CSE 410/510 Special Topics: Software Security

Instructor: Dr. Ziming Zhao

Heap-based Buffer Overflow

Heap Overflow

- Buffer overflows are basically the same on the heap as they are on the stack
- Heap cookies/canaries aren’t a thing
  - No ‘return’ addresses to protect
- In the real world, lots of cool and complex things like objects/structs end up on the heap
  - Anything that handles the data you just corrupted is now viable attack surface in the application
- It’s common to put function pointers in structs which generally are malloc’d on the heap

code/heapoverflow1

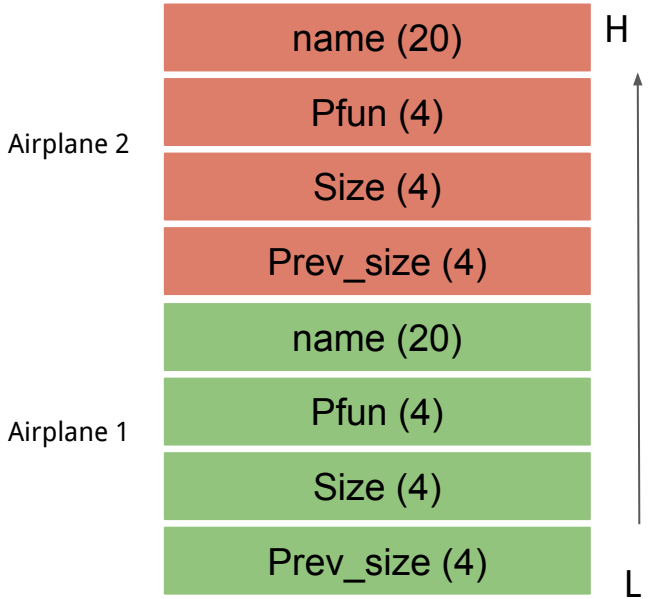
```
void fly()
{
        printf("Flying ...\n");
}

typedef struct airplane
{
        void (*pfun)();
        char name[20];
} airplane;
```

```
int main()
{
   printf("fly() at %p; print_flag() at %p\n", fly,
print_flag);

   struct airplane *p1 = malloc(sizeof(airplane));
   printf("Airplane 1 is at %p\n", p1);

   struct airplane *p2 = malloc(sizeof(airplane));
   printf("Airplane 2 is at %p\n", p2);

   p1->pfun = fly;
   p2->pfun = fly;

   fgets(p2->name, 10, stdin);
   fgets(p1->name, 50, stdin);

   p1->pfun();
   p2->pfun();

   free(p1);
   free(p2);
   return 0;
}
```

code/heapoverflow1

```
void fly()
{
        printf("Flying ...\n");
}

typedef struct airplane
{
        void (*pfun)();
        char name[20];
} airplane;
```

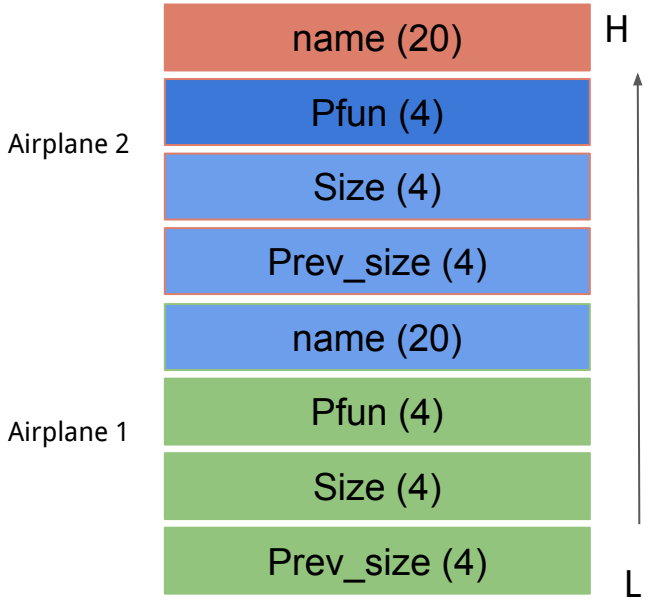
```
int main()
{
   printf("fly() at %p; print_flag() at %p\n", fly,
print_flag);

   struct airplane *p1 = malloc(sizeof(airplane));
   printf("Airplane 1 is at %p\n", p1);

   struct airplane *p2 = malloc(sizeof(airplane));
   printf("Airplane 2 is at %p\n", p2);

   p1->pfun = fly;
   p2->pfun = fly;

   fgets(p2->name, 10, stdin);
   fgets(p1->name, 50, stdin);

   p1->pfun();
   p2->pfun();

   free(p1);
   free(p2);
   return 0;
}
```



code/heapoverflow1

```
void secret()
{
        printf("The secret is bla bla...\n");
}

void fly()
{
        printf("Flying ...\n");
}

typedef struct airplane
{
        void (*pfun)();
        char name[20];
} airplane;
```

```
int main()
{
    printf("fly() at %p; secret() at %p\n", fly, secret);

    struct airplane *p1 = malloc(sizeof(airplane));
    printf("Airplane 1 is at %p\n", p1);

    struct airplane *p2 = malloc(sizeof(airplane));
    printf("Airplane 2 is at %p\n", p2);

    p1->pfun = fly;
    p2->pfun = fly;

    fgets(p2->name, 10, stdin);
    fgets(p1->name, 50, stdin);

    p1->pfun();
    p2->pfun();

    free(p1);
    free(p2);
    return 0;
}
```



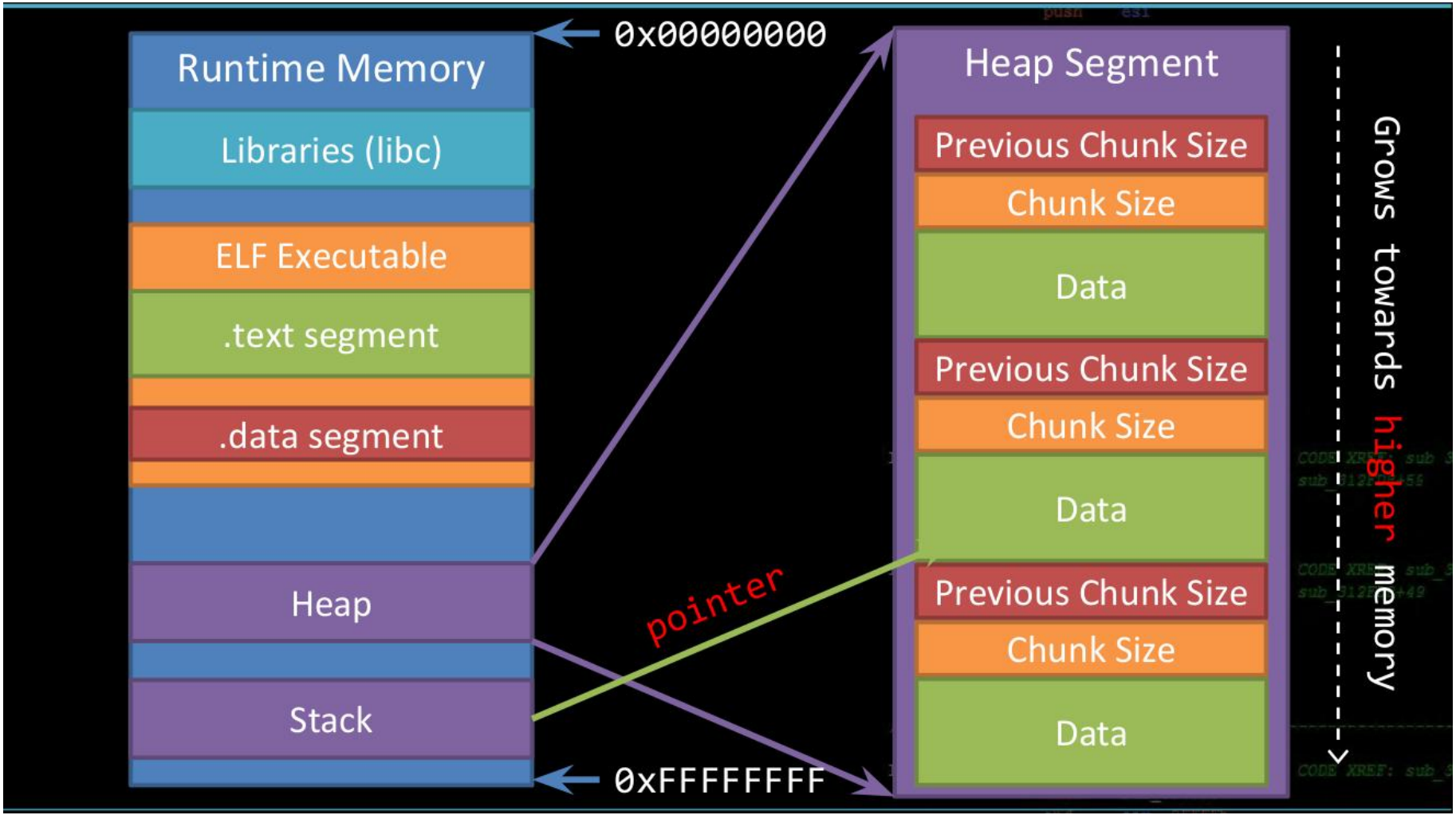
Exploit looks like

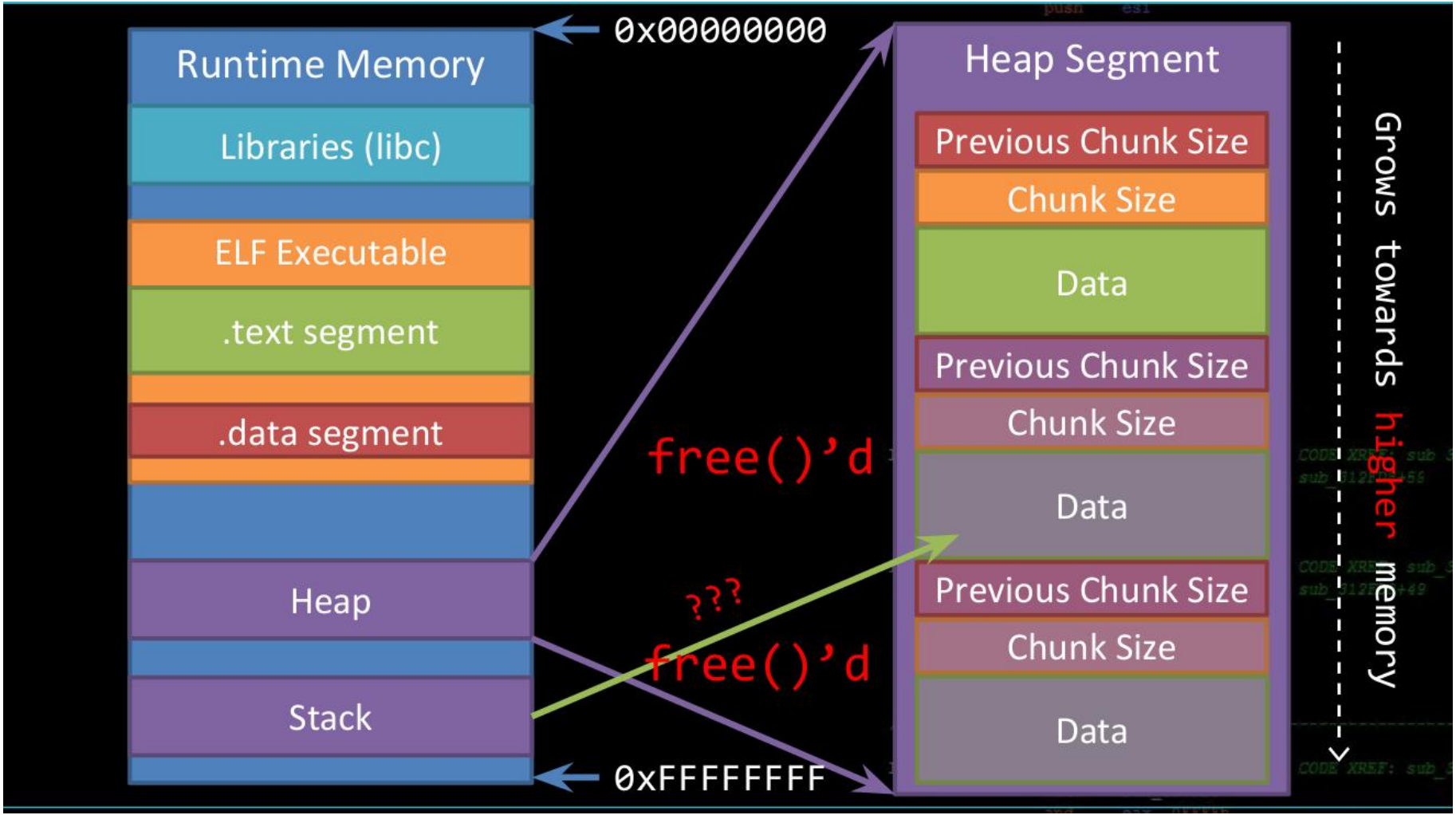
```
python -c "print 'a\n' + 'a'*28 + '\x4d\x62\x55\x56'" | ./heapoverflow32
```

Use after free (UAF)

A class of vulnerability where data on the heap is freed, but a leftover reference or ‘dangling pointer’ is used by the code as if the data were still valid.

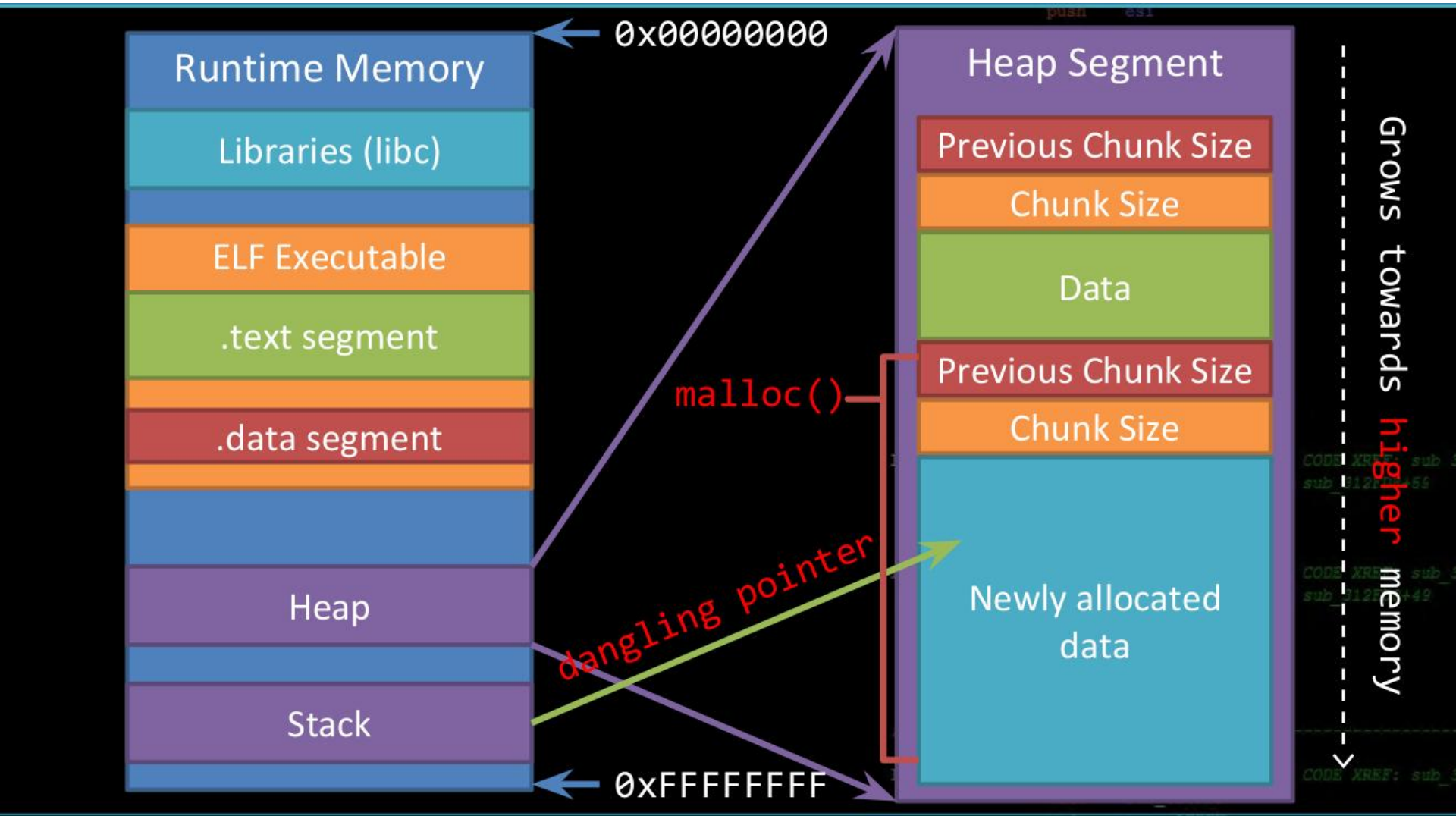
Most popular in Web Browsers, complex programs


0x00000000
Runtime Memory
Libraries (libc)
ELF Executable
.text segment
.data segment
Heap
Stack
0xFFFFFFFF
pointer
Heap Segment
Previous Chunk Size
Chunk Size
Data
Previous Chunk Size
Chunk Size
Data
Previous Chunk Size
Chunk Size
Data
Grows towards higher memory


0x00000000
Runtime Memory
Libraries (libc)
ELF Executable
.text segment
.data segment
Heap
Stack
0xFFFFFFFF
free()'d
???
free()'d
Heap Segment
Previous Chunk Size
Chunk Size
Data
Previous Chunk Size
Chunk Size
Data
Previous Chunk Size
Chunk Size
Data
Grows towards higher memory

Dangling Pointer

Dangling Pointer
– A left over pointer in your code that references free’d data and is prone to be re-used
– As the memory it’s pointing at was freed, there’s no guarantees on what data is there now
– Also known as stale pointer, wild pointer


0x00000000
Runtime Memory
Libraries (libc)
ELF Executable
.text segment
.data segment
Heap
Stack
0xFFFFFFFF
malloc()
dangling pointer
Heap Segment
Previous Chunk Size
Chunk Size
Data
Previous Chunk Size
Chunk Size
Newly allocated data
Grows towards higher memory

Exploit UAF

To exploit a UAF, you usually have to allocate a different type of object over the one you just freed

code/heapoverflow2

```
void fly()
{
        printf("Flying ...\n");
}

typedef struct airplane
{
        void (*pfun)();
        char name[20];
} airplane;

typedef struct car
{
    int volume;
    char name[20];
} car;
```

```
int main()
{ printf("fly() at %p; print_flag() at %u\n", fly, (unsigned int)print_flag);

  struct airplane *p = malloc(sizeof(airplane));
  printf("Airplane is at %p\n", p);
  p->pfun = fly;
  p->pfun();
  free(p);

  struct car *p1  = malloc(sizeof(car));
  printf("Car is at %p\n", p1);

  int volume;
  printf("What is the volume of the car?\n");
  scanf("%u", &volume);
  p1->volume = volume;

  p->pfun();
  free(p);
  return 0;
}
```

Dlmalloc (using glibc 2.3 as an example)

```
struct malloc_chunk
{
        INTERNAL_SIZE_T prev_size; /* Size of previous chunk (if free). */
        INTERNAL_SIZE_T size; /* Size in bytes, including overhead. */

        struct malloc_chunk* fd; /* double links -- used only if free. */
        struct malloc_chunk* bk;
};

typedef struct malloc_chunk* mchunkptr;
```

Mem is the pointer returned by malloc() call, while **chunk pointer** is what malloc considers the start of the chunk.

