



CSE 127: Computer Security

Isolation and side-channels

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Some slides adopted from 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

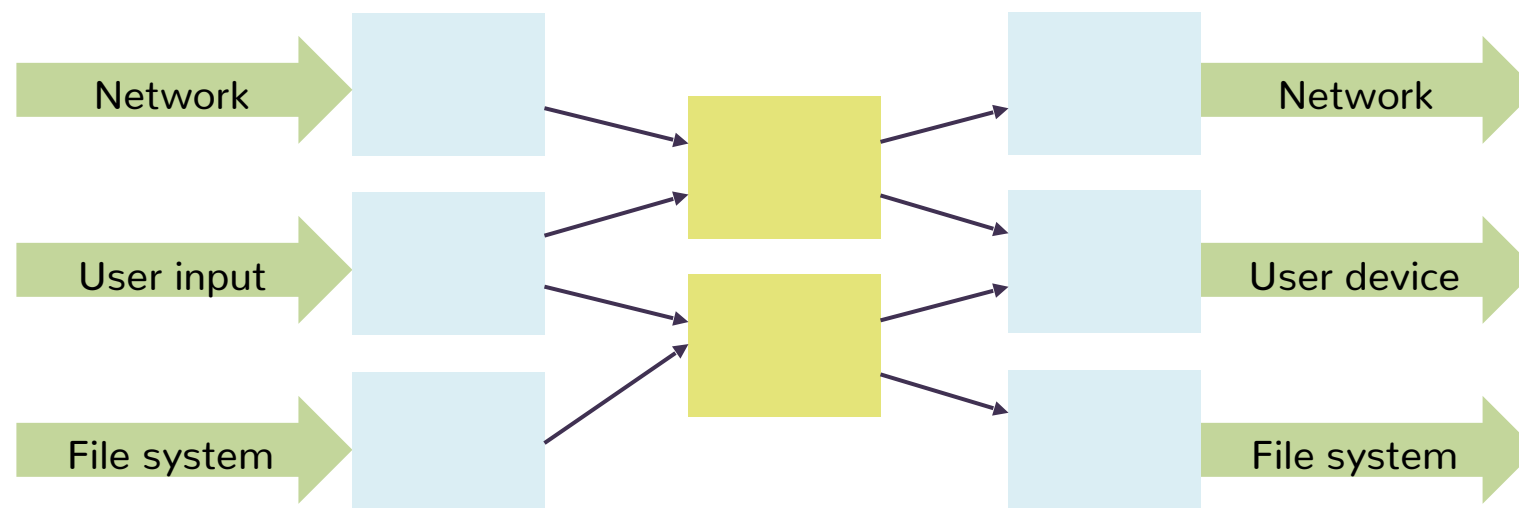
- Principle of least privilege ← almost always
- Privilege separation ← come in pair
- Defense in depth
 - Use more than one security mechanism
 - Fail securely/closed
- Keep it simple

Where have we seen this before?



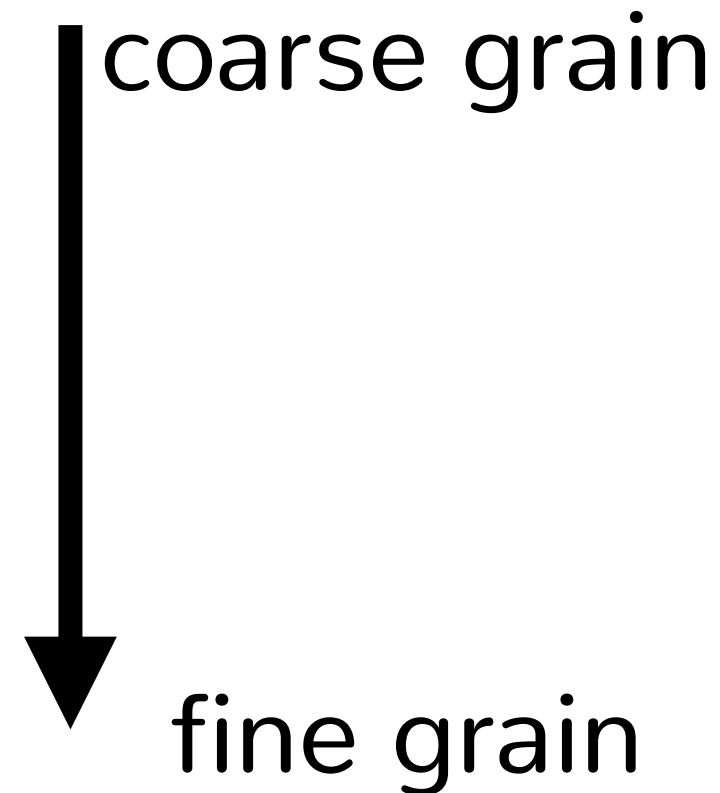
High-level idea

- 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
 - ...



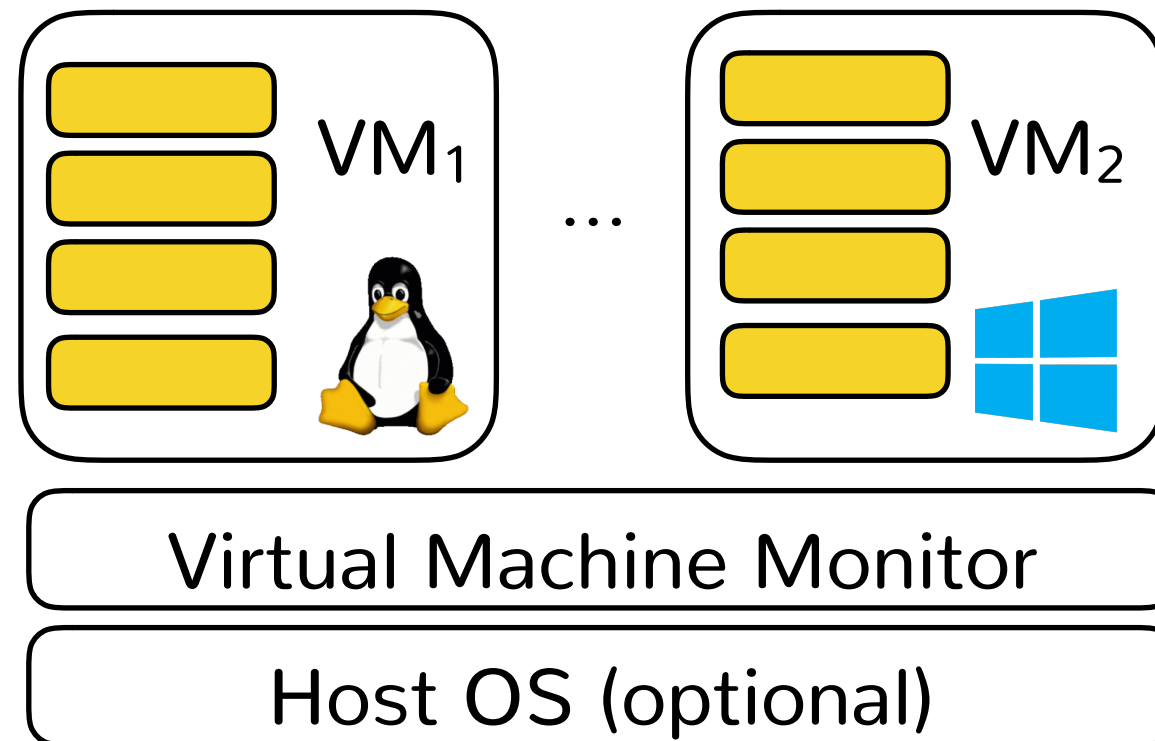
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What is the unit of isolation?

- It depends!
