SecDir: A Secure Directory to Defeat Directory Side-Channel Attacks

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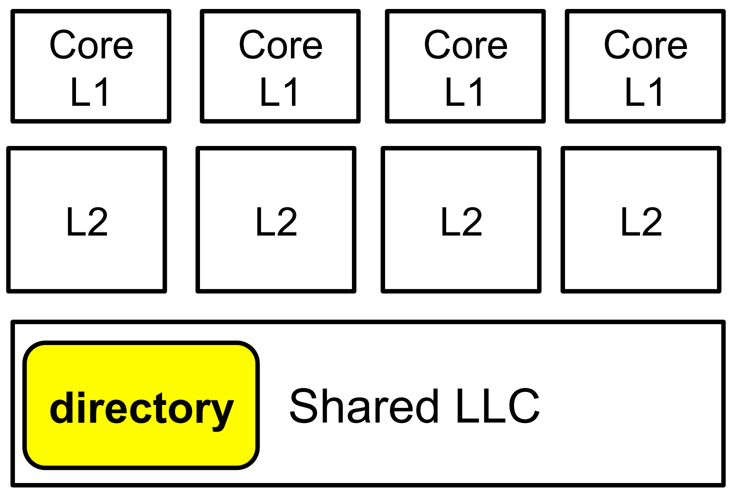
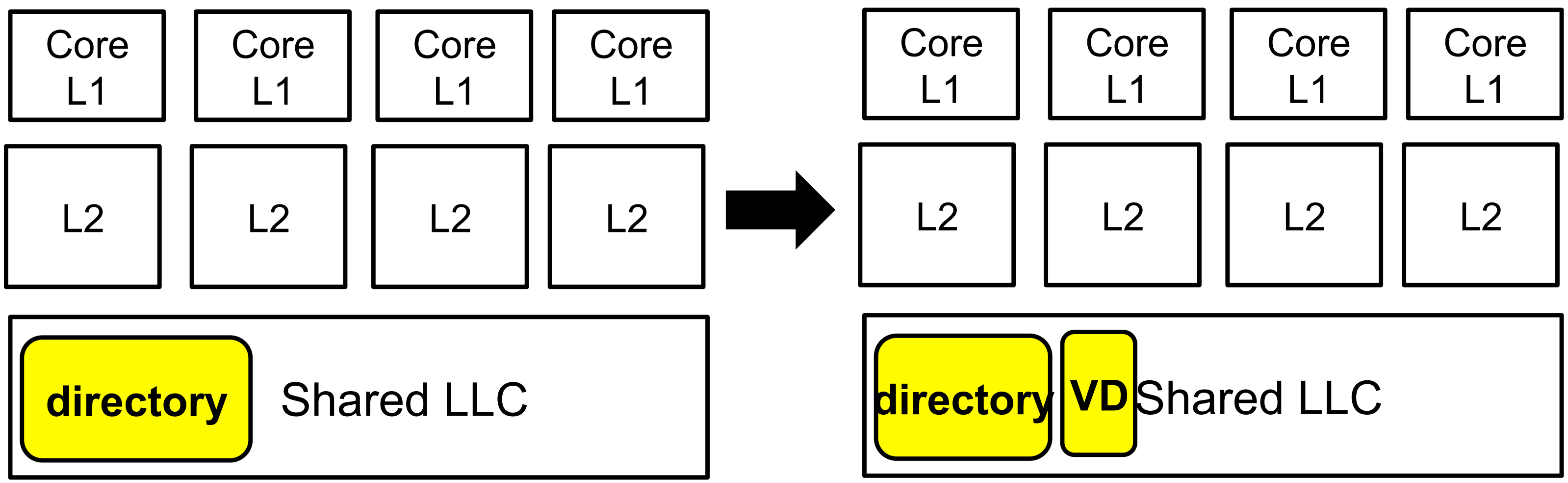
Motivation

- Cache-based side-channel attacks are serious security threats
- Directories are also vulnerable to side-channel attacks [Yan et al, S&P'19]
- It is challenging to design secure directories ***inexpensively*** and ***scalably***



Contribution: A Secure Directory (**SecDir**)

- Key: Block directory interference between processes
- Main idea: Take a portion of the storage used by conventional directory and re-assign it to per-core private directory (Victim Directory)