The whole heap is bounded from top by a ***wilderness*** chunk. In the beginning, this is the only chunk existing and malloc first makes allocated chunks by splitting the wilderness chunk.

glibc 2.3 allows for many heaps arranged into several ***arenas***—one arena for each thread

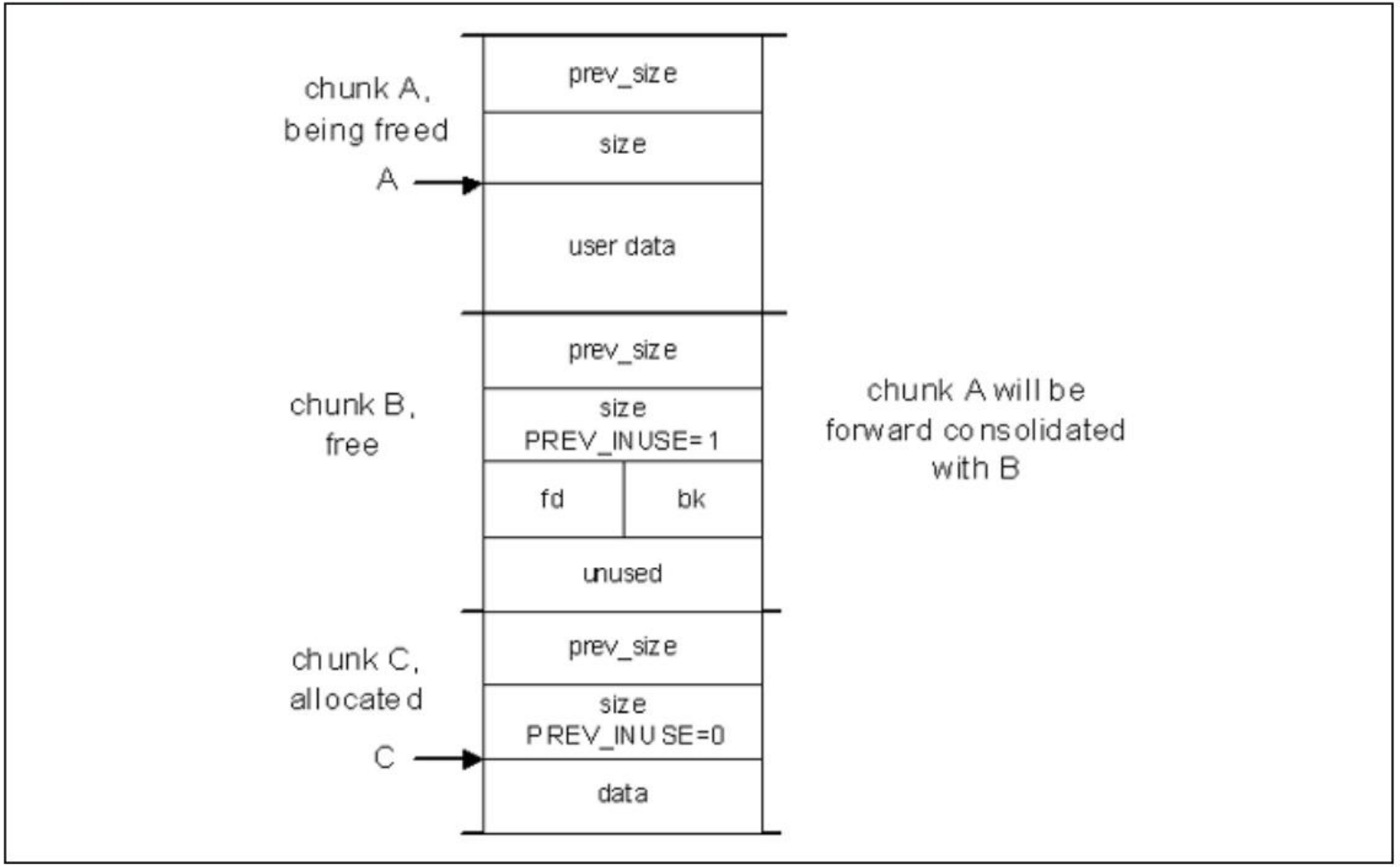
– From the book “Buffer Overflow Attacks: Detect, Exploit, Prevent” Syngree

Consolidating chunks when free()-d

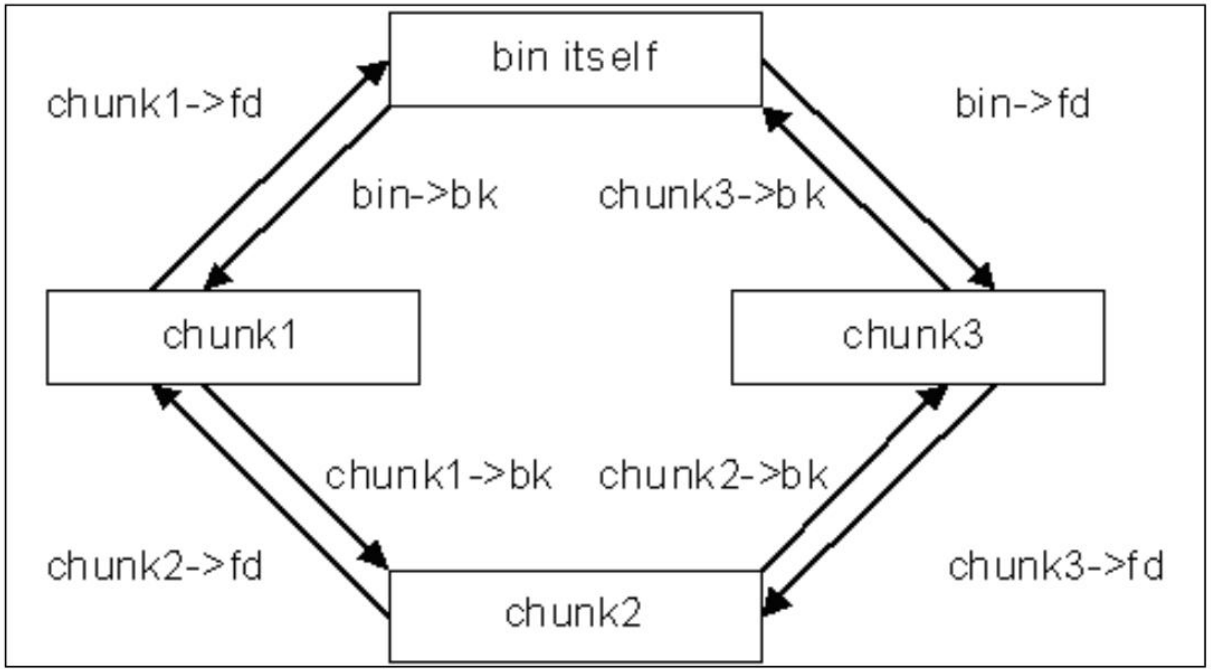
When a previously allocated chunk is free()-d, it can be either consolidated with previous (backward consolidation) and/or follow (forward consolidation) chunks, if they are free.

This ensures that there are no two adjacent free chunks in memory. The resulting chunk is then placed in a ***bin***, which is a ***doubly linked list of free chunks of a certain size***.

There is a set of bins for chunks of different sizes:
■ 64 bins of size 8 ■ 32 bins of size 64 ■ 16 bins of size 512
■ 8 bins of size 4096 ■ 4 bins of size 32768 ■ 2 bins of size 262144
■ 1 bin of size what's left


chunk A,
being freed
A
prev_size
size
user data
chunk B,
free
prev_size
size
PREV_INUSE=1
fd
bk
unused
chunk A will be
forward consolidated
with B
chunk C,
allocated
C
prev_size
size
PREV_INUSE=0
data

Example Bin with Three Free Chunks



FD and BK are pointers to “next” and “previous” chunks inside a linked list of a bin, ***not adjacent physical chunks***.

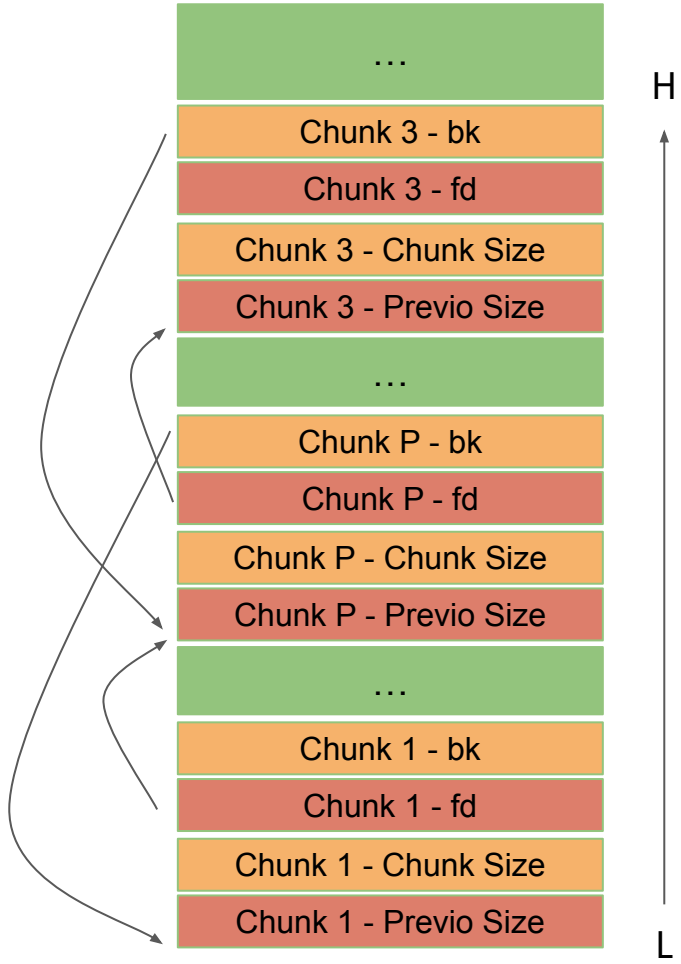
Pointers to chunks, physically next to and previous to this one in memory, can be obtained from current chunks by using **size** and **prev_size** offsets.

Pointers to physically next to and previous chunk

```
/* Ptr to next physical malloc_chunk. */
#define next_chunk(p) ((mchunkptr)( ((char*)(p)) + ((p)->size & ~PREV_INUSE) ))

/* Ptr to previous physical malloc_chunk */
#define prev_chunk(p) ((mchunkptr)( ((char*)(p)) - ((p)->prev_size) ))
```

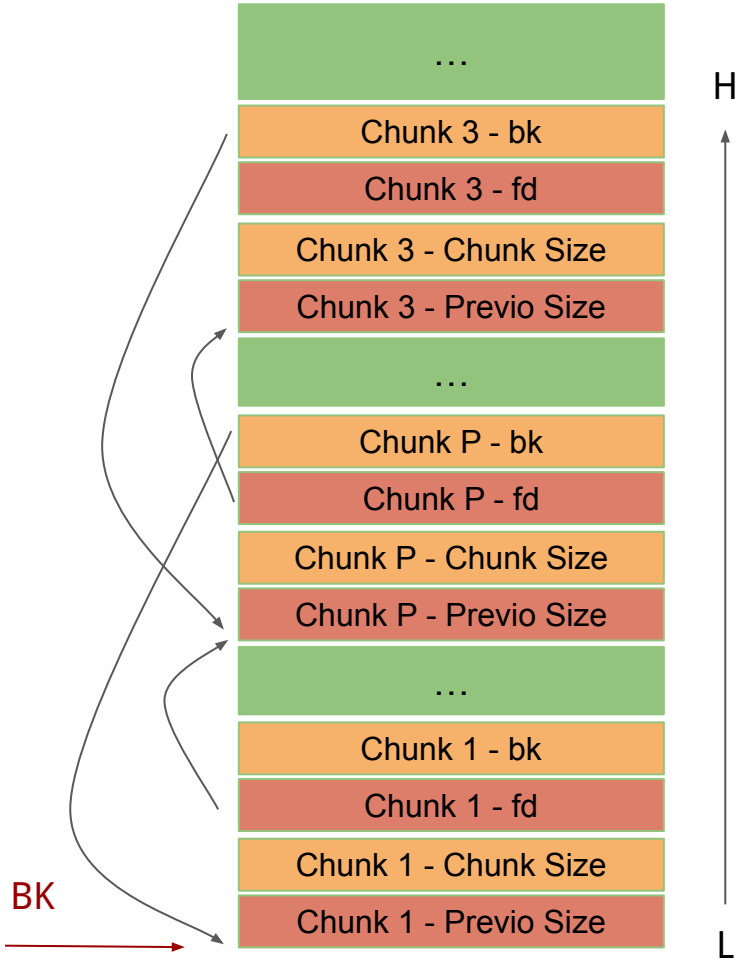
Unlink() a Free Chunk P from the Bin

```
#define unlink( P, BK, FD ) {
        BK = P->bk;
        FD = P->fd;
        FD->bk = BK;
        BK->fd = FD;
}
```



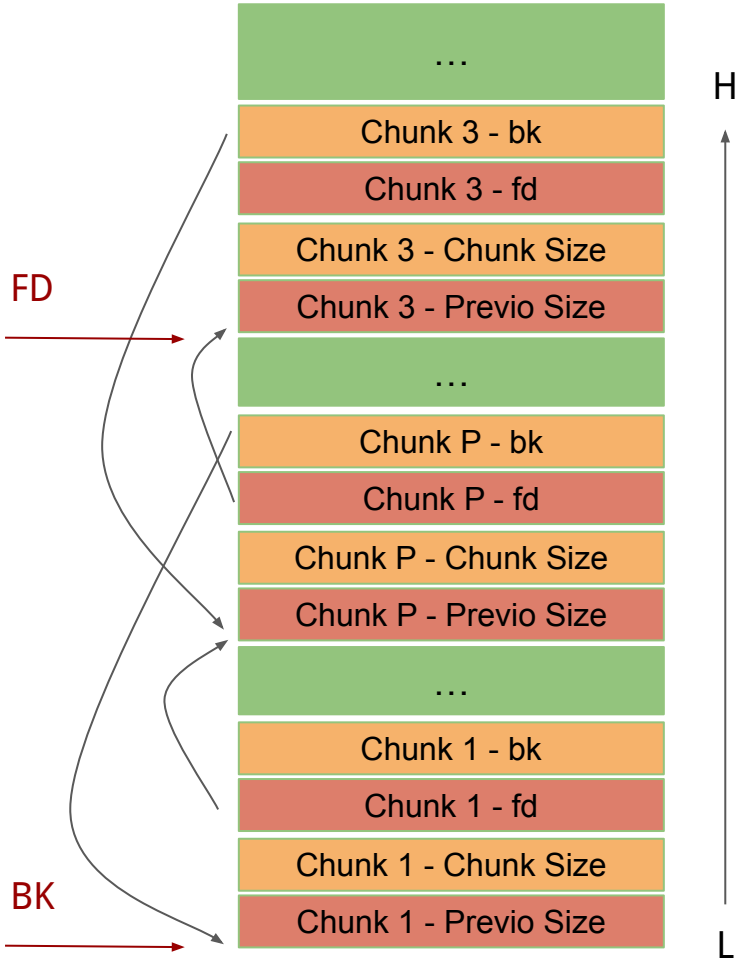
Unlink() a Free Chunk P from the Bin

```
#define unlink( P, BK, FD ) {
        BK = P->bk;
        FD = P->fd;
        FD->bk = BK;
        BK->fd = FD;
}
```



