SDC
STORAGE DEVELOPER CONFERENCE
SNIA ■ SANTA CLARA, 2015

Torturing Databases for Fun and Profit

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database

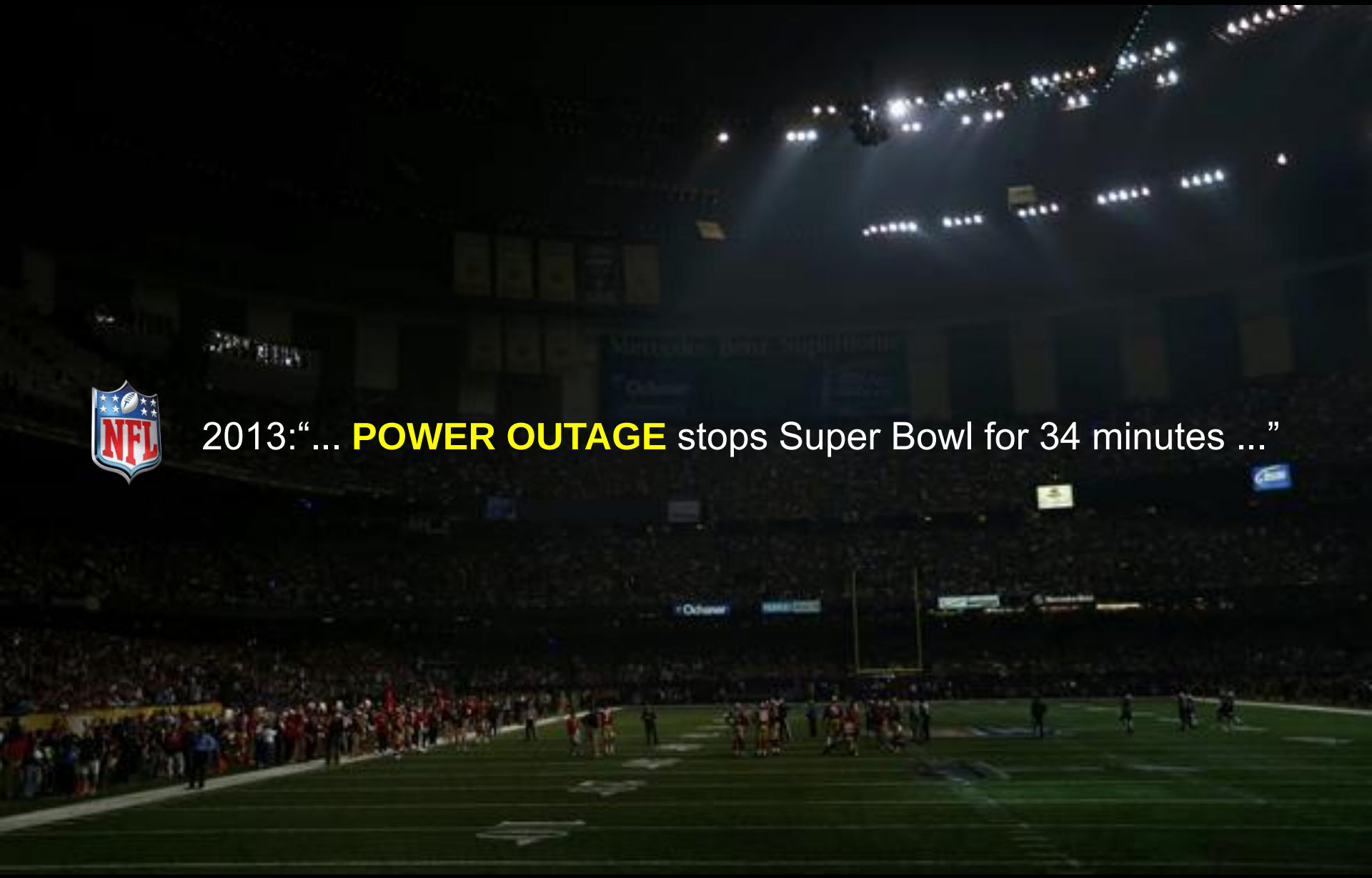
- ACID: atomicity, consistency, isolation, and durability - even under failures

List of databases survived

Everything is broken under simulated power faults

Database	File System	Workload					
		W-1	W-2	W-3	W-4.1	W-4.2	W-4.3
TokyoCabinet	ext3	D	D	D	ACD	ACD	ACD
	XFS	--	D	D	ACD	D	ACD
MariaDB	ext3	D	D	D	D	D	D
	XFS	D	D	D	D	D	D
LightningDB	ext3	--	--	--	--	--	D
	XFS	--	--	--	--	--	--
SQLite	ext3	D	D	--	D	D	D
	XFS	--	--	D	D	D	D
KVS-A	ext3	--	--	Hang	--	--	--
	XFS	--	--	--	--	--	--
SQL-A	ext3	D	D	D	D	D	D
	XFS	D	D	D	D	D	D
SQL-B	ext3	D	D	CD	CD	CD	CD
	XFS	CD	D	CD	CD	CD	CD
SQL-C	NTFS	D	D	D	D	D	D

Power faults cannot happen nowadays, right?


2013:“... POWER OUTAGE stops Super Bowl for 34 minutes ...”

2014:"... Data Center **OUTAGE** Takes Down Livestream, StackExchange."

2014:"... primary data center... **ALL POWER WAS OFF** ..."

2014:"Data Center ... **OUTAGE** ..."

2013:" A **POWER OUTAGE** at a key New Jersey data center ..."

2013:"**POWER OUTAGE** knocks DreamHost customers offline ..."

2013:" A data center **POWER OUTAGE** ...Visa downtime ..."

2013:"... **POWER OUTAGE** stops Super Bowl for 34 minutes ..."

2012:"Amazon Data Center **LOSES POWER** During Storm …"

2012:"**POWER OUTAGE** Hits London Data Center ..."

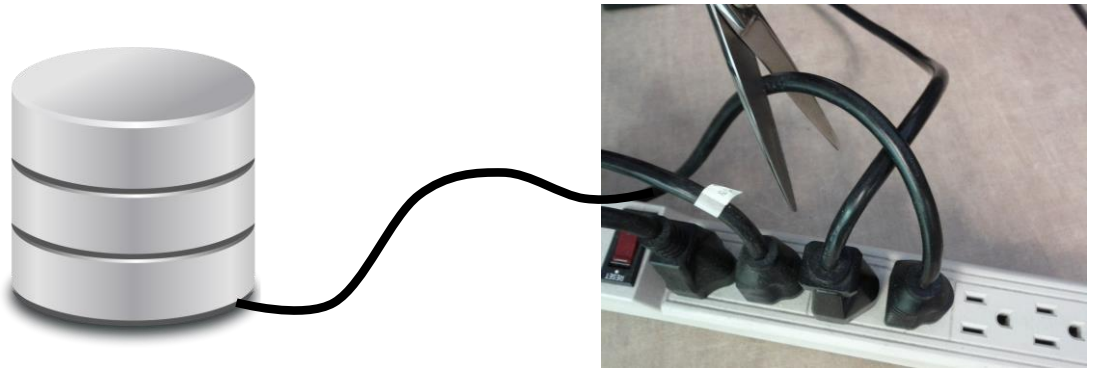
2012:"... human error ... a data center **POWER OUTAGE** ..."

2011:"Colocation provider Colo4 experienced a **POWER OUTAGE** …"

2010:"About 3,000 servers ... experienced an **OUTAGE** …"

2010:"Car Crash Triggers Amazon **POWER OUTAGE** …"

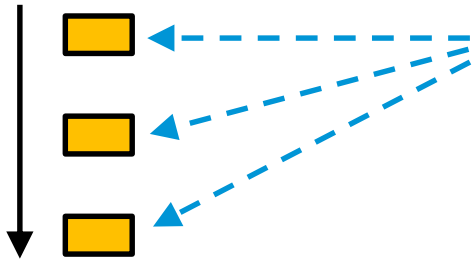
Database Torture 101



Fault Model: Clean termination of I/O stream

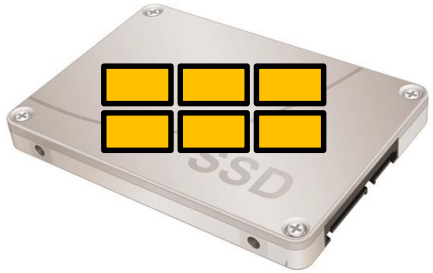
database

on-the-fly
I/O blocks

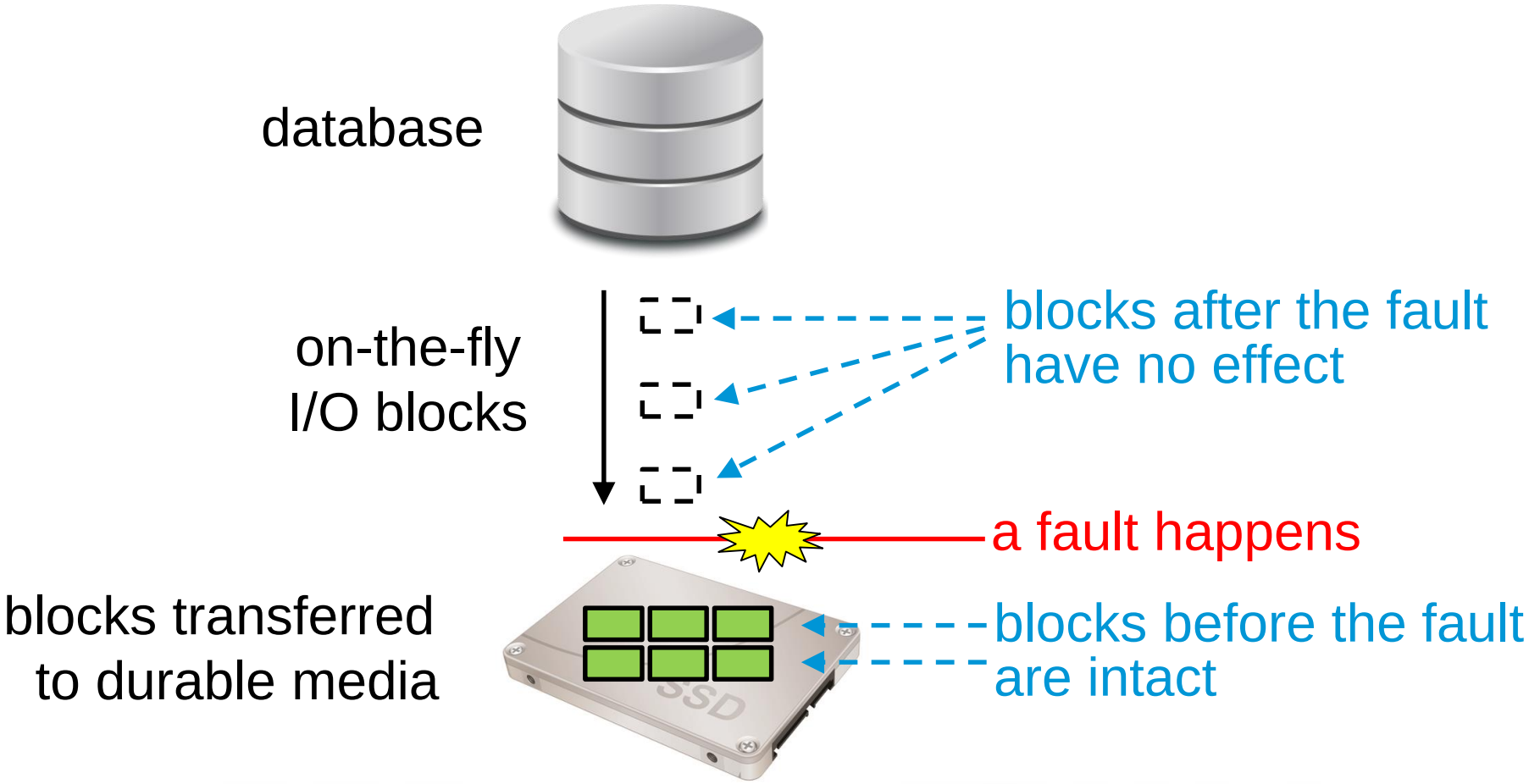


minimum atomic
transfer unit
(e.g., 512B/4KB)

blocks transferred
to durable media



Fault Model: Clean termination of I/O stream

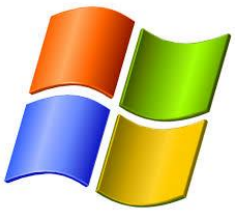


Why not introduce corruption/dropping/reordering?

- Unreasonable to require databases to handle arbitrary bad behavior introduced in the lower layers
- Simulated bad behavior w/o verification by real failures may be unrealistic
  - I/O path in kernel & device puts constraints on failure states

How do we test DBs on multiple OSes w/ high fidelity?

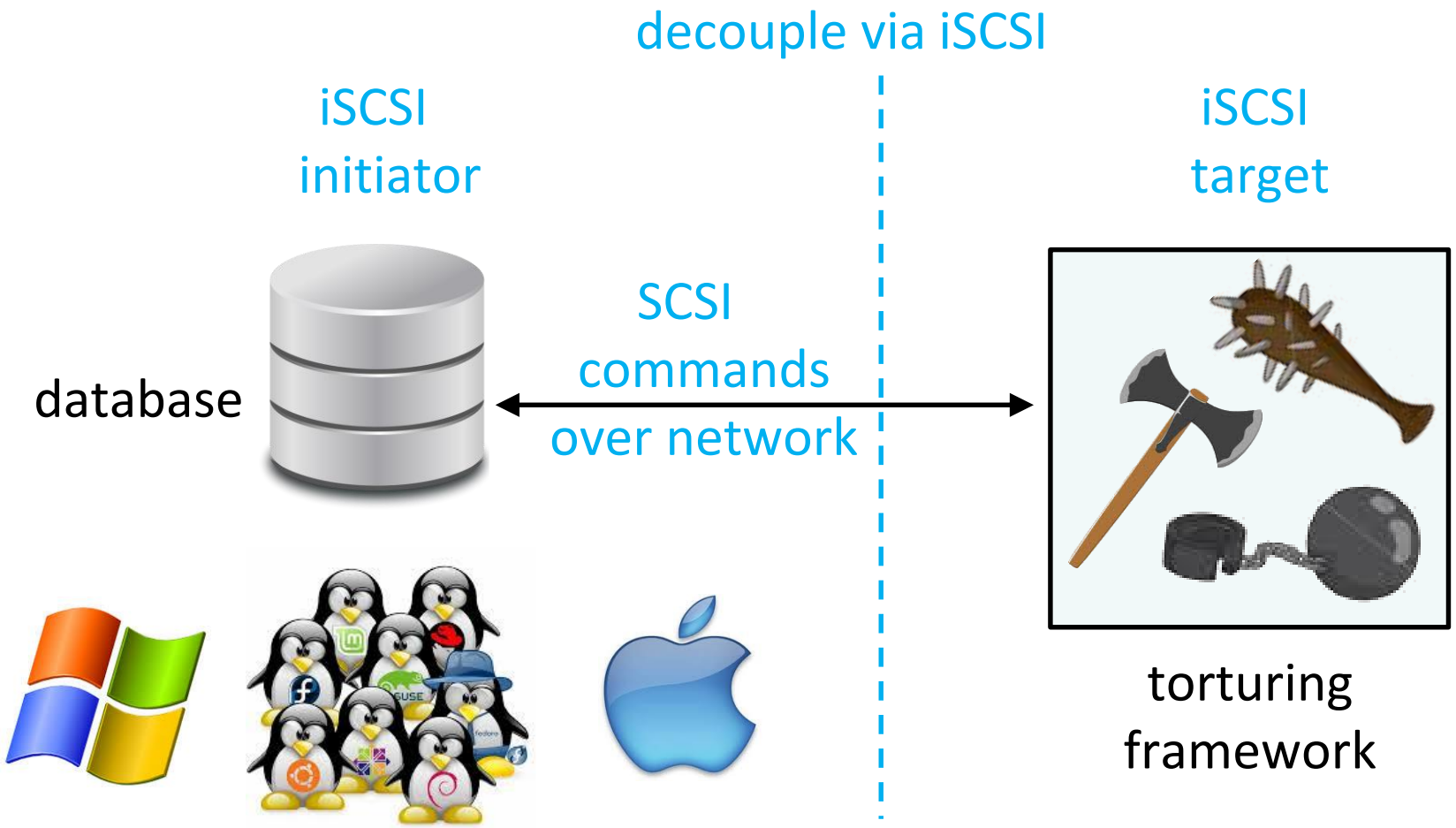
database



No disturbance on thread scheduling

No disturbance on interactions among DB, file system, I/O scheduler, …

How do we test DBs on multiple OSes w/ high fidelity?



