Fault Isolation and Quick Recovery in Isolation File Systems

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File-System Availability Is Critical

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- Main data access interface
  - ➡ desktop, laptop, mobile devices, file servers

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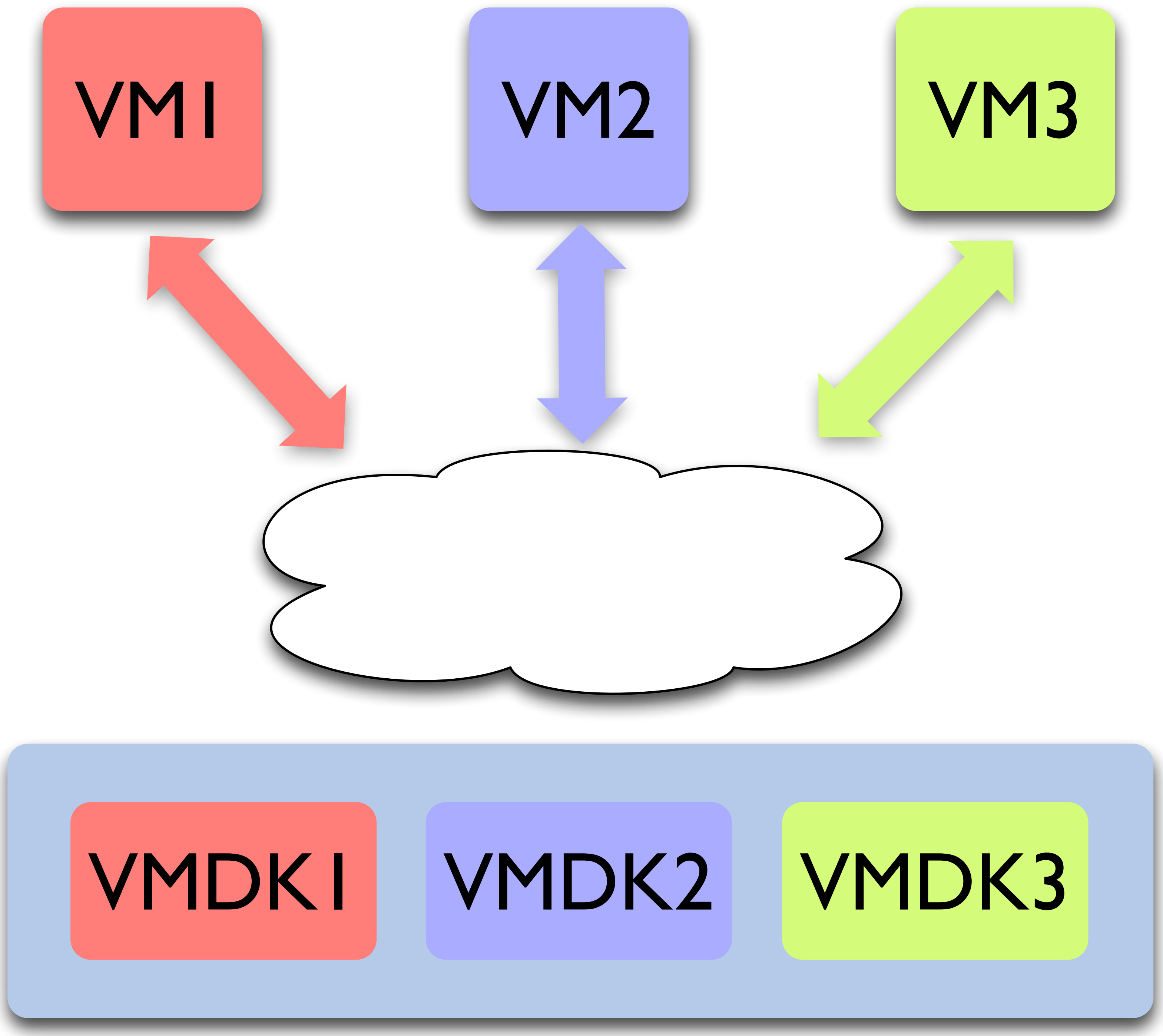
Global failures considered harmful

- read-only, crash

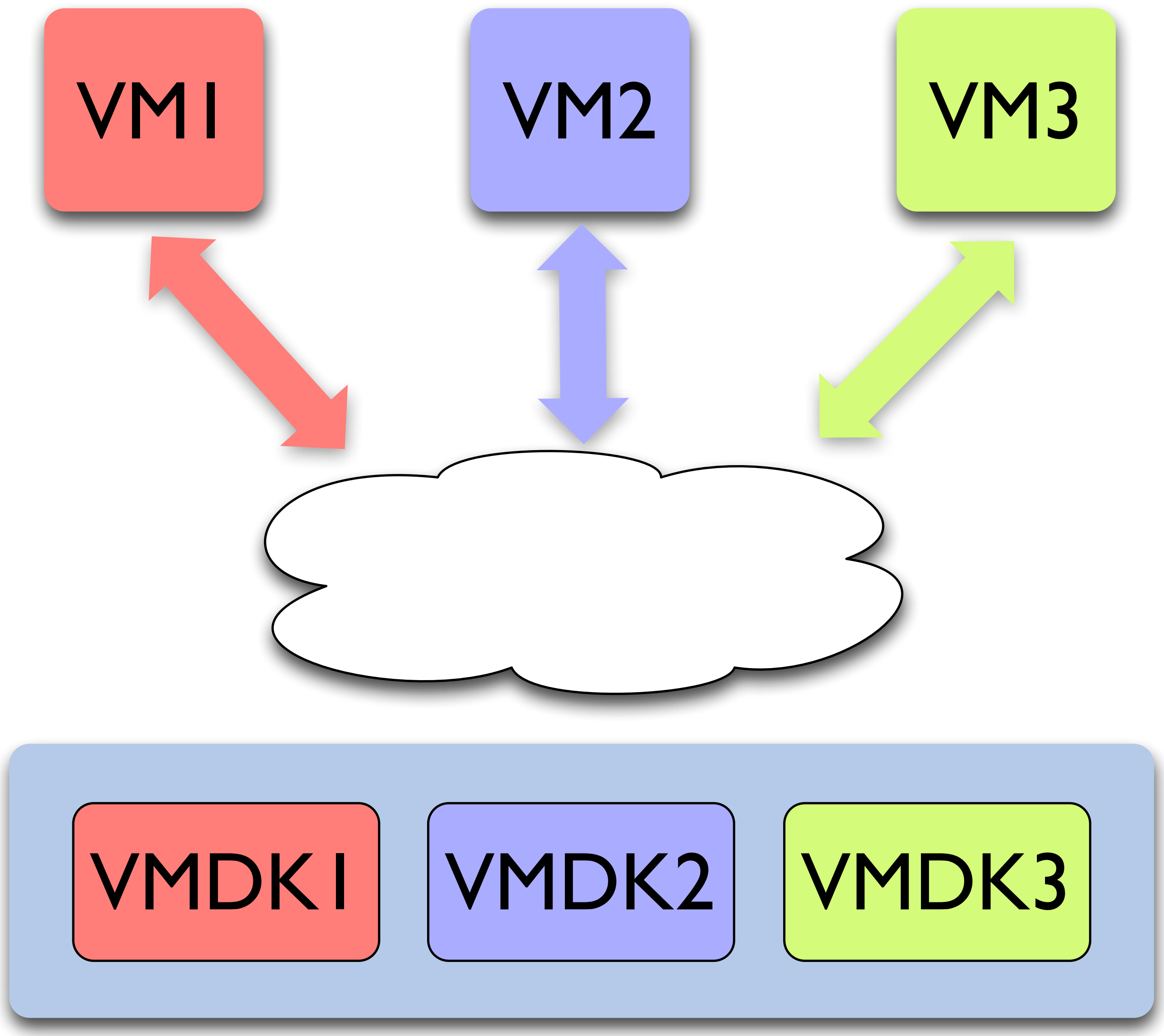
Server Virtualization

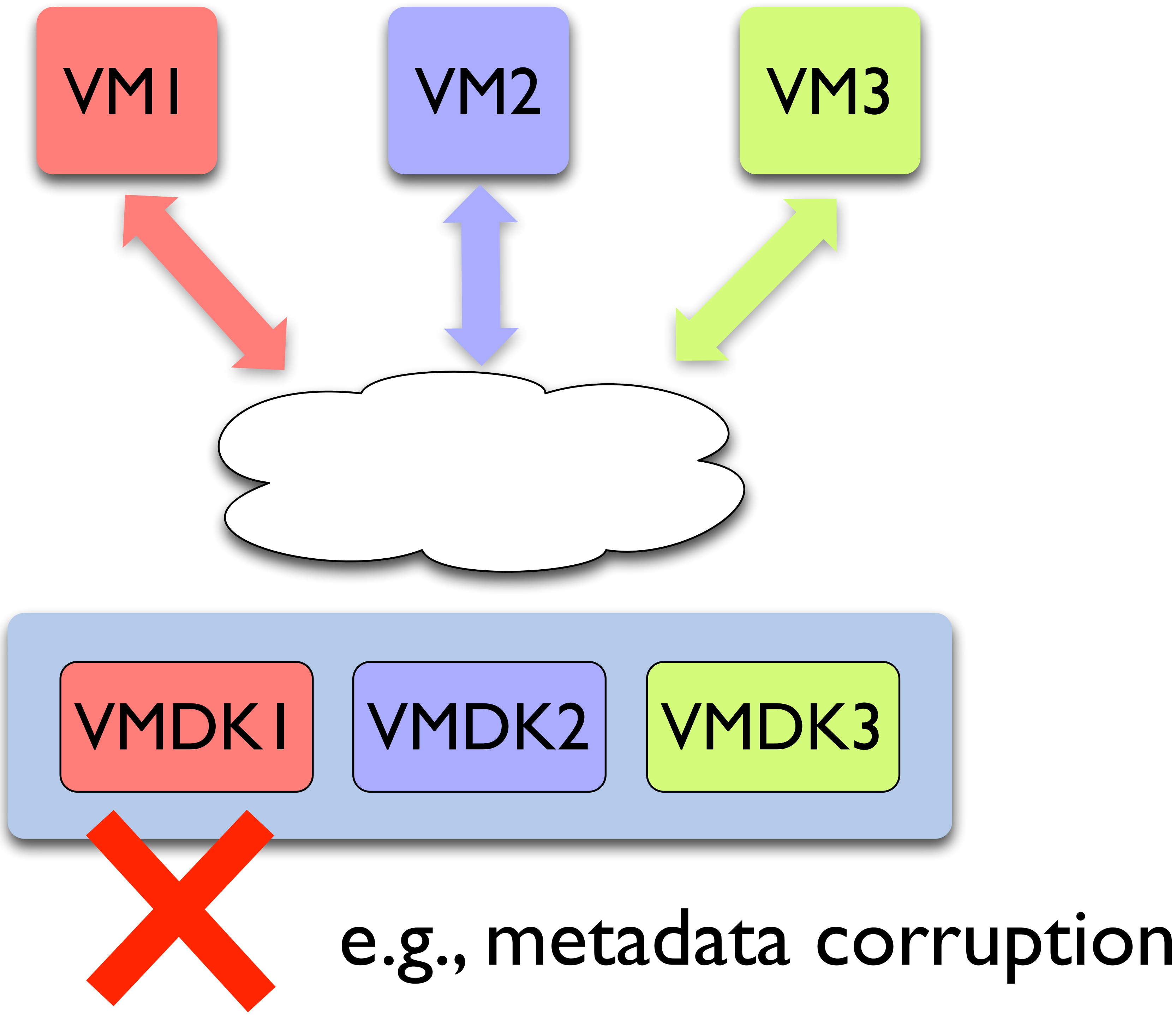


Guest virtual machines

Hypervisor

Shared file system


VM1
VM2
VM3
VMDK1
VMDK2
VMDK3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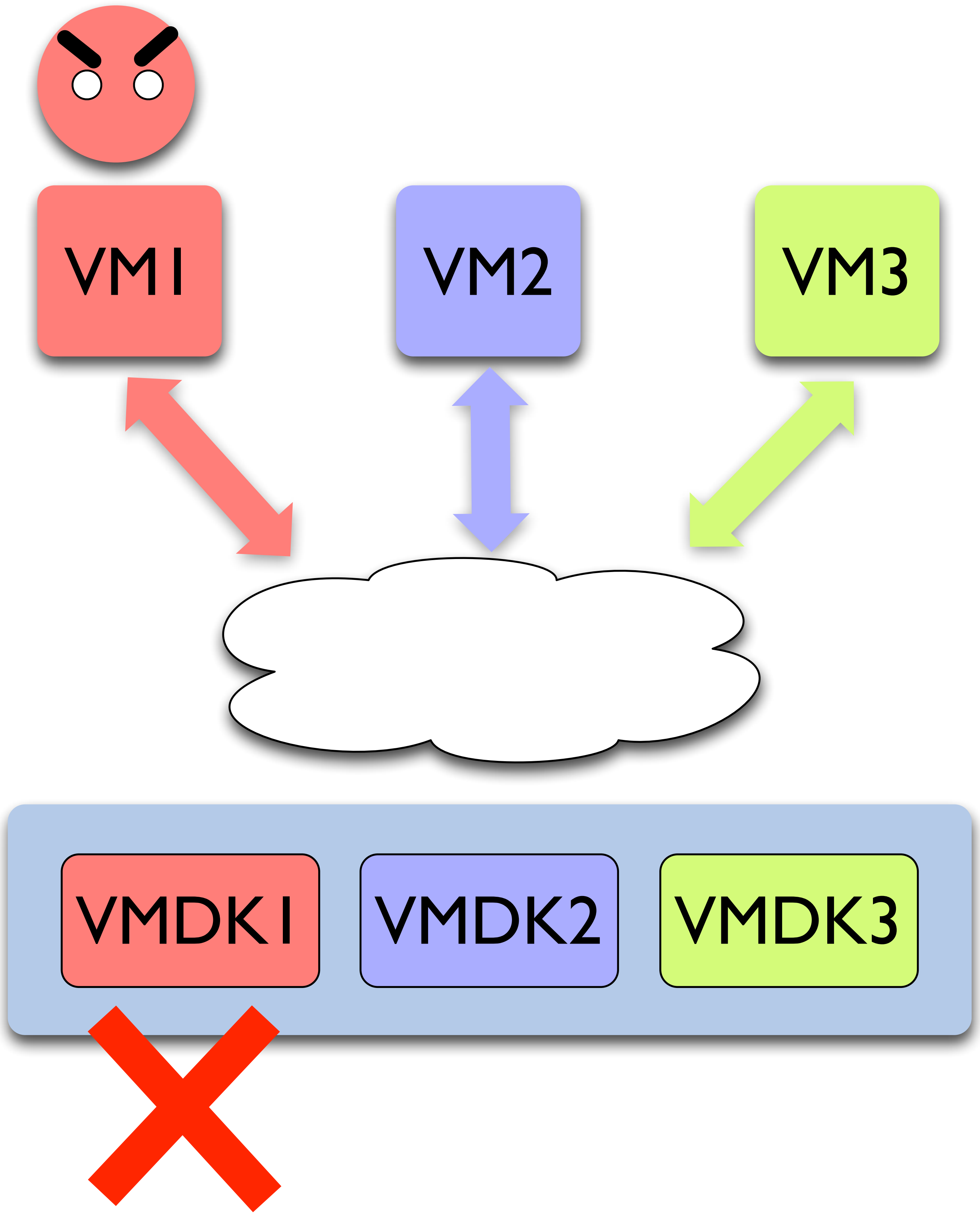
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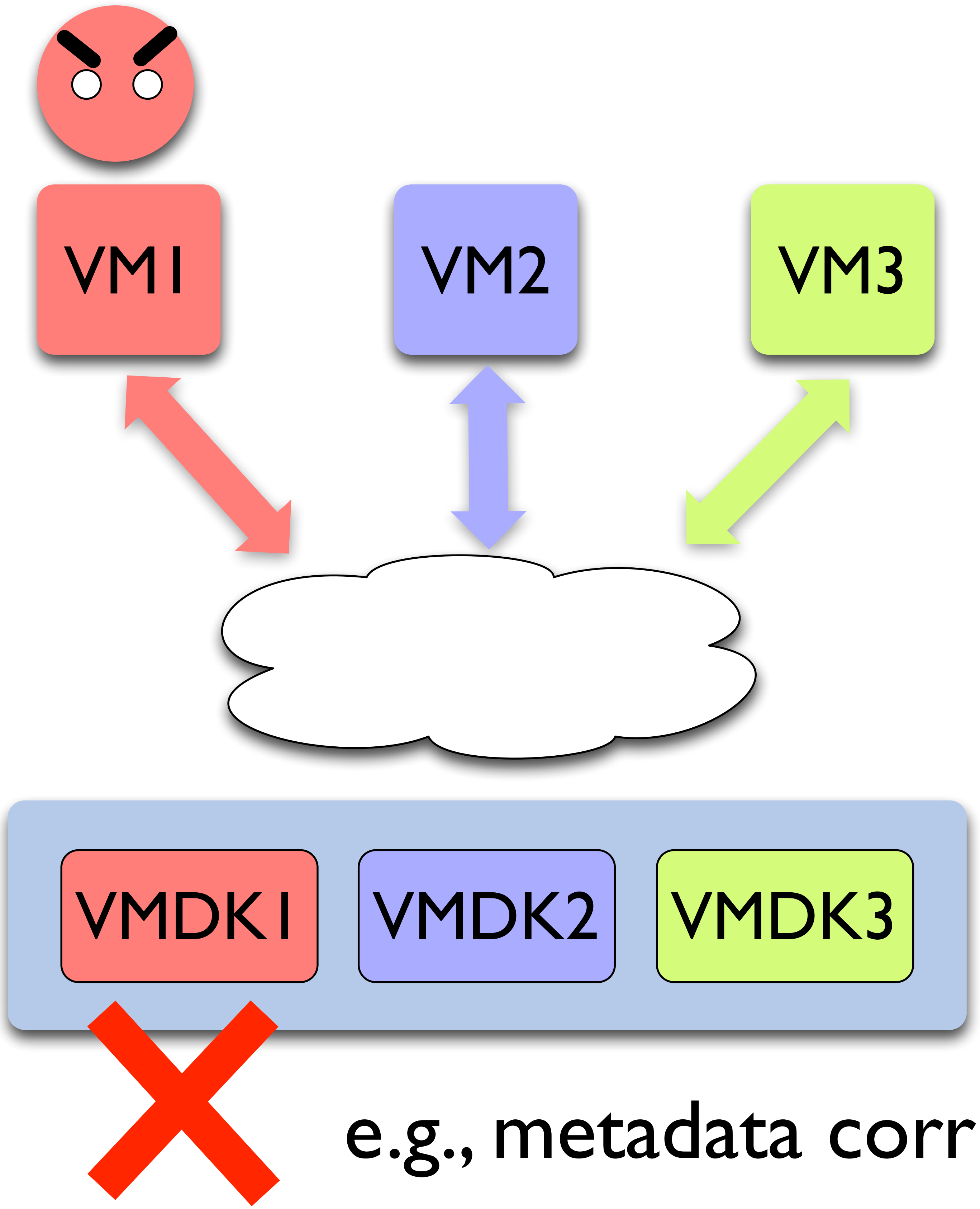