 - Physical Machine
 - Virtual Machine ← most popular,
 - OS Process ← focus in class
 - Library
 - Function
 - ...

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
```

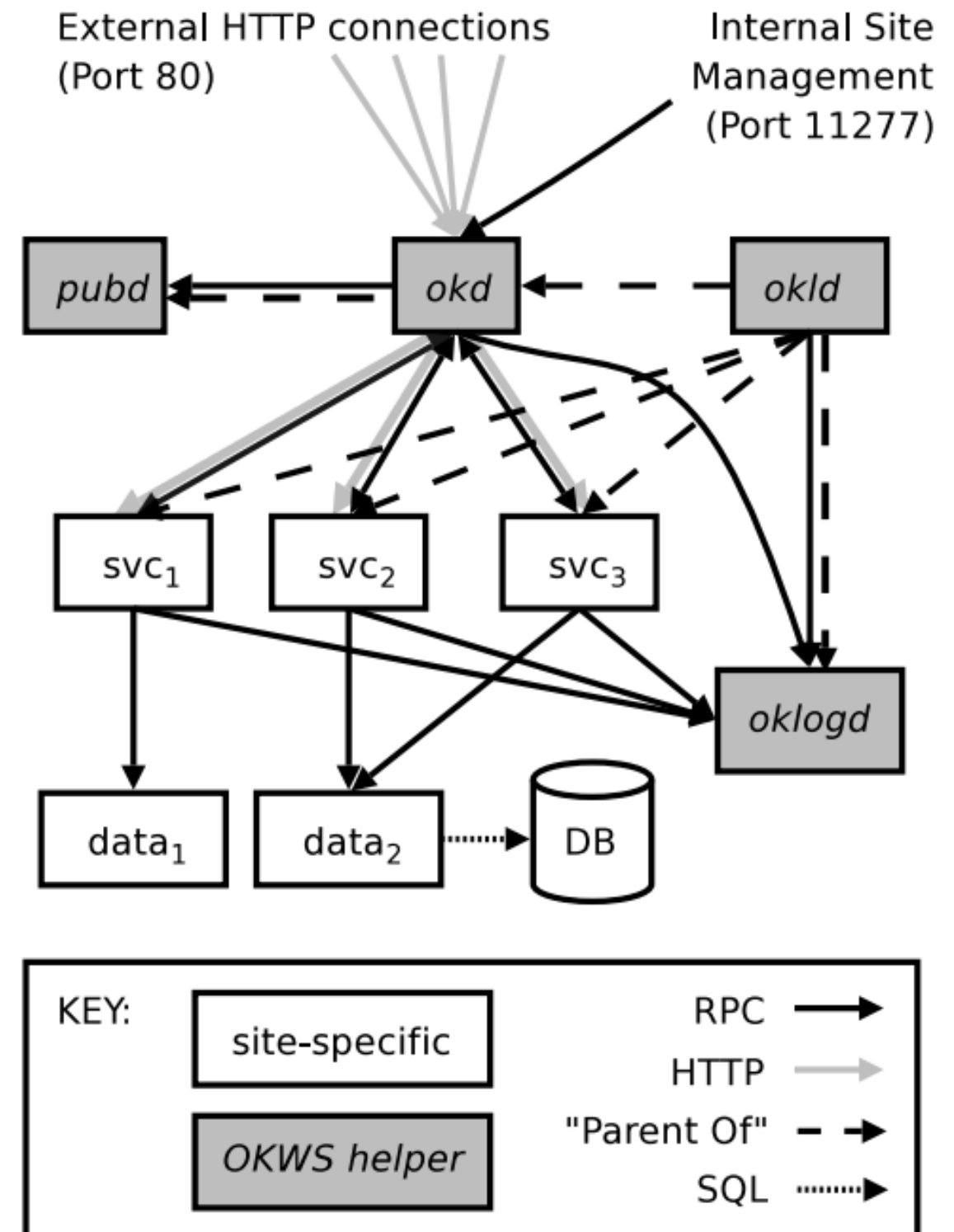
```
drwxrwxrwt 16 root root 700 Feb 6 17:38 /tmp/
```

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

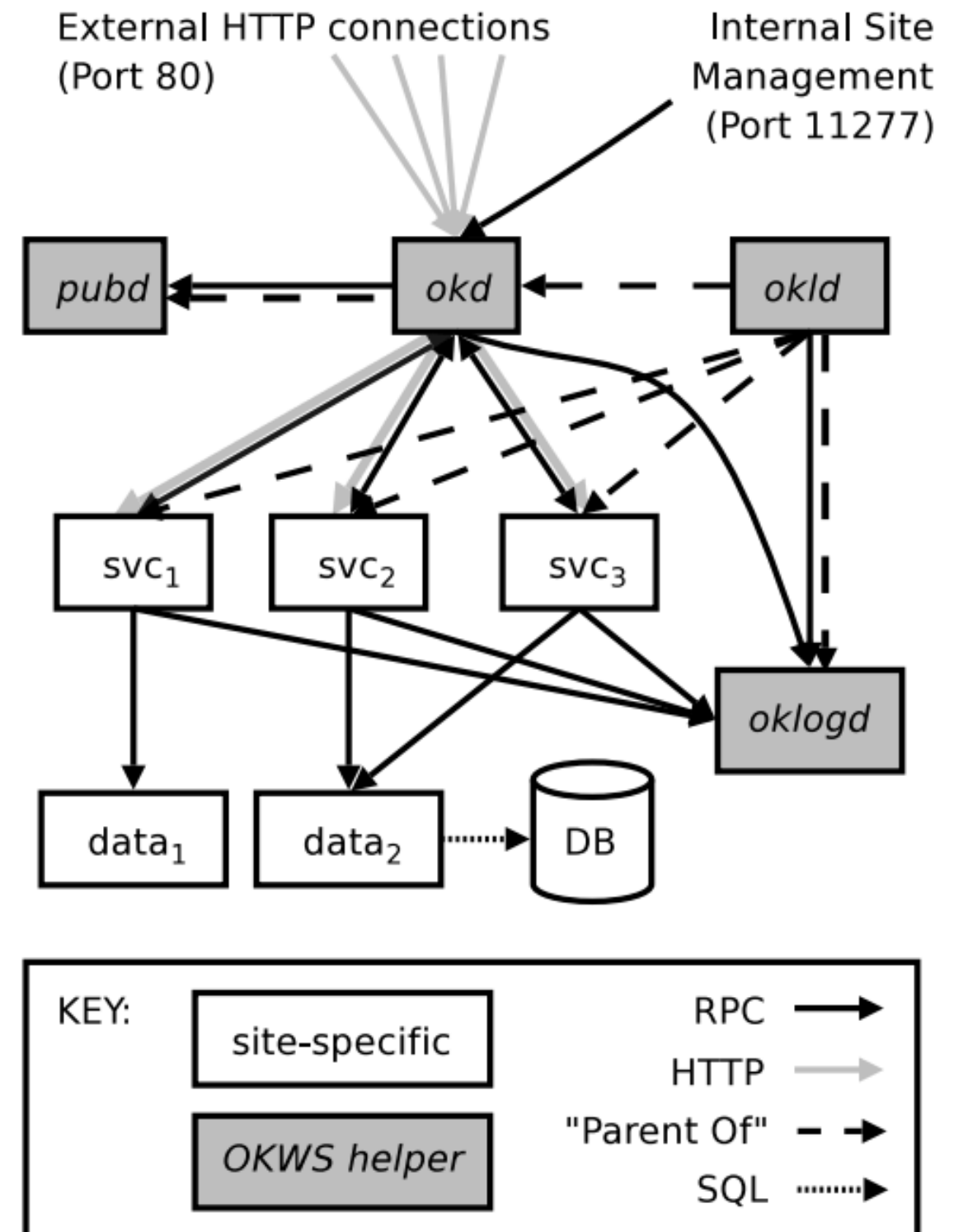
Example 2: OK_{Cupid} WebS_{erver}

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



Example 2: OK_{Cupid} WebS_{erver}

process	chroot jail	run directory	uid	gid
<i>okld</i>	/var/okws/run	/	root	wheel
<i>pubd</i>	/var/okws/htdocs	/	www	www
