CSE 127: Computer Security

Isolation and side-channels

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Some slides adopted from Nadia Heninger,John Mitchell, Dan Boneh, and Stefan Savage

Today

Lecture objectives:

- Understand basic principles for building secure systems
- Understand mechanisms used in building secure systems
- Understand a key limitation of these principles: side-channels

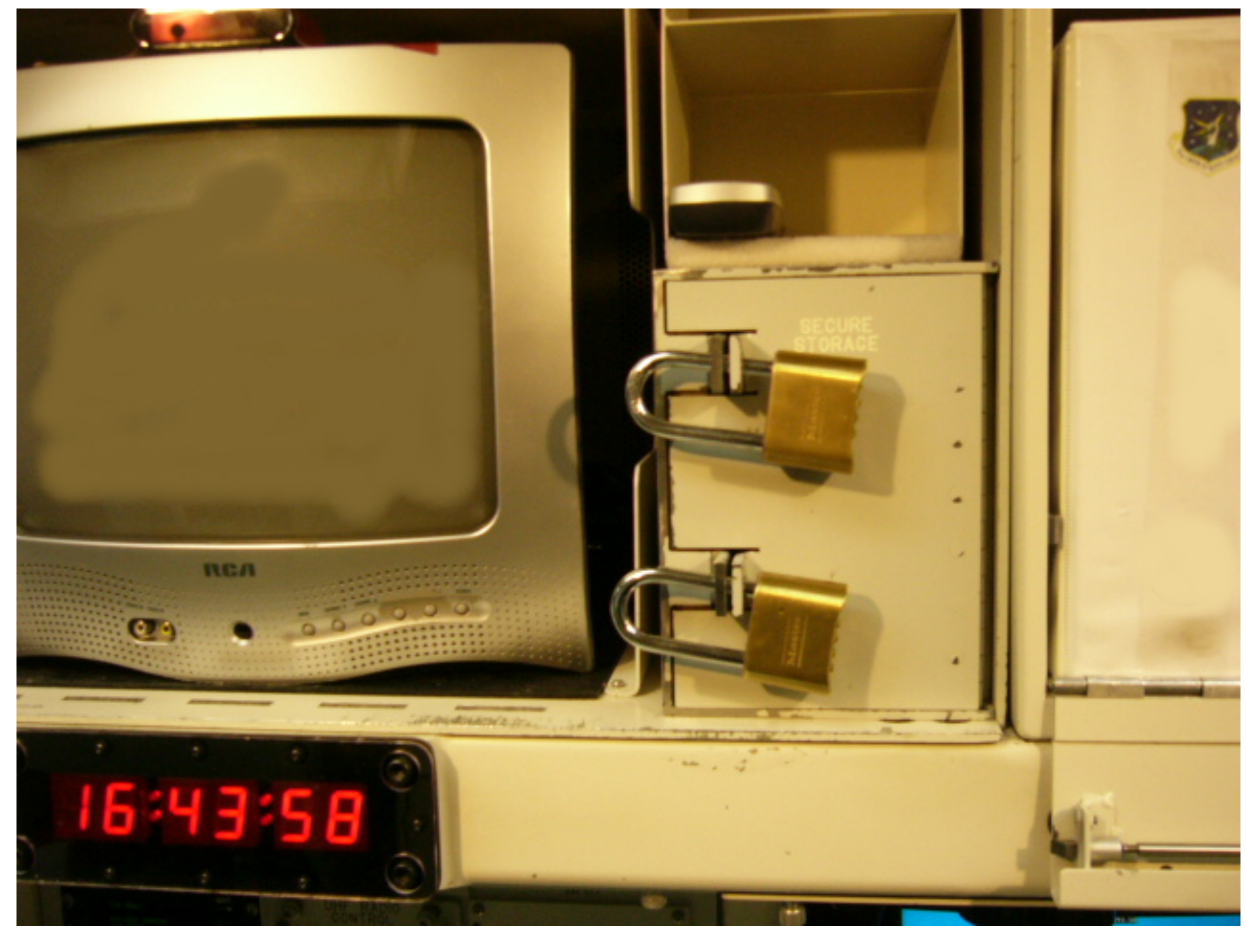
Principles of secure design

- Principle of least privilege
- Privilege separation
- Defense in depth
  - Use more than one security mechanism
  - Fail securely/closed
- Keep it simple

Principles of secure design

- Principle of least privilege ← almost always
- Privilege separation ← come in pair
- Defense in depth
  - ➤ Use more than one security mechanism
  - ➤ Fail securely/closed
- Keep it simple

Where have we seen this before?



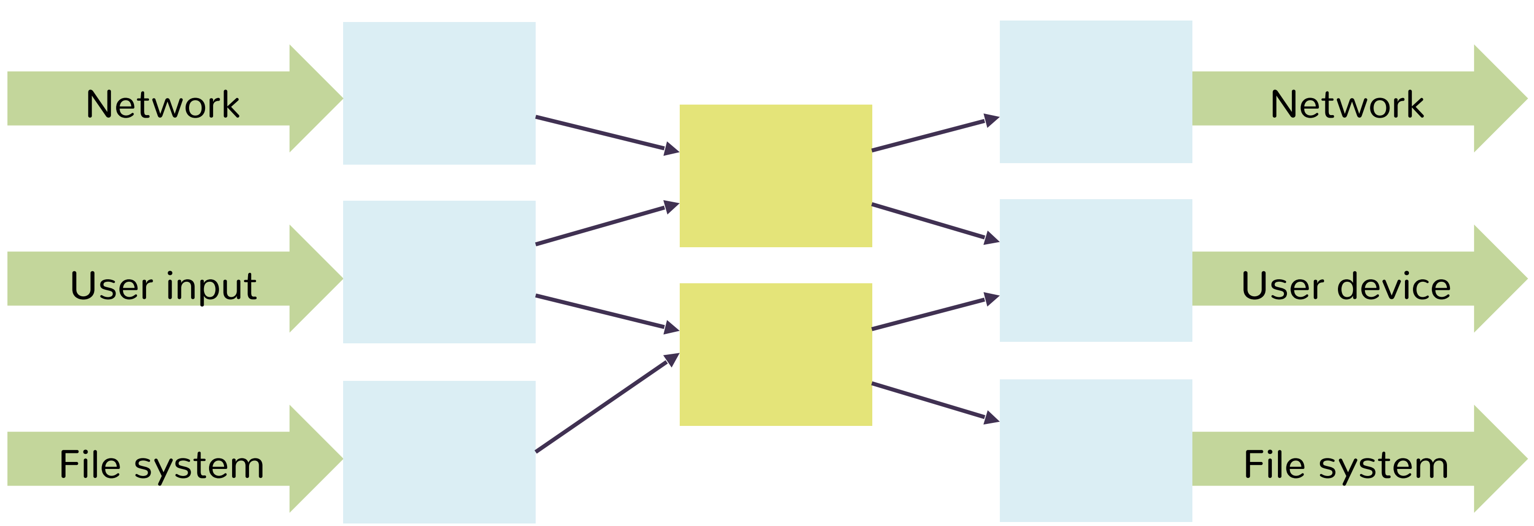
least privilege

privilege separation

High-level idea

- Separate the system into isolated least-privileged compartments
- Mediate interaction between compartments according to security policy

- What's the goal/attacker model assumption?
  - Limit the damage due to any single compromised component



What is the unit of isolation?

