PTRS_PER_PGD, PTRS_PER_PUD, PTRS_PER_PMD, PTRS_PER_PTE

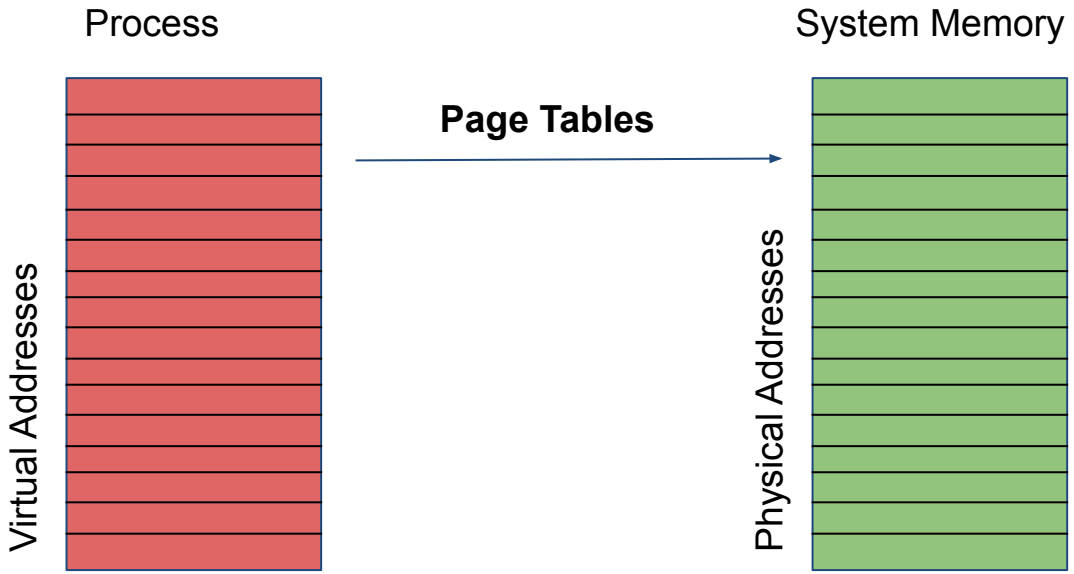
LF Live MENTORSHIP SERIES

Page Table Diagram

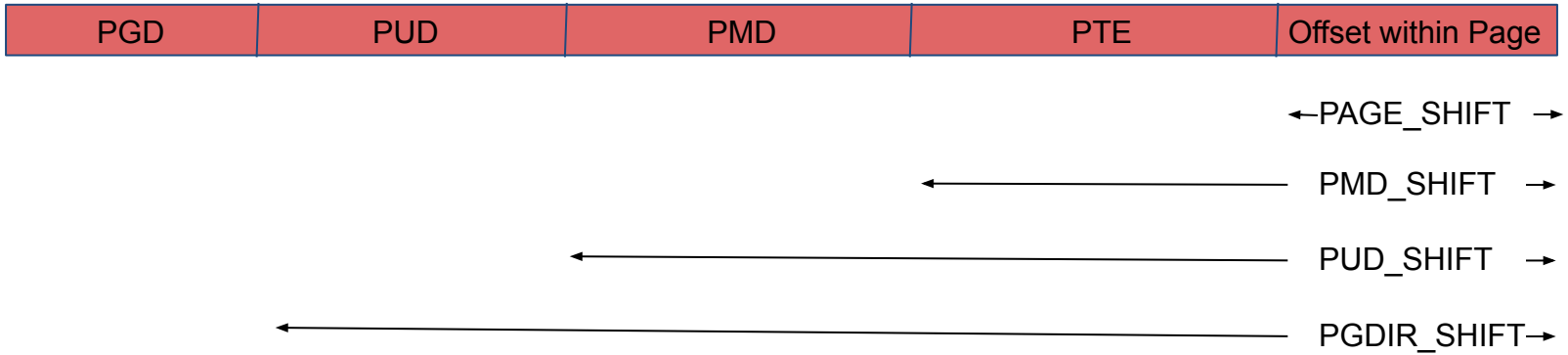


Page Table Entries

- Typed for containing Table Page
  - pgd_t, pud_t, pmd_t, pte_t
- Provide a pointer to next Table Page (or User Data)
  - Page Frame Number (PFN) or Physical Address
  - Always points to PAGE, so PAGE_SHIFT bits available
- Entries contain flags such as:
  - _PAGE_PRESENT
  - _PAGE_RW
  - _PAGE_DIRTY
  - _PAGE_PSE

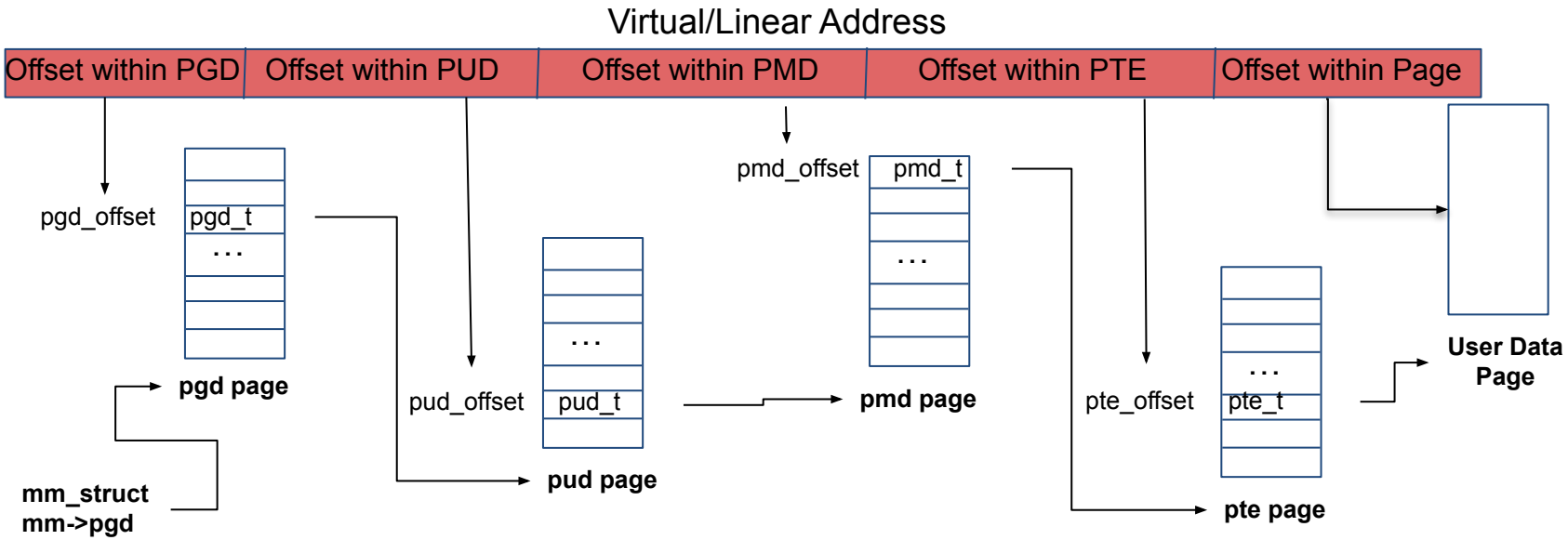

Process
System Memory
Page Tables
Virtual Addresses
Physical Addresses

Virtual Address
bits per unsigned long



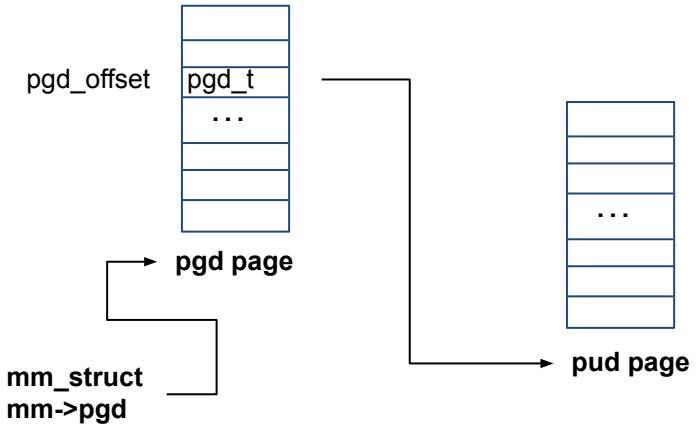
PGDIR_SHIFT - 39 PUD_SHIFT - 30 PMD_SHIFT - 21 PAGE_SHIFT - 12