<i>oklogd</i>	/var/okws/log	/	oklogd	oklogd
<i>okd</i>	/var/okws/run	/	okd	okd
<i>svc₁</i>	/var/okws/run	/cores/51001	51001	51001
<i>svc₂</i>	/var/okws/run	/cores/51002	51002	51002
<i>svc₃</i>	/var/okws/run	/cores/51003	51003	51003

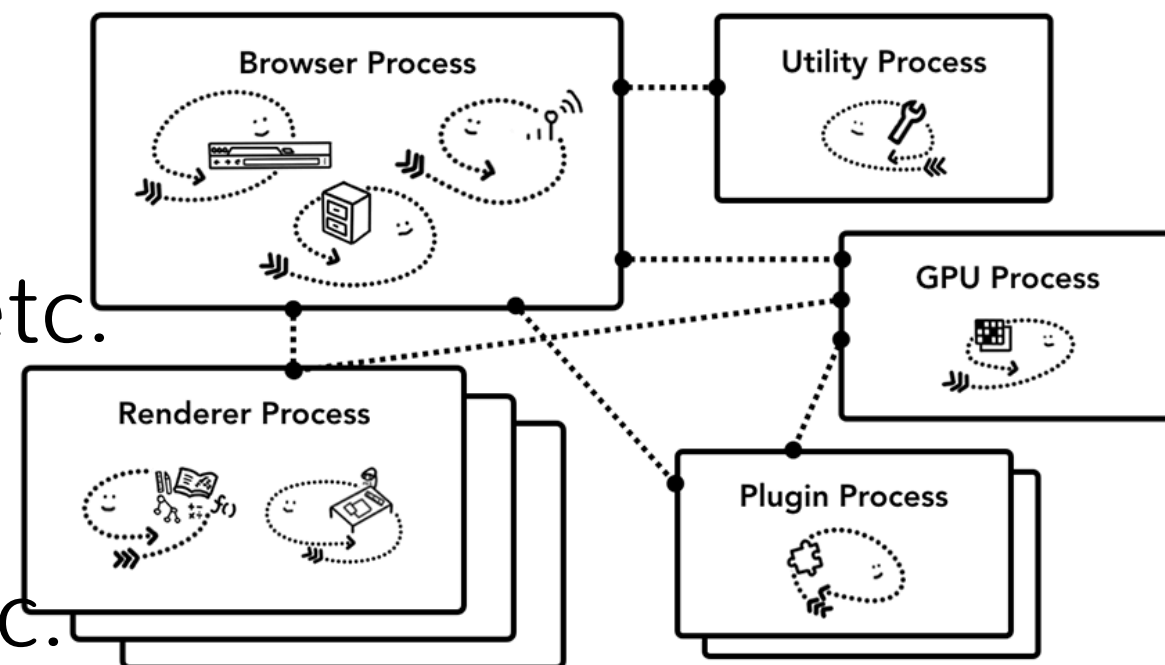


Example 3: Modern browsers

- Browser process
 - Handles the privileged parts of browser (e.g., network requests, address bar, bookmarks, etc.)

- Renderer process

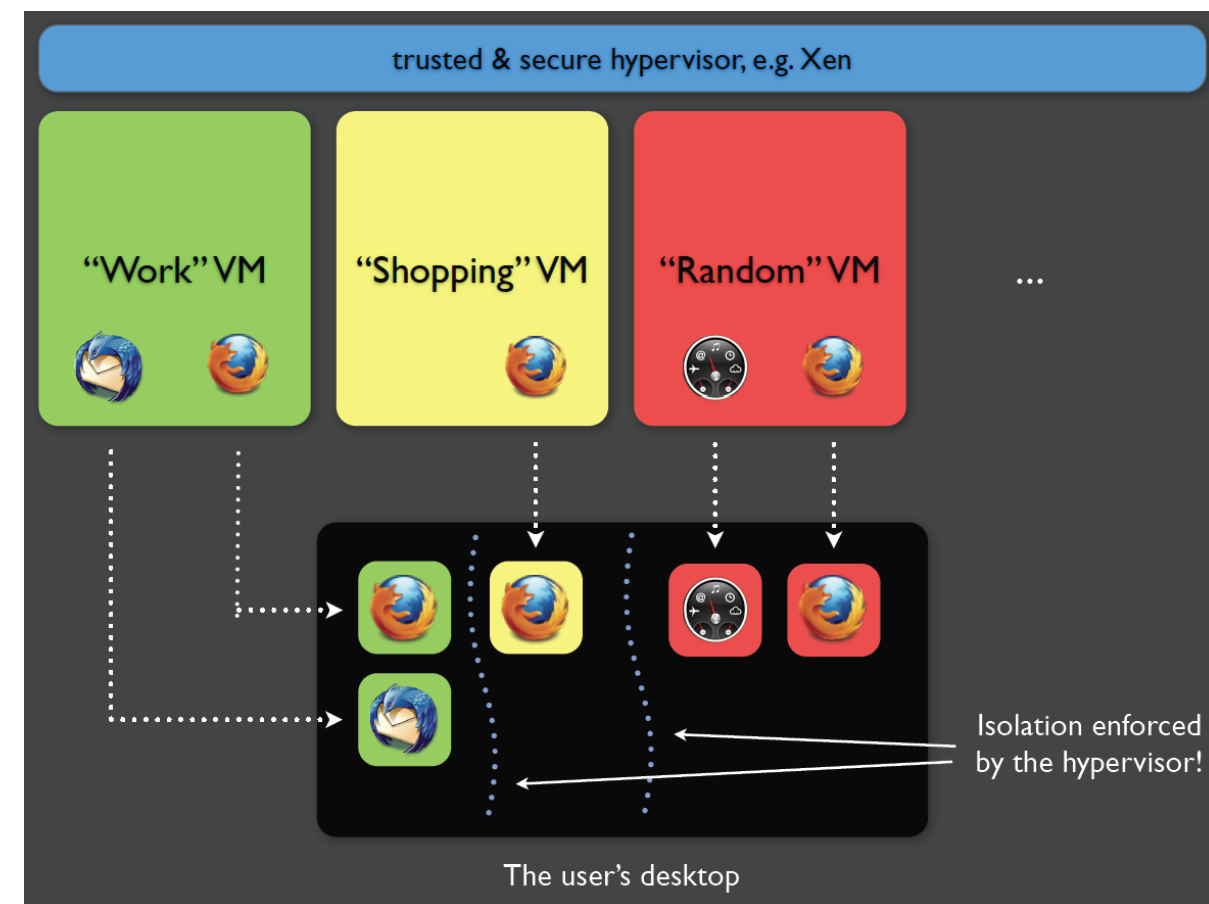
- Handles untrusted, attacker content: JS engine, DOM, etc.
 - Communication restricted to RPC to browser/GPU proc.