- It depends!
  - Physical Machine
  - Virtual Machine
  - OS Process
  - Library
  - Function
  - ...

coarse grain

↓

fine grain

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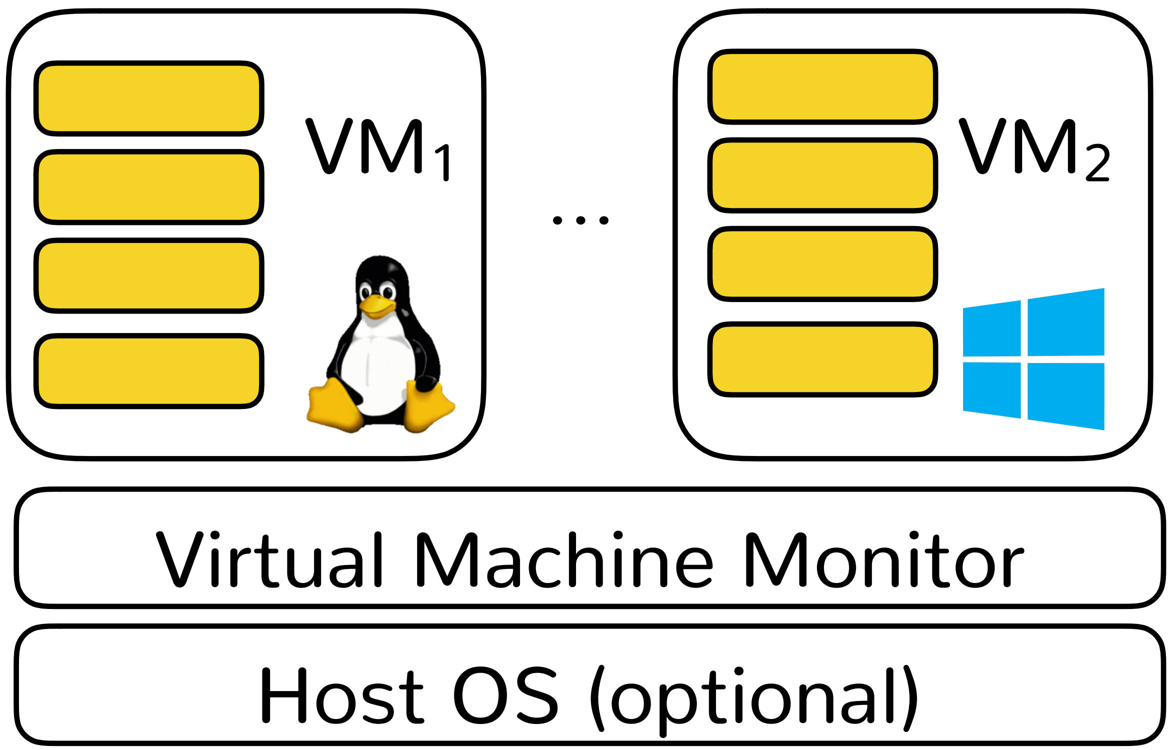
most popular,

focus in class

The Virtual Machine abstraction (Isolate guest OSes and apps)



The process abstraction (Isolate apps from each other)

- OS ensures that processes are memory isolated from each other
- In UNIX, each process has set of UIDs
  - Used to mediate which files process can read/write
- Conceptually easy to further restrict privileges
  - To do anything useful (e.g., open socket, read file, etc.) process must perform syscall into kernel; interpose on all syscalls and allow/deny according to policy

How are these used to to build secure (least-privileged and privilege separated) systems?

Brief interlude: How do user IDs (UIDs) work?

- Permissions in UNIX granted according to UID
  - A process may access files, network sockets, ...
- Each process has UID
- Each file has ACL
  - Grants permissions to users according to UIDs and roles (owner, group, other)
  - Everything is a file!

How many UIDs does a process have?

Process UIDs

- Real user ID (RUID)
  - ➢ same as the user ID of parent (unless changed)
  - ➢ used to determine which user started the process
- Effective user ID (EUID)
  - ➢ from setuid bit on the file being executed, or syscall
  - ➢ determines the permissions for process
- Saved user ID (SUID)
  - ➢ Used to save and restore EUID

SetUID demystified (a bit)

- Root
  - ID=0 for superuser root; can access any file
- fork and exec system calls
  - Typically inherit three IDs of parent
  - Exec of program with setuid bit: use owner of file
- setuid system call lets you change EUID

SetUID demystified (a bit)

- There are actually 3 bits:
  - setuid - set EUID of process to ID of file owner
  - setgid - set $EG_{roup}ID$ of process to GID of file
  - sticky bit
    - on: only file owner, directory owner, and root can rename or remove file in the directory
    - off: if user has write permission on directory, can rename or remove files, even if not owner

Examples of setuid and sticky bits

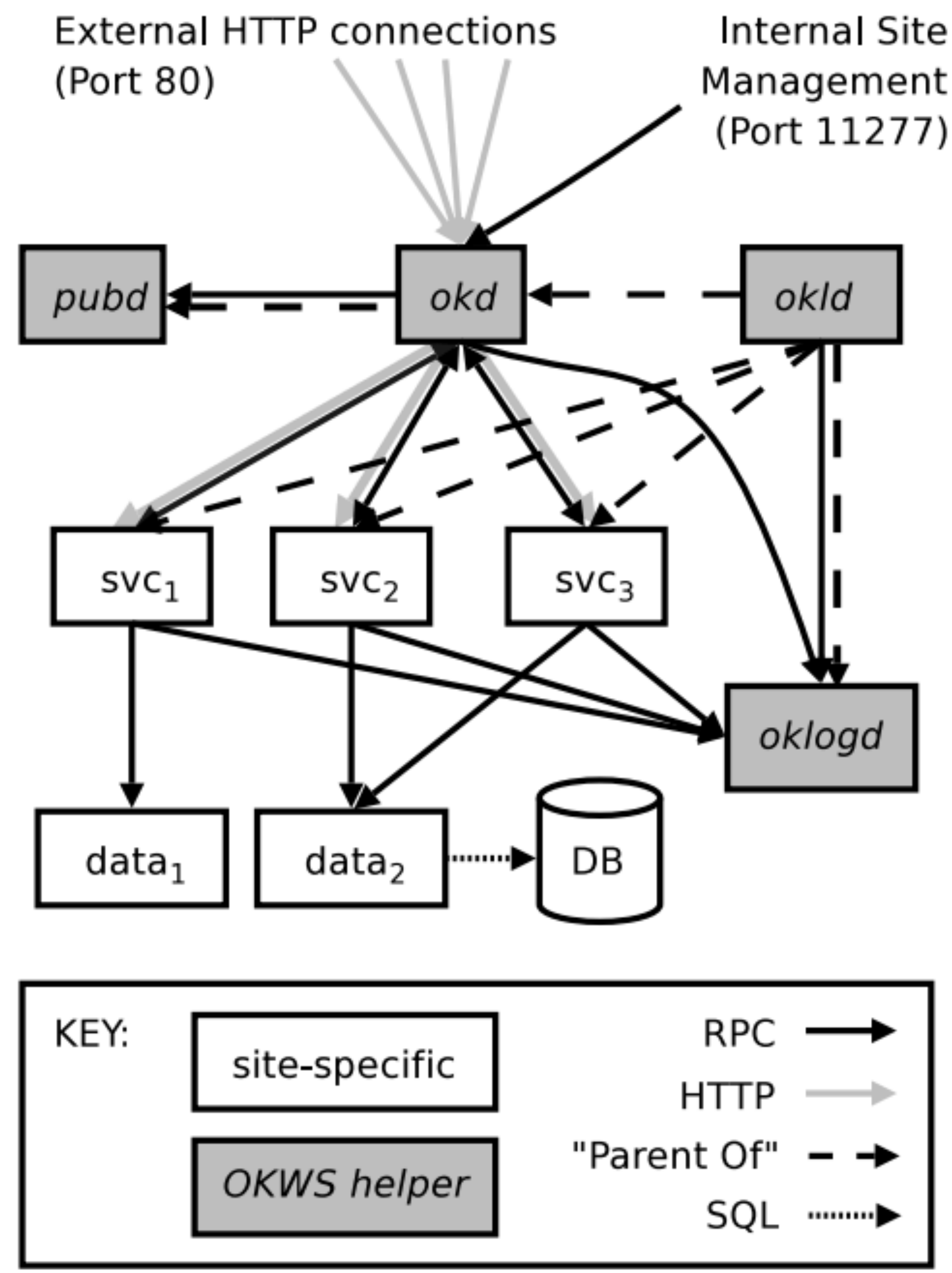
```
-rwsr-xr-x 1 root root 55440 Jul 28  2018 /usr/bin/passwd

drwxrwxrwt 16 root root  700 Feb  6 17:38 /tmp/
```

Example 1: Android

- Each app runs with own process UID
  - Memory + file system isolation
- Communication limited to using UNIX domain sockets + reference monitor checks permissions
  - User grants access at install time + runtime