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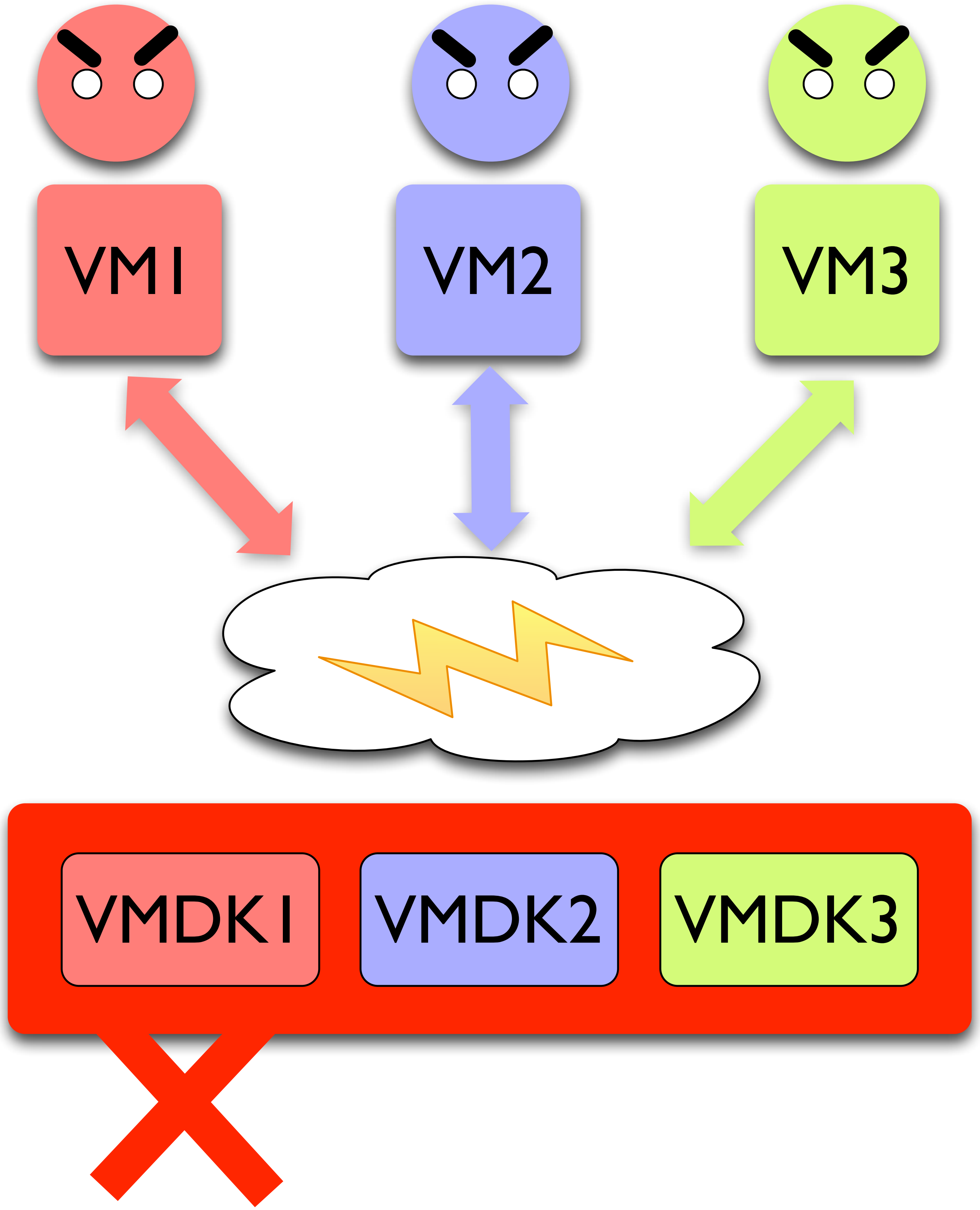

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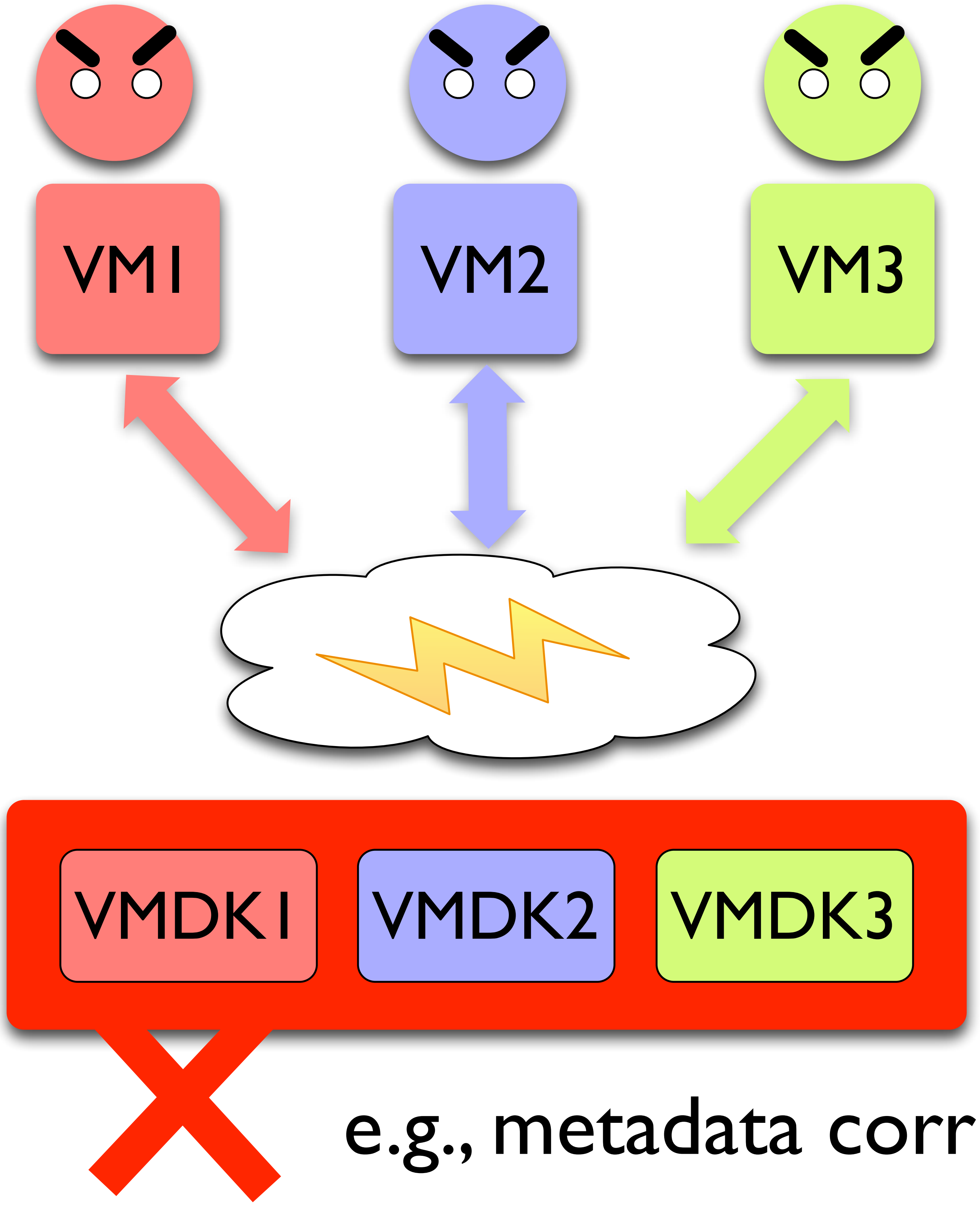
are affected

ReadOnly
or
Crash



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Our Solution

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A new abstraction for fault isolation

- support multiple independent fault domains
- protect a group of files for a domain

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Isolation file systems

- fine-grained fault isolation
- quick recovery

Introduction

Study of Failure Policies

Isolation File Systems

Challenges

Questions to Answer

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What global failure policies are used ?

- failure types
- number of each type

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What global failure policies are used ?

- failure types
- number of each type

What are the root causes of global failures ?

- related data structures
- number of each cause

Methodology

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Three major file systems

- Ext3 (Linux 2.6.32), Ext4 (Linux 2.6.32)
- Btrfs (Linux 3.8)

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Analyze source code

- identify types of global failures
- count related error handling functions
- correlate global failures to data structures

Q1:

What global failure policies

are used ?

Global Failure Policies

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Definition

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Read-Only

- e.g., ext3_error():
  - mark file system as read-only
  - abort the journal

Read-Only Example

```
ext3/balloc.c, 2.6.32

read_block_bitmap(...){

 1    bitmap_blk = desc->bg_block_bitmap;
 2    bh = sb_getblk(sb, bitmap_blk);
 3    if (!bh){
 4        ext3_error(sb, "Cannot read block
                          bitmap");
          return NULL;
      }
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```

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Read-Only

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Crash

- e.g., BUG(), ASSERT(), panic()
- crash the file system or operating system

Crash Example

```
btrfs/disk-io.c, 3.8

open_ctree(...) {

    root->node = read_tree_block(...);
    BUG_ON(!root->node);
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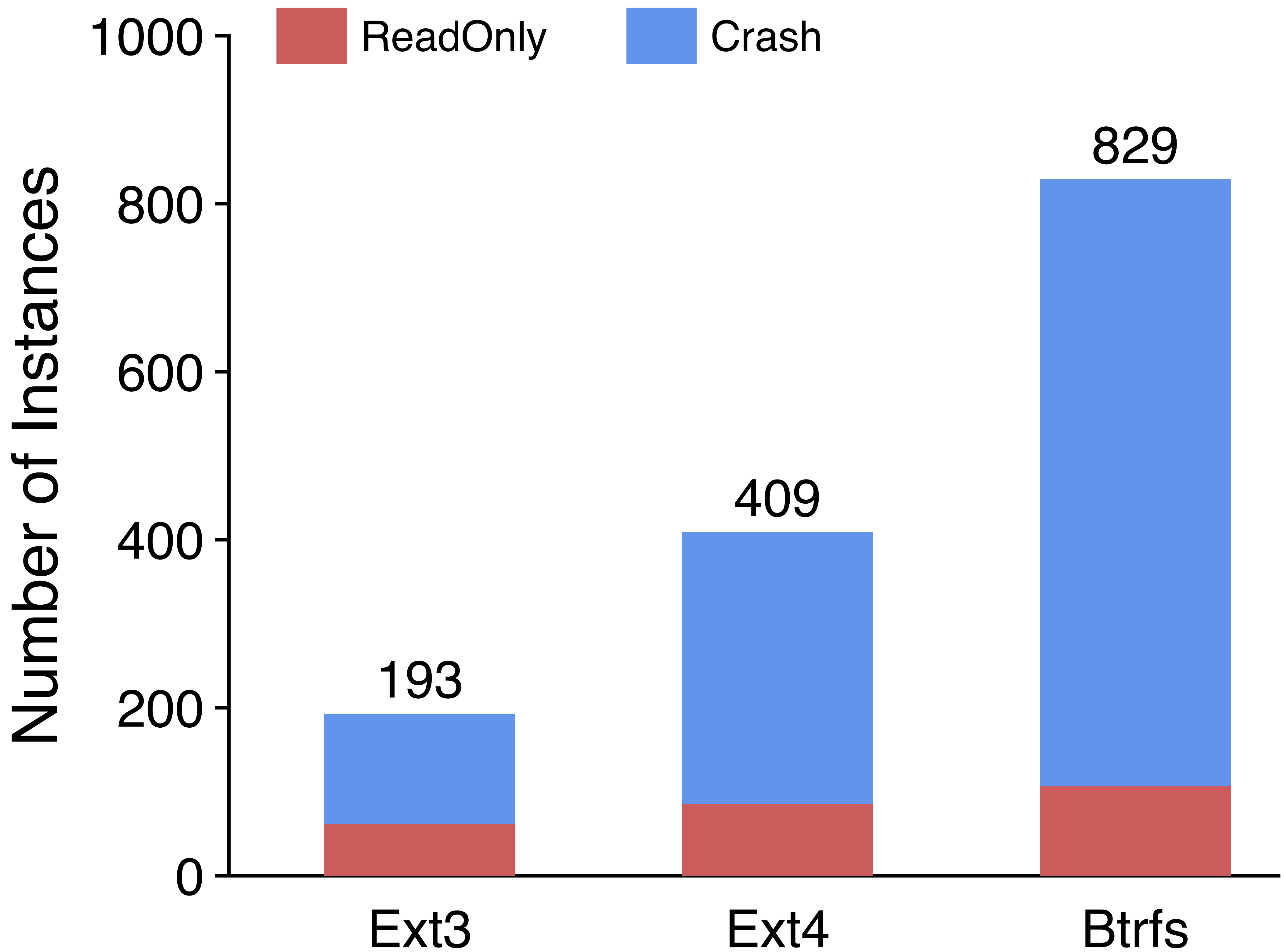
ReadOnly
Crash
Number of Instances
1000
800
600
400
200
0
193
409
829
Ext3
Ext4
Btrfs

Read-only and crash are common in modern file systems

Over 67% of global failures will crash the system

Q2:

What are the root causes of global failures ?

Global Failure Causes

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Metadata corruption

- metadata inconsistency is detected
- e.g., a block/inode bitmap corruption

Metadata Corruption Example

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ext3/dir.c, 2.6.32

ext3_check_dir_entry(...){

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I/O failure

- metadata I/O failure and journaling failure
- e.g., fail to read an inode block

I/O Failure Example

```
ext4/namei.c, 2.6.32

empty_dir(...){

1    bh = ext4_bread(NULL, inode, &err);
     if (bh && err)
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- e.g., fail to read an inode block

Software bugs

- unexpected states detected
- e.g., allocated block is not in a valid range

Software Bug Example

```
ext3/balloc.c, 2.6.32

ext3_rsv_window_add(...){

 1    if (start < this->rsv_start)
          p = &(*p)->rb->left;
 2    else if (start > this->rsv_end)
          p = &(*p)->rb->right;
 3    else {
         rsv_window_dump(root, 1);
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i-bitmap	1	1		Yes
inode	1	2	2	Yes
super	1			Yes
dir-entry	4	4	3	Yes
gdt	3		2	Yes
indir-blk	1	1		**No**
xattr	5	2	1	**No**
block			5	Yes/No
journal		3	27	Yes
journal_head			31	Yes
buf_head			16	Yes
handle		22	9	Yes
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Shared-disk file systems OCFS2

- inspired by Ext3 design
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  - host virtual machine images
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Shared-disk file systems OCFS2

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Global failures are also prevalent

- a single piece of corrupted metadata can fail the whole file system on multiple nodes !