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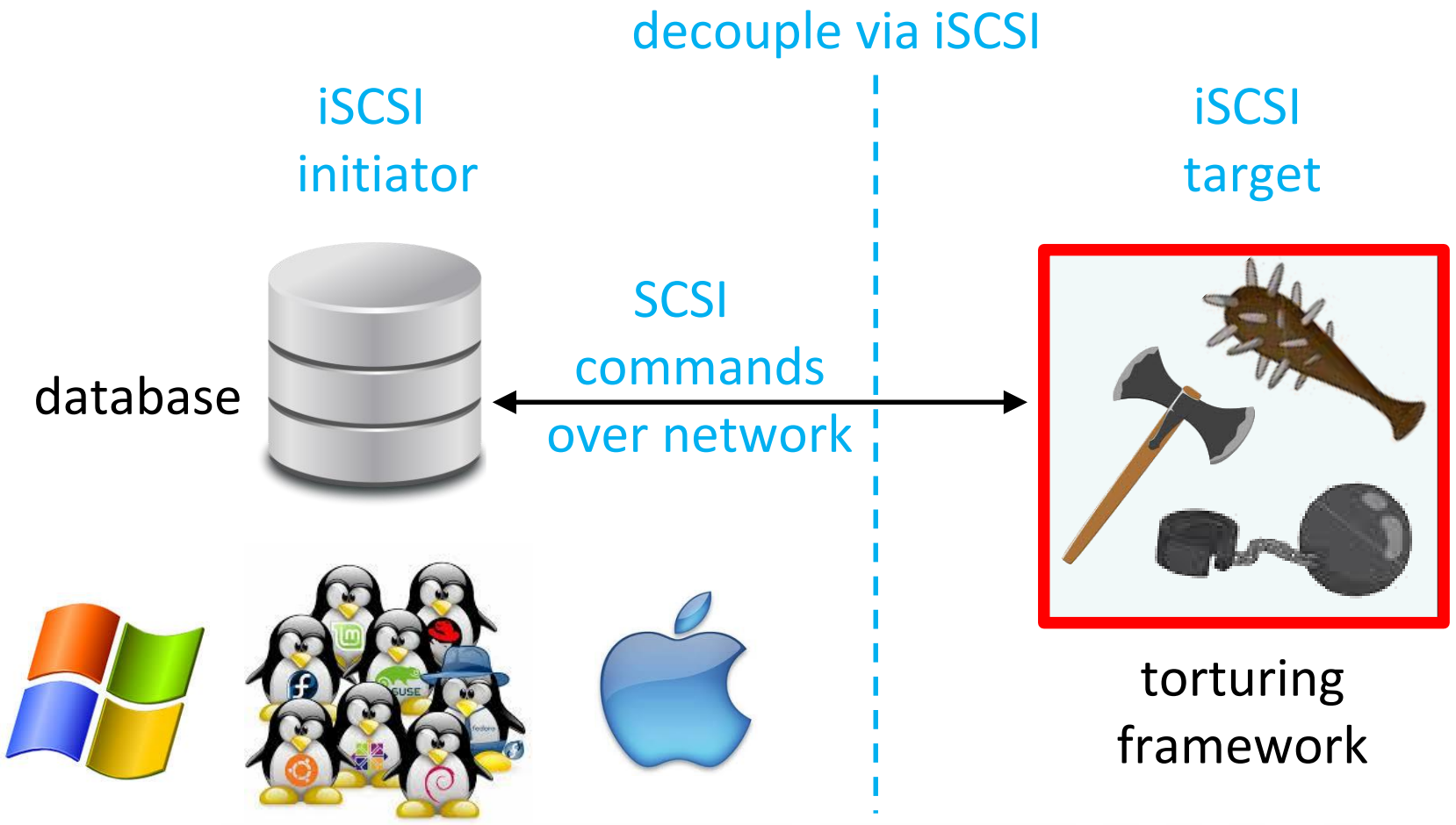
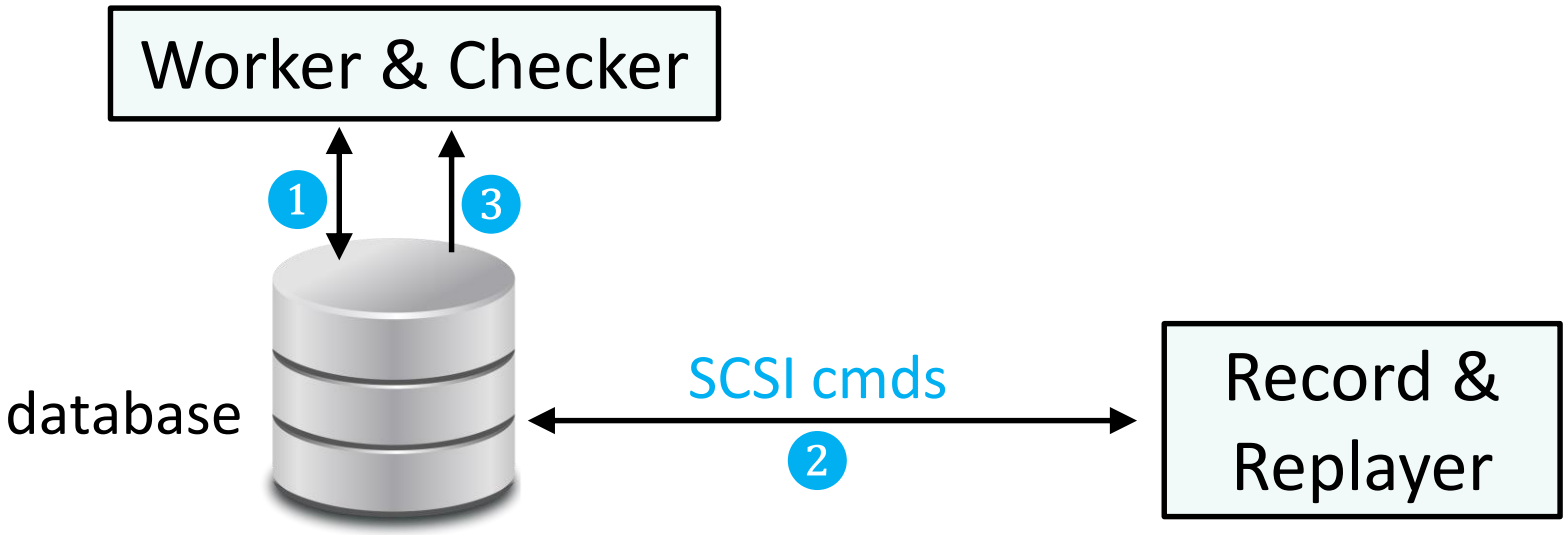


Framework Overview



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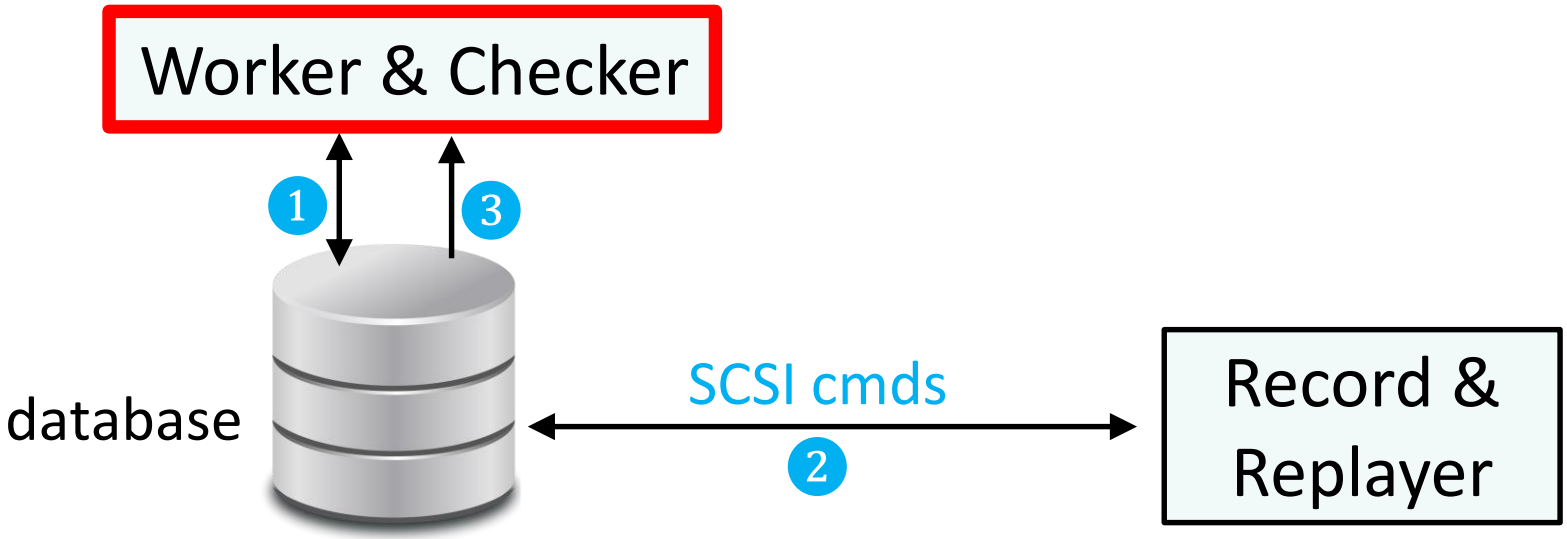
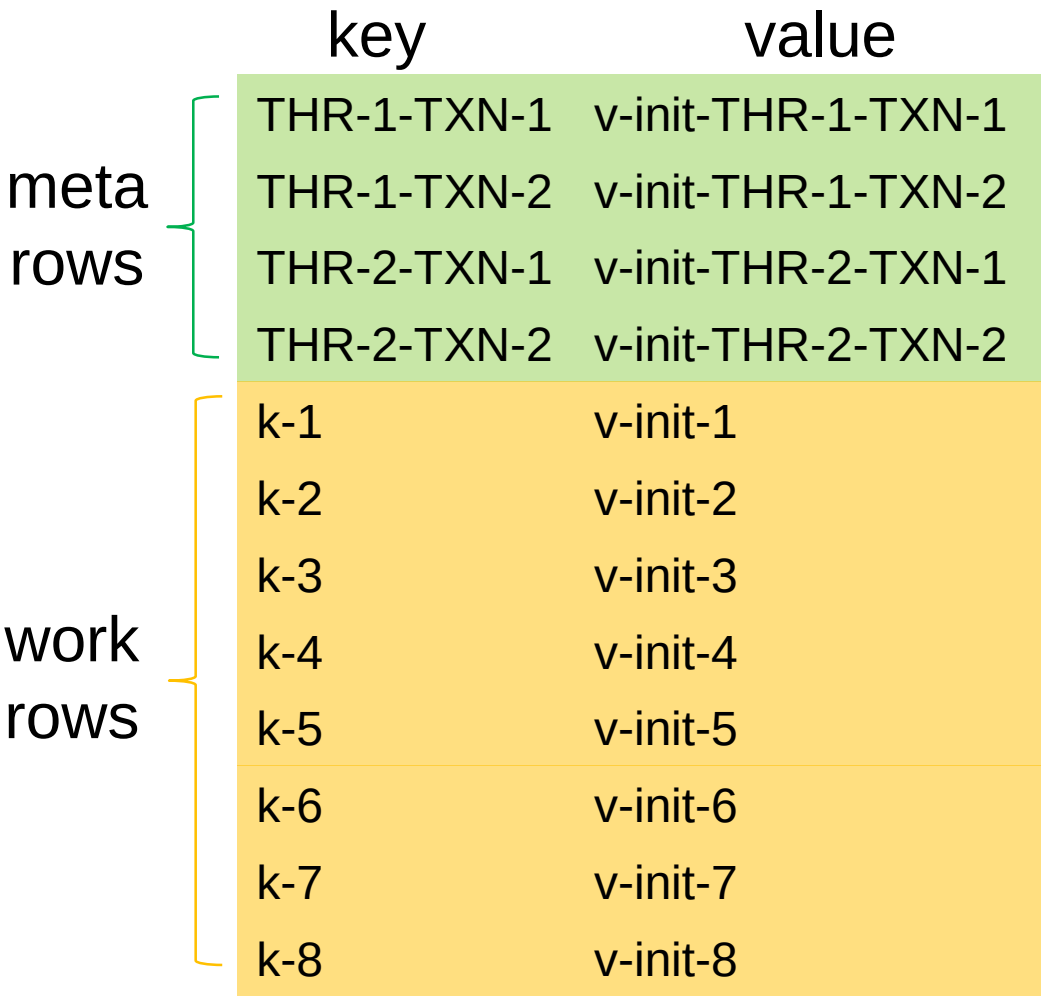
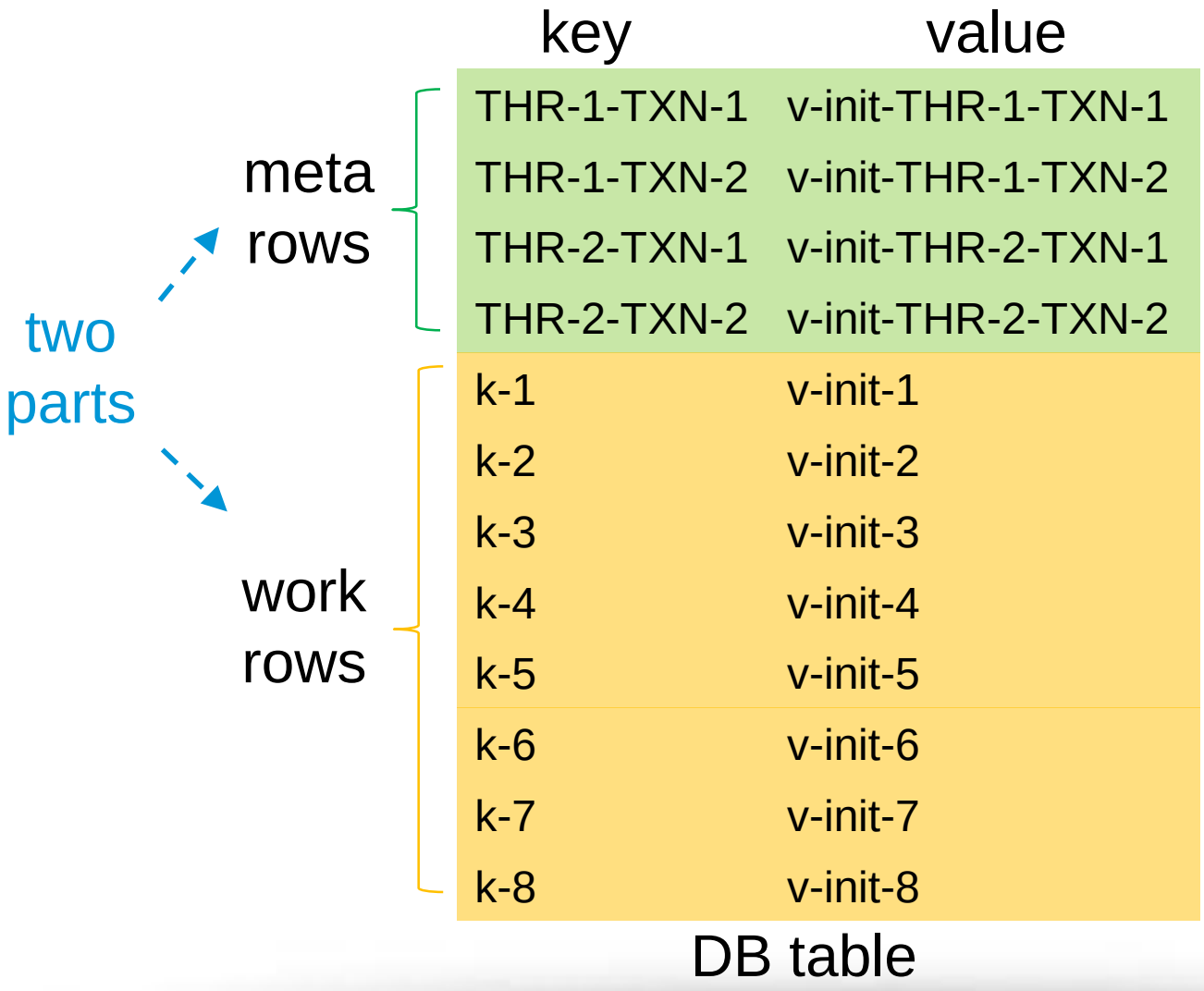