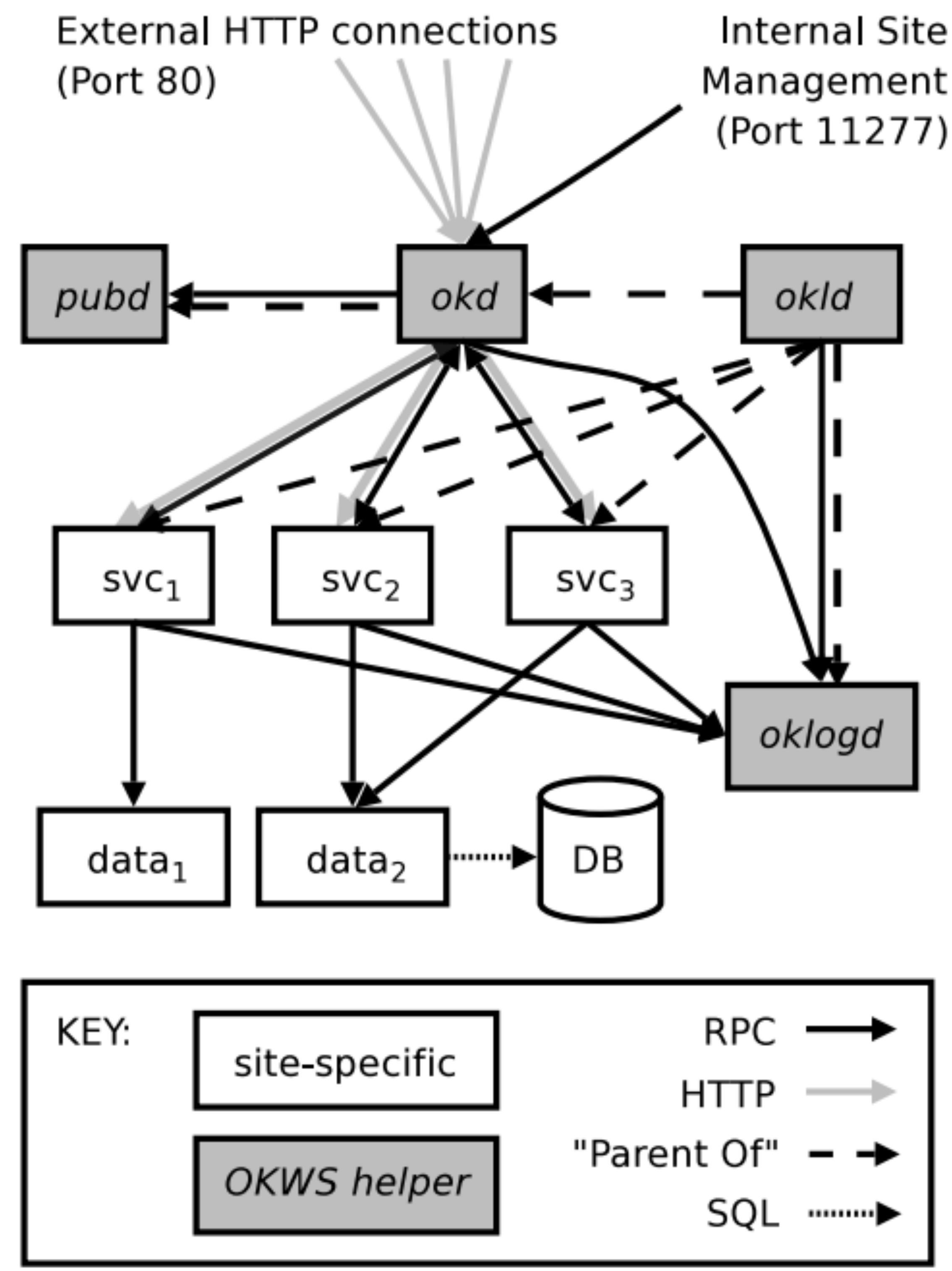
Example 2: OK_{Cupid} W_{eb} S_{erver}

- Each service runs with unique UID
    - Memory + file system isolation
- Communication limited to structured RPC



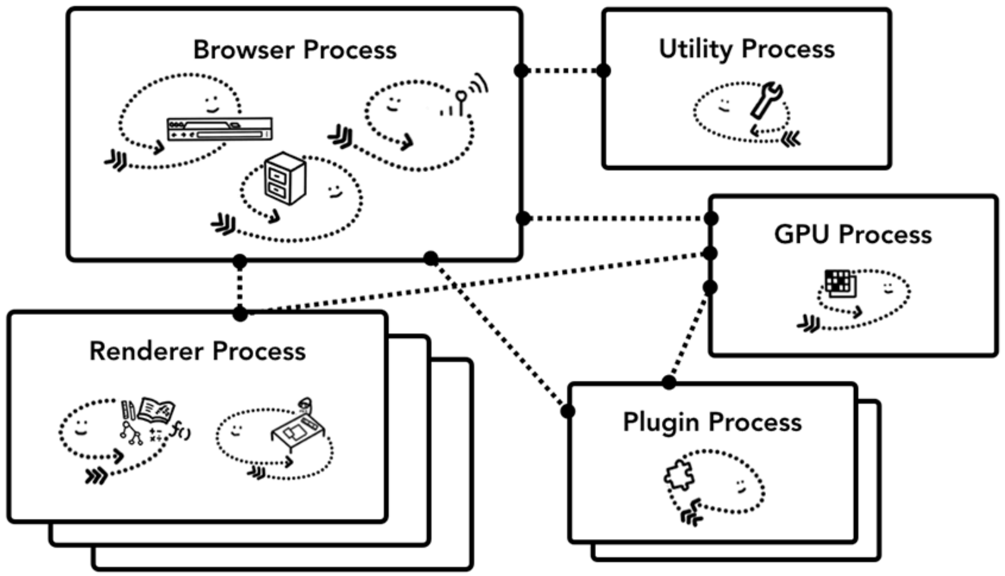
Example 2: OK$_{\text{Cupid}}$W$_{\text{eb}}$S$_{\text{erver}}$

process	*chroot* jail	run directory	uid	gid
okld	`/var/okws/run`	`/`	`root`	`wheel`
pubd	`/var/okws/htdocs`	`/`	`www`	`www`
oklogd	`/var/okws/log`	`/`	`oklogd`	`oklogd`
okd	`/var/okws/run`	`/`	`okd`	`okd`
svc_1	`/var/okws/run`	`/cores/51001`	`51001`	`51001`
svc_2	`/var/okws/run`	`/cores/51002`	`51002`	`51002`
svc_3	`/var/okws/run`	`/cores/51003`	`51003`	`51003`



Example 3: Modern browsers

- Browser process
  - ➤ Handles the privileged parts of browser (e.g., network requests, address bar, bookmarks, etc.)
- Renderer process
  - ➤ Handles untrusted, attacker content: JS engine, DOM, etc.
  - ➤ Communication restricted to RPC to browser/GPU process

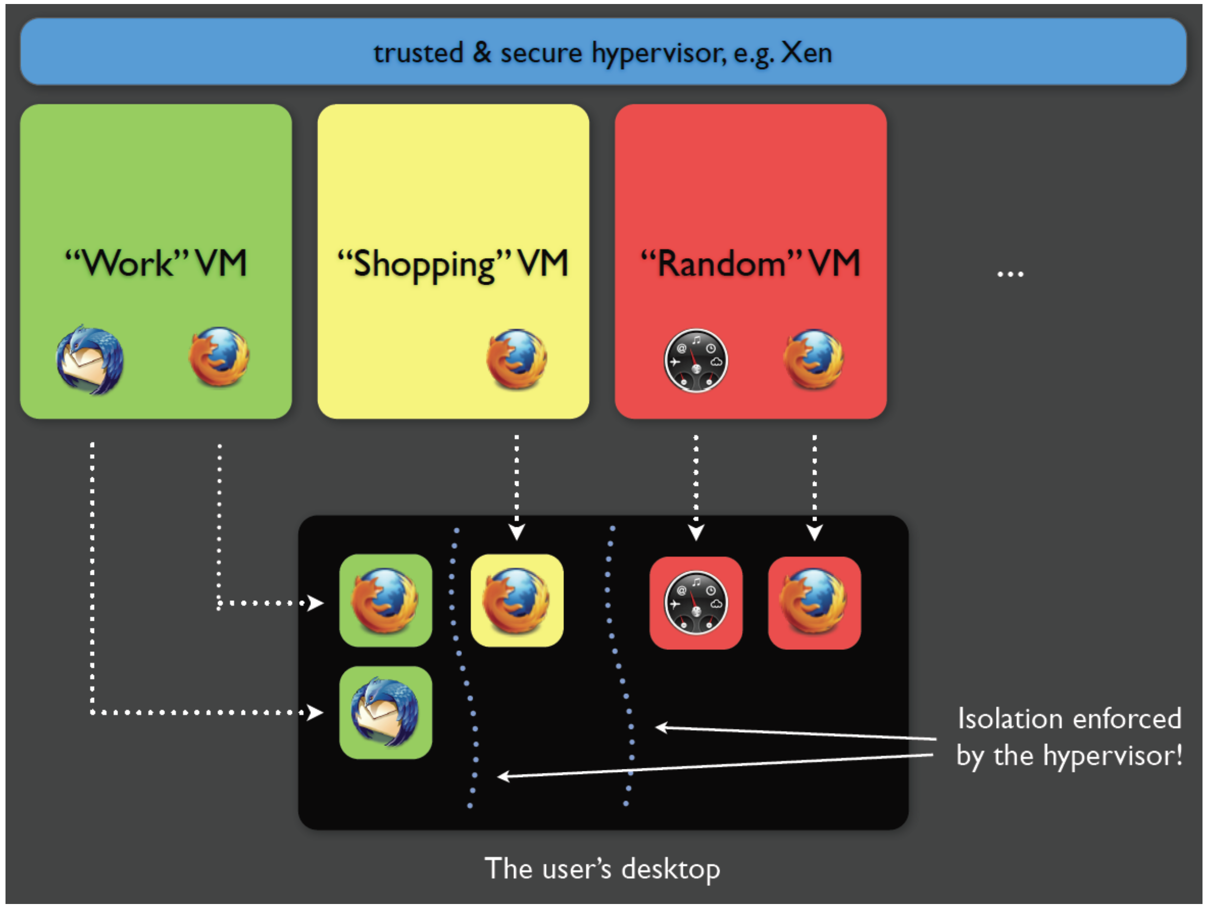


- Many other processes (GPU, plugin, etc)

https://developers.google.com/web/updates/2018/09/inside-browser-part1

Example 4: Qubes OS

- Trusted domain
  - ➤ VM that manages the GUI and other VMs
- Network, USB domains
  - ➤ Isolated domains that handle untrusted data
  - ➤ Communicates with other VMs via firewall domain



