J-NVM: Off-Heap Persistent Objects in Java

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Non-volatile main memory

new persistent medium (in-between **SSD** and **DRAM**)

Durable

resists reboots, power loss

High-density

smallest DIMM = 128 GB

Byte addressable

persistent memory abstraction

High-performance

low latency (seq. read/write ~ 160/90ns)
high bandwidth (up to 8.10GB/s, *2nd gen*)

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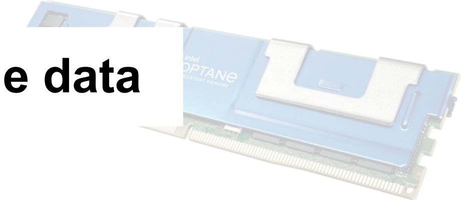

Direct byte-addressability of durable data

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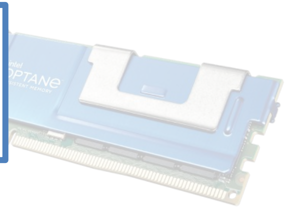

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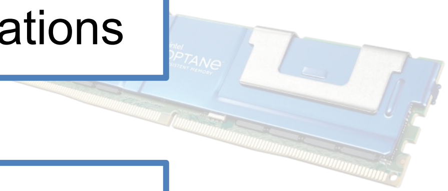


Direct byte-addressability of durable data

↓

1- Dramatic **throughput** and **latency** improvement for persistent data applications

↓

2- Simpler **code** bases with **single data representation** and **no file I/Os**

Why Java?

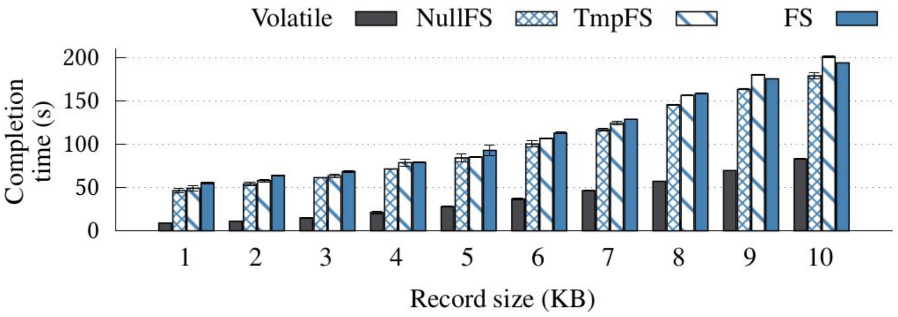
Many data stores & processing frameworks

- Spark, Hadoop, Kafka, Flink, Cassandra, HBase, Elasticsearch, etc.

Lack of *efficient* interfaces

- **FS/ext4-dax**
  - almost as slow as tmpfs
  - dual representation (consistency)
  - cost of marshalling
- **PCJ (JNI+PMDK)**
  - slower than FS on YCSB benchmark

Infinispan Datastore Backends



Varying record size in YCSB-F.

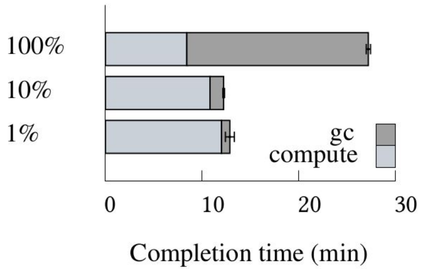
Problematic: Java-native NVMM interface

Prior works: *internal design*

= [Espresso, AutoPersist, go-pmem]

Managed Persistent Objects

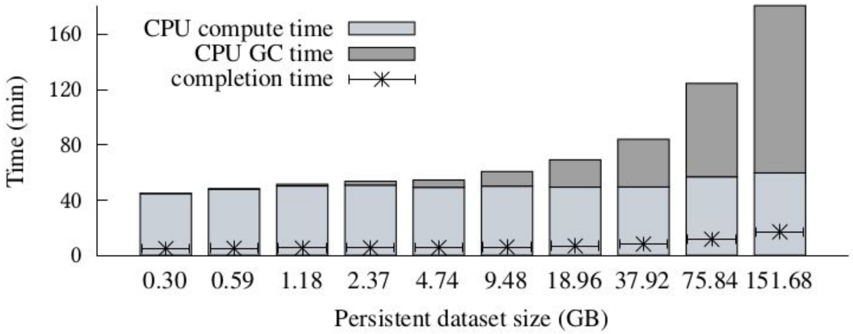
Infinispan datastore in-memory cache ratio



