Transparent Huge Pages

Table of contents

- Why we need contiguous memory and huge pages?
- Page sizes
- Hugetlbfs, Transparent Huge Pages and DAX
- Transparent Huge Pages
  - Advantages and disadvantages
  - Original implementation
  - Improvements
    - Huge zero page
    - Controlling
    - Support for tmpfs/shmem
    - THP for filesystems
    - Reducing data structures
- Compound pages and folios

How to capture 100G Ethernet traffic at wire speed to local disk
Christoph Lameter (LCA 2020)
https://www.youtube.com/watch?v=uBBaVtHkiOI

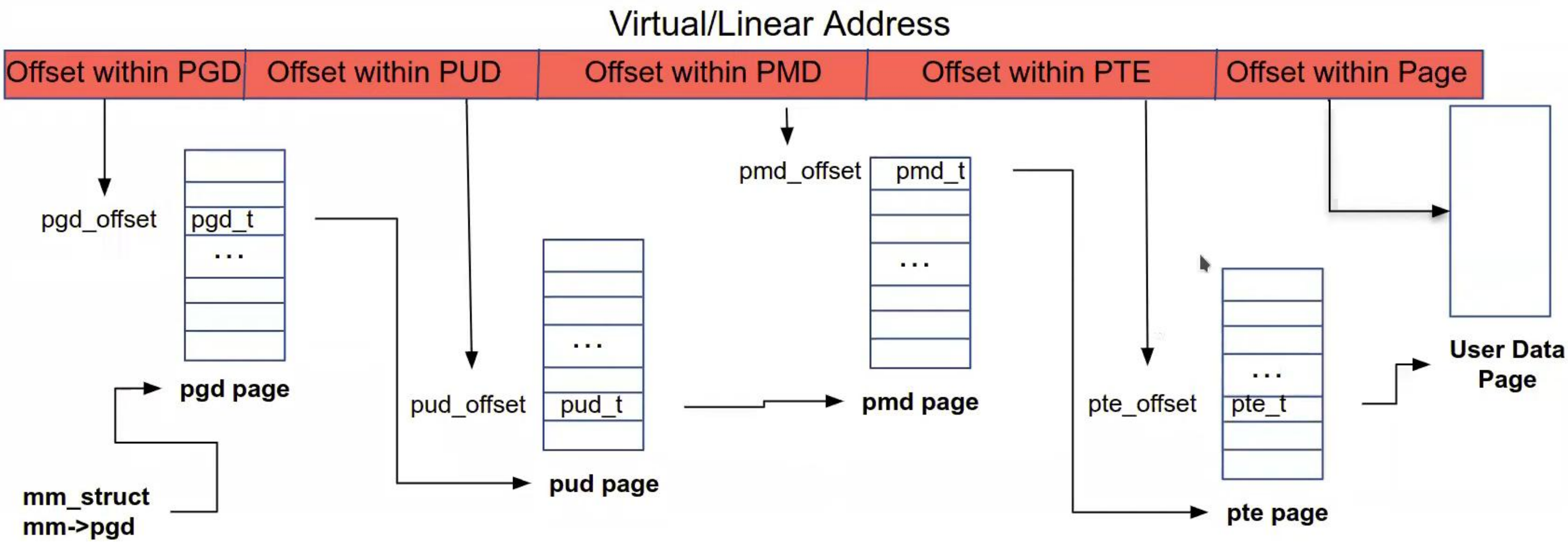
The best solution would be to have the OS do what is necessary for high performance. We need

- **Contiguous memory**.
- **Larger chunks of memory than 4K** managed by the OS.
- If we want to support **multiple page sizes** then we need the ability to defragment memory. A fundamental change how we manage objects in the kernel. They would need to be **movable** in order to recover contiguous memory areas to be able to consistently provide larger page sizes than the basic page.

Systems with **terabytes of memory** are not uncommon for many database or cloud provider companies like AWS, Google, Meta, IBM, Oracle, and others. On a system with terabytes of DRAM, there can be **millions** of **struct page** objects.

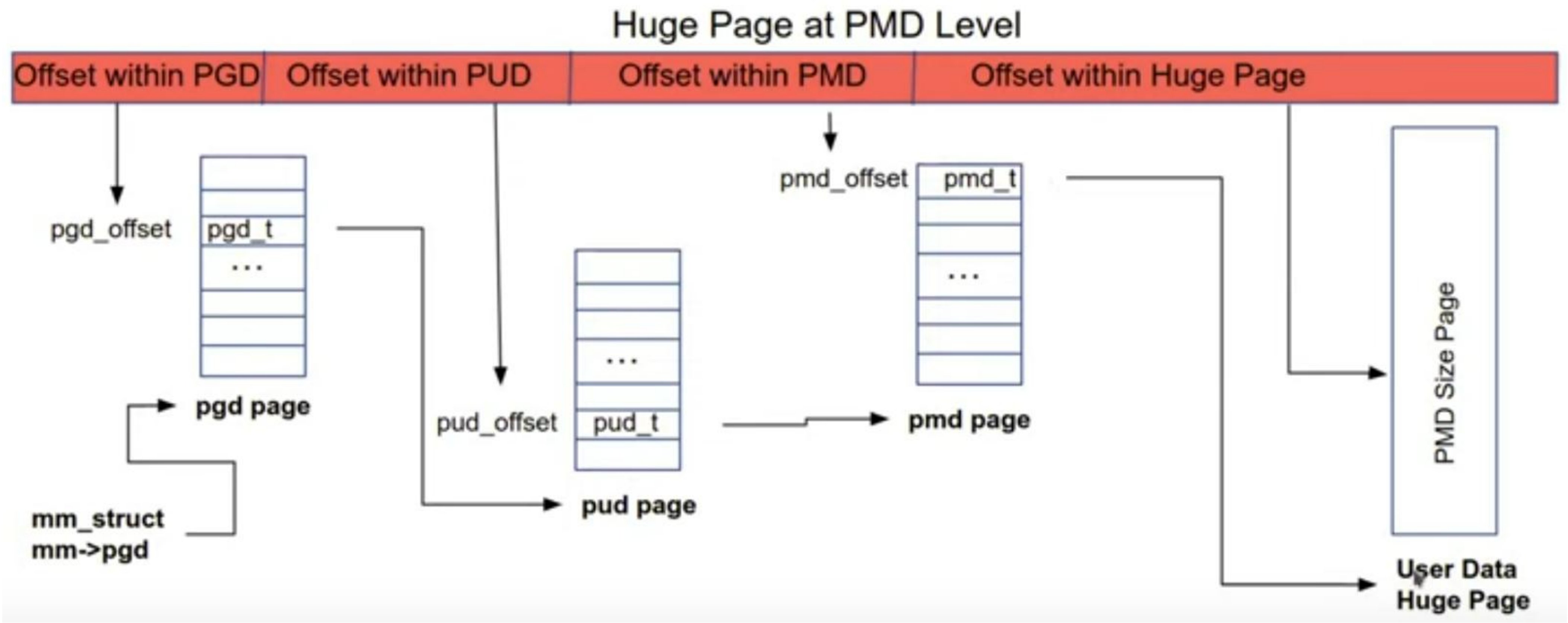
Currently, the struct page structure is **64 bytes in size** and can consume **up to 1.6%** of the total physical memory, which can amount to several gigabytes on a system with terabytes of memory.