- AppVM domains
  - ➤ Apps run in isolation, in different VMs

Today

Lecture objectives:

- Understand basic principles for building secure systems
- Understand mechanisms used in building secure systems
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Many mechanisms at play

- ACL on files used by OS to restrict which processes (based on UID) can access files (and how)
- Namespaces (in Linux) are used to partition kernel resources (e.g., mnt, pid, net) between processes
  - Core part of Docker and other's containers
- Syscall filtering (seccomp-bpf) is used to allow/deny system calls and filter on their arguments
- Etc.

A common, necessary mechanism: memory isolation

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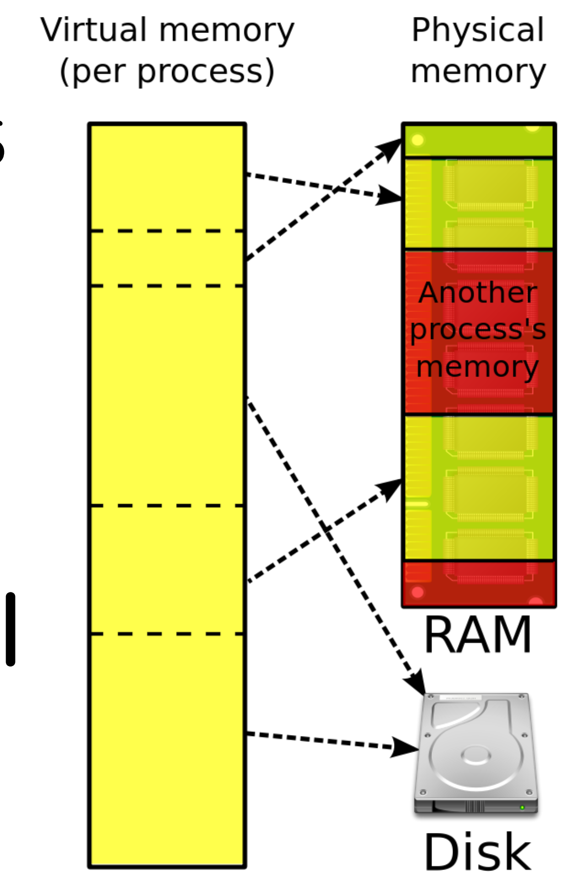
- VM, OS process, and even finer grained in-process isolation all rely on memory isolation
- Why?

A common, necessary mechanism: memory isolation

- VM, OS process, and even finer grained in-process isolation all rely on memory isolation
- Why?
  - ➤ If attacker can break memory isolation, they can often hijack control flow!

Process memory isolation

- How are individual processes memory-isolated from each other?
  - ➤ Each process gets its own virtual address space, managed by the operating system
- Memory addresses used by processes are virtual addresses (VAs) not physical addresses (PAs)
  - ➤ When and how do we do the translation?



https://en.wikipedia.org/wiki/Virtual_memory#/media/File:Virtual_memory.svg

When do we do the translation?

- Every memory access a process performs goes through address translation
  - Load, store, instruction fetch
- Who does the translation?

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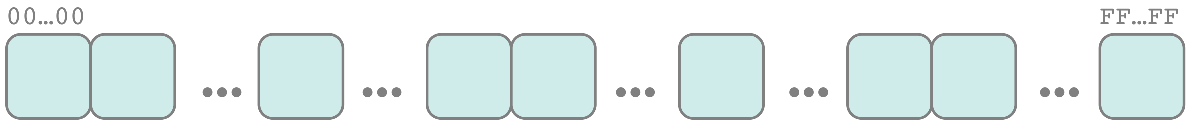
- Every memory access a process performs goes through address translation
    - Load, store, instruction fetch
- Who does the translation?
    - The CPU’s memory management unit (MMU)

How does the MMU translate VAs to PAs?

- Using 64-bit ARM architecture as an example…
- How do we translate arbitrary 64bit addresses?
  - We can't map at the individual address granularity!
  - 64 bits * 2^{64} (128 exabytes) to store any possible mapping

Address translation (closer)

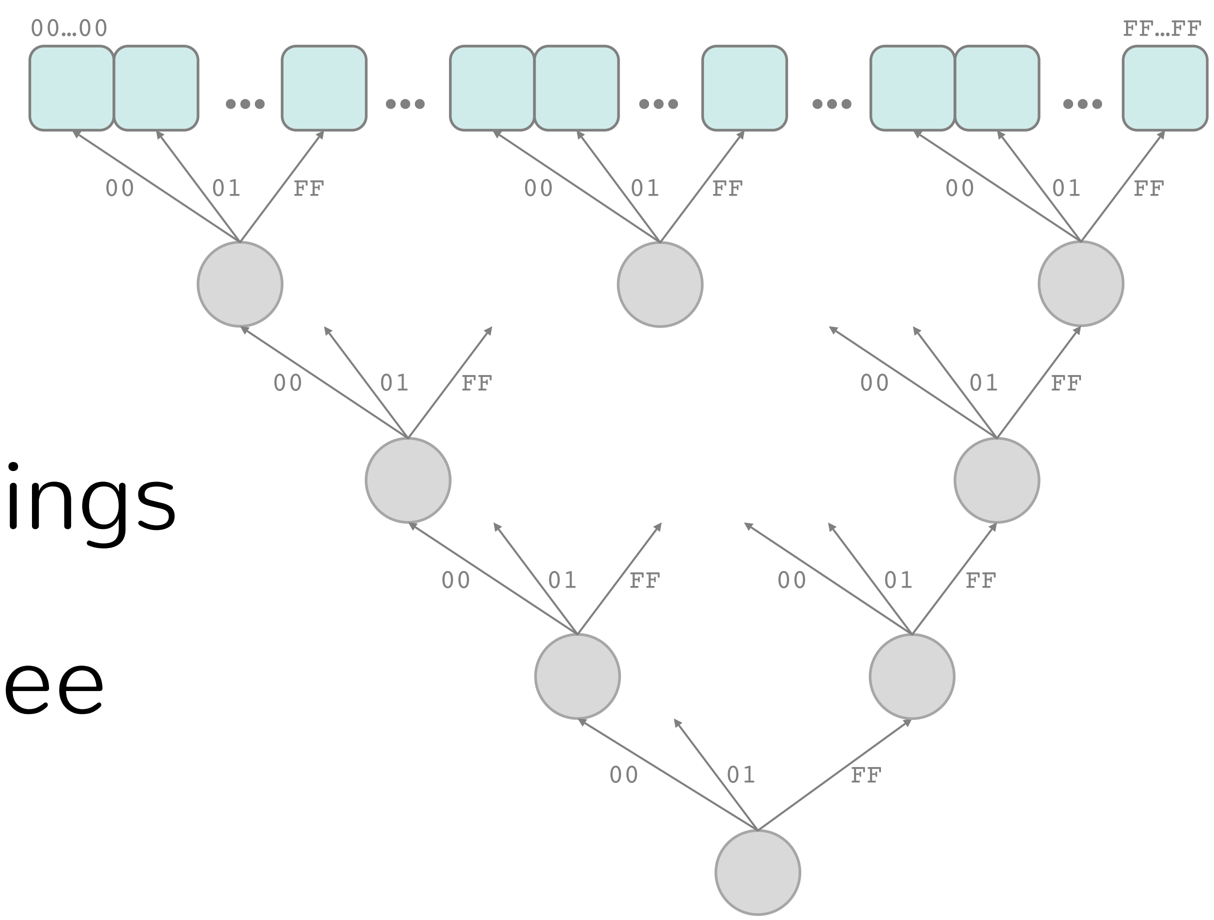


- Page: basic unit of translation
  - ➤ Usually 4KB = 2^{12}
- How many page mappings?
  - ➤ Still too big!
  - ➤ 52 bits * 2^{52} (208 petabytes)

So what do we actually do?