X86_64 4 Level Page Tables


Virtual/Linear Address
Offset within PGD
Offset within PUD
Offset within PMD
Offset within PTE
Offset within Page
pgd_offset
pgd_t
pgd page
mm_struct
mm->pgd
pud_offset
pud_t
pud page
pmd_offset
pmd_t
pmd page
pte_offset
pte_t
pte page
User Data Page

Virtual/Linear Address

Offset within PGD	Offset within PUD	Offset within PMD	Offset within PTE	Offset within Page



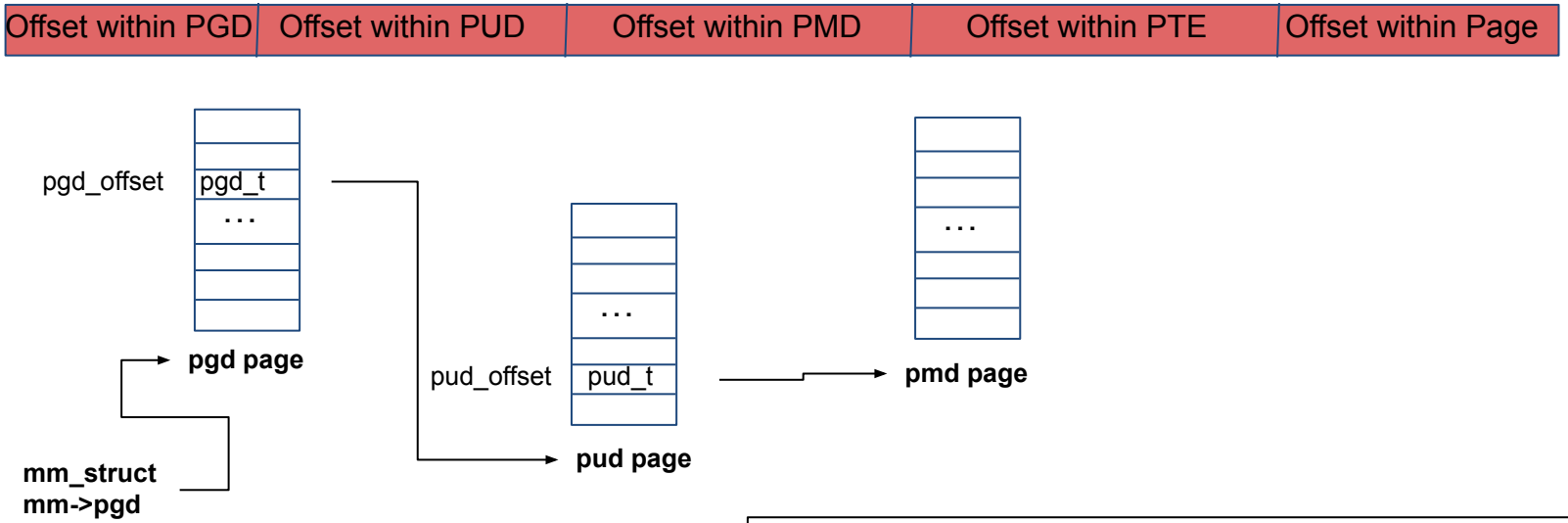

```
pgd_offset = virtual_address >> PGDIR_SHIFT
```

mask off upper bits

pgd_offset - Index into PGD page

0 - 511

Virtual/Linear Address

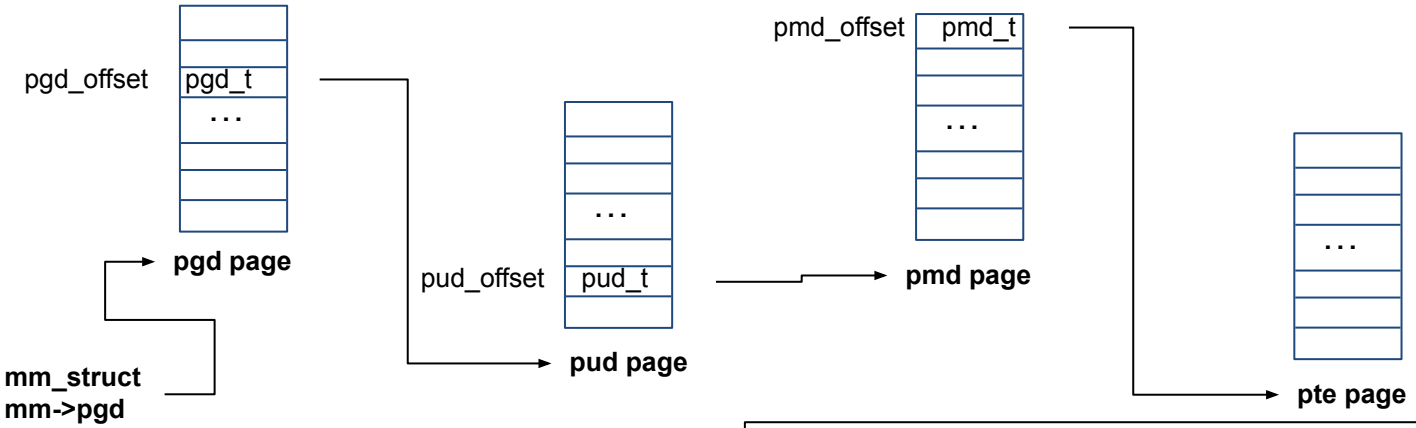



```
pud_offset = virtual_address >> PUD_SHIFT
```

mask off upper bits

pud_offset - Index into PUD page

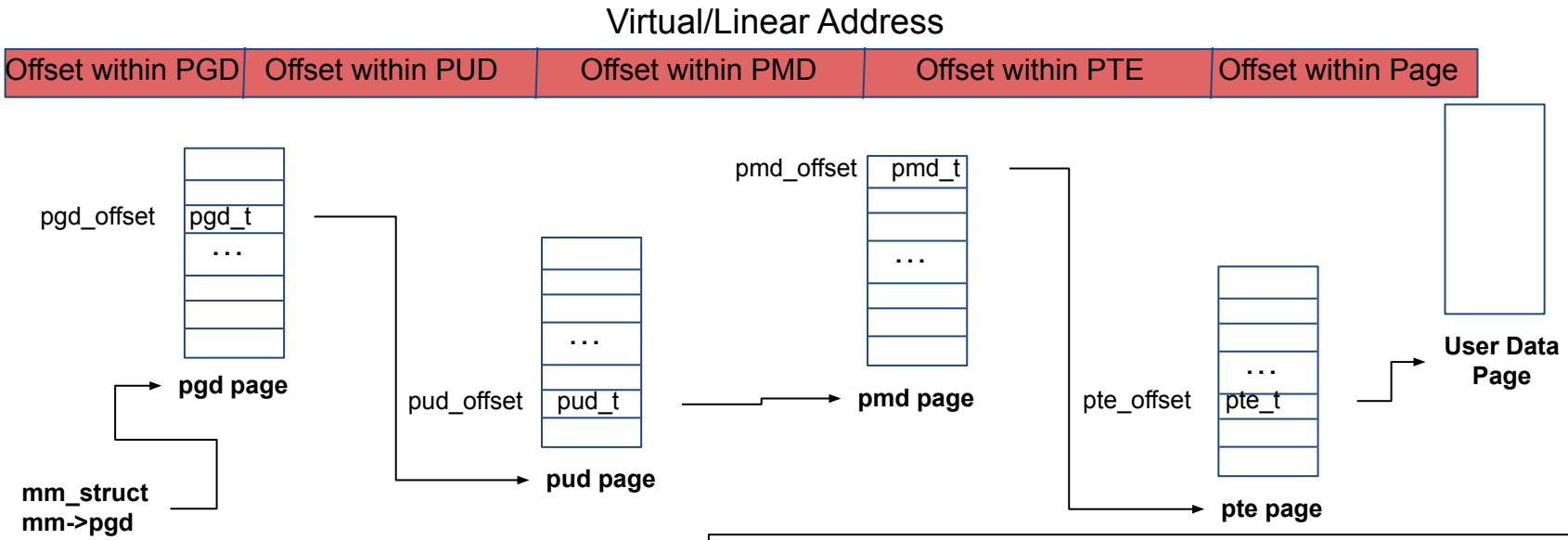
Virtual/Linear Address




```
pmd_offset = virtual_address >> PMD_SHIFT
```