Workload Example

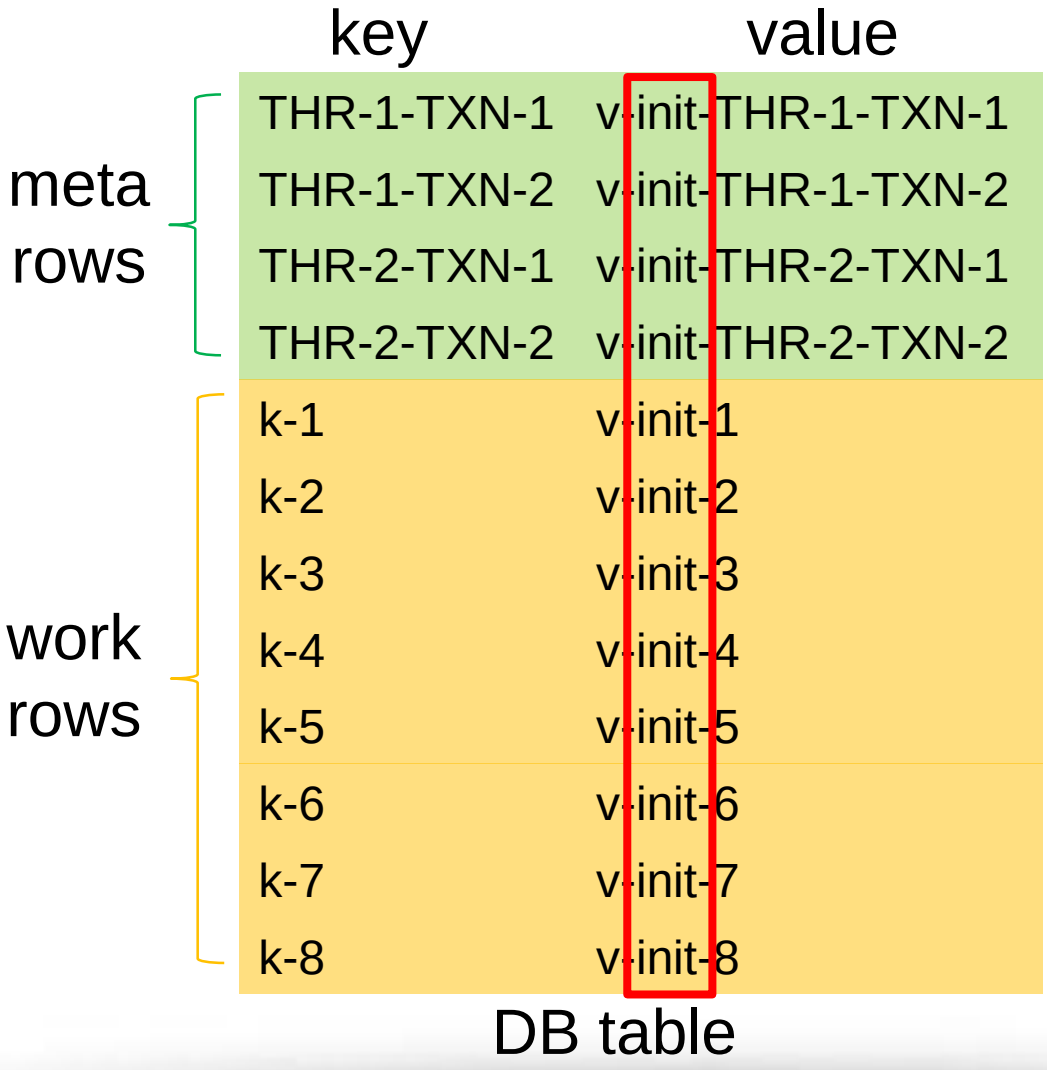


Workload Example

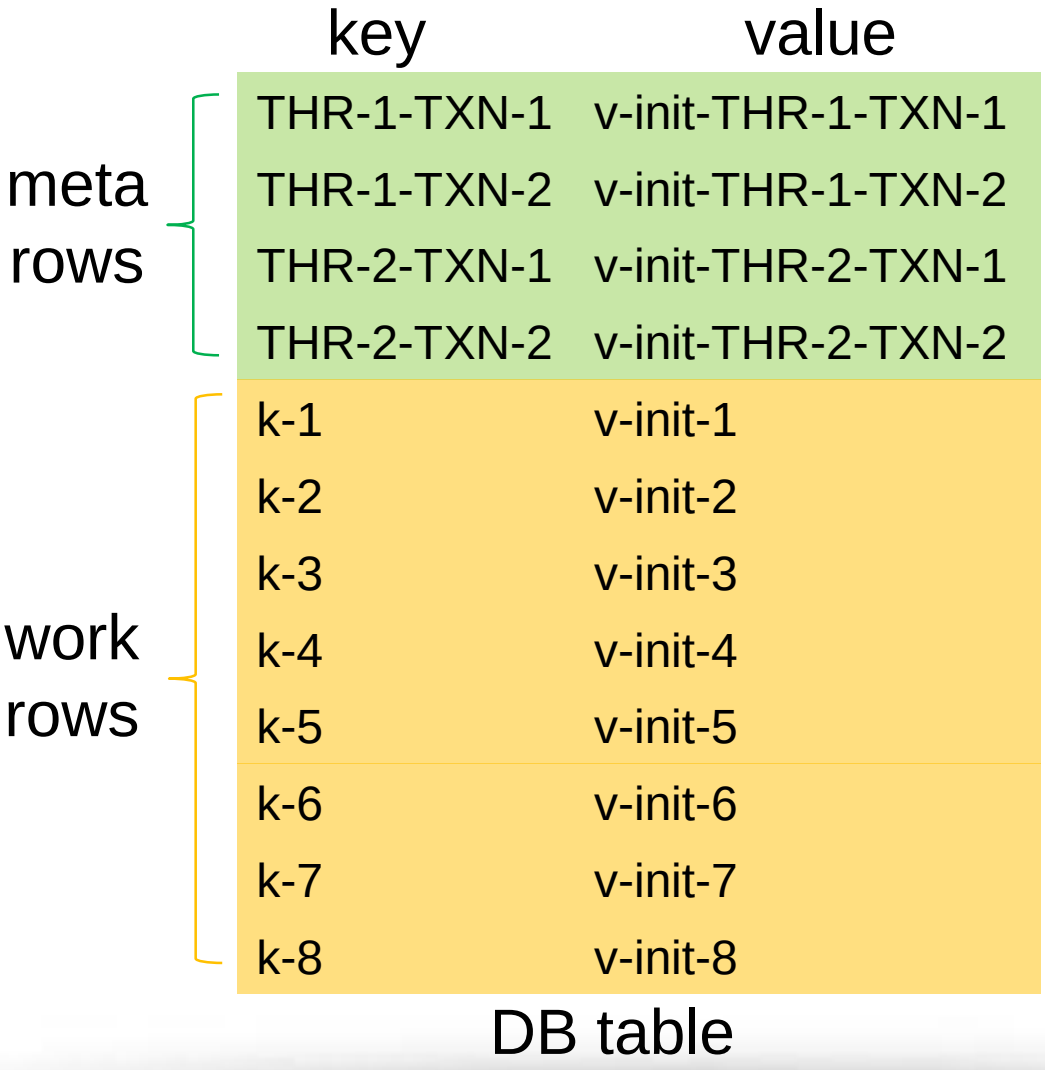


2 threads,
2 transactions
per thread

Has known initial state



Each transaction updates N random work rows + 1 meta row



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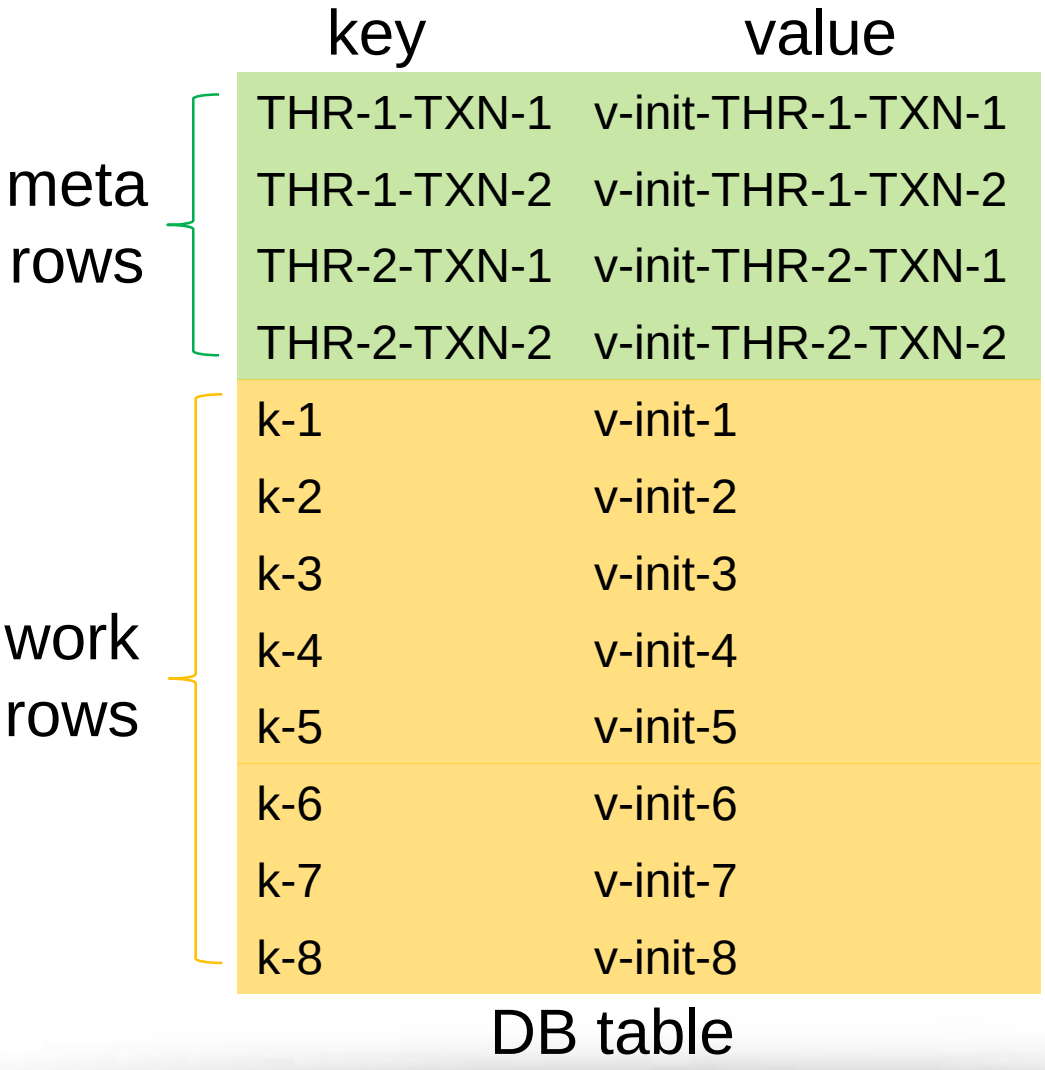
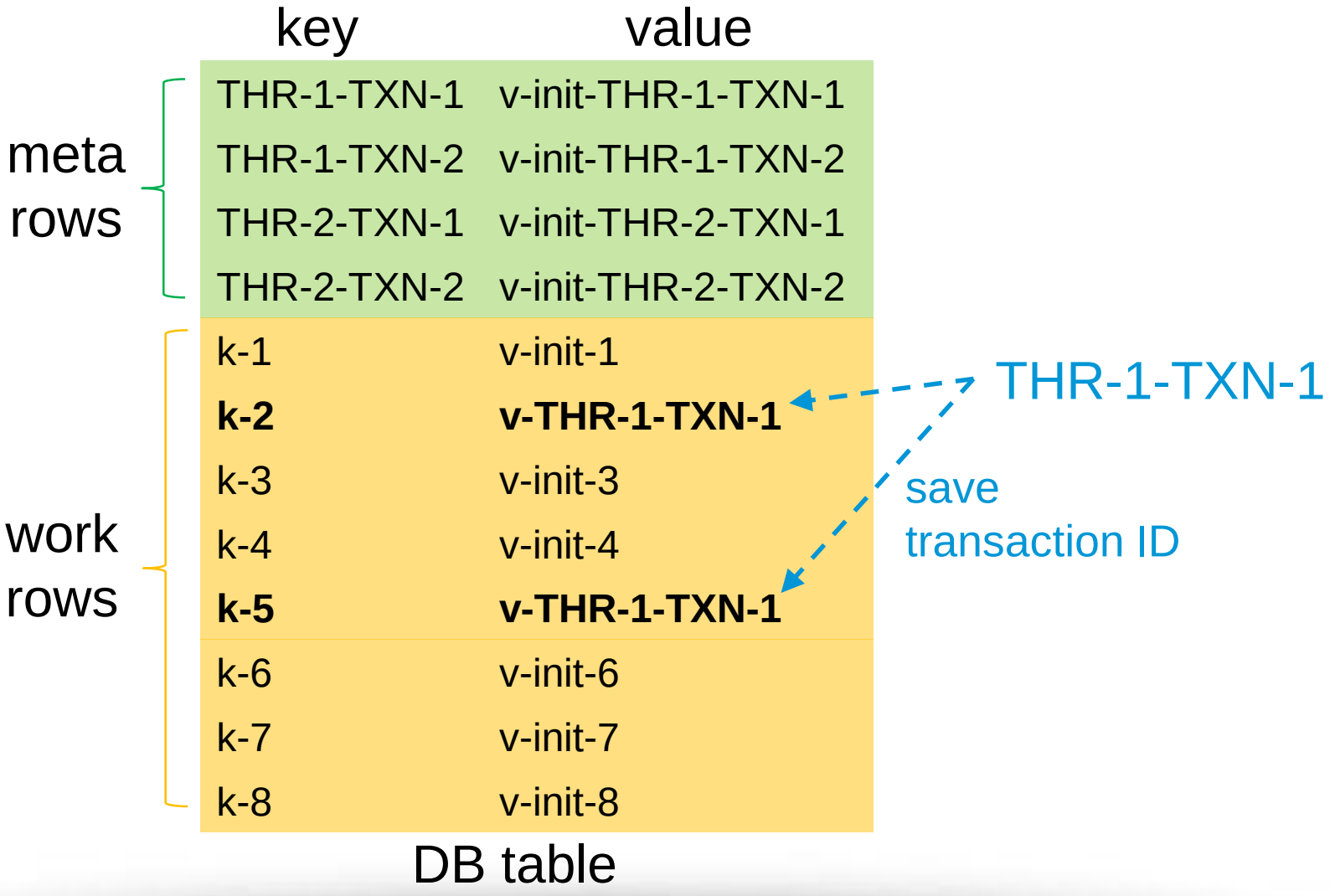


THR-1-TXN-1

Each transaction updates N random work rows + 1 meta row



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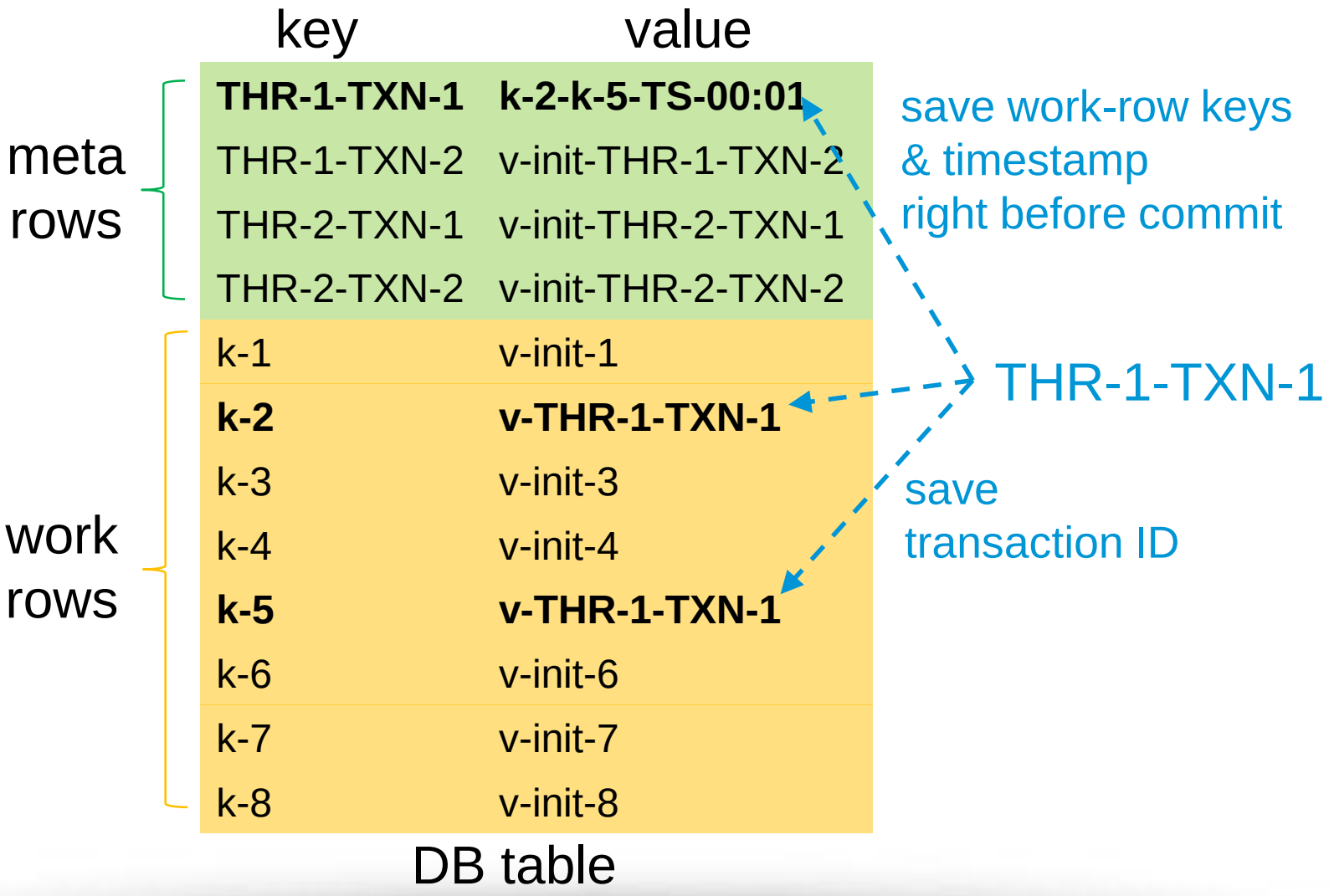
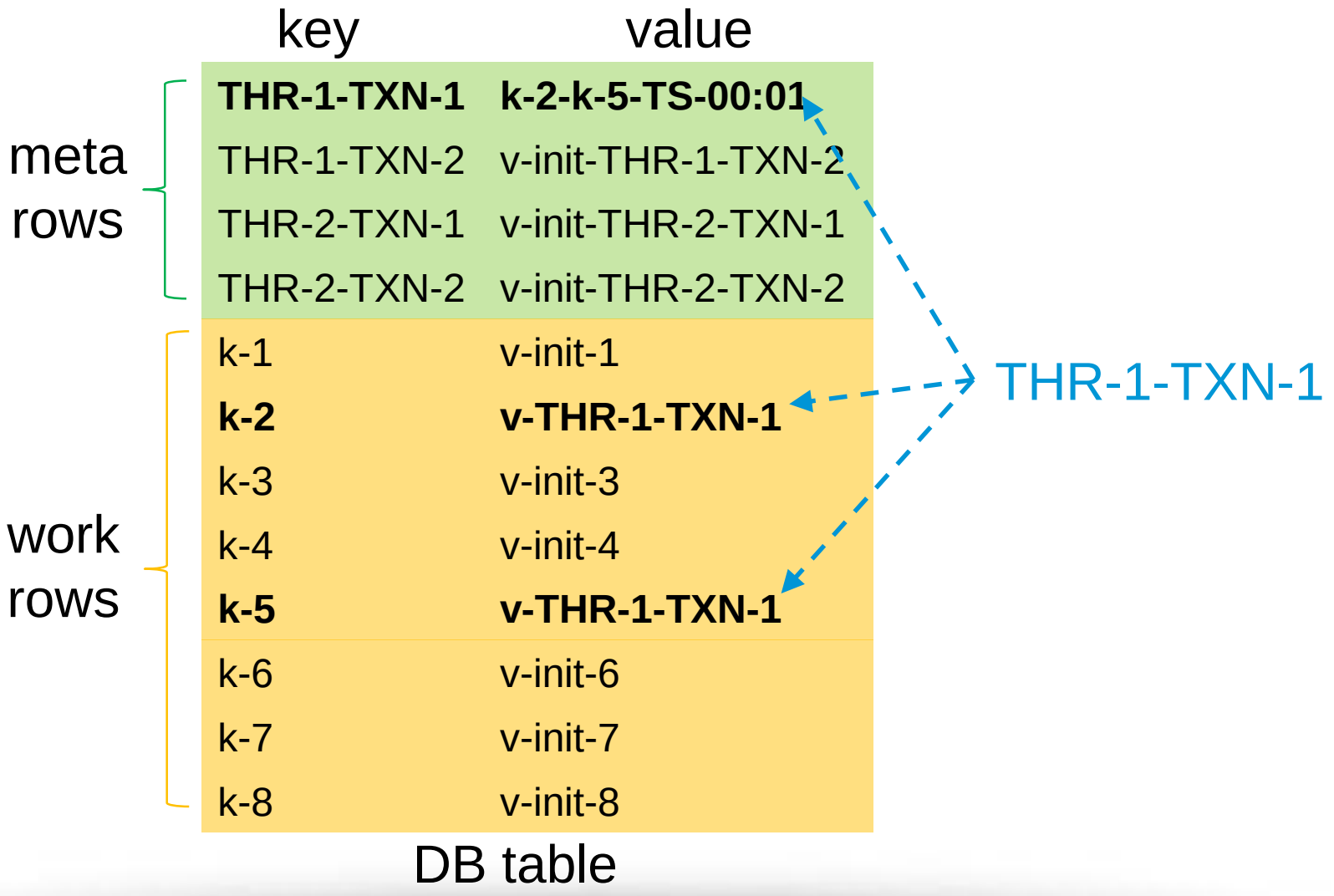


