Addressing Software Challenges for Smart Infrastructures using Software Persistent Memory

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Requrements for Smart Infrastructures

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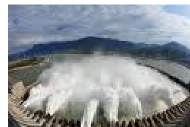
Self-management

- Self-management is based on intelligence

Requrements for Smart Infrastructures



Self-management

- Self-management is based on intelligence
- Intelligence demands memory

Requrements for Smart Infrastructures

Self-management

- Self-management is based on intelligence
- Intelligence demands memory
- Fault-tolerant intelligence demands *persistent memory*

Simulating Smart Infrastructures

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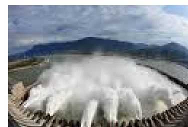
Large-scale simulations

- Massively parallel and long-running (days, weeks)

Simulating Smart Infrastructures



Large-scale simulations

- Massively parallel and long-running (days, weeks)
- Demand tolerance to software, system, or power failure

Simulating Smart Infrastructures

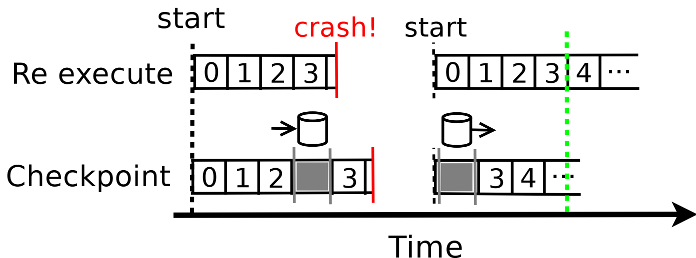
Large-scale simulations

- Massively parallel and long-running (days, weeks)
- Demand tolerance to software, system, or power failure
- Need for *persistent memory*

The Problem

Software, System, or Power Failure

- Solution I: Software re-execution
- Solution II: Recover from a full system or process checkpoint



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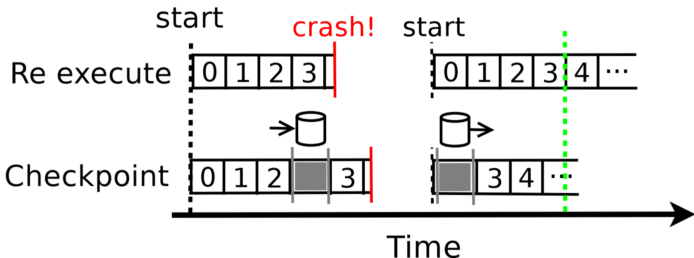
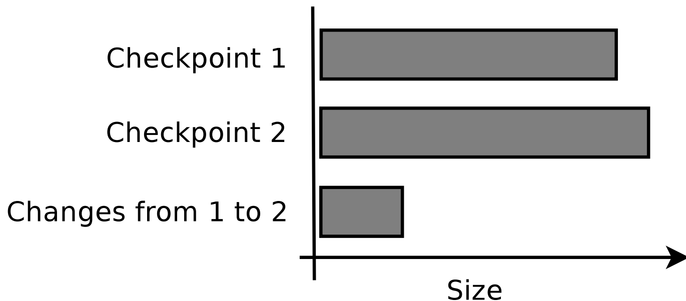


These solutions still incur substantial overhead.

Problems With Existing Checkpointing Solutions

Program characteristics

- Programs usually modify a subset of data



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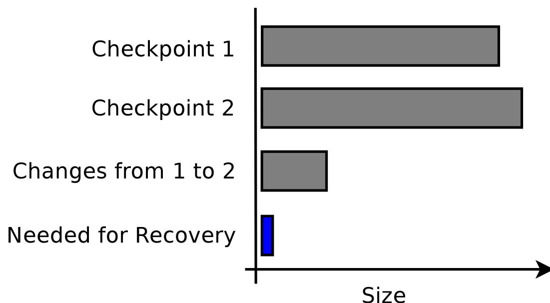

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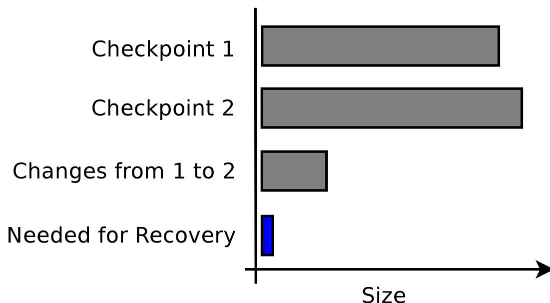

Manual tracking is cumbersome, inefficient, and less portable.

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The developer would need to:

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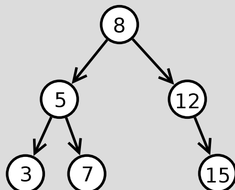

Initial Tree

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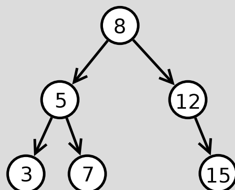

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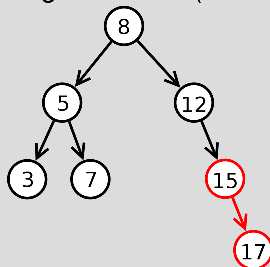

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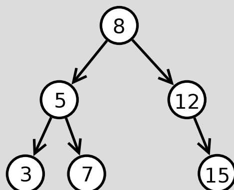

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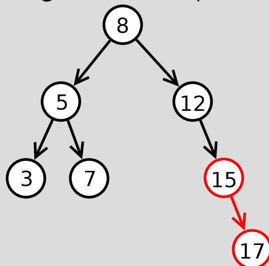

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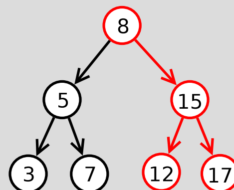

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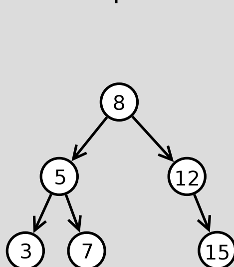

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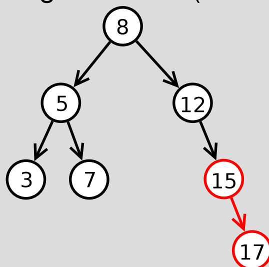

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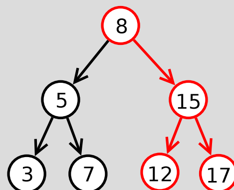

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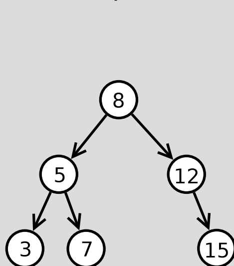

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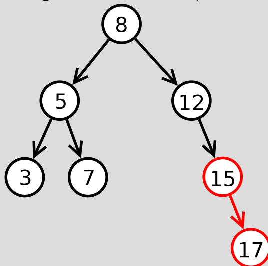

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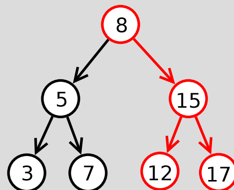

Final Tree

- Keep track of complex dependencies (*cumbersome*)
- Serialize arbitrary data structures (*cumbersome*)

Software Persistent Memory (*SoftPM*)

Applications allocate, and interact with, persistent memory in much the same way as they work with volatile memory.

