Persistent Memory Programming on Conventional Hardware

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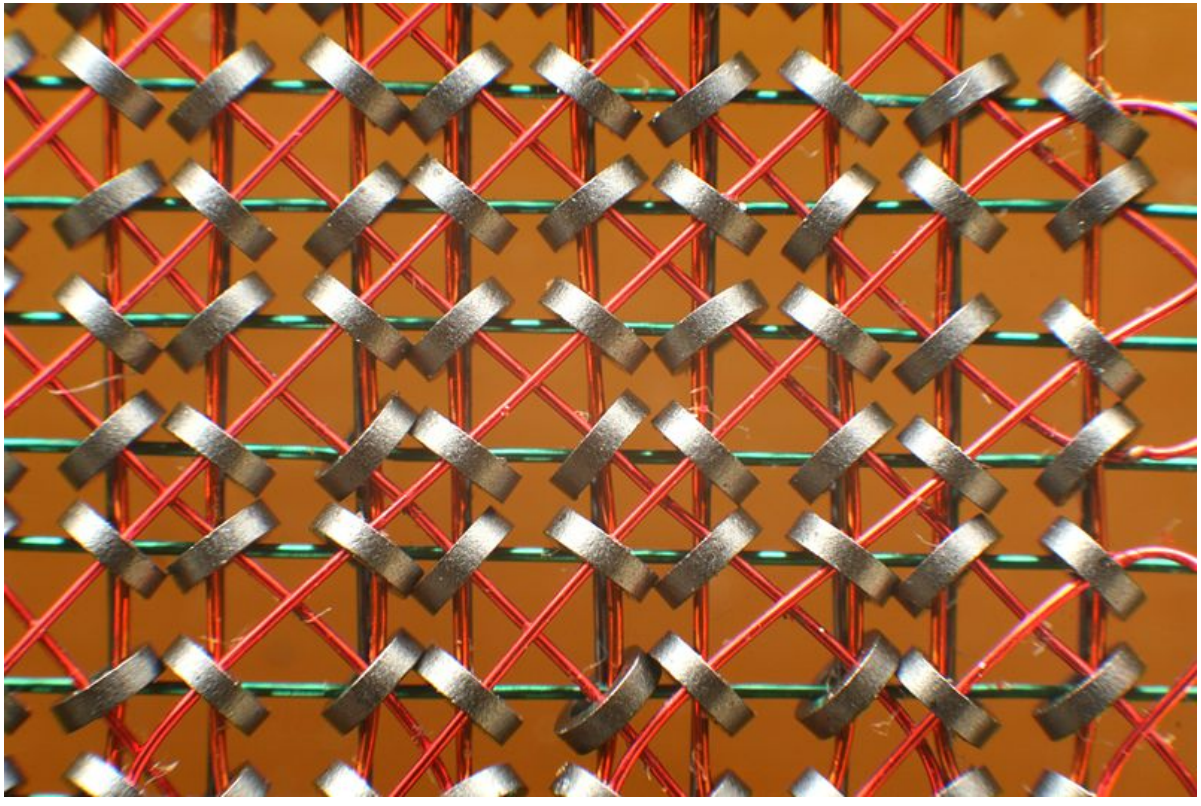
NVM Returns



Advantage: Simplicity

- Fewer moving parts: no quirky external persistent store
- Single data format: no translators, serializers, parsers
- Single paradigm: no mental context switching, "impedance mismatch"
- Often improves cost, correctness, performance