Fully exercise concurrency control



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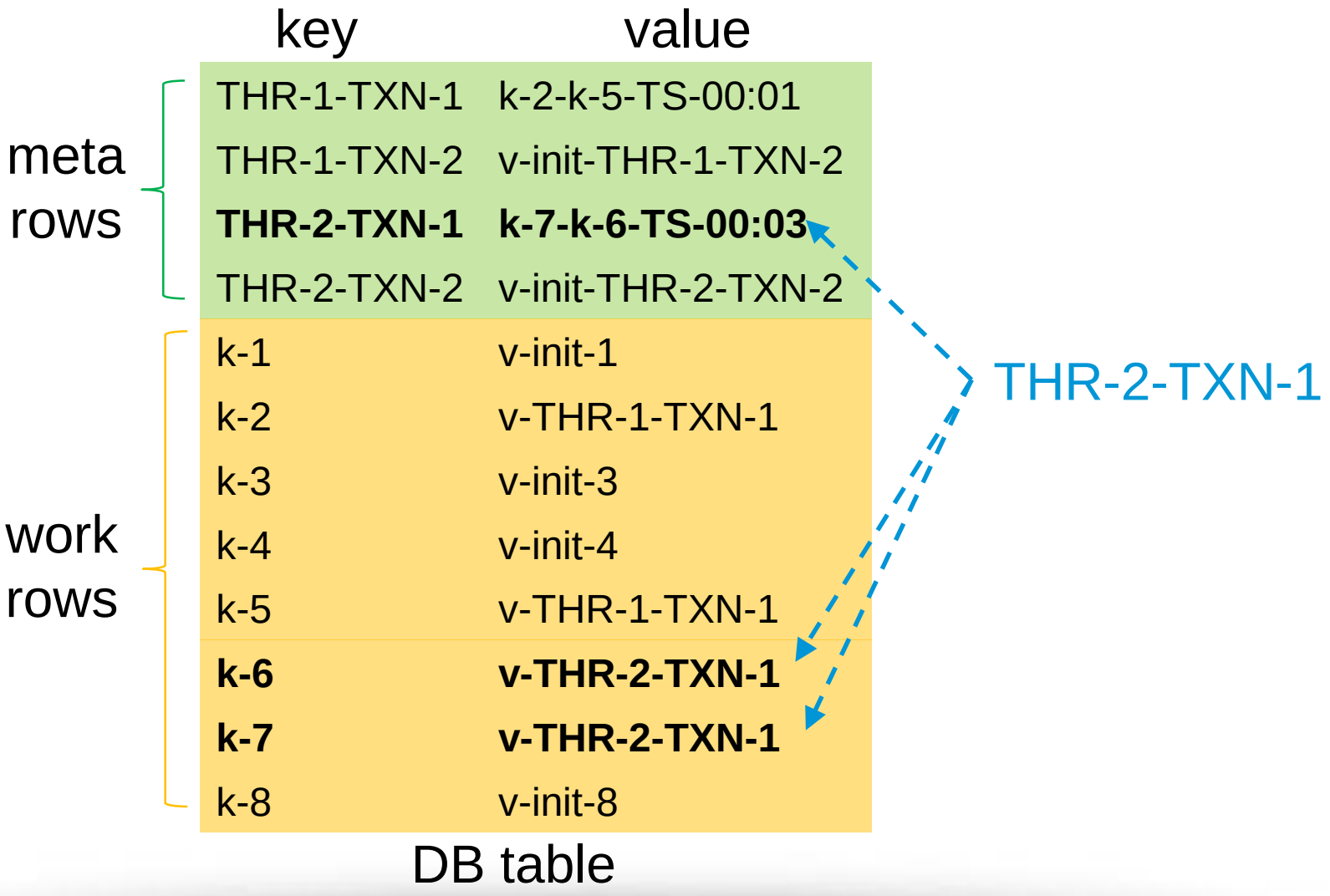

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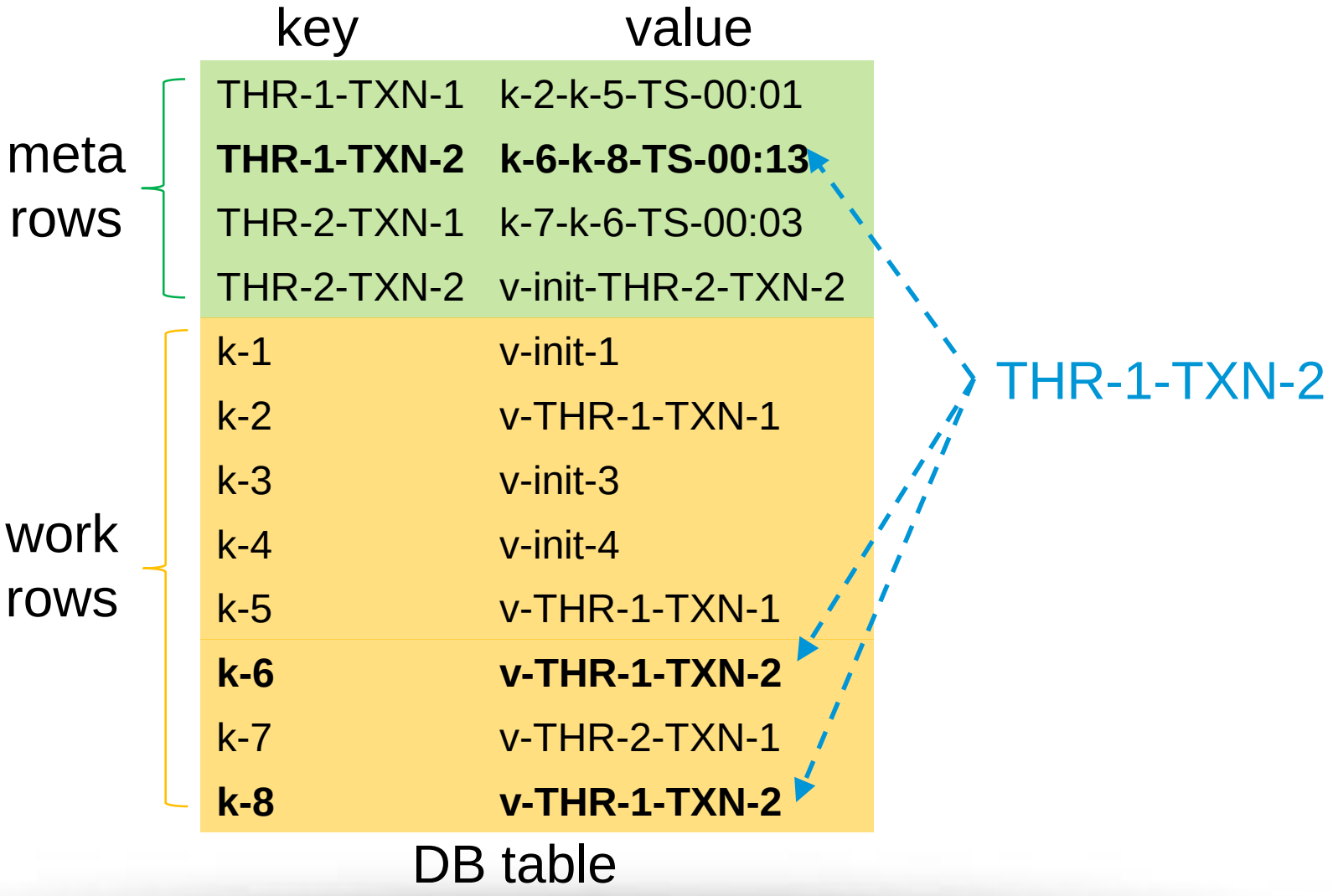

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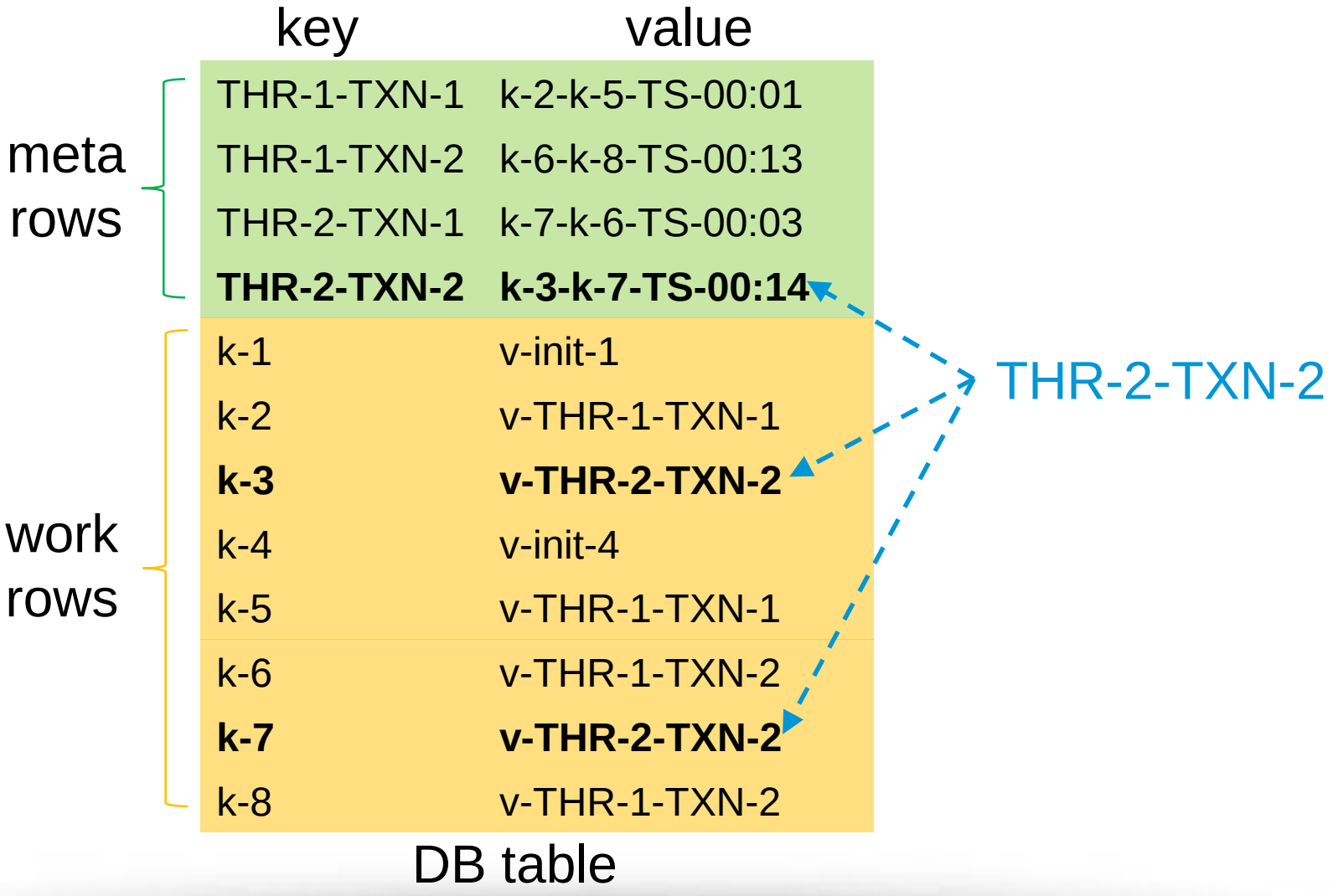

A power fault just happened during our workload ...

Is there any ACID violation after recovery?

	key	value
meta rows	THR-1-TXN-1	k-2-k-5-TS-00:01
	THR-1-TXN-2	k-6-k-8-TS-00:13
	THR-2-TXN-1	k-7-k-6-TS-00:03
	THR-2-TXN-2	v-init-THR-2-TXN-2
work rows	k-1	v-init-1
	k-2	v-THR-1-TXN-1
	k-3	v-THR-2-TXN-2
	k-4	v-init-4
	k-5	v-THR-1-TXN-1
	k-6	v-THR-1-TXN-2
	k-7	v-THR-2-TXN-2
	k-8	v-THR-1-TXN-2

recovered DB table

Is there any ACID violation after recovery?

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	THR-1-TXN-2	k-6-k-8-TS-00:13
	THR-2-TXN-1	k-7-k-6-TS-00:03
	THR-2-TXN-2	v-init-THR-2-TXN-2
work rows	k-1	v-init-1
	k-2	v-THR-1-TXN-1
	k-3	v-THR-2-TXN-2
	k-4	v-init-4
	k-5	v-THR-1-TXN-1
	k-6	v-THR-1-TXN-2
	k-7	v-THR-2-TXN-2
	k-8	v-THR-1-TXN-2

recovered DB table

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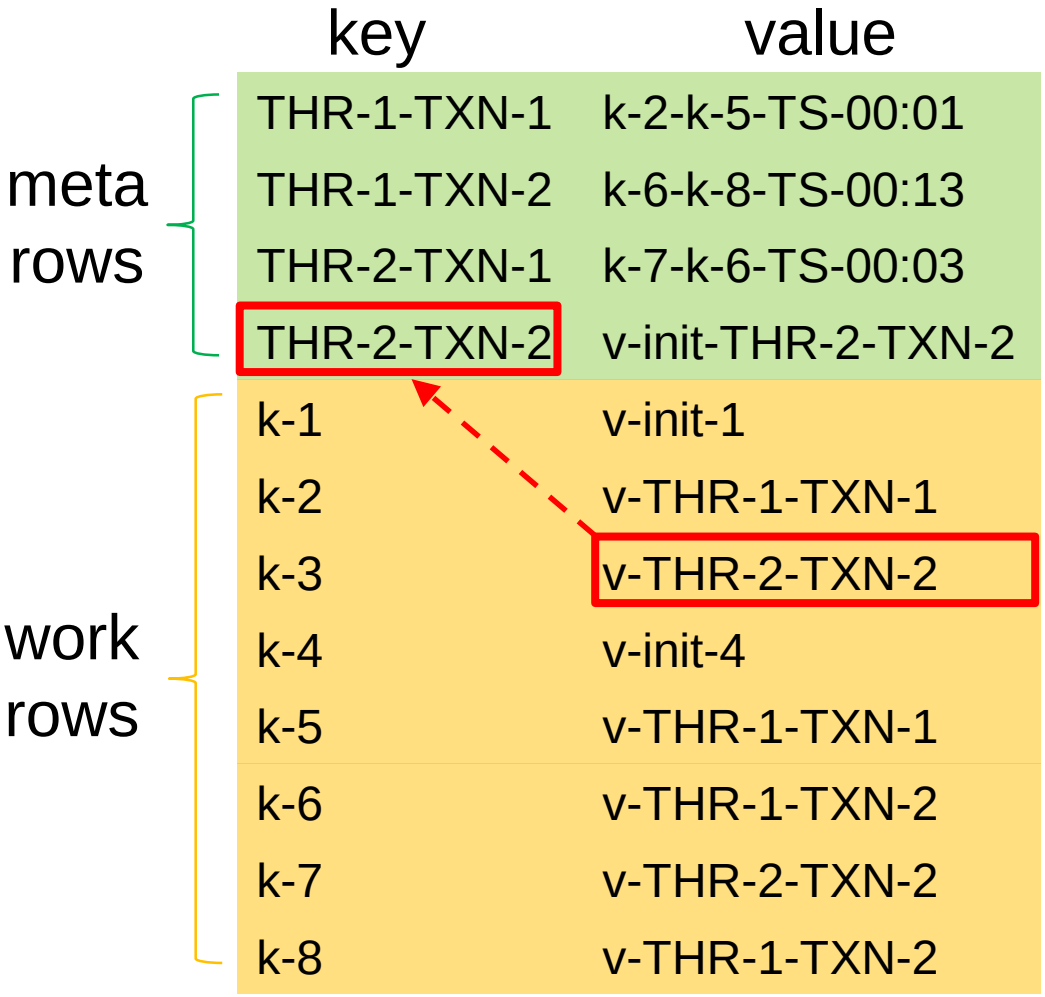