Page size 4KB



Mike Kravetz, Huge page concepts in Linux, https://www.youtube.com/watch?v=n67gCNiKVcw

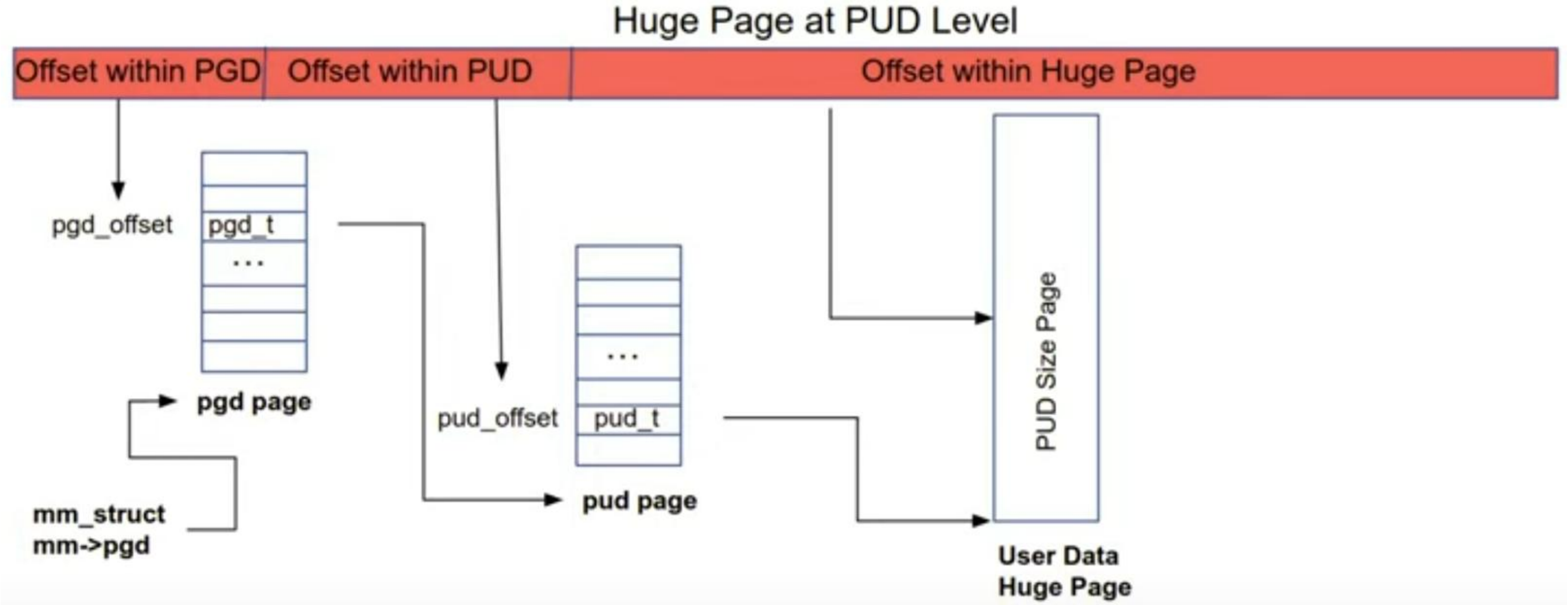
Page size 2MB



Page_PSE – Page Size Extension
Huge page size = 2^(12+9)= 2^21 = 2MB

Mike Kravetz, Huge page concepts in Linux,
https://www.youtube.com/watch?v=n67gCNiKVcw

Page size 1GB



Huge page size = 2^(12+9+9)= 2^30 = 1GB

Mike Kravetz, Huge page concepts in Linux, https://www.youtube.com/watch?v=n67gCNiKVcw