- Many other processes (GPU, plugin, etc)

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

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

Many mechanisms at play

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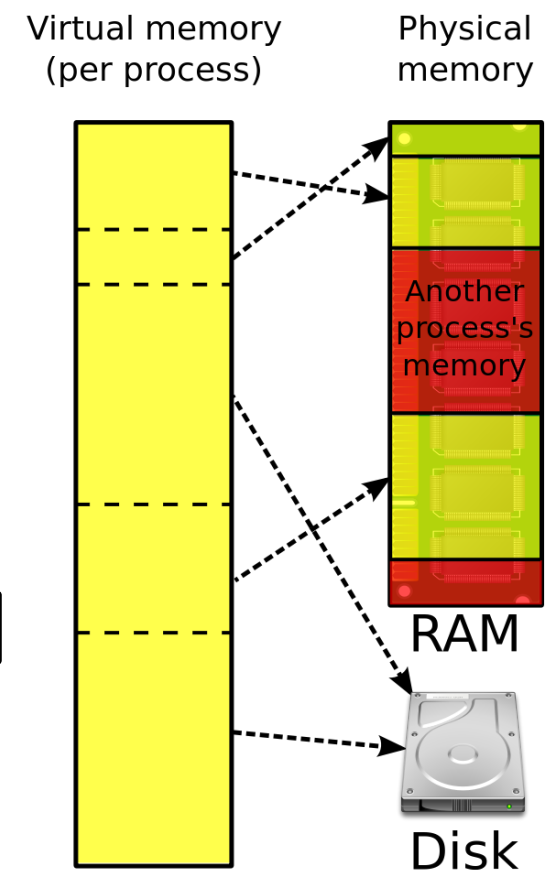
- VM, OS process, and even finer grained in-process isolation all rely on memory isolation
- Why?

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?



When do we do the translation?

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

When do we do the translation?

- 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)

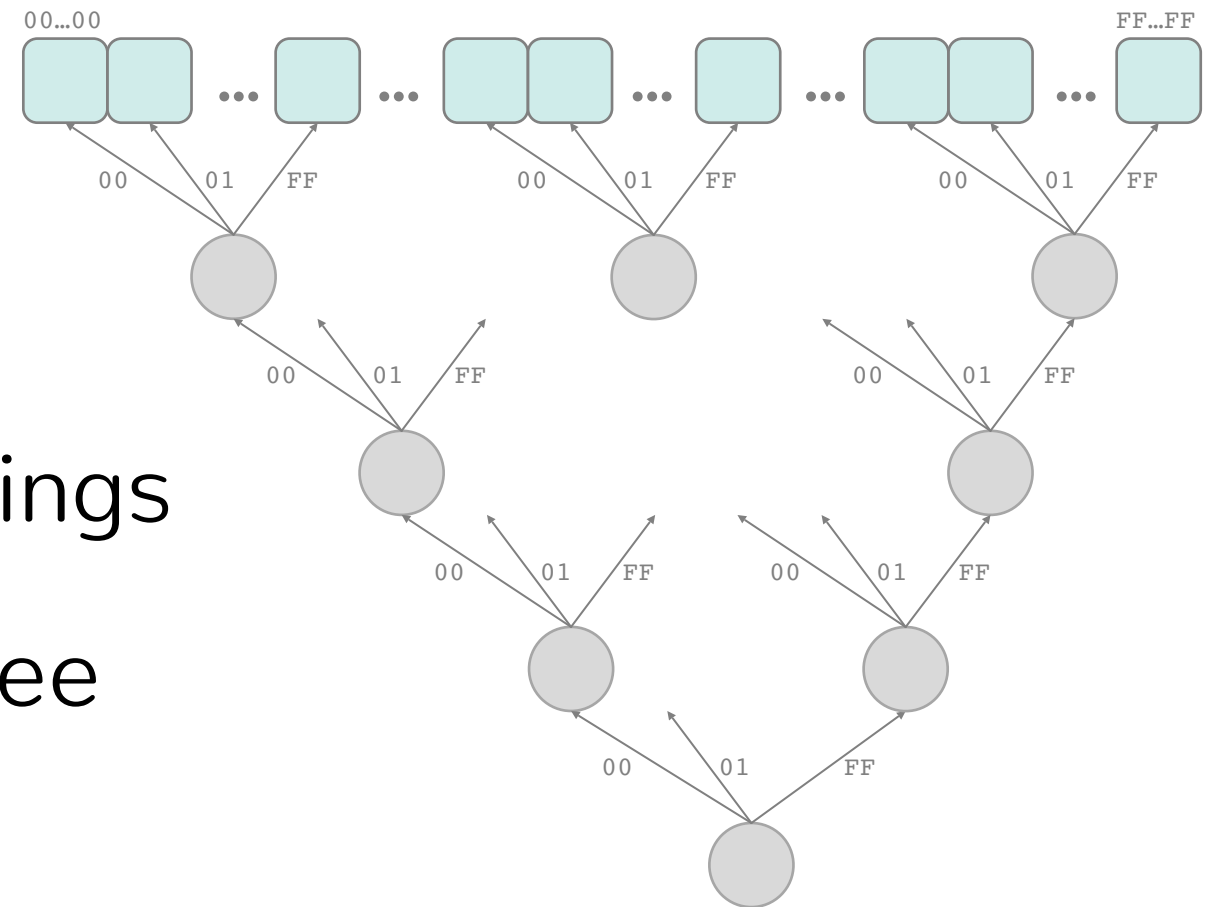