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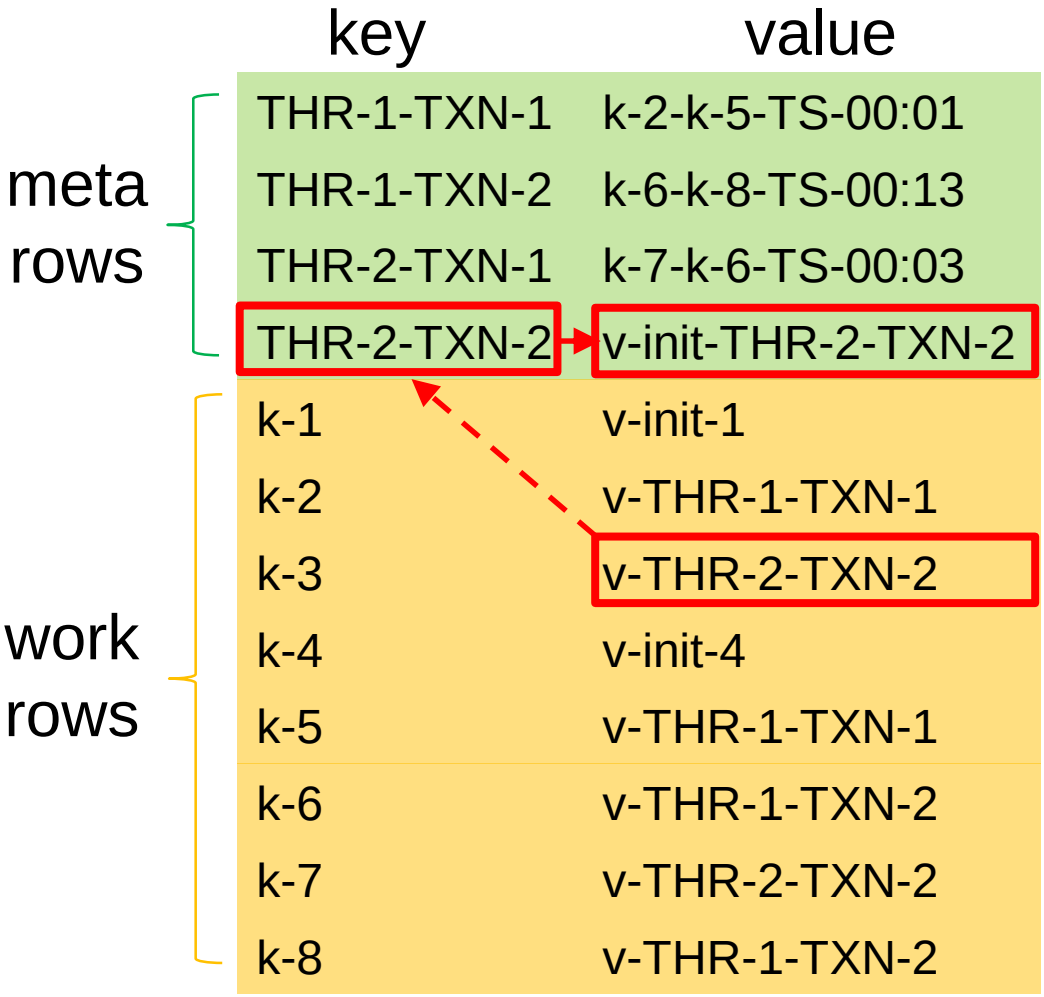

recovered DB table

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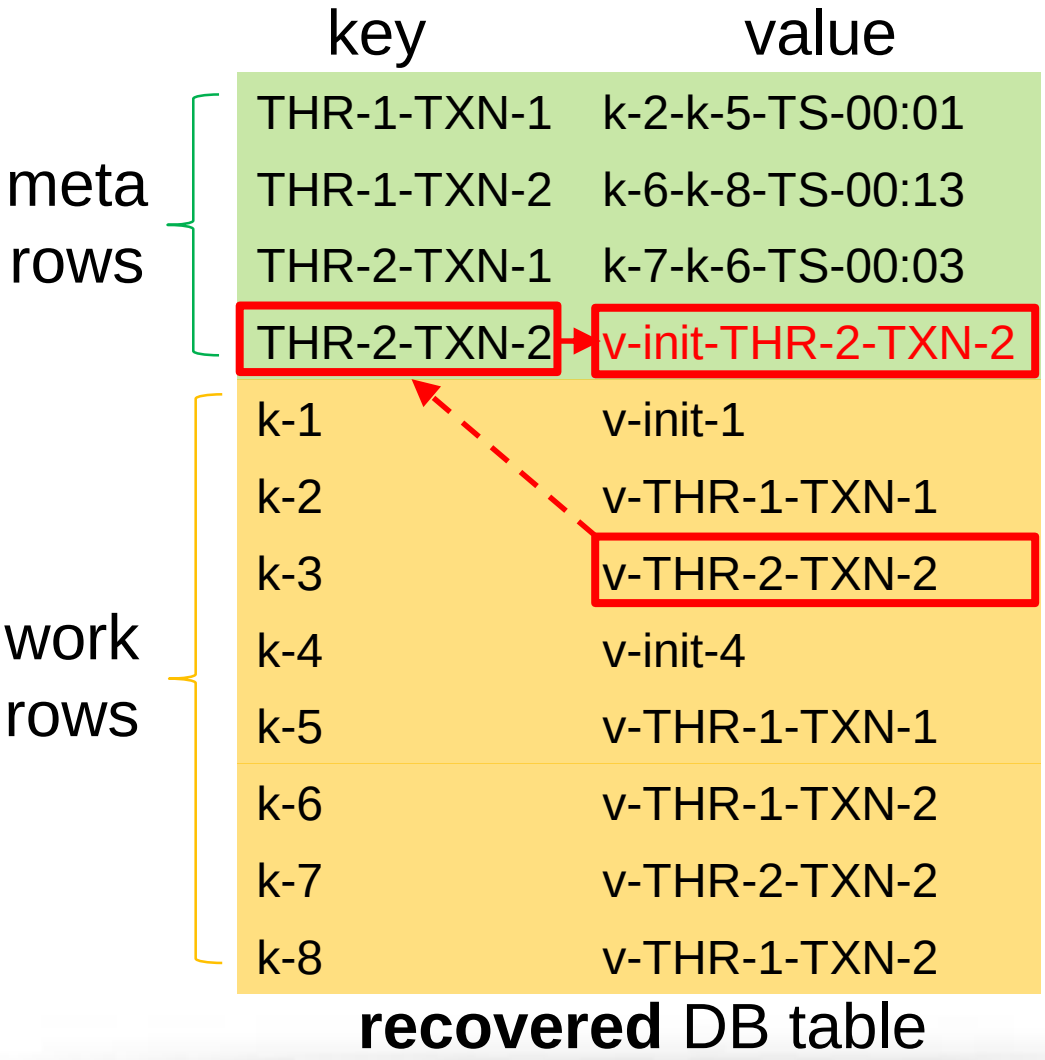


recovered DB table

Atomicity violation!
The meta row should have been updated w/ the work row in the same transaction

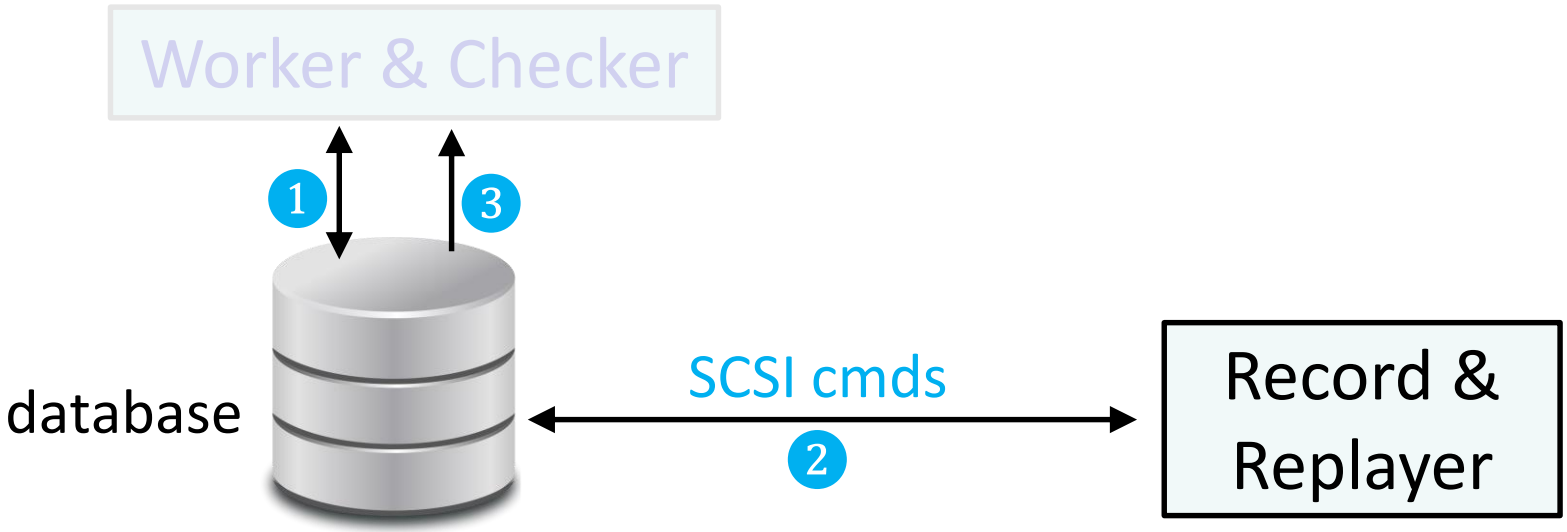
Is there any ACID violation after recovery?

	key	value
meta rows	THR-1-TXN-1	k-2-k-5-TS-00:01
	THR-1-TXN-2	k-6-k-8-TS-00:13
	THR-2-TXN-1	k-7-k-6-TS-00:03
	THR-2-TXN-2	v-init-THR-2-TXN-2
work rows	k-1	v-init-1
	k-2	v-THR-1-TXN-1
	k-3	v-THR-2-TXN-2
	k-4	v-init-4
	k-5	v-THR-1-TXN-1
	k-6	v-THR-1-TXN-2
	k-7	v-THR-2-TXN-2
	k-8	v-THR-1-TXN-2

recovered DB table

allow checking time & order related properties

Framework Overview



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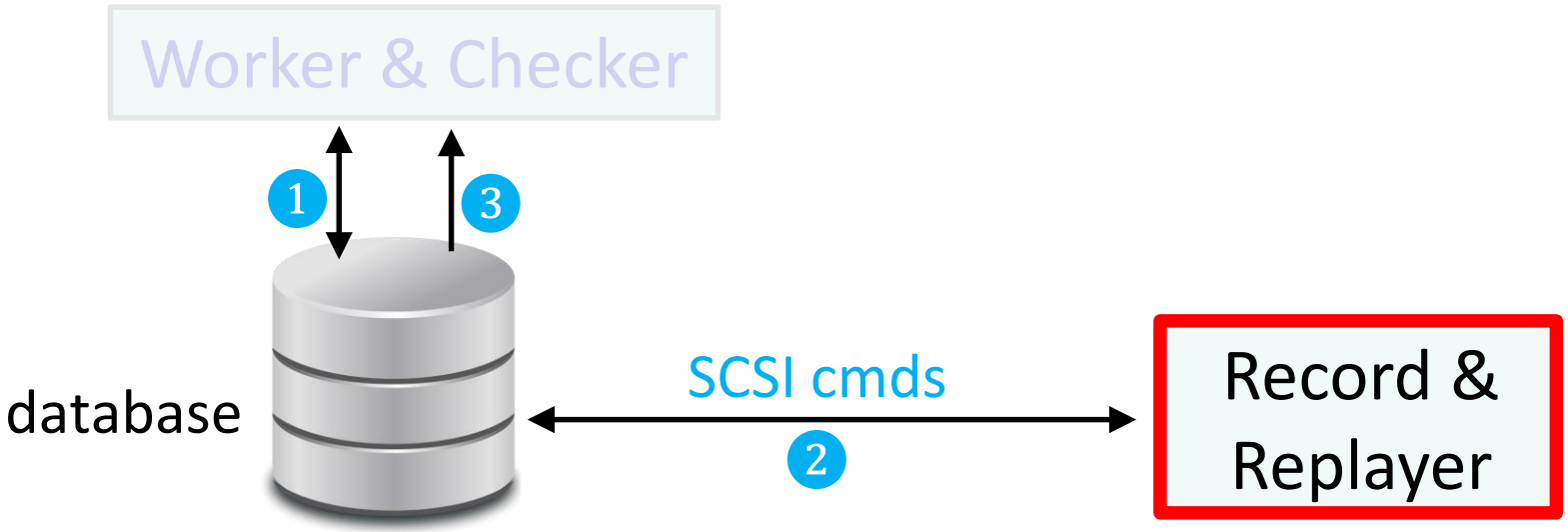
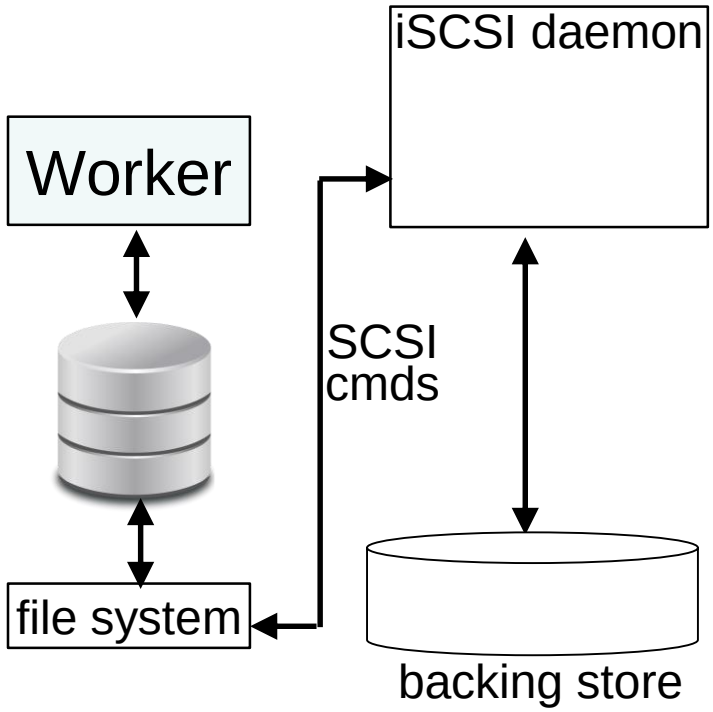


