J-NVM: Off-Heap Persistent Objects in Java

Anatole Lefort, Yohan Pipereau, Kwabena Amponsem,
Pierre Sutra, Gaël Thomas

Télécom SudParis
Institut Polytechnique de Paris

Published at SOSP'21

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*)

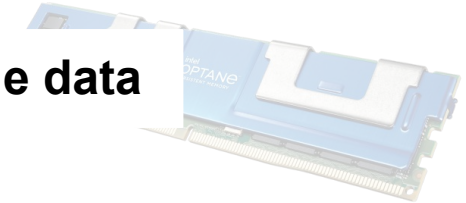
Non-volatile main memory

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

Durable
resists reboots, power loss

High-density
smallest DIMM = 128 GB

Direct byte-addressability of durable data



Byte addressable
persistent memory abstraction

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

Non-volatile main memory

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

Durable
resists rebo

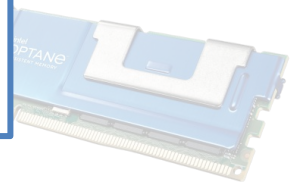
High-density
smallest DI

Byte addressal
persistent memory abstraction

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

Direct byte-addressability of durable data

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



Non-volatile main memory

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

Durable
resists reboots, power loss

High-density
smallest DI

Byte addressable
persistent m

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

Direct byte-addressability of durable data

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

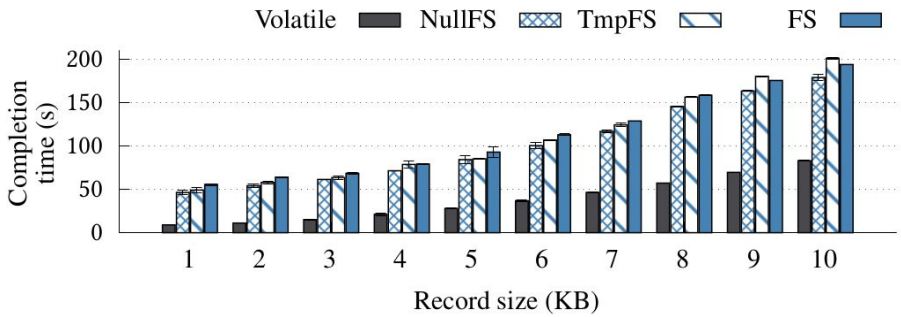
2- Simpler **code** bases with **single data representation** and **no file I/Os**

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.

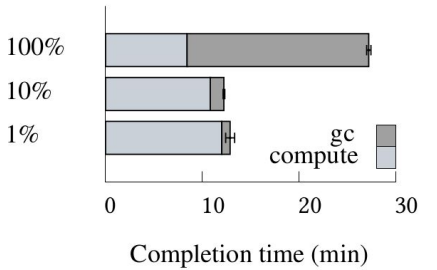
Problematic: Java-native NVMM interface

Prior works: *internal design*

= [Espresso, AutoPersist, go-pmem]

Managed Persistent Objects

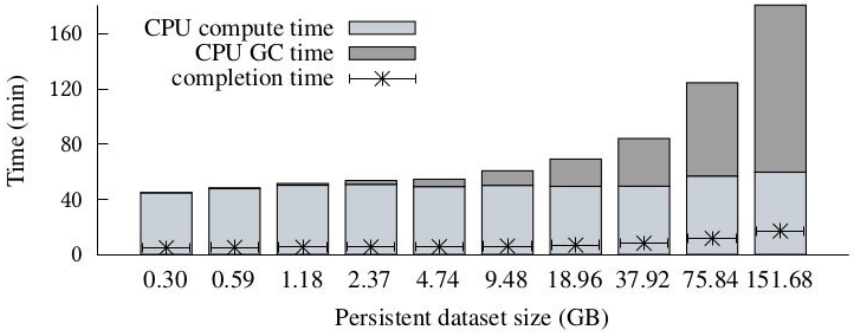
Infinispan datastore in-memory cache ratio



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)