Multi-level page tables

- Sparse tree of page mappings
- Use VA as path through tree
- Leaf nodes store PAs
- Root is kept in register so MMU can walk the tree



How do we get isolation between processes?

- Each process gets its own tree
  - Tree is created by the OS
  - Tree is used by the MMU when doing translation
    - This is called “page table walking”
  - When you context switch: OS needs to change root
- Kernel has its own tree

Access control

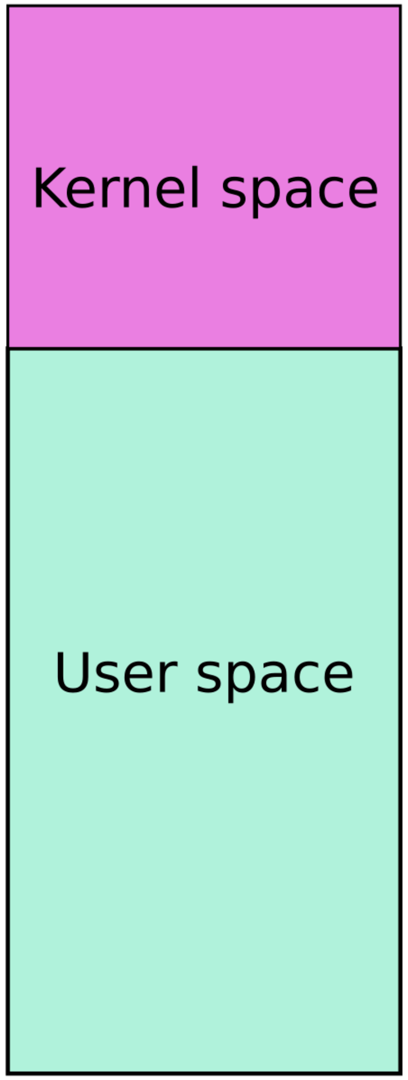
- Not everything within a processes' virtual address space is equally accessible
- Page descriptors contain additional access control information
  - Read, Write, eXecute permissions
  - Who sets these bits? (The OS!)

Example of access control usage

*This changed due to Meltdown.

Example of access control usage

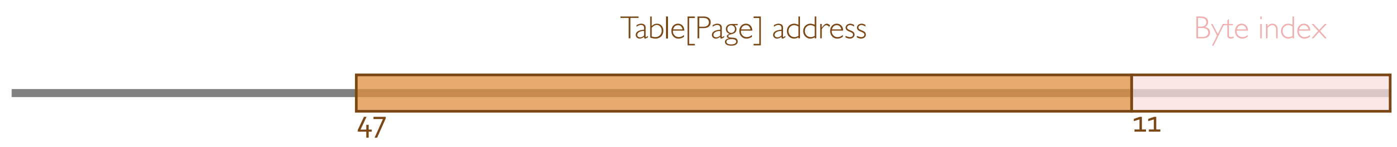
- Kernel’s virtual memory space is* mapped into every process, but made inaccessible in usermode
  - Makes context switching fast!



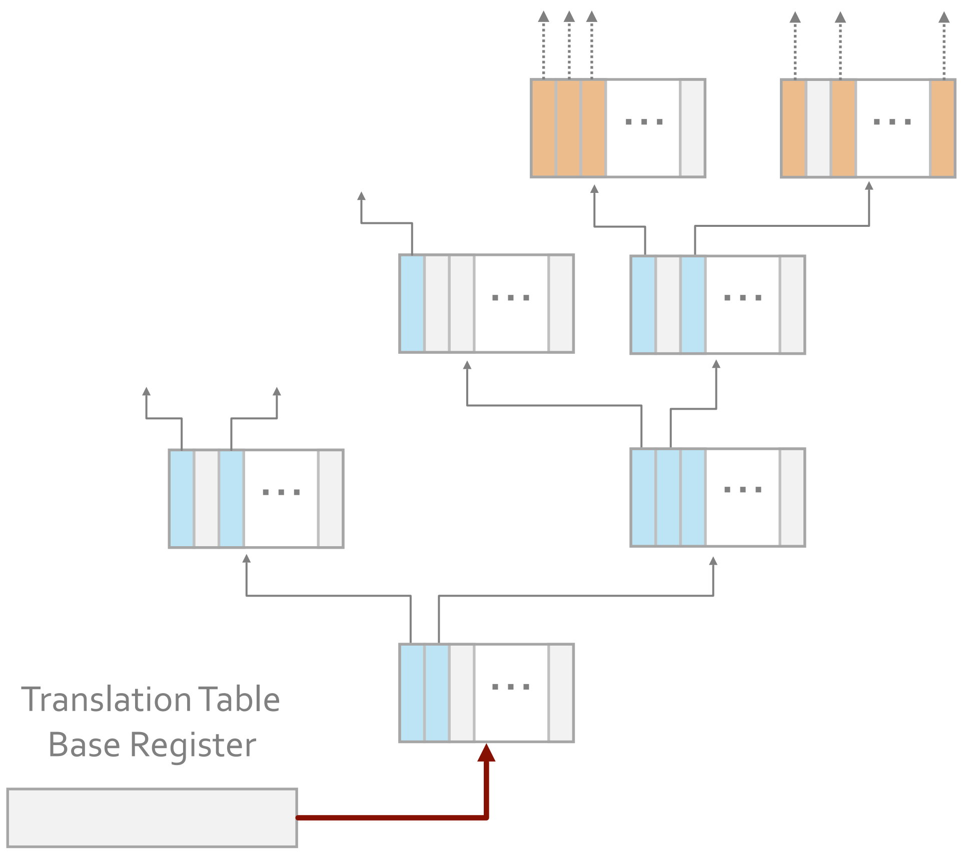
*This changed due to Meltdown.

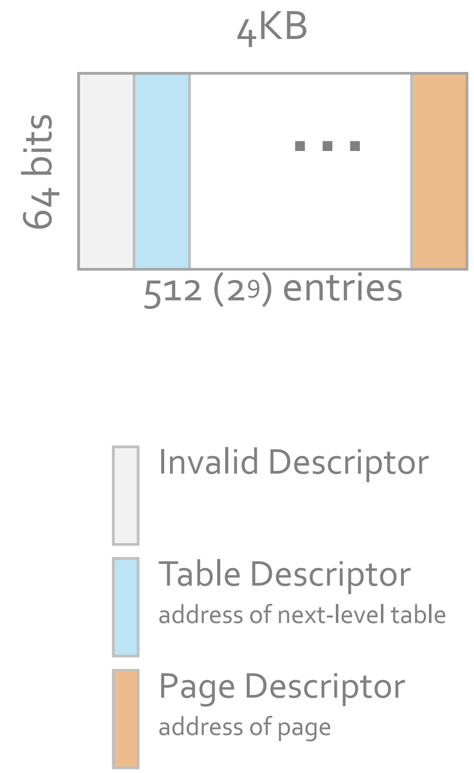
Example of page table walk

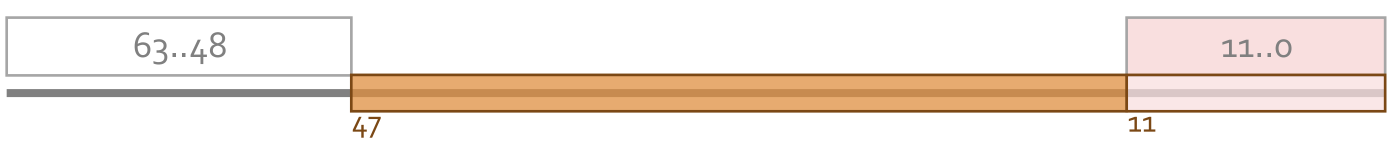
- In reality, the full 64bit address space is not used.
  - Working assumption: 48bit addresses