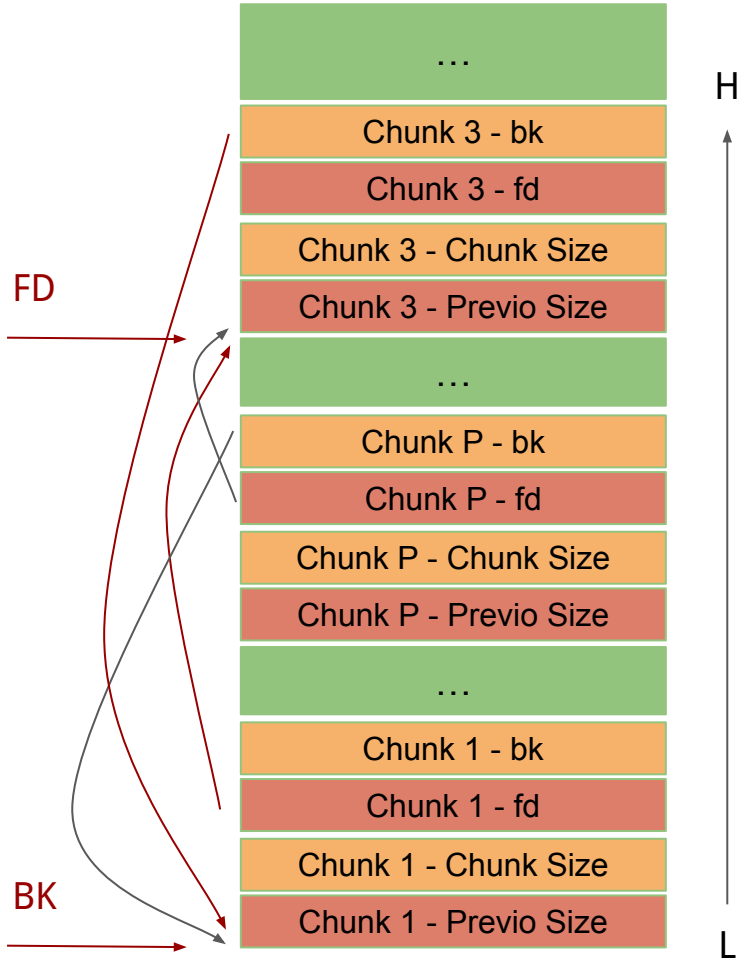
Unlink() a Free Chunk P from the Bin

```
#define unlink( P, BK, FD ) {
        BK = P->bk;
        FD = P->fd;
        FD->bk = BK;
        BK->fd = FD;
}
```



Unlink() a Free Chunk P from the Bin

```
#define unlink( P, BK, FD ) {
        BK = P->bk;
        FD = P->fd;
        FD->bk = BK;
        BK->fd = FD;
}
```

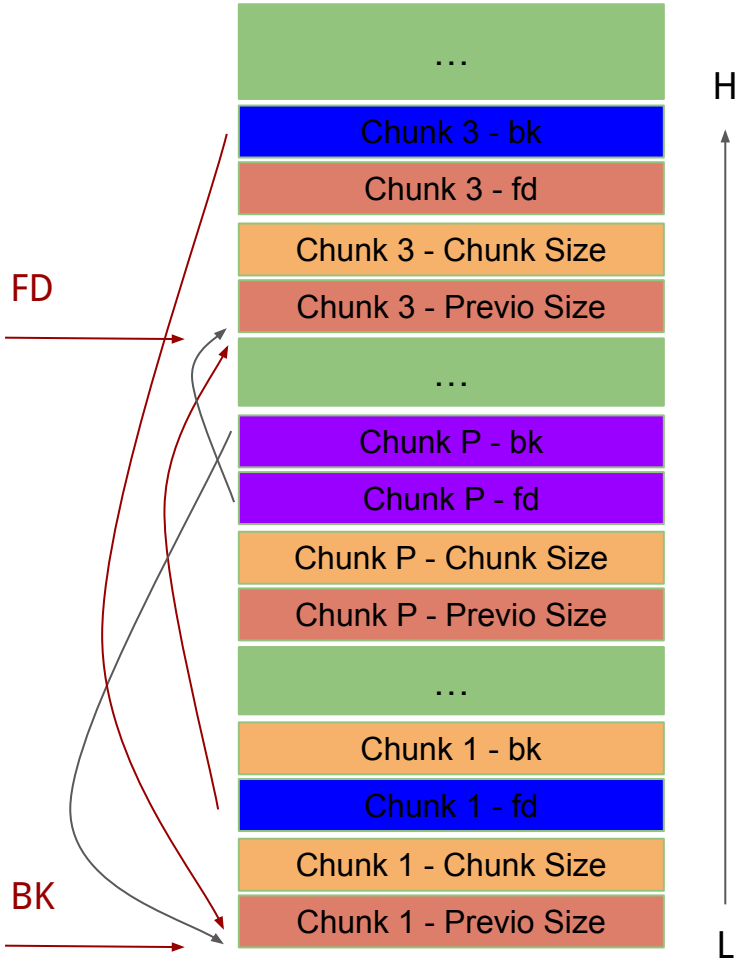


Unlink() from an Attacker's Point of View

```
*(P->fd+12) = P->bk;
// 4 bytes for size, 4 bytes for prev_size and 4 bytes for fd

*(P->bk+8) = P->fd;
// 4 bytes for size, 4 bytes for prev_size
```

Arbitrary write attack?

If an attacker is able to overwrite these two pointers and force the call to unlink(), he can overwrite any memory location.

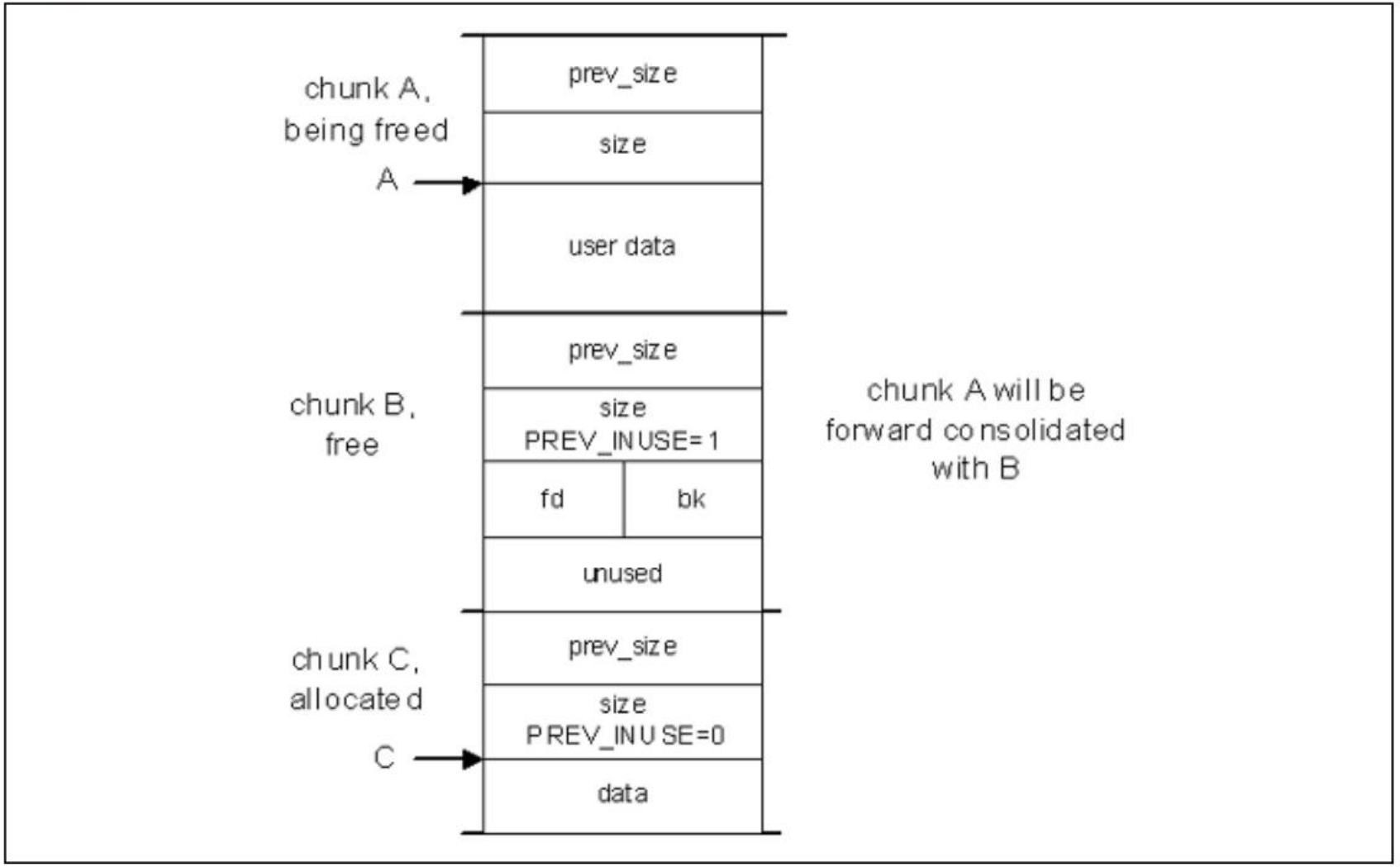


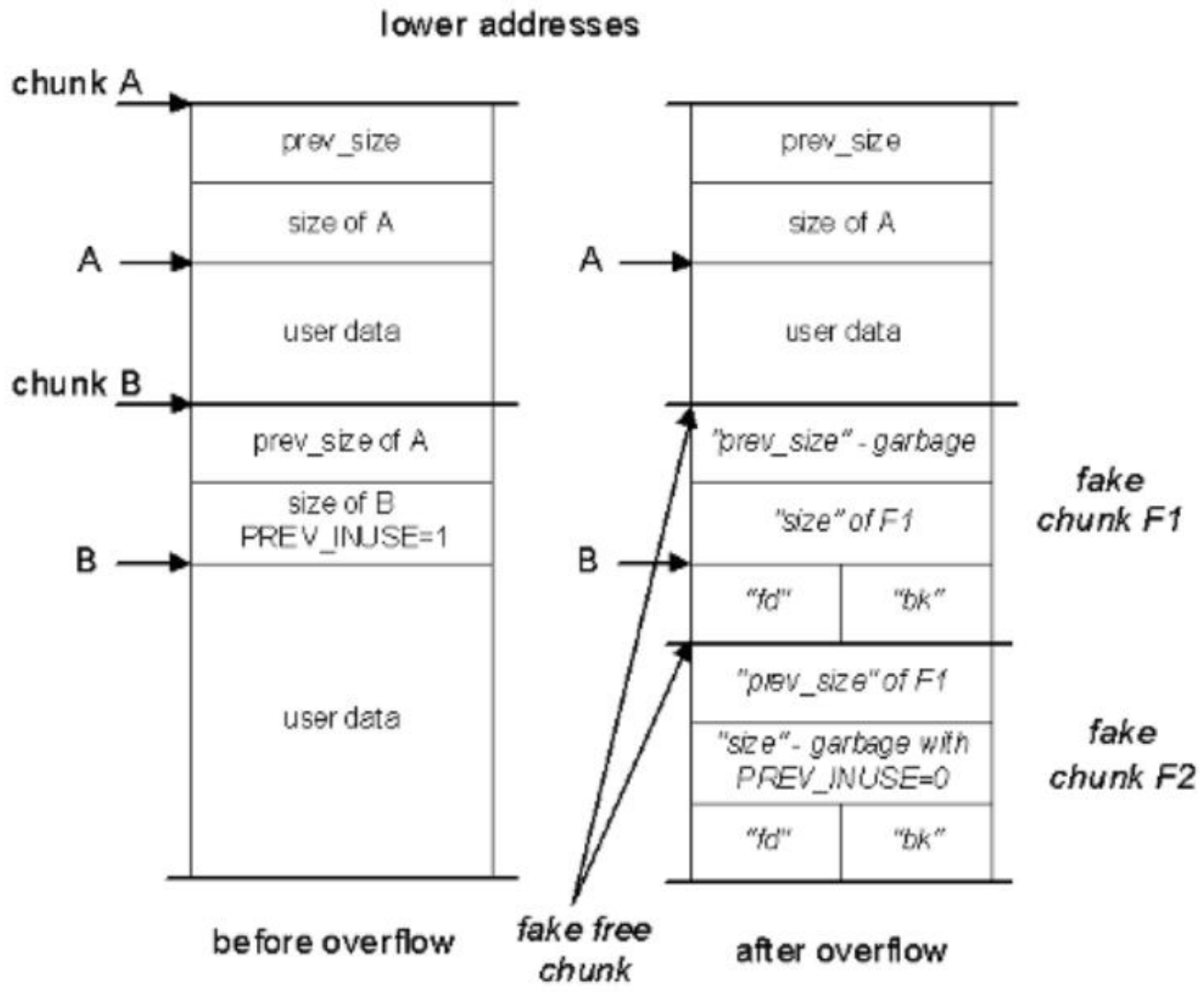
The free() Algorithm

- free(0) has no effect.
- If the chunk was allocated via mmap, it is released via munmap(). Only large chunks are MMAP-ped, and we are not interested in thes.
- If a returned chunk borders the current high end of memory (wilderness chunk), it is consolidated into the wilderness chunk, and if the total unused topmost memory exceeds the trim threshold, malloc_trim() is called.
- Other chunks are consolidated as they arrive, and placed in corresponding bins.

The free() Algorithm - last case

- If no adjacent chunks are free, then the freed chunk is simply linked into corresponding with bin via frontlink().
- If the chunk next in memory to the freed one is free and if this next chunk borders on wilderness, then both are consolidated with the wilderness chunk.
- If not, and the previous or next chunk in memory is free and they are not part of a most recently split chunk (this splitting is part of malloc() behavior and is not significant to us here), they are taken off their bins via unlink(). Then they are merged (through forward or backward consolidation) with the chunk being freed and placed into a new bin according to the resulting size using frontlink(). If any of them are part of the most recently split chunk, they are merged with this chunk and kept out of bins. This last bit is used to make certain operations faster.


chunk A,
being freed
A
prev_size
size
user data
chunk B,
free
prev_size
size
PREV_INUSE=1
fd
bk
unused
chunk A will be
forward consolidated
with B
chunk C,
allocated
C
prev_size
size
PREV_INUSE=0
data



1. Overwrite A and B
2. Create a fake chunk F1 and F2, so that when free(A), unlink(F1) is also called.
3. F1->FD has the address we want to overwrite and F1->BK has the data we want to overwrite

CSE 410/510 Special Topics: Software Security

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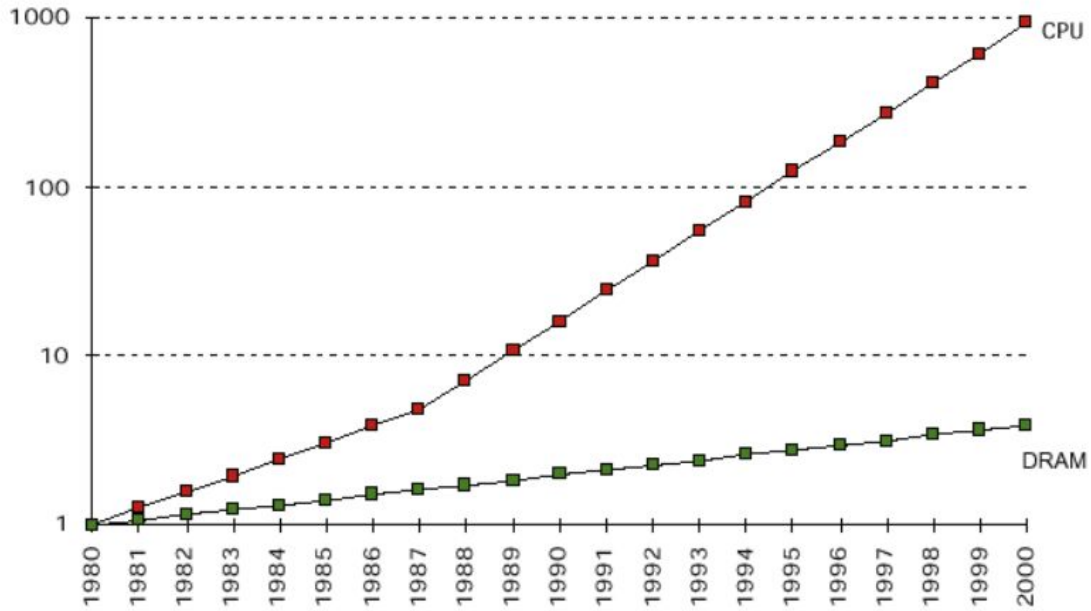
Today’s Agenda

1. Cache side channel attack
2. Meltdown
3. Spectre

Speed Gap Between CPU and DRAM



Memory Hierarchy

A tradeoff between Speed, Cost and Capacity

Ideally one would desire an indefinitely large memory capacity such that any particular … word would be immediately available. … We are … forced to recognize the possibility of constructing a hierarchy of memories, each of which has greater capacity than the preceding but which is less quickly accessible.

A. W. Burks, H. H. Goldstine, and J. von Neumann
Preliminary Discussion of the Logical Design of an Electronic Computing Instrument, 1946

CPU Cache

A cache is a small amount of fast, expensive memory (SRAM). The cache goes between the CPU and the main memory (DRAM).

It keeps a copy of the most frequently used data from the main memory.

All levels of caches are integrated onto the processor chip.

Access Time

		Access Time in 2012
Cache	Static RAM	0.5 - 2.5 ns
Memory	Dynamic RAM	50- 70 ns
Secondary	Flash	5,000 - 50,000 ns
	Magnetic disks	5,000,000 - 20,000,000 ns

Cache Hits and Misses

A cache hit occurs if the cache contains the data that we’re looking for.