SoftPM Goals

Developer specifies:

- Top-level data structures to persist
- When to create checkpoints
- How to recover execution from restored data in memory

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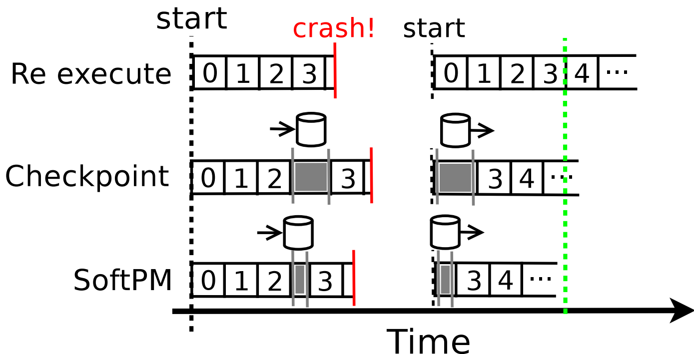
The solution will:

- Require minimal source code changes
- Automatically detect data to be checkpointed
- Track changes to data
- Minimize checkpoint creation and restoration time

SoftPM Basic Approach

- Implements application directed checkpointing
- Data to be checkpointed is automatically discovered
- Fast checkpoints and recovery



The Container Abstraction

Simple container

- Self-describing unit of persistent memory
- One or more containers per application of arbitrary size
- Applications create a container and specify a root structure
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Versioned container

- Each persistence point creates new container version
- Past versions are restoreable with a single operation
- Past versions are browsable
- Container version is branch-able

Using *SoftPM* : An Example

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typedef struct l {
  int v;
  struct l *n;
} list;
```

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  a() {
    list *l = malloc(...);
    l->v = X;
    list *e1 = malloc(...);
    e1->v = Y;
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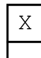

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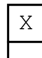

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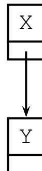

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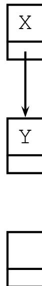

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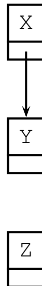

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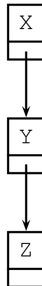

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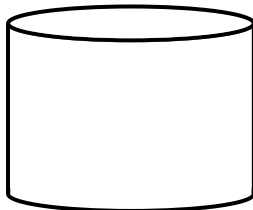

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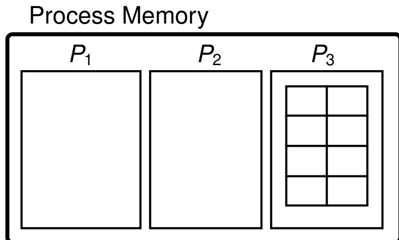

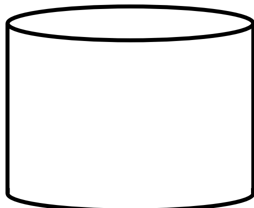

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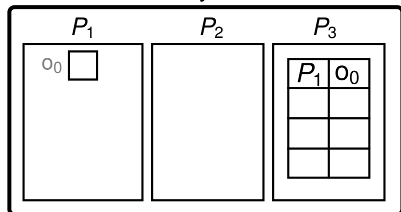

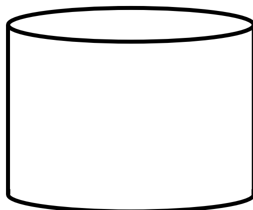

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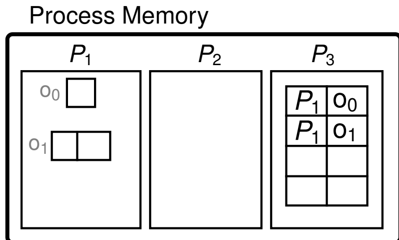

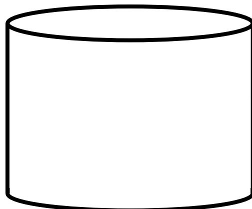

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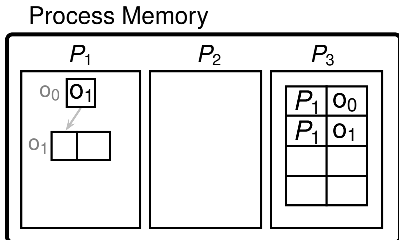

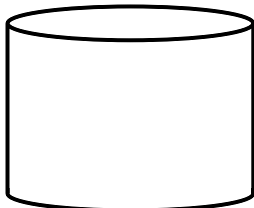

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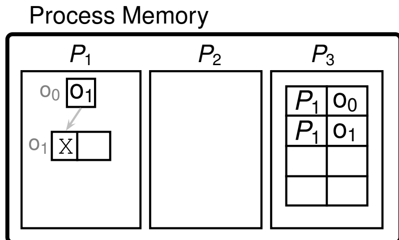

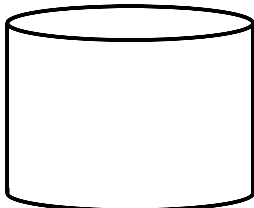

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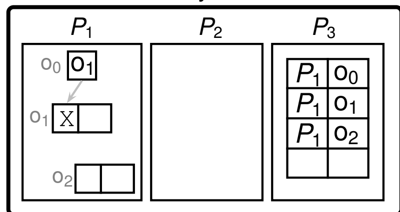

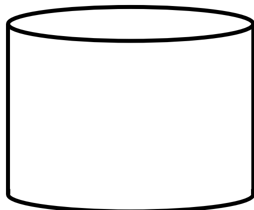

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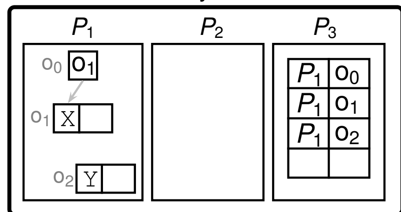

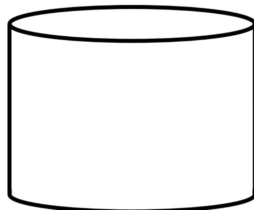

Creating a Persistence Point