Fixed dataset size - 80GB on heap for 100% cache

Varying cache ratio (YCSB-F)

go-redis-pmem with increasing dataset size



Increasing dataset (YCSB-F, go-pmem)

Features

managed persistent objects

orthogonal persistence (`pnew`, `@persistentRoot`)

heavily-modified runtime

failure-atomic blocks

non-scalable

Garbage collectors can not scale to large persistent datasets

Prior works: *internal design*

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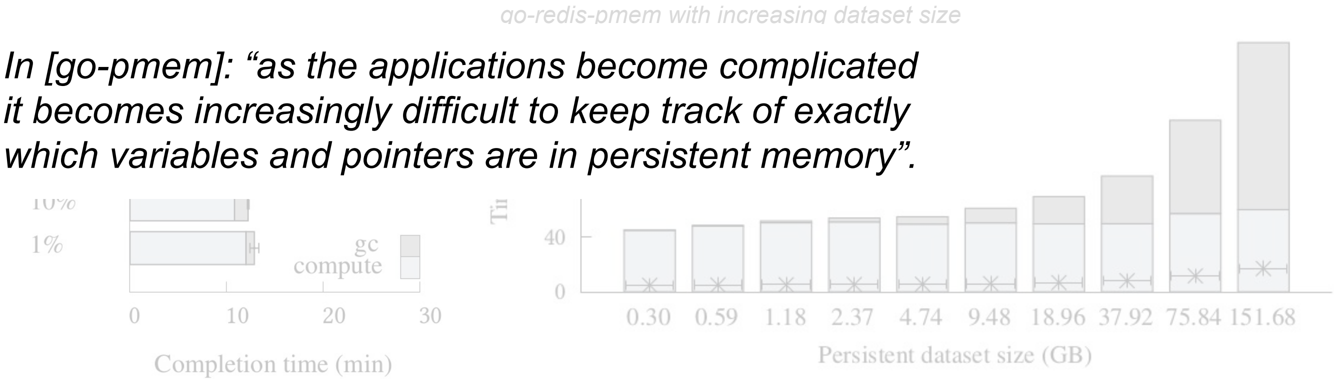
Managed Persistent Objects

In [go-pmem]: “as the applications become complicated it becomes increasingly difficult to keep track of exactly which variables and pointers are in persistent memory”.



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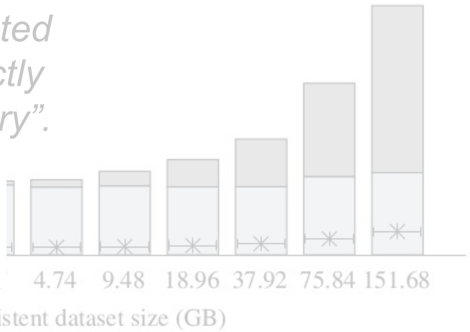
Infinispan datastore in-memory cache ratio

code instrumentation = made whole JVM 51% slower in [Autopersist]



Completion time (min)

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Overview

J-NVM = Off-Heap Persistent Objects

Challenges	→	**Features**
single data representation		*off-heap* persistent objects
programming model		class-centric model (code generator + PDT library)
direct access to NVMM		sun.misc.Unsafe
durability abstraction		failure-atomic blocks + fine-grained
scalability (large persistent dataset)		see evaluation