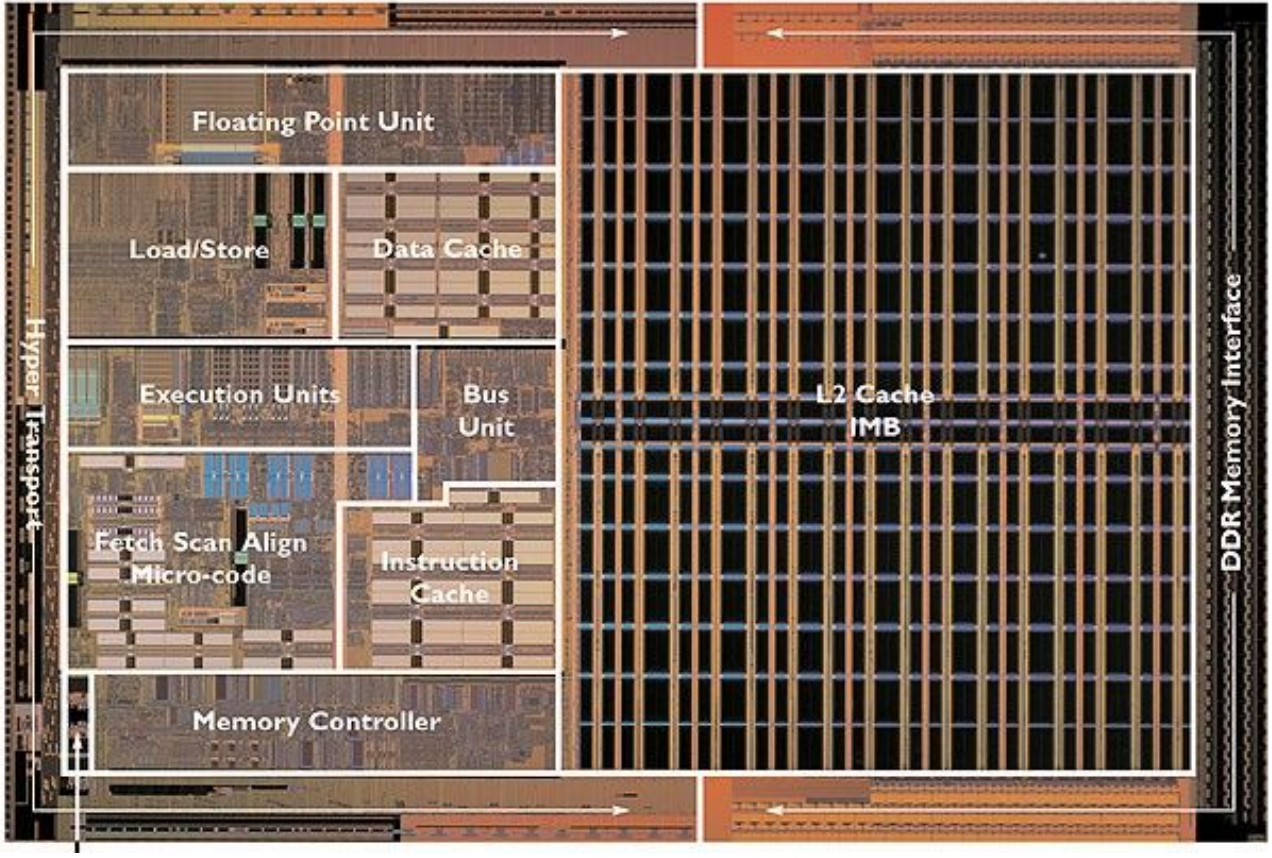
A cache miss occurs if the cache does not contain the requested data.

Cache Hierarchy

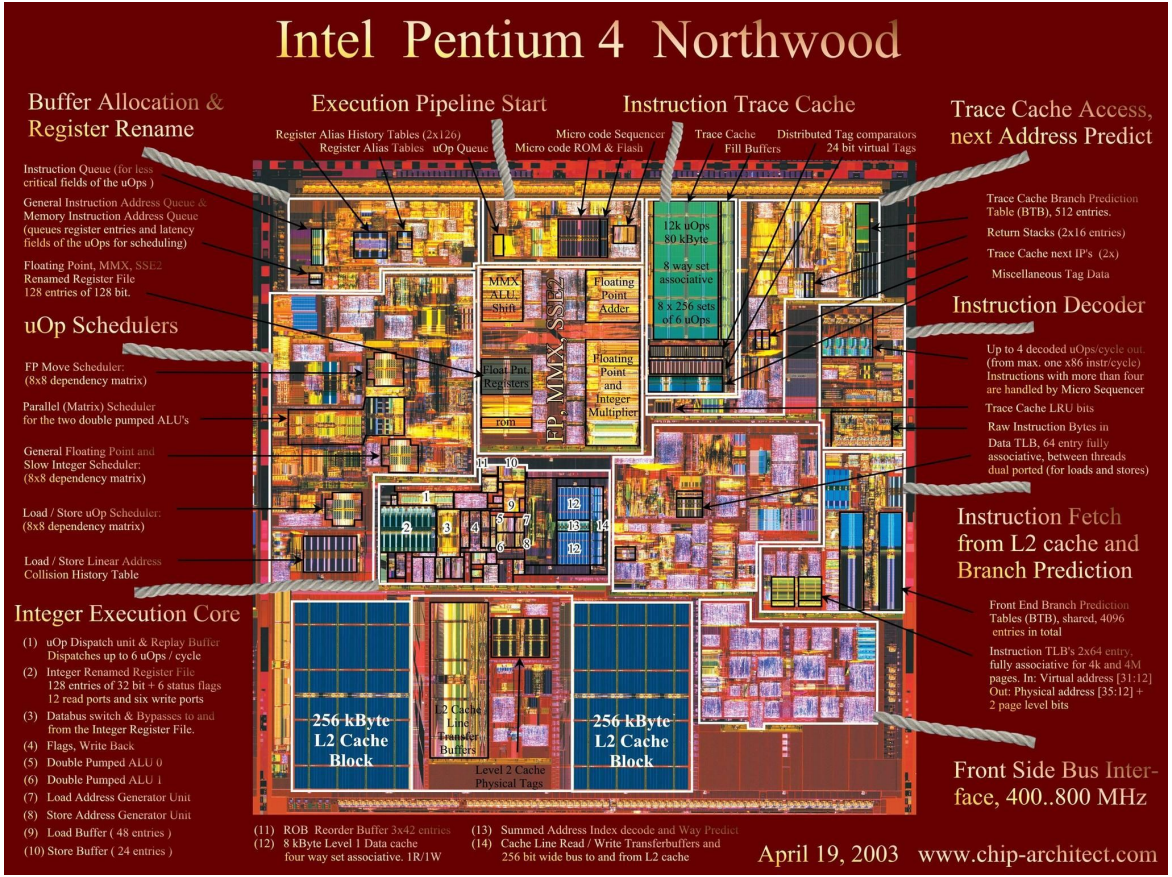
L1 Cache is closest to the CPU. Usually divided in Code and Data cache

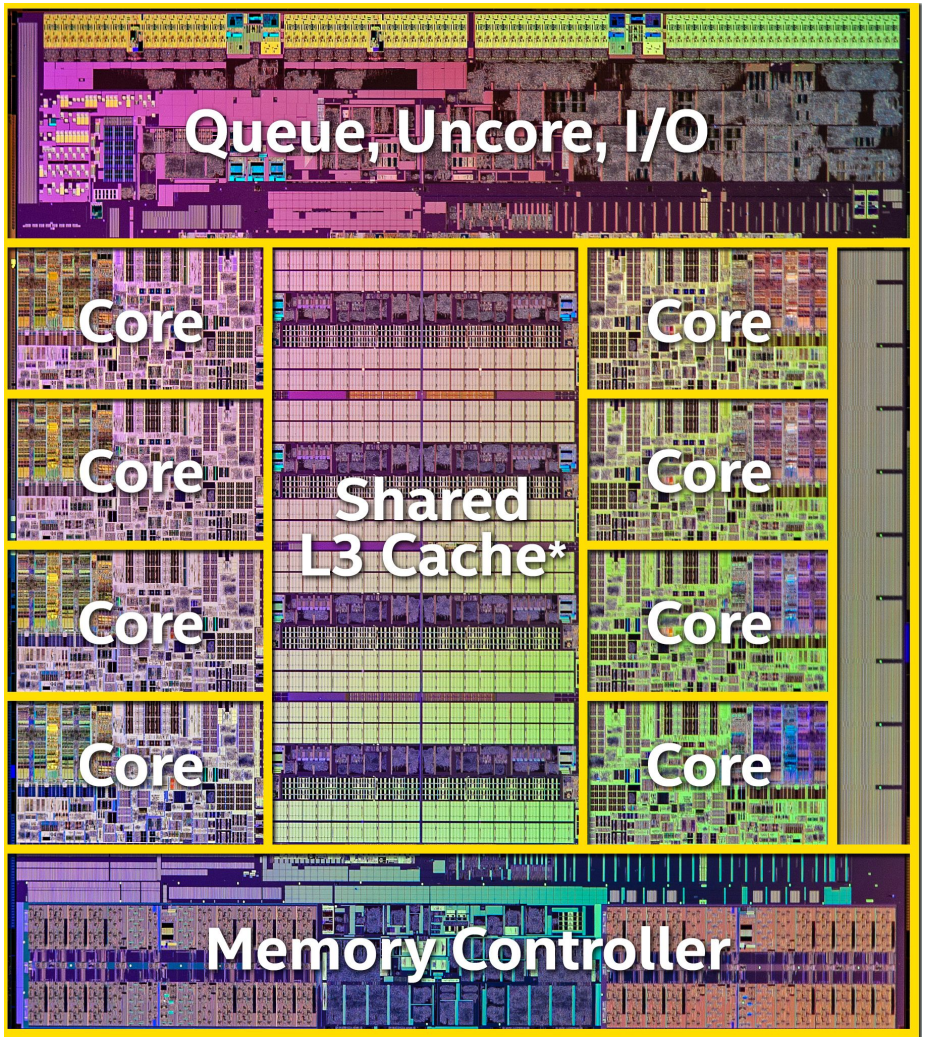
L2 and L3 cache are usually unified.

Cache Hierarchy



Cache Hierarchy




Queue, Uncore, I/O
Core
Core
Core
Core
Shared
L3 Cache*
Core
Core
Core
Core
Memory Controller

Cache Line/Block

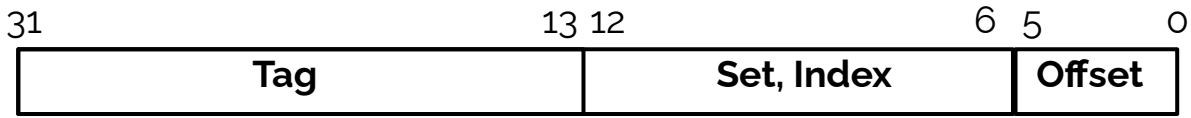
The minimum unit of information that can be either present or not present in a cache.

64 bytes in modern Intel and ARM CPUs

n-Way Set-Associative Cache

Any given block/line in the main memory may be cached in any of the *n* cache lines in one **cache set**.

n-Way Set-Associative Cache



32KB 4-way set-associative data cache, 64 bytes per line

Number of sets

= Cache Size / (Number of ways * Line size)

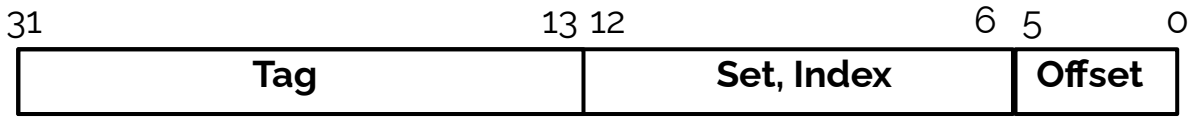
= 32 * 1024 / (4 * 64)

= 128

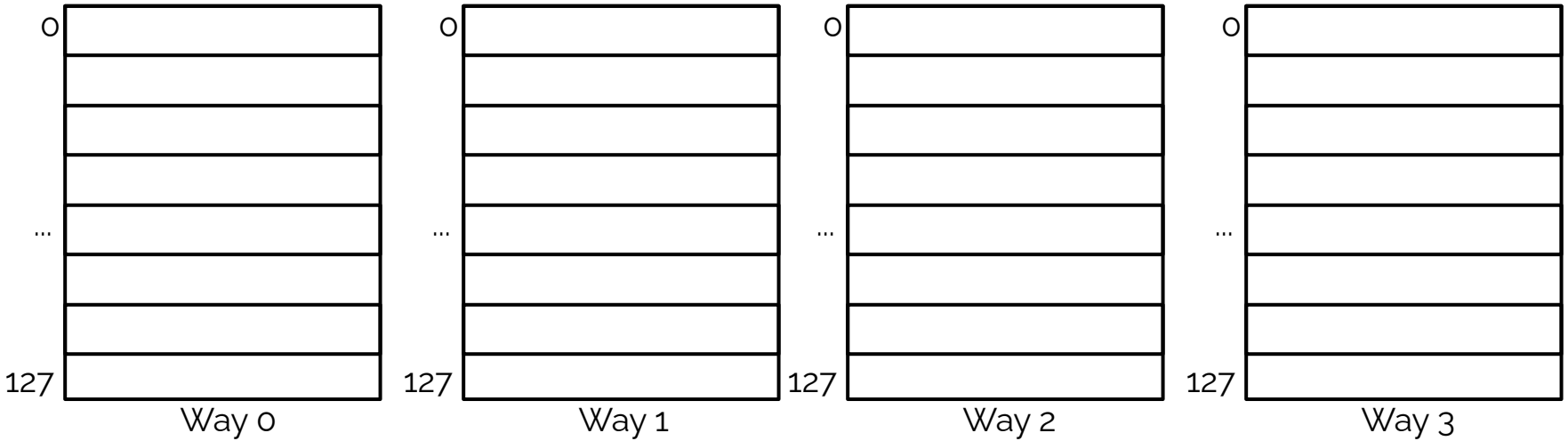
https://www.geeksforgeeks.org/virtually-indexed-physically-tagged-vipt-cache/

PIPT VIVT

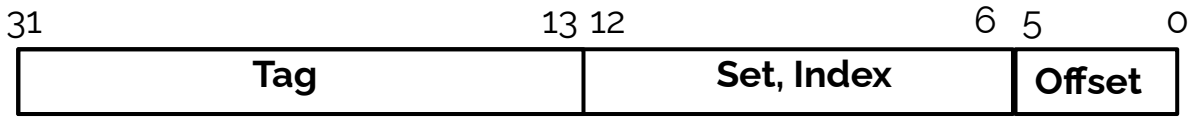
n-Way Set-Associative Cache



32KB 4-way set-associative data cache, 64 bytes per line

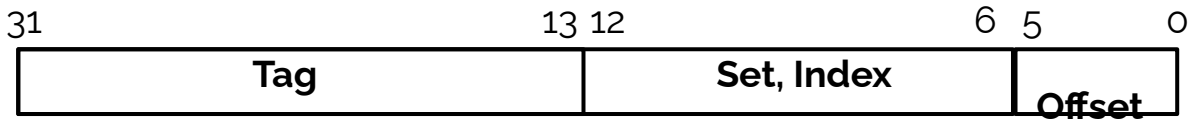


n-Way Set-Associative Cache

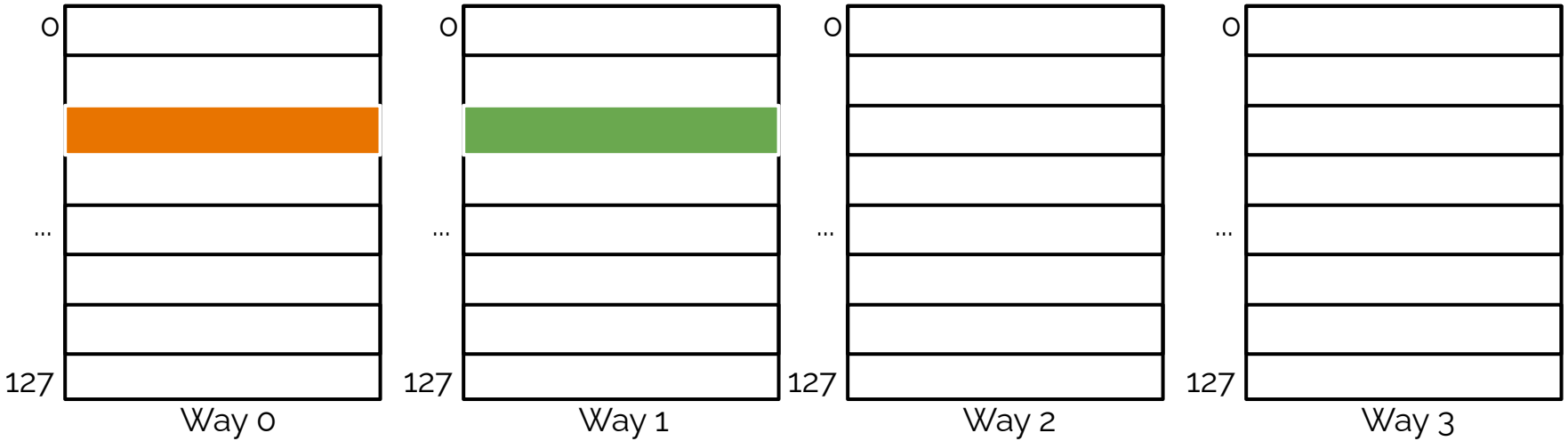


32KB 4-way set-associative data cache, 64 bytes per line

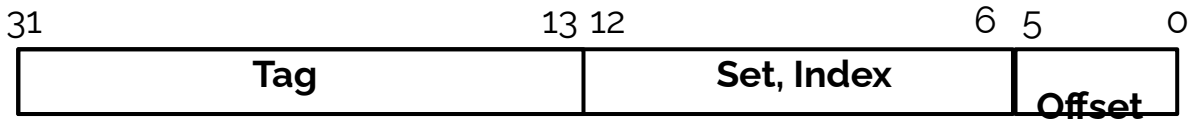
n-Way Set-Associative Cache



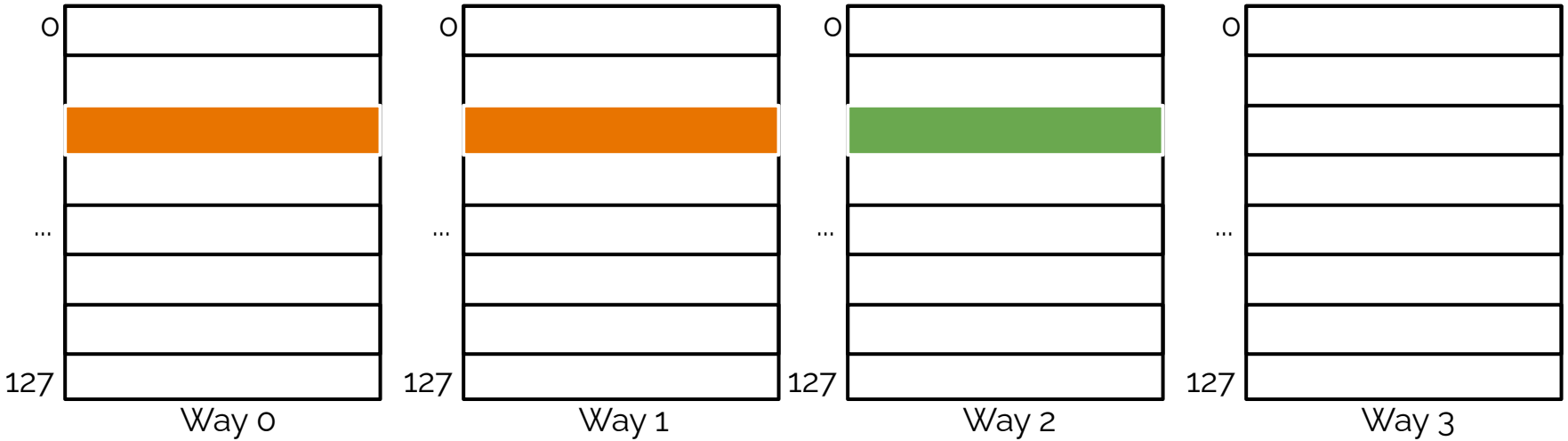
32KB 4-way set-associative data cache, 64 bytes per line