```
struct pcont {
  list *L;
} C;
a() {
  if (!(cid = pCRestore(&C)))
    cid = pCAlloc(&C);
  list *l = malloc(...);
  C->L = l;
  l->v = X;
  list *e1 = malloc(...);
  e1->v = Y;
▶ l->n = e1;
  list *e2 = malloc(...);
  e2->v = Z;
  e1->n = e2;
  pPoint(cid);
  }
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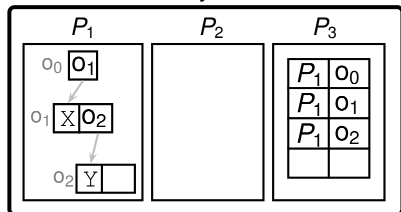
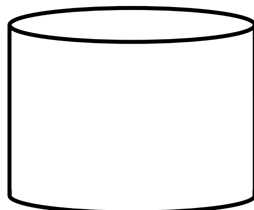
}
```





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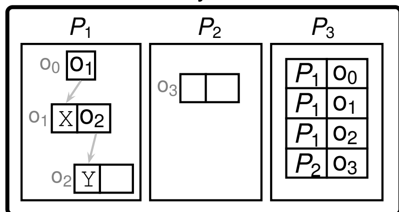

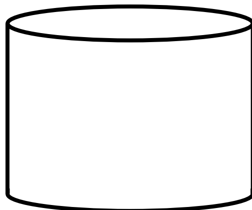

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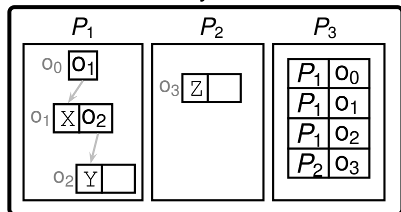

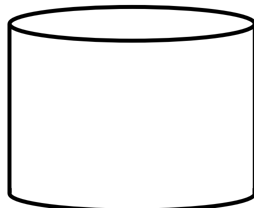

Persistent Medium

Creating a Persistence Point

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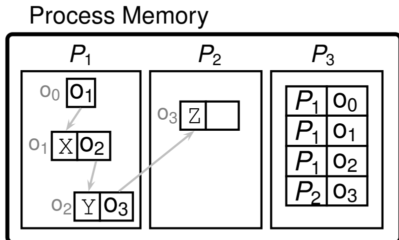

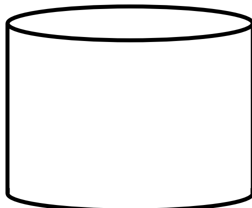

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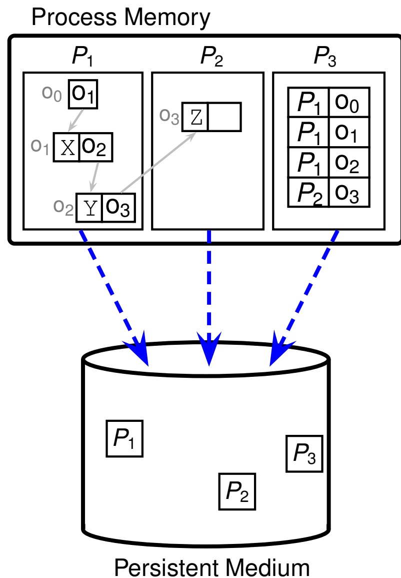

Restoring a Persistence Point

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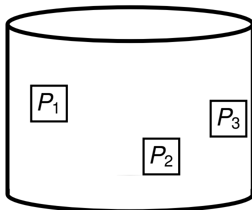

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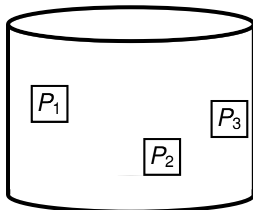
Prev	Curr



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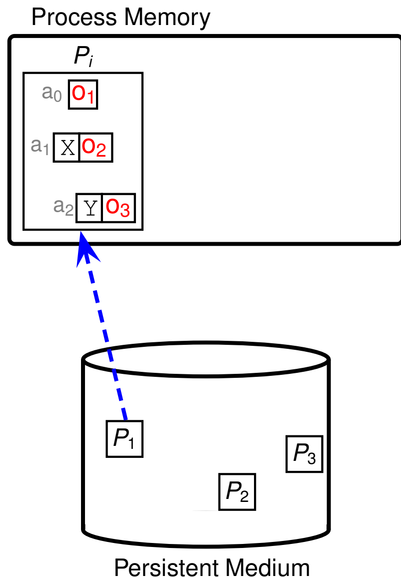
Prev	Curr
P_1	P_i



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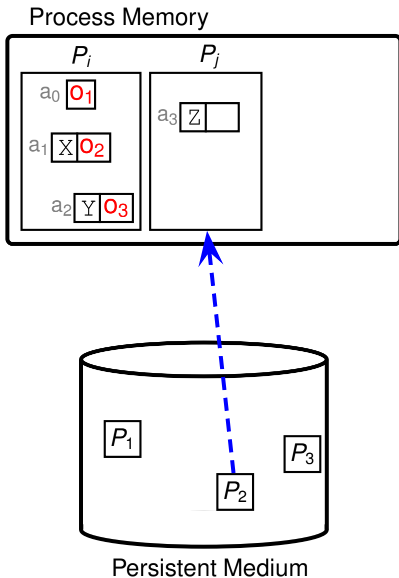
Prev	Curr
P_1	P_i
P_2	P_j



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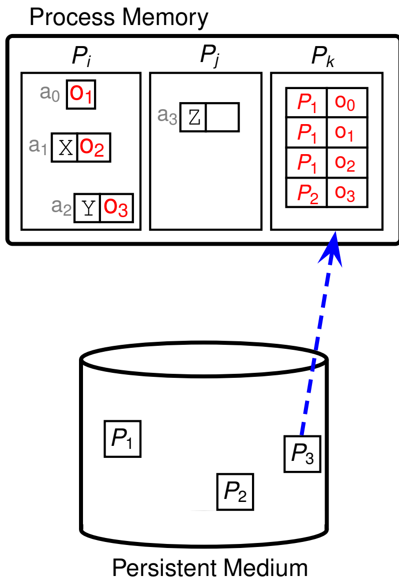

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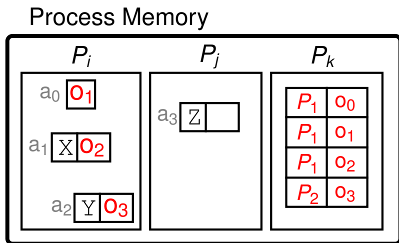

Prev	Curr
▶ P_1	P_i
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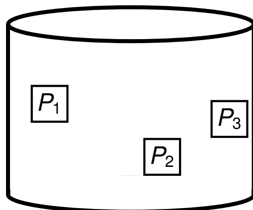
P_3	P_k



Persistent Medium

Restoring a Persistence Point

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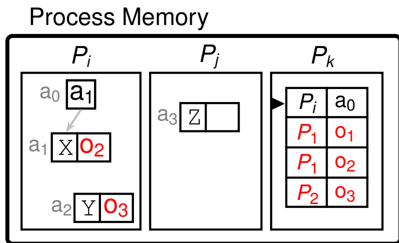
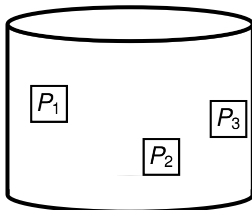


Prev	Curr
P_1	P_i
P_2	P_j
P_3	P_k



Persistent Medium

Restoring a Persistence Point