Current Abstractions

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File and directory

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Partitions

- multiple file systems on separated partitions
- a single panic on a partition can crash the whole operating system
- static partitions, dynamic partitions
- management of many partitions

All files on a file system implicitly share

a single fault domain

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Current file-system abstractions do not
provide fine-grained fault isolation

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Study of Failure Policies

Isolation File Systems

- New Abstraction
- Fault Isolation
- Quick Recovery
- Preliminary Implementation on Ext3

Challenges

Isolation File Systems

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Fine-grained partitioned

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Elastic

- dynamically grow and shrink its size

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- contains a group of files and *related metadata*
- an independent fault domain

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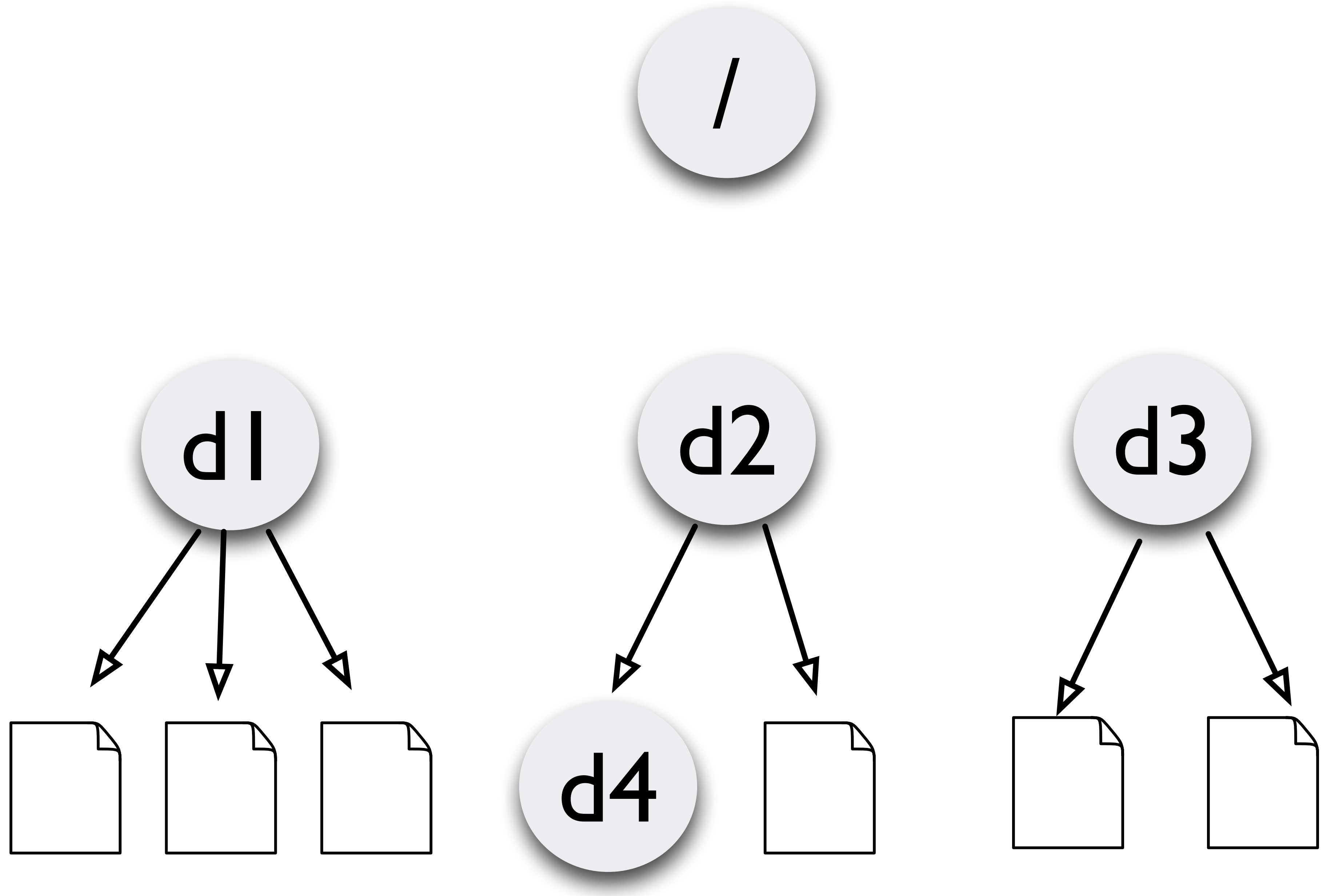
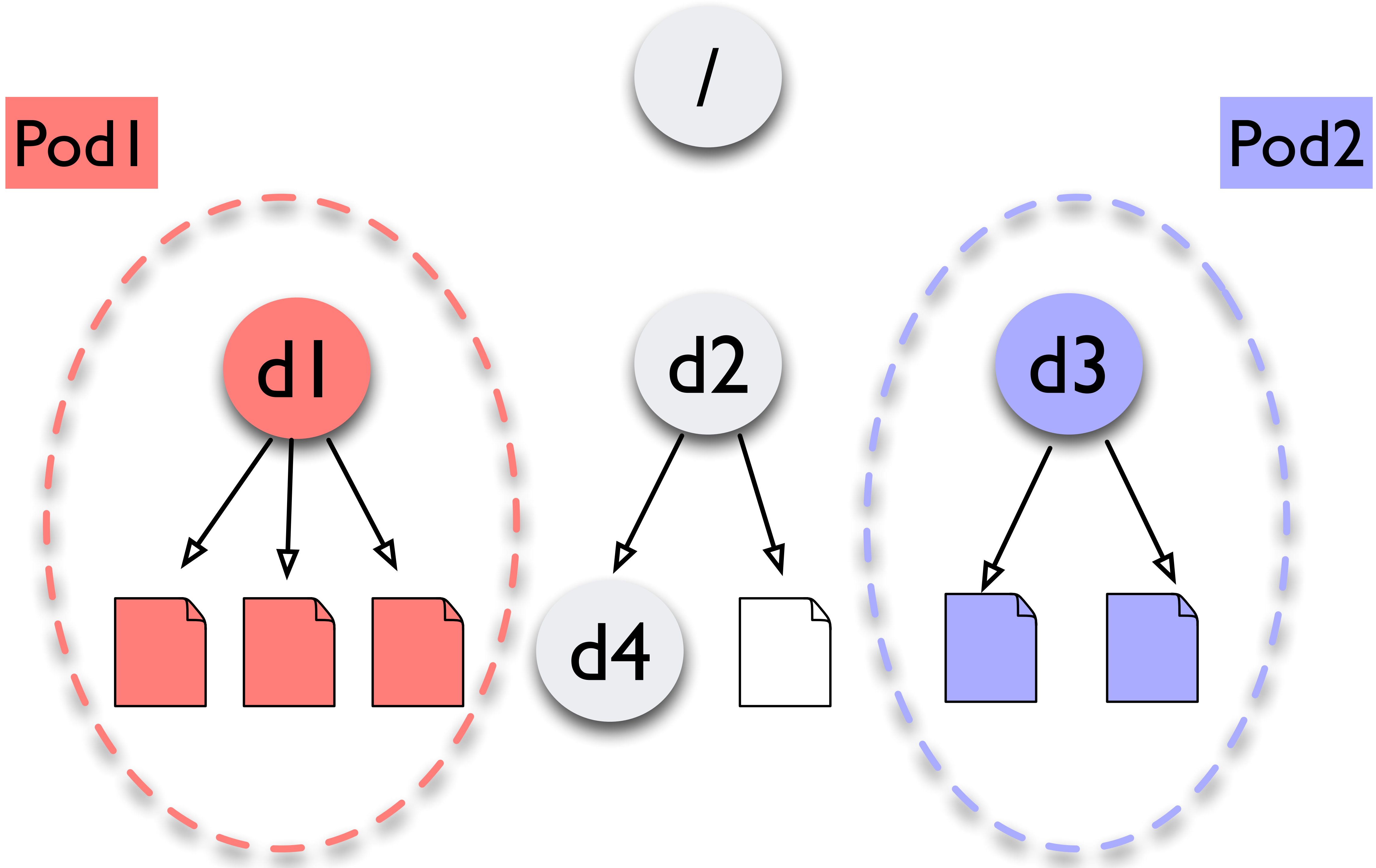
Operations

- create a file pod
- set / get file pod's attributes
  - failure policy
  - recovery policy
- bind / unbind a file to pod
- share a file between pods


/
d1
d2
d3
d4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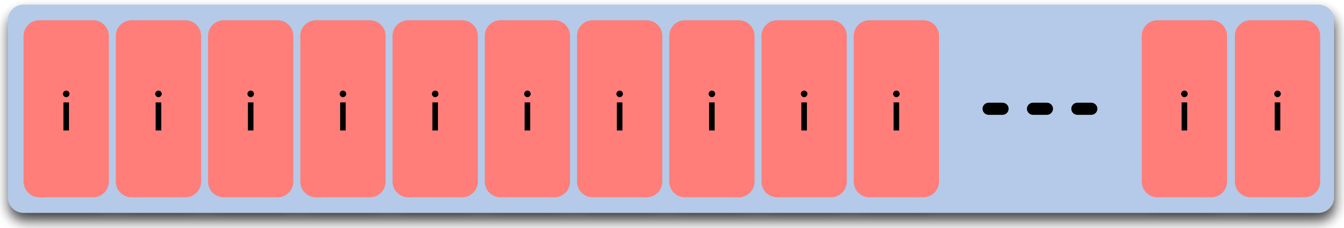
For example

- ➡ multiple inodes are stored in a single inode block



an inode block

Metadata Isolation

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- hard to isolate a failure for metadata

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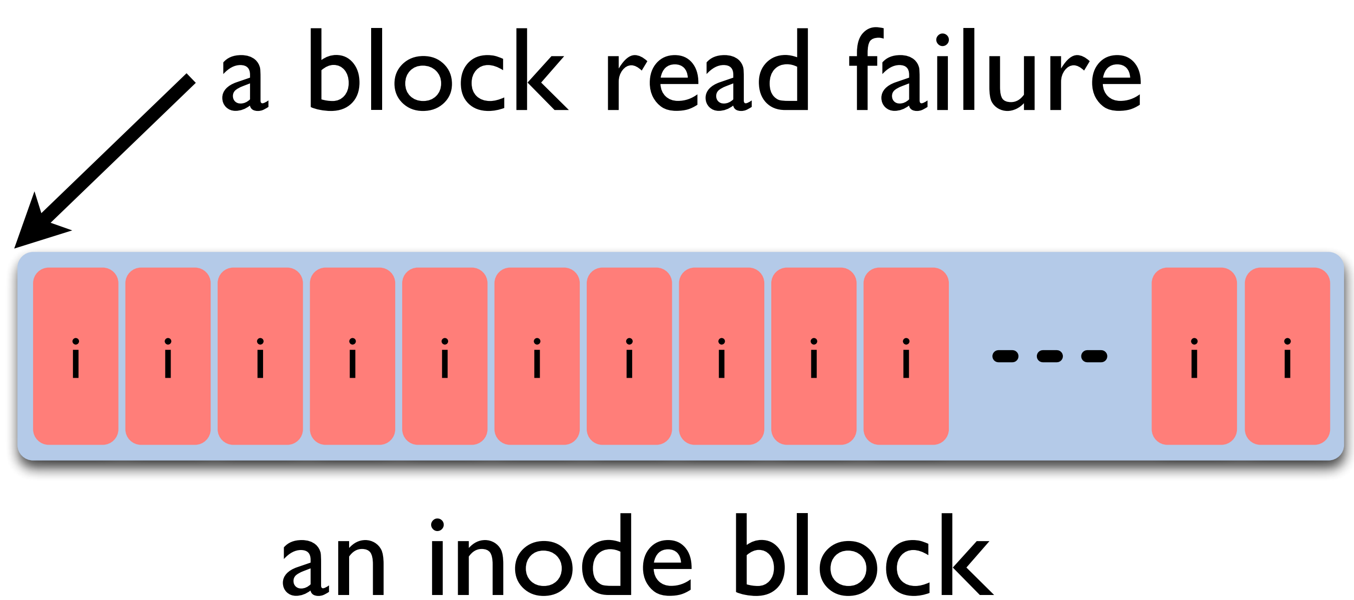
- an I/O failure can affect multiple files



Key Idea 1:

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Isolate metadata for file pods

Localize Failures

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- convert global failures to local failures
- same failure semantics
- only fail the faulty pod

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Read-Only

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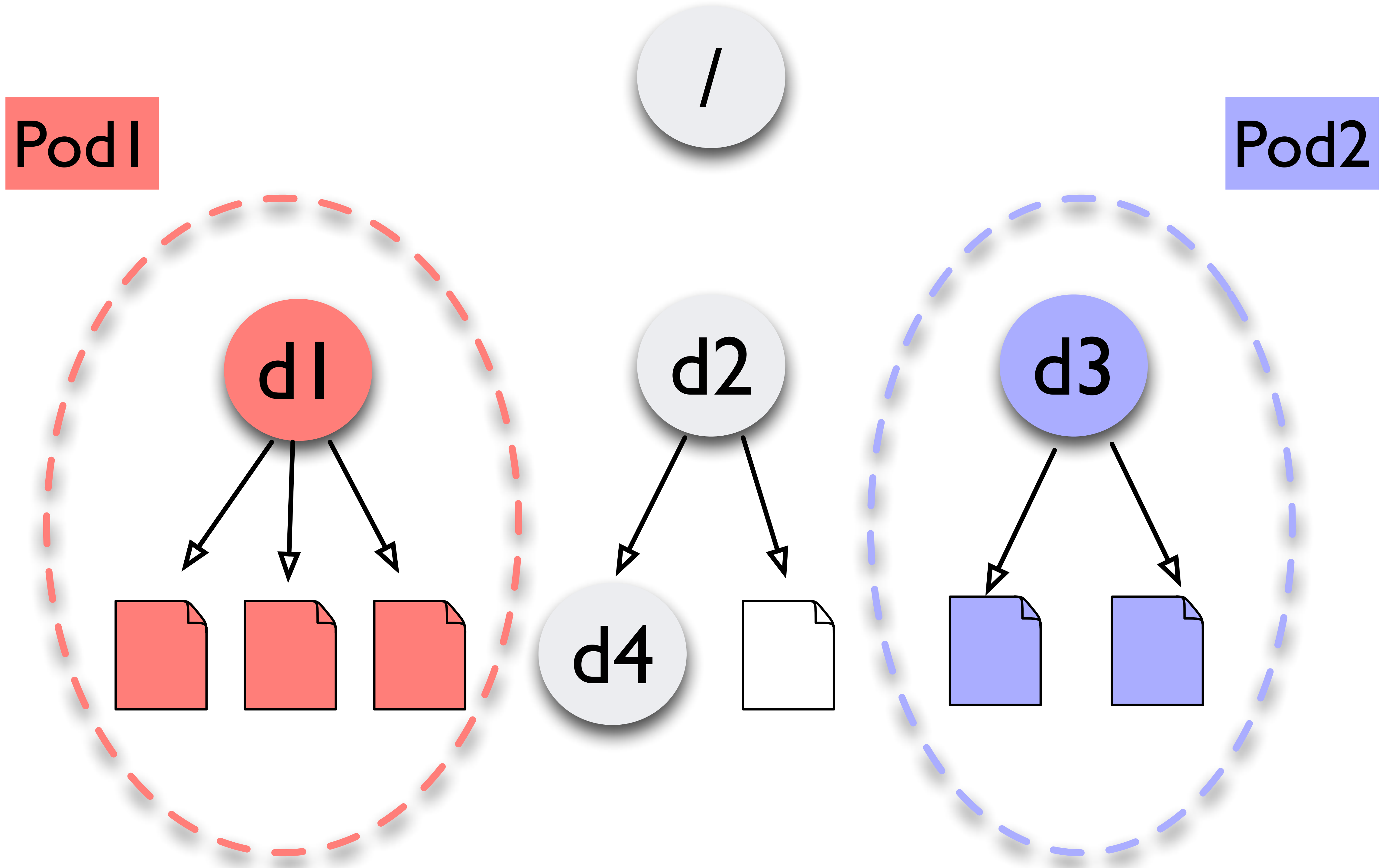
Crash