Outline

Introduction

- NVMM
- why Java?
- prior works
- overview

System Design

- programming model
  - persistent objects
  - code generator
- JPFA
- JPDT

Evaluation

- YCSB benchmark
- recovery

Conclusion

Overview

J-NVM = Off-Heap Persistent Objects

Key idea

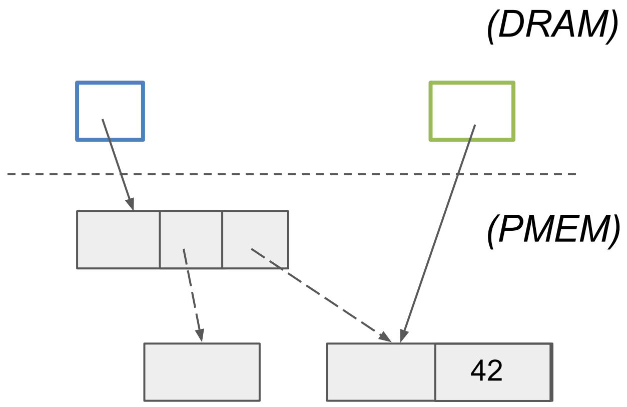
each persistent object is decoupled into

- *a persistent data structure*: unmanaged, allocated off-heap (NVMM)
- *a proxy*: managed, allocated on-heap (DRAM)

Programming model - *persistent objects*

Persistent object is

- a persistent data structure
    - holds object fields
- a proxy
    - holds object methods
    - implement `PObject` interface
    - intermediate access to pers. data structure
    - instantiated lazily (low GC pressure)



Alive when reachable (from persistent root)

```
Map root = JNVM.root();
Simple s = root.get(“Simple”);
s.setX(42);
```

Class-centric model

- safe references thanks to the type system

Programming model - *life cycle*

Constructor

- allocate NVMM
- attach persistent data structure

Re-Constructor

- re-attach proxy
- re-build soft state via resurrect()

Destructor

- explicit **JNVM**.free() to reclaim NVMM
- detach proxy
- ready to be GCed

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Simple s = new Simple(42);
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(DRAM)

(PMEM)

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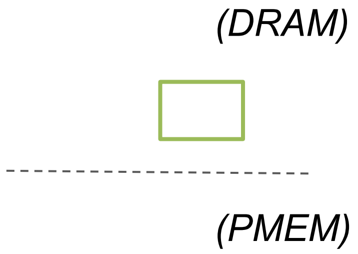

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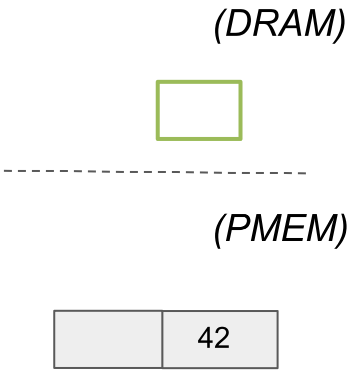

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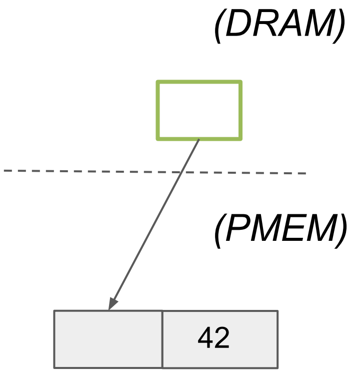

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Simple s = t.getSimple();
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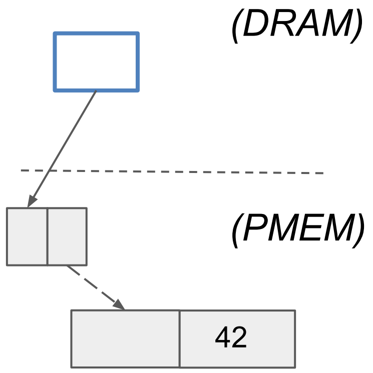

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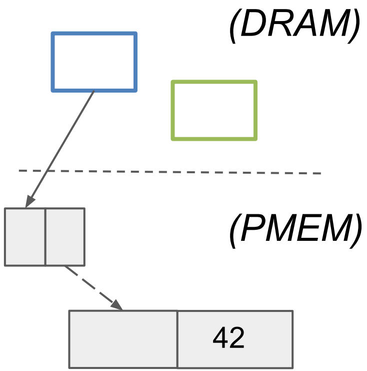