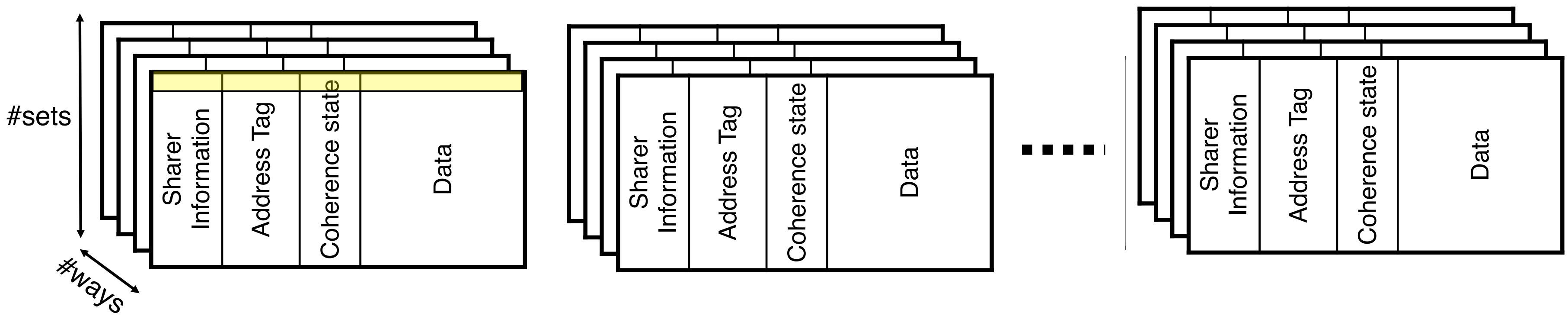


Outline

- Background
- The Problem
- Threat Model
- SecDir Design
- Evaluation

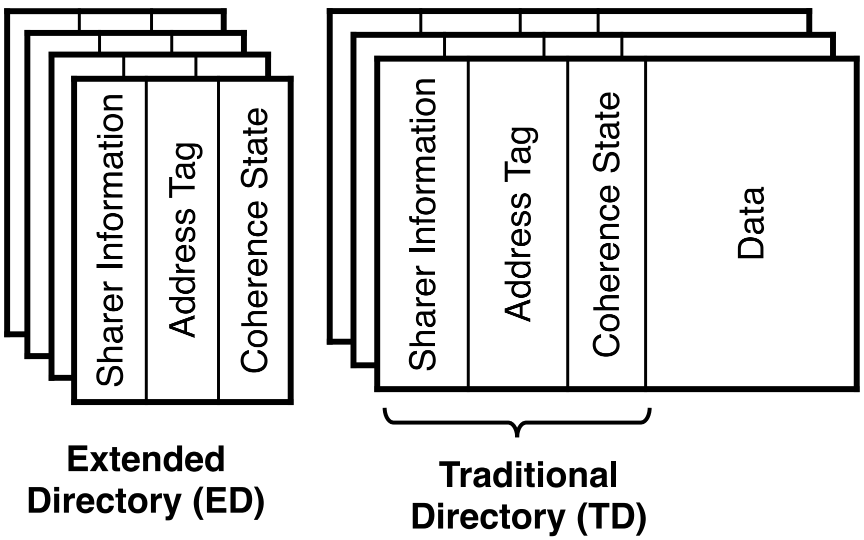
Directory Basics

- Directory is used to keep presence information for cache lines
- A directory entry contains “sharer information”, address tag, coherence state
  - Sharer information: N presence bits, where N is # of cores in machine
- Directory is **partitioned** into slices like LLC using a hash function



Directories in Non-inclusive Cache Hierarchies [Yan et al, S&P'19]

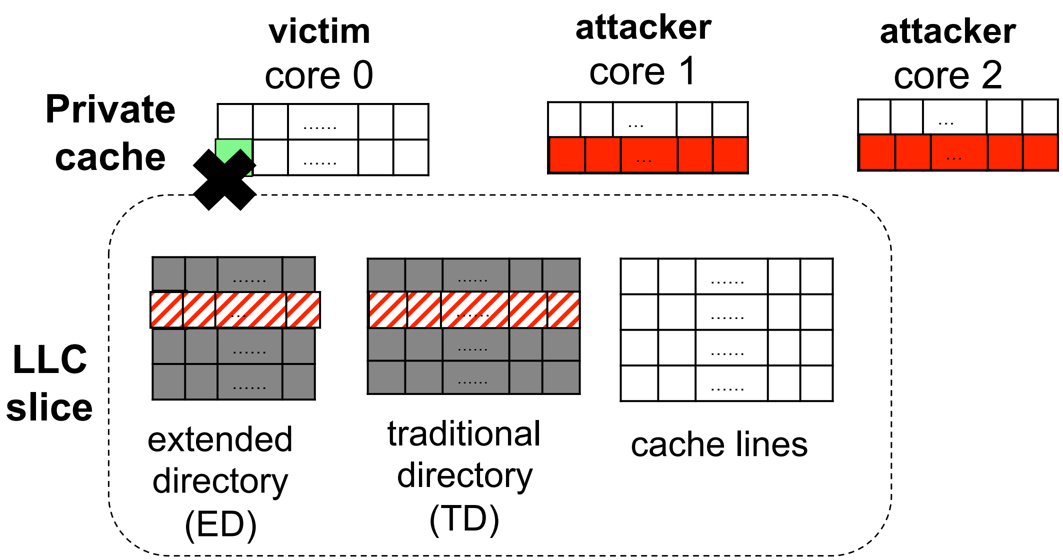
- Trend to have non-inclusive cache hierarchies
- Added **Extended Directory** to hold state for lines that are in private caches (L2)



Slice of Intel Skylake-X/SP LLC and directory

Directories are Vulnerable to Side-Channel Attacks [Yan et al, S&P'19]

- Every single line in the cache hierarchy has a directory entry
- Directory conflict → Evicts victim's directory entry → Evicts victim's cache line
- **Root cause: Limited per-slice directory associativity**



Defense Goal & Threat Model

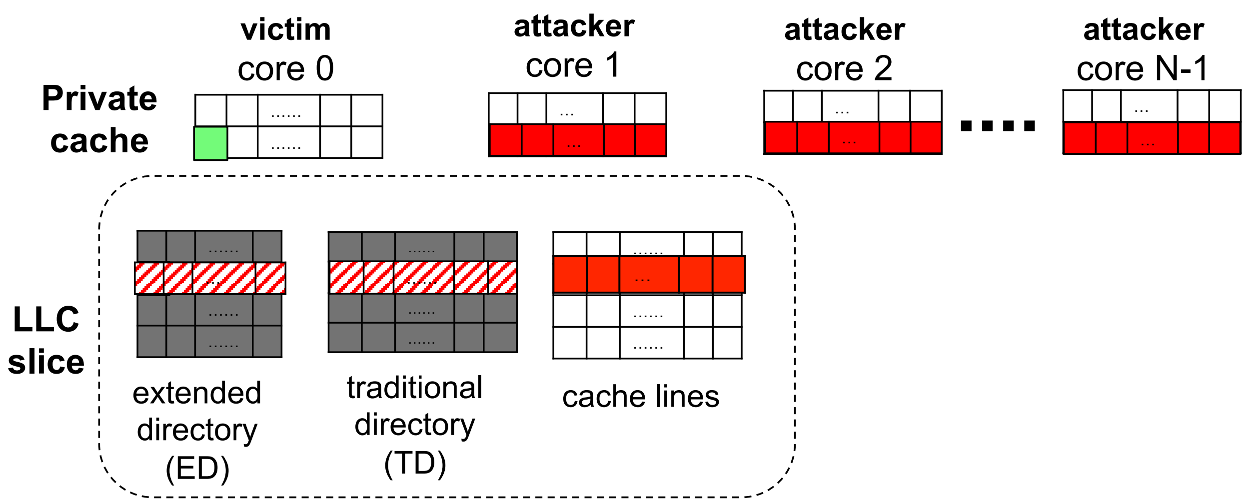
Goal: A secure directory to block directory interference between processes

		Co-location	
		Same-core	**Cross-core**
Attack Strategy	**Active**		**X**
	Passive		