mask off upper bits

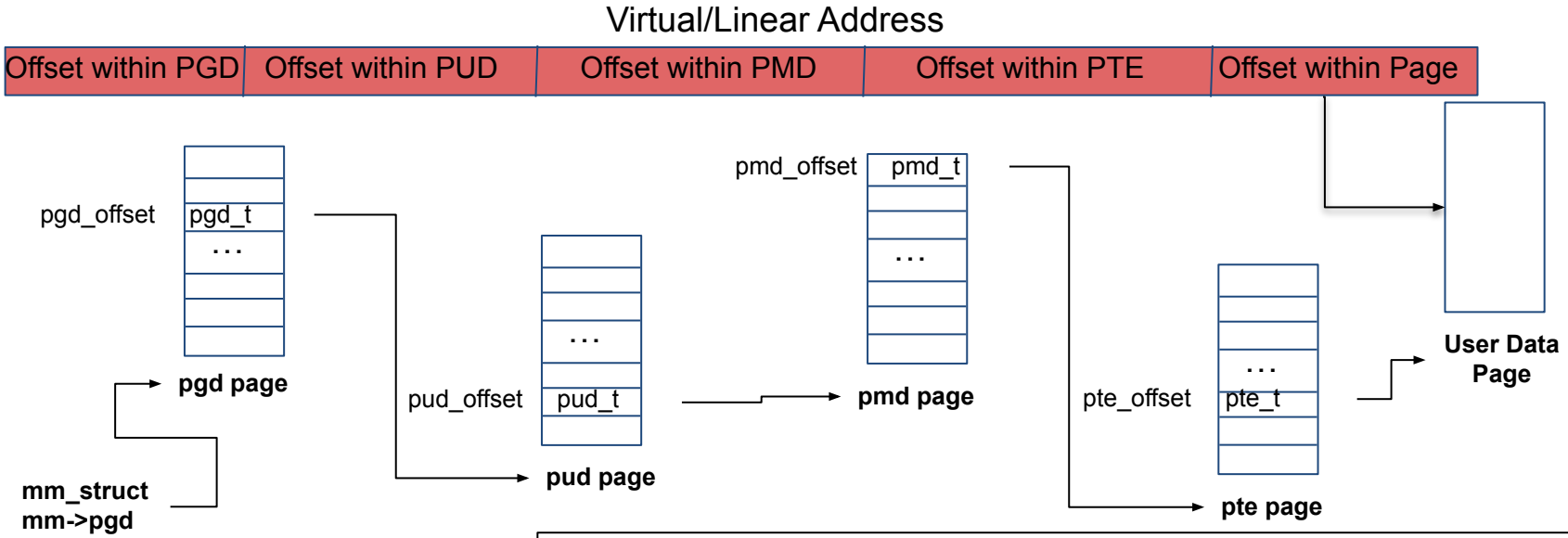
pmd_offset - Index into PMD page




```
pte_offset = virtual_address >> PTE_SHIFT
```

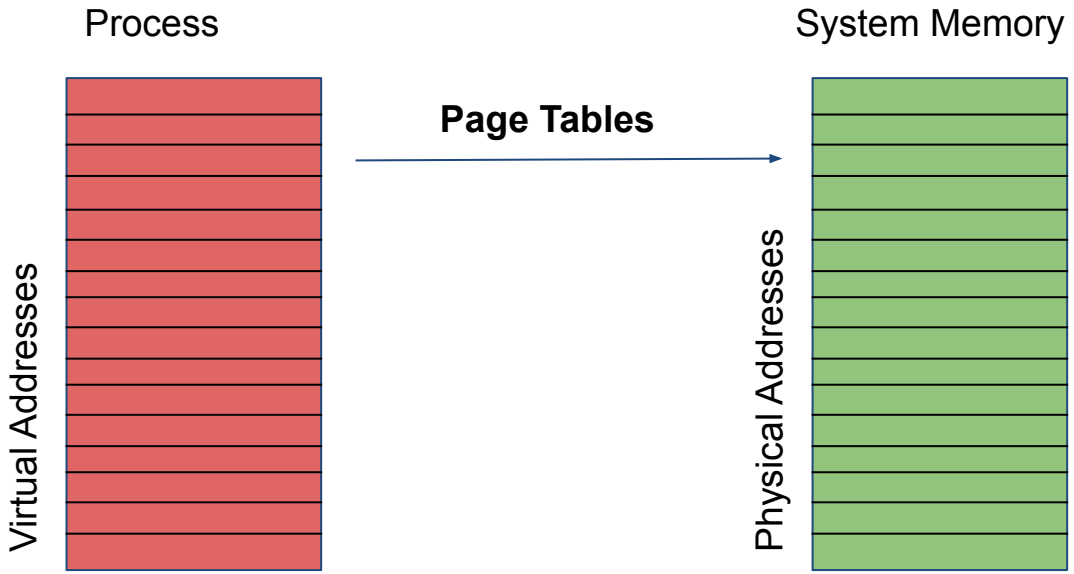
mask off upper bits

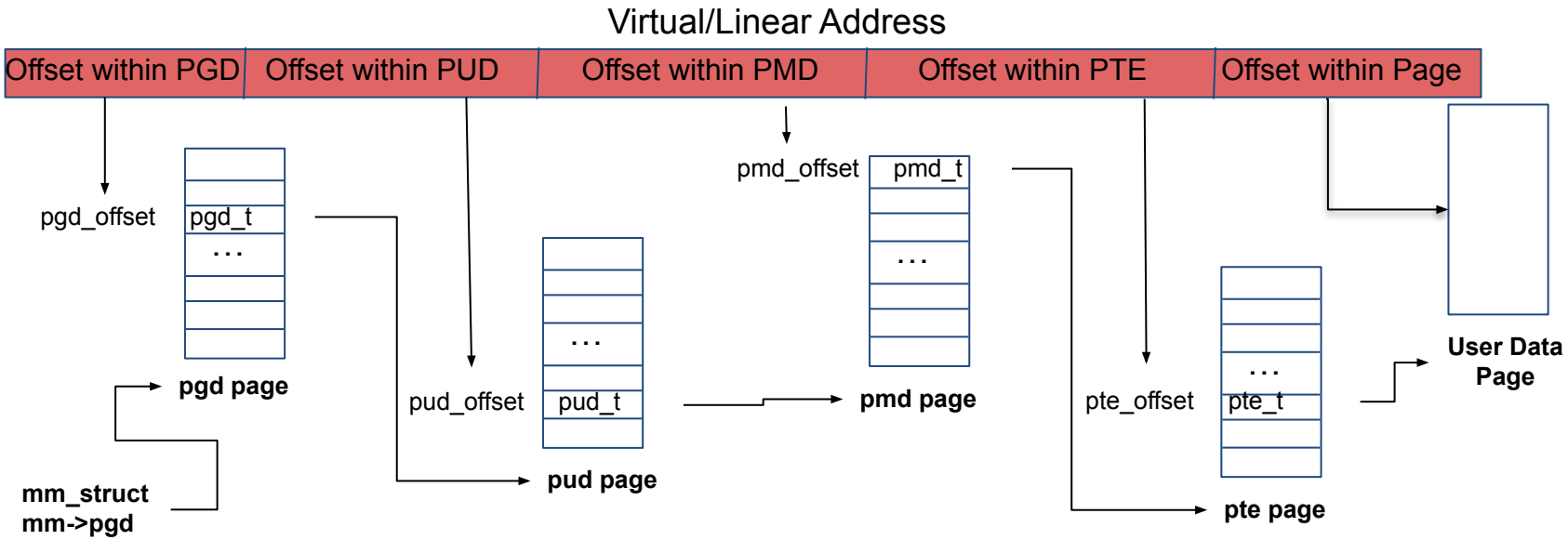
pte_offset - Index into PTE page




```
Offset within Page = virtual_address >> PAGE_SHIFT
                                   mask off upper bits
```