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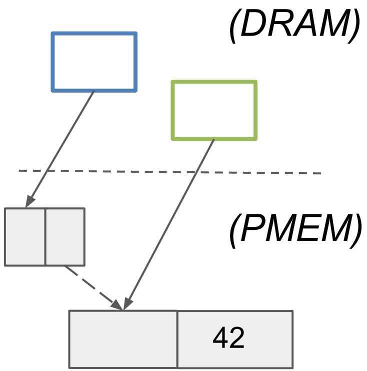

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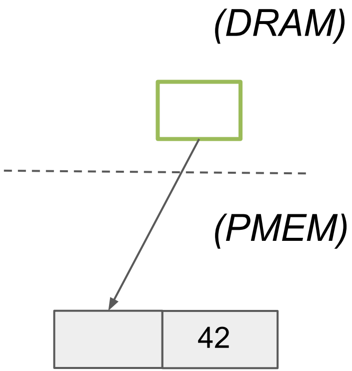

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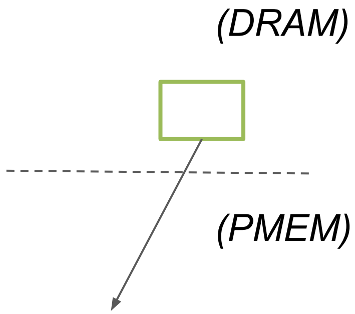

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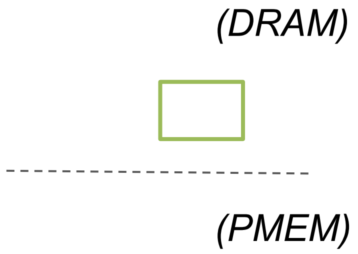

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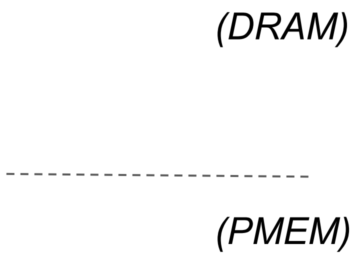

Overview

J-NVM = Off-Heap Persistent Objects

Tooling

- built-in off-heap memory management for NVMM
- **code generator:** automatic decoupling for POJOs
- **J-PFA:** automatic failure-atomic code
- **J-PDT:** data types + collections for persistent memory
- low-level API (for experts)
- recovery-time GC

J-NVM, HMEM'22.

Programming model - *code generator*

```
@Persistent(fa="non-private")
class Simple {
  PString msg;
  int x;
  transient int y;

  Simple(int x) {
    this.x = x;
    this.msg = new PString("Hello, NVMM!");
  }

  void inc() { x++; }
}
```

```
// transformed code
class Simple implements PObject {
  transient int y;
  long addr; // persistent data structure

  Simple(int x) {
    JNVM.faStart();
    this.addr = JNVM.alloc(getClass(), size());
    setX(x);
    setMsg(new PString("Hello, NVMM!"));
    JNVM.faEnd();
  }

  Simple(long addr) {
    this.addr = addr;
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Goals

- class-wide off-heap layout
- generate constructor, re-constructor
- replace (non-transient) field accesses
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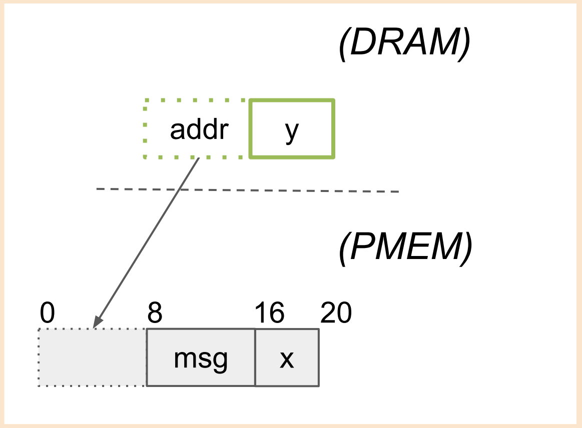

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```java
// transformed code (continued)
  long addr; // the persistent data structure
  long size() { return 12; }

  PString getMsg() { return (PString)
          JNVM.readPObject(addr, 0); }

  void setMsg(PString v) {
          JNVM.writePObject(addr, 0, v); }

  int getX() {return JNVM.readInt(addr, 8);}

  void setX(int v) {JNVM.writeInt(addr, 8, v);}
```