Page table walk







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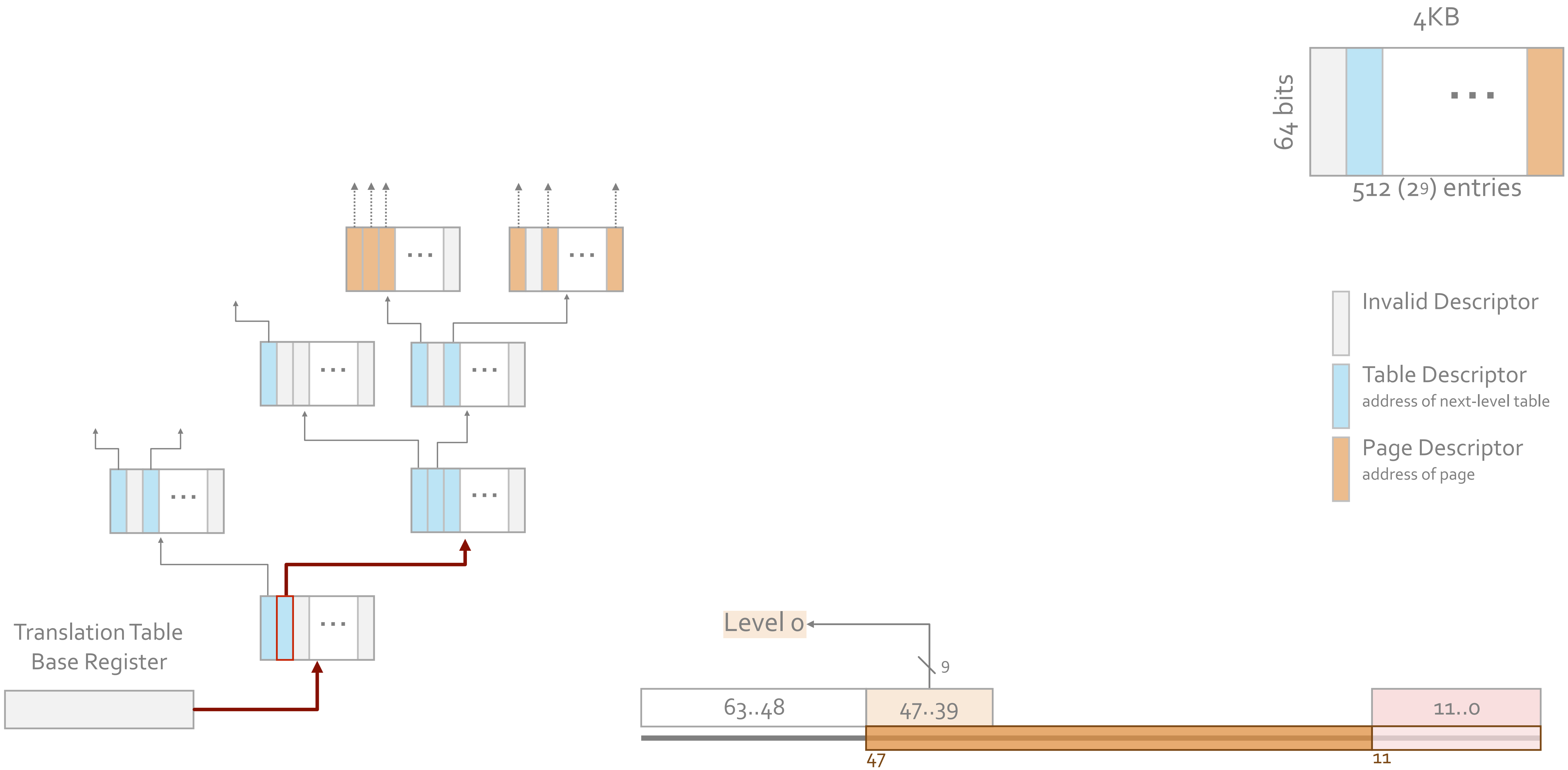

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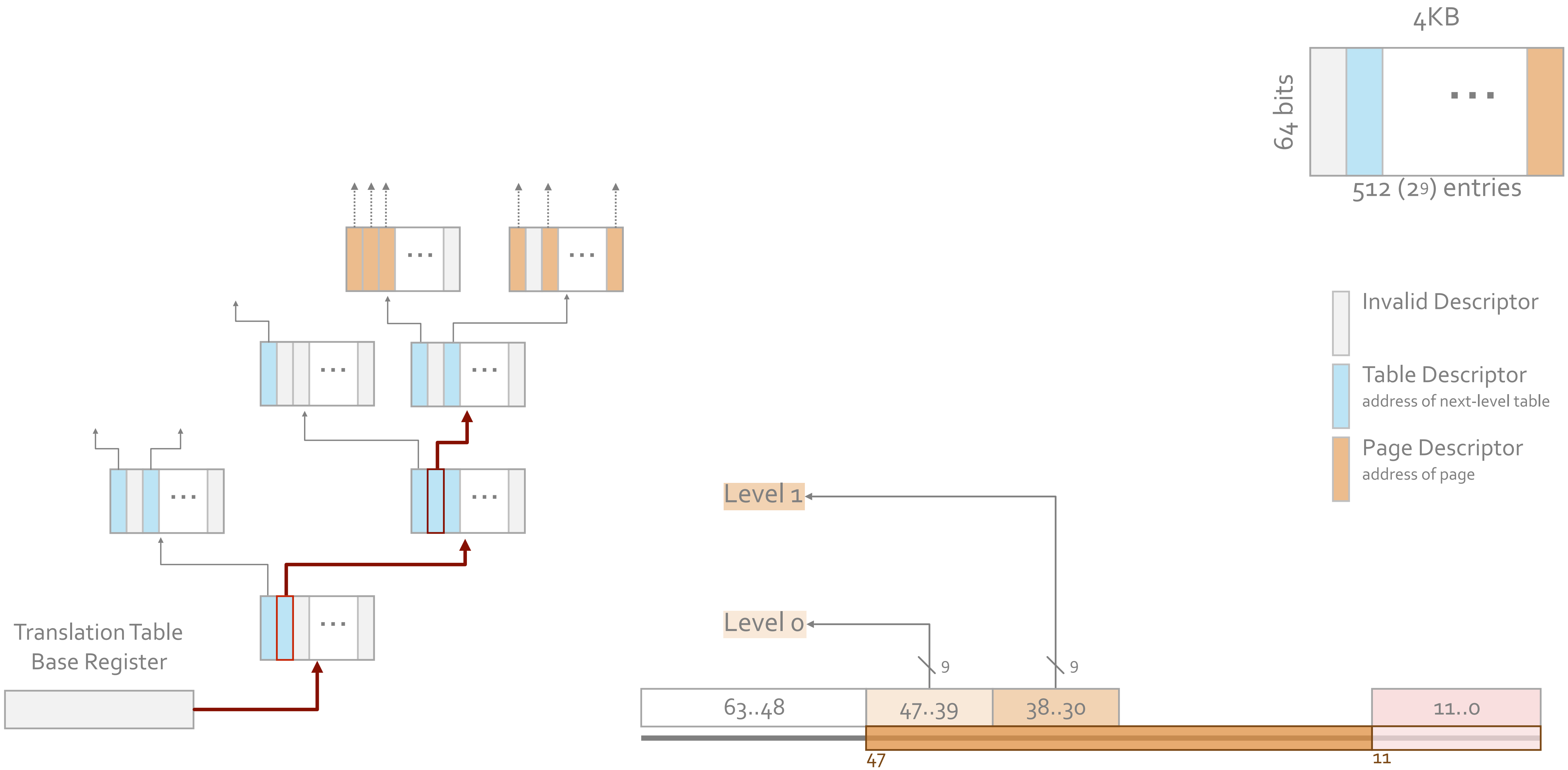