** Victim self-conflicts (e.g. in victim's private structures) are not considered leakage*

Naïve Secure Directory Designs Are Not Scalable

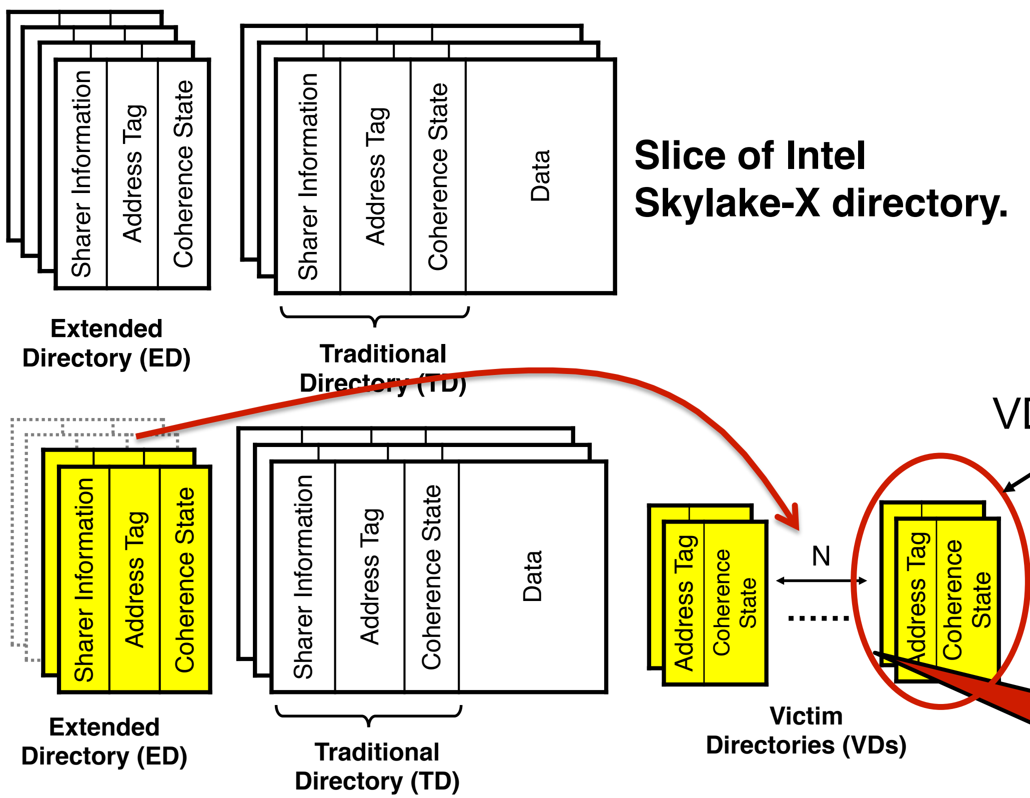
- Strategy I: Substantially increase associativity of each directory slice
  - Unrealistic: Need too high associativity (e.g. > 300 for a 22-core machine)



Naïve Secure Directory Designs Are Not Scalable

- Strategy I: Substantially increase associativity of each directory slice
  - Unrealistic: Need too high associativity (e.g. > 300 for a 22-core machine)
- Strategy II: Way-partition the directory slice (at least 1 way per security domain)
  - Unacceptable: Inflexible, low performance and limiting

Our proposal: **SecDir**



Slice of Intel Skylake-X directory.

Main idea: Take part of the storage used by conventional directory and re-assign it to per-core private directories: **Victim Directories (VD)**

Slice of SecDir.

Provide per-core isolation

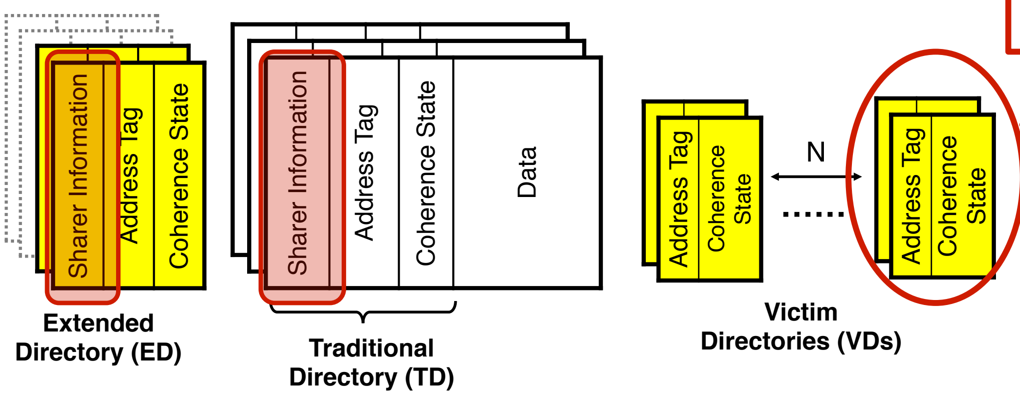
Our proposal: **SecDir**

- Provides inexpensive and **scalable** isolation
- Uses modest storage

N: number of cores
S: number of slices

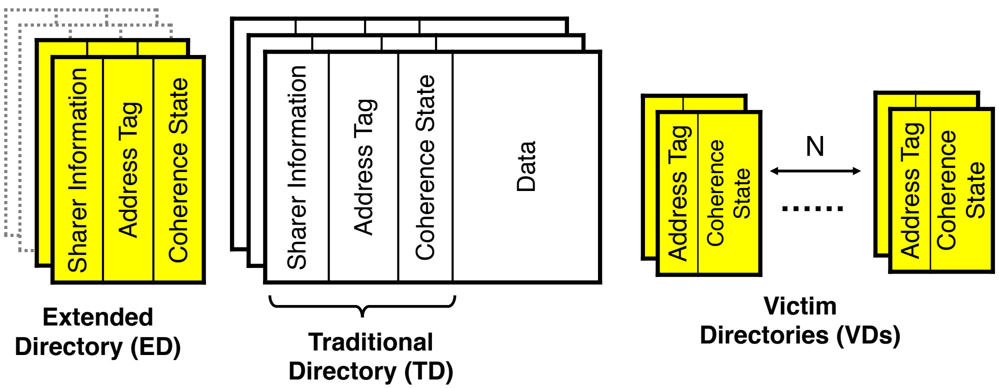
VD bank size = $1/N \times$ L2 size
Total VD per core = $S \times 1/N \times$ L2 size
= L2 size

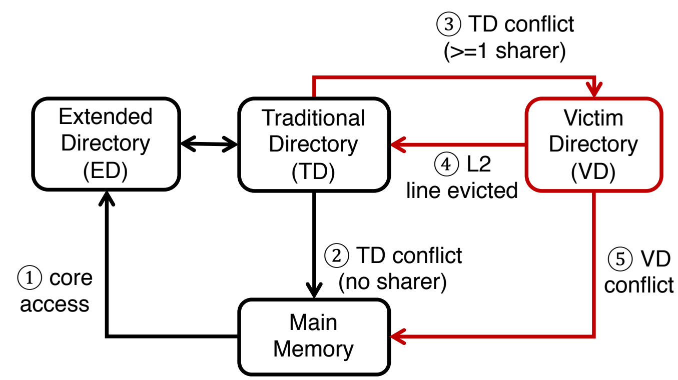
VD size for a core is **constant** irrespective to *N*