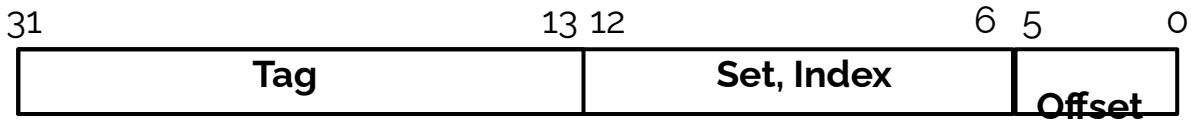
n-Way Set-Associative Cache



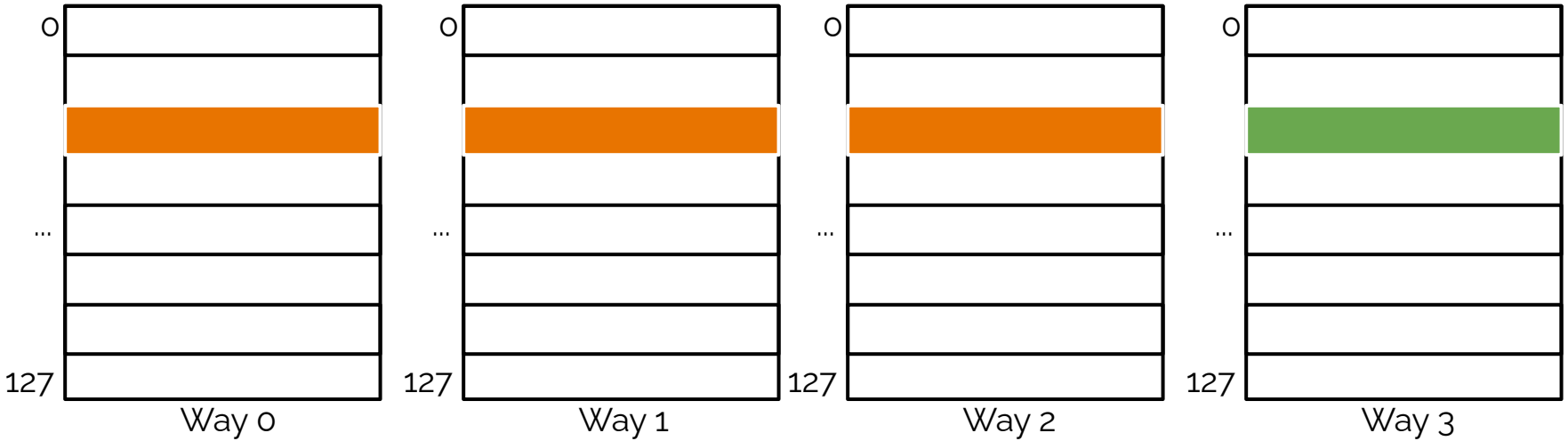
32KB 4-way set-associative data cache, 64 bytes per line



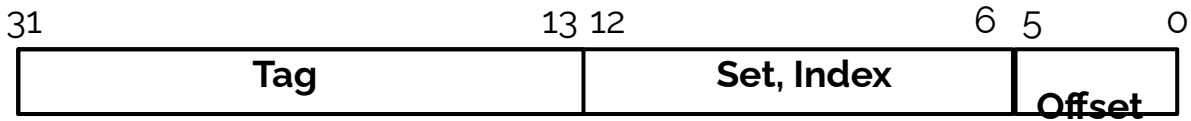
n-Way Set-Associative Cache



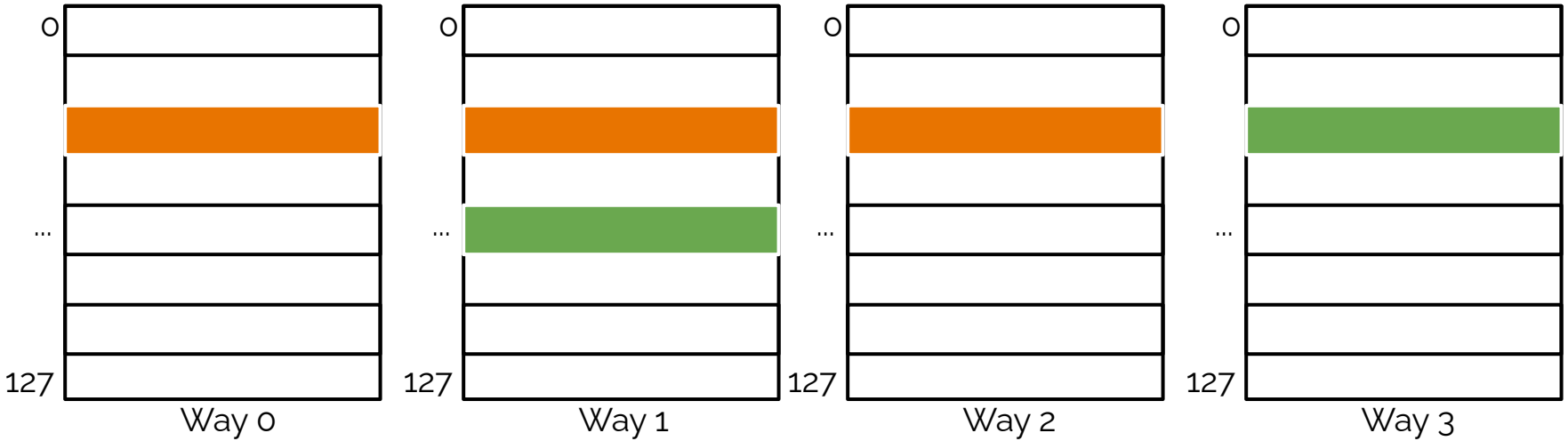
32KB 4-way set-associative data cache, 64 bytes per line



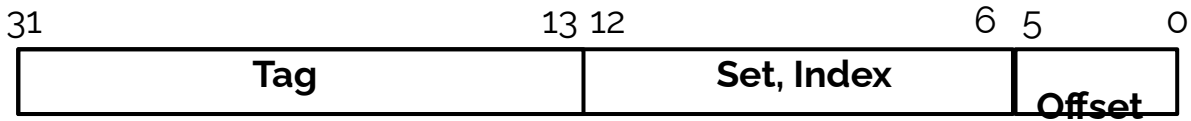
n-Way Set-Associative Cache



32KB 4-way set-associative data cache, 64 bytes per line



Cache Line/Block Content



32KB 4-way set-associative data cache, 64 bytes per line

Congruent Addresses

Each memory address maps to one of these cache sets.

Memory addresses that map to the same cache set are called **congruent**.

Congruent addresses compete for cache lines within the same set, where replacement policy needs to decide which line will be replaced.

Replacement Algorithm

Least recently used (LRU)

First in first out (FIFO)

Least frequently used (LFU)

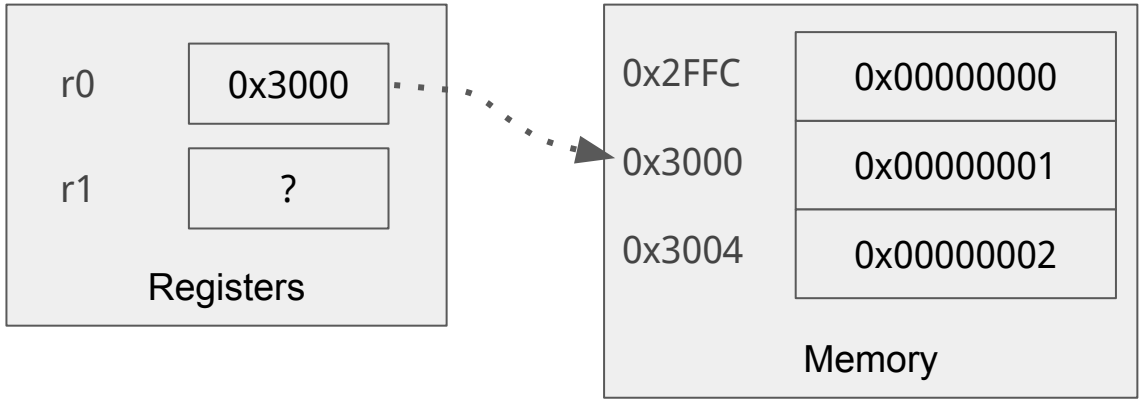
Random

Cache Side-Channel Attacks

Cache side-channel attacks utilize time differences between a cache hit and a cache miss to infer whether specific code/data has been accessed.

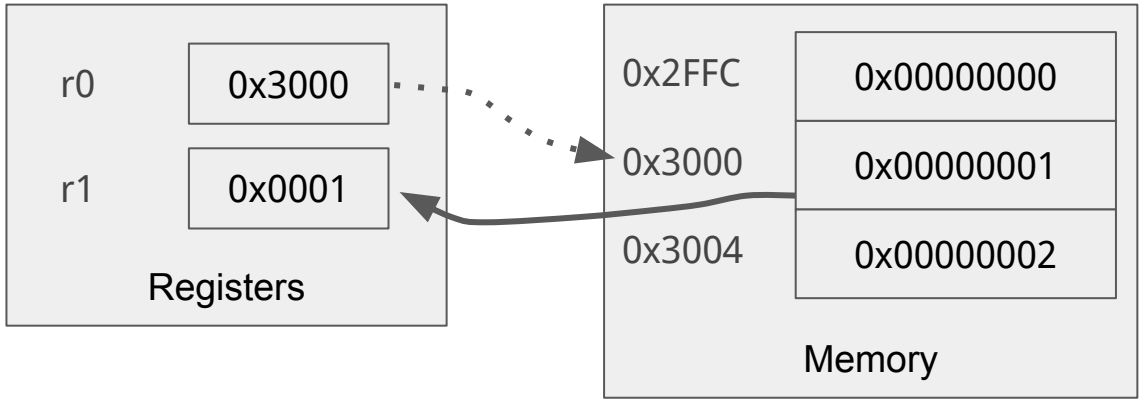
Cache Side-Channel Attack

```
; Assume r0 = 0x3000

; Load a word:

LDR r1, [r0]
```



Cache Side-Channel Attack

```
; Assume r0 = 0x3000

; Load a word:

LDR r1, [r0]
```

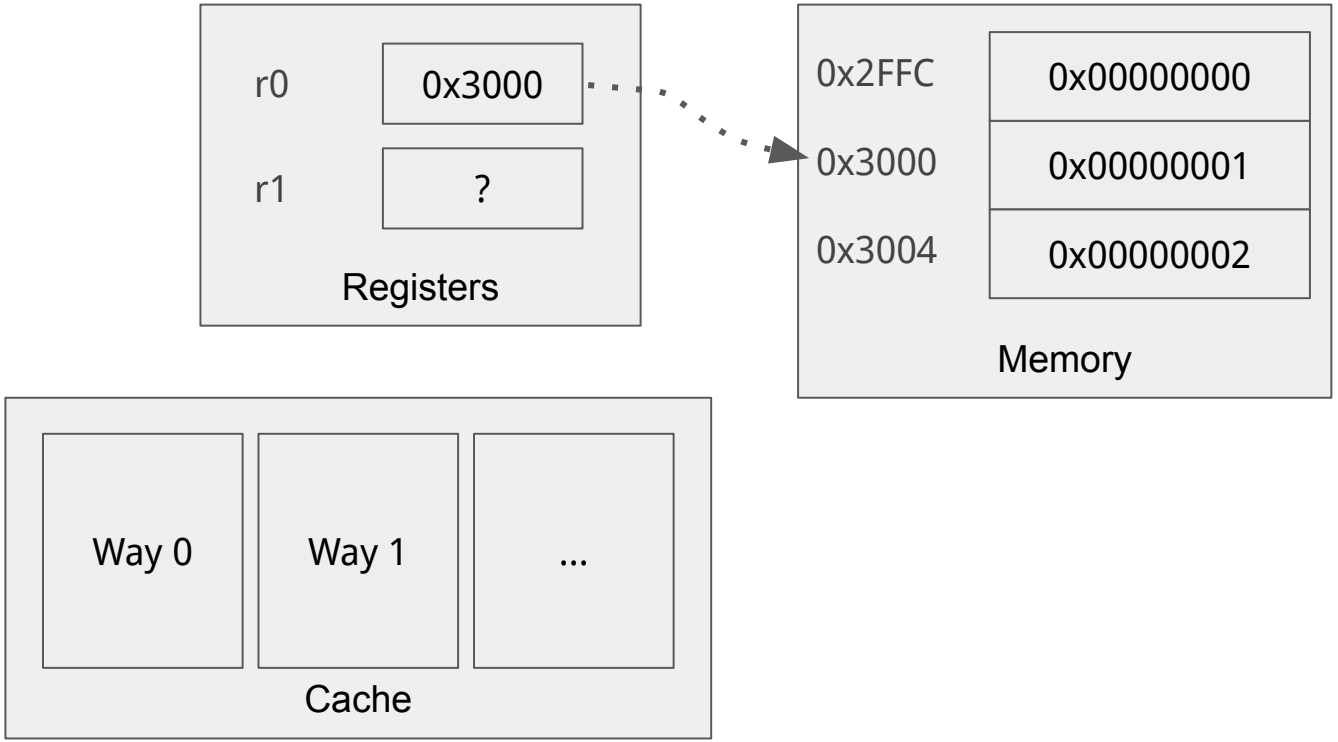


Cache Side-Channel Attack

; Assume r0 = 0x3000

; Load a word:

LDR r1, [r0]

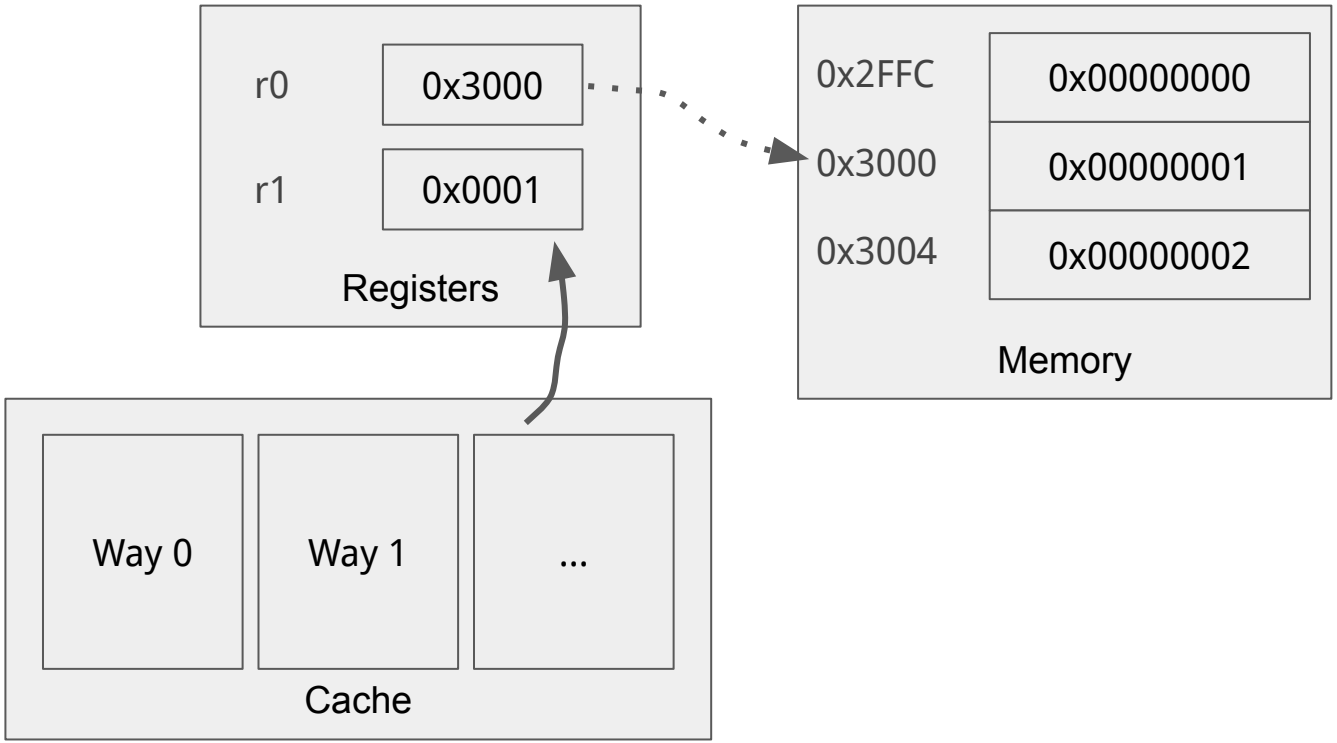


Cache Side-Channel Attack

; Assume r0 = 0x3000

; Load a word:

LDR r1, [r0]

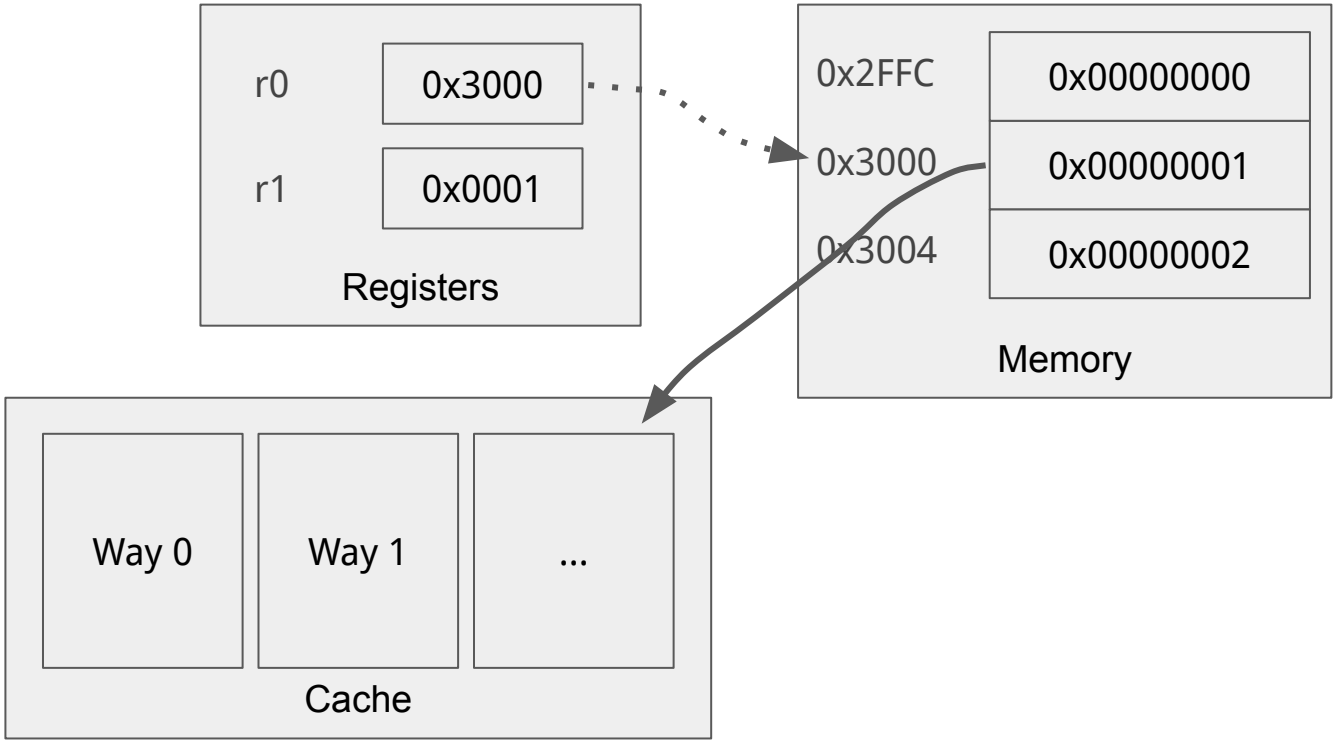


Cache Side-Channel Attack

; Assume r0 = 0x3000

; Load a word:

LDR r1, [r0]

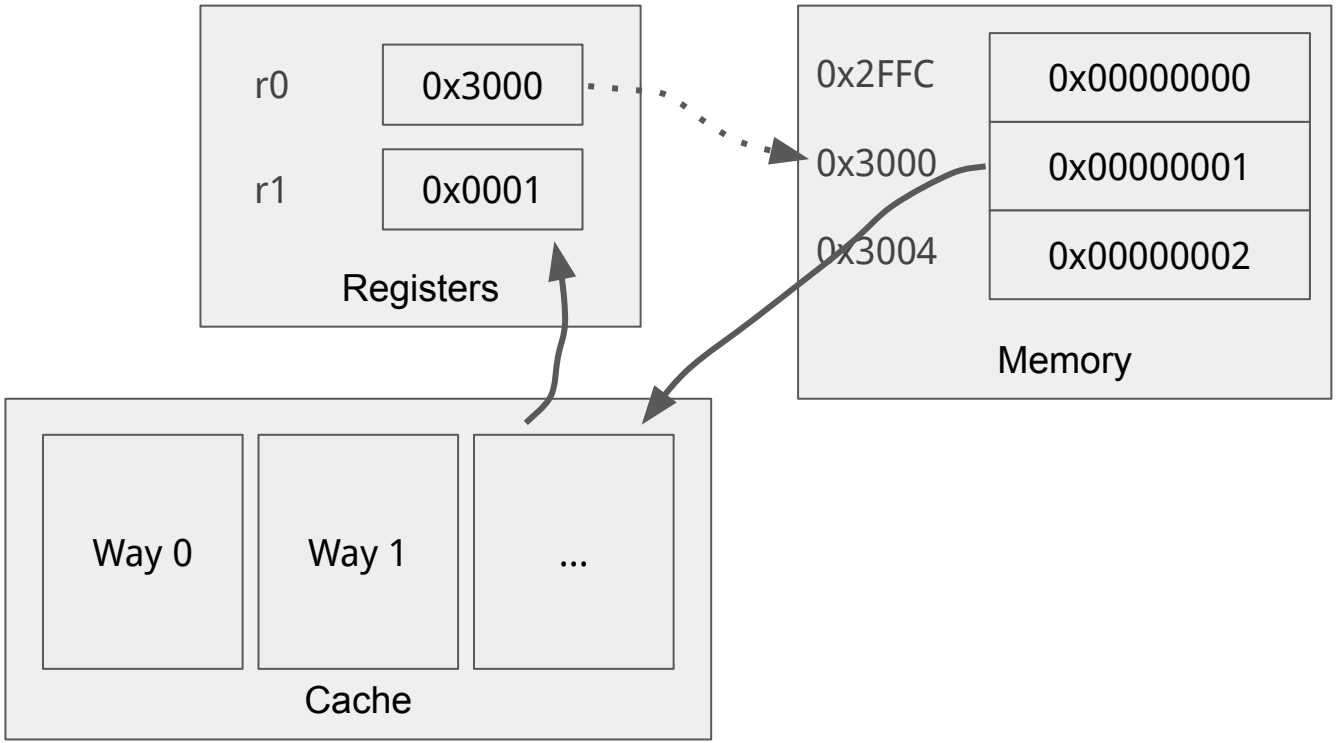


Cache Side-Channel Attack

; Assume r0 = 0x3000

; Load a word:

LDR r1, [r0]



Cache Side-Channel Attack

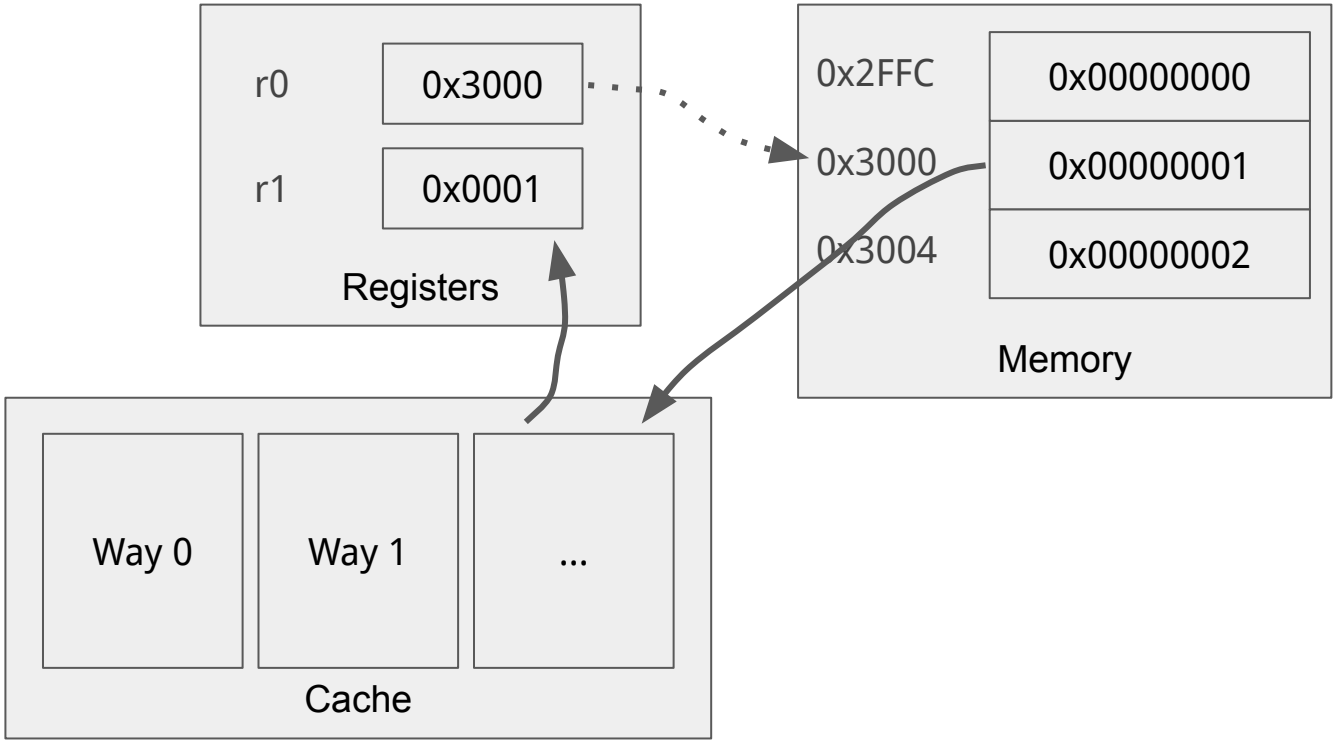
; Assume r0 = 0x3000

; Load a word:

;Get current time t1

LDR r1, [r0]

;Get current time t2; t2 - t1



Attack Primitives

Evict+Time

Prime+Probe

Flush+Flush

Flush+Reload

Evict+Reload

2.4.1 *Evict+Time*

In 2005 Percival [66] and Osvik et al. [63] proposed more fine-grained exploitations of memory accesses to the CPU cache. In particular, Osvik et al. formalized two concepts, namely *Evict+Time* and *Prime+Probe* that we will discuss in this and the following section. The basic idea is to determine which specific cache sets have been accessed by a victim program.

Algorithm 1 *Evict+Time*

1: Measure execution time of victim program.
2: Evict a specific cache set.
3: Measure execution time of victim program again.

The basic approach, outlined in Algorithm 1, is to determine which cache set is used during the victim's computations. At first, the execution time of the victim program is measured. In the second step, a specific cache set is evicted before the program is measured a second time in the third step. By means of the timing difference between the two measurements, one can deduce how much the specific cache set is used while the victim's program is running.

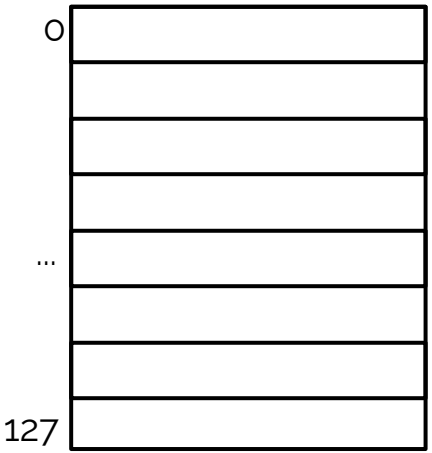
Osvik et al. [63] and Tromer et al. [81] demonstrated with *Evict+Time* a powerful type of attack against AES on OpenSSL implementations that requires neither knowledge of the plaintext nor the ciphertext.

