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# Towards an Alternative Guest Memory Architecture

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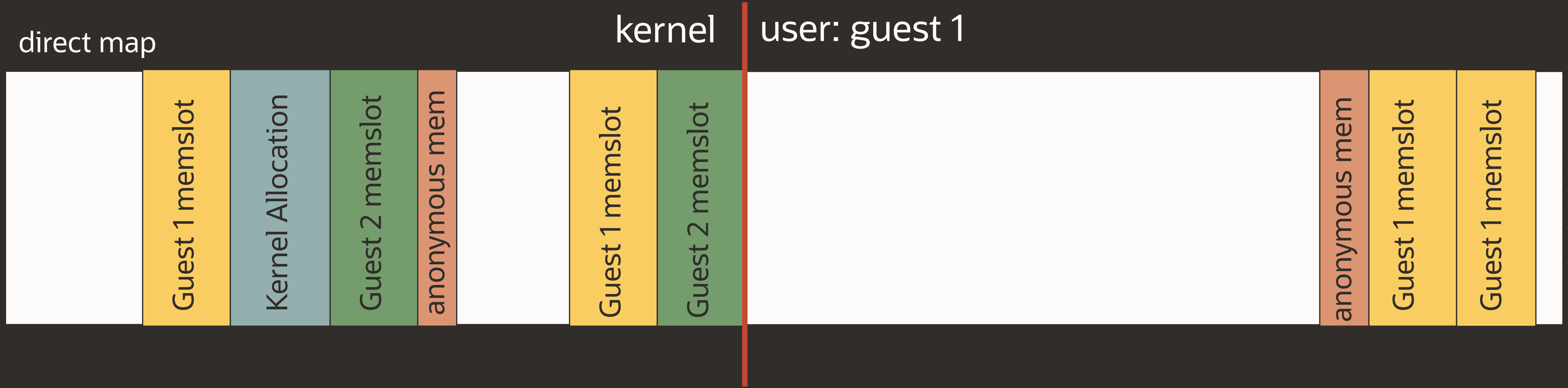
# Motivation

## The direct map

- Linux keeps a direct map of all physical memory
- This address space is modified in many ways (ioremap, add_pages, boot)
- Portions are defined by various metadata (e.g. struct page, memblock)
- What reflected in page tables maybe managed in higher order chunks



## Metadata

- The direct map is backed by metadata called `struct page`
- Used by page cache and anon, required for most kernel services
- Tracks references to a PFN, mappings, amongst others
- Usually accessible via get_user_pages() and PFN to metadata conversions

## `struct page`/metadata overheads

- **64 bytes** in size per PAGE_SIZE (4096 on x86_64)
  - KVM adds another 8bytes per spte
  - PTEs another 8byte per 4K albeit amenable to hugepte
  - "Just" 1.75% of host physical memory, right?
- Extrapolating:
  - 32 - 36 GB for a 2Tb machine
  - 128 - 160 GB for an 8Tb machine
  - 1.2 TB for a 64Tb machine

## Security vulnerabilities

Spectrev1: speculatively execute arbitrary instructions that load data from the direct map.

Spectrev2: similar to variant 1 but for indirect branches.

Spectrev3: could leak any memory from the direct map in userspace

Spectrev4: utilize values speculatively read out-of-order to leak data mapped by the kernel

L1TF / MDS: data in the direct map could be leaked through CPU resources like the L1 data cache for L1TF, or micro-architectural buffers (MDS)

Most mean that data mapped by the CPU can be leaked:

**kVA address space maps all memory, therefore all is leakable**

## Can we do better for hypervisors?

- `struct page` does not **really** reflect underlying page size in the page tables
- Modern platforms won’t need most kernel services (e.g no I/O)
- Efficiency lost in a mostly idle structure
- While potentially leaking customer data through the direct map

# Removing struct page?

## /dev/mem and mem=NNN

- A metadata-less map with a single contiguous chunk of any memory kind
- Only 4K PTEs (no huge pages)
- No access control between multiple VMMs
- VMM needs to manage multiple VMAs with different page offsets
- No way to give that memory back

  Can target *any* memory

# The Device DAX Interface

- Character device mmap-able providing strict direct access to memory
- Memory map initialized at device creation
- Gives control to application on clearing, access, alignment, exceptions
- Provides facilities to return memory back to the kernel (dax_kmem)

An emulated devdax device through `memmap=X@Y`

Requires user knowledge of memory map to select a RAM range

*Note: devdax != (pmem || fsdax)*

# Device DAX Limitations

- Inherits design of NVDIMM persistent namespaces
  - No support for discontiguous regions
- Long device initialization times due to ‘struct page’ init/clearing
- No use of compound pages (despite providing hugepage ptes)