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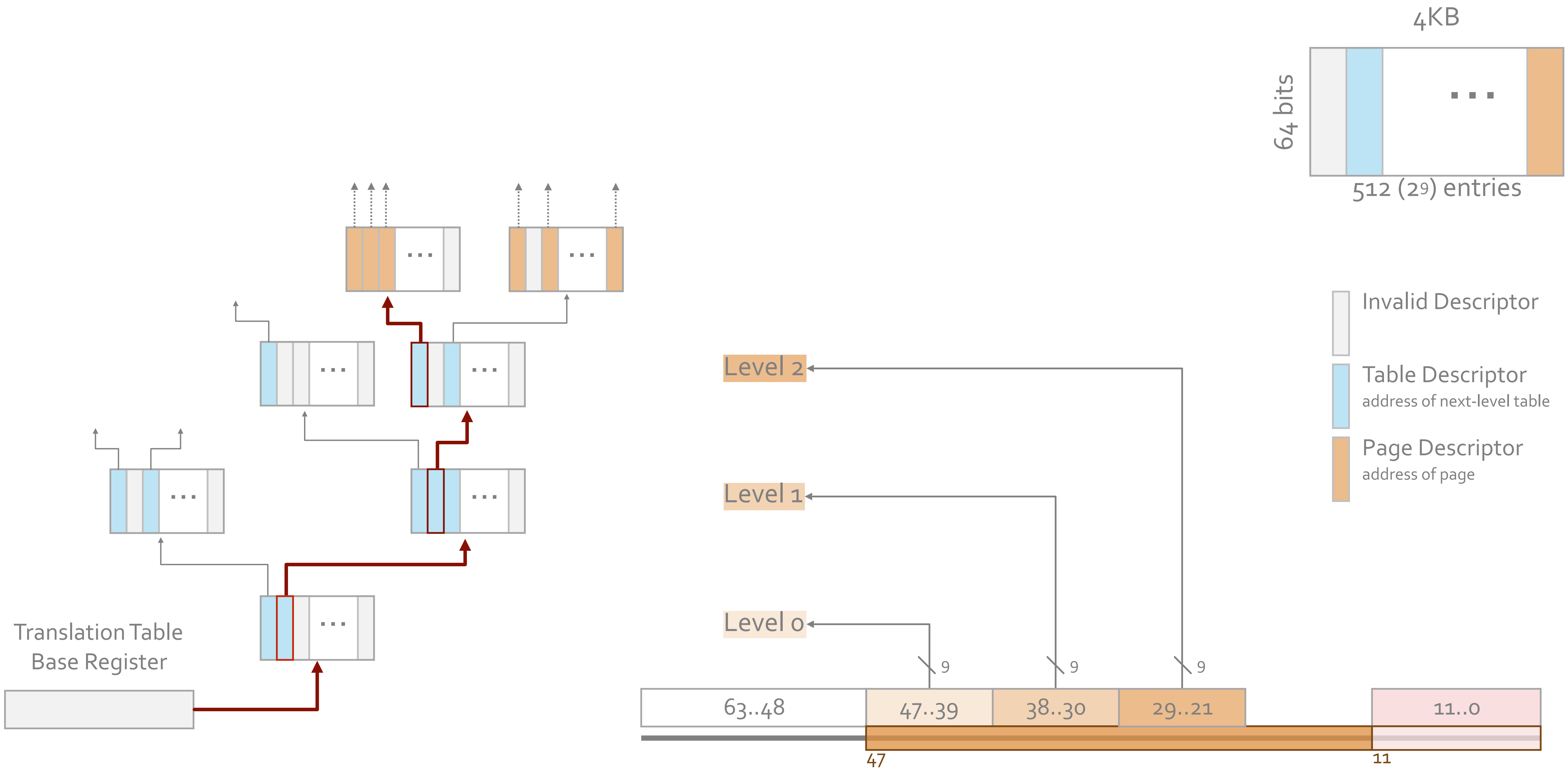

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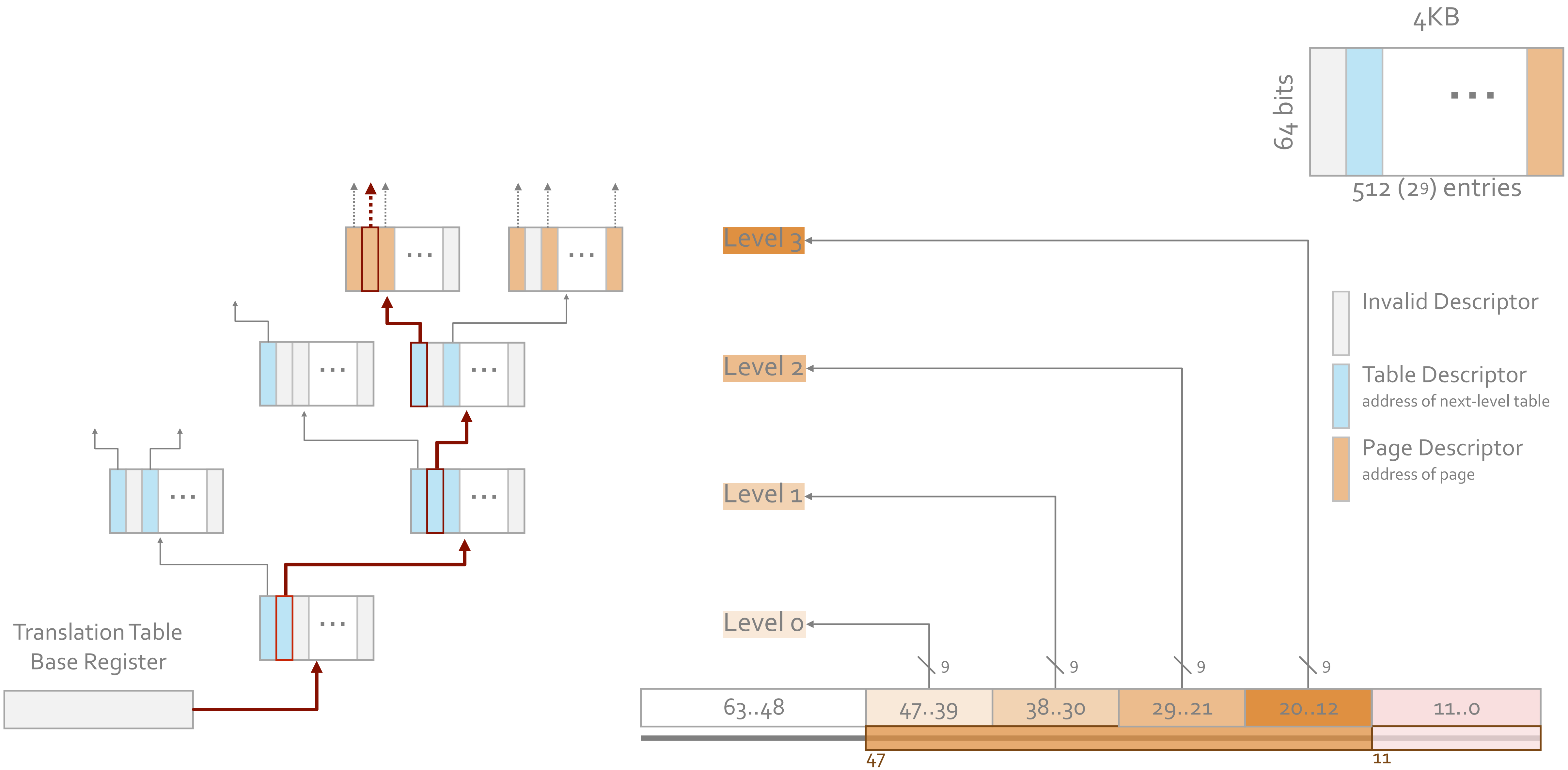

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- Small cache of recently translated addresses
  - Before translating a referenced address, the processor checks the TLB
- What does the TLB give us?
  - Physical page corresponding to virtual page (or that page isn't present)
  - If page mapping allows the mode of access (access control)

What should we do about TLB on context switch?

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- Can flush the TLB (was most popular)
- If HW has process-context identifiers (PCID), don't need to flush: entries in TLB are partitioned by PCID

What about memory isolation for VMs?

How is the memory of VMs isolated?

- Need to isolate process in one VM from the process (or the kernel) of another VM
- Address translation is more complicated
  - VM/Guest VA to VM PA translation is not enough
  - Why not?

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- How do we isolate VMM from guest VMs?
  - Similar to kernel: VMM is assigned VPID 0

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How can you defeat VM/process isolation?

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- Find a bug in the kernel or hypervisor!
  - Kernels are huge and have a huge attack surface: syscalls
  - Developers make mistakes—from forgetting to check and sanitize values that come from user space to classical memory safety bugs.