- Page: basic unit of translation
 - Usually $4\text{KB} = 2^{12}$
- How many page mappings?
 - Still too big!
 - $52 \text{ bits} * 2^{52}$ (208 petabytes)

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?

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

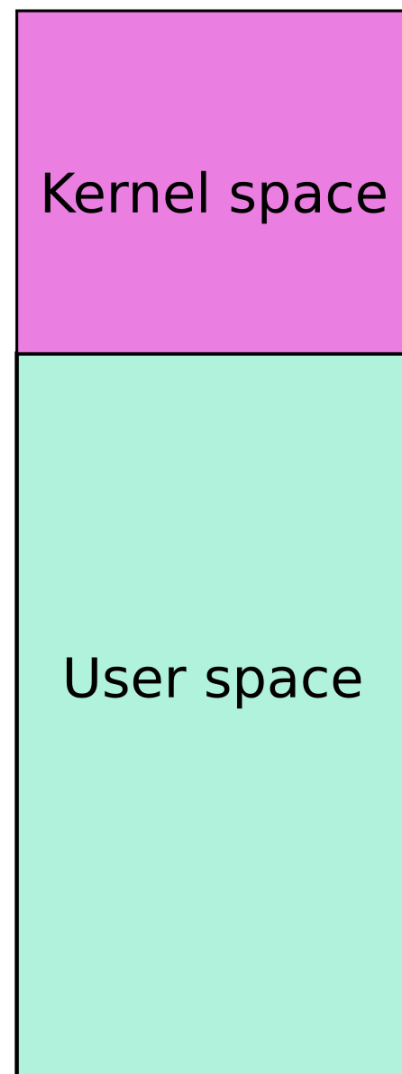
Access control

- 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

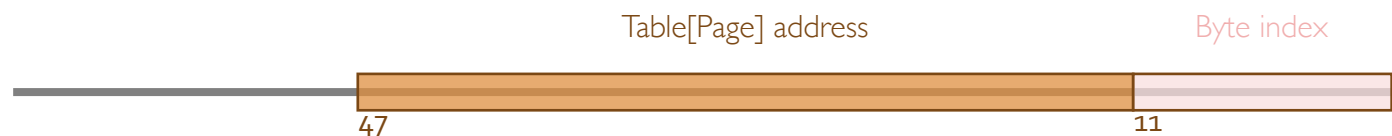
Example of access control usage

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

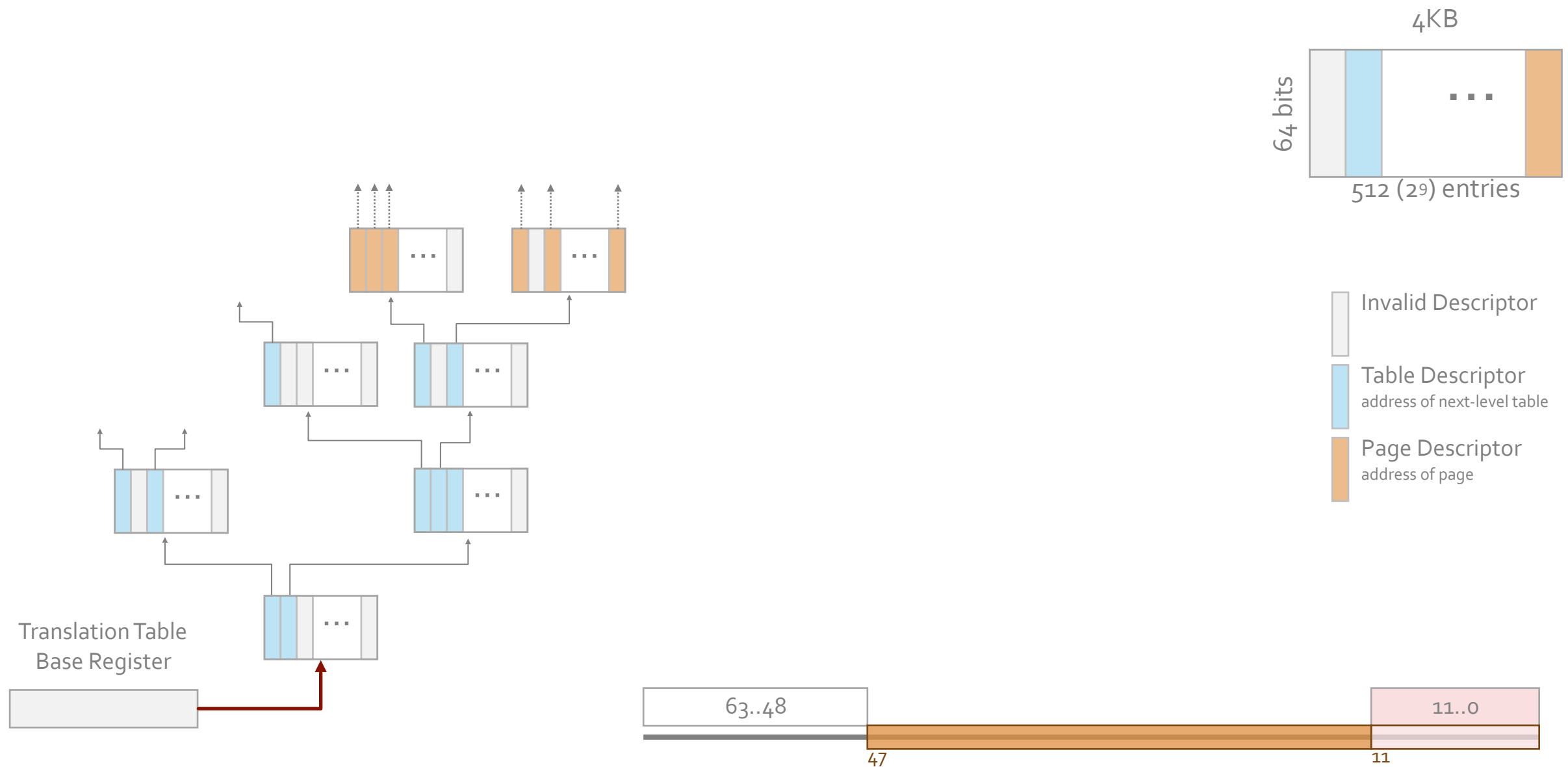


Example of page table walk

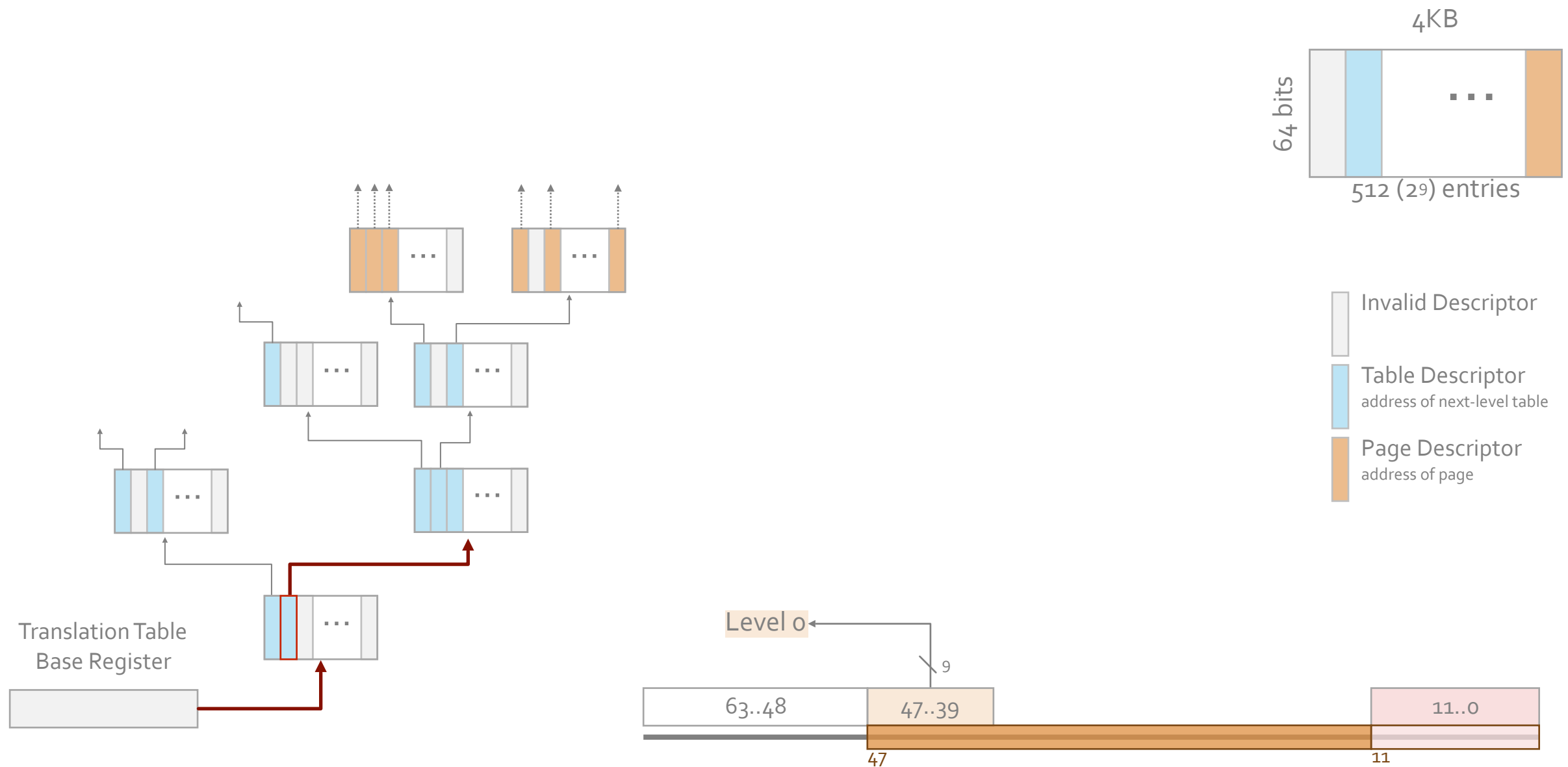
- In reality, the full 64bit address space is not used.
