SDC

STORAGE DEVELOPER CONFERENCE

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Solving the Challenges of Crash Recoverability in Persistent Memory Programming

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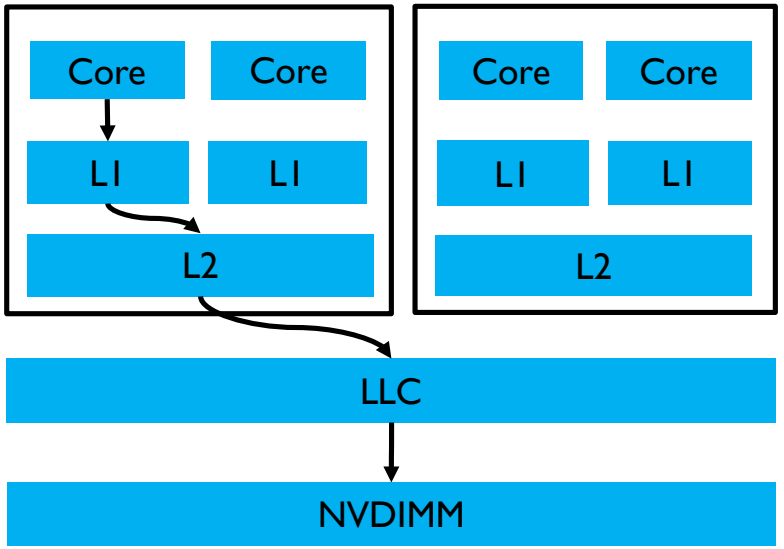
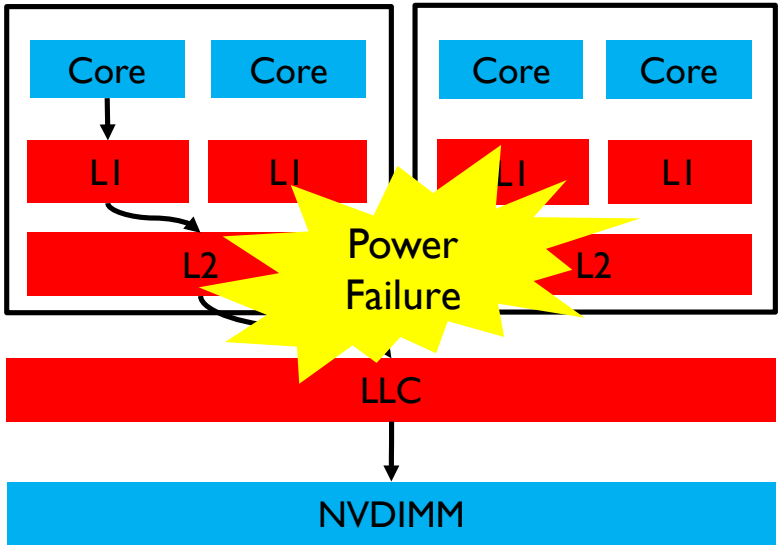
Persistent Memory

- Survive power or system failures
- Byte addressable
- Load/store instructions



Store != Persist

- Stored data is not persistent until it reaches the persistent memory domain
- Persistence order and store order can be different
- Volatile cache does not survive power loss



Crash Recoverability

- A power or system failure can leave a data structure in corrupted or unrecoverable state
- Crash recoverability at data structure level is crucial to higher level data consistency

Address Book Example

writeaddressbook.c

```
struct address {
        char name[64];
        char address[64];
        int valid;
};
int main()
{
        struct address *head = NULL;
        int fd;

        fd = open("addressbook.pmem", O_CREAT|O_RDWR, 0666);
        posix_fallocate(fd, 0, sizeof(struct address));
        head = (struct address *)mmap(NULL, sizeof(struct address),
                PROT_READ|PROT_WRITE, MAP_SHARED, fd, 0);
        close(fd);
        strcpy(head->name, "Clark Kent");
        strcpy(head->address, "344 Clinton St, Metropolis, DC 95308");
        head->valid = 1;

}
```

readaddressbook.c

```
struct address {
        char name[64];
        char address[64];
        int valid;
};
int main()
{
        struct address *head = NULL;
        int fd;

        fd = open("addressbook.pmem", O_RDWR);
        head = (struct address *)mmap(NULL, sizeof(struct address),
                PROT_READ|PROT_WRITE, MAP_PRIVATE|
                MAP_NORESERVE, fd, 0);
        close(fd);
        if (head->valid == 1)
                printf("%s %s\n", head->name, head->address);
        ……
}
```