Persistent Memory

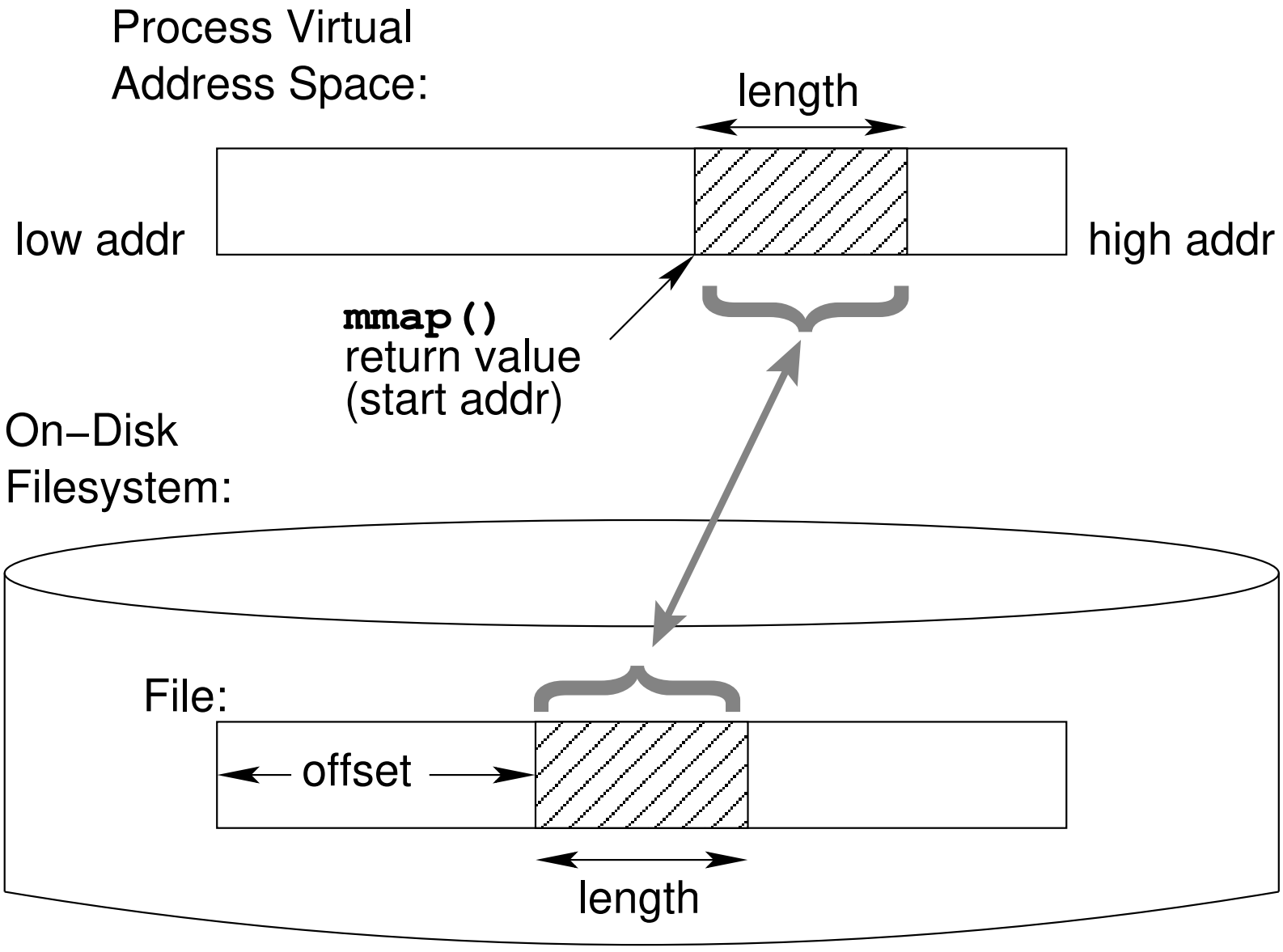
- *Software* abstraction
- Corresponding programming style
- Similar to NVM-style programming, some of same advantages
- Implementable on conventional hardware, without NVM
- This talk: C/C++ on POSIX/Linux

Persistent Memory

Persistent Memory: Elements

- Application data in file-backed memory mapping
- Sparse backing files: pay-as-you-go
- Pointer casts interpret file as application data types
- Persistent heap allocates from file-backed memory mapping
- Sliding persistent heap beneath legacy software

mmap()


Process Virtual
Address Space:
length
low addr
high addr
mmap()
return value
(start addr)
On−Disk
Filesystem:
File:
offset
length