SecDir Blocks Directory Interference

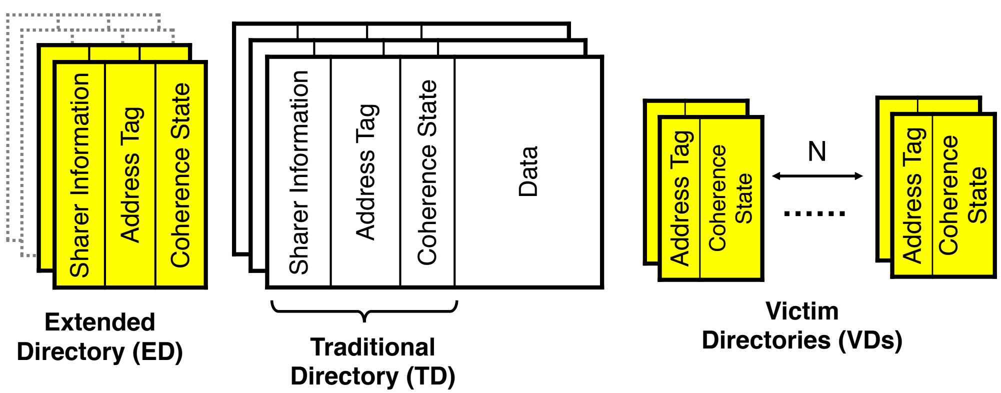
- Consider each directory transition and its security implications

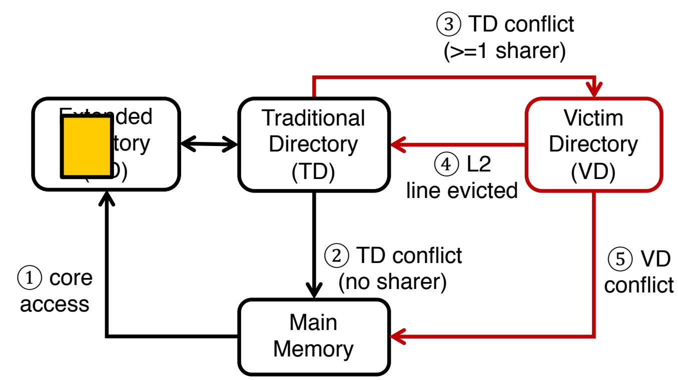




SecDir Blocks Directory Interference

- Consider each directory transition and its security implications
  - ED←→ TD: Line location does not change; *no leakage*





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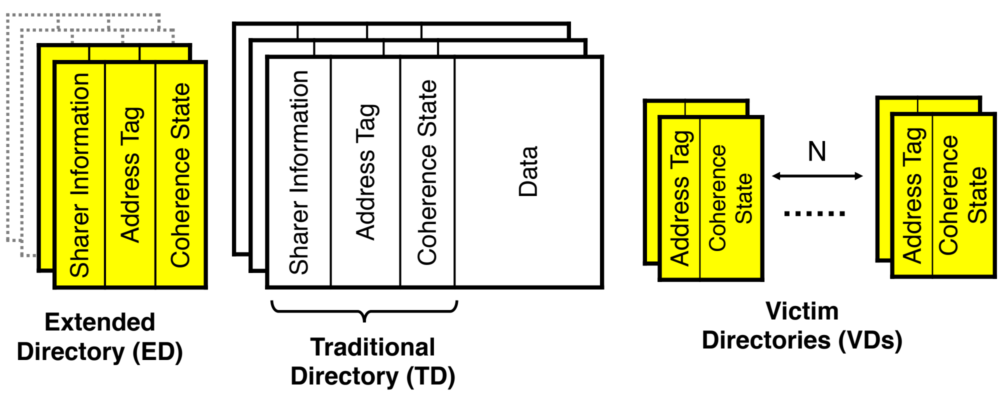

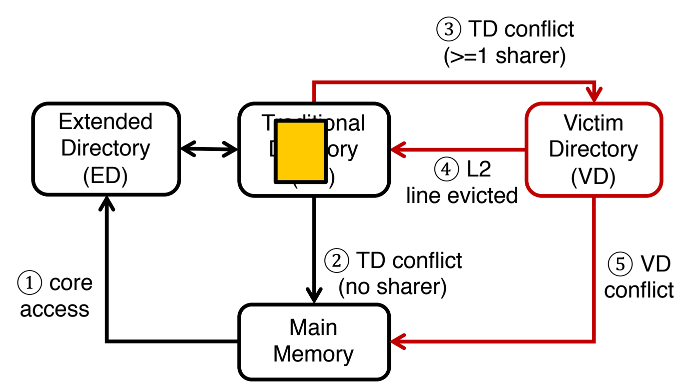

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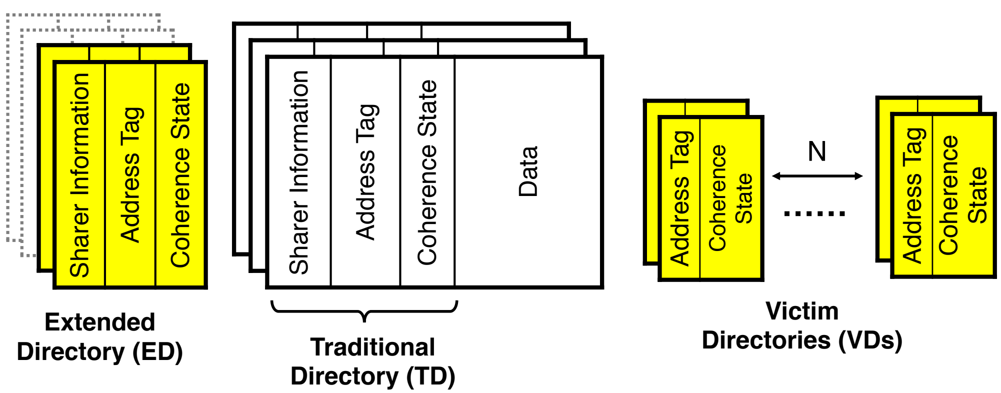
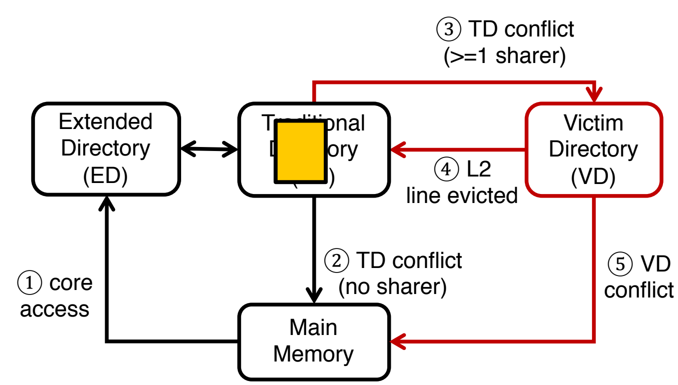
  - ③ TD → VD: Line location does not change. VD of every sharer receives a copy. *no leakage*