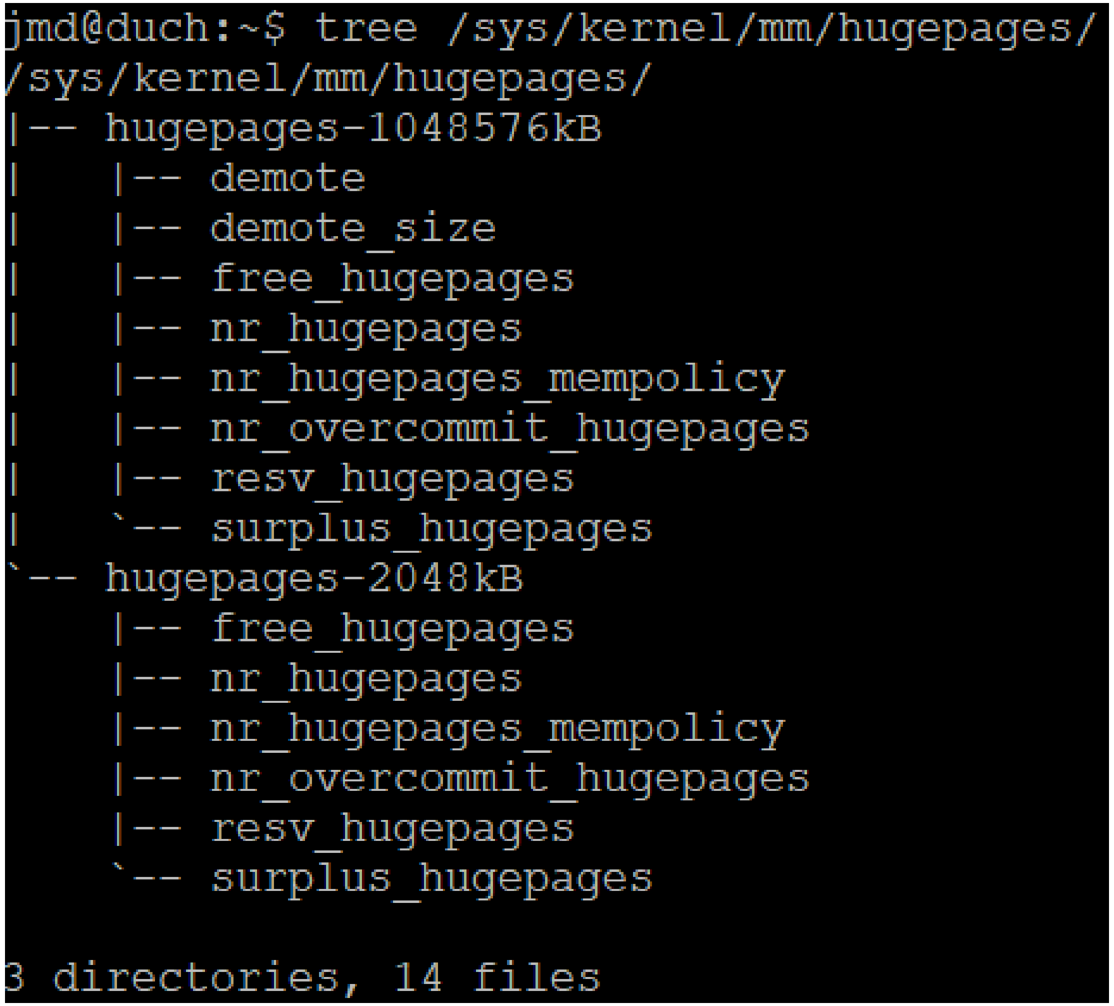
Possible approaches – overview (2018)

- **Hugetlbfs** (RAM-based filesystem)
  - Original/oldest method.
  - Preallocation at boot or early system init time.
  - Memory ONLY available for hugetlbfs.
  - Every file on this filesystem is backed by huge pages and is accessed with mmap() or read().
  - Taking advantage of it requires application awareness or library support (**libhugetlbfs**).
  - When there are multiple mount points (to make different page sizes available), it gets more complicated.
  - Good for 'single purpose' use cases.

- **Promoting huge page usage**, Christopher Lameter, Mike Kravetz https://www.linuxplumbersconf.org/event/2/contributions/157/ Linux Plumbers Conference 2018, Vancouver
- https://www.kernel.org/doc/Documentation/filesystems/dax.txt

- **Transparent Huge Pages (THP)**
  - Enabled by default on most distributions.
  - No system configuration or application changes required (although desirable for optimal usage).
  - Single huge page size (PMD_SIZE).
- **DAX (Persistent Memory)**
  - Mechanism that is used to **bypass the page cache** and **map files stored in persistent memory directly into user space**.
  - Uses 2M and 1G mappings by default.
  - Does not work correctly on architectures which have virtually mapped caches such as ARM, MIPS and SPARC.
  - Various features have to be turned off when DAX is in use, and others must be bypassed. It gives the whole subsystem the feel of a permanent experiment, and that makes people not want to use it (2019).

Huge pages



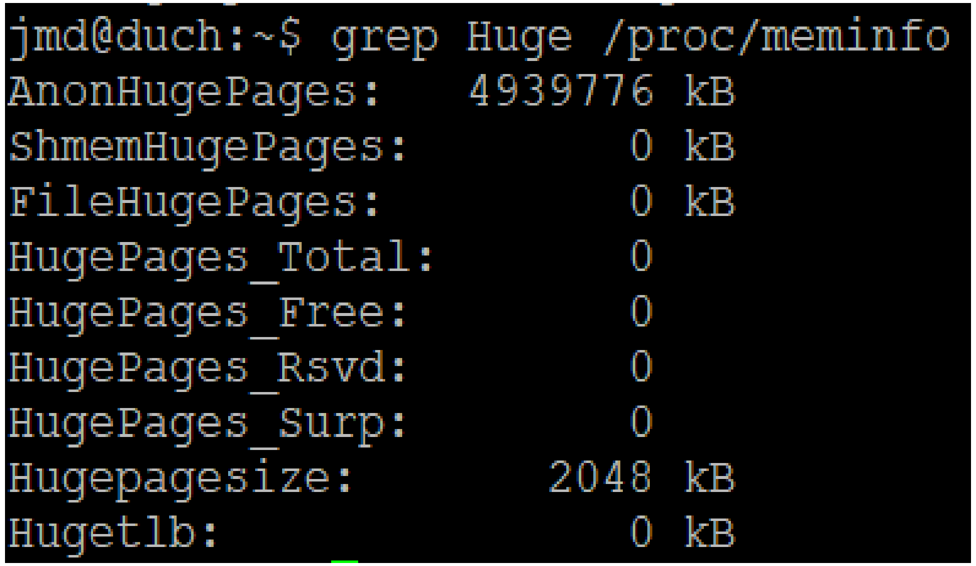
```
jmd@duch:~$ tree /sys/kernel/mm/hugepages/
/sys/kernel/mm/hugepages/
|-- hugepages-1048576kB
|    |-- demote
|    |-- demote_size
|    |-- free_hugepages
|    |-- nr_hugepages
|    |-- nr_hugepages_mempolicy
|    |-- nr_overcommit_hugepages
|    |-- resv_hugepages
|    `-- surplus_hugepages
`-- hugepages-2048kB
     |-- free_hugepages
     |-- nr_hugepages
     |-- nr_hugepages_mempolicy
     |-- nr_overcommit_hugepages
     |-- resv_hugepages
     `-- surplus_hugepages

3 directories, 14 files
```

Hugetlbfs multiple page size pools

104857KB=1024*1024KB=2^20*2^10B=2^30B=**1GB**

2048KB=2*2^10*2^10B=**2MB**



```
jmd@duch:~$ grep Huge /proc/meminfo
AnonHugePages:   4939776 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
```

Default hugetlb page size: **2MB**

THP – Advantages and disadvantages

- THP works by **quietly substituting huge pages** into a process's address space when
  - those page are available and
  - it appears that the process would benefit from the change.
- Introduced to Linux in 2.6.38 (**2011**) by **Andrea Arcangeli**.