- crash a file pod instead of the whole system
- provide the same initial states after crash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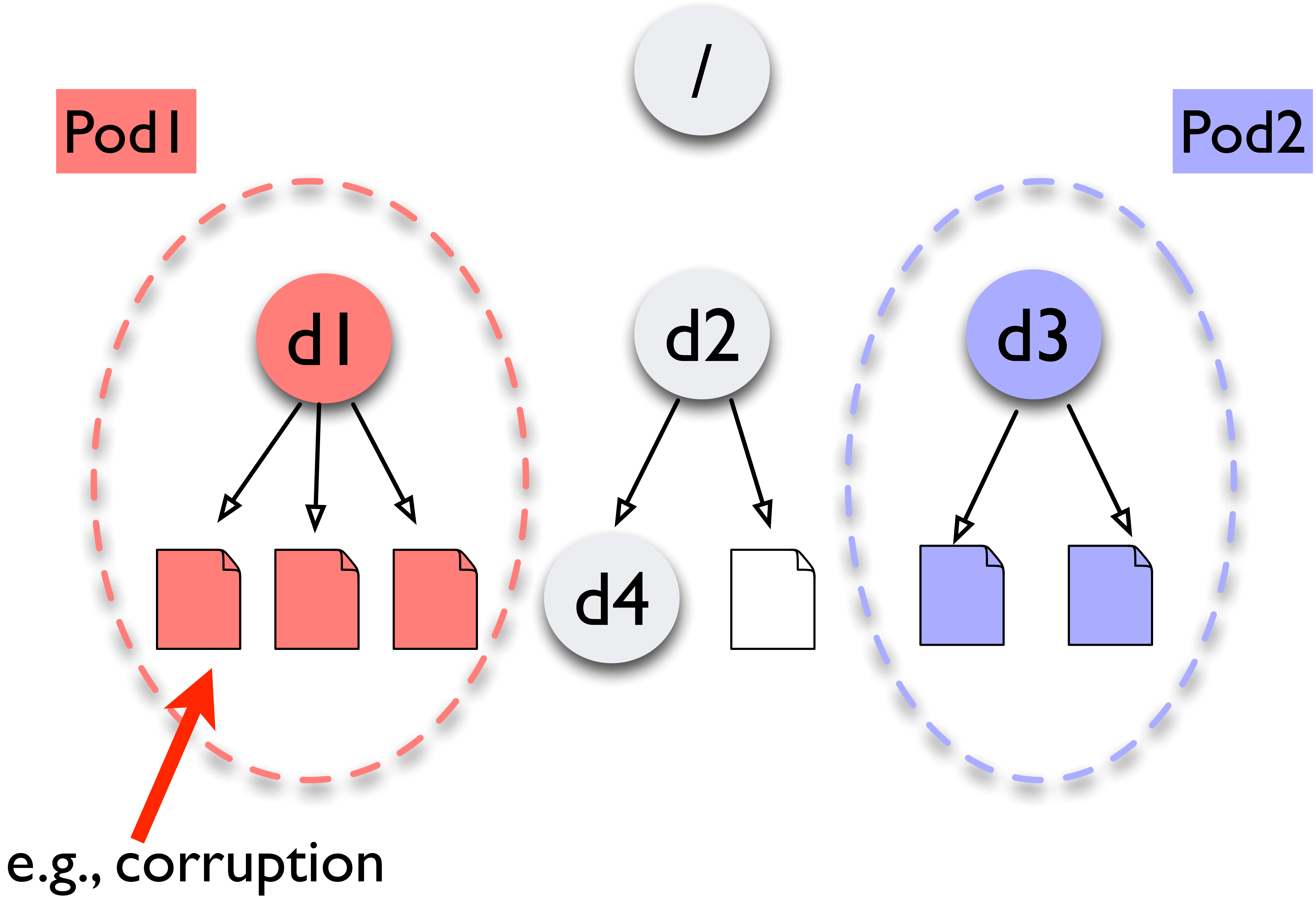
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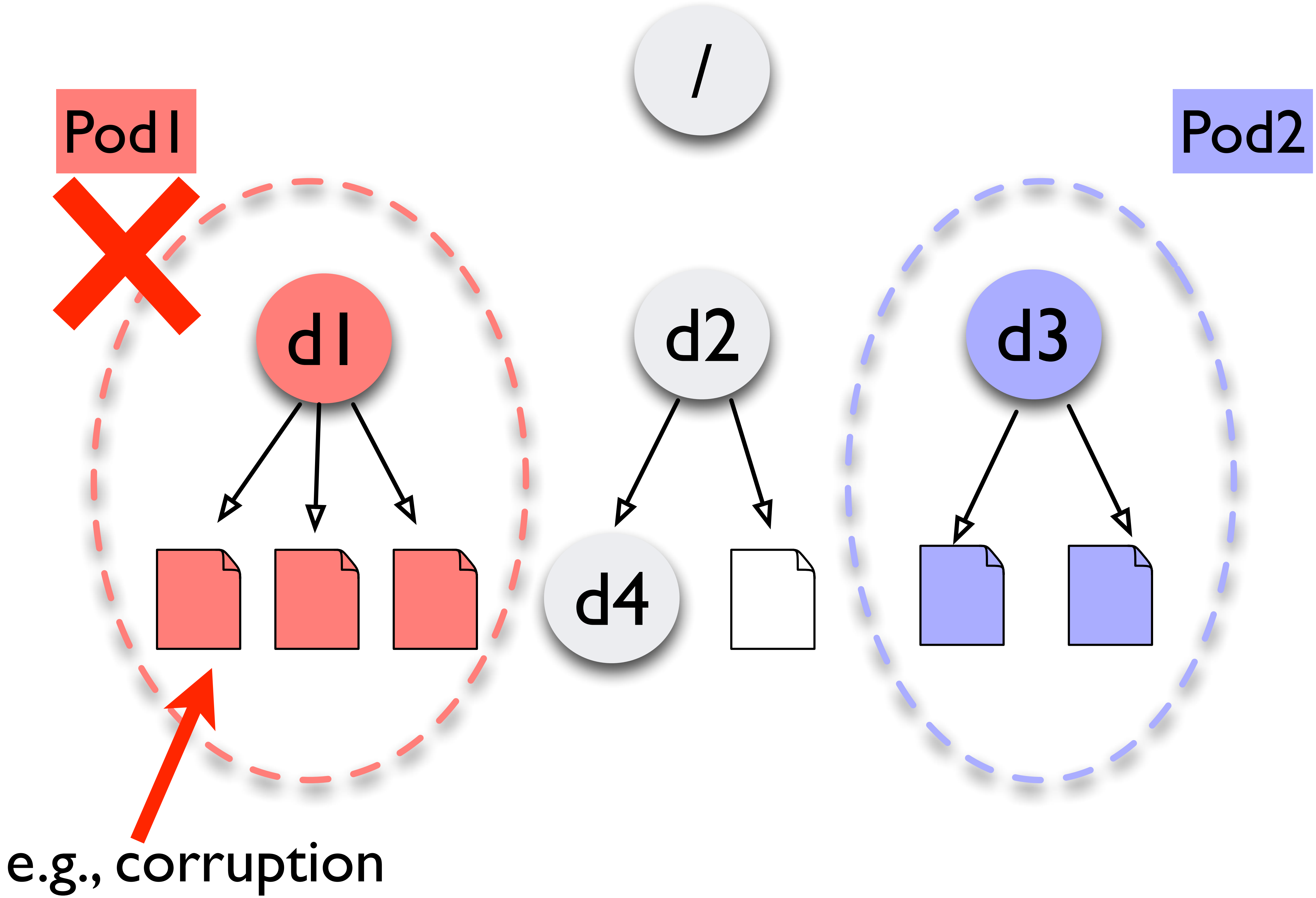
e.g., corruption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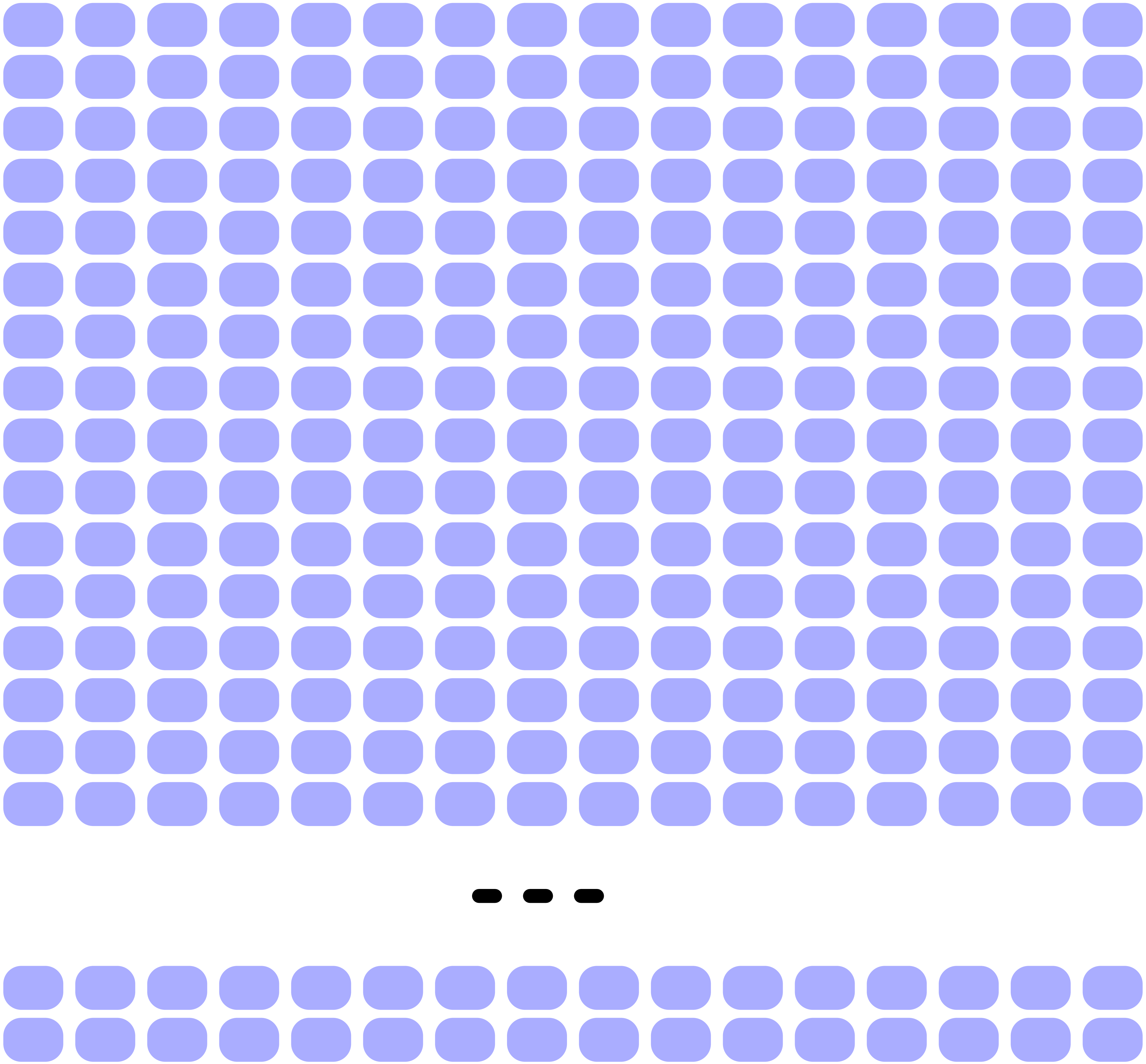
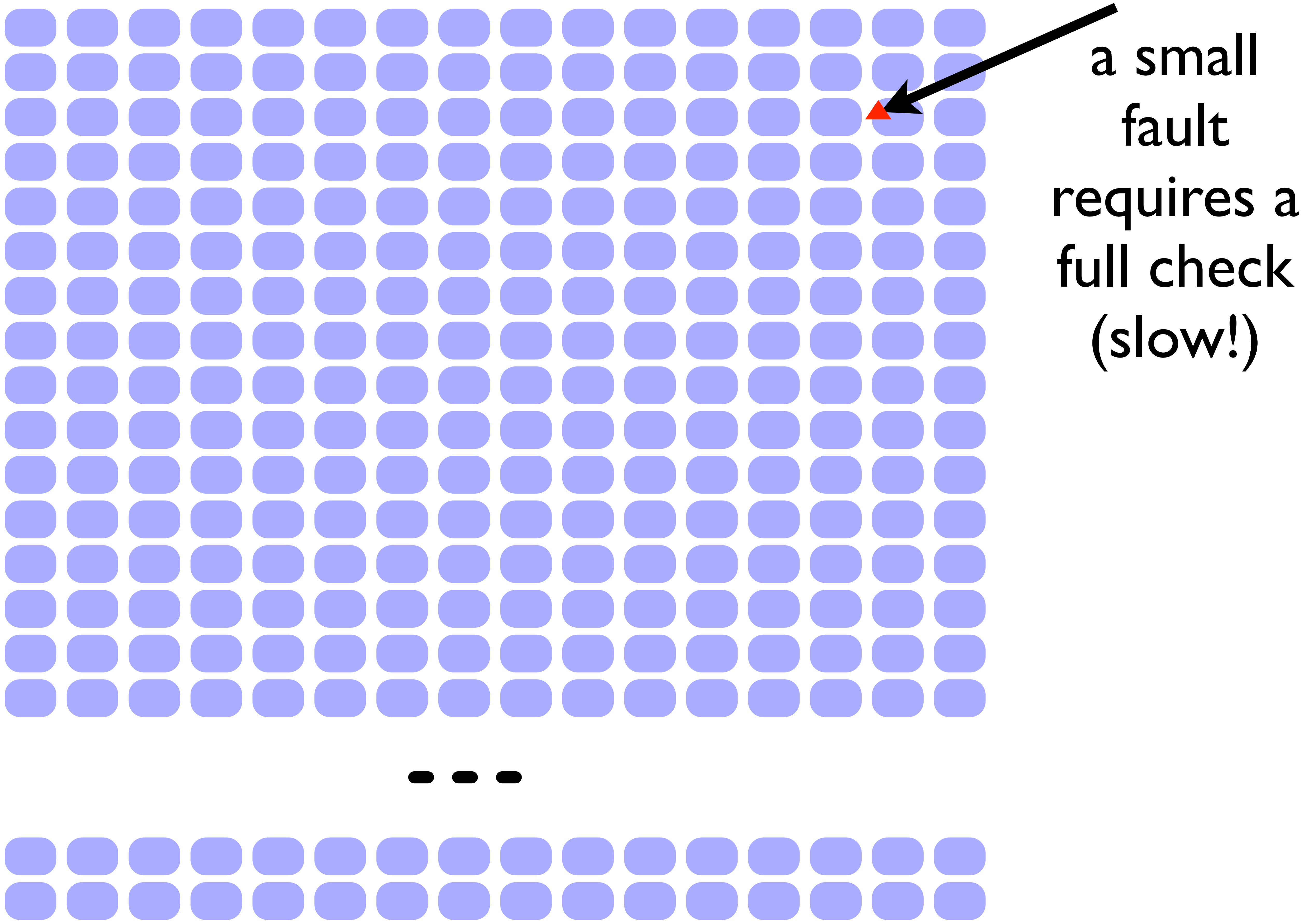
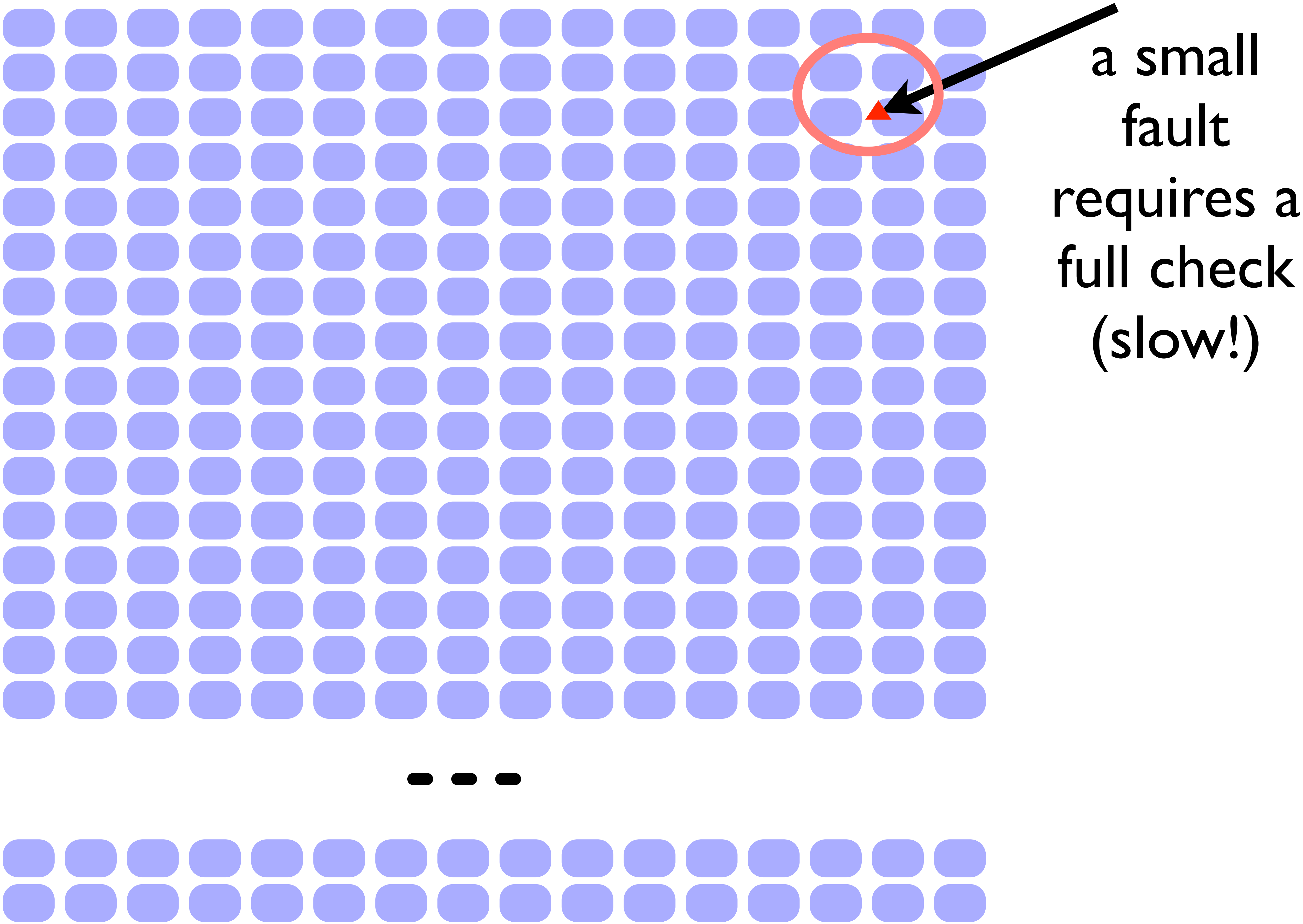
Quick Recovery

File system recovery is slow

- a small error requires a full check
- many random read requests
- 7 hours to sequentially read a 2 TB disk




a small fault requires a full check (slow!)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Key Idea 2:

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Minimize the file system checking range during recovery

Quick Recovery

Quick Recovery

Metadata Isolation

- file pod as the unit of recovery
- check and recover independently
- both online and offline

Quick Recovery

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When recover ?

- leverage internal detection mechanism

Quick Recovery

Metadata Isolation

- file pod as the unit of recovery
- check and recover independently
- both online and offline

When recover ?

- leverage internal detection mechanism

How to recover more efficiently ?