Warm-Up: In-Place "abc" $\rightarrow$ "ABC"

```
char *start, *end, *p;

/* trivially interpret file as byte array */
start = (char *)mmap(NULL, filesize, PROT_READ | PROT_WRITE,
                     MAP_SHARED, filedescriptor, 0);

end = start + filesize - 2;
for (p = start; p < end; p++) {  /* access persistent data... */
  if ('a' == * p    &&
      'b' == *(p+1) &&  /* ... via LOADs ... */
      'c' == *(p+2)) {
                        * p    = 'A';
                        *(p+1) = 'B';  /* ... and STOREs */
                        *(p+2) = 'C';
                     }
}  /* cf. sed */
```

Typed Data Structures

```
struct foo { int bar; double qux; } *foop;

/* interpret file contents as application-defined type */
foop = (struct foo *)mmap(NULL, filesize,
                          PROT_READ | PROT_WRITE,
                          MAP_SHARED, filedescriptor, 0);

/* access/update persistent data ... */
if (foop->bar)          /* ... via LOADs ... */
    foop->qux *= 2.0;   /* ... and STOREs, with type checking */
```

Persistent Heap, Gordian Knot Edition

From `famus` Example 2

```
typedef struct { void *mapaddr, *root, *avail, *end; } *pheap_t;  /* persistent heap bookkeeping */
static pheap_t e_pheap;

static void *M(size_t s) {  /* simple bump-pointer allocator */
  void *r = e_pheap->avail;
  size_t u = sizeof *e_pheap, nu = s / u + (0 == s % u ? 0 : 1);
  e_pheap->avail = (pheap_t)(e_pheap->avail) + nu;
  assert(e_pheap->avail <= e_pheap->end);  /* out of memory? */
  return r;
}

static void F(void *p) { assert(NULL != p); return; }  /* just leak it */

#define BA bad_alloc
#define OP operator
#define NU (size_t s) throw (BA) { void *r = M(s); if (!r) throw (e); return r; }
#define DL (void * p) throw (  ) { F(p); }

BA e;

void * OP new   NU void OP delete   DL  /* overload global operators */
void * OP new[] NU void OP delete[] DL
```

Sliding Persistent Heap Beneath C++ STL <map>

From famus Example 2

```
void *ma;  /* address to map backing file */
...
ssize_t n = read(backing_file_fd, &ma, sizeof ma);    /* is address already in backing file? */
if (NULL == ma) {
  /* find good address range to map backing file; famus provides code */
}

e_pheap = (pheap_t)mmap(...);

map<string, int> *m;  /* entry point to persistent C++ STL <map> */

if (NULL == e_pheap->mapaddr) {                        /* initialize newborn persistent heap */
  e_pheap->mapaddr = e_pheap;  /* map at same addr next time */
  e_pheap->avail = 1+e_pheap;
  e_pheap->end = (char *)e_pheap + s;
  m = new map<string, int>;
  e_pheap->root = m;  /* root ptr set to entry persistent <map> */
}
else {                                                 /* resume existing persistent heap */
  m = (map<string,int>*)e_pheap->root;  /* find <map> via root */
}

/* preliminaries over; use the <map> as usual; below is input word frequency counter */
while (cin >> w) {
  if ("dump" == w)
    for (map<string, int>::const_iterator it = m->begin(); it != m->end(); ++it)
      cout << "dump: " << it->first << " " << it->second << endl;
  else if (m->find(w) == m->end()) (*m)[w] = 1;
  else                             (*m)[w]++;
}
```

Is the <map> Persistent?

```
% truncate -s 409600 backf   # create empty sparse file

% (echo foo; echo bar; echo '[dump]')  |  ./ex_02  backf
dump: bar 1
dump: foo 1

% (echo qux; echo foo; echo '[dump]')  |  ./ex_02  backf
dump: bar 1
dump: foo 2
dump: qux 1
```