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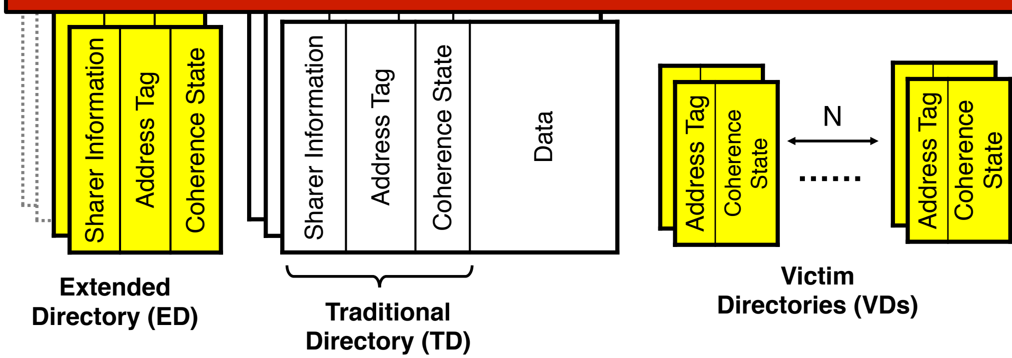
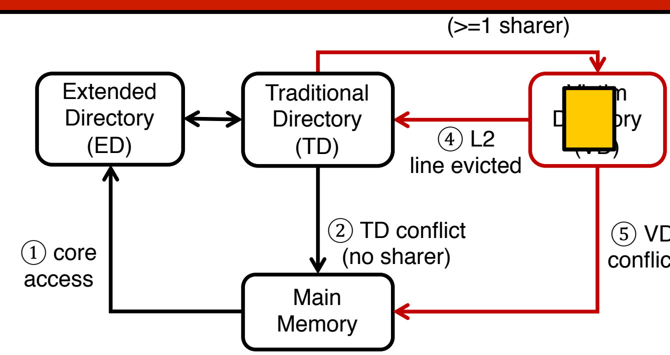
SecDir prevents cache line evictions due to attacker induced directory interference





SecDir Optimizations

- Provides high associativity in VD
  - *VD supports Cuckoo hashing to increase effective* VD associativity
- Delivers efficient directory lookup
  - *Uses a “Early-Miss” (EM) bit* → skips many VD lookups

Experimental Setup and Benchmarks

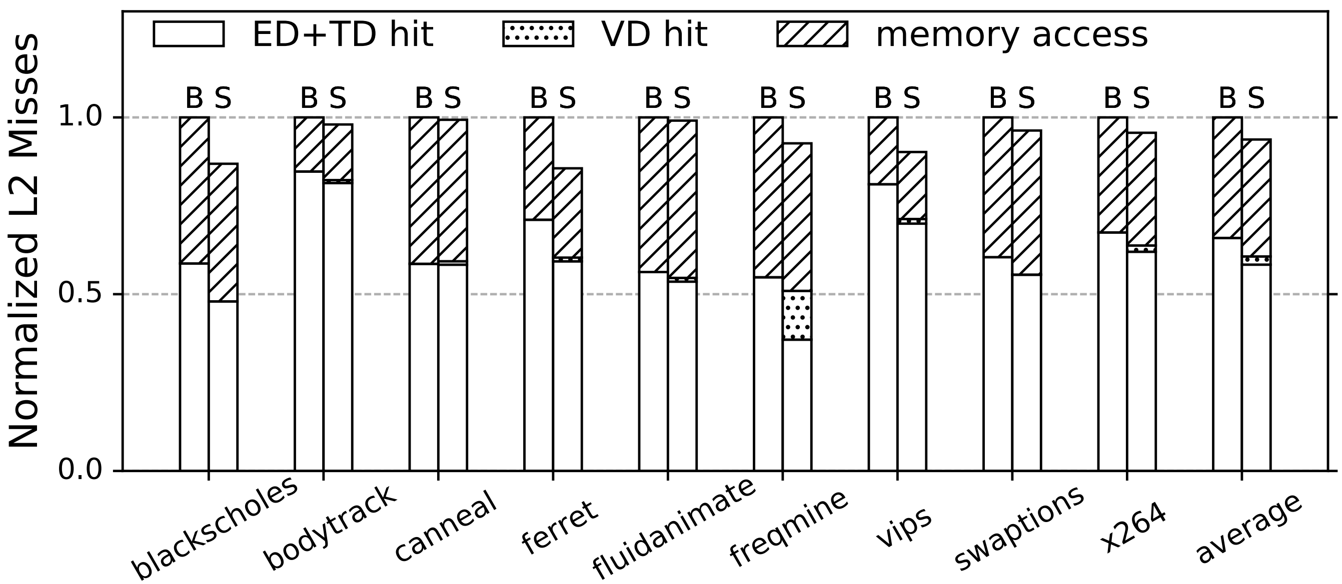
- Configurations: two 8-core designs
  - Baseline: Use Skylake-X directory (ED associativity=12)
  - SecDir: Take 4 ways from the ED to create the VD
    - Remaining ED is as big as L2
    - Augment VD in each slice with 28.5KB → per-core VD is as big as L2

- Benchmarks:
  - SPEC Mixes: Groups of programs running 8 threads, with different characteristics
  - PARSEC: Individual parallel programs running with 8 threads

Evaluation Results – PARSEC

- ED/TD conflicts migrate entries to VD without evicting L2 lines → fewer L2 misses