- only check the faulty pod
- narrow down to certain data structures

Introduction

Study of Failure Policies

Isolation File Systems

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Challenges

Ext3 Layout

Ext3 Layout

A disk is divided into block groups

- ➡ physical partition for disk locality

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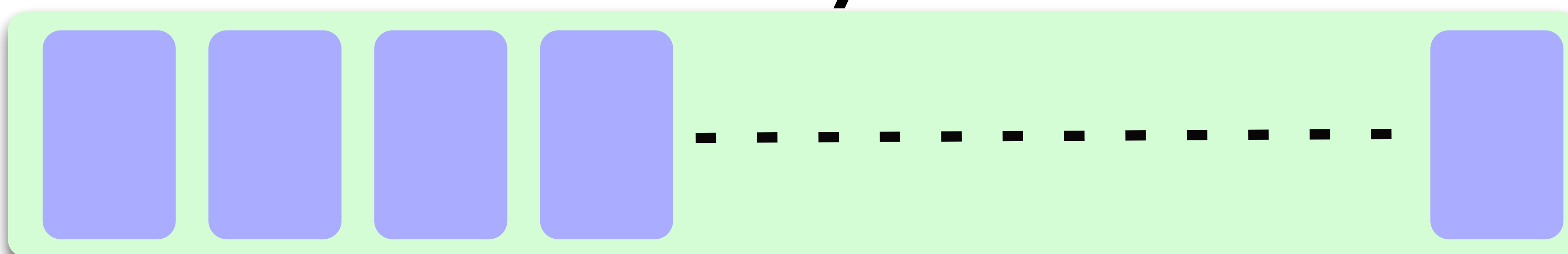
disk layout



Ext3 Layout

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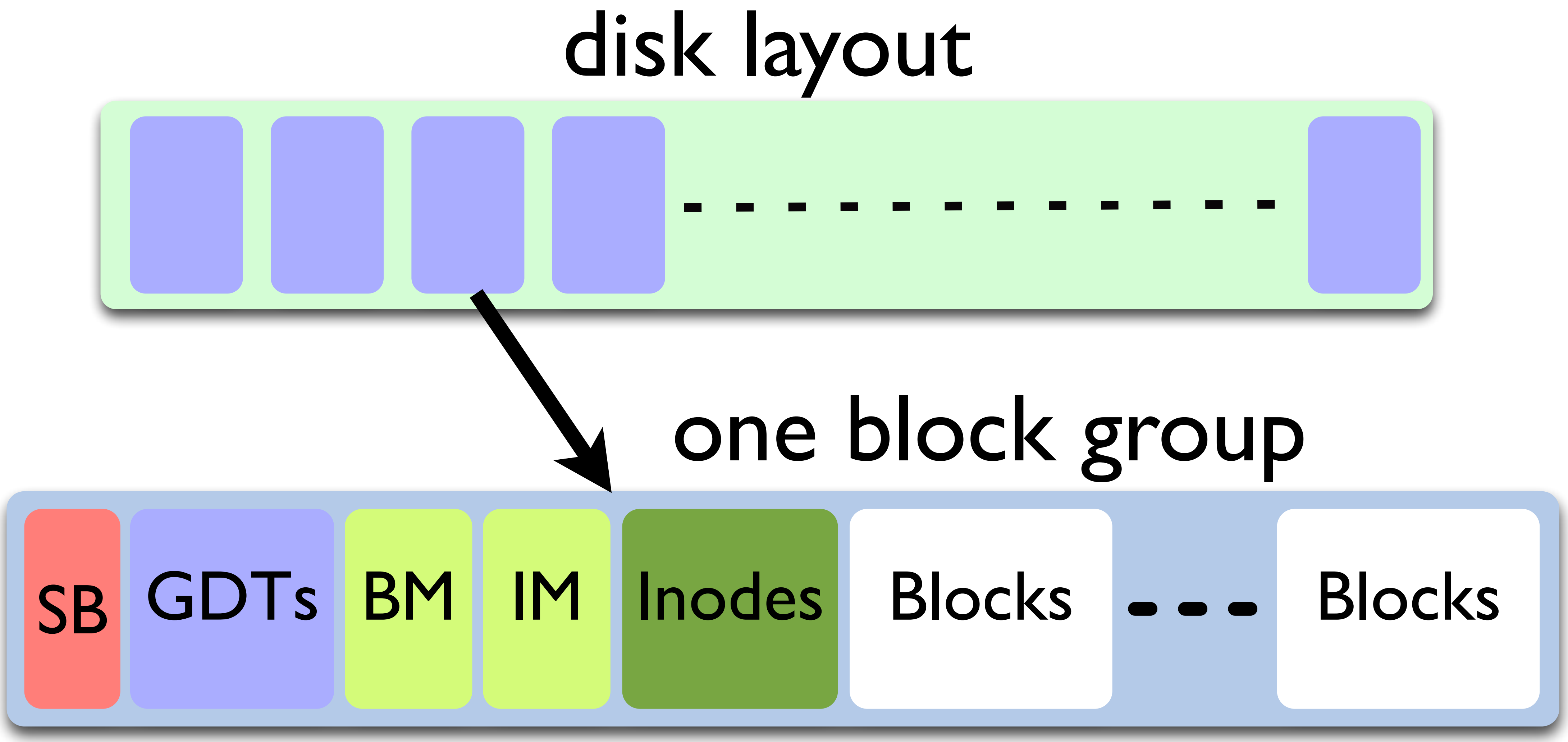
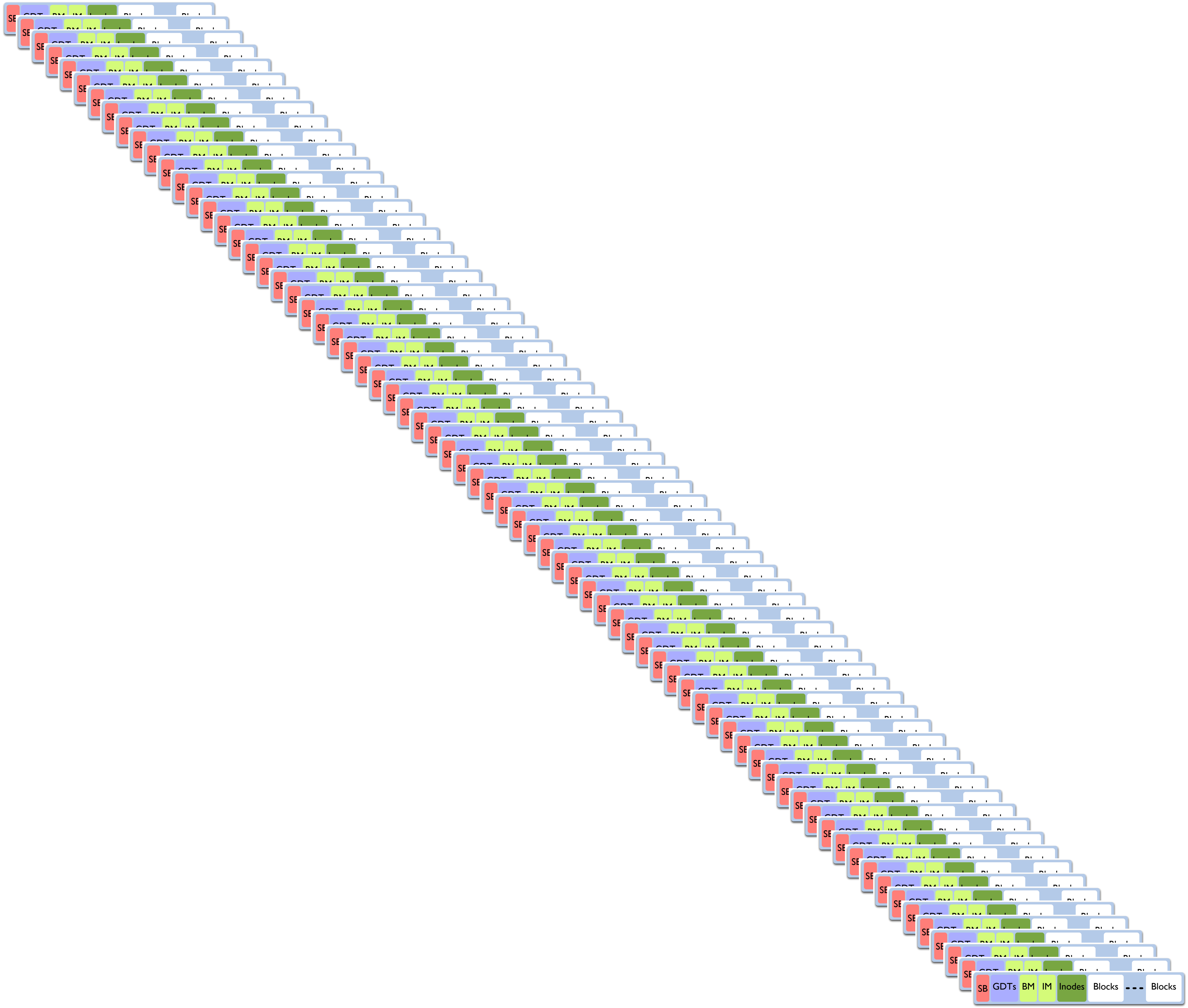
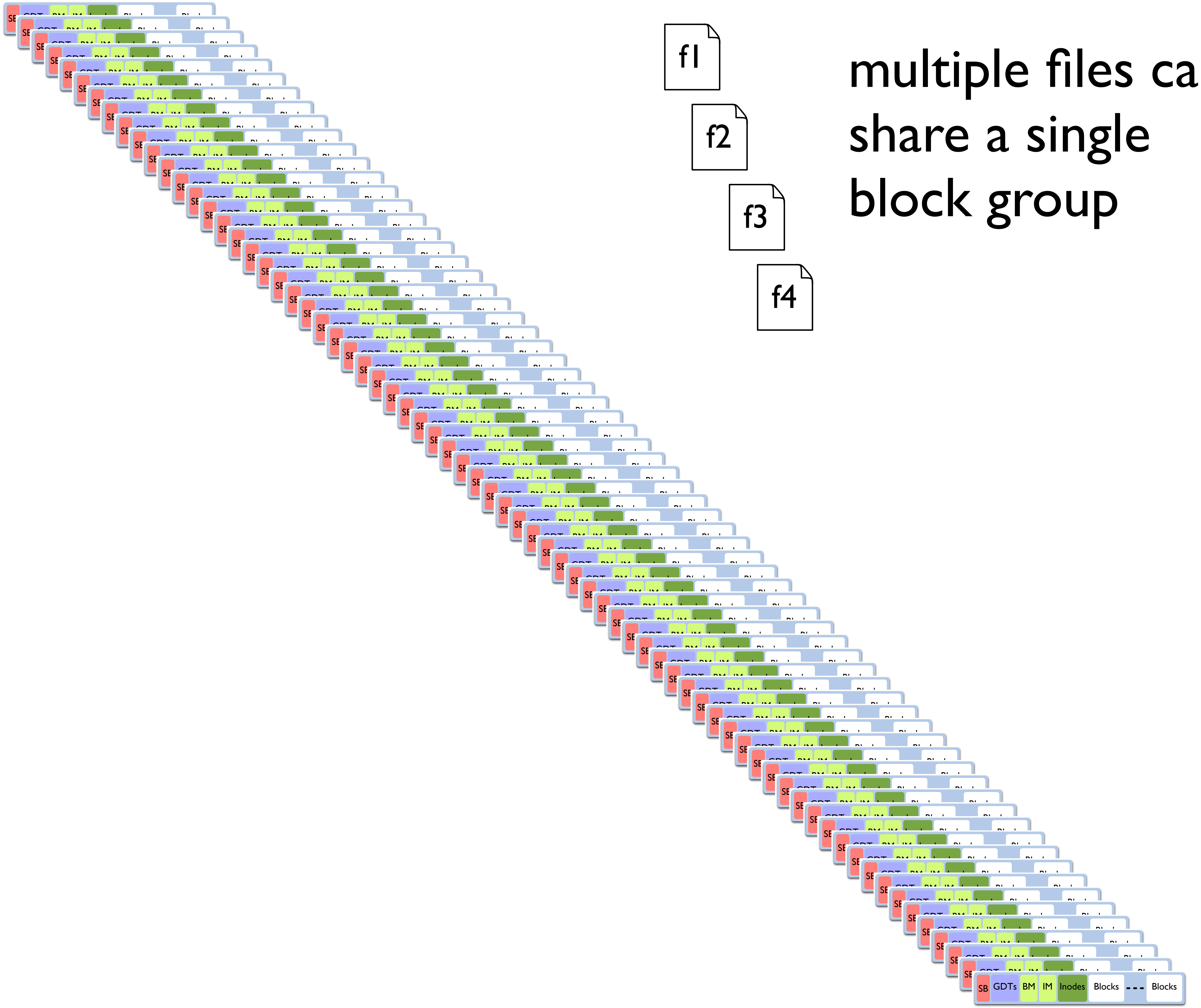
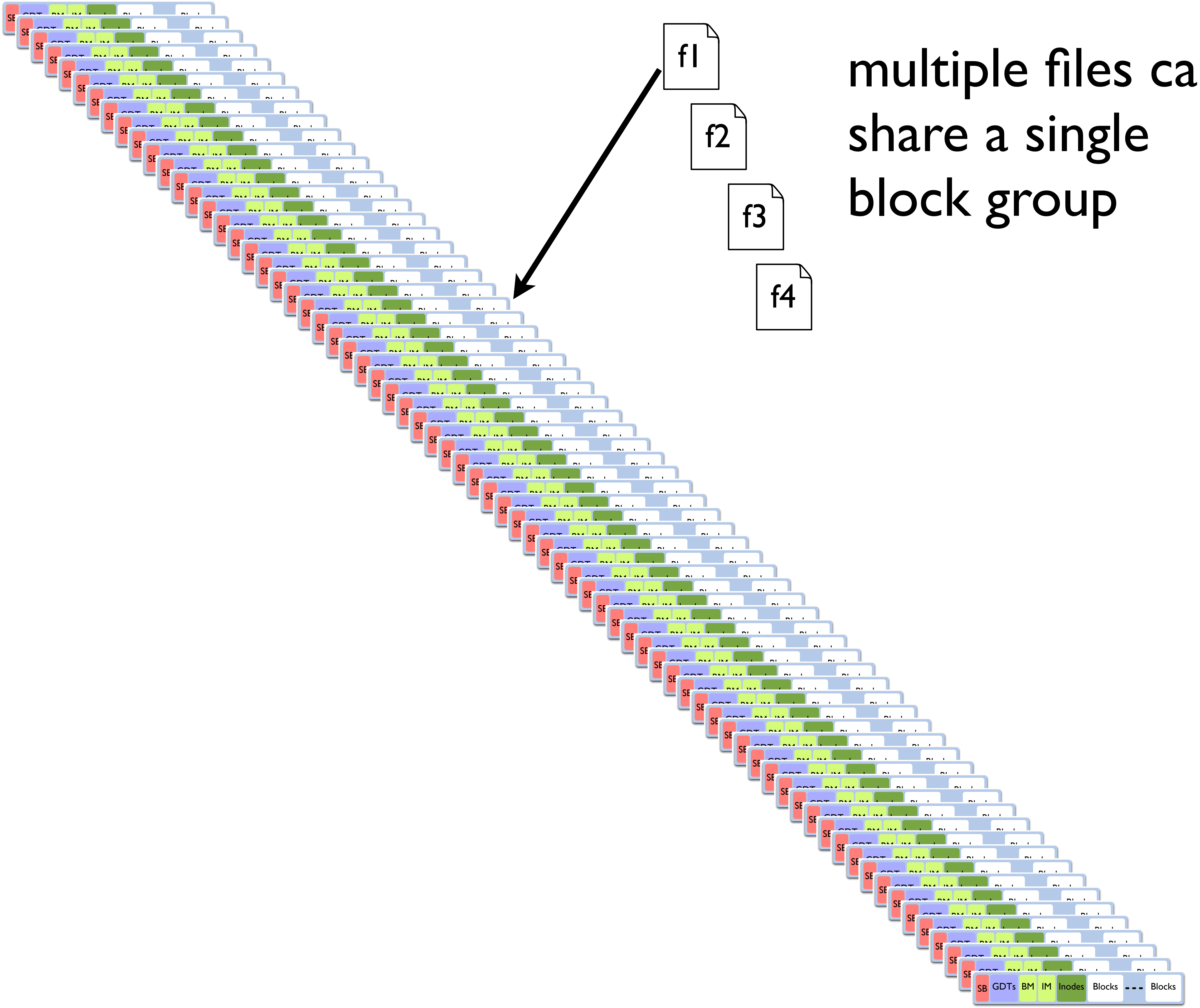
- physical partition for disk locality




SB
GDTs
BM
IM
Inodes
Blocks
Blocks

multiple files can share a single block group





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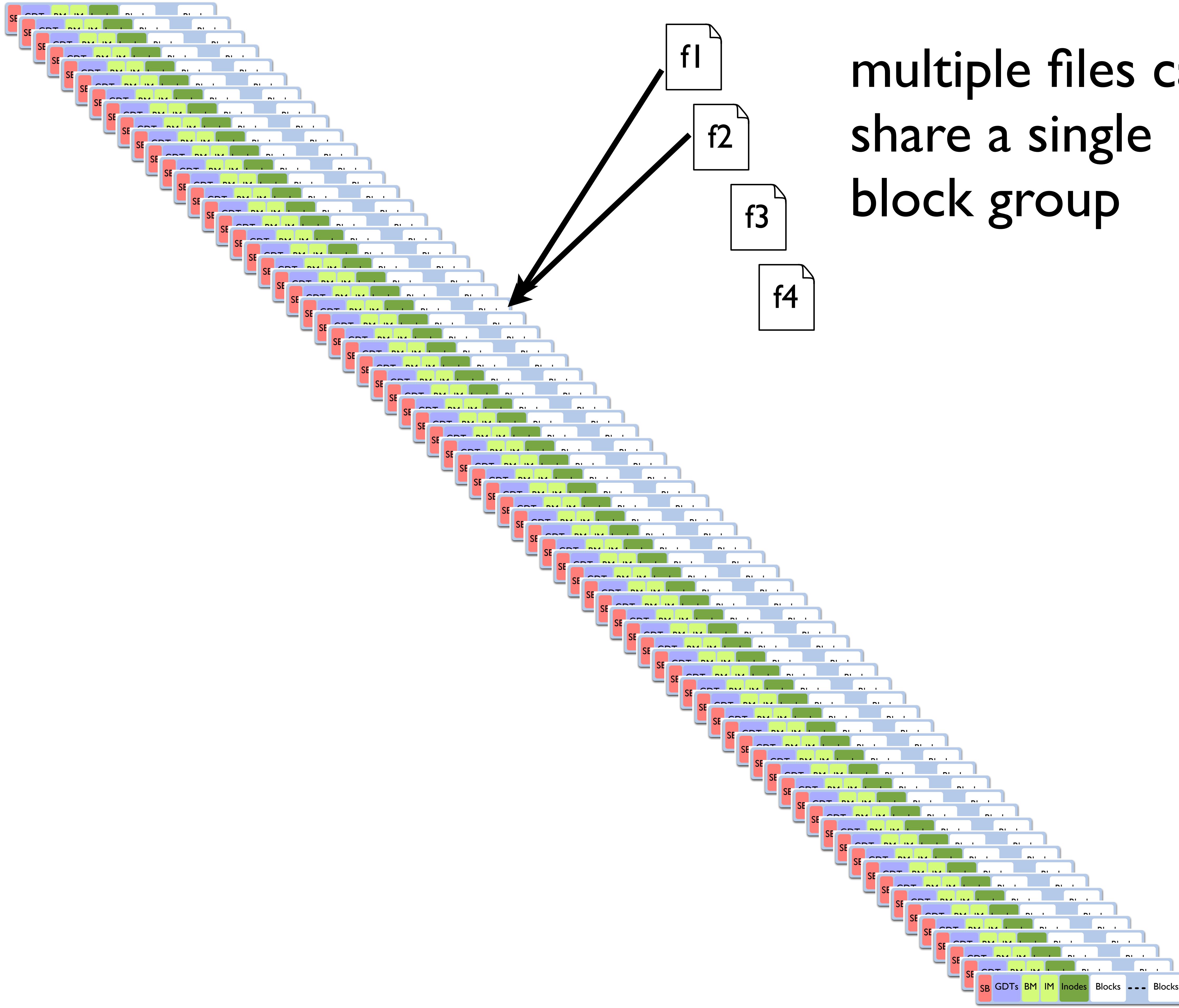