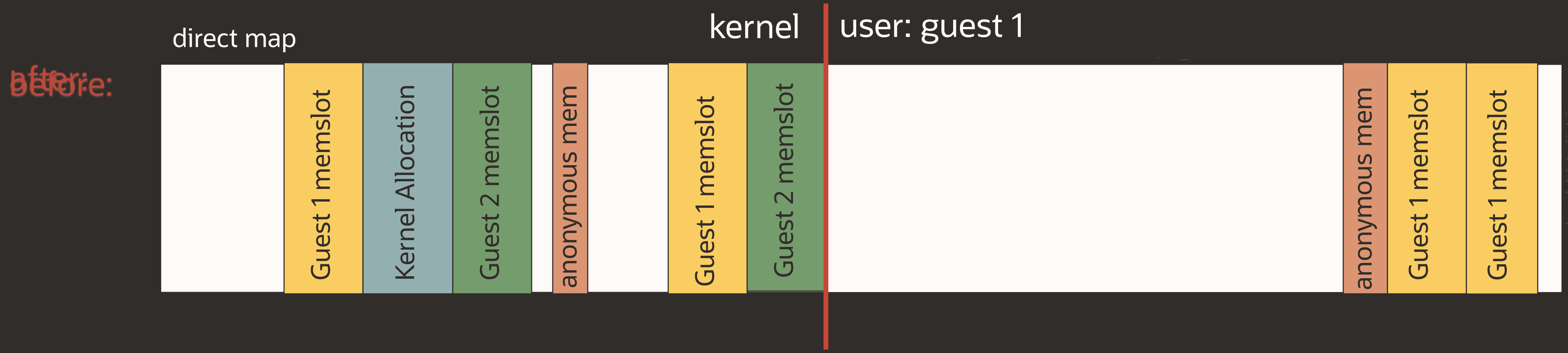
Need arch support for devmap PTEs

## Device DAX for volatile memory (`dax_hmem`)

- Removes the need for the memmap=X@Y hack
- Uses **actual** conventional memory in EFI
  - EFI memory map entries marked with EFI_MEMORY_SP attribute
- Ability for firmware to dedicate memory for userspace
- Will also be used when platforms support HMAT (e.g. HBM2)
- Application can pick ranges to create or restore a memory device (kexec)
  - Or use DAX simple range allocator

# Device DAX without struct page

- Introduce a VM_PFNMAP mmap() with static PFN mappings
- Leverage existing KVM support for VM_PFNMAP (by Karim Ahmed)
- 2M/1G Hugepage support for PAGE_SPECIAL
- Fix the cop out of MCEs on memory not managed by kernel
  Reserve memory types for PFNs to mapped as WB



# Example usage

Adding to kernel command line (example host is 386G per node, on 2 nodes):

```
efi_fake_mem=368G@16G:0x40000,368G@400G:0x40000
```

Dumping ranges or dax regions:

```
$ cat /proc/iomem | grep Soft
        200000000-ffffffff : Soft Reserved
        1200000000-1ffffffff : Soft Reserved
$ daxctl list -Riu
```

Using it on Qemu:

```
-m 30G
-object memory-backend-file,id=mem,size=30G,mem-path=/dev/dax0.1,share=on,align=1G
-numa node,memdev=mem
```

Managing the region:

```
$ daxctl create-device -s 30G [--no-metadata] -a 1G -r 0
$ daxctl disable-device dax0.1 && daxctl destroy-device dax0.1
$ daxctl disable-device dax0.1 && daxctl reconfigure-device dax0.1 -s 16G
```

## Use cases for pageless/secret memory in KVM

- Let KVM bind these DAX devices
- Replace all SLAB/SLUB usage call sites with this pageless/secret memory

  e.g. struct kvm_ioapic ; kvm_vcpu ; struct kvm_pit; vcpu arch data

- Userspace VMM usage as a global memory pool for all its allocations

## Advantages

- Guest memory not as prone to leakage
- Gain a ton of memory back for more guests
- Memory preserved for VMM fast live restart
- No need to hunt all those SpectreV1 gadgets

## Pitfalls

- Case by case basis to support no struct page
- Stripped of most kernel services
  (only KVM, mm, VFIO*)
- Needs better tracking across subsystems
  (i.e. follow_pfn() not enough?)
- I/O only copy based
  (e.g. `vhost_net.experimental_zcopytx=0`)

# Future directions?

# ASI and Pageless Memory

- Deny list (Pageless) versus Allow list (ASI)
- Both complement each other: protecting VMM and kernel private data
- Perhaps a potential performance improvement?

## Huge Pages and less struct pages?

- I/O could work better without struct pages
- Remove assumption over PAGE_SIZE/PAGE_MASK in offset computation
- Letting subsystems learn to only deal with head pages
- Example is recent support for Large Pages in the page cache work

# Huge Pages and less struct pages

- Do we need all those pages for a preallocated hugetlbfs/DAX page?
- What falls apart if portions of vmemmap reuse the same pages?

  https://lore.kernel.org/linux-mm/20200915125947.26204-1-songmuchun@bytedance.com/

- DAX support for “regular” huge pages

## Current Status and Conclusions

- 5.10 will have improved partitioning of DAX regions
- `struct page` removal and better DAX hugepages support effort to continue
- Tries to introduce a boundary between hypervisor and guest memory
- Taught us that the kernel mapping isn't always necessary

# Resources

- struct page, The linux physical page frame data structure

  https://blogs.oracle.com/linux/struct-page%2C-the-linux-physical-page-frame-data-structure

- pageless DAX initial proposal: http://lore.kernel.org/r/20200110190313.17144-1-joao.m.martins@oracle.com

  latest: https://github.com/jpemartins/linux pageless-dax

# Thank you

**Questions?**