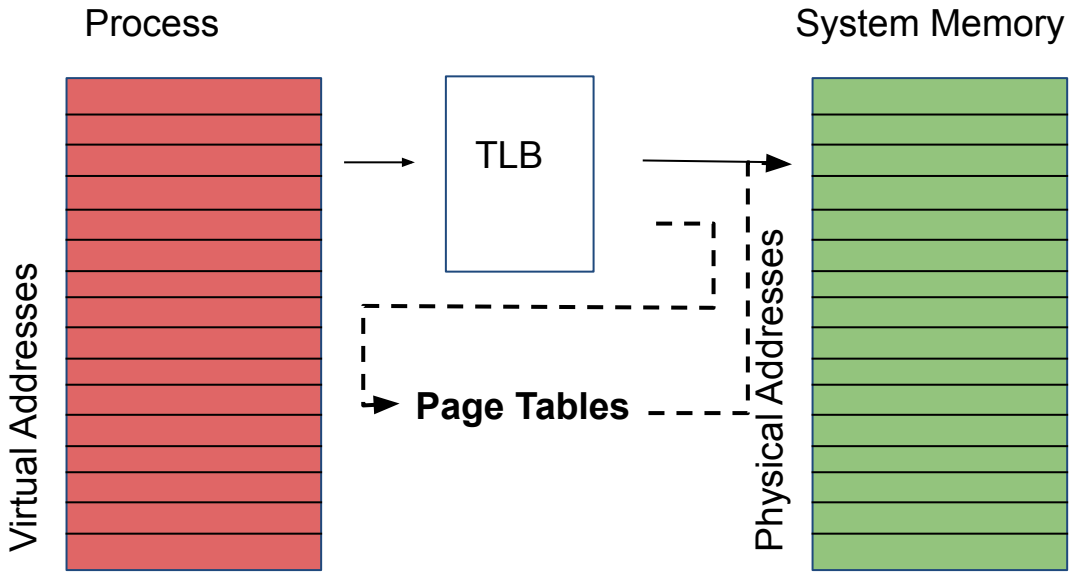
Finally have our data. Yeah!


Process
System Memory
Page Tables
Virtual Addresses
Physical Addresses


Virtual/Linear Address
Offset within PGD
Offset within PUD
Offset within PMD
Offset within PTE
Offset within Page
pgd_offset
pgd_t
pgd page
mm_struct
mm->pgd
pud_offset
pud_t
pud page
pmd_offset
pmd_t
pmd page
pte_offset
pte_t
pte page
User Data Page

Translation Lookaside Buffer TLB

- Normally part of a CPU's Memory Management Unit (MMU)
- A TLB is a cache of virtual-to-physical translations
  - Information stored in Page Tables
- Typically a scarce resource


Process
System Memory
TLB
Virtual Addresses
Physical Addresses
Page Tables

TLB Sizes

Processor	ITLB 4K	ITLB 2M	DTLB 4K	DTLB 2M	DTLB 1G	STLB 4K	STLB 2M	STLB 1G
Nehalem	128	7	64	32	4	512	-	-
Sandy Br.	128	8	64	32	4	512		-
Haswell	128	8	64	32	4	1024		-
Sky Lake	128	8	64	32	4	1536		16
Ice Lake						2048	1024	1024

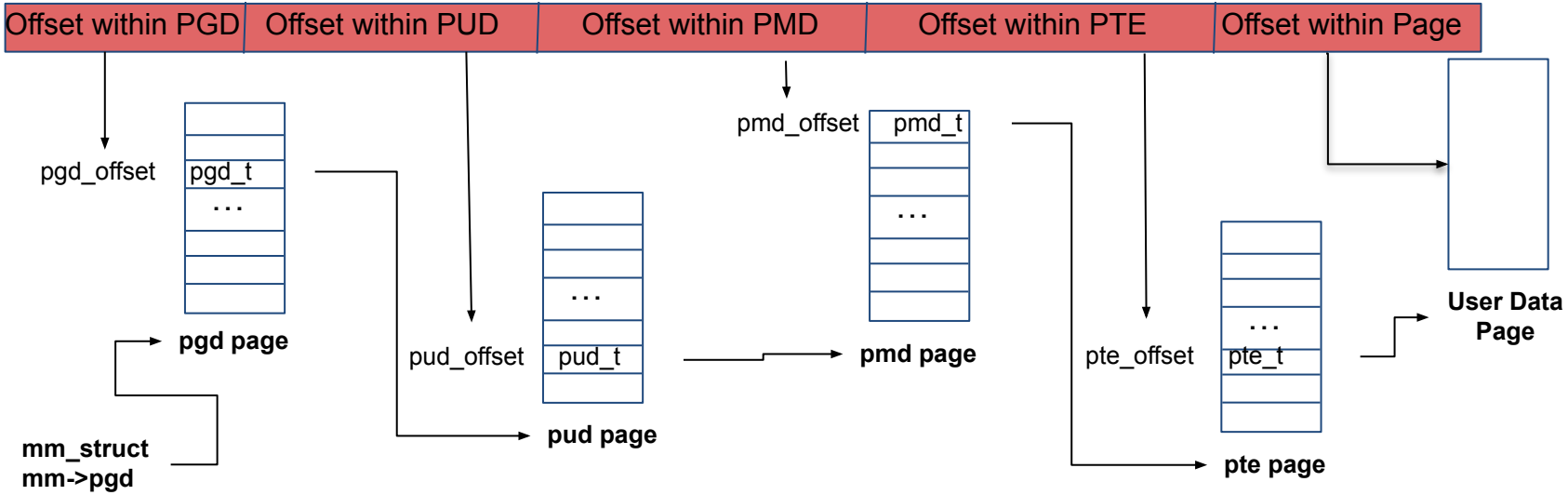
Virtual Memory in the Kernel

- Kernel mostly uses virtual memory addresses
- Kernel also has a set of page tables
  - Translate from kernel virtual addresses to kernel data