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  - E.g., Meltdown breaks process isolation

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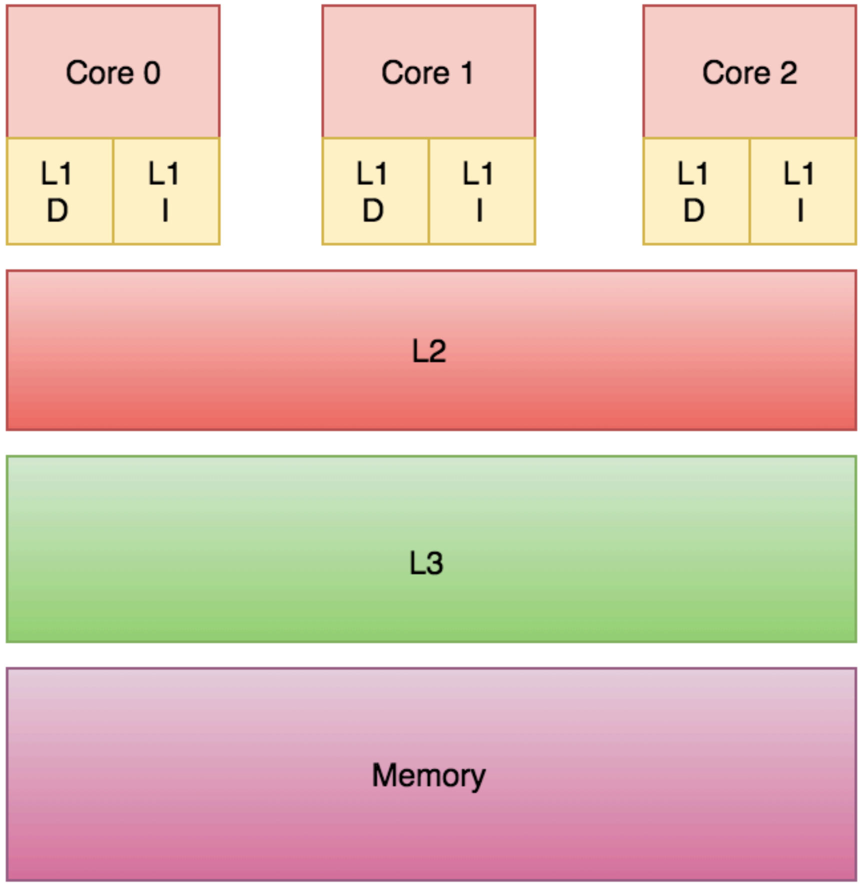
- Find a hardware bug
  - E.g., Meltdown breaks process isolation
- Exploit OS/hardware side-channels
  - Cache-based side channels are the easiest/most popular

What is the cache?

- Main memory is huge… but slow
- Processors try to “cache” recently used memory in faster, but smaller capacity, memory cells closer to the actual processing core

Cache hierarchy

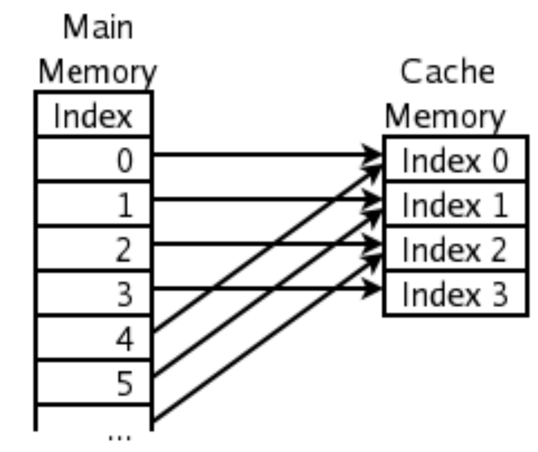
- Caches are such a great idea, let's have caches for caches!
- The close to the core, the:
  - Faster
  - Smaller



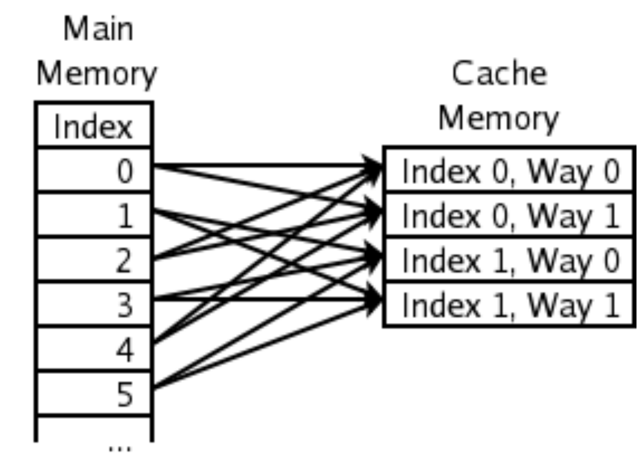
https://en.wikipedia.org/wiki/Cache_hierarchy

How is the cache organized?

- Cache line: unit of granularity
  - E.g., 64 bytes



- Cache lines grouped into sets
  - Each memory address is mapped to a set of cache lines



- What happens when we have collisions?
  - Evict!

https://en.wikipedia.org/wiki/CPU_cache

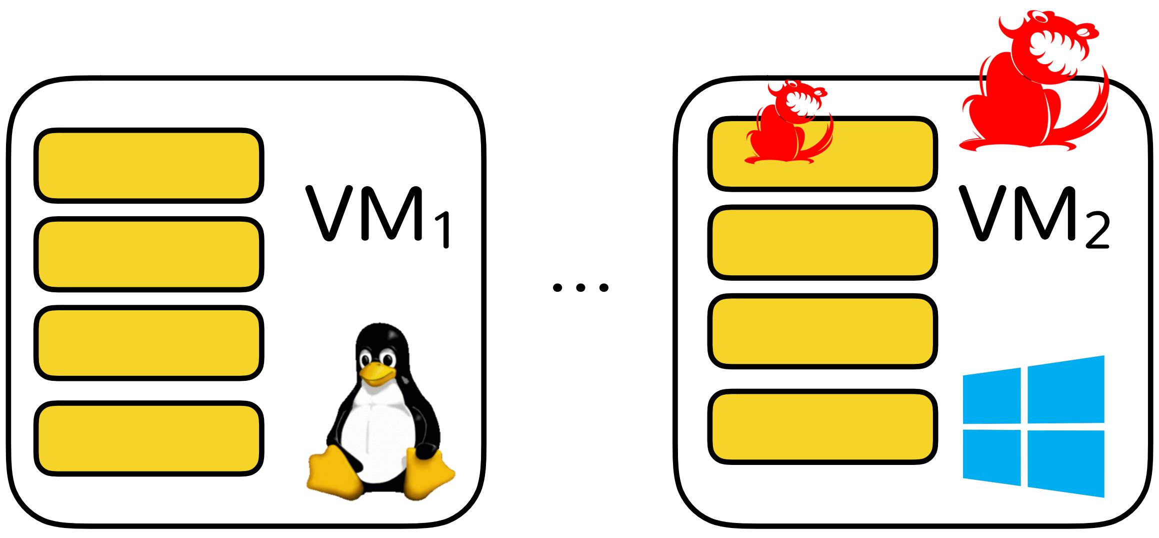
Cache side channel attacks

- Cache is a shared system resource
  - "Just a performance optimization"
  - Not isolated by process, VM, or privilege level
- We abuse this shared resource to learn information about another process, VM, etc.

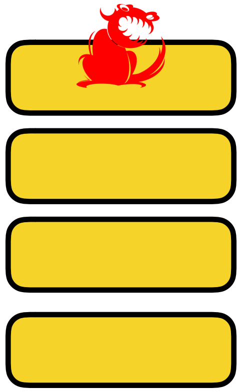
Threat model

- Attacker and victim are isolated (e.g., in separate processes) but on the same physical system
- Attacker is able to invoke (directly or indirectly) functionality exposed by the victim
  - What's an example of this?
- Attacker should not be able to infer anything about the contents of victim memory

Threat model: co-located VM



Threat model: co-located process



What is a side channel?

- Many algorithms have memory access patterns that are dependent on sensitive memory contents
  - What are some examples of this?
- So? If attacker can observe access patterns they can learn secrets

Quite a few approaches

- Evict and Time
- Prime and Probe
- Flush and Reload
- Prime and Abort
- Flush and Flush

Quite a few approaches

- Can work on different caches (L1 to L3)
- Can work on both I$ and D$
- Assumption: VA to PA mapping known to attacker
  - Not all rely on this but can often infer this

Evict & Time

- ➤ Run the victim code several times and time it
- ➤ Evict cache line(s)
- ➤ Run the victim code again and time it

- If it is slower than before, cache lines evicted by the attacker must've been used by the victim
  - ➤ We now know something about the <u>addresses</u> accessed by victim code
  - ➤ In some cases addresses are secret (e.g., AES)

Prime & Probe

- Prime the cache
  - Access many memory locations so that previous cache contents are replaced
- Let victim code run
- Time access to own memory locations (slower means evicted by victim)
  - We now know something about the <u>addresses</u> accessed by victim code

Flush & Reload

(Only for shared memory)

- Flush (specific lines from) the cache
- Let victim code run
- Time access to different memory locations, faster means used by victim
  - We now know something about the <u>addresses</u> accessed by victim code

How practical are these?

- “Our robust and error-free channel even allows us to build an SSH connection between two virtual machines, where all existing covert channels fail.”

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- "Our robust and error-free channel even allows us to build an SSH connection between two virtual machines, where all existing covert channels fail."
    - ➤ Hello from the Other Side: SSH over Robust Cache Covert Channels in the Cloud by Clementine Maurice, Manuel Weber, Michael Schwarz, Lukas Giner, Daniel Gruss, Carlo Alberto Boano, Kay Romer, Stefan Mangard