- **Advantages**
  - The size of page tables decreases, as does the number of page faults required to get an application into RAM.
  - A single TLB entry will be mapping a much larger amount of virtual memory in turn reducing the number of TLB misses.
  - The TLB miss will run faster (fewer page-table levels are required to span the same range of virtual addresses).
- **Disadvantages**
  - The amount of wasted memory will increase as a result of internal fragmentation.
  - Larger pages take longer to transfer from secondary storage, increasing **page fault latency** (while decreasing **page fault counts**).
  - The time required to simply clear very large pages can create significant kernel latencies.

THP – Original implementation

- **Patchset by Andrea Arcangeli** (2011)
  - When a fault happens, the kernel will **attempt to allocate** a huge page to satisfy it. Should the allocation succeed, the huge page will be filled, any existing small pages in the new page's address range will be released, and the huge page will be inserted into the VMA. If no huge pages are available, the kernel **falls back** to small pages and the application never knows the difference.
  - Huge pages must be **swappable**, lest the system run out of memory. Rather than complicate the swapping code with an understanding of huge pages, **a huge page is split back into its component small pages** if that page needs to be reclaimed.
  - **Khugepaged** kernel thread will occasionally attempt to allocate a huge page; if it succeeds, it will scan through memory looking for a place where that huge page can be substituted for a bunch of smaller pages. Thus, available huge pages should be quickly placed into service, maximizing the use of huge pages in the system as a whole.
  - The current patch only works with **anonymous pages**.
  - Up to 10% improvements for some benchmarks.

THP – Enhancements

- **Patchset by Kirill Shutemov** – **Zero pages** (2012)
  - Adds a special, zero-filled huge page to function as the huge zero page. Only one such page is needed, since the transparent huge pages feature only uses one size of huge page.
- **Patchset by Andi Kleen** – **Supporting variable-sized huge pages** (2013)
  - Some modern architectures permit multiple huge page sizes, and where the system admin has configured the system to provide huge page pools of different sizes, applications may want to choose the page size used for their allocation.
  - Extends the `shmget()` and `mmap()` system calls to allow the caller to select the size used for huge page allocations.
- **Patchset by Alex Thorlton** – **Controlling transparent huge pages** (2013)
  - The feature can be **turned off globally**, but what about situations where some applications benefit while others do not?
  - Provides an option to **disable transparent huge pages on a per-process basis**. This operation sets a flag in the `task_struct` structure; setting that flag causes the memory management system to avoid using huge pages for the associated process. And that allows the creation of mixed workloads, where some processes use transparent huge pages and others do not.

SKIP

THP for filesystems (page cache)

- Patchset by Kirill Shutemov – **THP in the page cache** (October 2016, ver. 4.8)
  - Two implementations competed (Hugh Dickins from Google lost).
  - Adds support for transparent huge pages in the page cache in **tmpfs/shmem** (other filesystems may be added in the future).
  - One of the primary goals was the ability for applications to access individual 4KB subpages of a huge page without the need to split the huge page itself.
  - Using **compound pages** (used also for anonymous THP and for files in the hugetlbfs). The first of the range of (small) pages that makes up a huge page is the **head page**, while the rest are **tail pages**. Most of the important metadata is stored in the head page. Using compound pages allows the entire huge page to be represented by a single entry in the LRU lists, and all buffer-head structures, if any, are tied to the head page.
  - Unlike DAX, transparent huge pages do not force any constraints on a file's on-disk layout.
- Huge pages in the ext4fs (2017)

With tmpfs the creation of a huge page causes the addition of 512 (single-page) entries to the radix tree; this cannot work in ext4. It is also necessary to add DAX support and to make it work consistently. There are a few other problems; for example, readahead doesn't currently work with huge pages. The maximum size of the readahead window is 128 KB, far less than the size of a huge page. Huge pages also cause any shadow entries in the page cache to be ignored, which could worsen the system's page-reclaim decisions.

Kirill A. Shutemov

SKIP

THP for filesystems, performance

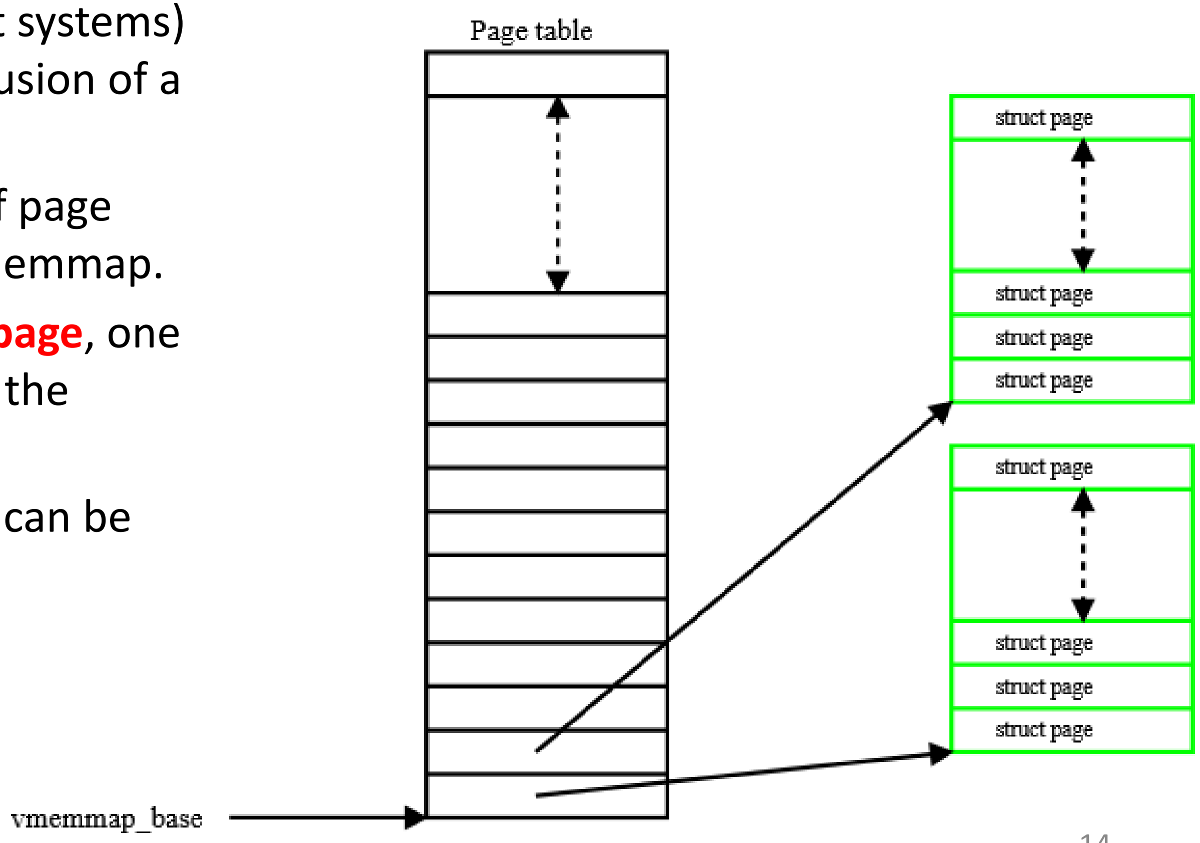
- Transparent huge pages for filesystems (2019)
  - Facebook is trying to reduce misses on the TLB for instructions by putting hot functions into huge pages. Those functions are collected up into an 8MB region in the generated executable.
  - At run time, the application creates an 8MB temporary buffer and the hot section of the executable memory is copied to it. The 8MB region in the executable memory is then converted to a huge page.
  - This results in a 5-10% performance boost without requiring any kernel changes to support it.
  - There is no support for writing to the THP, thus no **writeback** is required. That would prove to be a sticking point.
- Transparent huge pages, NUMA locality and performance regressions, Dueling memory-management performance regressions (2019)
  - Some patches were made to tackle with performance regressions, but then have to be reverted.
  - If the system is configured to always enable memory compaction and a huge page allocation is requested, the page allocator will refuse to allocate pages on remote nodes. It behaves as if the program had been explicitly bound to the current node, which was never the intended result. The reasoning that led to this behavior is that it is better to allocate local 4KB pages than remote huge pages. But the kernel goes beyond that in this situation, refusing to allocate *any* pages on remote nodes and potentially forcing the local node deeply into swap.