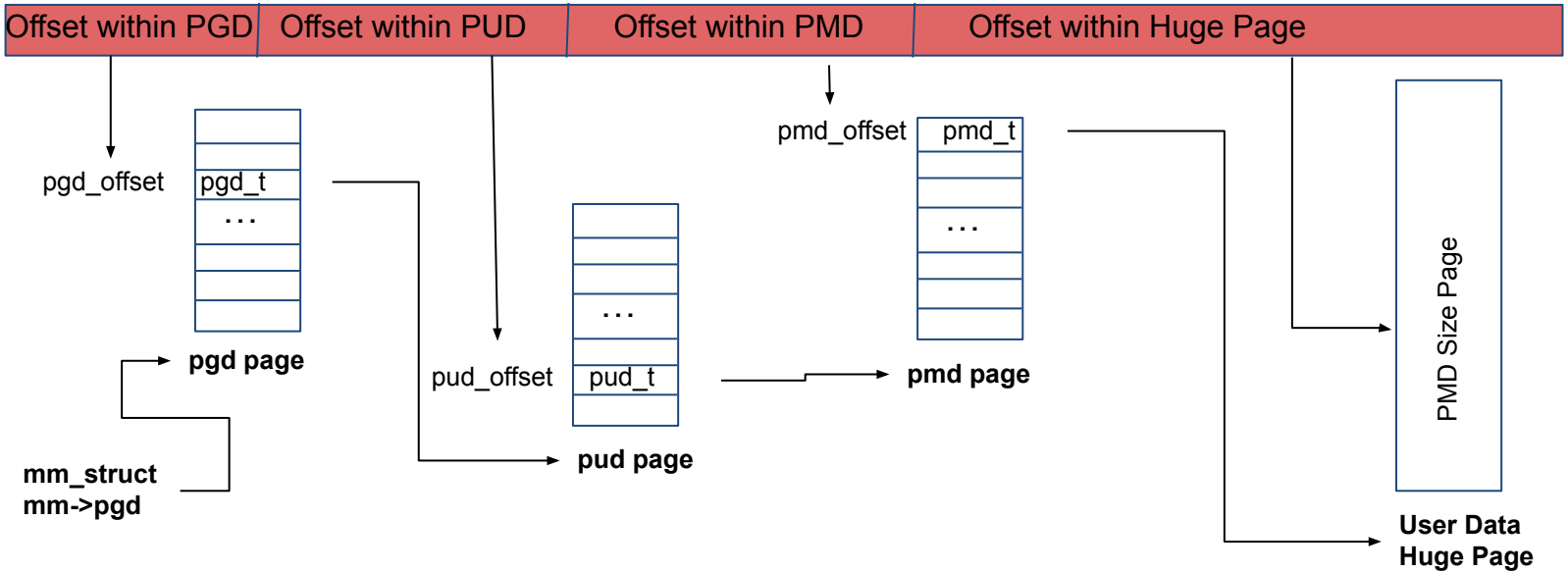
Huge Pages … Finally!

- Huge Page sizes are typically associated with Page Table Level (PMD, PUD)
- Sizes Architecture dependent
- MMU/TLB support
- Huge Pages are contiguous areas of physical memory
  - Aligned to huge page size
  - Buddy Allocator contiguous areas less than MAX_ORDER in size
  - alloc_contig_pages() for areas greater than MAX_ORDER
  - CMA Allocator, MemBlock Allocator, Firmware

Page at PTE Level

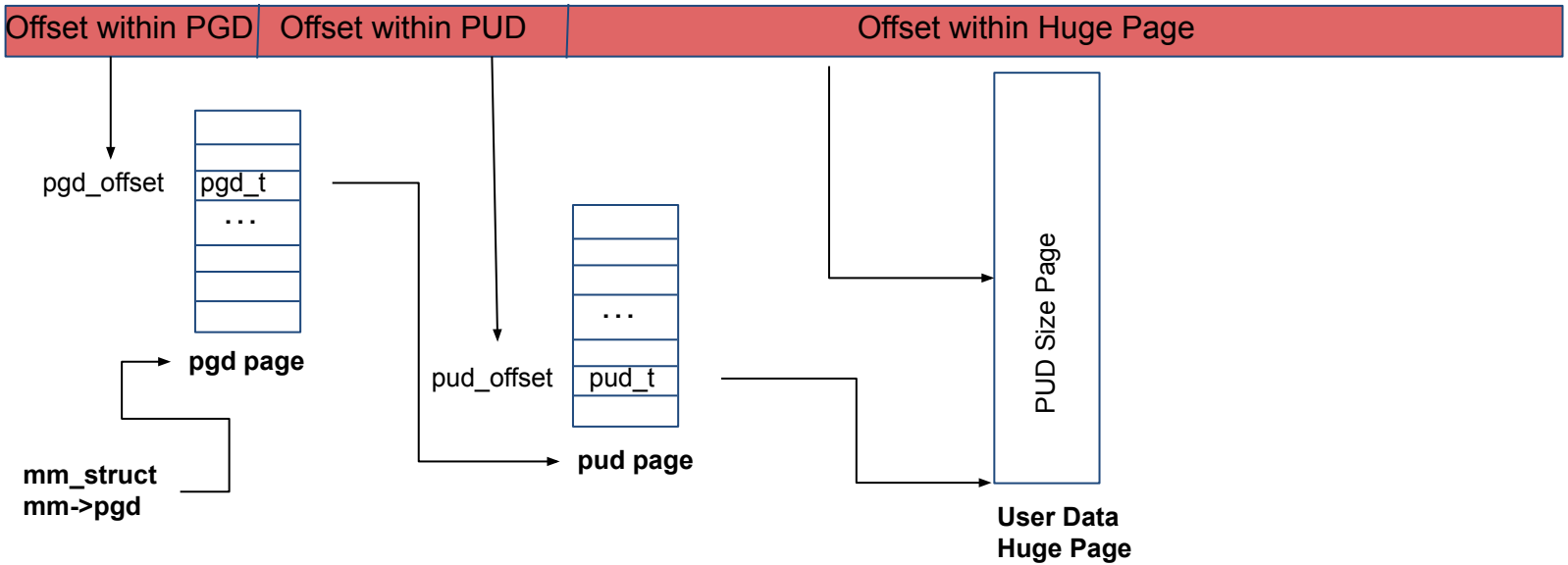


Huge Page at PMD Level



`_PAGE_PSE` flag set in pmd_t (X86)

Huge Page at PUD Level



`_PAGE_PSE` flag set in pud_t (X86)

LF live MENTORSHIP SERIES

Huge Pages *MAY* Increase Performance

Pros

- Fewer Translation Entries
- Less time Servicing TLB misses
- Access Pattern Dependent

Cons

- Less Granular Page Size
- Fewer TLB entries
- Access Pattern Dependent

Benchmark Benchmark Benchmark

LF live MENTORSHIP SERIES

Intel Processor TLB Sizes

Processor	ITLB 4K	ITLB 2M	DTLB 4K	DTLB 2M	DTLB 1G	STLB 4K	STLB 2M	STLB 1G
Nehalem	128	7	64	32	4	512	-	-
Sandy Br.	128	8	64	32	4	512		
Haswell	128	8	64	32	4	1024		
Sky Lake	128	8	64	32	4	1536		16
Ice Lake						2048	1024	1024

Huge Page APIs in Linux

- Transparent Huge Pages - THP
  - *Transparent* to the application
  - Automatic with some control
- Hugetlbfs
  - Requires application modification
  - Sysadmin intervention/setup

Transparent Huge Pages - THP

- Primarily used for anonymous memory
  - Can be used in tmpfs
  - Limited support for file mappings (XFS, experimental)
- Currently PMD_SIZE support only
- System control via `/sys/kernel/mm/transparent_hugepage/enabled`

```
always [madvise] never
```

THP application use via madvise

```
madvise(void *addr, size_t length, int advice)

MADV_HUGEPAGE
              Enable Transparent Huge Pages (THP) for pages in the range
spec -
              ified by addr and length. Currently, Transparent Huge Pages
              work only with private anonymous pages (see mmap(2)). The
ker -
              nel will regularly scan the areas marked as huge page candidates
              to replace them with huge pages. The kernel will also allocate
              huge pages directly when the region is naturally aligned to the
              huge page size (see posix_memalign(2)).

MADV_NOHUGEPAGE
              Ensures that memory in the address range specified by addr and
```