What Could Be in The Memory After The Power Failure?

Clark Kent\0
344 Clinton St, Metropolis, DC 95308\0
1

Clark Kent\0
344 Clinton St, Metropolis, DC 95308\0
0

Clark Kent\0
\0
1

\0
\0
1

\0
344 Clinton St, Metropolis, DC 95308\0
1

.....

Flushing Cached Stores to Memory

Instruction	Function
CLFLUSH	Flush cache line
CLFLUSHOPT	Flush cache line optimized
CLWB	Cache line write back

- A store fence is usually needed after CLFLUSHOPT or CLWB instruction(s) to enforce correct ordering
- Compilers provide intrinsic functions, _mm_clflushopt(), _mm_sfence(), etc.
- NVML provides high level APIs, pmem_flush(), pmem_persist(), etc.

Flushing Cached Stores Example

```
struct {
        int x;
        ……
        int y;        //x and y are in different cache lines
} z;        // z is in persistent memory
z.x = 0;
_mm_clflushopt(&z.x);
_mm_sfence();
……
z.y = 1;    // z.x is already in persistent memory domain
```


But ……

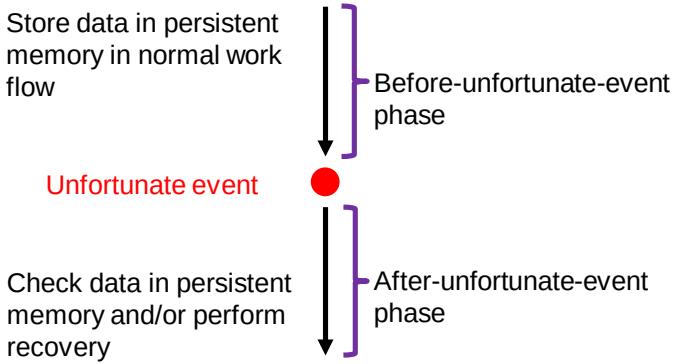
- When a cache line should be flushed?
  - Missing cache line flushes may leave data structures corrupted or unrecoverable
  - Excessive cache line flushes hurt performance
- In what order should cache lines be flushed (or what is the persistence order)?
  - Is it correct to flush “head->address” and “head->name” after “head->valid” is set?
- In what order should data be stored?
  - Is it correct to set “head->valid” before storing “head->address” and/or “head->name”?

Intel® Persistence Inspector

- Dynamic tool for finding missing/redundant cache flushes, missing store fences etc.
- Issues do not need to actually occur
- No source changes required
- Pinpoint issues to exact source locations with stack traces

Unfortunate Events and Persistent Memory Applications

- An unfortunate event, for example, a power failure, divides a persistent memory application into 2 phases
- Normal completion is a special unfortunate event



Two Phases of Address Book Example

Before-unfortunate-event: writeaddressbook

```
struct address {
        char name[64];
        char address[64];
        int valid;
};
int main()
{
        struct address *head = NULL;
        int fd;

        fd = open("addressbook.pmem", O_CREAT|O_RDWR, 0666);
        posix_fallocate(fd, 0, sizeof(struct address));
        head = (struct address *)mmap(NULL, sizeof(struct address),
                PROT_READ|PROT_WRITE, MAP_SHARED, fd, 0);
        close(fd);
        strcpy(head->name, "Clark Kent");
        strcpy(head->address, "344 Clinton St, Metropolis, DC 95308");
        head->valid = 1;
}
```

After-unfortunate-event: readaddressbook

```
struct address {
        char name[64];
        char address[64];
        int valid;
};
int main()
{
        struct address *head = NULL;
        int fd;

        fd = open("addressbook.pmem", O_RDWR);
        head = (struct address *)mmap(NULL, sizeof(struct address),
                PROT_READ|PROT_WRITE, MAP_PRIVATE|
                MAP_NORESERVE, fd, 0);
        close(fd);
        if (head->valid == 1)
                printf("%s %s\n", head->name, head->address);
        ……
}
```


Why Two Phases?