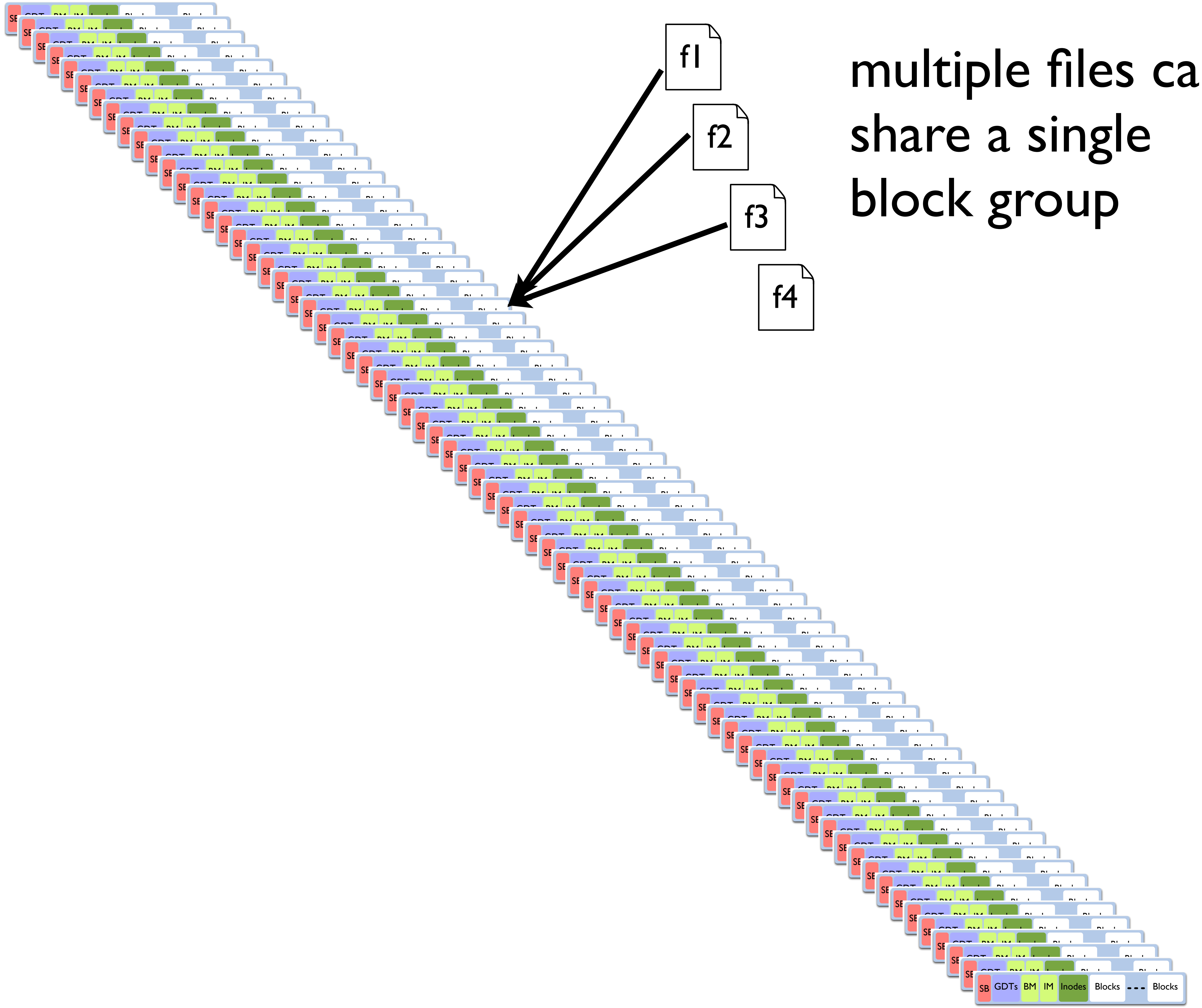

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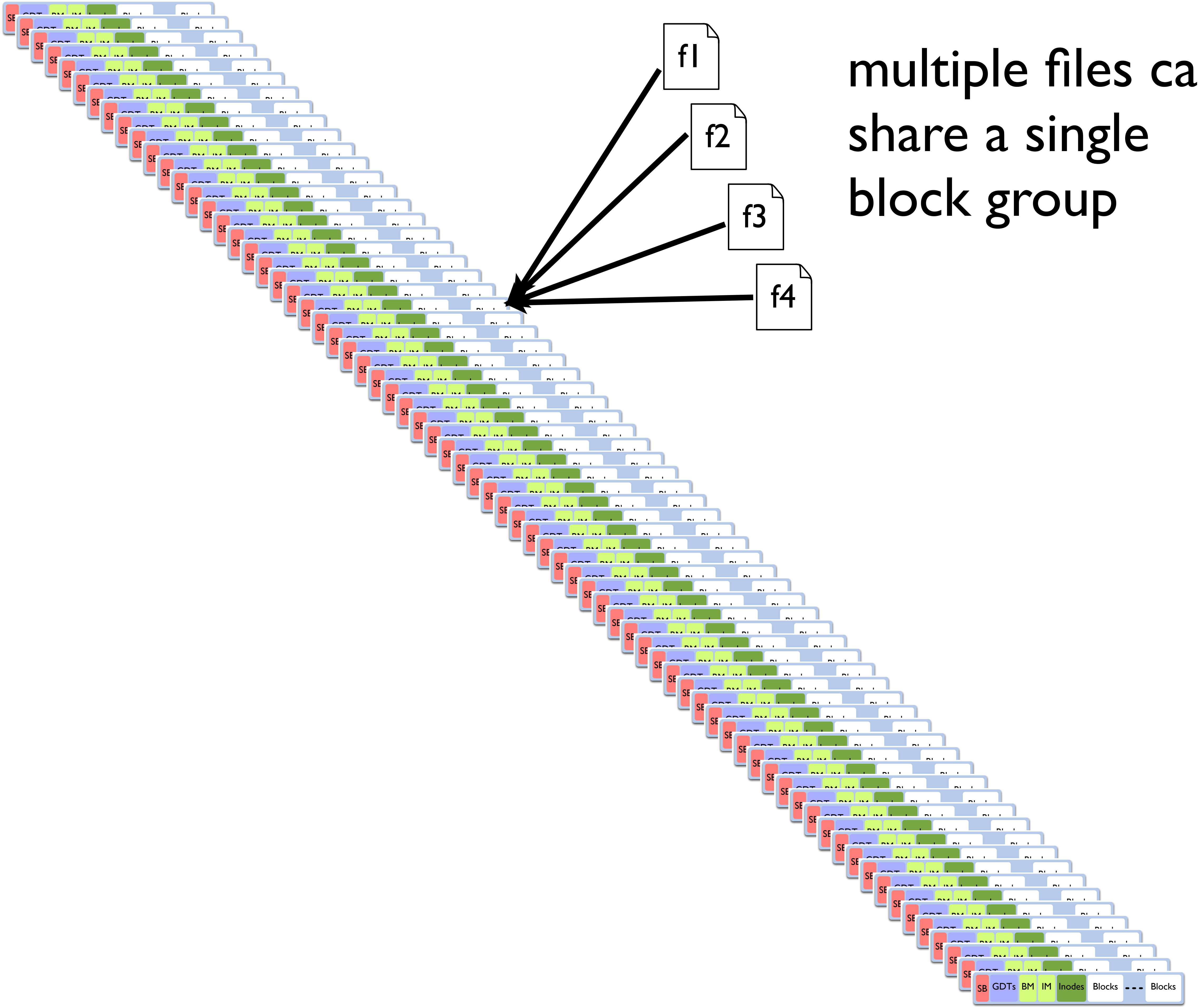

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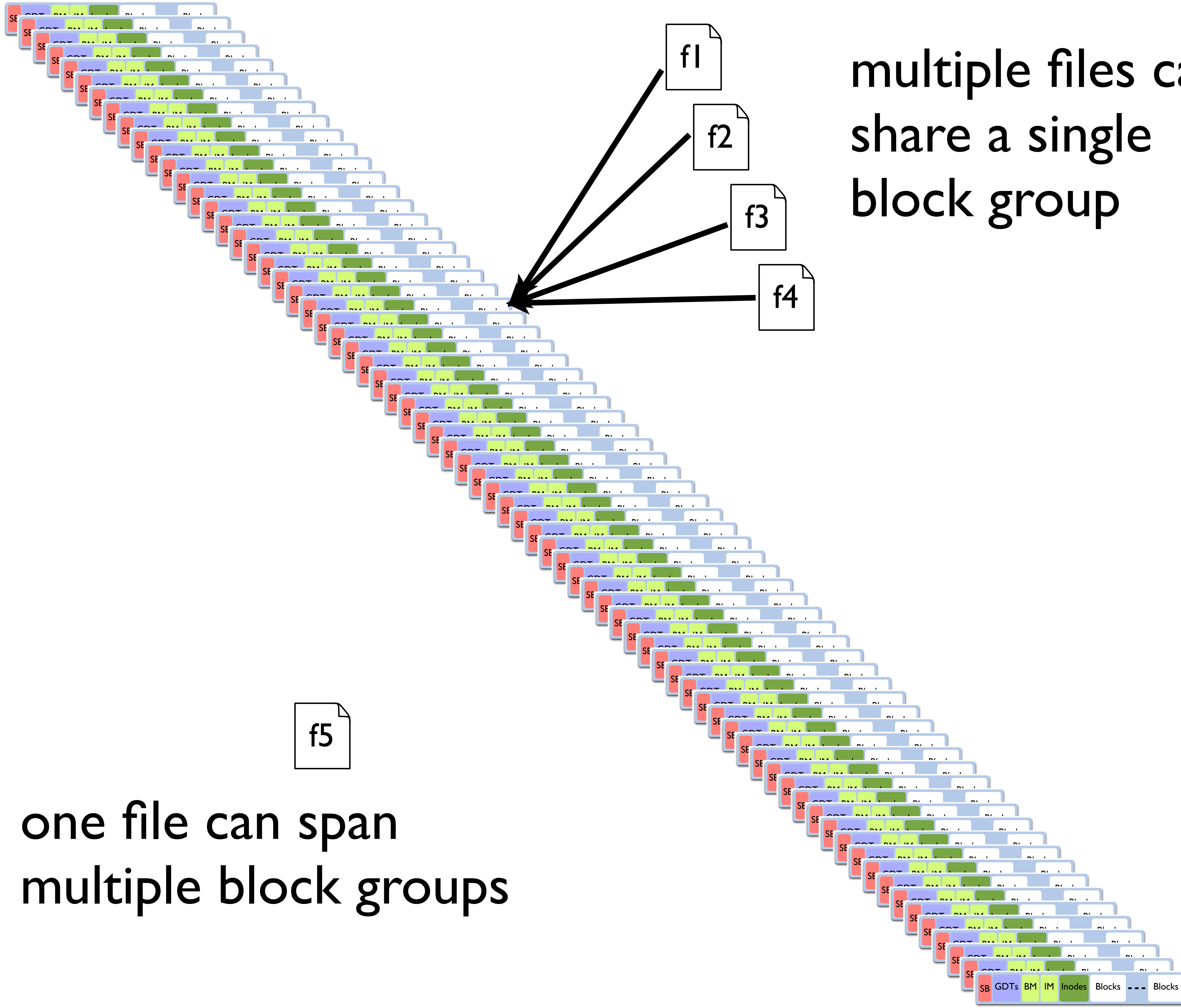
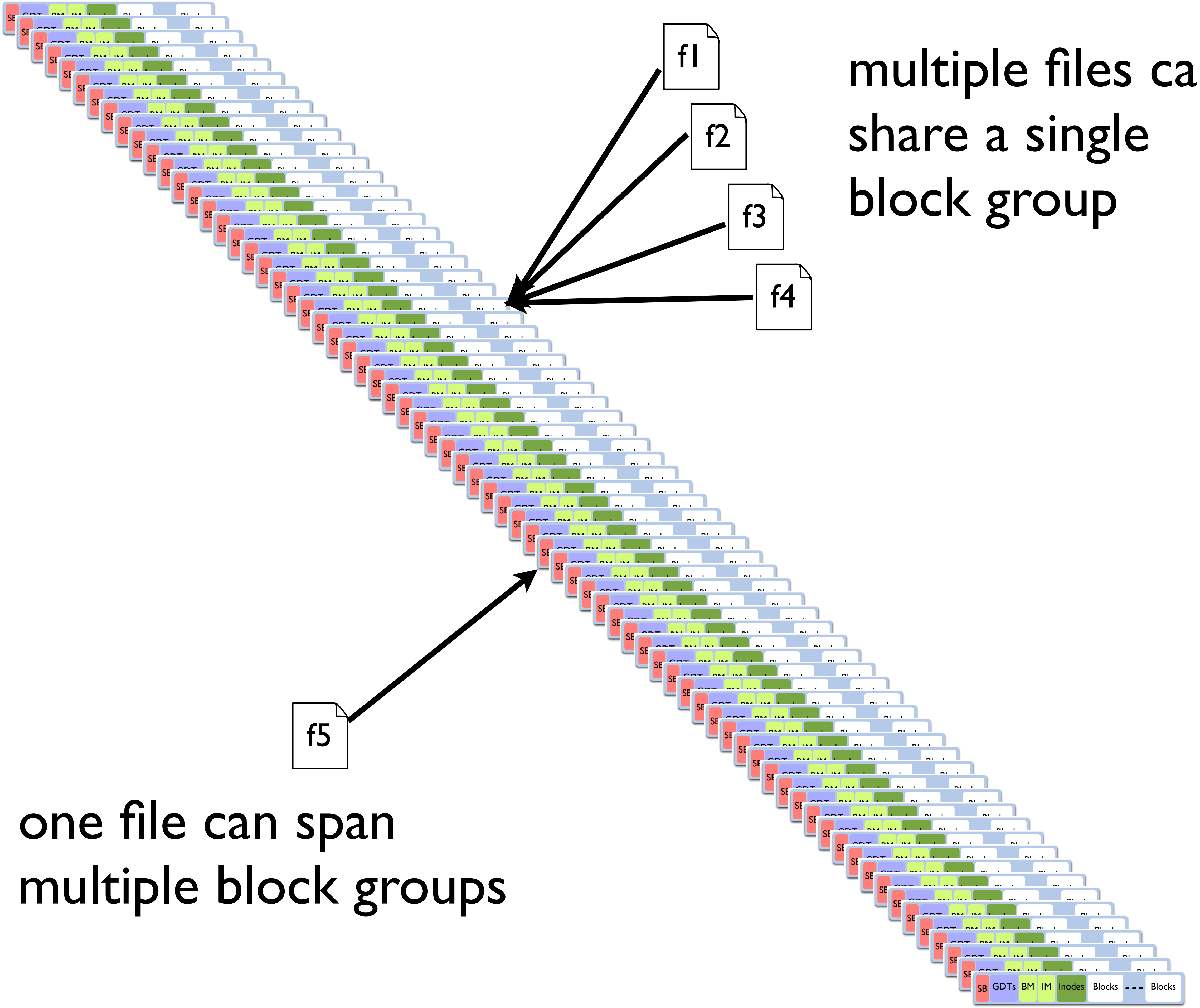