LF live MENTORSHIP SERIES

THP Tunables

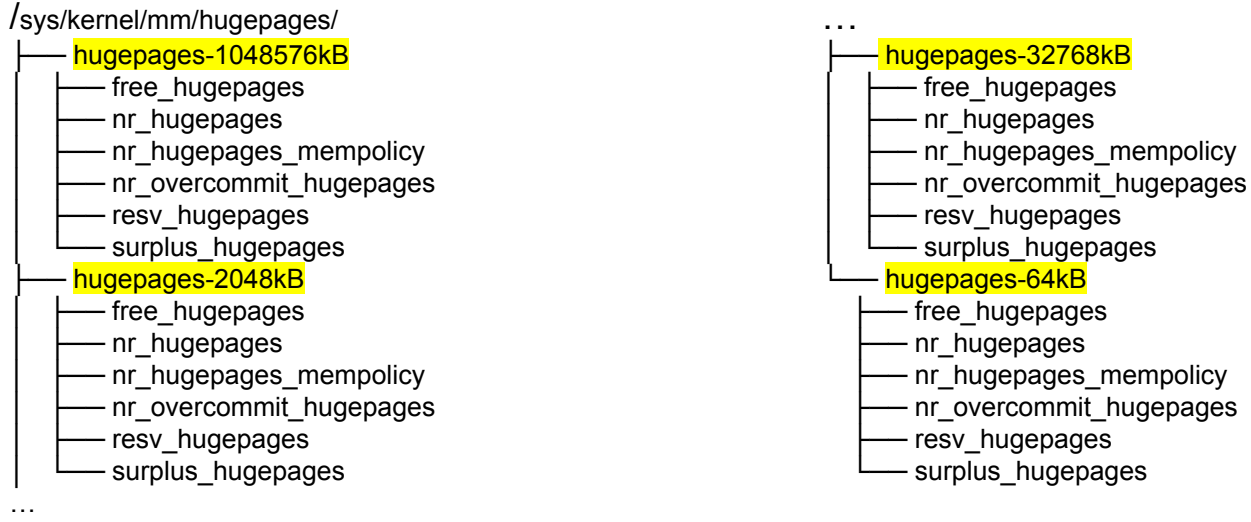
```
/sys/kernel/mm/transparent_hugepage
├── defrag
├── enabled
├── hpage_pmd_size
├── khugepaged
│   ├── alloc_sleep_millisecs
│   ├── defrag
│   ├── full_scans
│   ├── max_ptes_none
│   ├── max_ptes_shared
│   ├── max_ptes_swap
│   ├── pages_collapsed
│   ├── pages_to_scan
│   └── scan_sleep_millisecs
├── shmem_enabled
└── use_zero_page
```

Hugetlbfs

- Requires Application modification
- Huge Pages are generally preallocated via sysadmin control
- Has been used by database for many years
- More recent use as backing for Virtual Machines
  - THP commonly used to back VMs
- Multiple Huge Page Sizes as supported by Architecture

Pools of hugetlb pages are created/preallocated
Application use the pages in these pools

Hugetlbfs Multiple Page Size Pools (arm64 4K Base Page Size)



LF live MENTORSHIP SERIES

Default Hugetlb Page Size

```
# grep Huge /proc/meminfo
AnonHugePages:     71680 kB
ShmemHugePages:        0 kB
FileHugePages:         0 kB
HugePages_Total:       0
HugePages_Free:        0
HugePages_Rsvd:        0
HugePages_Surp:        0
Hugepagesize:       2048 kB
Hugetlb:               0 kB
```

Populating Hugetlb Page Pools

Boot Time

- `hugepagesz=X hugepages=Y`
  - `hugepages=N1:Y1,N2:Y2,N3:Y3,N4:Y4`
- `hugepage_cma=Y`
  - `hugepage_cma=N1:Y1,N2:Y2,N3:Y3,N4:Y4`
- `default_hugepagesz=X`

Run Time

- `echo N > /sys/kernel/mm/hugepages/hugepages-<size>/nr_hugepages`
- `echo N > /proc/sys/vm/nr_hugepages`

Mounting Hugetlbfs Filesystems

```
mount -t hugetlbfs \
        -o uid=<value>,gid=<value>,mode=<value>,pagesize=<value>,size=<value>,\
        min_size=<value>,nr_inodes=<value> none /mnt/huge
```

- All files in filesystem are backed by Huge Pages
- pagesize if the Huge Page size
- Most file/filesystem, operations supported
  - write system call NOT supported

Application use via System V Shared memory

```
shmget(key, size, SHM_HUGETLB)
```

- Creates a shared memory segment backed by Huge Pages
- Additional flags `SHM_HUGE_2MB`, `SHM_HUGE_1GB` …
  - Specify the Huge Page Size

Application use via mmap

```
void *mmap(addr, length, prot, flags, fd, offset)
```

- `fd` File in a mounted hugetlbfs filesystem
  - Backed by huge pages of the filesystem size
- flags `MAP_ANONYMOUS | MAP_HUGETLB`
  - Anonymous mapping backed by huge pages
  - flags `MAP_HUGE_2MB, MAP_HUGE_1GB` …
    - Size of pages to back anonymous mapping
- addr and offset must be aligned to underlying Huge Page size

Running out of Huge Pages

- Huge Pages are generally limited to those in the Pool
- Huge Pages are not swappable or reclaimable
- When we are out, we are out
- Page fault with no Huge Pages available == SIGBUS
- Situation mitigated with Huge Page Reservations

Huge Page Reservations

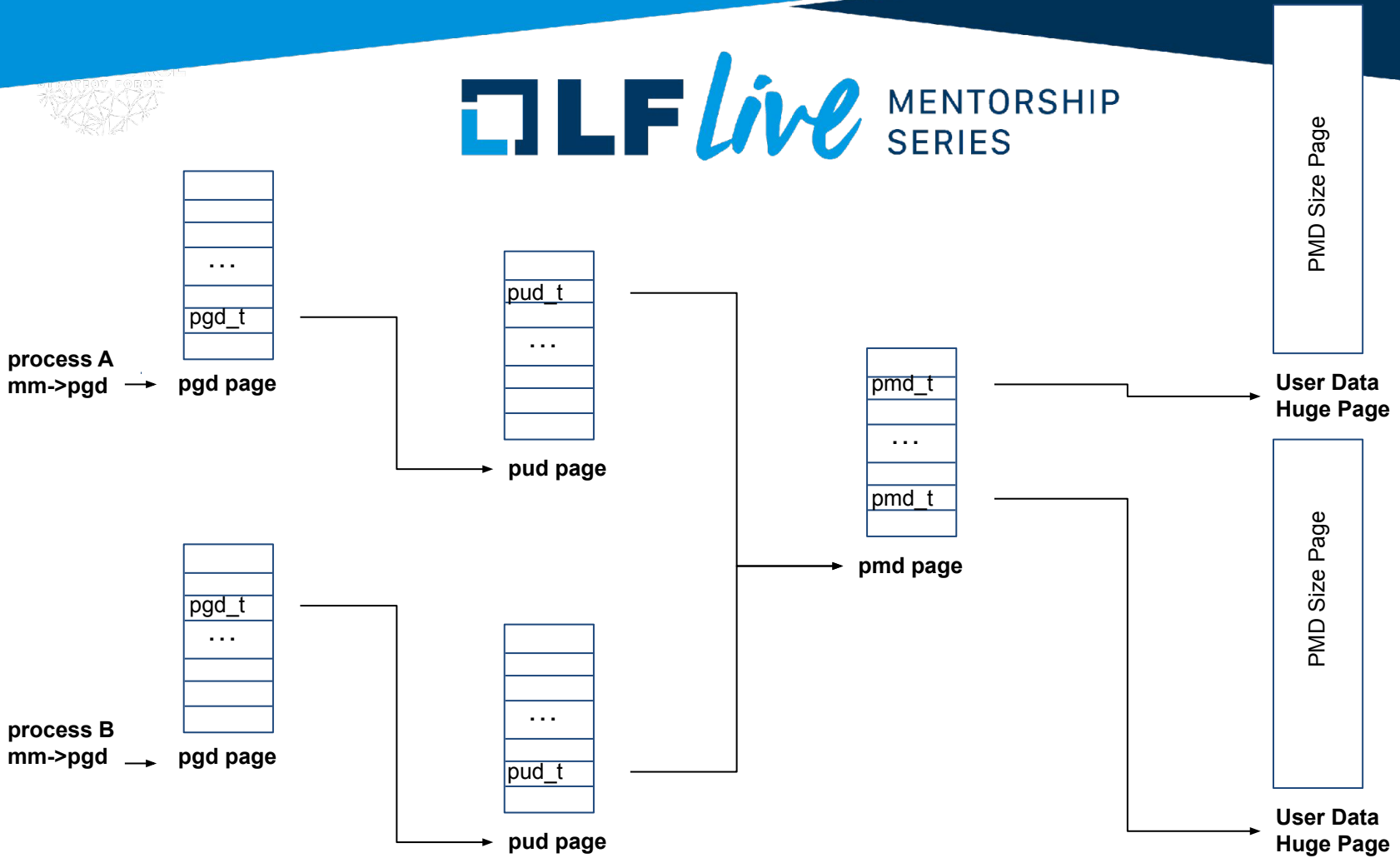
- Global counter per-pool (`resv_hugepages/HugePages_Rsvd`)
- Incremented at `mmap/shmget` time
    - ENOMEM if not enough huge pages for reservation
- Decremented at page fault/allocation time
- `resv_map` internal data struct tracks reservations at a page level for all mappings
- HugePages Available = HugePages_Free - HugePages_Rsvd