Prime+Probe

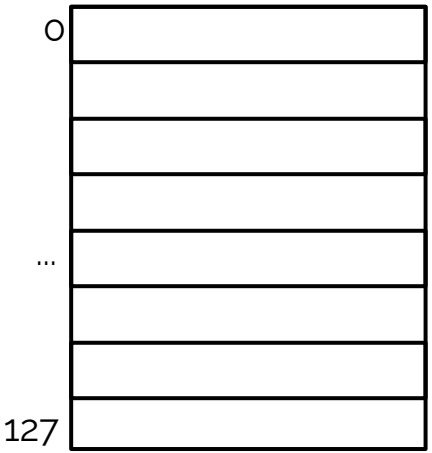
Step 1 Prime: Attacker occupies a set

Attacker Address Space

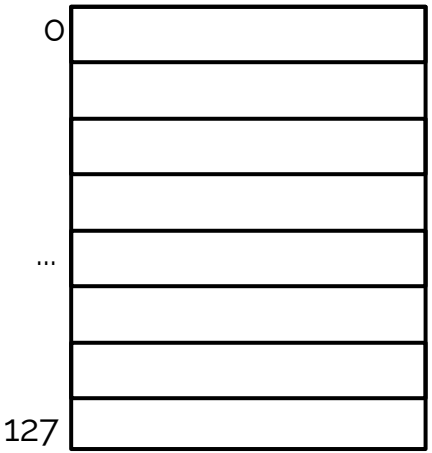
Victim Address Space



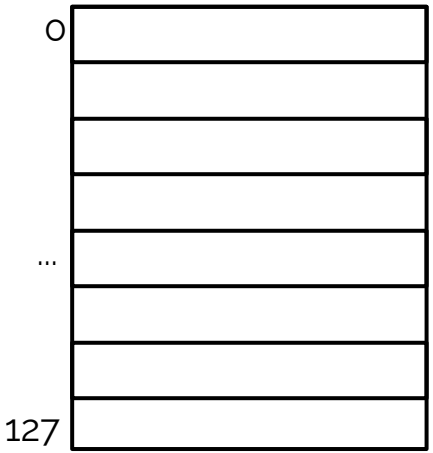
Way 0



Way 1



Way 2



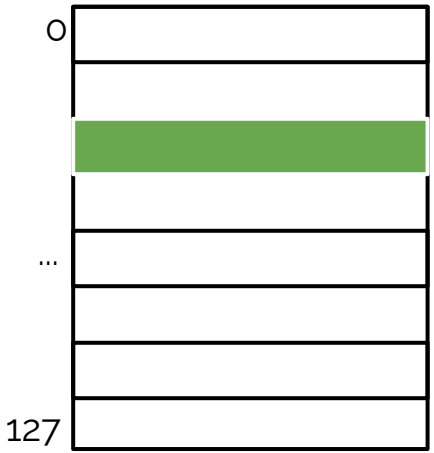
Way 3

Prime+Probe

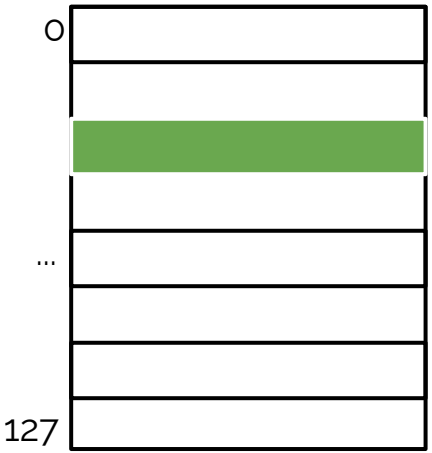
Step 1 Prime: Attacker occupies a set

Attacker Address Space

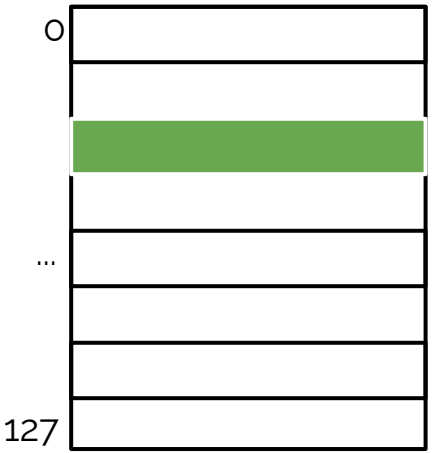
Victim Address Space



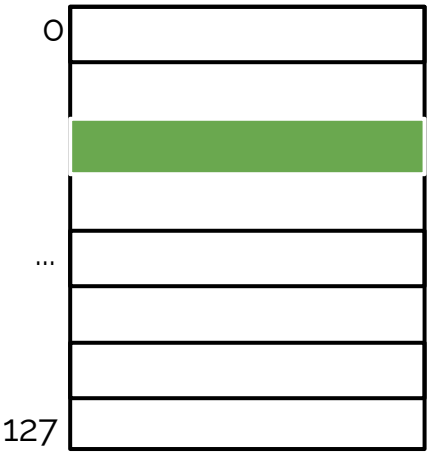
Way 0



Way 1



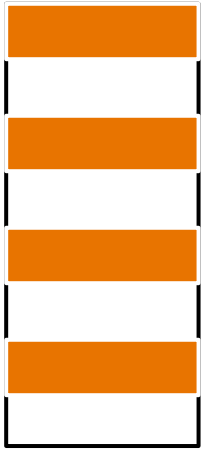
Way 2



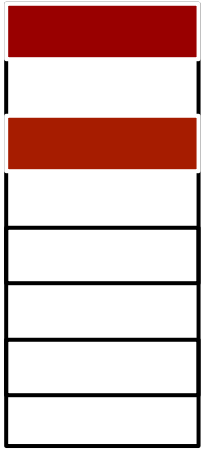
Way 3

Prime+Probe

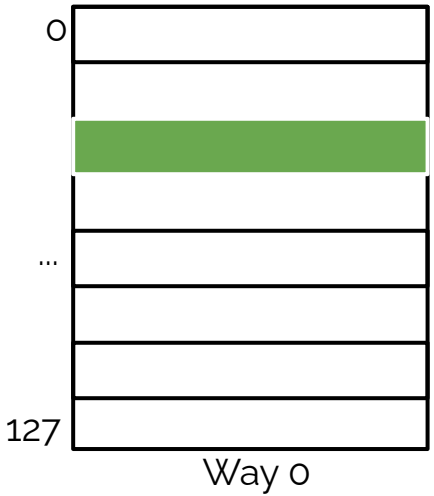
Step 2: Victim runs

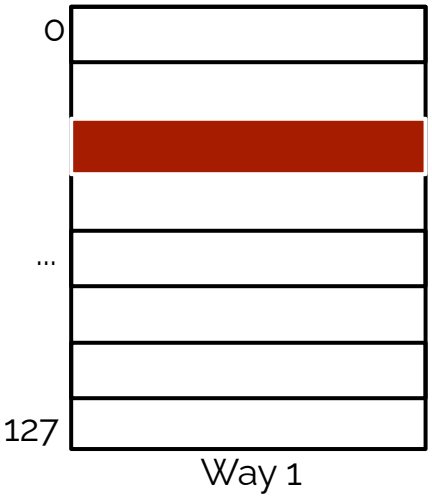


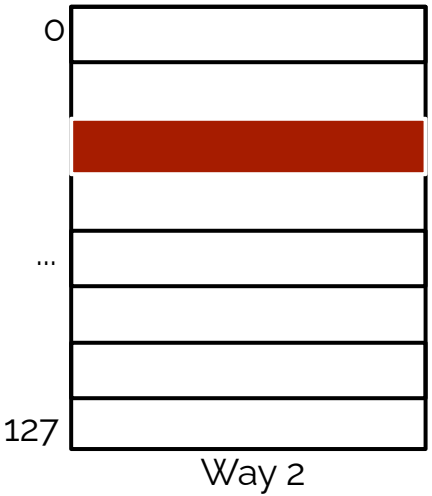
Attacker Address Space

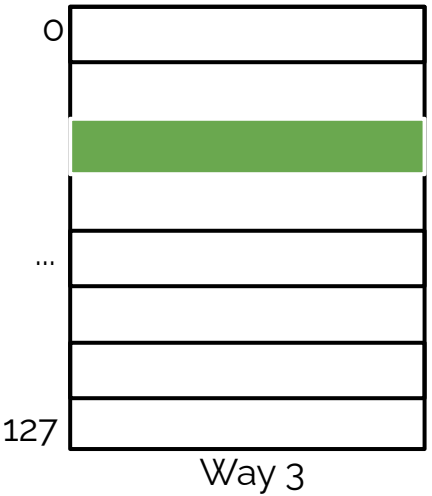


Victim Address Space





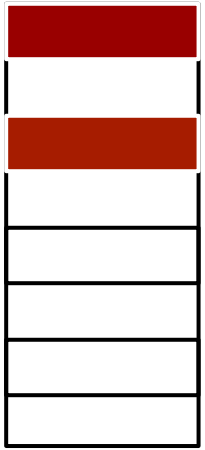




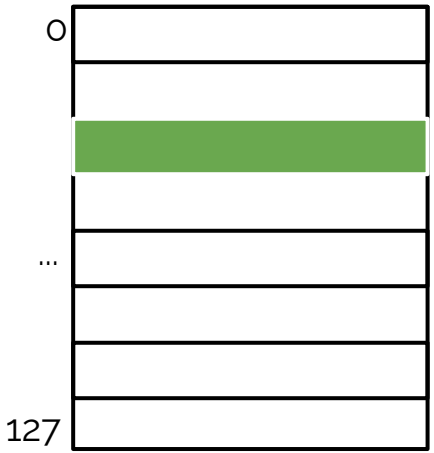
Prime+Probe

Step 3 Probe: Attacker accesses memory again and measures the time

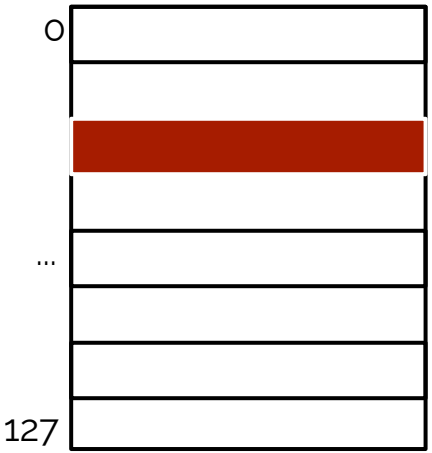
Attacker Address Space



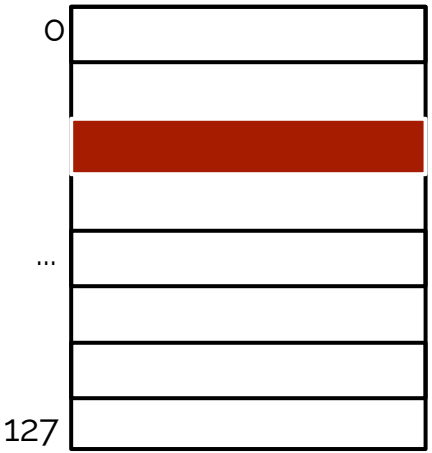
Victim Address Space



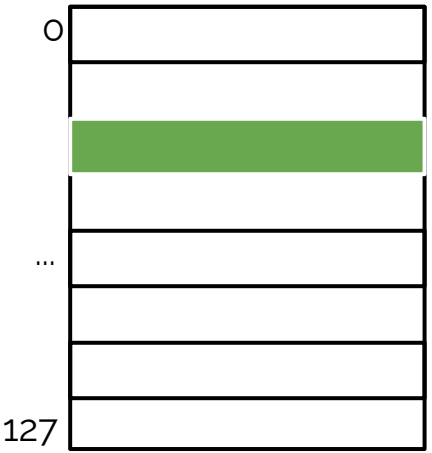
Way 0



Way 1



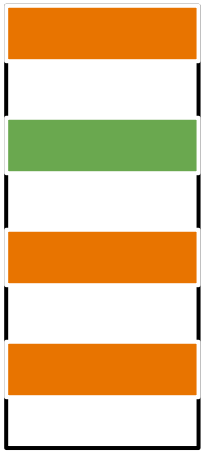
Way 2



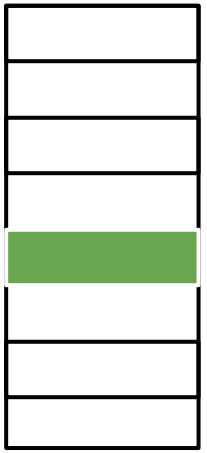
Way 3

Flush+Reload

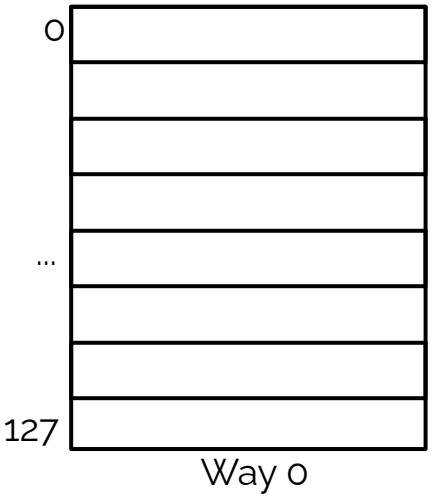
A memory block is cached

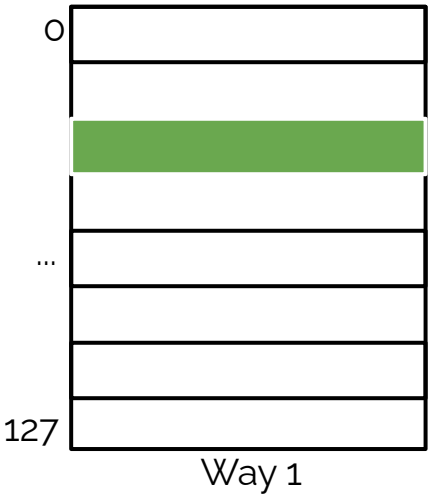


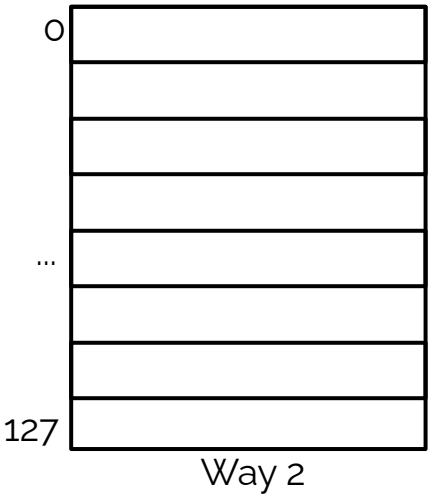
Attacker Address Space

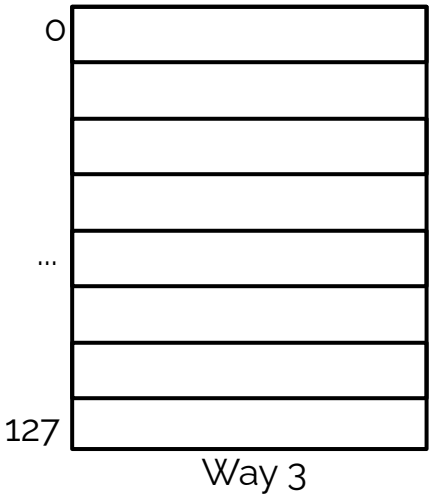


Victim Address Space





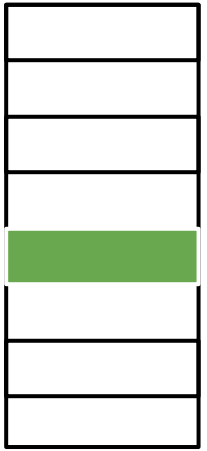




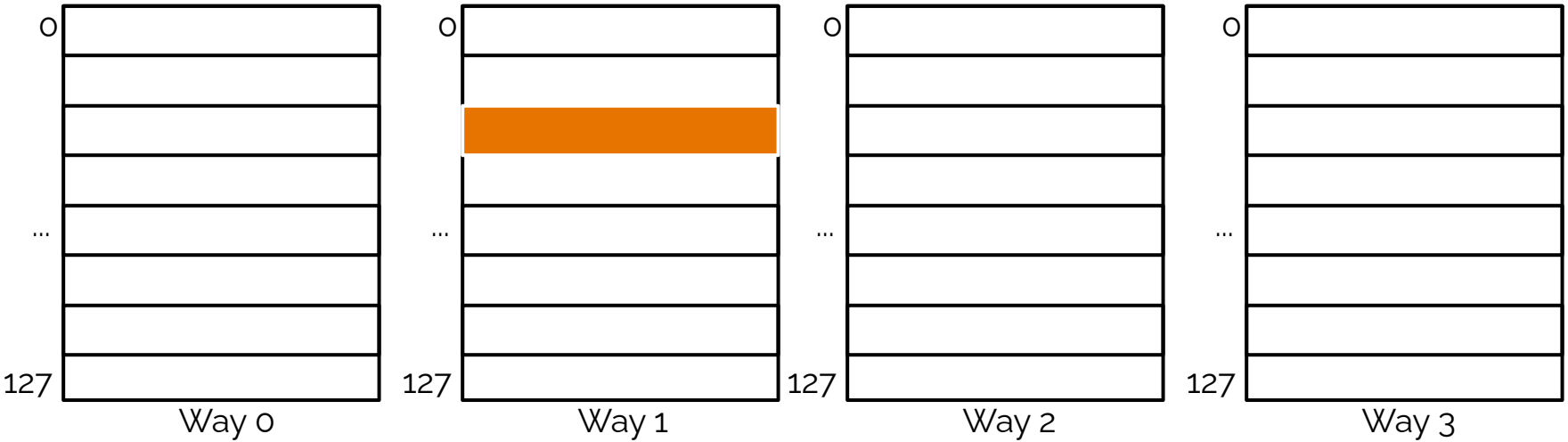
Flush+Reload

Attacker Address Space

Step 1 Flush: Attacker flushes this memory block out of cache



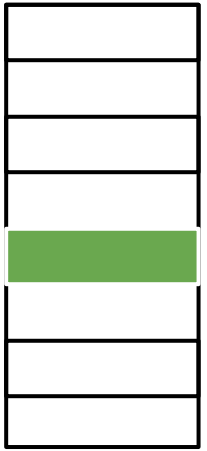
Victim Address Space



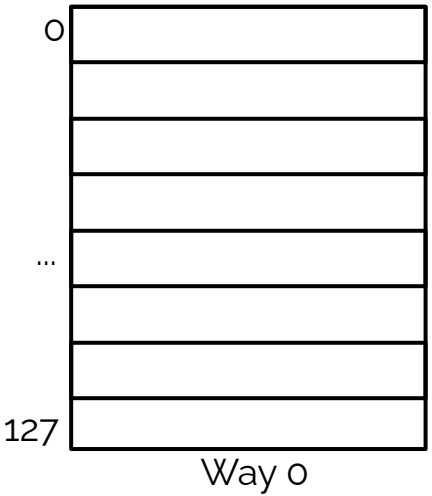
Flush+Reload

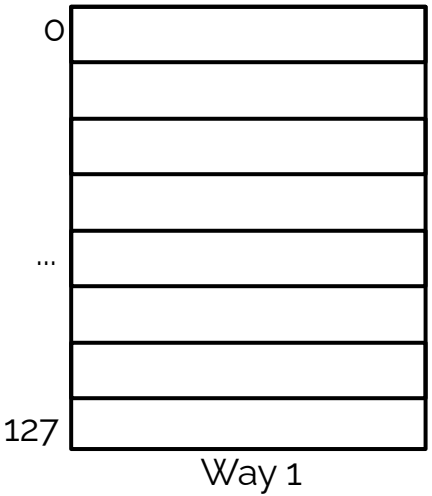
Step 2 Reload: Victim may / may not access that block again

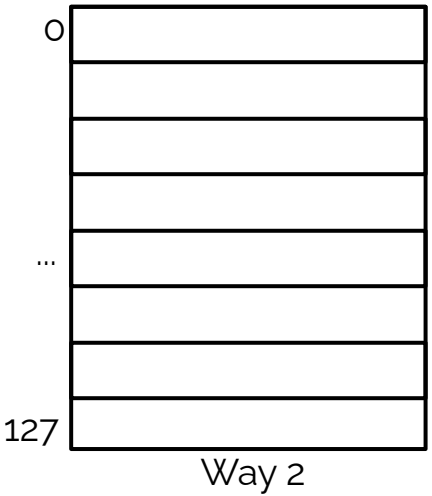
Attacker Address Space

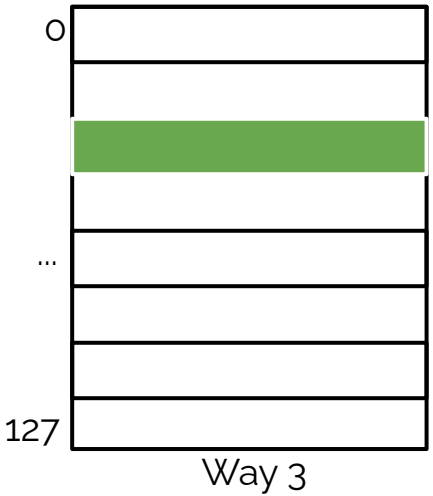


Victim Address Space



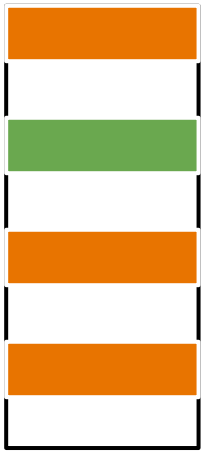




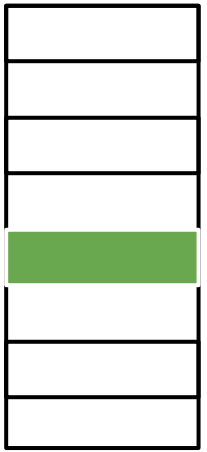


Flush+Reload

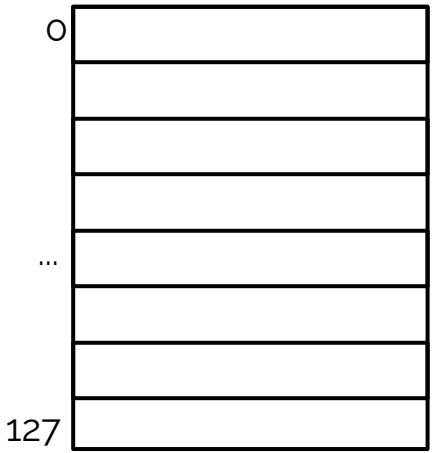
Step 3 Probe: Attacker accesses that block again and measure