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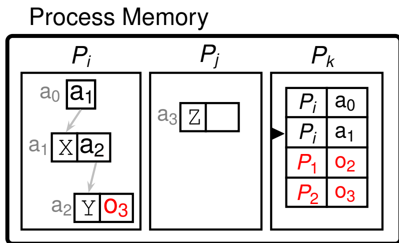

Prev	Curr
► P_1	P_i
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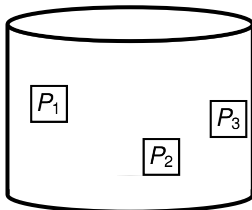

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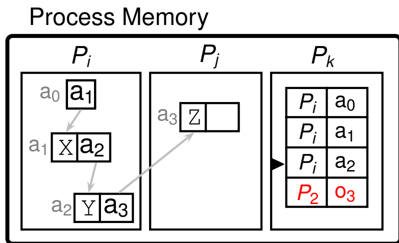

Prev	Curr
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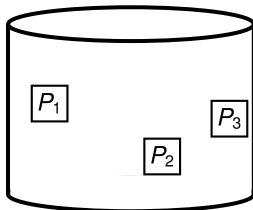

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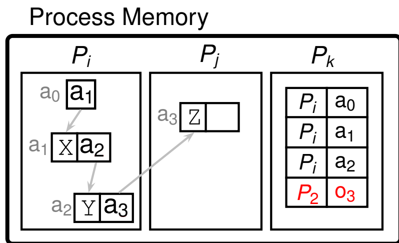

Prev	Curr
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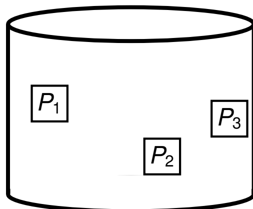

Persistent Medium

Restoring a Persistence Point

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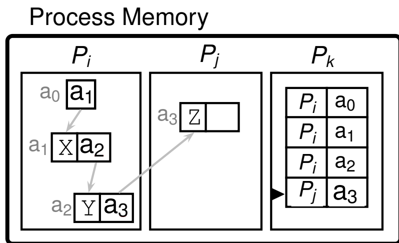

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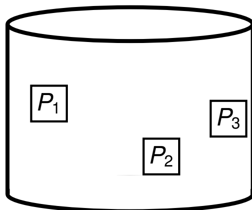

Persistent Medium

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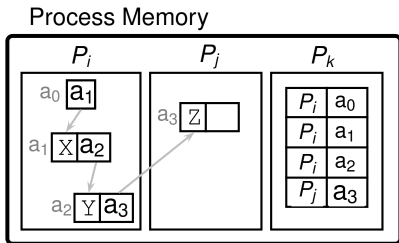

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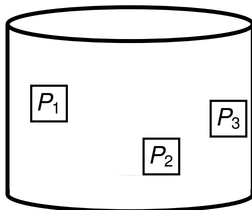

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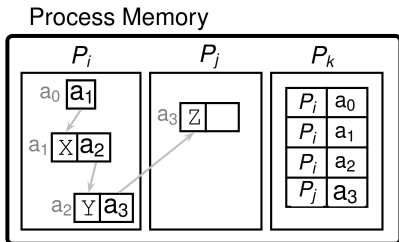

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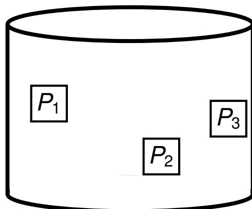
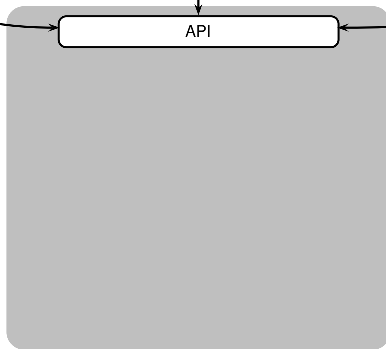


Persistent Medium

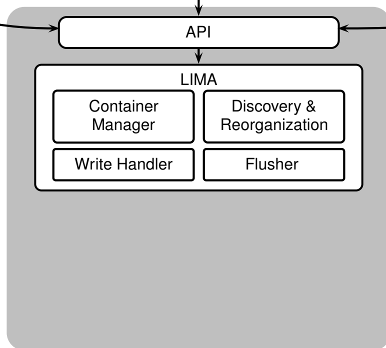
SoftPM Architecture

Recoverability Record-Replay Execution Branching

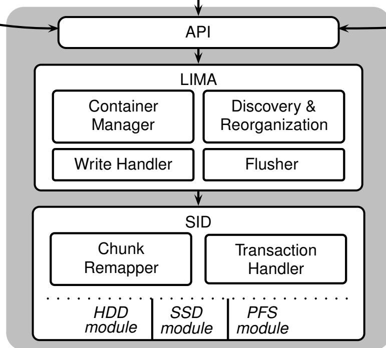
SoftPM Architecture



SoftPM Architecture



SoftPM Architecture



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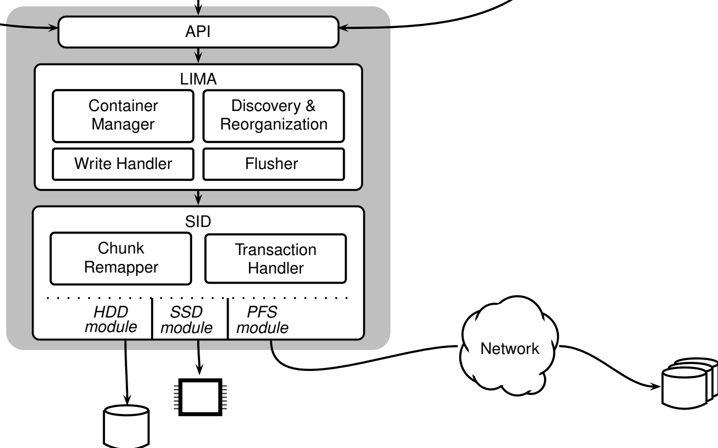
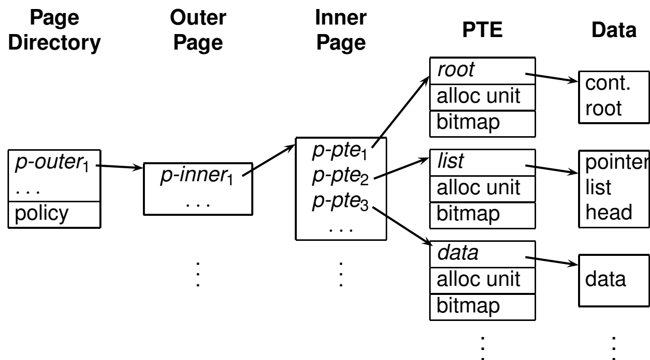


LIMA: Container Page Table



LIMA: Container Manager

Container Allocation

- Initialize container metadata
- Create container page table
- Initialize container pointer list

LIMA: Container Manager

Container Allocation

- Initialize container metadata
- Create container page table
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Container Restoration

- Load container data
- Fix pointers
- Return container root structure