PMD Sharing

- Processes can share PMD pages in their Page Tables
  - Only on x86 and arm64
- SHARED Hugetlb mappings (file or anonymous)
- Shared Virtual Range must be at least 1GB (`PUD_SIZE`) and aligned

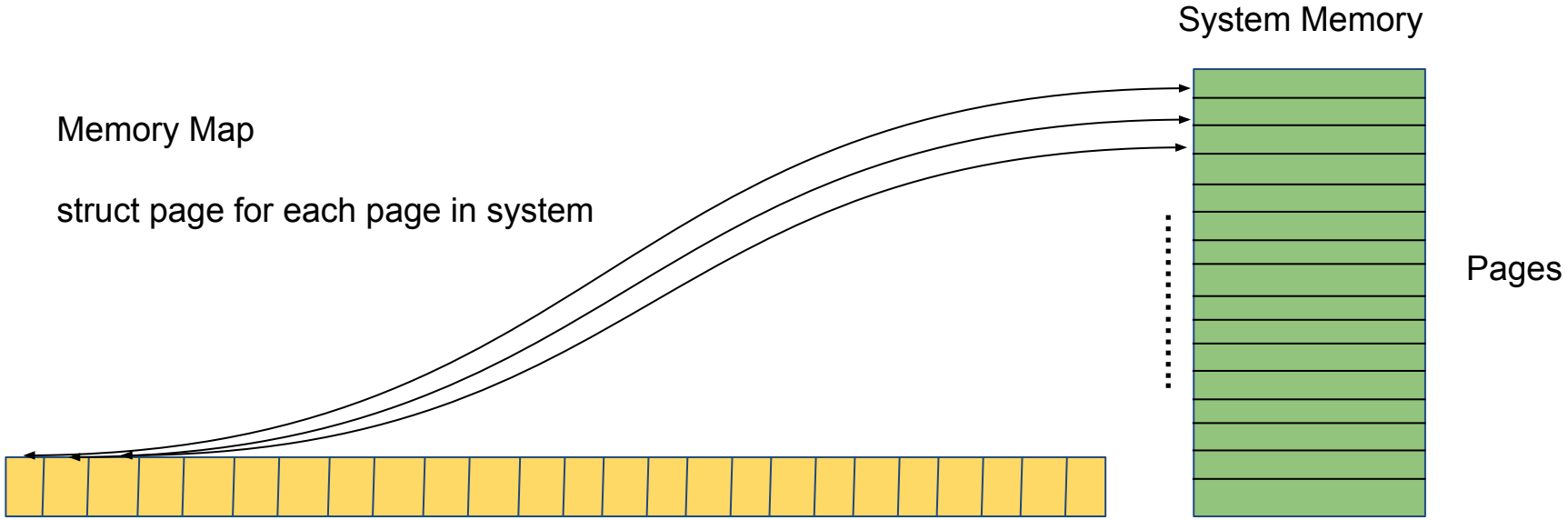
Example: 1TB Shared Mapping, 10,000 Processes sharing the mapping

- 4K PMD Page per 1G of shared mapping
- 1TB = 1024G * 9,999 shared mappings
- 39GB memory savings

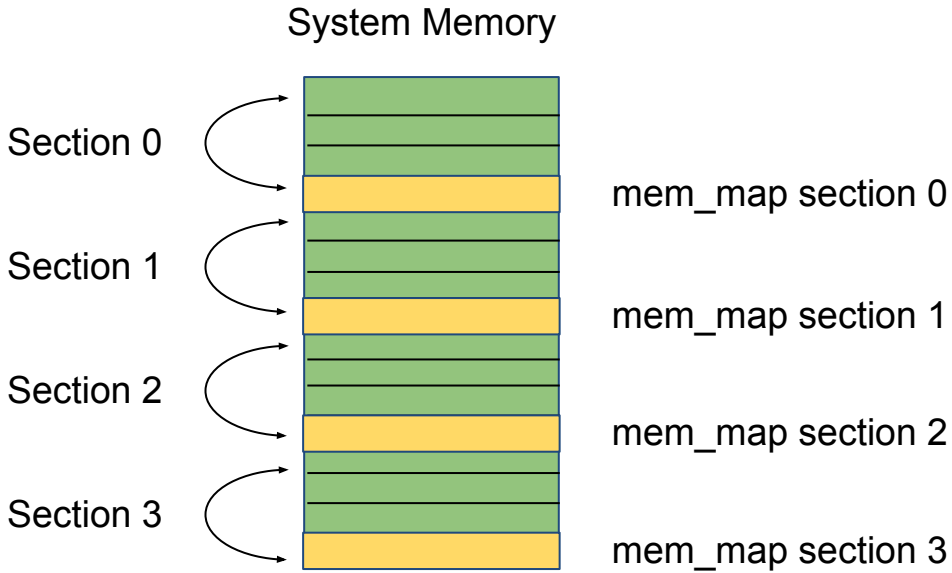

process A
mm->pgd
pgd page
pgd_t
pud page
pud_t
pmd page
pmd_t
pmd_t
PMD Size Page
User Data
Huge Page
process B
mm->pgd
pgd page
pgd_t
pud page
pud_t
PMD Size Page
User Data
Huge Page