- Persistence matters only if the application stops upon an unfortunate event
- Persistence matters only if the data is used after the application restarts after an unfortunate event
- How data is used after an unfortunate event defines how (the order in which) data should get persistent before the unfortunate event

Using Intel® Persistence Inspector (1/3)

- Step 1: Analyze before-unfortunate-event phase
  - Watch and record persistent memory events

```
$ pmeminsp check-before-unfortunate-event -pmem-file \
addressbook.pmem -- writeaddressbook
```


Using Intel® Persistence Inspector (2/3)

- Step 2: Analyze after-unfortunate-event phase
  - Find persistence orders

```
$ pmeminsp check-after-unfortunate-event -pmem-file \
addressbook.pmem – readaddressbook
```


Using Intel® Persistence Inspector (3/3)

- Step 3: Report
  - Check and report potential persistence order violations

$ pmeminsp report – writeaddressbook readaddressbook

```
#=============================================================================
# Diagnostic # 1: Missing cache flush
#-------------------
 The first memory store
   of size 8 at address 0x7F062D148050 (offset 0x50 in /samples/addressbook.pmem)
   in /samples/addressbook/writeaddressbook!main at writeaddressbook.c:45 - 0x71E
   in /lib/x86_64-linux-gnu/libc.so.6!__libc_start_main at <unknown_file>:<unknown_line> - 0x21F43
 is not flushed before the second memory store
   of size 4 at address 0x7F062D148080 (offset 0x80 in /samples/addressbook/addressbook.pmem)
   in /samples/addressbook/writeaddressbook!main at writeaddressbook.c:46 - 0x73F
   in /lib/x86_64-linux-gnu/libc.so.6!__libc_start_main at <unknown_file>:<unknown_line> - 0x21F43
```

First store location and call stack

Second store location and call stack

Address Book Example (Corrected)

writeaddressbook.c

```
struct address {
        char name[64];
        char address[64];
        int valid;
};
int main()
{
        struct address *head = NULL;
        int fd;

        fd = open("addressbook.pmem", O_CREAT|O_RDWR, 0666);
        posix_fallocate(fd, 0, sizeof(struct address));
        head = (struct address *)mmap(NULL, sizeof(struct address),
                PROT_READ|PROT_WRITE, MAP_SHARED, fd, 0);
        close(fd);
        strcpy(head->name, "Clark Kent");
        strcpy(head->address, "344 Clinton St, Metropolis, DC 95308");
        _mm_clflushopt(&(head->name));
        _mm_clflushopt(&(head->address));
        _mm_sfence();
        head->valid = 1;
        _mm_clflushopt(&(head->valid));
        _mm_sfence();
}
```

readaddressbook.c

```
struct address {
        char name[64];
        char address[64];
        int valid;
};
int main()
{
        struct address *head = NULL;
        int fd;

        fd = open("addressbook.pmem", O_RDWR);
        head = (struct address *)mmap(NULL, sizeof(struct address),
                PROT_READ|PROT_WRITE, MAP_PRIVATE|
                MAP_NORESERVE, fd, 0);
        close(fd);
        if (head->valid == 1)
                printf("%s %s\n", head->name, head->address);
        ……
}
```


Takeaways

- Persistent memory presents new challenges to software developers
- To maintain data recoverability and consistency, cached data updates need to be flushed to persistent memory domain in correct orders
- Intel® Persistence Inspector tool helps developers solve the challenges

Questions?

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