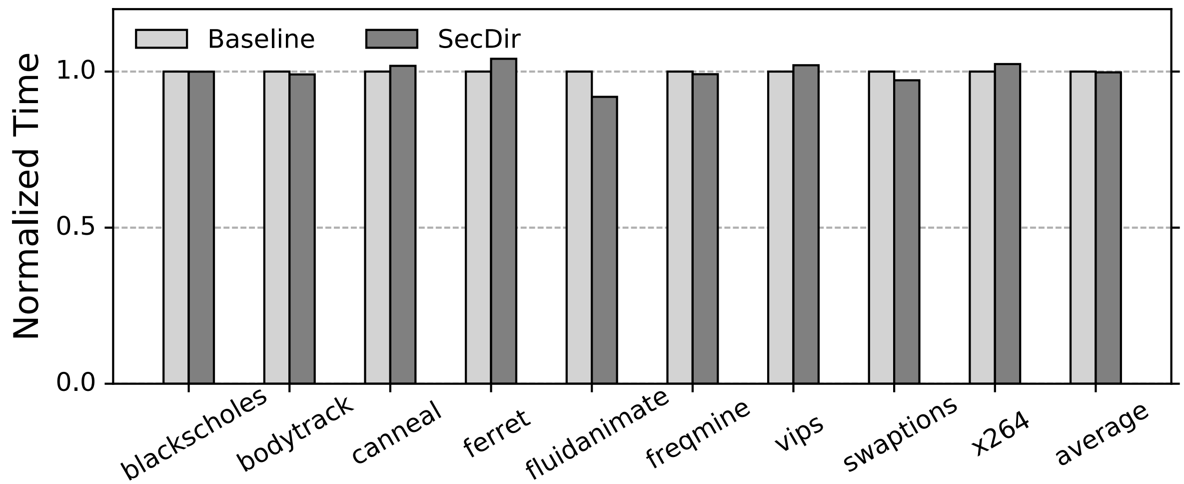
B: baseline S: SecDir



Evaluation Results – PARSEC

- Under benign conditions, the performance overhead is negligible
  + Fewer L2 misses
  - VD accesses add 5-10 cycles

Summary: Secure and little performance impact



More in the paper & Discussion

- More performance results for SPECMIX
- Security discussion
  - VD timing issues
- Performance evaluation
  - Effects of the two optimizations: cuckoo hashing and Early-Miss bits
  - Storage and area overhead

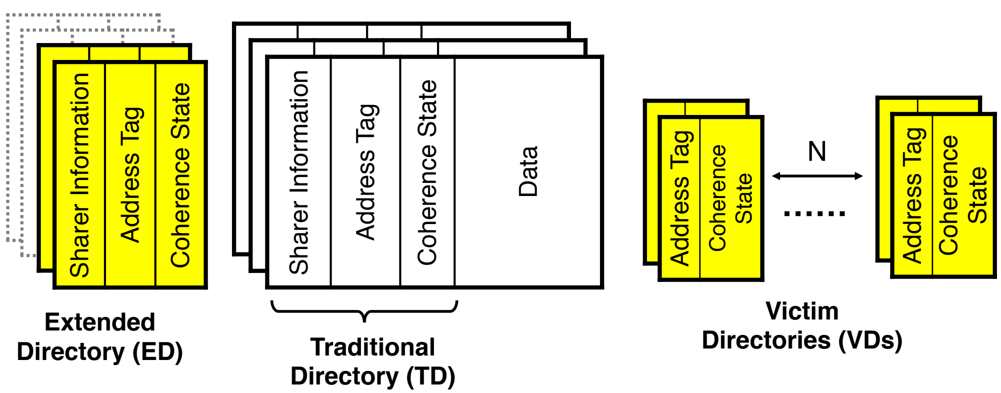
Conclusion

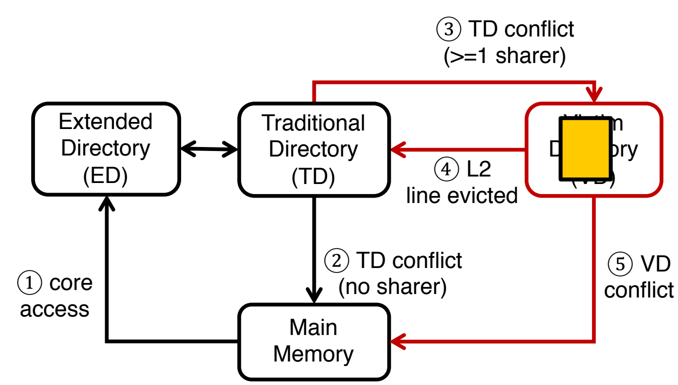
- Directories are vulnerable to side-channel attacks [Yan et al, S&P'19]
- Naïve solutions are not effective
- Contribution: **SecDir**
  - Main idea: Take a portion of the storage used by conventional directory and re-assign it to per-core private directory (Victim Directory)
  - Provides isolation inexpensively and scalably
  - Uses moderate storage

Q&A

SecDir Blocks Directory Interference

- Consider each directory transition and its security implications
  - ED←→ TD: Line location does not change; *no leakage*
  - ② TD → Memory: Line is in LLC but in no L2; *L2 self-conflicts*
  - ③ TD → VD: Line location does not change. VD of every sharer receives a copy. *no leakage*
  - ④ VD → TD: L2 wants to write back the cache line to LLC; *L2 self-conflict*