Garbage collectors can not scale to large persistent datasets

Features

managed persistent objects

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

heavily-modified runtime

failure-atomic blocks

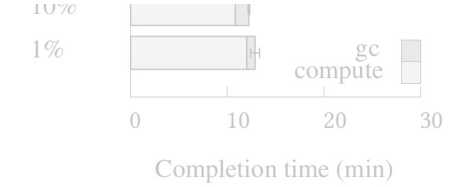
non-scalable

Prior works: *internal design*

= [Espresso, AutoPersist, go-pmem]

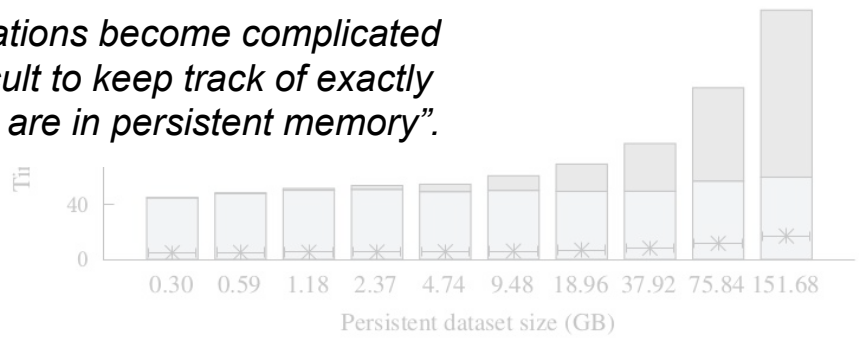
Managed Persistent Objects

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".



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

Varying cache ratio (YCSB-F)



Increasing dataset (YCSB-F, go-pmem)

Garbage collectors can not scale to large persistent datasets

Features

managed persistent objects

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

heavily-modified runtime

failure-atomic blocks

non-scalable

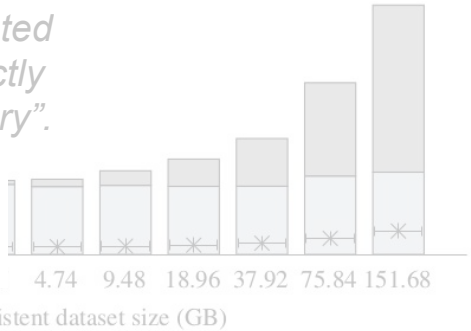
Prior works: *internal design*

= [Espresso, AutoPersist, go-pmem]

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".

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



Completion time (min)

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

Varying cache ratio (YCSB-F)

Increasing dataset (YCSB-F, go-pmem)

Garbage collectors can not scale to large persistent datasets

Features

managed persistent objects

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

heavily-modified runtime

failure-atomic blocks

non-scalable

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

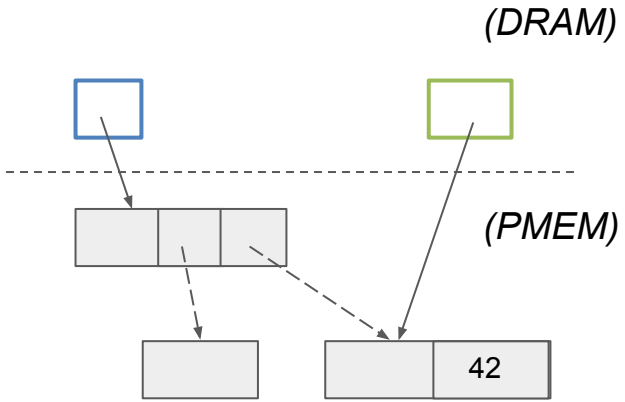
- *a persistent data structure*: unmanaged, allocated off-heap (NVMM)
- *a proxy*: managed, allocated on-heap (DRAM)

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)

Class-centric model
- safe references thanks to the type system




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

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

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

(DRAM)

(PMEM)