THP – Data structures

- There is one **page structure** for each **physical page** in the system; in common configurations, that means one **64-byte structure** for every **4096-byte page**.
- The preferred memory model in current times (for 64-bit systems) is **sparsemem-vmemmap**; it uses MMU to restore the illusion of a simple, linear map (called the **vmemmap**).
- Whenever memory is added to the, a suitable number of page structures is allocated and the set is mapped into the vmemmap.
- On a system with **4096-byte pages** and a **64-byte struct page**, one page of memory needs to be allocated and mapped into the vmemmap array for every 64 page structures.
- Once that is done, the page structure for any given page can be found by using its page-frame number as an offset from vmemmap_base (on x86 systems).

Reducing page structures for huge pages (December 2020)

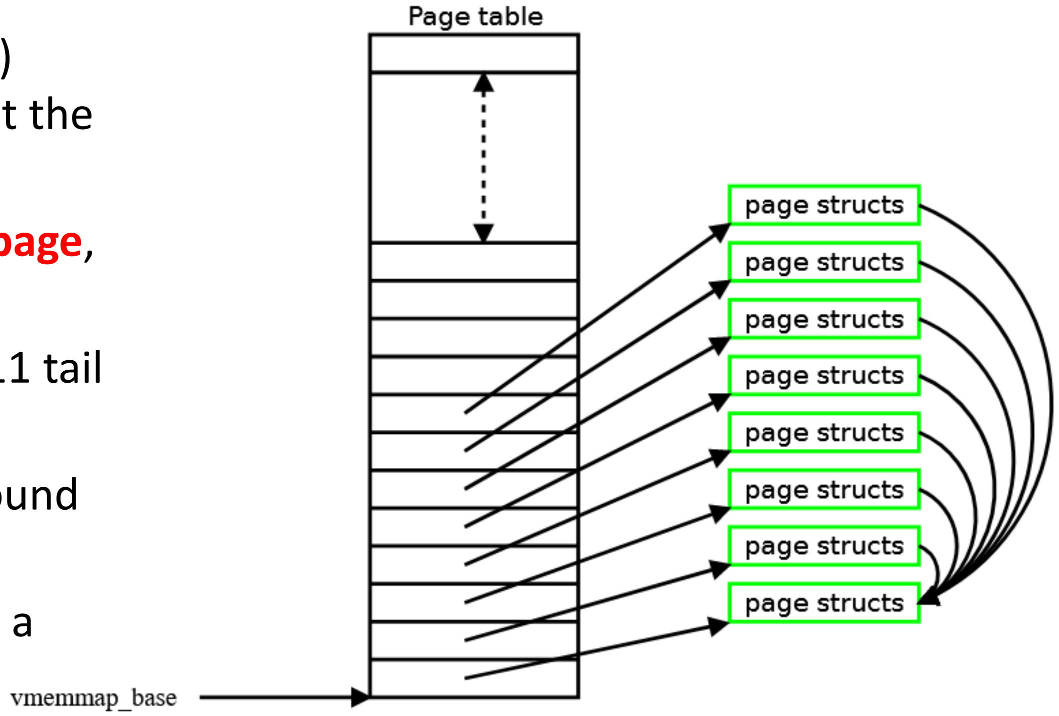
- *Nodes in NUMA systems have distinct ranges of memory with, possibly, large gaps between them.*
- *Memory can be plugged into a system (or removed from it) at run time.*
- *Virtualized guests can have memory injected into them (or removed) while they run as well.*
- *As a result, the simple, linear model of memory no longer works.*



THP – Data structures

- A **compound page** is formed when a group of **adjacent pages** is grouped together into a larger unit.
- The most common use is for **huge pages**.
- Whenever a huge page is created from a set of single (base) pages, the associated page structures are changed to reflect the compound page that they now represent.
- The first base page in a compound page is called the **head page**, while all of the others are called **tail** pages.
- A 2MB huge page is thus made up of one head page and 511 tail pages.
- The page structure for the head page is marked as a compound page, and represents the whole set.
- The page structures for the tail pages, instead, contain only a pointer to the head page.