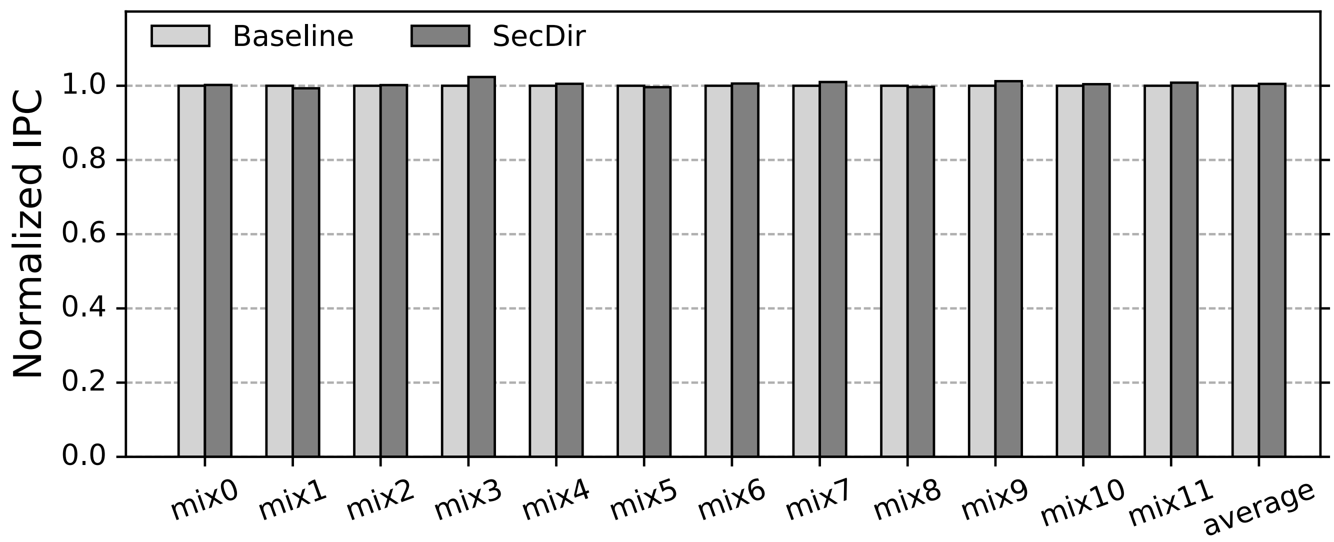




Evaluation of SPECMIX

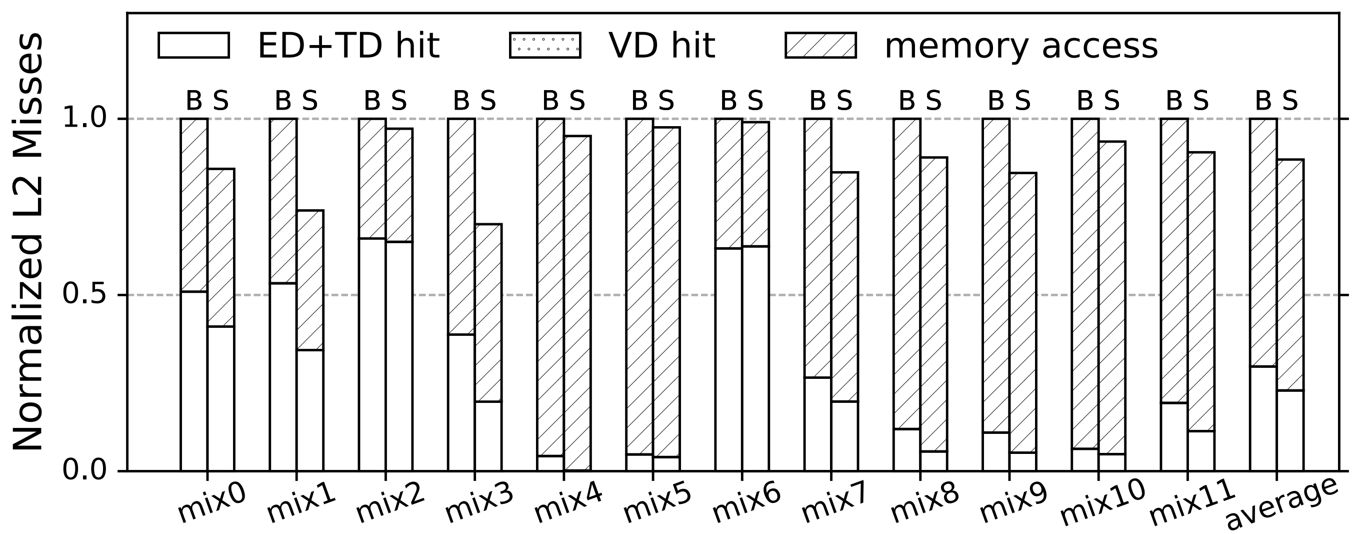
- Under benign conditions, the performance overhead is negligible
  + ED/TD conflicts migrate entries to VD: do not evict L2 lines → fewer L2 misses
  - VD accesses add 5-10 cycles

Summary: Secure and little performance impact



Evaluation of SPECMIX

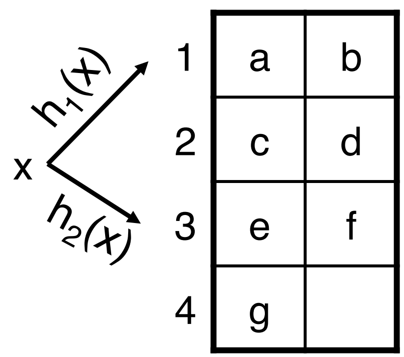
- SecDir has fewer L2 misses because fewer directory conflicts
- No VD hits (since no shared data) → VD accesses add to a DRAM latency



Minimizing VD Self-Conflicts

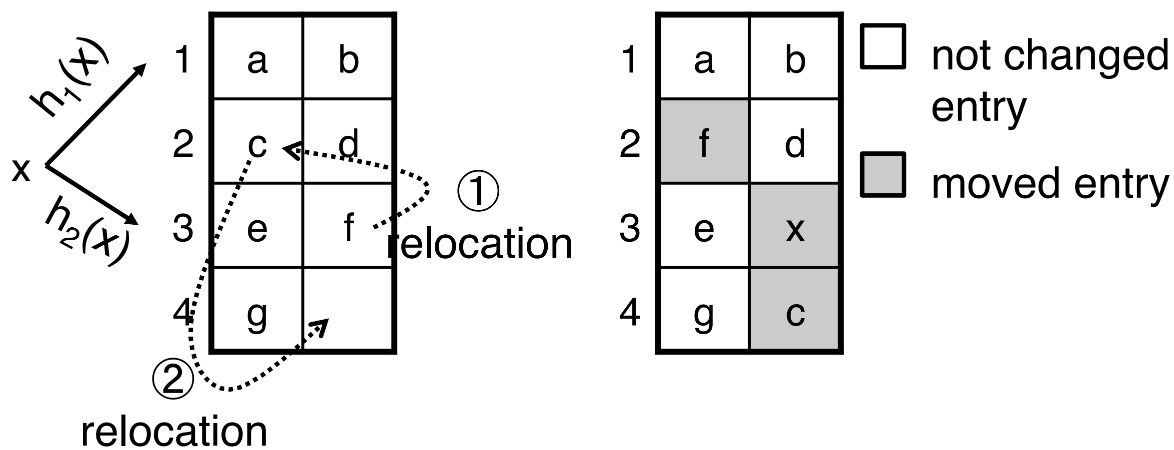
- Organize VD as Cuckoo Directory
- Performance: Longer lookup/insert latency
- Security:
  - Reduce VD self-conflicts
  - Obscures victim self-conflict patterns