Goals

- class-wide off-heap layout
- generate constructor, re-constructor
- replace (non-transient) field accesses
- wrap non-private methods
- generate or transform field accessors

J-PFA

Automatic crash-consistent update
usage = **JNVM**.faStart() *some code* **JNVM**.faEnd()

Per-thread persistent redo-log (inspired by Romulus)

Log new, free and updates
granularity = a block of PMEM

Do *not* log updates to “new” persistent objects
(e.g. allocated within the FA-block)

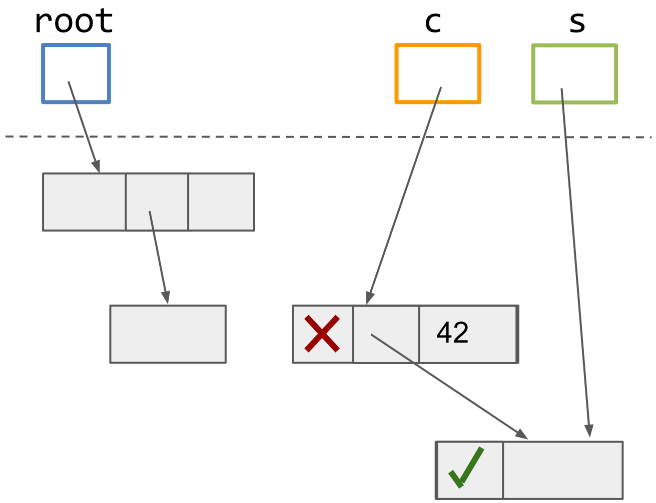
J-PDT + Low-level interface

J-PDT

- drop-in replacement for (part of) JDK e.g., string, native array, map.

Low-level interface

- unsafe.{pwb,pfence, psync}
- NVMM block allocator
- recovery time GC (à la Makalu)
- validation = 1 bit in object header
    - makes atomic reclamation easier
    - allows deferring object liveness
    - interpreted on recovery to reclaim reachable invalid objects



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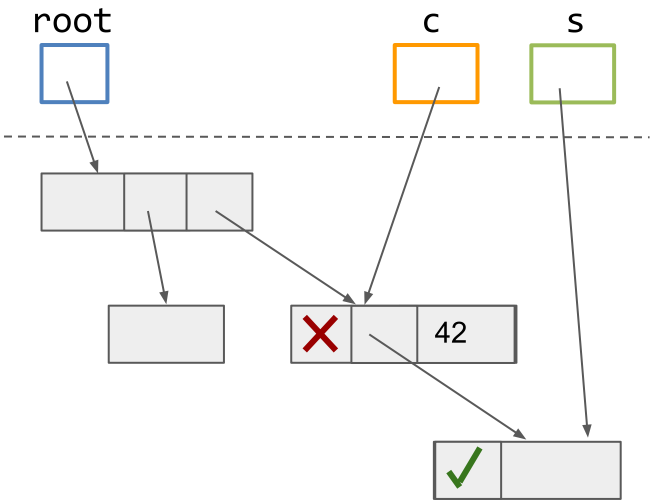

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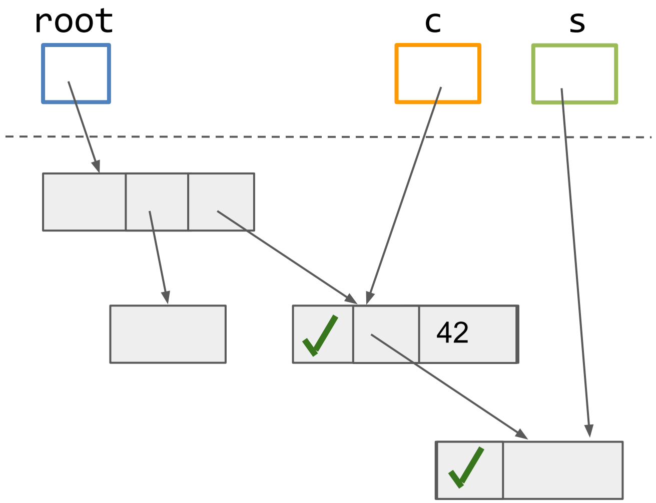