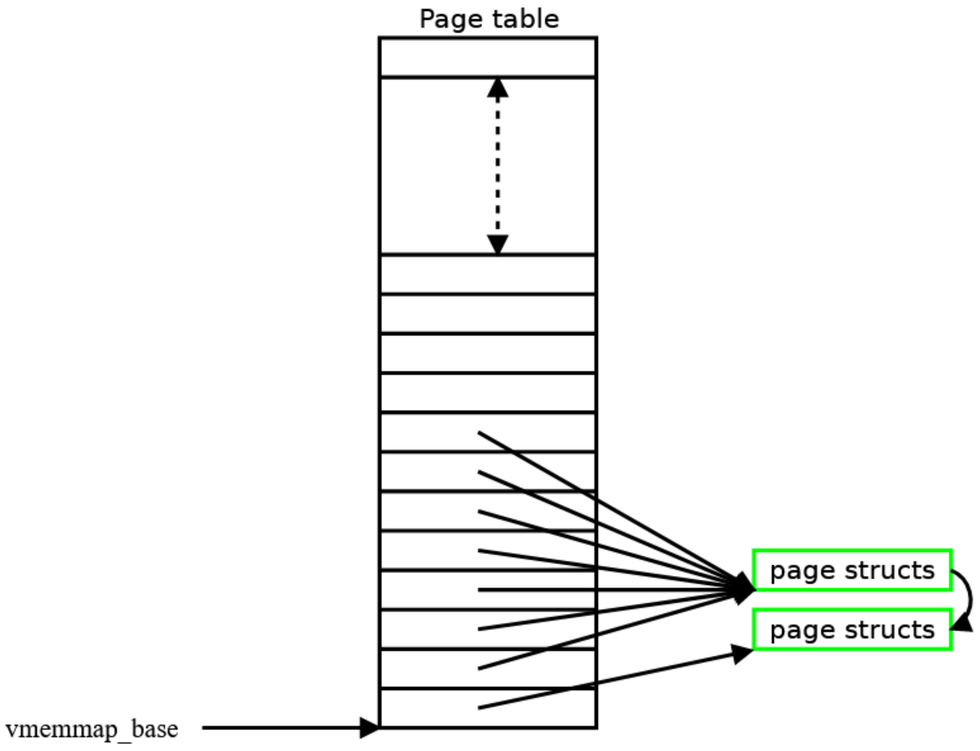
Thus, of the 512 page structures associated with a 2MB huge page, 511 are essentially identical copies of a sign saying "look over there instead". Those structures take up eight pages of memory in their own right, seven of which represent only tail pages and contain identical data.



[Reducing page structures for huge pages](#) (December 2020)

THP – Data structures

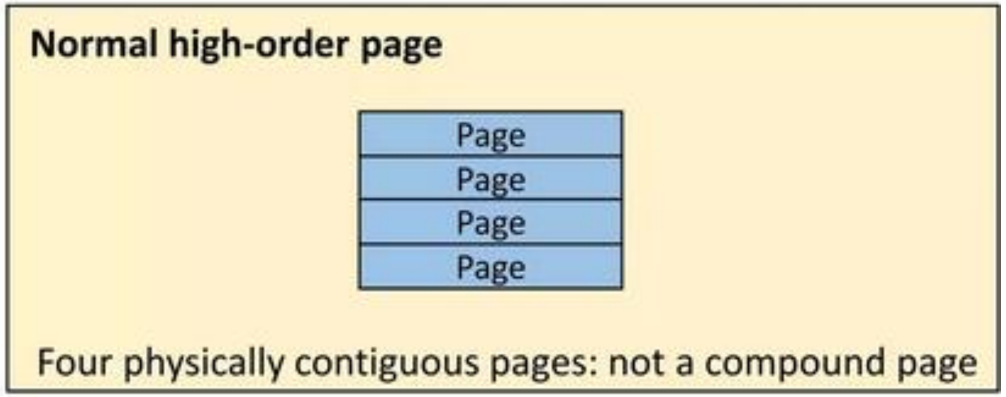
- One 2MB huge page is represented by eight pages of page structures, almost all of which correspond to tail pages and just point to the structure for the head page.
- Since **seven** of those **eight pages** all contain **identical pages**, they can be **replaced** with a **single page** instead; that one page can be mapped seven times to fill out the vmemmap array.
- Six pages of duplicated data can now be given back to the system for other uses for as long as the compound page continues to exist. 75% of the memory overhead for this compound page has just been eliminated.
- The savings for 1GB huge pages are even more dramatic; 4094 of the 4096 pages representing tail pages can be eliminated.
- Huge pages do not remain huge forever; they can be returned to the kernel or split up for a number of reasons. When that happens, the **full set of page structures must be restored**.



Reducing page structures for huge pages
(December 2020)

Normal high-order page and compound page

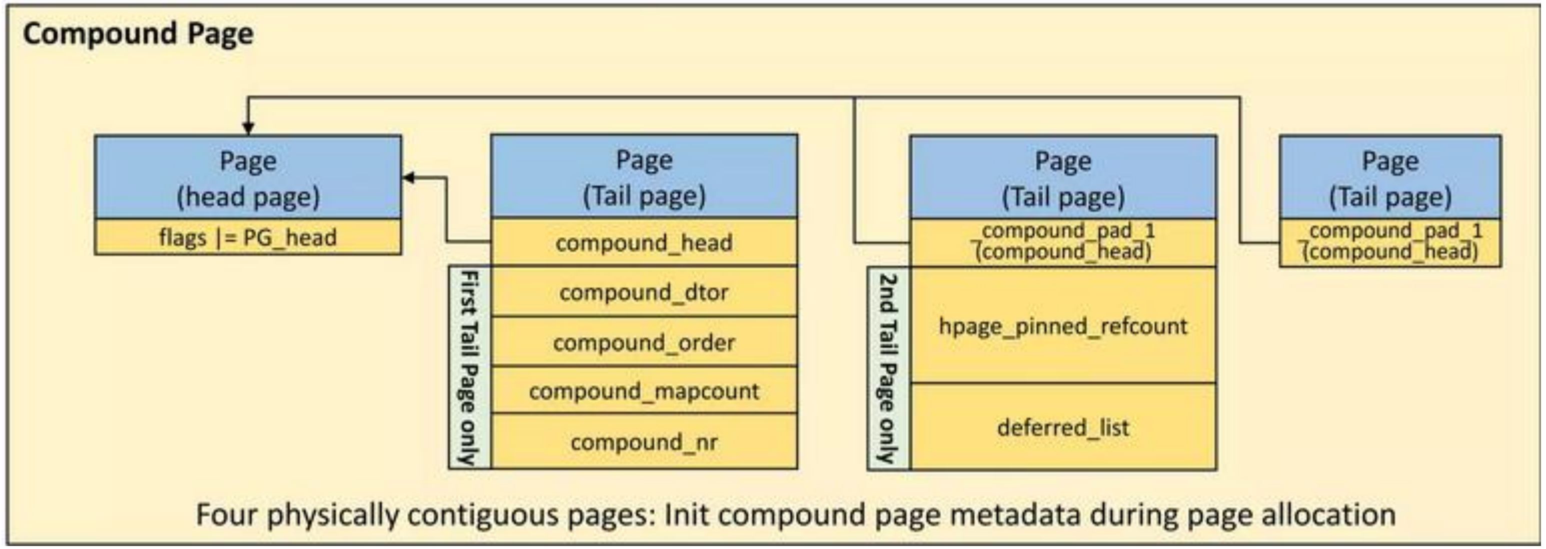
pages = alloc_pages(GFP_KERNEL, 2);