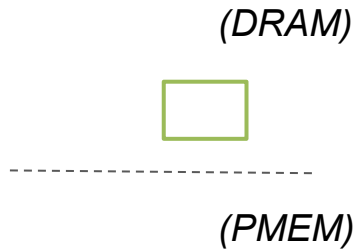
Programming model - *life cycle*

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

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



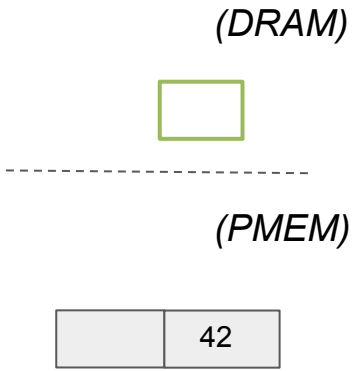
Programming model - *life cycle*

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

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



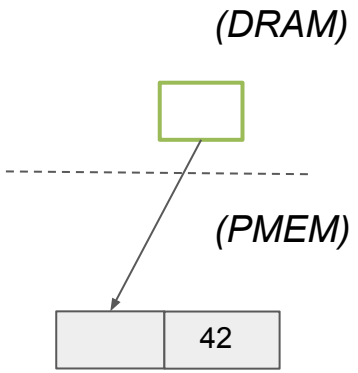
Programming model - *life cycle*

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

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



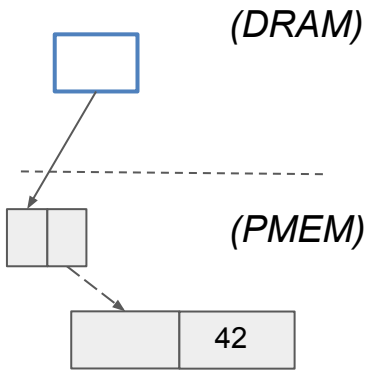
Programming model - *life cycle*

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

```
Simple s = t.getSimple();
```



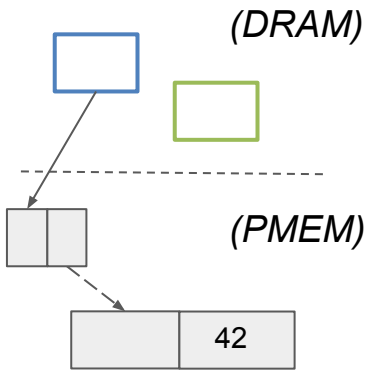
Programming model - *life cycle*

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

```
Simple s = t.getSimple();
```



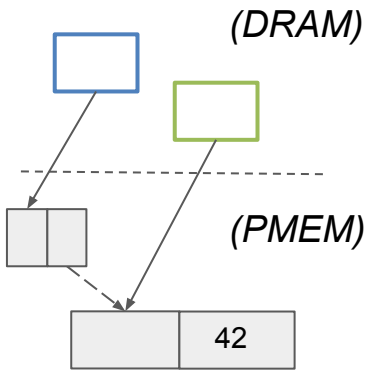
Programming model - *life cycle*

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

```
Simple s = t.getSimple();
```



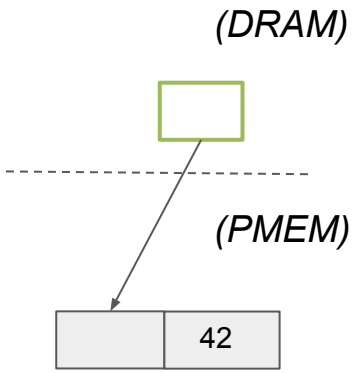
Programming model - *life cycle*

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

```
JNVM.free(s);
```



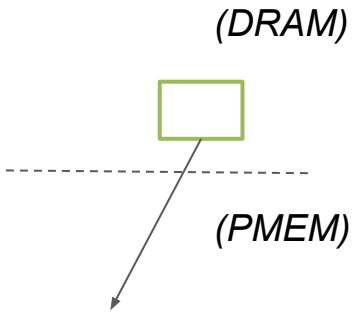
Programming model - *life cycle*

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

```
JNVM.free(s);
```



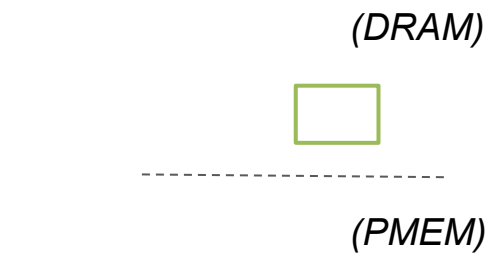
Programming model - *life cycle*

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

```
JNVM.free(s);
```



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

```
JNVM.free(s);
```

(DRAM)

(PMEM)