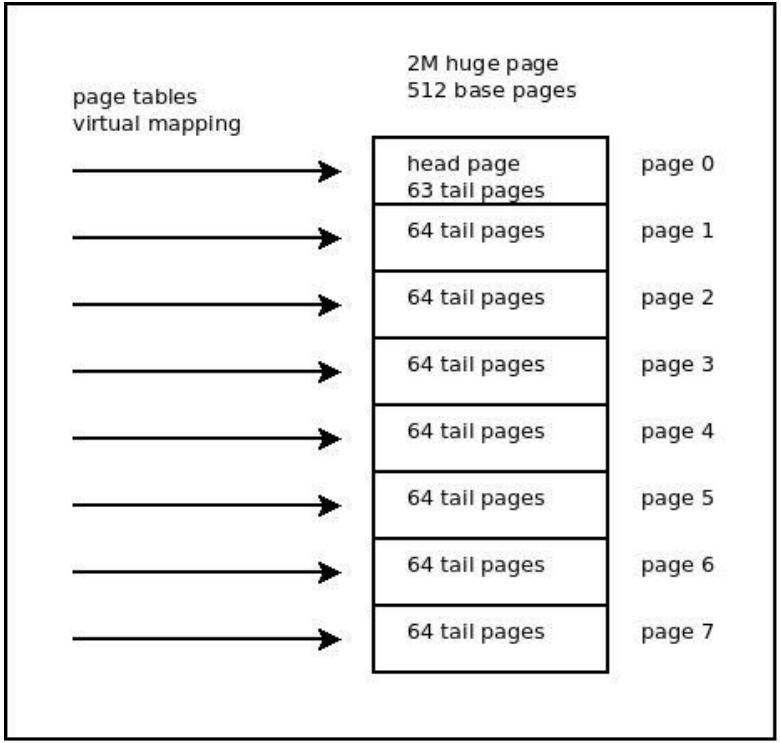
Hugetlb vmemmap Freeing

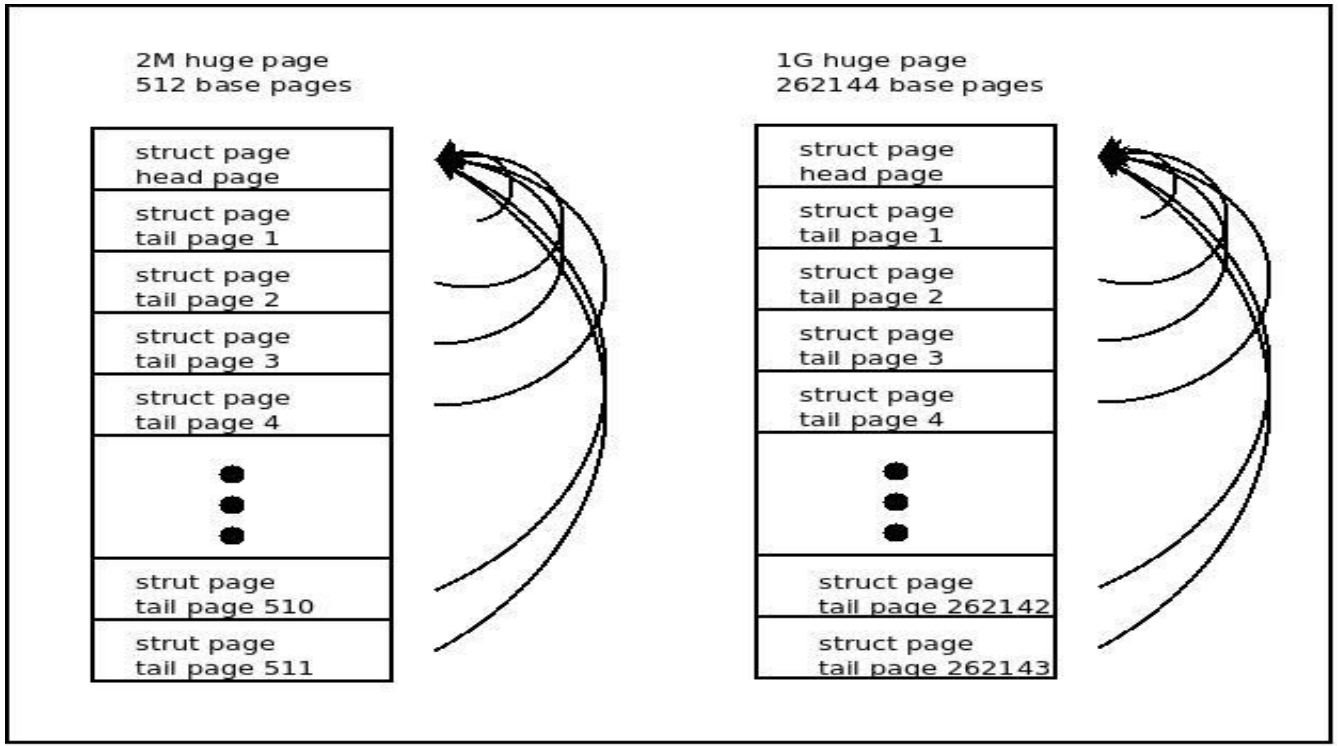
- Recently added in v5.14
- vmemmap - Virtually mapped memmap so entries are virtually contiguous
- Memory saving feature


System Memory
Memory Map
struct page for each page in system
Pages

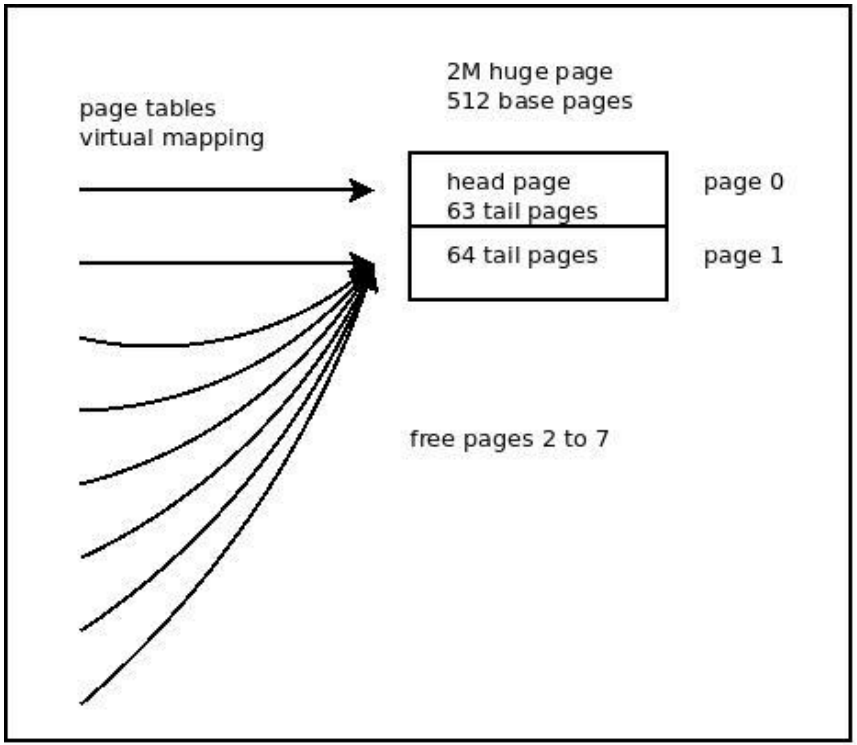
sparsemem Memory Model




page tables
virtual mapping
2M huge page
512 base pages
head page
63 tail pages
page 0
64 tail pages
page 1
64 tail pages
page 2
64 tail pages
page 3
64 tail pages
page 4
64 tail pages
page 5
64 tail pages
page 6
64 tail pages
page 7


2M huge page
512 base pages
struct page
head page
struct page
tail page 1
struct page
tail page 2
struct page
tail page 3
struct page
tail page 4
strut page
tail page 510
strut page
tail page 511
1G huge page
262144 base pages
struct page
head page
struct page
tail page 1
struct page
tail page 2
struct page
tail page 3
struct page
tail page 4
struct page
tail page 262142
struct page
tail page 262143

Remap and free pages of tail pages



Hugetlb vmemmap Freeing

- vmemmap pages freed at huge page allocation time
  - When added to hugetlb pools
- Only 2 vmemmap pages needed for each huge page
  - (v5.17 modification to reduce to 1 page needed)
- 2MB huge pages, 8 vmemmap pages total, free 6 pages
  - free 7 pages in v5.17
- 1GB huge pages, 4096 vmemmap pages total, free 4094 pages
  - free 4095 pages in v5.17

Hugetlb vmemmap Freeing

- Downside
  - Freed vmemmap pages must be allocated (and remapped) BEFORE huge pages can be removed from pool
  - Freeing a huge page can now fail if vmemmap can not be allocated

- Enabling
  - CONFIG_HUGETLB_PAGE_FREE_VMEMMAP
  - hugetlb_free_vmemmap=on (default off)
  - CONFIG_HUGETLB_PAGE_FREE_VMEMMAP_DEFAULT_ON

LF live MENTORSHIP SERIES

Summary

Huge Pages *MAY* Increase Performance

Pros

- Fewer Translation Entries
- Less time Servicing TLB misses
- Access Pattern Dependent

Cons

- Less Granular Page Size
- Fewer TLB entries
- Access Pattern Dependent

Benchmark Benchmark Benchmark

LF live MENTORSHIP SERIES

Thank you for joining us today!

We hope it will be helpful in your journey to learning more about effective and productive participation in open source projects. We will leave you with a few additional resources for your continued learning:

- The LF Mentoring Program is designed to help new developers with necessary skills and resources to experiment, learn and contribute effectively to open source communities.
- Outreachy remote internships program supports diversity in open source and free software
- Linux Foundation Training offers a wide range of free courses, webinars, tutorials and publications to help you explore the open source technology landscape.
- Linux Foundation Events also provide educational content across a range of skill levels and topics, as well as the chance to meet others in the community, to collaborate, exchange ideas, expand job opportunities and more. You can find all events at events.linuxfoundation.org.