Normal high-order page

Four physically contiguous pages: not a compound page

pages = alloc_pages(GFP_KERNEL | __GFP_COMP, 2);



Compound Page

Page (head page)

flags |= PG_head

Page (Tail page)

First Tail Page only

compound_head

compound_dtor

compound_order

compound_mapcount

compound_nr

Page (Tail page)

2nd Tail Page only

compound_pad_1 (compound_head)

hpage_pinned_refcount

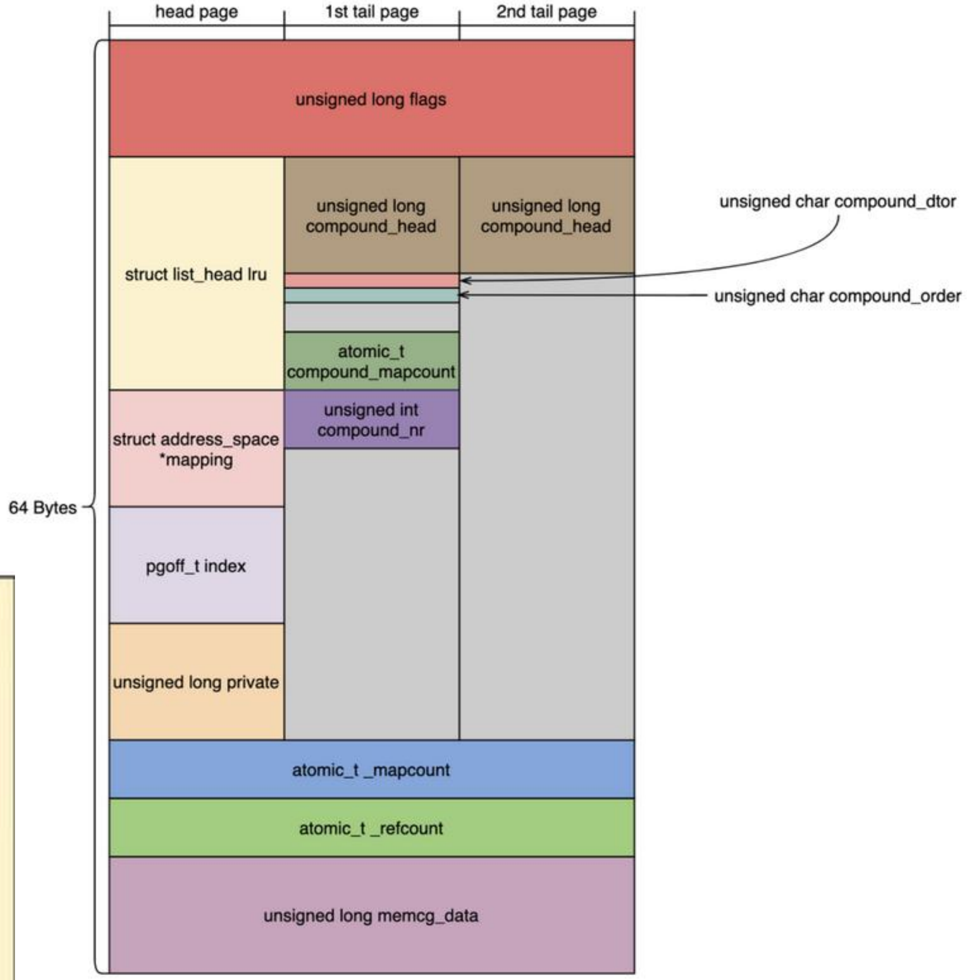
deferred_list

Page (Tail page)

compound_pad_1 (compound_head)

Four physically contiguous pages: Init compound page metadata during page allocation

(source: Adrian Huang, Memory Management with Page Folios, 2023)



head page | 1st tail page | 2nd tail page

64 Bytes

unsigned long flags

struct list_head lru

unsigned long compound_head

unsigned long compound_head

unsigned char compound_dtor

unsigned char compound_order

atomic_t compound_mapcount

unsigned int compound_nr

struct address_space *mapping

pgoff_t index

unsigned long private

atomic_t _mapcount

atomic_t _refcount

unsigned long memcg_data

(source: Yu Xu, New Features of Linux Memory management – Memory folios, November 2023)

Folios

Matthew Wilcox

- **Compound page** is a group of pages, represented by a **head page**. Other pages are called **tail pages**.
- A **folio** is a way of representing a set of **physically contiguous base pages**.
- It is a container for a **struct page** that is guaranteed not to be a tail page.
- Any function accepting a folio will operate on the full compound page (if, indeed, it is a compound page) with no ambiguity.
- The result is greater clarity in the kernel's memory-management subsystem; as functions are converted to take folios as arguments, it will become clear that they are not meant to operate on tail pages.
- The first set of folio patches was merged for the **5.16 kernel**.
- The plan is for **struct page** to shrink down to a single, **eight-byte memory descriptor**, the bottom few bits of which describe what type of page is being described. The descriptor itself will be specific to the page type; slab pages will have different descriptors than anonymous folios or pages full of page-table entries, for example.
- A key objective behind the move to descriptors is **reducing the size of the memory map**. The memory-map overhead can be reduced from **1.56% to 0.2%** of memory, which can save multiple gigabytes of memory on larger systems.