Capturing I/O trace without kernel modification



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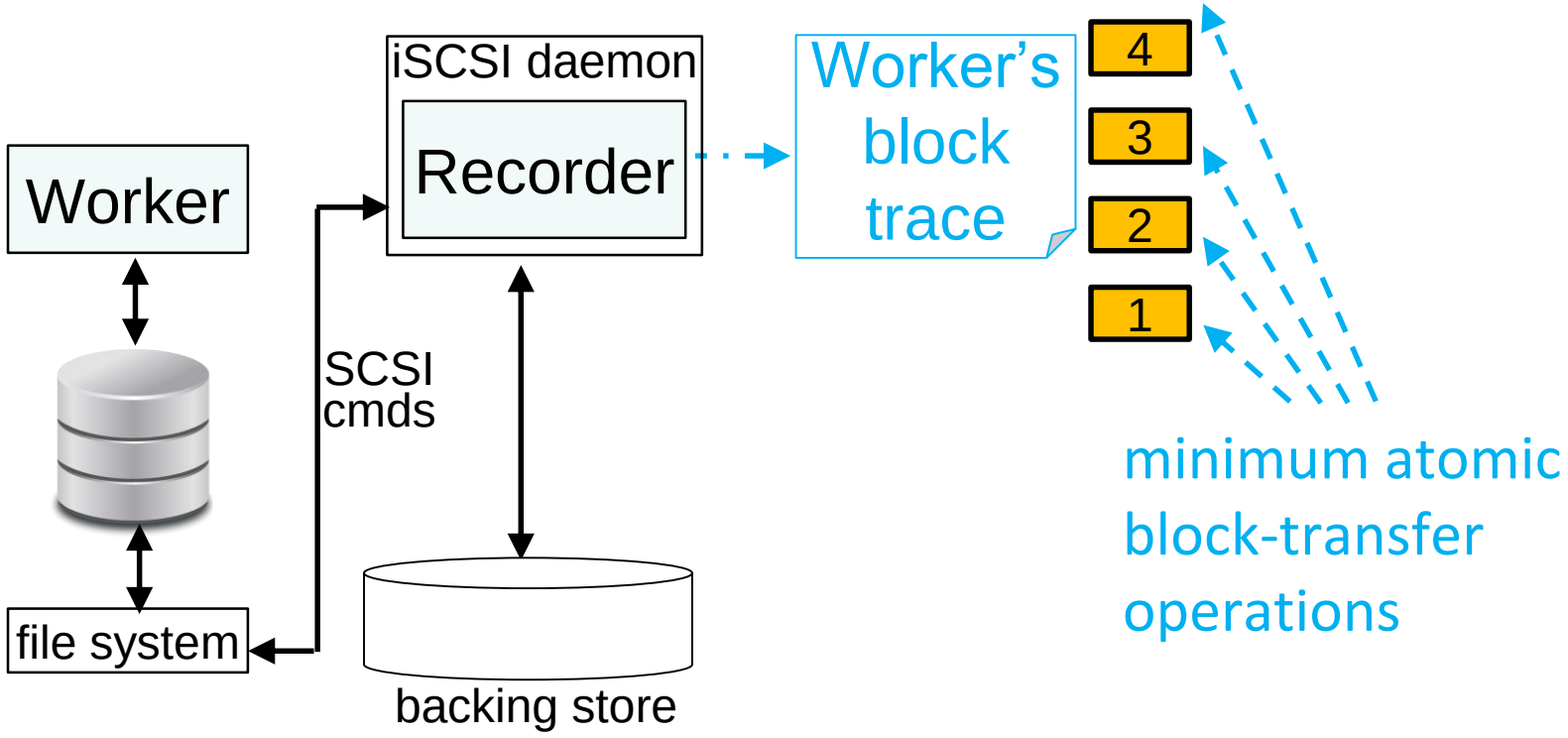
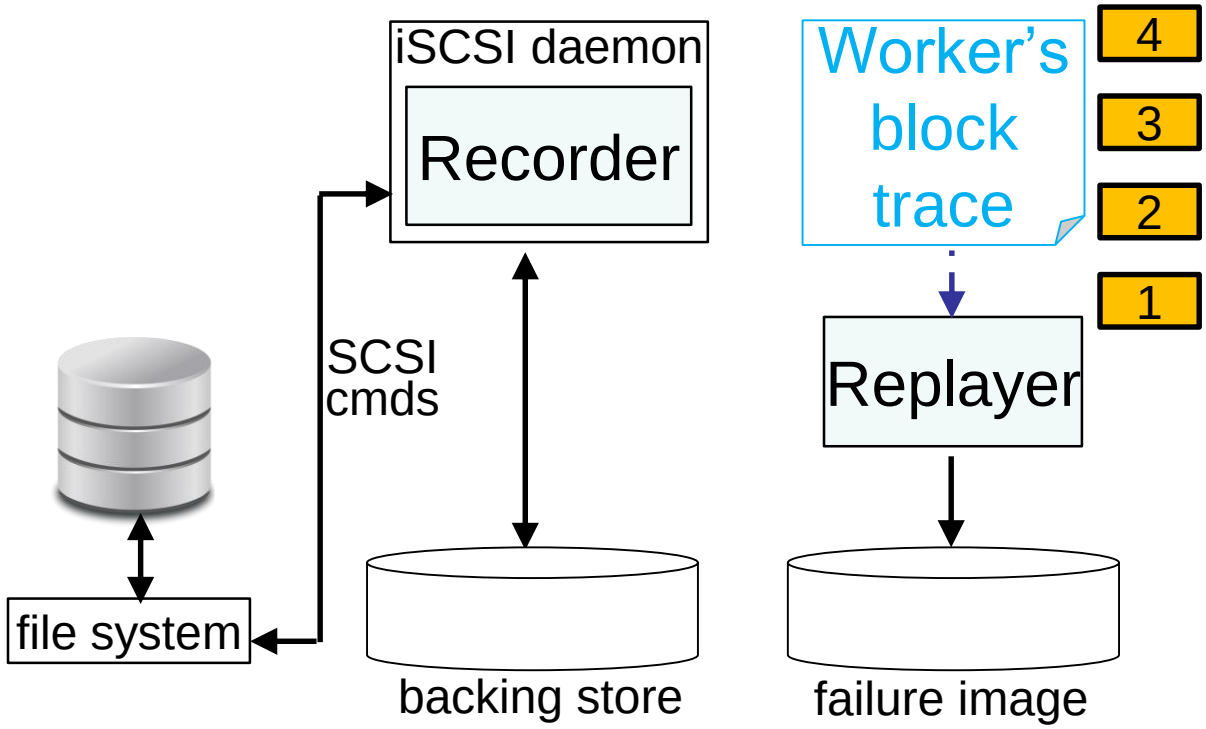


Constructing a post-fault disk image



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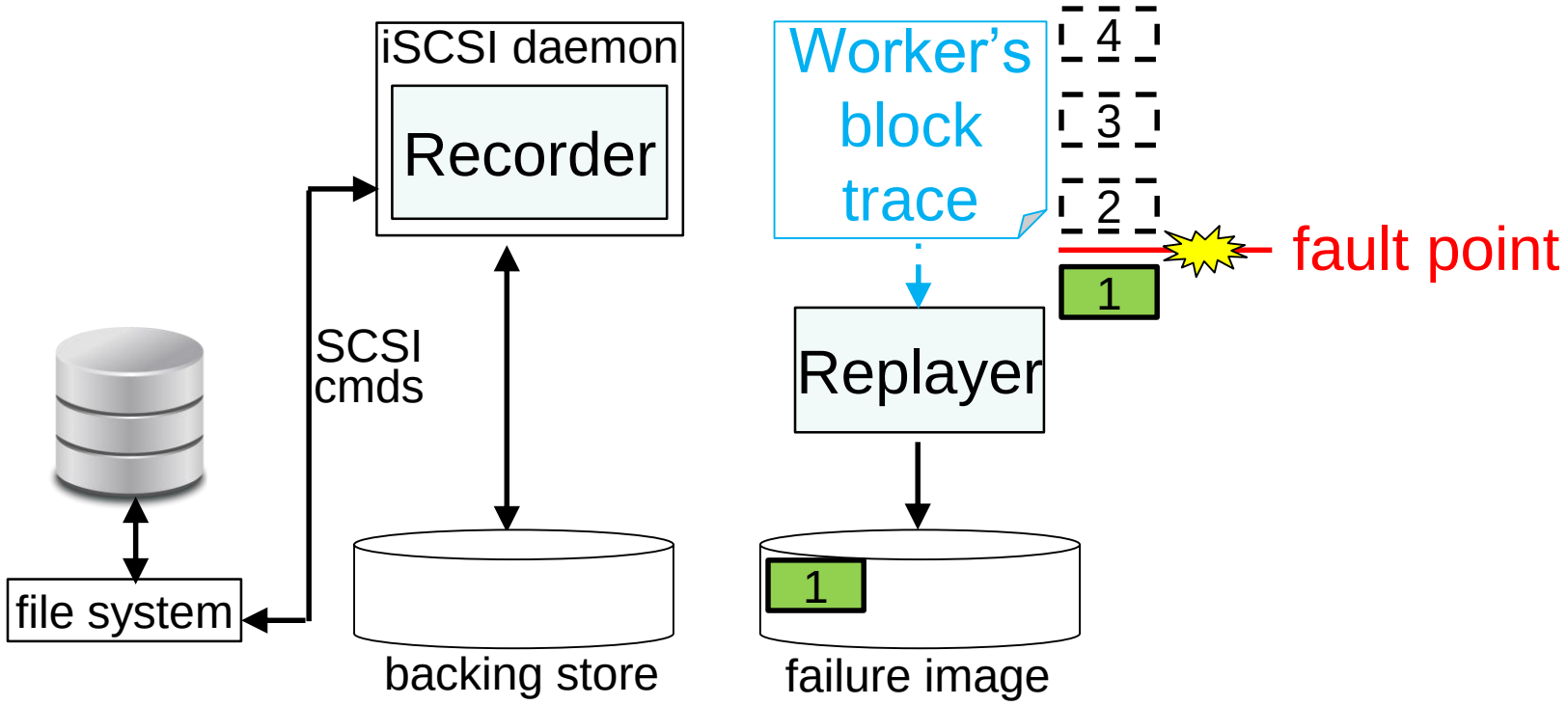
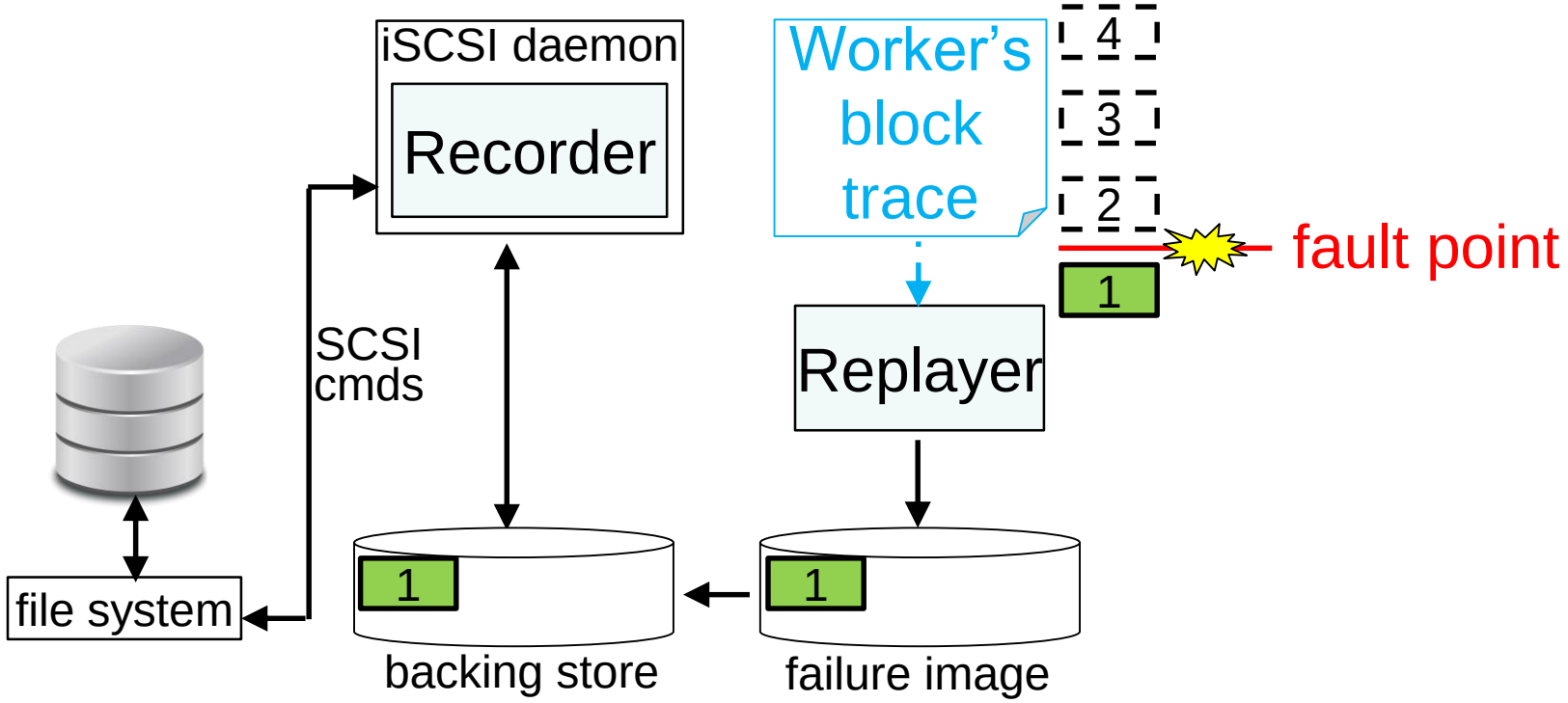


Checking the post-fault DB



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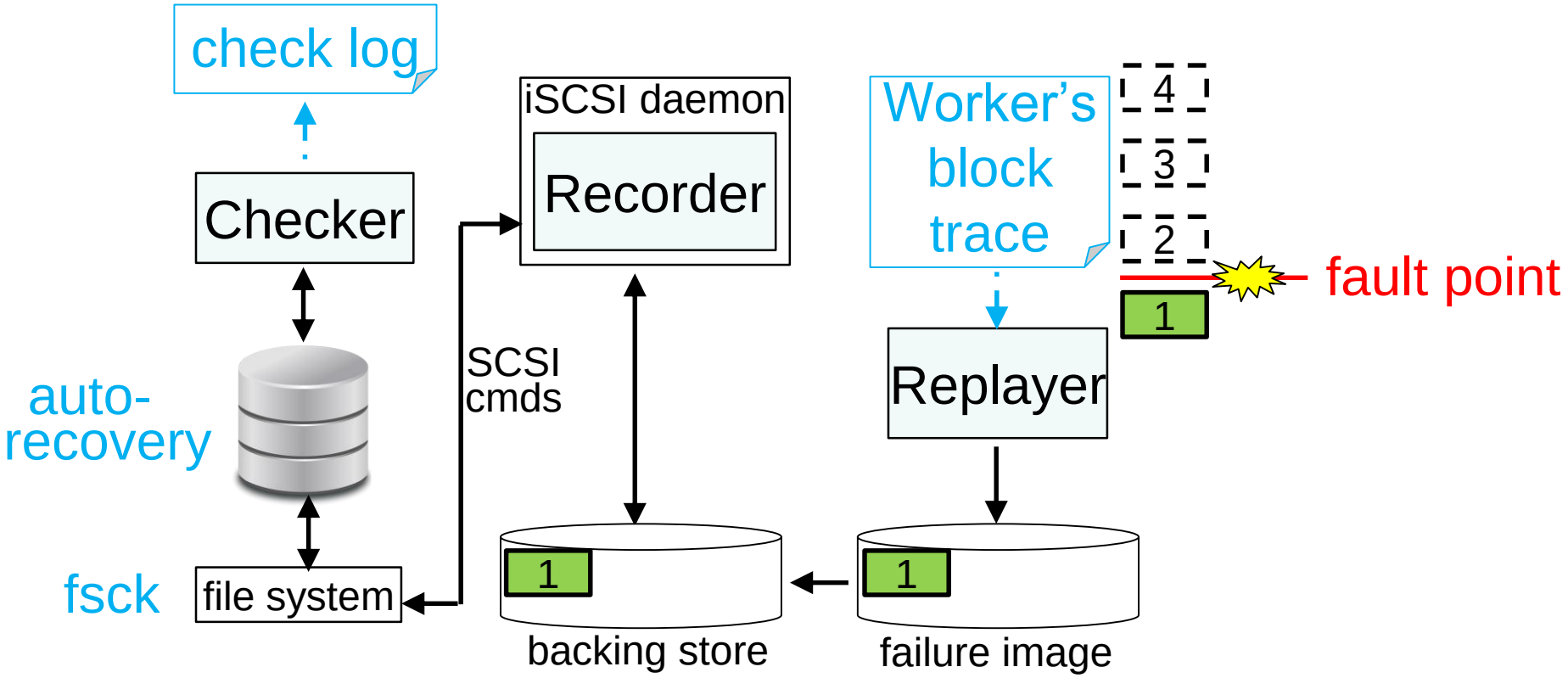
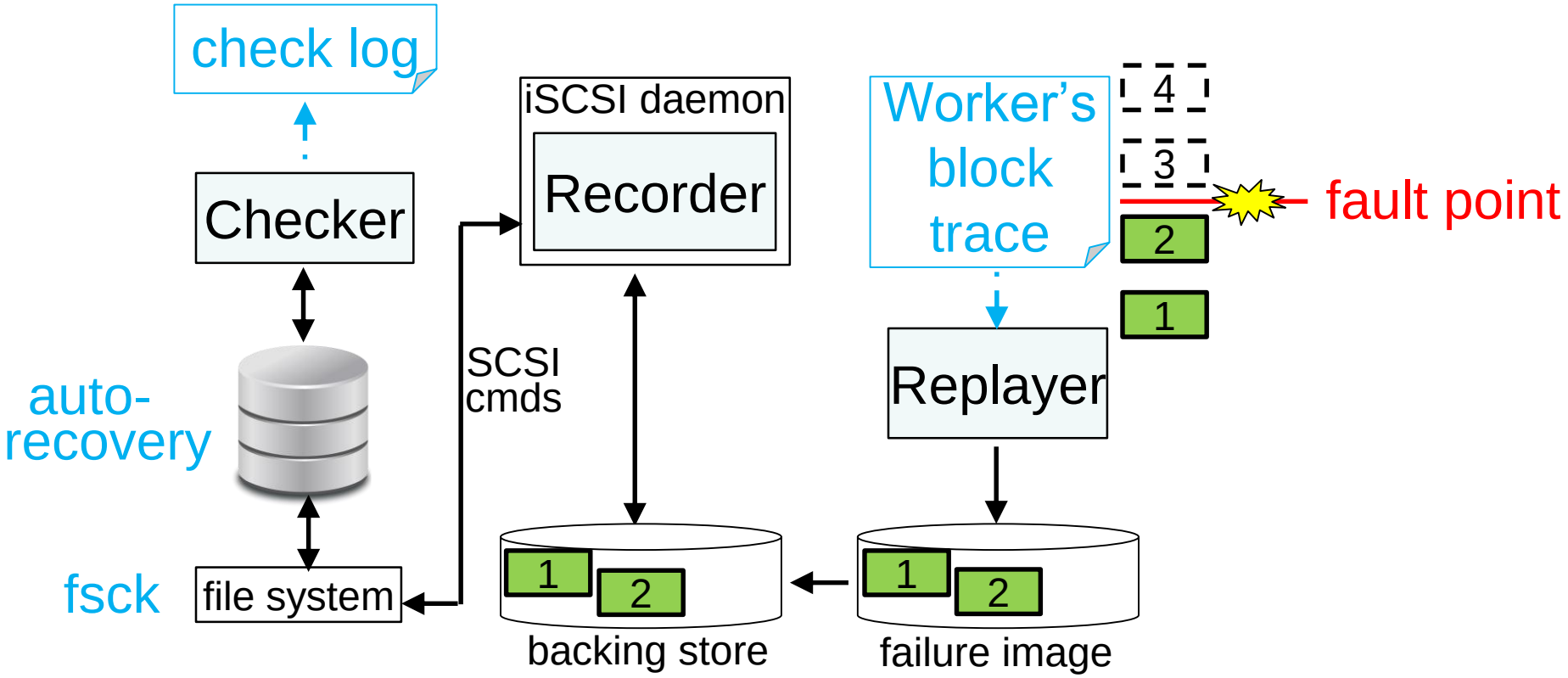