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

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;
    this.resurrect();
  }
}
```

Goals

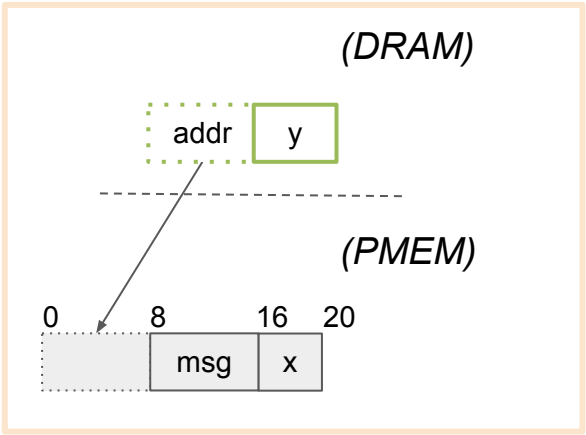
- class-wide off-heap layout
- generate constructor, re-constructor
- replace (non-transient) field accesses
- wrap non-private methods

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++; }
}
```



Goals

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

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++; }
}
```

Goals

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

```
// 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;
    this.resurrect();
  }
}
```

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++; }
}
```

Goals

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

```
// 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();
  }

  void inc() {
    JNVM.faStart();
    setX(getX()++);
    JNVM.faEnd();
  }
}
```

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++; }
}
```

Goals

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

```
// 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();
  }

  void inc() {
    JNVM.faStart();
    setX(getX()++);
    JNVM.faEnd();
  }
}
```

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 (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)

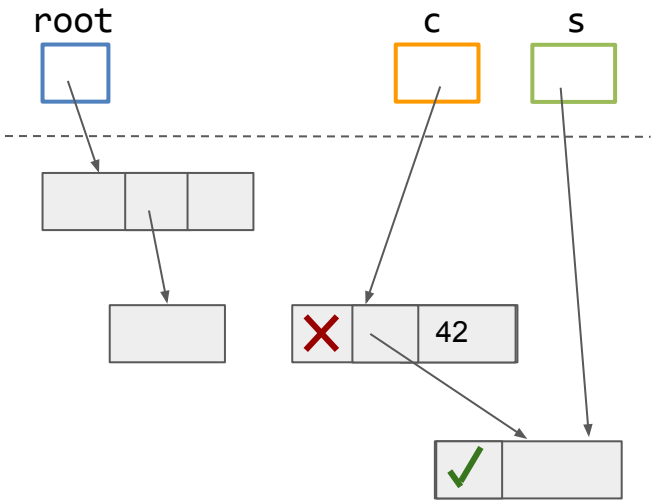
Log new, free and updates
granularity = a block of PMEM

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

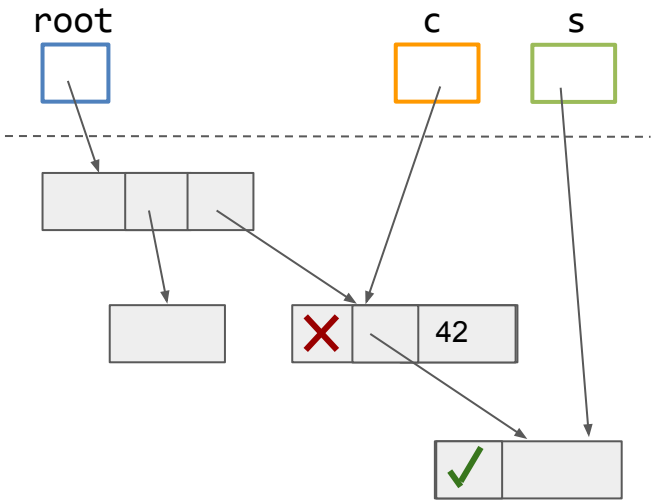