multiple files can share a single block group

one file can span multiple block groups



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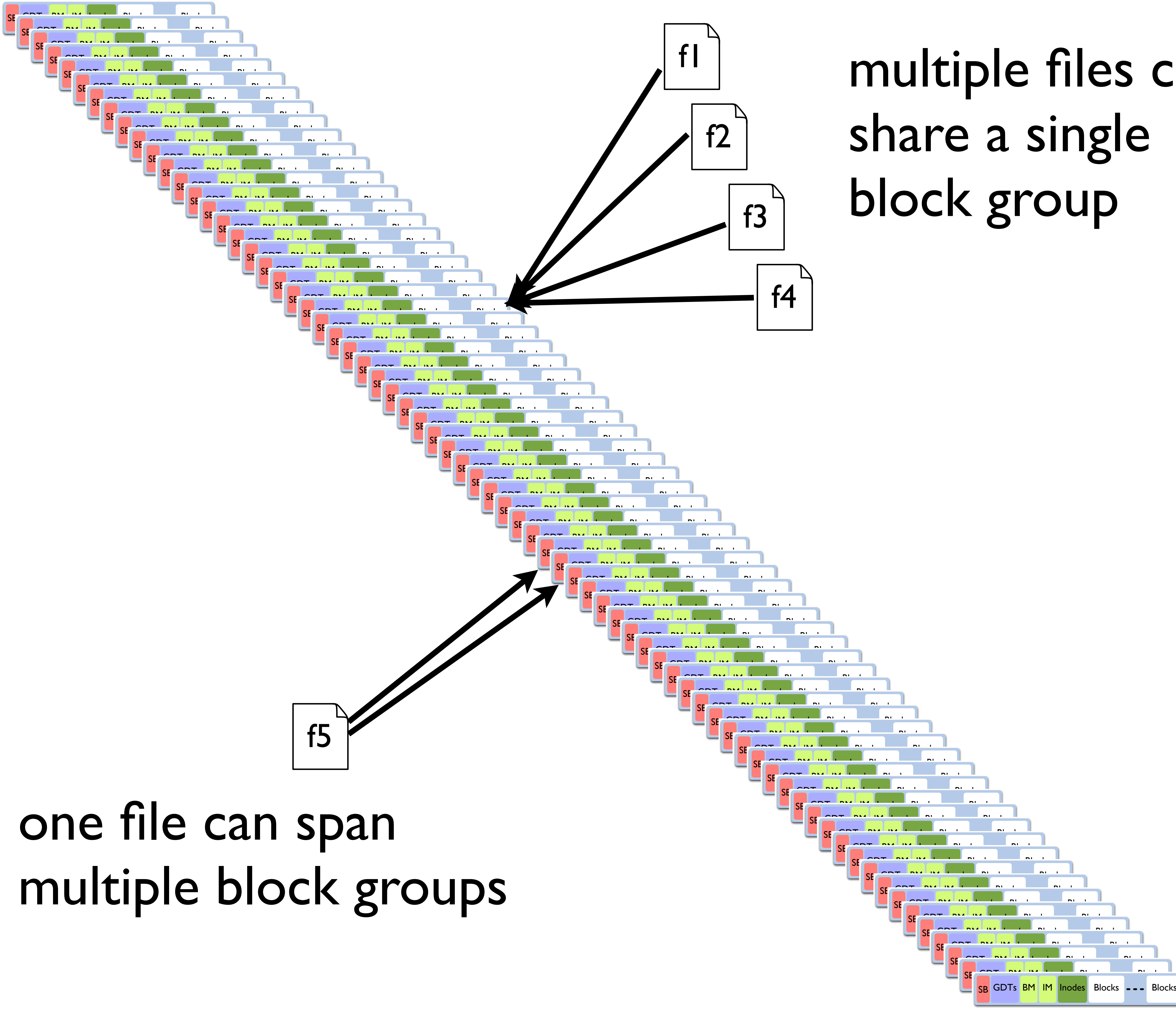

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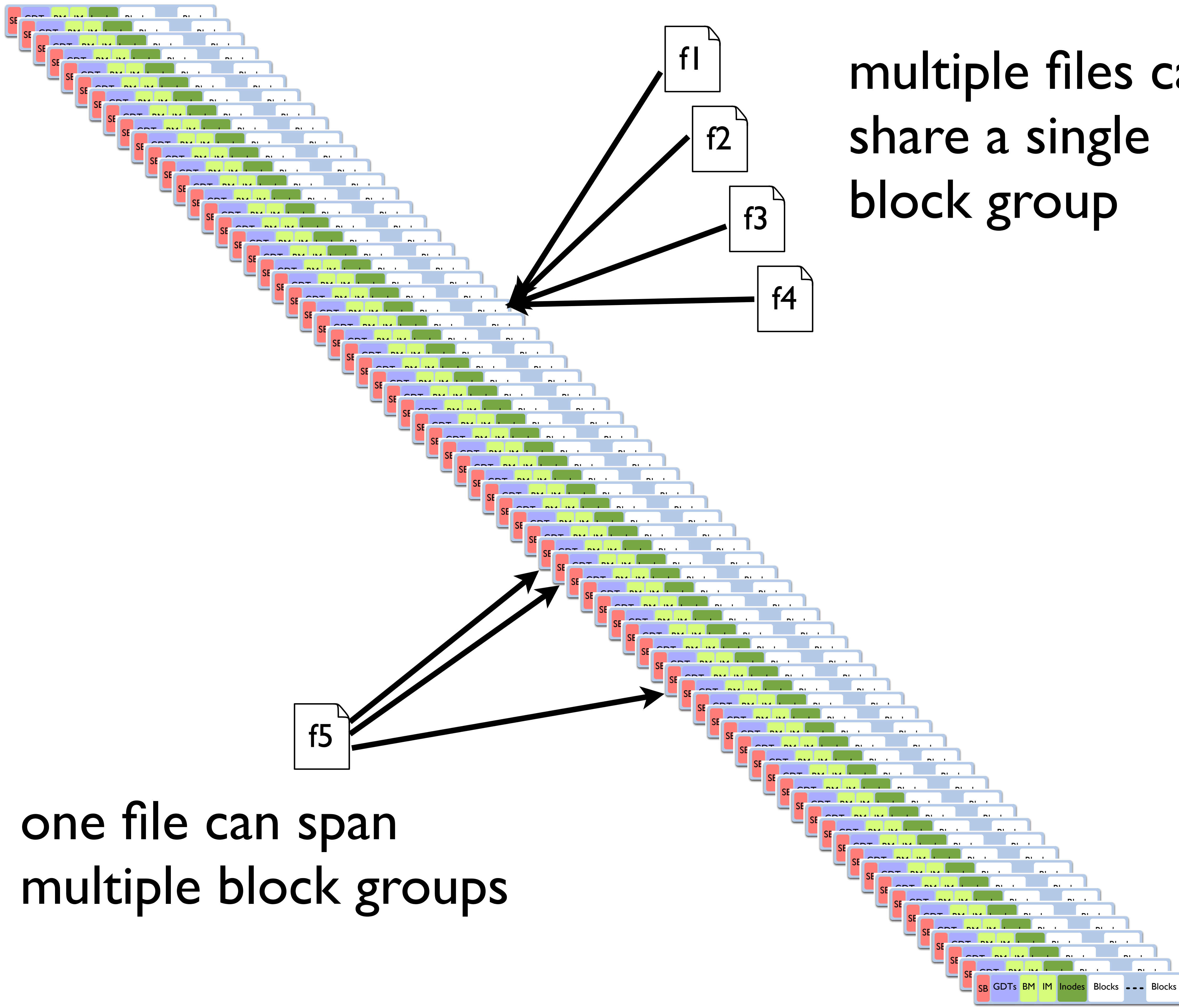

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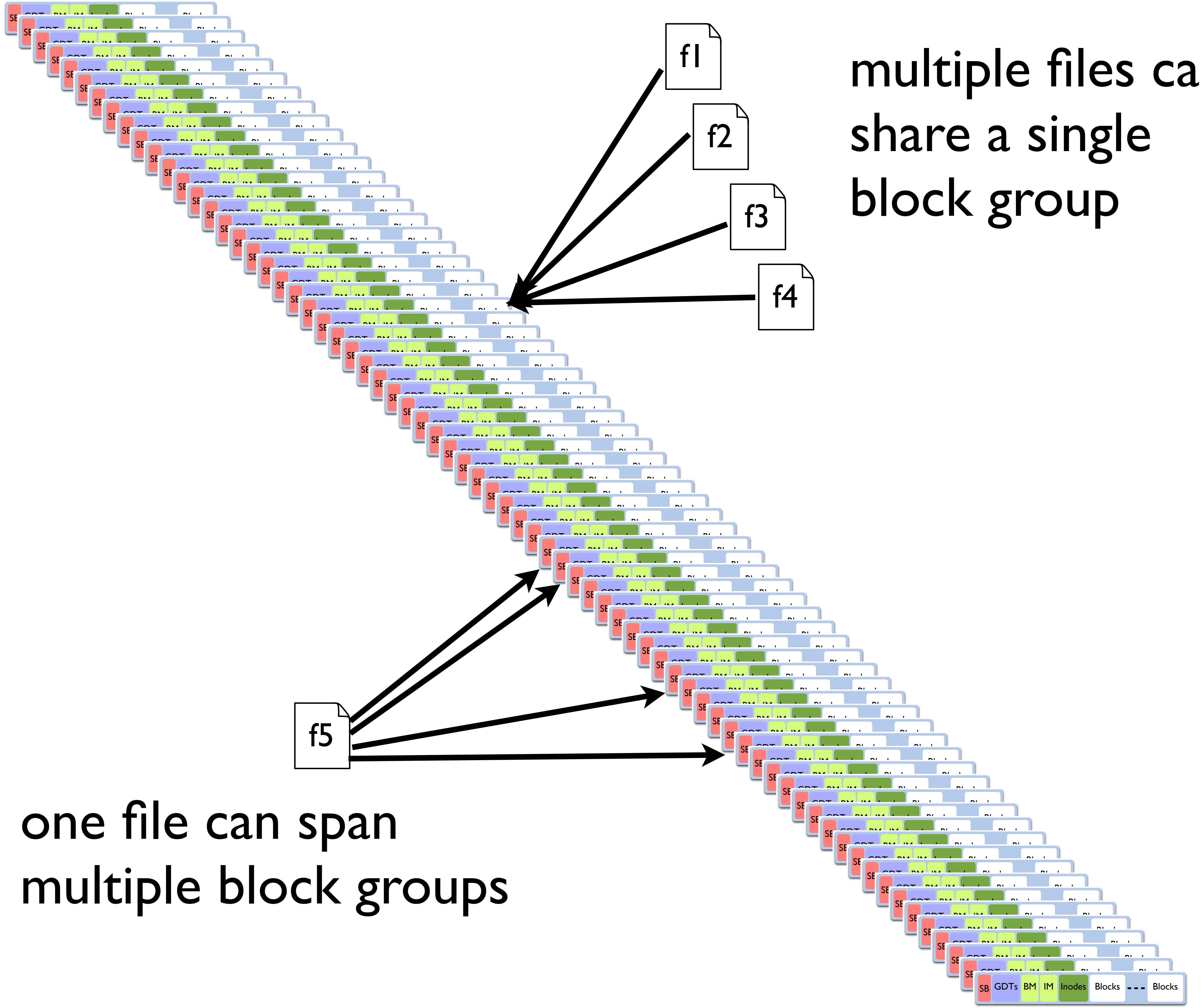

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Layout

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A file pod contains multiple block groups

- one block group only maps to one file pod
- performance locality and fault isolation

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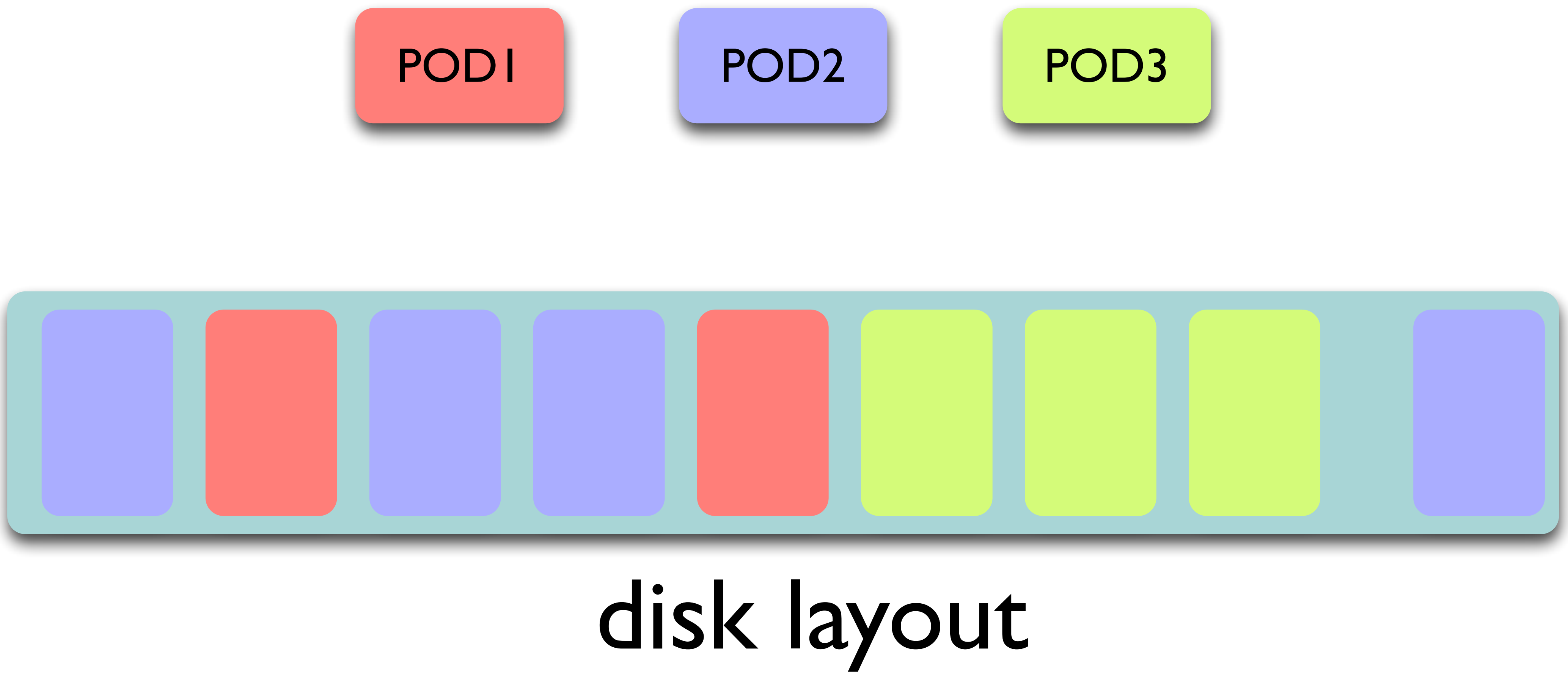


Data Structures

Data Structures

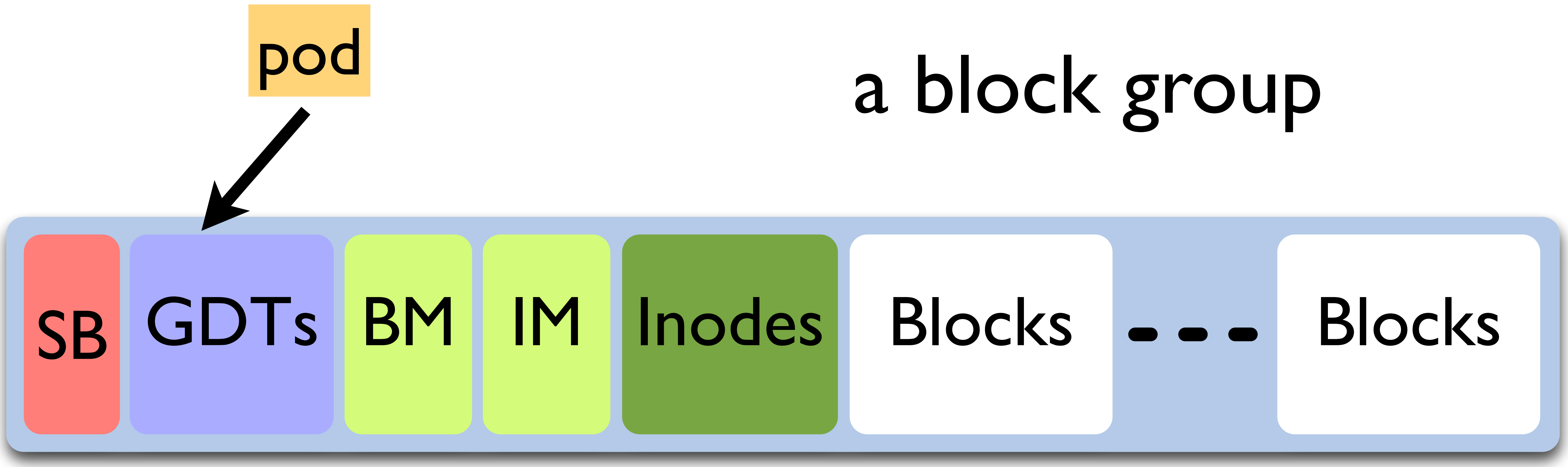
Pod related structure

- ➡ no extra mapping structures

Data Structures

Pod related structure

- no extra mapping structures
- embeds in group descriptors
- group descriptors are loaded into memory