LIMA: Discovery & Reorganization

Container Discovery

- Recursively follow pointers starting from container root
- Create persistent memory transitive closure set

LIMA: Discovery & Reorganization

Container Discovery

- Recursively follow pointers starting from container root
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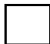
Memory Reorganization

- Memory allocation is managed by *SoftPM*
- Memory pages classified either as persistent or volatile
- Fix back-references after moving data

Automatically Discovering Data

We divide memory into 2 regions: **volatile** and **persistent.**
Hence, there can be 4 types of pointers:

Volatile



Persistent

Automatically Discovering Data

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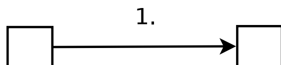
1. volatile $\rightarrow$ volatile

Volatile



Persistent

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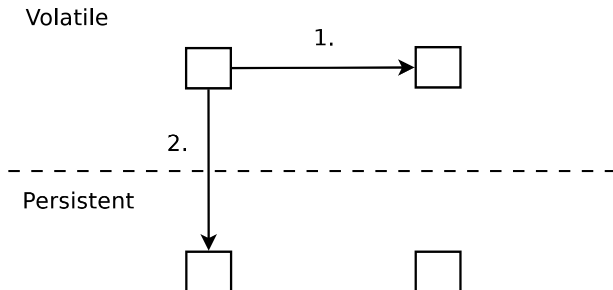
1. volatile → volatile
2. volatile → persistent



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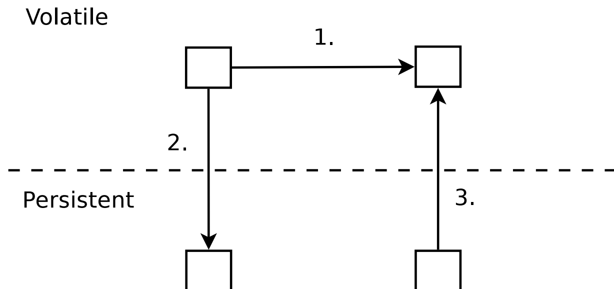
3. persistent → volatile



Automatically Discovering Data

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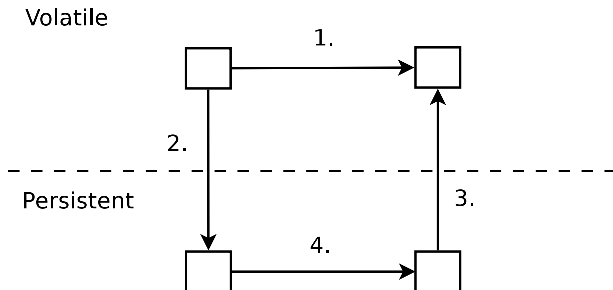
1. volatile → volatile
2. volatile → persistent
3. persistent → volatile
4. persistent → persistent



Automatically Discovering Data

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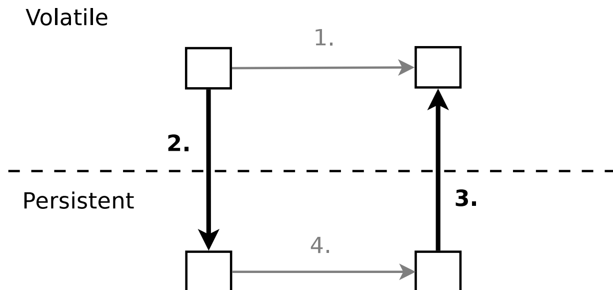
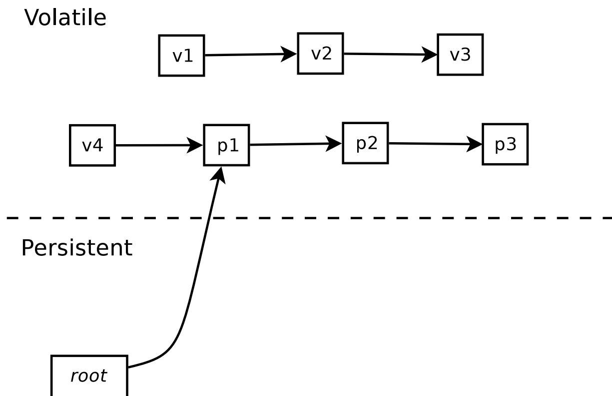
2. volatile → persistent ✓
3. persistent → volatile ✓
4. persistent → persistent



Automatically Discovering Data

Initially all memory is volatile except a *root* structure.



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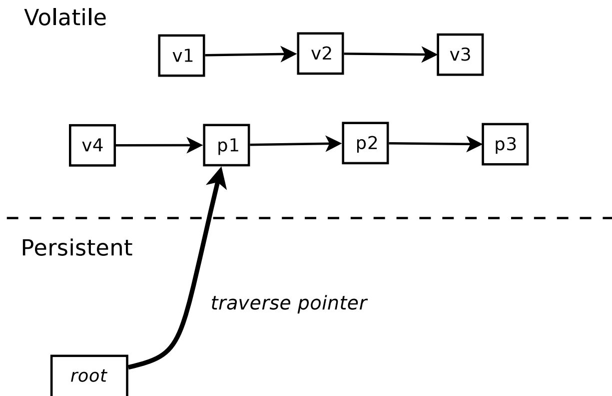

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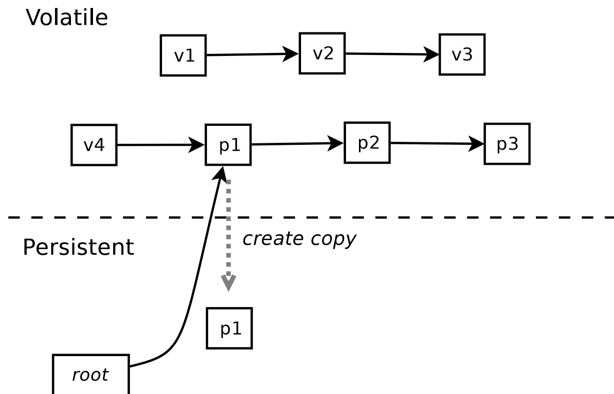

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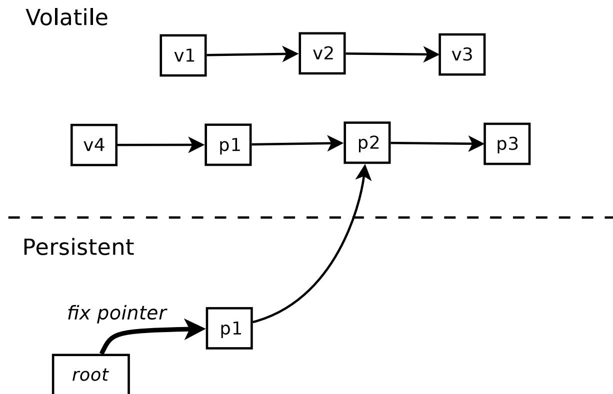