The state of the page in 2024, May 15, 2024, Jonathan Corbet

SKIP

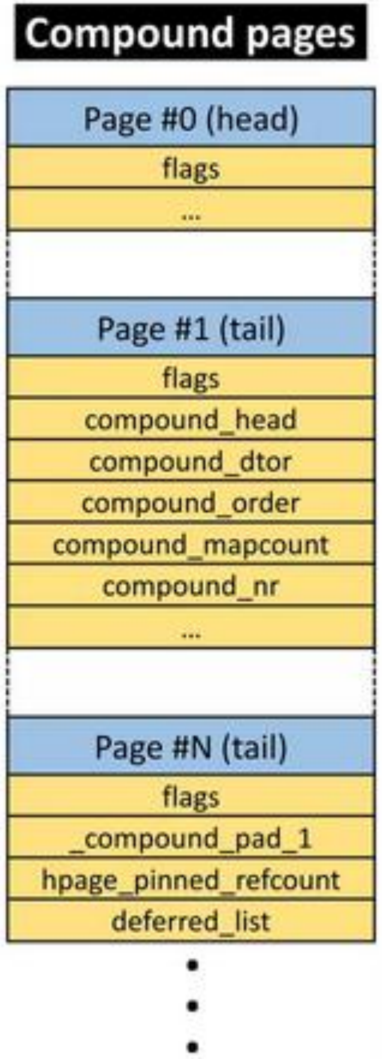
page struct vs folio struct

folio's benefit

- [Example] 512KB compound page
  - ✓ page struct: Need to maintain 128 page structs (1 head page and 127 tail pages)
  - ✓ folio struct: Maintain 3 page structs regardless of the size of compound pages.

folio struct's members

- _entire_mapcount
  - ✓ The compound page is mapped via a single PMD (huge page).
- _nr_pages_mapped
  - ✓ Number of individual subpages (PTE: 4KB pages) are mapped.
  - ✓ Scenario: Two processes map the same memory range
    - ✓ One process maps the entire 2MB compound page (Transparent Huge Page - THP): mapped via a single PMD
    - ✓ The other process maps some 4KB pages within this 2MB memory area: mapped via PTEs
    - ✓ Benefit about THP: No need to split the huge page if other processes map 4KB pages within the same memory area.
- _folio_nr_pages
  - ✓ Number of pages in this folio.
  - ✓ _folio_nr_pages = 1 << order, where order > 0.

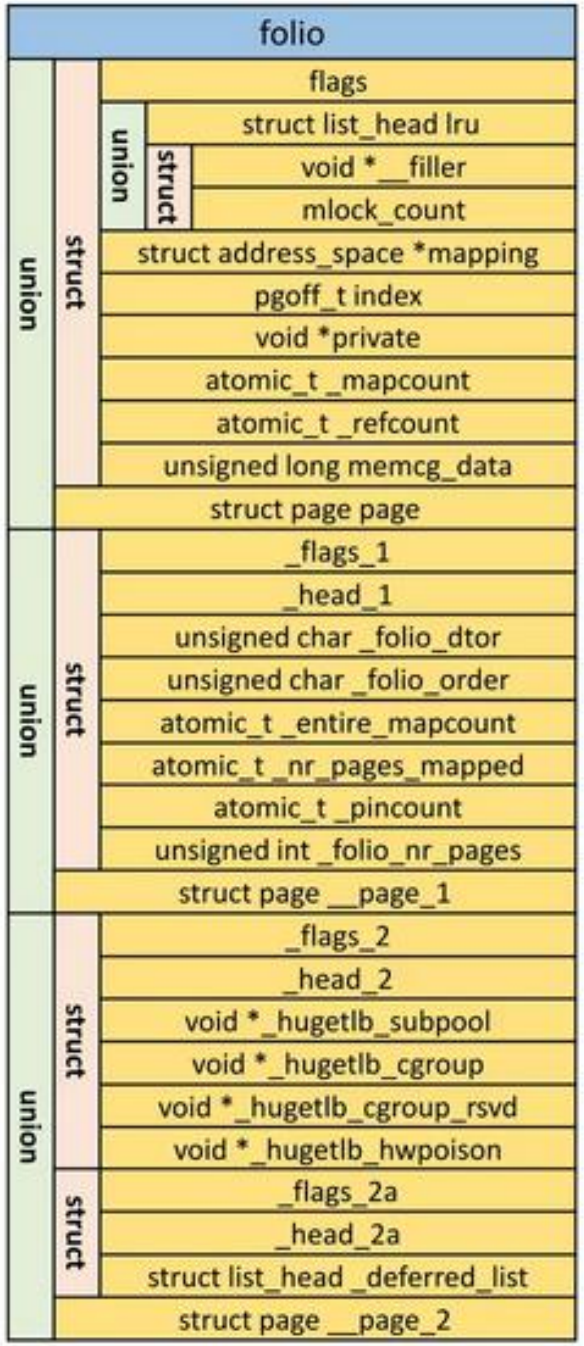


Compound pages

Page #0 (head)
flags
...

Page #1 (tail)
flags
compound_head
compound_dtor
compound_order
compound_mapcount
compound_nr
...

Page #N (tail)
flags
_compound_pad_1
hpage_pinned_refcount
deferred_list



folio
flags
struct list_head lru
void * __filler
mlock_count
struct address_space *mapping
pgoff_t index
void *private
atomic_t _mapcount
atomic_t _refcount
unsigned long memcg_data
struct page page
_flags_1
_head_1
unsigned char _folio_dtor
unsigned char _folio_order
atomic_t _entire_mapcount
atomic_t _nr_pages_mapped
atomic_t _pincount
unsigned int _folio_nr_pages
struct page __page_1
_flags_2
_head_2
void * _hugetlb_subpool
void * _hugetlb_cgroup
void * _hugetlb_cgroup_rsvd
void * _hugetlb_hwpoison
_flags_2a
_head_2a
struct list_head _deferred_list
struct page __page_2

(source: Adrian Huang, Memory Management with Page Folios, 2023)

Additional reading

- https://lwn.net/Kernel/Index/#Huge_pages
- https://www.kernel.org/doc/Documentation/vm/hugetlbpage.txt
- /Documentation/mm/transhuge.rst
- Proactive compaction, Jonathan Corbet, 2017.
- Proactive compation for the kernel, Nitin Gupta, April 2020.
- Memory: the flat, the discontiguous, and the sparse, Mike Rapaport, May 2019.
- The end of the DAX experiment, Jonathan Corbet, May 2019.
- Sidestepping kernel memory management with DMEMFS, Jonathan Corbet, December 2020.
- Large Pages in Linux, Matthew Wilcox, LCA 2020.
- Large Pages in the Linux kernel, Matthew Wilcox, February 2021.
- LWN – A memory-folio update, Jonathan Corbet, May 2022
- The state of the page in 2025, Jonathan Corbet, March 2025