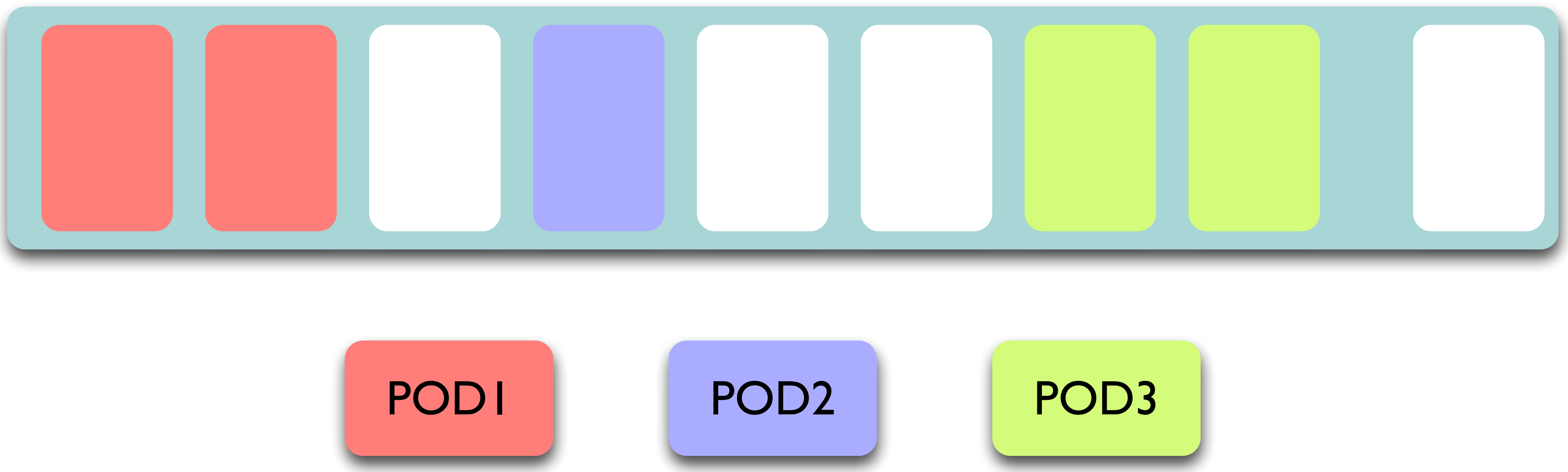


Algorithms

Algorithms

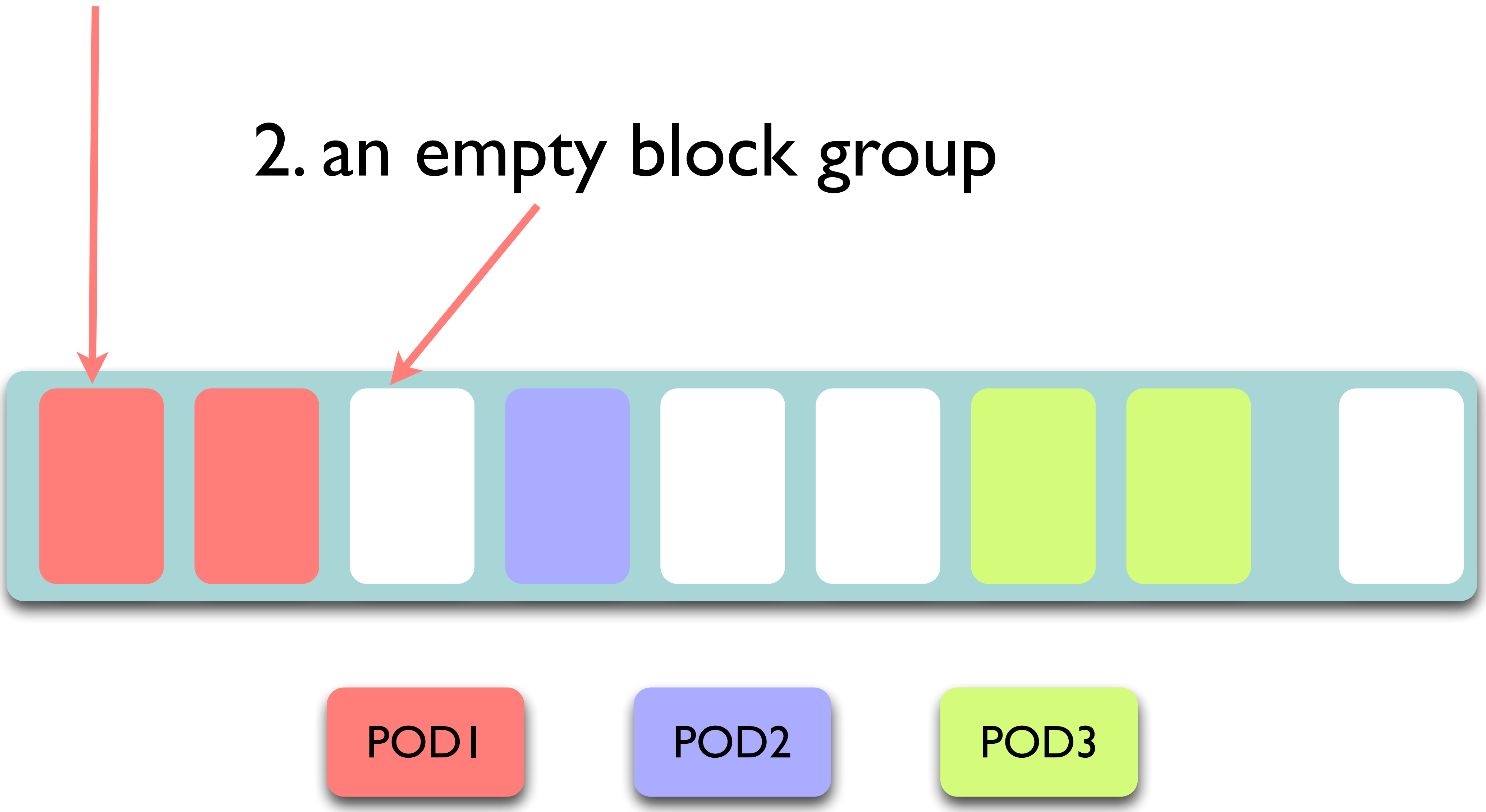
Pod based inode and block allocation

- preserve original allocation's locality
- allocation will not cross pod boundary


POD1
POD2
POD3

1. within the same pod

2. an empty block group



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De-fragmentation

- potential internal fragmentation

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Pod based inode and block allocation

- preserve original allocation's locality
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De-fragmentation

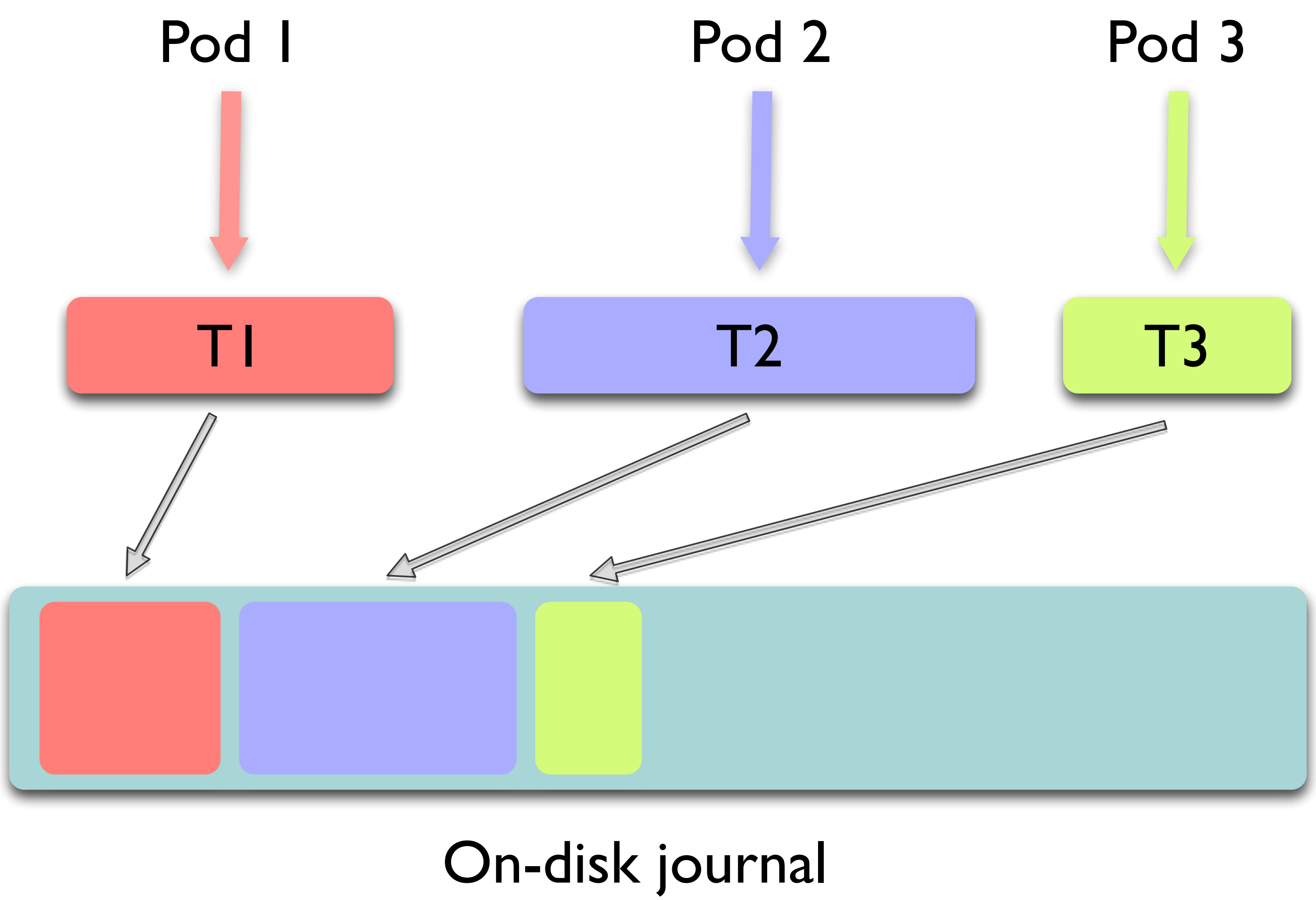
- potential internal fragmentation
- de-fragmentation for file pods
- similar solution in Ext4

Journaling

Journaling

Virtual transaction

- contains updates only from one pod

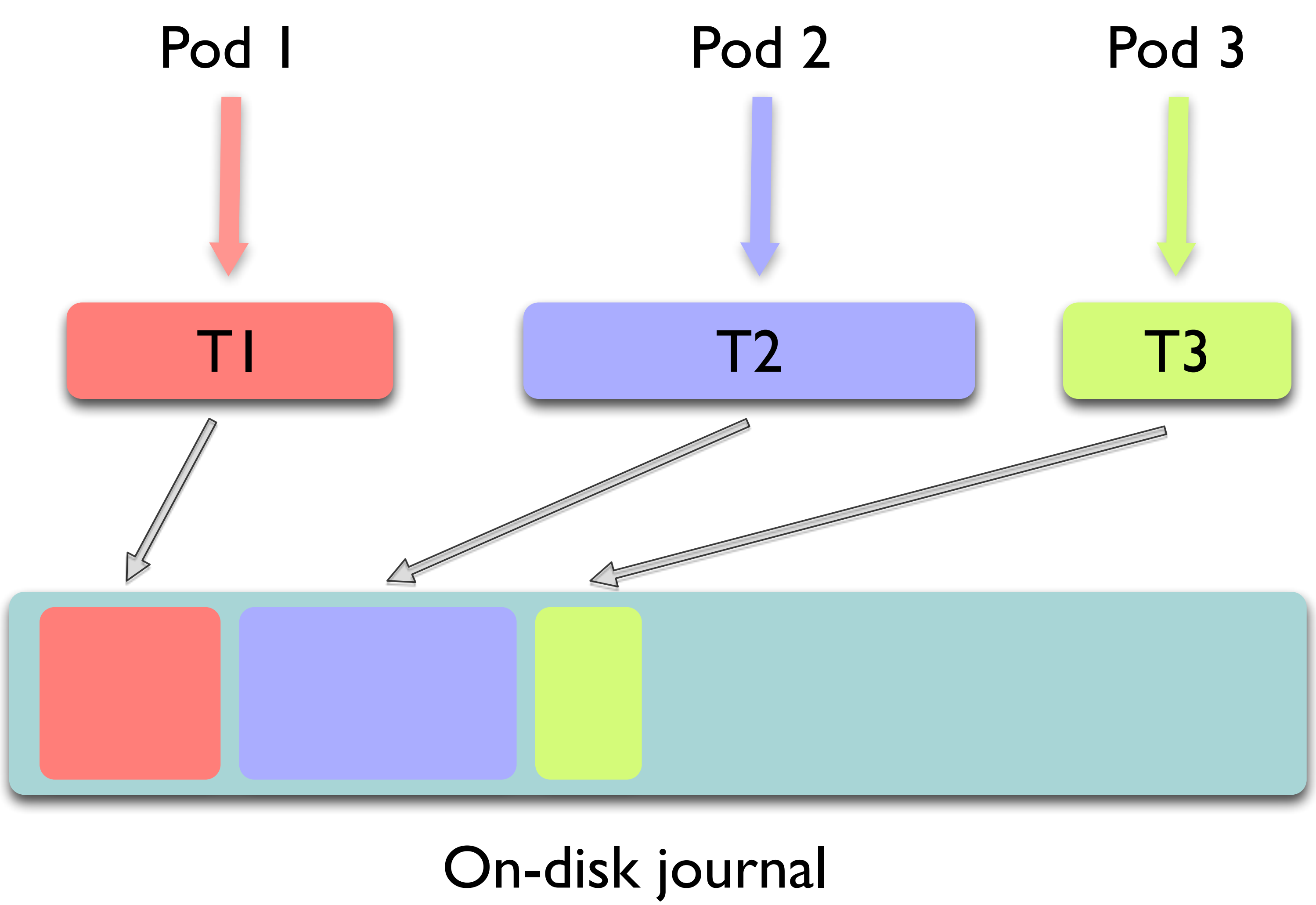


independent transactions

Journaling

Virtual transaction

- contains updates only from one pod
- better performance isolation

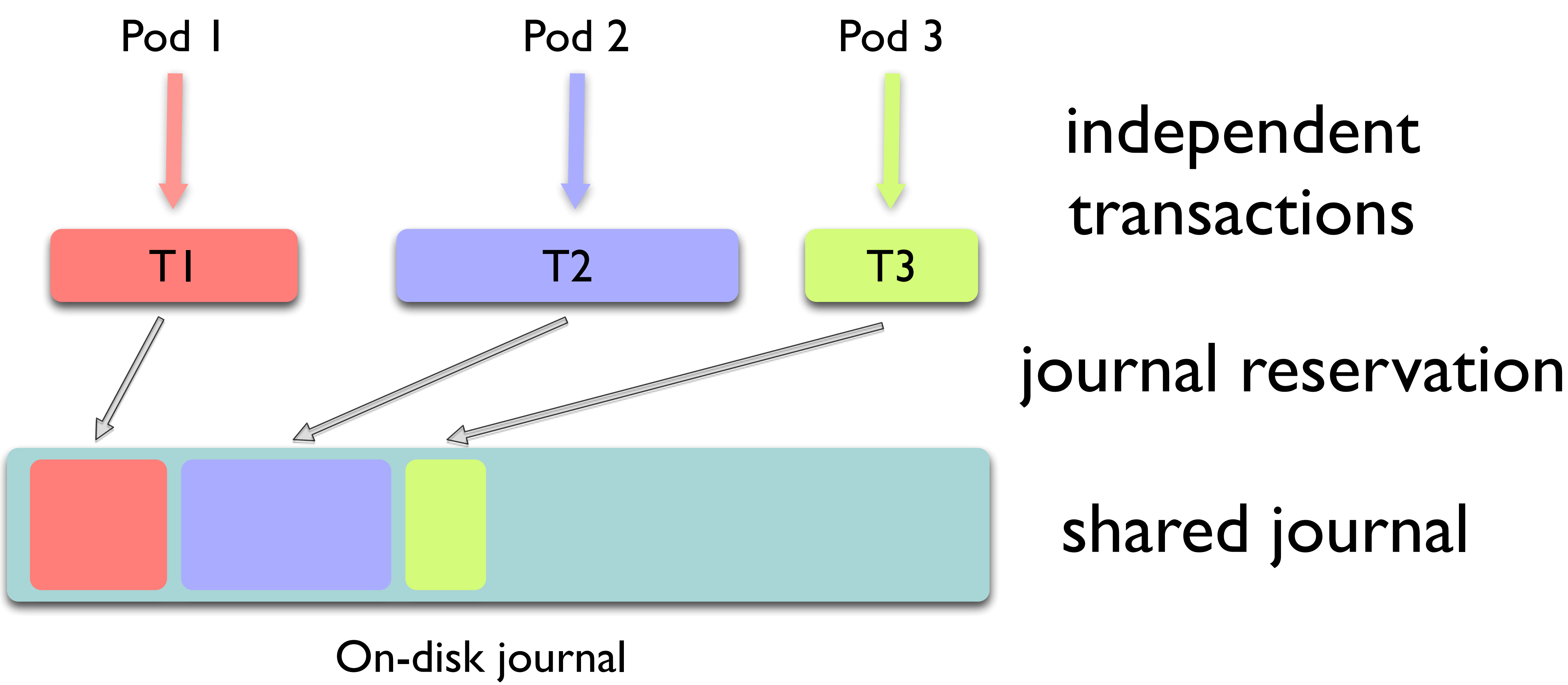


independent transactions

Journaling

Virtual transaction

- contains updates only from one pod
- better performance isolation
- commit multiple virtual transactions in parallel



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What we did

- a simple prototype for Ext3
- provide readonly isolation

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- a simple prototype for Ext3
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What we plan to do

- crash isolation
- quick recovery after failure
- other file systems: Ext4 and Btrfs

Challenges

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Metadata isolation

- tree-based directory structure
- globally shared metadata: super block, journal
- shared system states: block allocation tree

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Local failure

- is it correct to continue to run ?
- light-weight, stateless crash for a pod

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Metadata isolation

- tree-based directory structure
- globally shared metadata: super block, journal
- shared system states: block allocation tree

Local failure

- is it correct to continue to run ?
- light-weight, stateless crash for a pod

Performance

- potential overhead of managing pods
- better performance isolation
- better scalability

Failure is not an option.

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-- NASA

Global failure is not an option;

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local failure with quick recovery

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-- Isolation File Systems

Questions ?