```
Complex c = new Complex(s);
root.put("Complex", c);
c.validate();
```

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

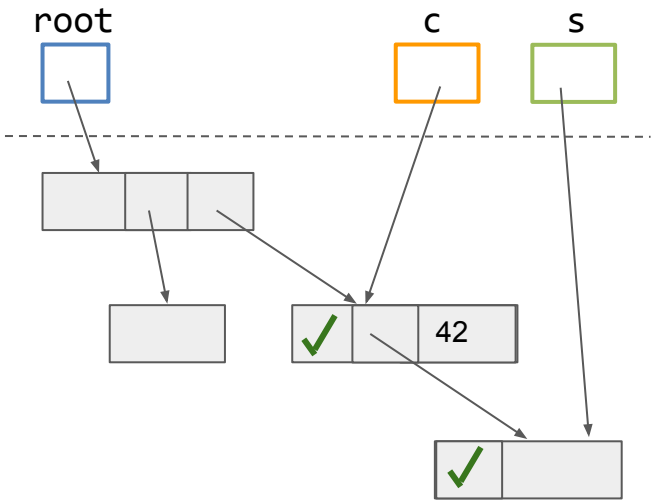



```
Complex c = new Complex(s);
root.put("Complex", c);
c.validate();
```

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




```
Complex c = new Complex(s);
root.put("Complex", c);
c.validate();
```

Outline

Introduction

- NVMM
- why Java?
- prior works
- overview

System Design

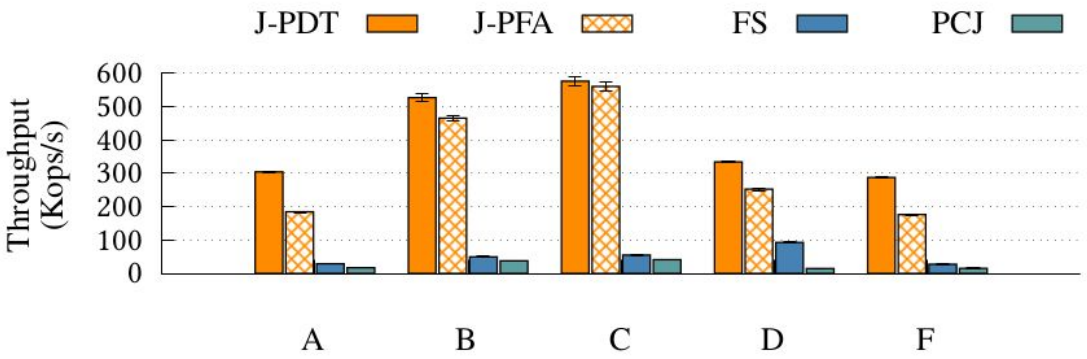
- programming model
  - persistent objects
  - code generator
- JPFA
- JPDT

Evaluation

- YCSB benchmark
- recovery

Conclusion

YCSB Benchmark



Durable backends for Infinispan:

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

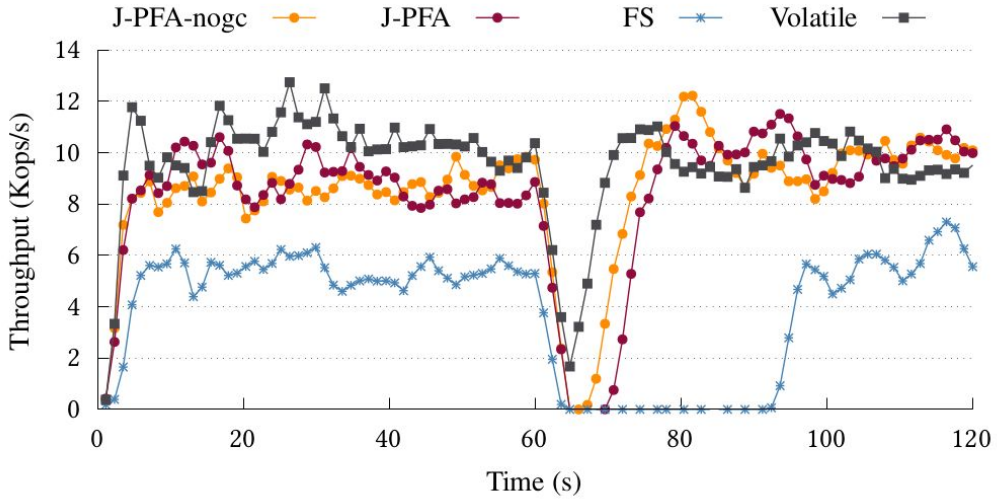
Hardware used:

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