Testing different fault points easily



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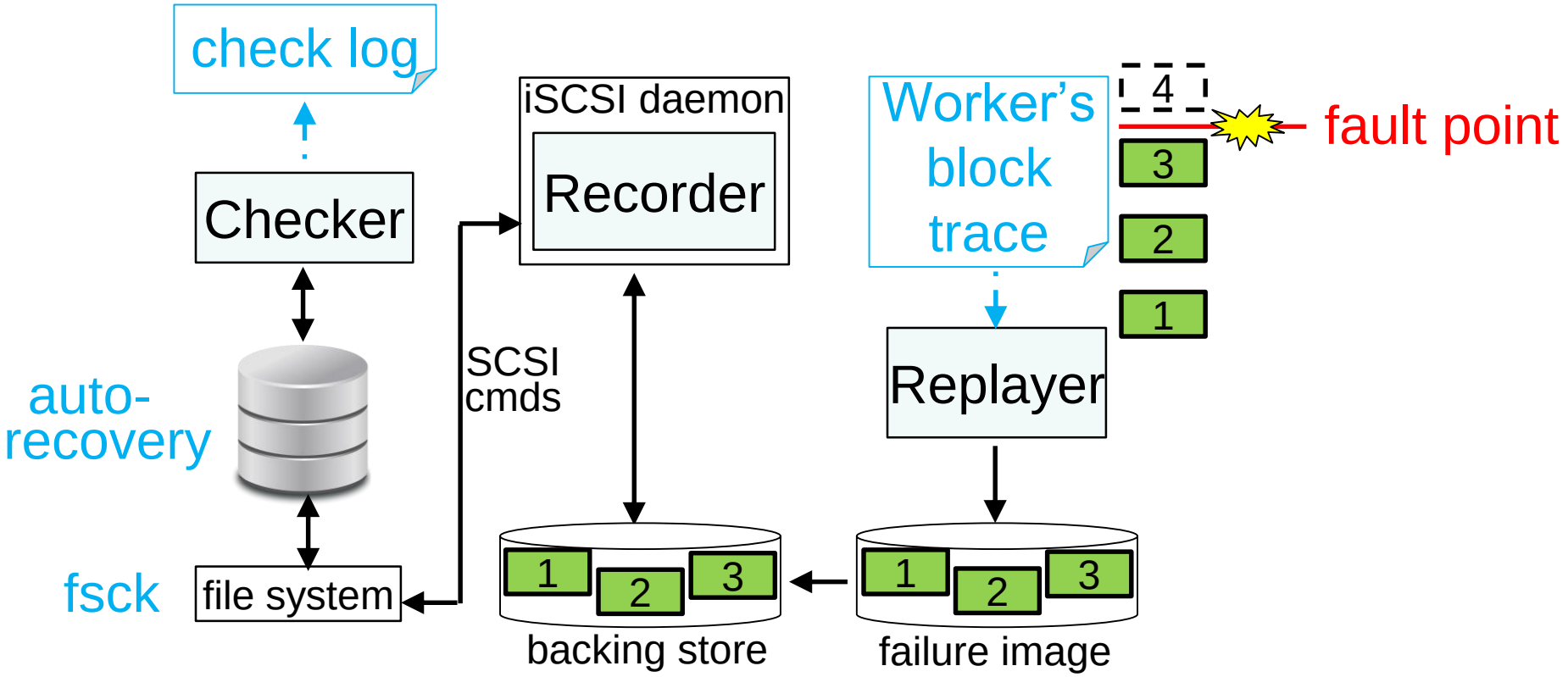
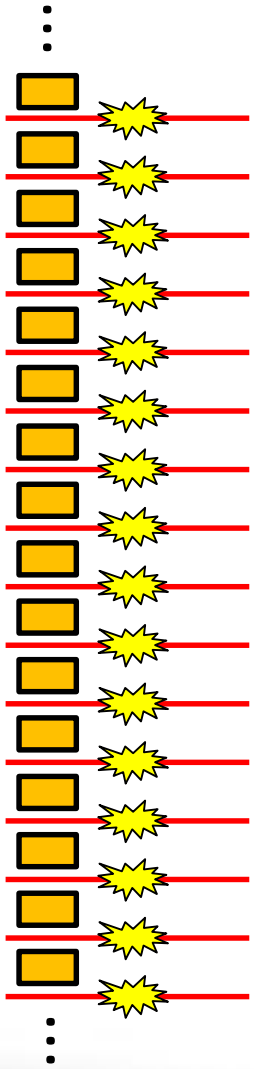


The framework is not good enough

- Sometimes need several days
  - too many mini operations, too many potential fault points



The framework is not good enough

- Sometimes need several days
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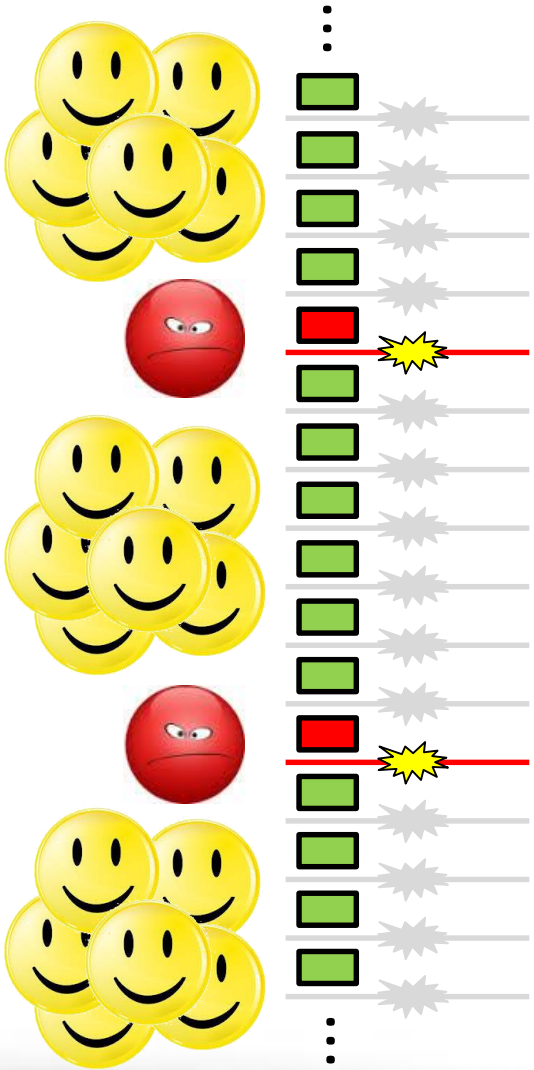
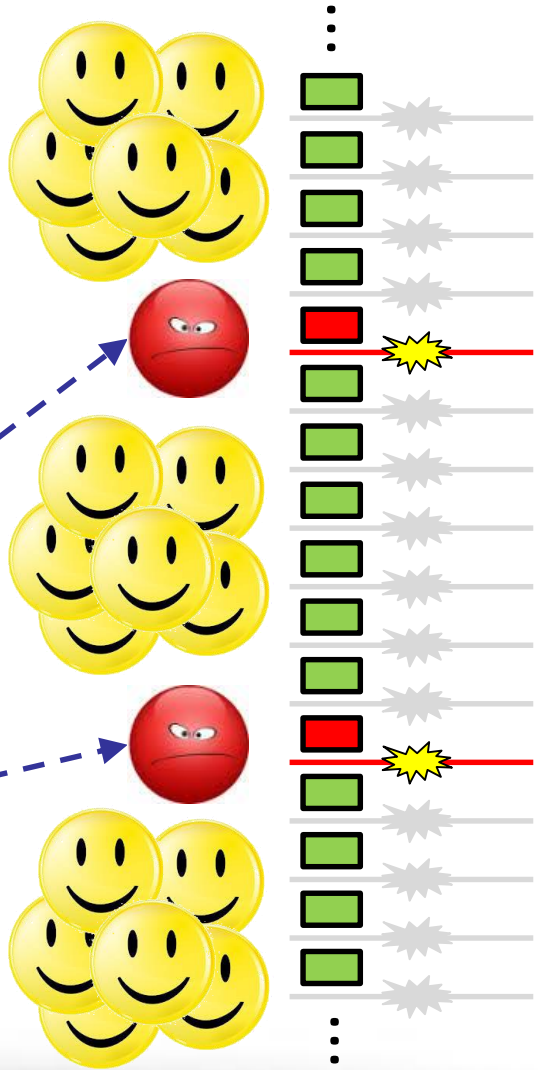
- We tried sampling
  - but only a few fault points trigger ACID violations



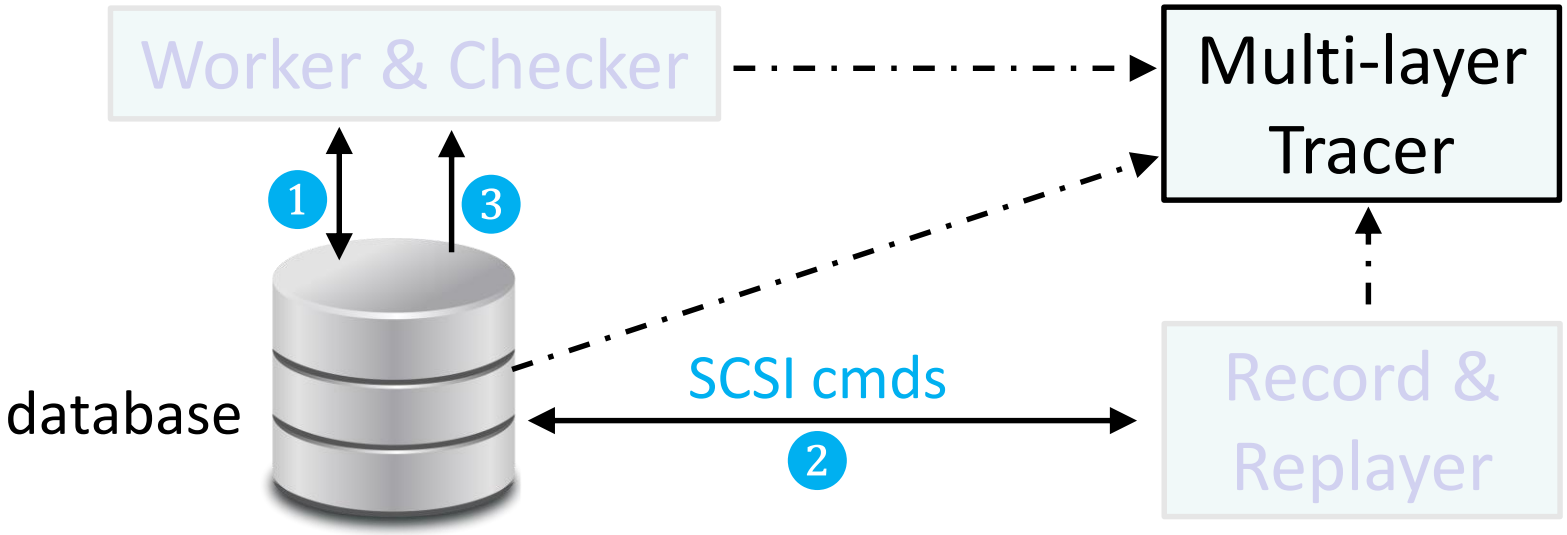
The framework is not good enough

- Sometimes need several days
  - too many mini operations, too many potential fault points
- We tried sampling
  - but only a few fault points trigger ACID violations
- Don’t know why



Enhanced Design

Framework Overview



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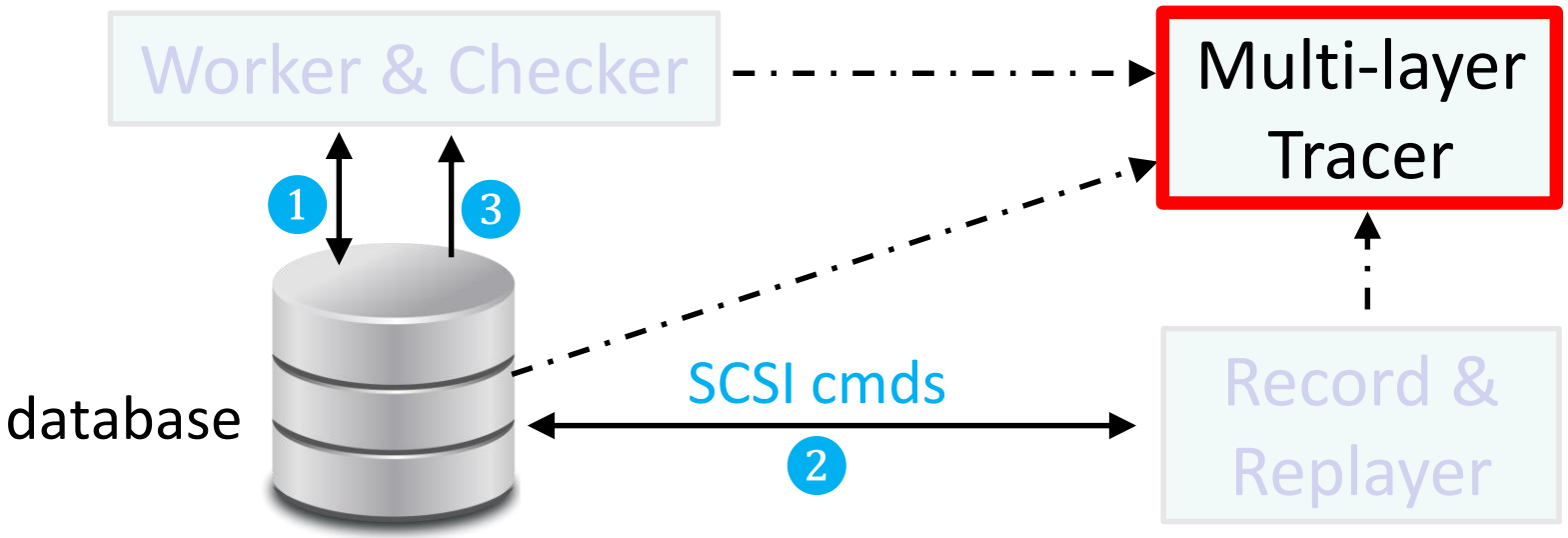
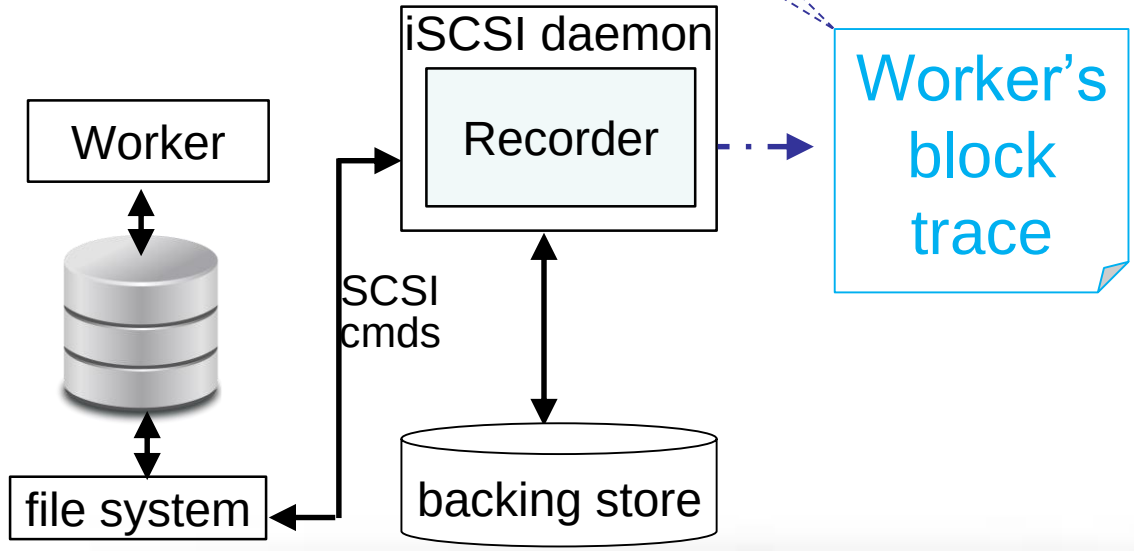