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- JPFA
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Evaluation

- YCSB benchmark
- recovery

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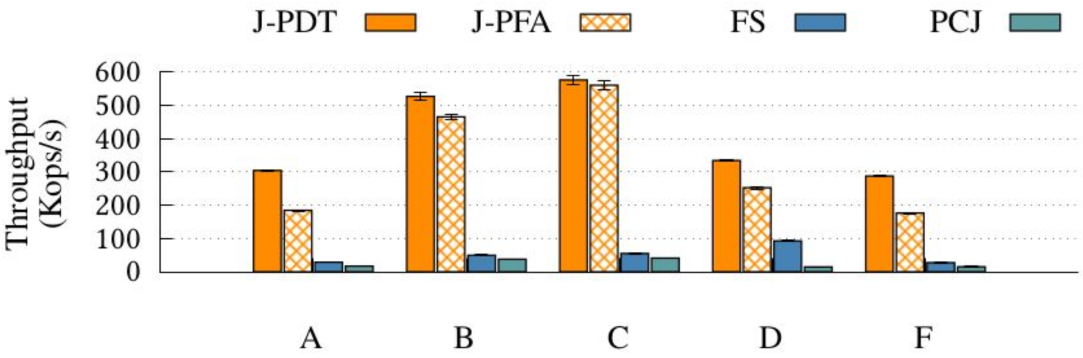
YCSB Benchmark



Durable backends for Infinispan:

- PCJ = HashMap from Persistent Collections Java (JNI + PMDK)
- FS: ext4-dax

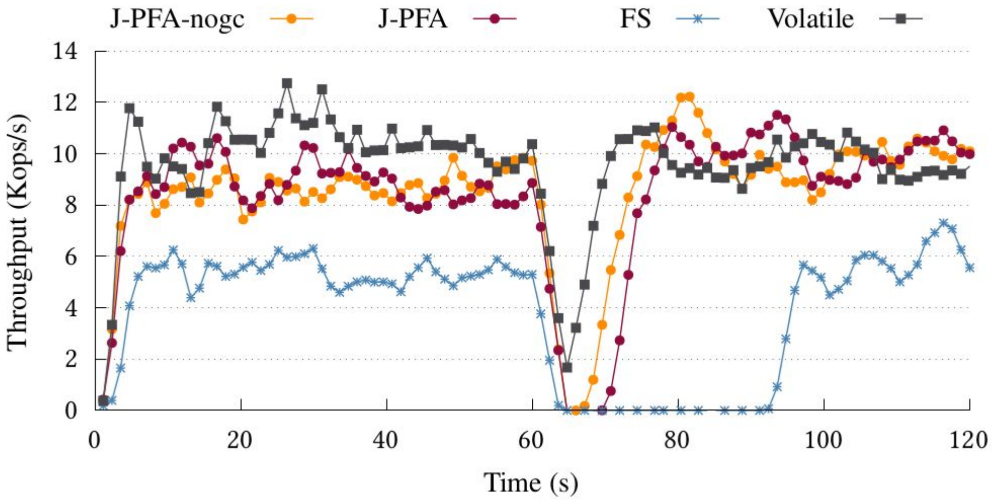
Hardware used:

4 Intel CLX 6230 HT 80-core
128GB DDR4,
4x128GB Optane (gen1)

Takeaways:

- J-NVM up to *10.5x* (resp. *22.7x)* than FS (resp. PCJ)
- no need for volatile cache

Recovery



TPC-B like benchmark
10M accounts (140 B each)
client-server setting
SIGKILL after 1 min

Takeaways:

- J-NVM is more than *5x* faster to recover than FS
- no-need for graph traversal in some cases (e.g., only FA blocks)

Conclusion

J-NVM = off-heap persistent objects

Each persistent object is composed of

- *a persistent data structure*: unmanaged, allocated off-heap (NVMM)
- *a proxy*: managed, allocated on-heap (DRAM)

Pros:

- unique data representation (no data marshalling)
- recovery-time GC (not at runtime, does not scale)
- consistently faster than external designs (JNI, FS)

Cons:

- explicit free ***but*** common for durable data
- limited code re-use ***but*** safer programming model