 - Working assumption: 48bit addresses



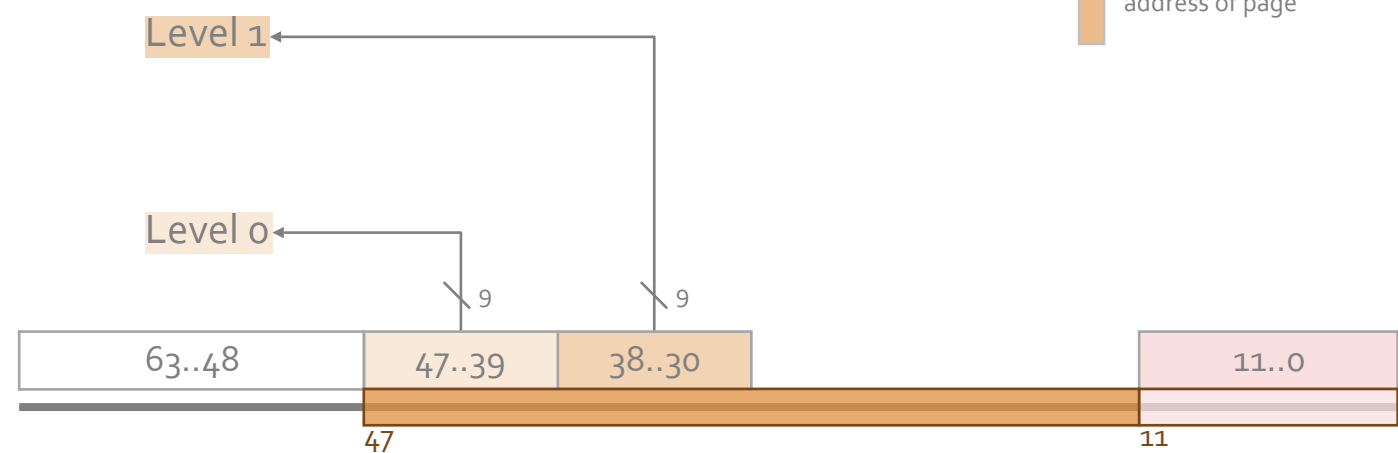
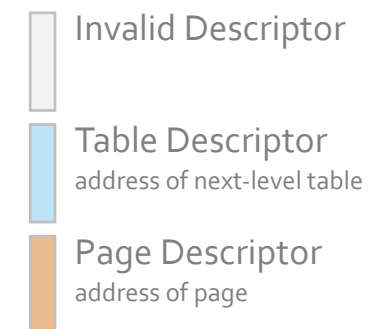
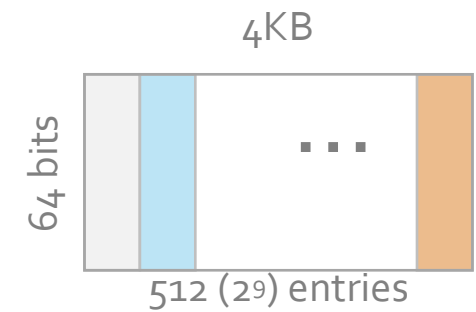
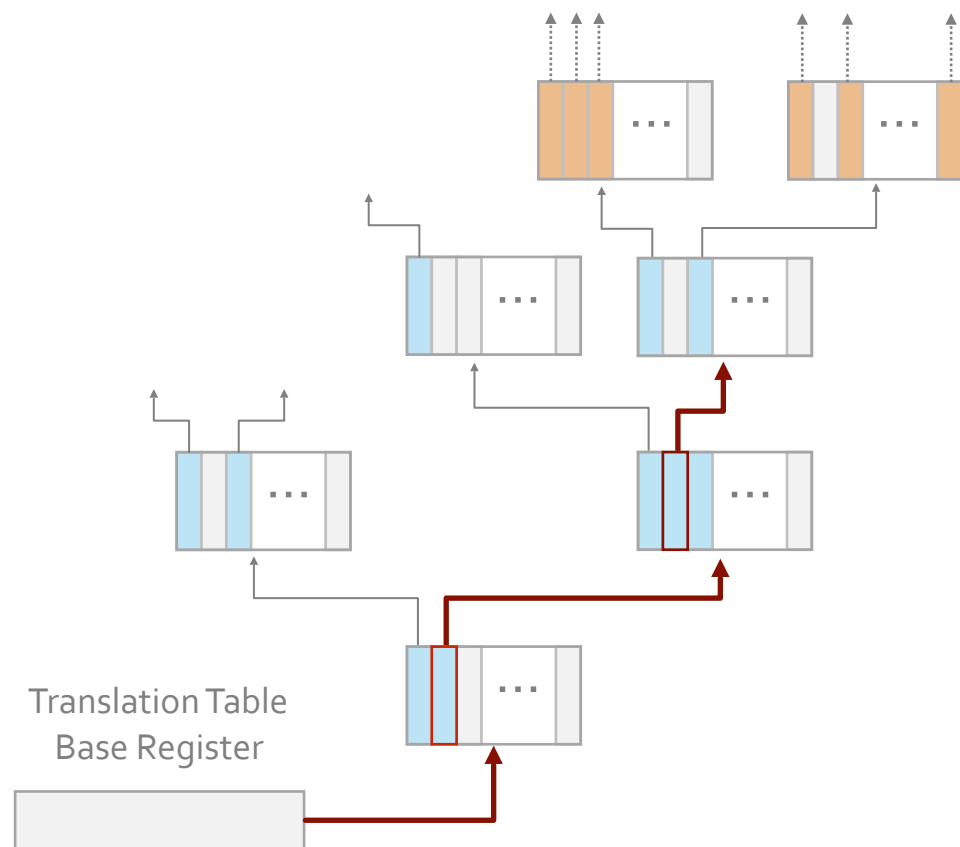
Page table walk



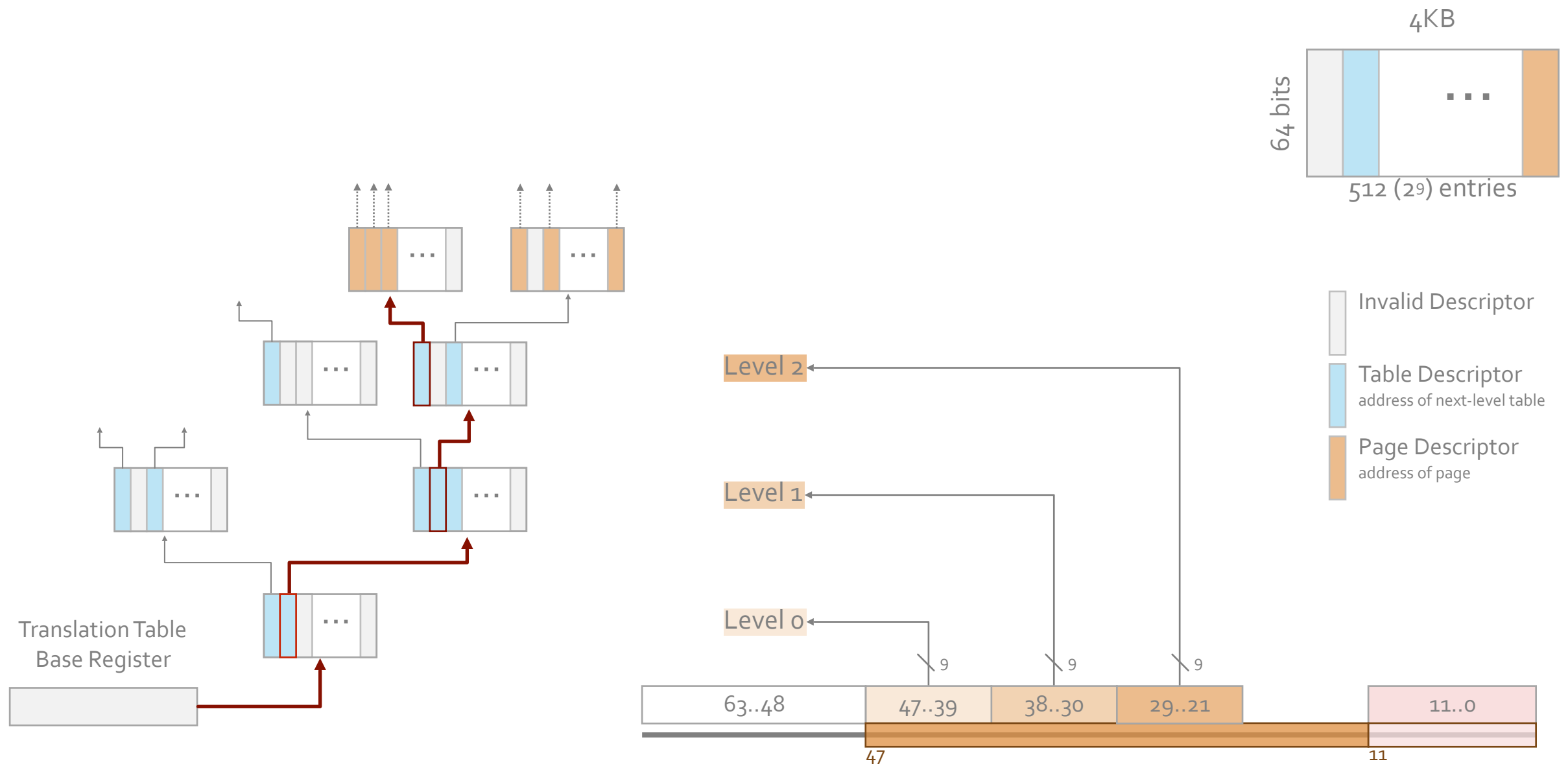
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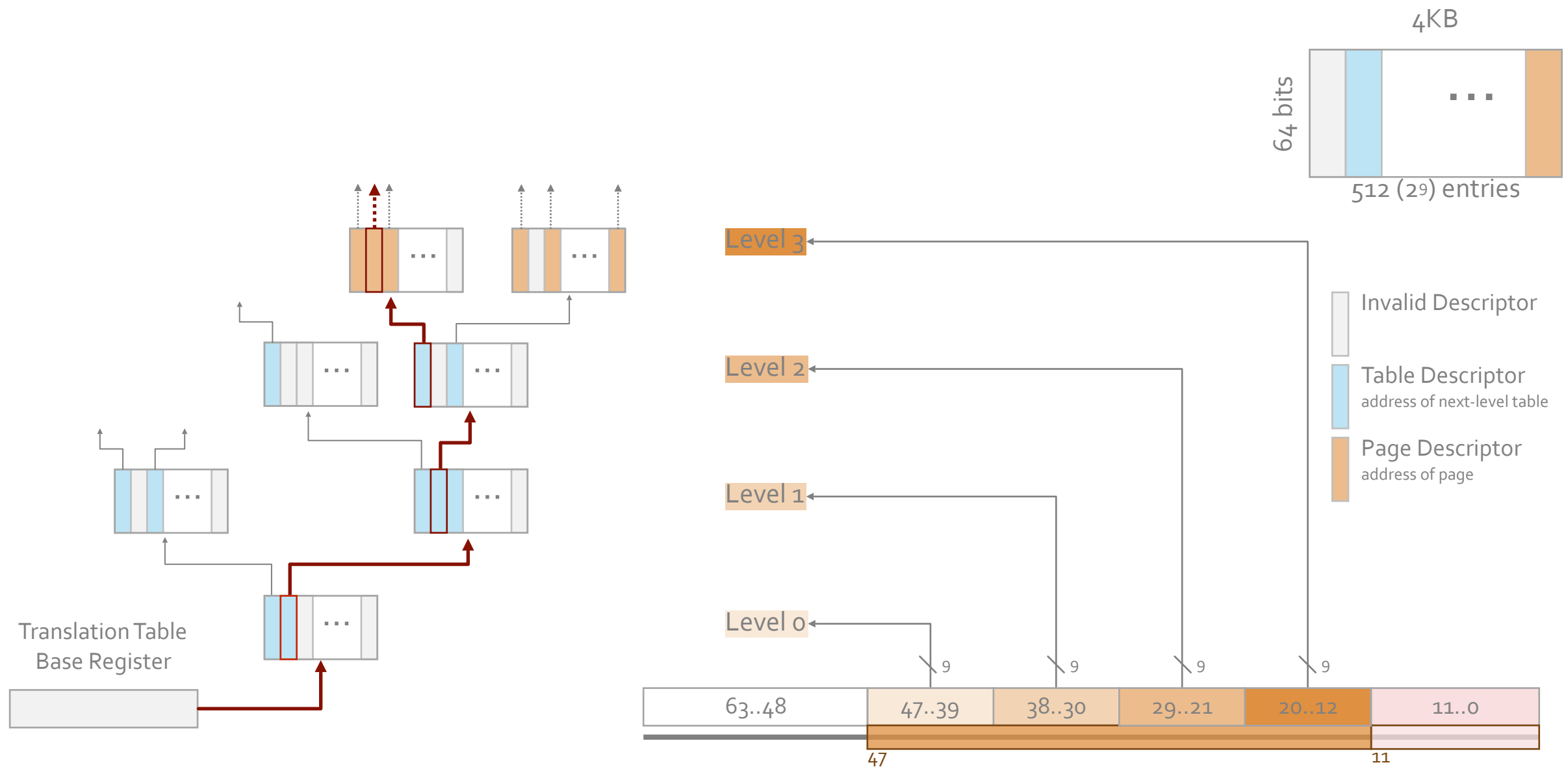
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 - Before translating a referenced address, the processor checks the TLB
- What does the TLB give us?
 - Physical page corresponding to virtual page (or that page isn't present)
 - If page mapping allows the mode of access (access control)

What should we do about TLB on
context switch?

What should we do about TLB on context switch?

- 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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 - Similar to kernel: VMM is assigned VPID 0

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 - Developers make mistakes—from forgetting to check and sanitize values that come from user space to classical memory safety bugs.