Fixed vs. Relocatable

Map persistent data at same address every time

- \+ allows conventional pointers: familiar, convenient
- \+ retrofit persistence onto legacy libraries, programs
- – not standard/portable (but works in practice)
- – inhibits sharing between independent programs
- *use for private heaps, existing code*

Make persistent data structures relocatable

- \+ facilitates sharing persistent data among independent apps
- \+ more standard/portable
- – requires offsets: less convenient/natural than pointers
- – incompatible with pointer-based existing code
- *use for shared databases*

Rules, Guidelines, Tips

- Avoid bugs due to lifetime mismatches
  - pointers from persistent to conventional memory
  - static, external, global variables
  - C++ `vtbl`
- Data races remain illegal
  - don't modify in-memory image during `msync()`
- Re-initialize mutexes etc. following re-start
  - PMDK has a sophisticated way

Failures

- Power outages, OS kernel panics, application process crashes
- May corrupt backing file
- Conventional `mmap()`/`msync()` not atomic w.r.t. failure

Scandal

- POSIX & default Linux filesystems don't support efficient standard failure-atomic update for *application data* in files
- Filesystems protect only *metadata*
  - cf. police prevent crime against cops
- Constructing atomicity from ordering primitives (`fsync()`, `msync()`) left as an exercise

What!? No Failure Atomicity!?

FAMS: Failure-Atomic `msync()`

- Backing file always reflects most recent `msync()`
  - even if failures occur
- Restricts behavior of conventional `mmap()`/`msync()`
  - easy to reason about
- Efficient
  - like ordinary `msync()`, writes only dirty pages
- Tolerates fail-stop failures
  - e.g., power outages, OS panic, application crash
  - direct corruption of backing file not tolerated
  - not magic; doesn't fix C/C++ safety problems

FAMS Rules, Guidelines, Tips

- All rules for conventional `mmap() / msync()`
- Call FAMS only when data consistent, invariants hold
- Check invariants carefully before calling FAMS
- Crash with confidence

FAMS Implementations

Past:

- "Ken," user-space library (USENIX ATC 2012)
- Linux kernel (EuroSys 2013)
- HP Advanced File System (FAST 2015)
- NOVA filesystem (FAST 2016)

Present/Future:

- XFS, Christoph Hellwig
- `famus`: failure-atomic `msync()` in user space

Experience

- Tycoon networked key-value store: 1 LOC
- SQLite database: 2 LOC
- Crash-resilient JavaScript interpreter ("V8Ken")
- HP Indigo printing presses

FAMS makes it easy to retrofit crash resilience

FAMS Attractions I

- Flexible implementation: OS, filesystem, library
- Storage is a placeholder (for most implementations)
  - local HDD/SSD, RAID array, cloud storage
  - durability, availability, endurance, performance
  - application doesn't change
- Big-data friendly (some implementations)
  - overall persistent data: max file size
  - working set: max virtual memory
  - "transaction size" (Δ between `msync()`s): free storage
- No pairing "begin transaction" / "end transaction"
  - cf. malloc/free, lock/unlock, open/close

FAMS Attractions II

- Easy to retrofit crash resilience onto legacy code
- Easy to reason about: restricts familiar semantics
- Easy to check global invariants: before calling FAMS
- Data versioning for free (in some implementations)
- No special hardware required

famus: Failure-Atomic msync() in User Space

- Clean-slate re-write from scratch
- Modification tracking: Linux soft dirty bits
- Atomicity: UNDO logging
- Supports data versioning
  - Every failure-atomic msync() call defines a version
  - Retain UNDO logs, apply to backing file to revert
- Preliminary release
  - http://web.eecs.umich.edu/~tpkelly/famus/
  - WARNING: No powerfail tests yet
  - performance not optimal
- Questions, support, feedback: tpkelly@eecs.umich.edu

Summary

- Persistent memory is a *software* abstraction
- Style of programming & benefits similar to NVM programming
- Implementable on conventional hardware
- Failure-atomic `msync()` addresses failures
- `famus` implements FAMS on Linux
  - `http://web.eecs.umich.edu/~tpkelly/famus/`