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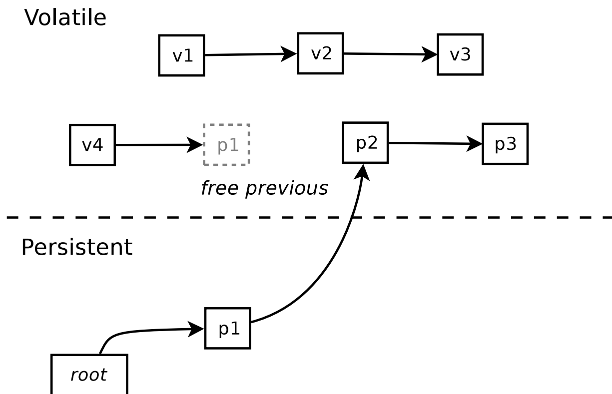

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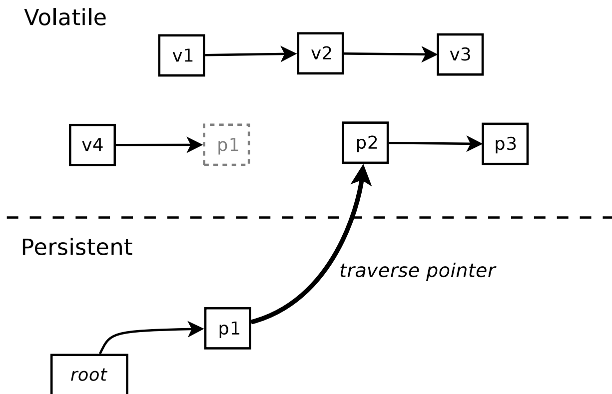

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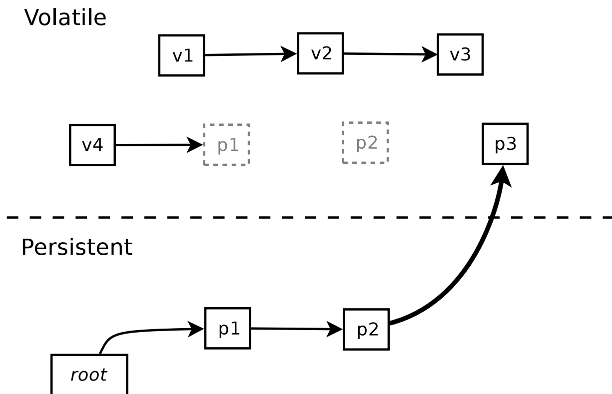

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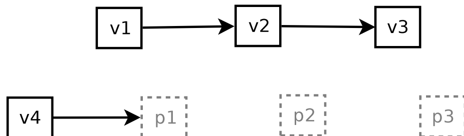
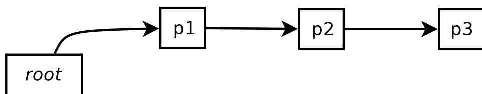


Persistent



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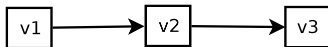

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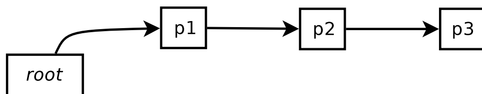

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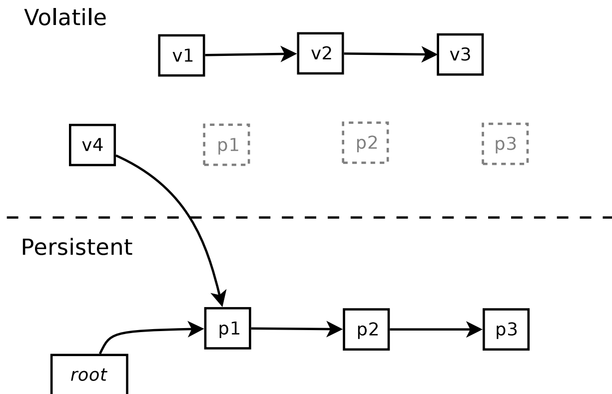

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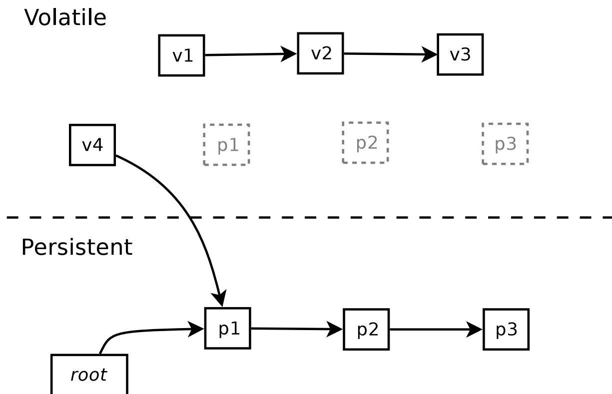

We refer to this root structure and it's closure as **container**.

What Modifications are Needed?

Developer responsibility

- Allocate the containers
- Assign root structures to containers
- Make root structures point to data
- Invoke persistence point creation operations

Pointer Detection in *SoftPM*

Life-cycle of a pointer

- **Allocation:** memory is allocated to store the pointer
- **Initialization:** value of pointer is initialized
- **Use:** pointer value is used
- **Deallocation:** memory used to store pointer is deallocated

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Two-phase pointer detection

- **Static analysis:** CIL-based source translation stage
- **Dynamic analysis:** Runtime tracking of **initialized** pointers

SoftPM Static Analysis

Type Definition	Usage

`struct list {`
`int val;`
`struct list *next;`
`};`
	`struct list *l = malloc(n);`

CIL-based static translation hints

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`};`
	`struct list *l = malloc(n);`
	`mallocat(l, n);`
	`pointerat(&l);`

CIL-based static translation hints

- Record the location/size of memory allocation/move operations
- Register the location of all initialized pointers
  - ✓ Explicit initialization: *l-value* of assignment operations