VD bank



Example: VD Offers High Associativity

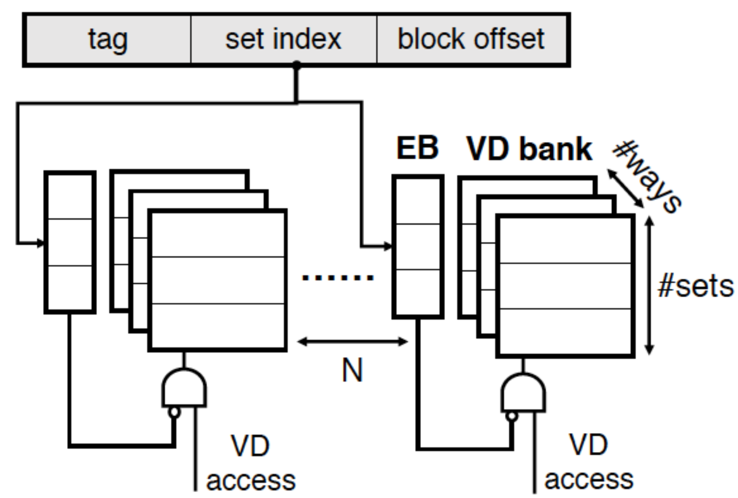
- Example: insert x into an almost full VD



(a) Before inserting item x (b) After item x inserted

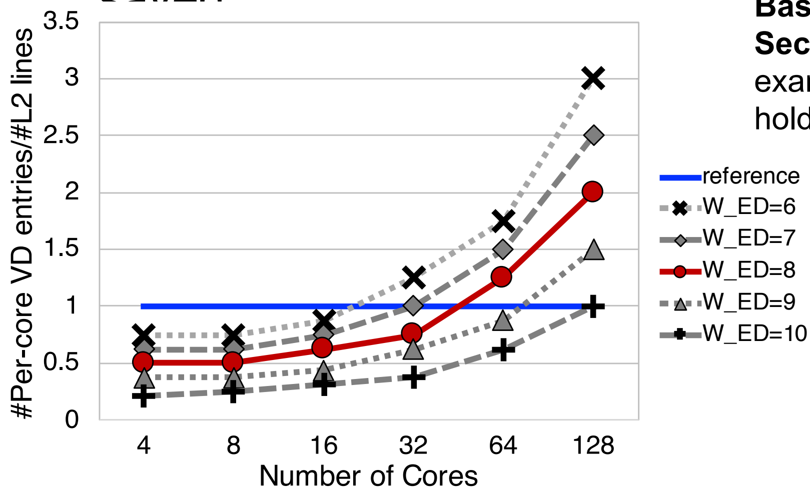
Early Detection of VD Misses

- Under benign conditions: VD will be highly underutilized
- Want to quickly detect when a VD access will miss → save E
  - Add an Empty Bit (EB) per set and bank
  - If all the entries in that set of that bank are Invalid → EB is set



SecDir Uses Low Area

- VD does not store "sharing information"
- More cores → More bits of sharing information "saved"



Baseline: Skylake-X directory (W_{ED}=12). **SecDir:** Take some ED ways for VD. For example, keep W_{ED}=8 (such that ED can hold as many lines as L2).

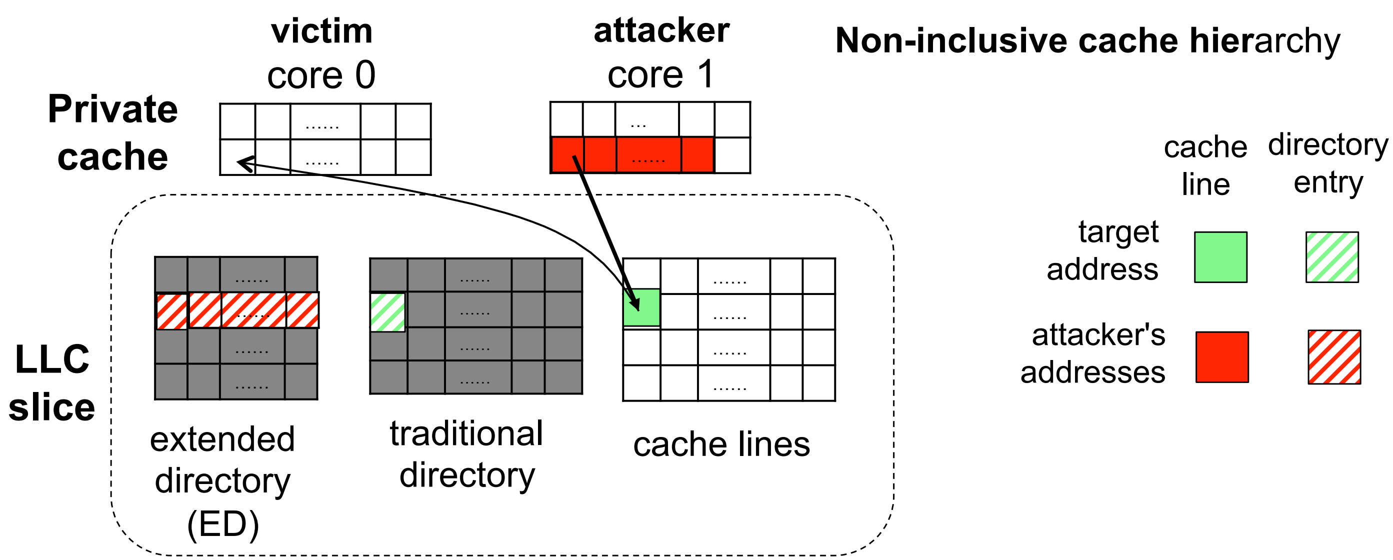
Summary: by stealing 4 ways of ED, we quickly attain a per-core VD that has as many entries as L2 lines

Comparing the number of per-core VD entries machine-wide to the number of L2 lines. Values above 1 mean that the per-core VD has more entries than lines in L2.

Directories are Vulnerable to Attacks

[Yan S&P'19]

- As the victim re-accesses the data → directory entry reloaded
- Attacker can observe the directory changing



SecDir Properties

- Provides inexpensive and scalable isolation
- Provides high associativity
- Uses low storage
- Delivers efficient directory lookup

Benchmarks

- SPEC Mixes

  Profile applications on baseline to classify them into

  CCF (core cache fit); LLCF (LLC fit); LLCT (LLC

Categories	Name	Applications	Name	Applications
CCF, CCF	mix0	gobmk, sjeng	mix1	hmmer, gamess
LLCF, LLCF	mix2	bzip2, omnetpp	mix3	gromacs, zeusmp
LLCT, LLCT	mix4	libquantum, lbm	mix5	bwaves, sphinx3
CCF, LLCF	mix6	sjeng, omnetpp	mix7	h264ref, zeusmp
CCF, LLCT	mix8	gobmk, libquantum	mix9	namd, bwaves
LLCF, LLCT	mix10	omnetpp, bwaves	mix11	zeusmp, lbm

Table 5: SPEC workload mixes.

- PARSEC