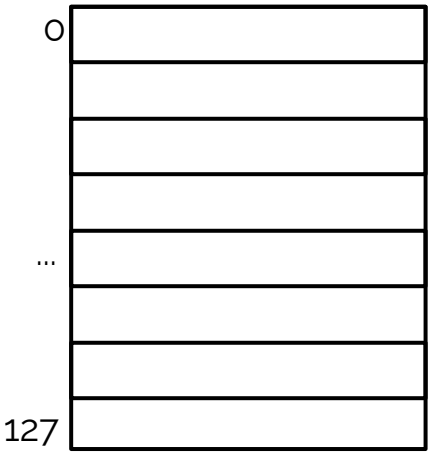
Attacker Address Space



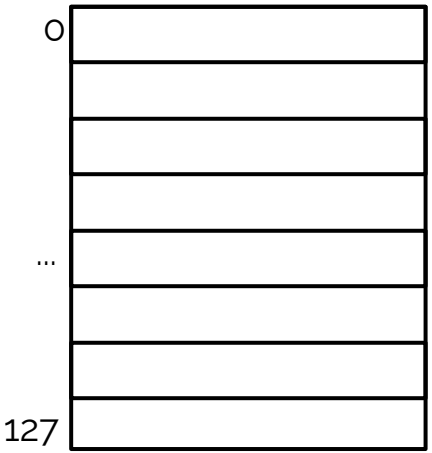
Victim Address Space



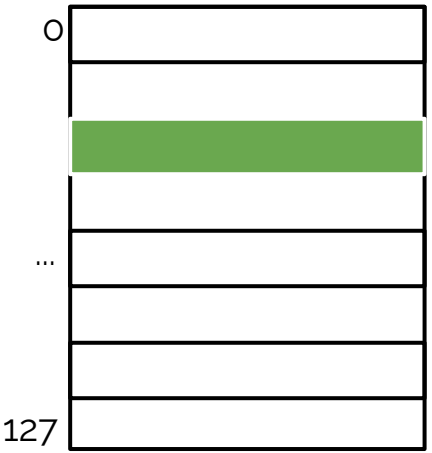
Way 0



Way 1



Way 2



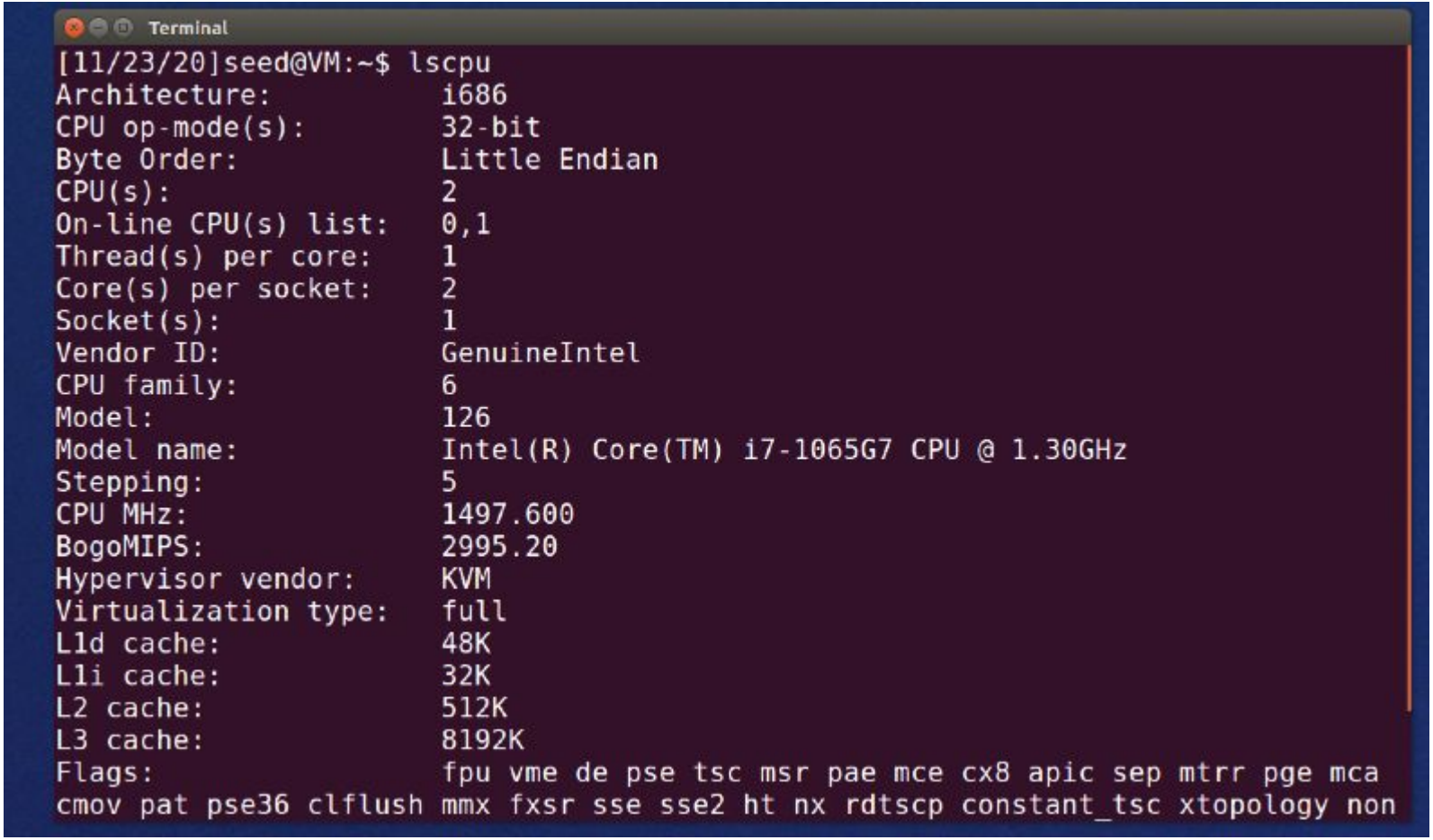
Way 3

Cachetime.c from SEED labs

```
uint8_t array[10*4096];

int main(int argc, const char **argv) {
  int junk=0;
  register uint64_t time1, time2;
  volatile uint8_t *addr;
  int i;

  // Initialize the array
  for(i=0; i<10; i++) array[i*4096]=1;

  // FLUSH the array from the CPU cache
  for(i=0; i<10; i++) _mm_clflush(&array[i*4096]);

  // Access some of the array items
  array[2*4096] = 200;
  array[8*4096] = 200;

  for(i=0; i<10; i++) {
    addr = &array[i*4096];
    time1 = __rdtscp(&junk);
    junk = *addr;
    time2 = __rdtscp(&junk) - time1;
    printf("Access time for array[%d*4096]: %d CPU cycles\n",i, (int)time2);
  }
  return 0;
}
```

Flush_reload.c from SEED labs

gcc -march=native CacheTime.c


Terminal
[11/23/20]seed@VM:~$ lscpu
Architecture: i686
CPU op-mode(s): 32-bit
Byte Order: Little Endian
CPU(s): 2
On-line CPU(s) list: 0,1
Thread(s) per core: 1
Core(s) per socket: 2
Socket(s): 1
Vendor ID: GenuineIntel
CPU family: 6
Model: 126
Model name: Intel(R) Core(TM) i7-1065G7 CPU @ 1.30GHz
Stepping: 5
CPU MHz: 1497.600
BogoMIPS: 2995.20
Hypervisor vendor: KVM
Virtualization type: full
L1d cache: 48K
L1i cache: 32K
L2 cache: 512K
L3 cache: 8192K
Flags: fpu vme de pse tsc msr pae mce cx8 apic sep mtrr pge mca
cmov pat pse36 clflush mmx fxsr sse sse2 ht nx rdtscp constant_tsc xtopology non

Meltdown and Spectre

https://meltdownattack.com/

https://cve.mitre.org/cgi-bin/cvename.cgi?name=CVE-2017-5754

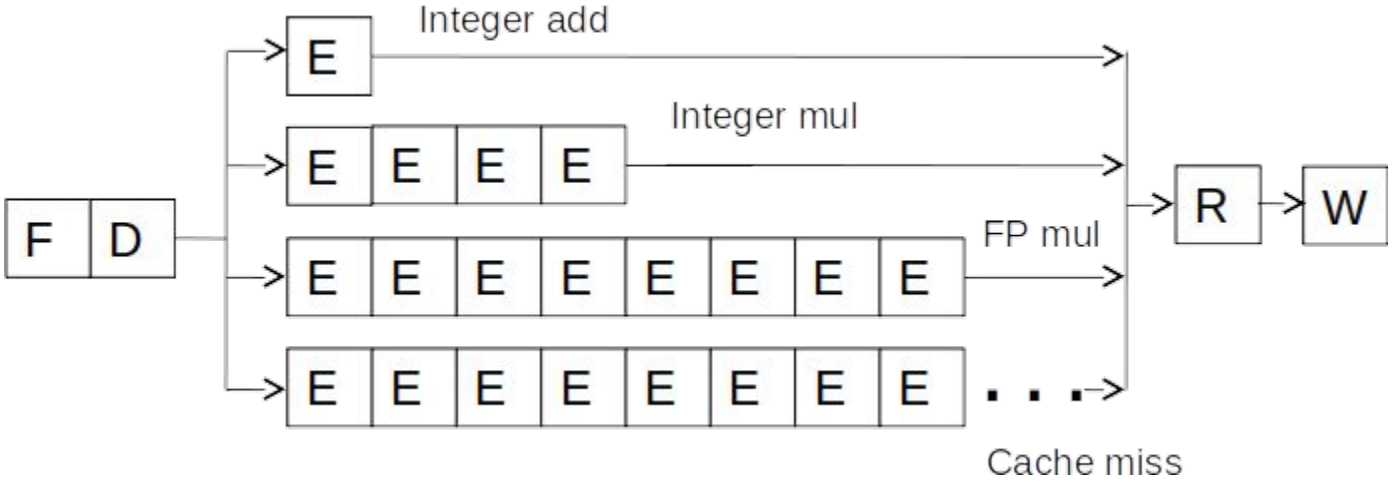
Meltdown Basics

Meltdown allows attackers to read arbitrary physical memory (including kernel memory) from an unprivileged user process

Meltdown uses ***out of order instruction execution*** to leak data via a processor covert channel (cache lines)

Meltdown was patched (in Linux) with KAISER/KPTI

An In-order Pipeline



Problem: A true data dependency stalls dispatch of younger instructions into functional (execution) units

Dispatch: Act of sending an instruction to a functional unit

Can We Do Better?

What do the following two pieces of code have in common (with respect to execution in the previous design)?

```
IMUL  R3 ← R1, R2
ADD   R3 ← R3, R1
ADD   R1 ← R6, R7
IMUL  R5 ← R6, R8
ADD   R7 ← R3, R5
```

```
LD    R3 ← R1 (0)
ADD   R3 ← R3, R1
ADD   R1 ← R6, R7
IMUL  R5 ← R6, R8
ADD   R7 ← R3, R5
```

Answer: First ADD stalls the whole pipeline!
ADD cannot dispatch because its source registers unavailable
Later independent instructions cannot get executed

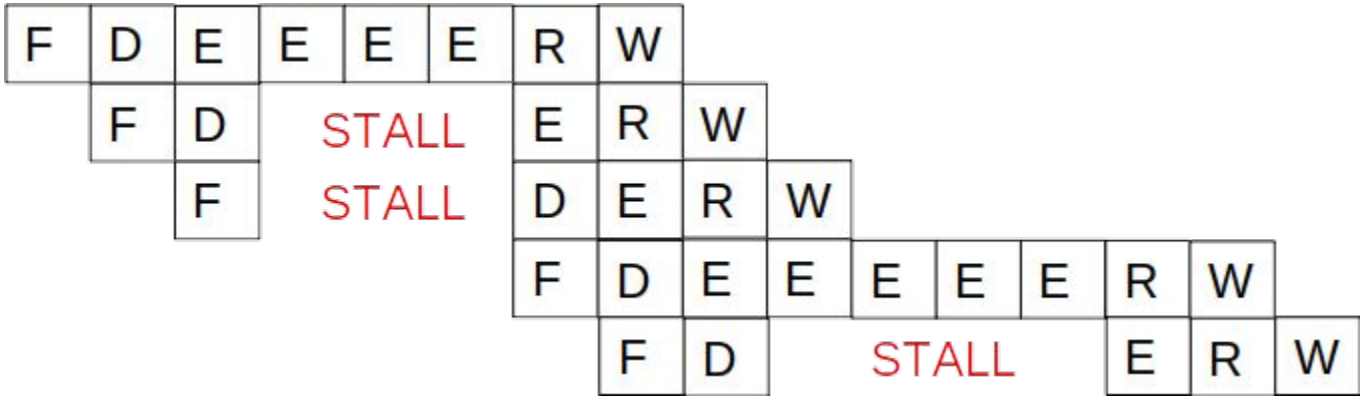
Out-of-Order Execution (Dynamic Instruction Scheduling)

Idea: Move the dependent instructions out of the way of independent ones; Rest areas for dependent instructions: Reservation stations

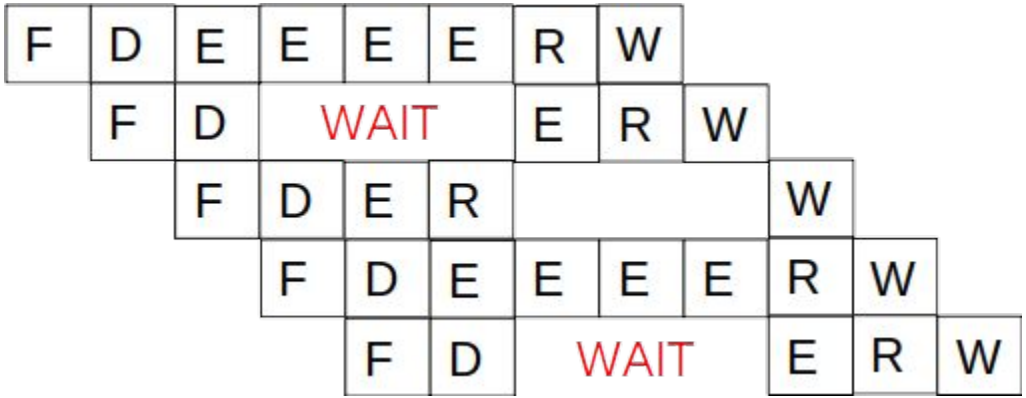
Monitor the source “values” of each instruction in the resting area. When all source “values” of an instruction are available, “fire” (i.e. dispatch) the instruction. Instructions dispatched in dataflow (not control-flow) order

Benefit: Latency tolerance: Allows independent instructions to execute and complete in the presence of a long latency operation

In-order vs. Out-of-order Dispatch



IMUL R3 ← R1, R2
ADD R3 ← R3, R1
ADD R1 ← R6, R7
IMUL R5 ← R6, R8
ADD R7 ← R3, R5



```c
#include <linux/kernel.h>
#include <linux/init.h>
#include <linux/vmalloc.h>
#include <linux/version.h>
#include <linux/proc_fs.h>
#include <linux/seq_file.h>
#include <linux/uaccess.h>

static char secret[8] = {'S','E','E','D','L','a','b','s'};
static struct proc_dir_entry *secret_entry;
static char* secret_buffer;

static int test_proc_open(struct inode *inode, struct file *file)
{
#if LINUX_VERSION_CODE <= KERNEL_VERSION(4,0,0)
   return single_open(file, NULL, PDE(inode)->data);
#else
   return single_open(file, NULL, PDE_DATA(inode));
#endif
}

static ssize_t read_proc(struct file *filp, char *buffer,
                         size_t length, loff_t *offset)
{
   memcpy(secret_buffer, &secret, 8);
   return 8;
}

static const struct file_operations test_proc_fops =
{
   .owner = THIS_MODULE,
   .open = test_proc_open,
   .read = read_proc,
   .llseek = seq_lseek,
   .release = single_release,
};

static __init int test_proc_init(void)
{
   // write message in kernel message buffer
   printk("secret data address:%p\n", &secret);

   secret_buffer = (char*)vmalloc(8);

   // create data entry in /proc
   secret_entry = proc_create_data("secret_data",
                  0444, NULL, &test_proc_fops, NULL);
   if (secret_entry) return 0;

   return -ENOMEM;
}

static __exit void test_proc_cleanup(void)
{
   remove_proc_entry("secret_data", NULL);
}

module_init(test_proc_init);
module_exit(test_proc_cleanup);[12/02/20]seed@VM:~/Meltdown_Attack$
```

Speculative Execution

The processor can preserve its current register state, make a prediction as to the path that the program will follow, and speculatively execute instructions along the path.

If the prediction turns out to be correct, the results of the speculative execution are committed (i.e., saved), yielding a performance advantage over idling during the wait.

Otherwise, when the processor determines that it followed the wrong path, it abandons the work it performed speculatively by reverting its register state and resuming along the correct path.

Speculative Execution

Speculative execution on modern CPUs can run several hundred instructions ahead.

Speculative execution is an optimization technique where a computer system performs some task that may not be needed. Work is done before it is known whether it is actually needed, so as to prevent a delay that would have to be incurred by doing the work after it is known that it is needed.

Branch Prediction

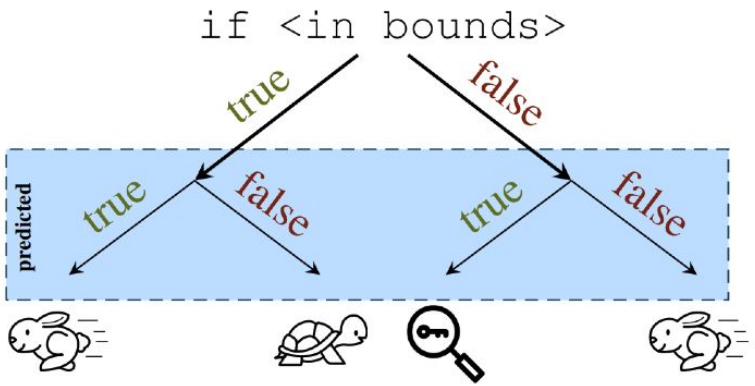
During speculative execution, the processor makes guesses as to the likely outcome of branch instructions.

The branch predictors of modern Intel processors, e.g., Haswell Xeon processors, have multiple prediction mechanisms for direct and indirect branches.

Spectre V1

Conditional branch misprediction

```
if (x < array1_size)
    y = array2[array1[x] * 4096];
```



Spectre V2

Indirect branches can be poisoned by an attacker and the resulting misprediction of indirect branches can be exploited to read arbitrary memory from another context.

Spectre vs. Meltdown

Meltdown does not use branch prediction. Instead, it relies on the observation that when an instruction causes a trap, following instructions are executed out-of-order before being terminated.

Second, Meltdown exploits a vulnerability specific to many Intel and some ARM processors which allows certain speculatively executed instructions to bypass memory protection.

Meltdown accesses kernel memory from user space. This access causes a trap, but before the trap is issued, the instructions that follow the access leak the contents of the accessed memory through a cache covert channel.