  - ✓ Implicit initialization: *memory copying/move* operations

LIMA: Write Handler and Flusher

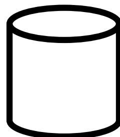
Write Handler

- Writes are monitored at a chunk (multi-page) granularity
- One page-fault per chunk between persistence points
- Asynchronous persistence points use COW pages

Persistence
Point

Persistent
Memory

Persistent
Medium



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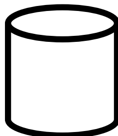

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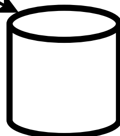

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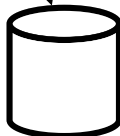

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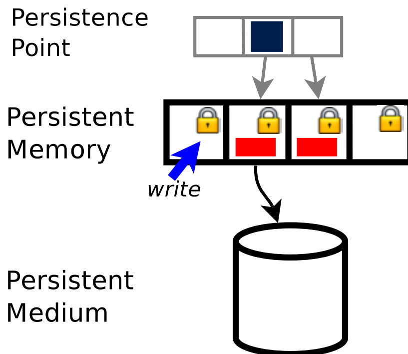

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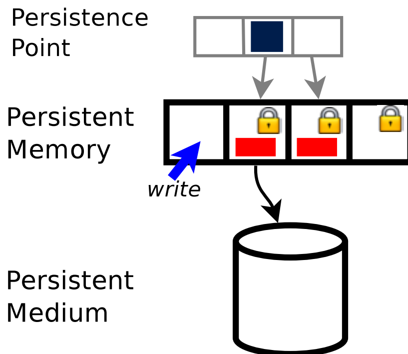

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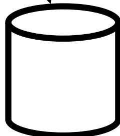

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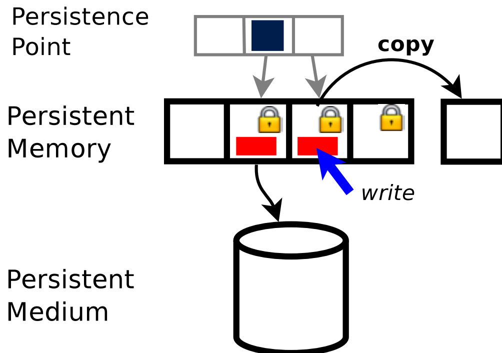

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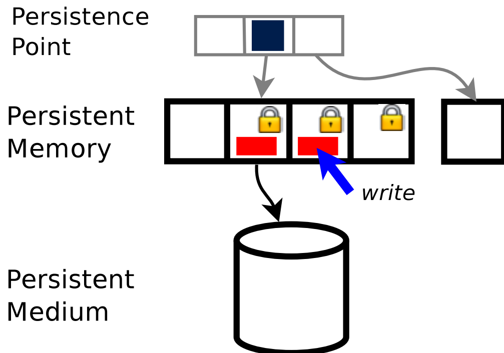

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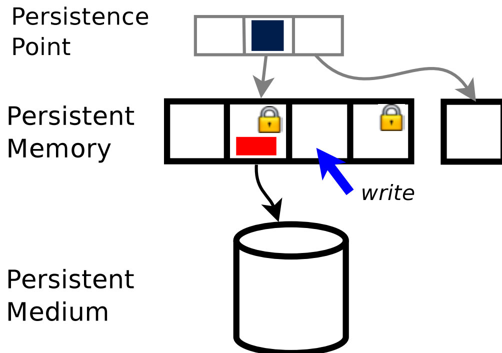

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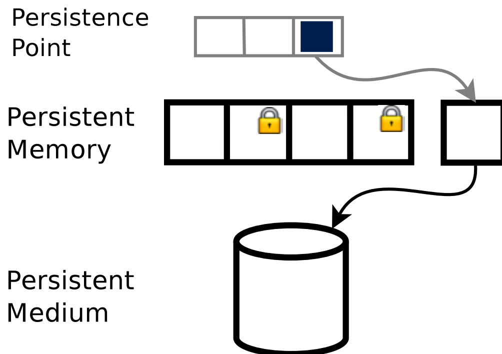

Storage I/O Driver (SID)

High-performance I/O

- Asynchronous I/O improves storage I/O efficiency
- Chunk remapping writes provide storage location flexibility

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- Three different storage I/O drivers

Scalability

- Custom parallel file system metadata management
- Custom parallel file system space management

Evaluation

Configurations

- **ALP**: Application-level persistence using the file system
- ***SoftPM***: Using SSD or disk drive

Development complexity evaluation

- Evaluate using basic data structure types
- Complexity measure using lines of code (LoC)

Performance evaluation

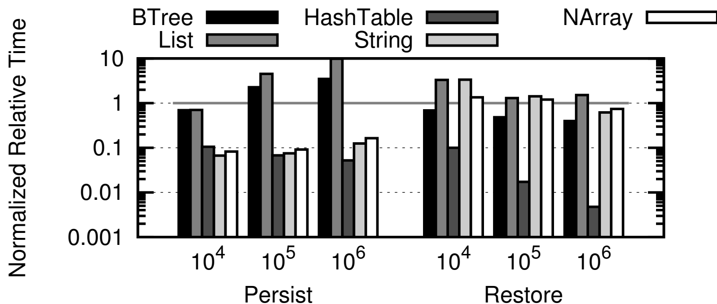
- Microbenchmarks create 1 or more containers