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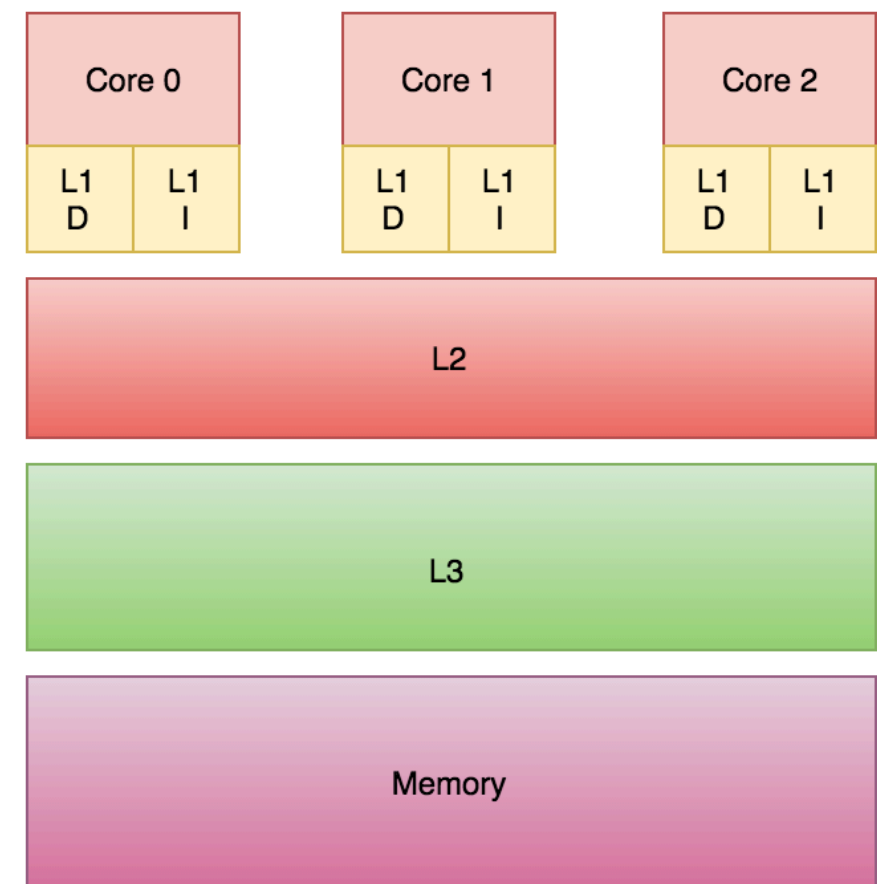
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- Find a hardware bug
 - E.g., Meltdown breaks process isolation
- Exploit OS/hardware side-channels
 - Cache-based side channels are the easiest/most popular

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

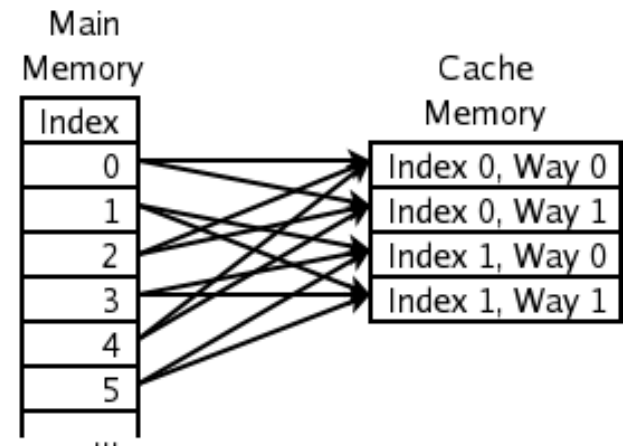
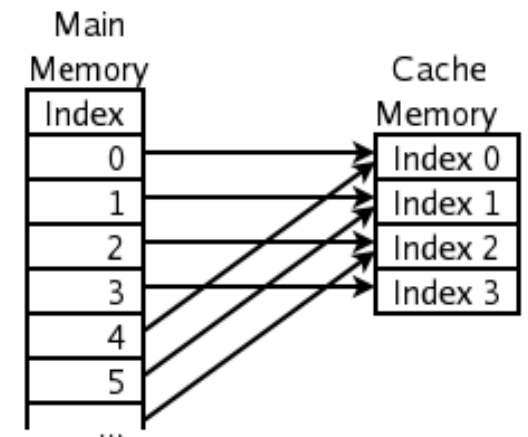
Cache hierarchy

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



How is the cache organized?

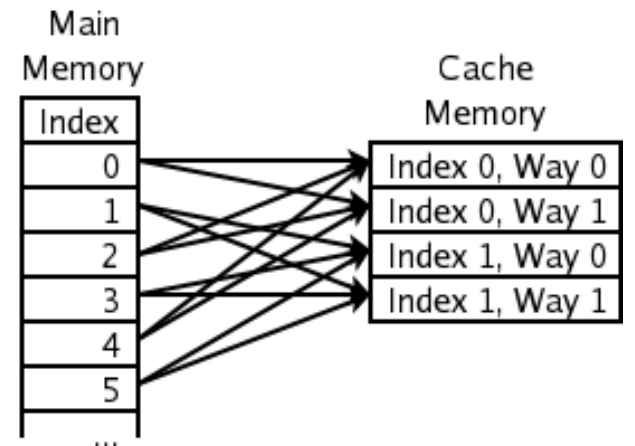
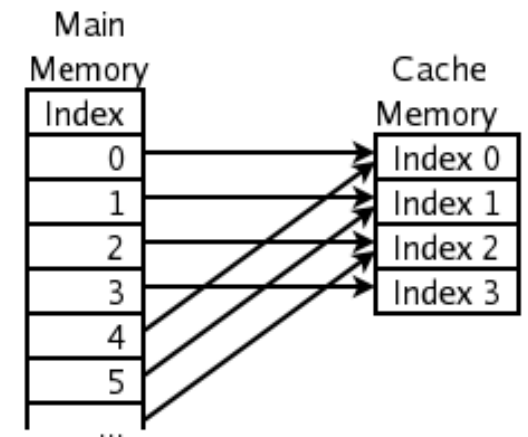
- Cache line: unit of granularity
 - E.g., 64 bytes
- Cache lines grouped into sets
 - Each memory address is mapped to a set of cache lines



- What happens when we have collisions?

How is the cache organized?

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- What happens when we have collisions?
 - Evict!

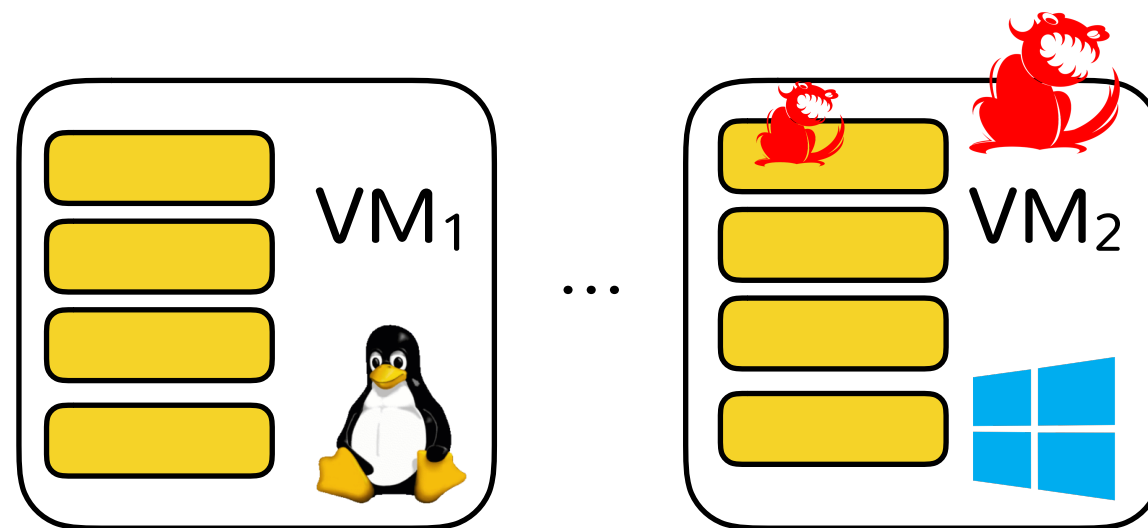
Cache side channel attacks

- Cache is a shared system resource
 - Not isolated by process, VM, or privilege level
 - Archies: “Just a performance optimization”
- Can 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

Evict & Time

- Run the victim code several times and time it
- Evict (portions of) the cache
 - How?
- 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 addresses accessed by victim code

Prime & Probe

- Prime the cache
 - Access many memory locations so that previous cache contents are replaced
- Let victim code run
- Time access to different memory locations, slower means evicted by victim
 - We now know something about the addresses accessed by victim code

Flush & Reload

(Only for shared memory)

- Flush the cache
- Let victim code run
- Time access to different memory locations, faster means used by victim
 - We now know something about the addresses 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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 - 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