- Populate each container with a single data structure type
- Container size is variable
- Perform random updates when update is necessary
- Vary update locality

Evaluating Development Complexity

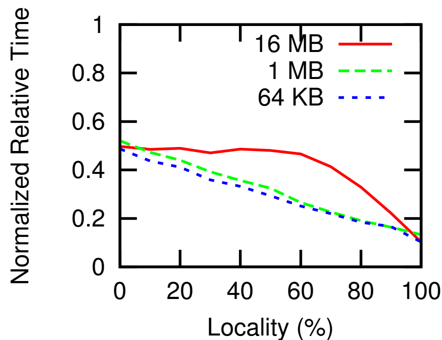
Data Structure	ALP			SoftPM	
	LoC	*P*	*R*	*P*	*R*
String	28	7	13	2	1
N-Dimensional Array	104	13	17	2	1
Linked List	60	9	11	2	1
Hash Table	229	87	18	2	1
Binary Tree	70	14	40	2	1

P: persistence LoC
R: restoration LoC

Sensitivity to the Data Structure



Update Locality, Scalability, and Portability



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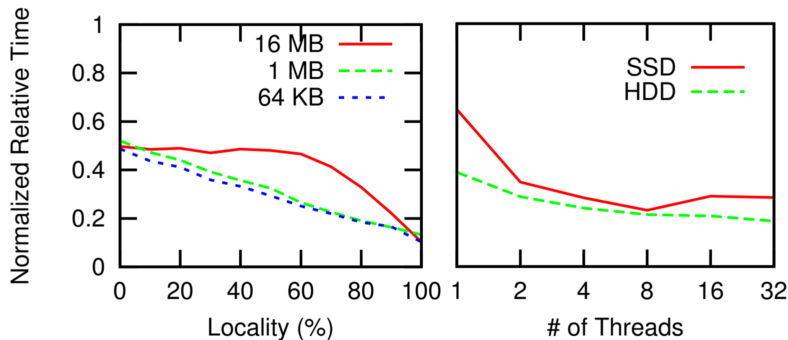

SQLite: A Case Study

SQLite: An in-memory production database

- Claim: Most widely deployed SQL DB engine
- 39KLoC
- Uses a variety of data structures (HTs, trees, arrays, etc.)
- Does not provide Tx commit support

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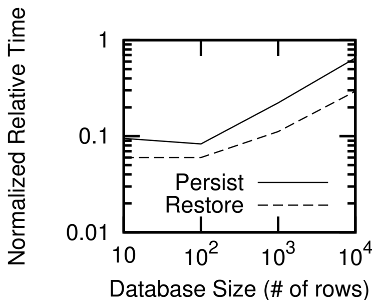

Caveats

When is *SoftPM* less relevant?

- Unstructured data (e.g., strings, audio) easy to serialize
- Unstructured data do not typically get modified in place
- When subsets of data structures must be serialized

Unresolved issues

- Container size restrictions
- Container sharing semantics across processes

Summary

Simplifying reliable software development

- A memory abstraction for persistent data
- Fully automated persistence
- Transactional persistence
- High-performance persistence
- Versioning, branching, and out-of-core support (under development)

The *SoftPM* Team

Daniel C.

Daniel G.

Jorge

Leonardo

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Daniel C.

Daniel G.

Jorge

Leonardo

Jason

Jinpeng

Ming

Raju

Thank you!

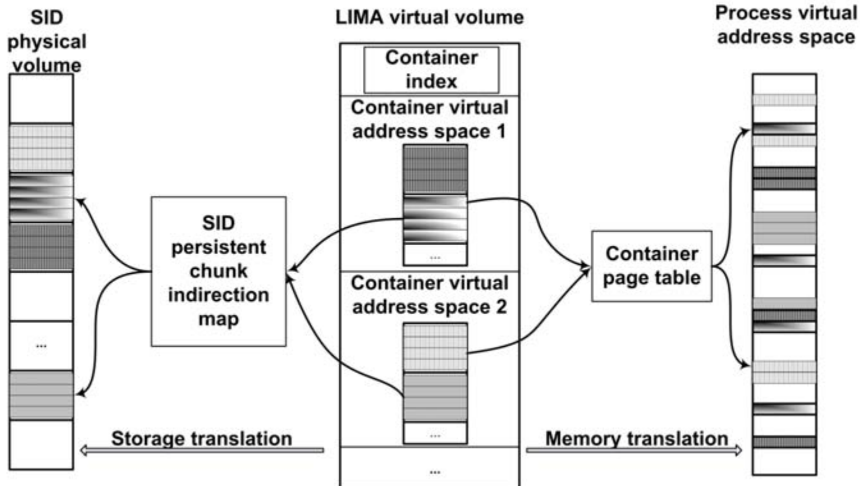
Backup Slides

SoftPM API

API v1.0

- Container administration
  `pCAlloc` / `pCFree` / `pCDelete` / `pExclude`
- Container persistence management
  `pCSetAttr` / `pCGetAttr` / `pPoint` / `pPointSync`
- Restoring and navigating through branches
  `pCRestore` / `pCSwitch` / `pCClone`

Indirection Summary



Distribution of Overheads