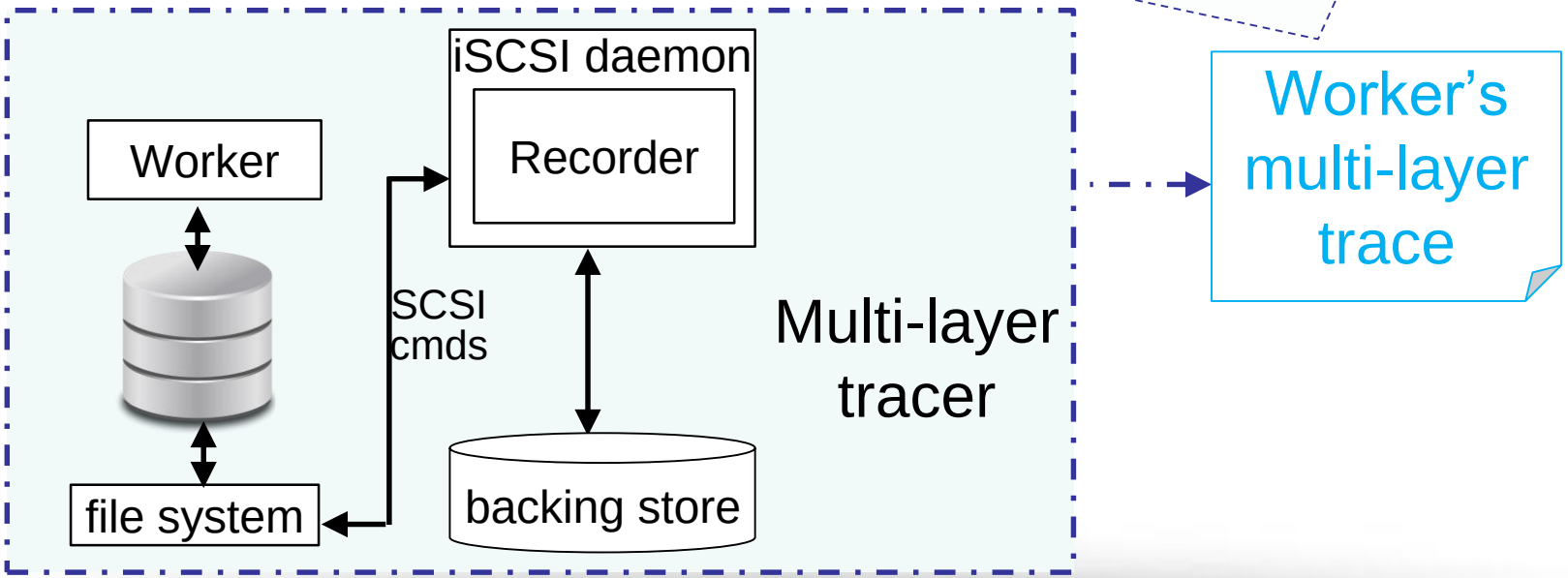
Original trace provides little semantics

op#	content	LBA
1	0a080101 ...	1012
2	0a080001 ...	6541
3	98393bc0 ...	9598
4	00000100 ...	9602



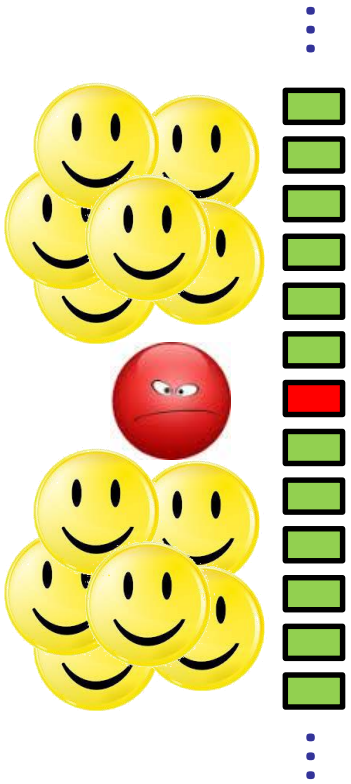
Enhancing w/ more context

op#	content	LBA	timestamp	cmd#	file	syscall
1	0a080101 ...	1012	139...013065	1	x.db	msync(x.db)
2	0a080001 ...	6541	139...210438	2	x.log	fsync(x.log)
3	98393bc0 ...	9598	139...355253	3	fs-j	fsync(x.log)
4	00000100 ...	9602	139...506097	3	fs-j	fsync(x.log)



What makes some fault points special?

checking result



Worker's multi-layer trace

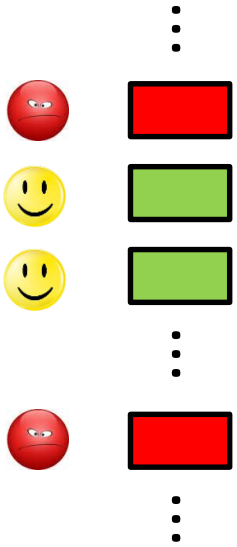
op#	content	LBA	ts	cmd#	file	syscall
…	…	…	…	…	…	…
…	…	…	…	…	…	…
…	…	…	…	…	…	…
…	…	…	…	…	…	…
…	…	…	…	…	…	…
…	…	…	…	…	…	…
…	…	…	…	…	…	…
…	…	…	…	…	…	…
…	…	…	…	…	…	…
…	…	…	…	…	…	…
…	…	…	…	…	…	…
…	…	…	…	…	…	…

anything special?

Five patterns found

- REP_p : repetitive LBA (Logical Block Address)

checking result



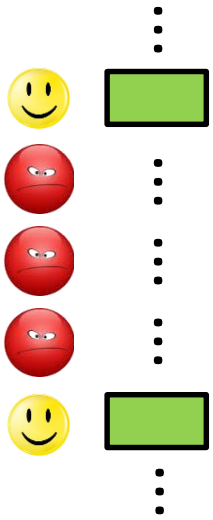
Worker's multi-layer trace

...	LBA	...
...	...	...
...	**1038**	...
...	2347	...
...	2351	...
...	...	...
...	**1038**	...
...	...	...

fixed location for important metadata & in-place update

Five patterns found

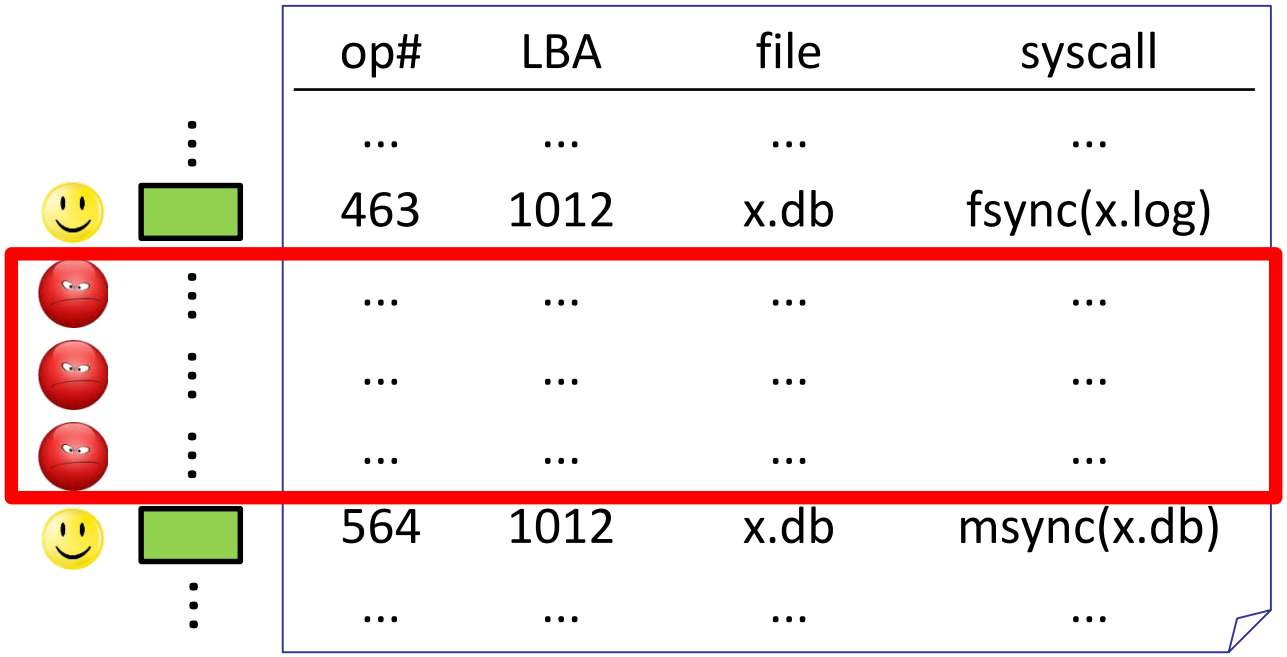
- $MMAP_p$: unintended update to mmap'ed blocks



op#	LBA	file	syscall
…	…	…	…
463	1012	x.db	fsync(x.log)
…	…	…	…
…	…	…	…
…	…	…	…
564	1012	x.db	msync(x.db)
…	…	…	…

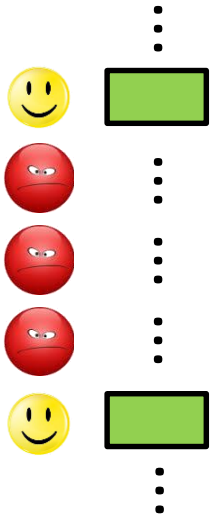
Five patterns found

- $MMAP_p$: unintended update to mmap'ed blocks



Five patterns found

- $MMAP_p$: unintended update to mmap'ed blocks

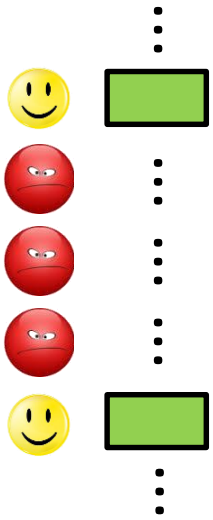


op#	LBA	file	syscall
…	…	…	…
463	1012	x.db	fsync(x.log)
…	…	…	…
…	…	…	…
…	…	…	…
564	1012	x.db	msync(x.db)
…	…	…	…

intended

Five patterns found

- $MMAP_p$: unintended update to mmap'ed blocks

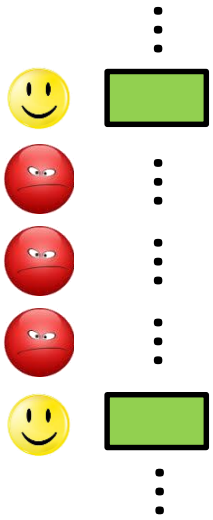


op#	LBA	file	syscall
…	…	…	…
463	1012	x.db	fsync(x.log)
…	…	…	…
…	…	…	…
…	…	…	…
564	1012	x.db	msync(x.db)
…	…	…	…

intended

Five patterns found

- $MMAP_p$: unintended update to $mmap$'ed blocks

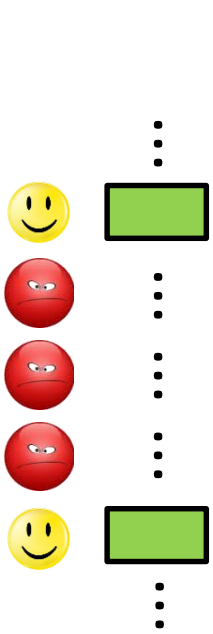


op#	LBA	file	syscall	
…	…	…	…	
463	1012	x.db	fsync x.log	unintended
…	…	…	…	
…	…	…	…	
…	…	…	…	
564	1012	x.db	msync(x.db)	intended
…	…	…	…	

implicit flush of dirty blocks by kernel or FS under heavy transactions

Five patterns found

- $MMAP_p$: unintended update to mmap'ed blocks



op#	LBA	file	syscall
…	…	…	…
463	**1012**	**x.db**	**fsync(x.log)**
…	…	…	…
…	…	…	…
…	…	…	…
564	**1012**	**x.db**	**msync(x.db)**
…	…	…	…

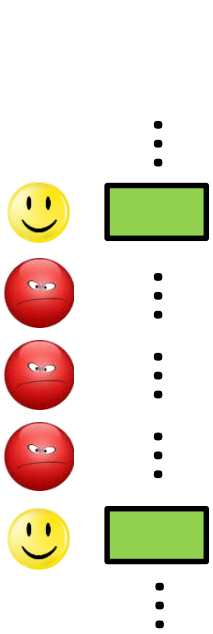
unintended

special region

intended

Five patterns found

- $MMAP_p$: unintended update to mmap'ed blocks



op#	LBA	file	syscall
…	…	…	…
463	**1012**	**x.db**	**fsync(x.log)**
…	…	…	…
…	…	…	…
…	…	…	…
564	**1012**	**x.db**	**msync(x.db)**
…	…	…	…

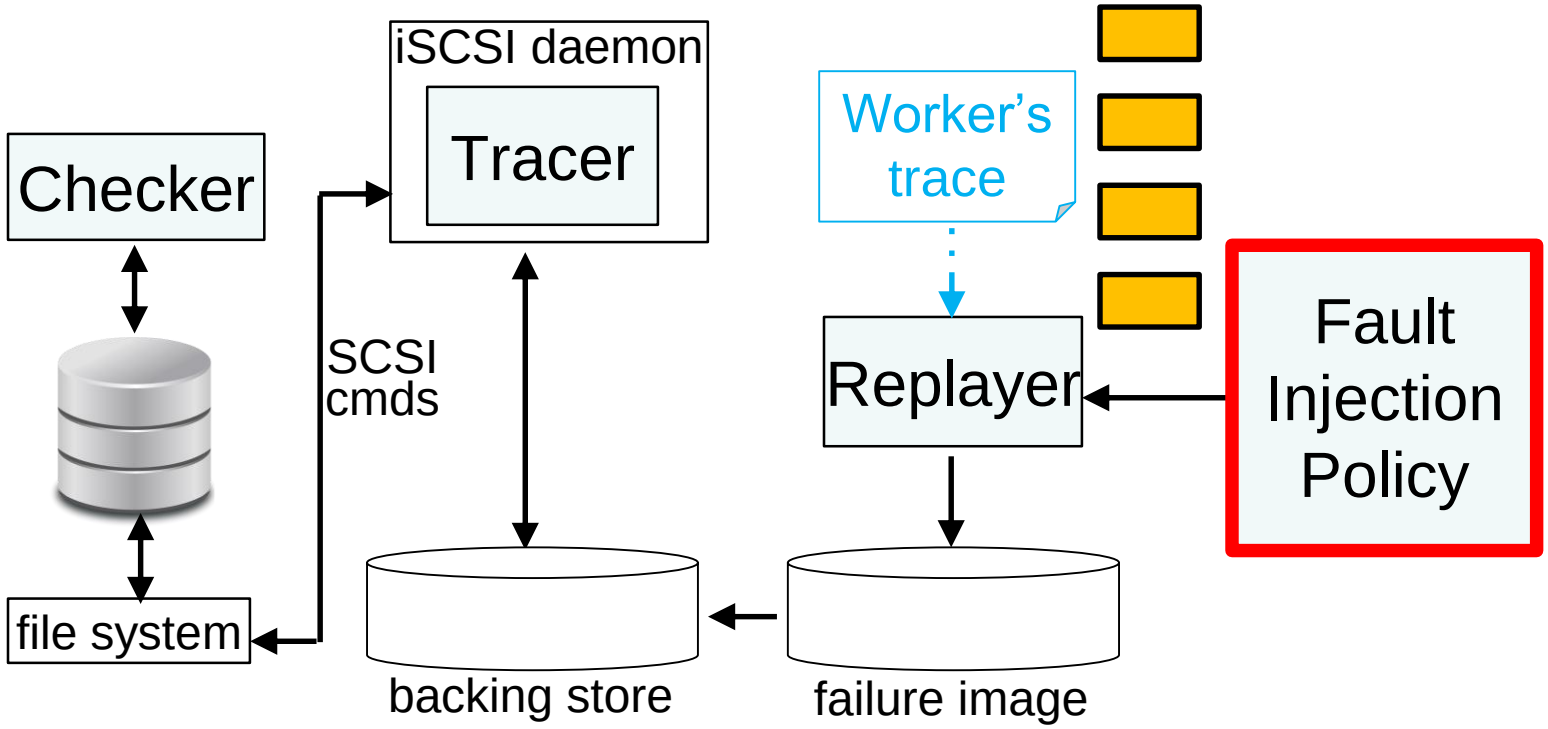
unintended

special region

intended

- Three more patterns: $JUMP_p$, $HEAD_p$, $TRAN_p$

Add fault injection policy to determine where to inject faults



Alternative to Exhaustive: Pattern-based Ranking

Worker's multi-layer trace

op#	LBA	cmd#	file	syscall	
1	348	1	x.db	msyc(x.db)	1
2	352	2	x.log	fsync(x.log)	2
3	356	2	x.log	fsync(x.log)	3
4	360	2	x.log	fsync(x.log)	4
5	364	2	x.log	fsync(x.log)	5
6	370	3	x.log	fsync(x.log)	6
7	348	4	x.db	fsync(x.log)	7
8	906	5	fs-j	fsync(x.log)	8

Scoreboard

$MMAP_p$	REP_p	$JUMP_p$	$HEAD_p$	$TRAN_p$	total score

Alternative to Exhaustive: Pattern-based Ranking

Worker's multi-layer trace

op#	LBA	cmd#	file	syscall	
1	348	1	x.db	msyc(x.db)	1
2	352	2	x.log	fsync(x.log)	2
3	356	2	x.log	fsync(x.log)	3
4	360	2	x.log	fsync(x.log)	4
5	364	2	x.log	fsync(x.log)	5
6	370	3	x.log	fsync(x.log)	6
7	348	4	x.db	fsync(x.log)	7
8	906	5	fs-j	fsync(x.log)	8

Scoreboard

$MMAP_p$	REP_p	$JUMP_p$	$HEAD_p$	$TRAN_p$	total score
0					
0					
0					
0					
0					
0					
1					
1					

Alternative to Exhaustive: Pattern-based Ranking

Worker's multi-layer trace

op#	LBA	cmd#	file	syscall	
1	348	1	x.db	msyc(x.db)	1
2	352	2	x.log	fsync(x.log)	2
3	356	2	x.log	fsync(x.log)	3
4	360	2	x.log	fsync(x.log)	4
5	364	2	x.log	fsync(x.log)	5
6	370	3	x.log	fsync(x.log)	6
7	348	4	x.db	fsync(x.log)	7
8	906	5	fs-j	fsync(x.log)	8

Scoreboard

$MMAP_p$	REP_p	$JUMP_p$	$HEAD_p$	$TRAN_p$	total score
0	1				
0	0				
0	0				
0	0				
0	0				
0	0				
1	1				
1	0				

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Worker's multi-layer trace

op#	LBA	cmd#	file	syscall	
1	348	1	x.db	msyc(x.db)	1
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6	370	3	x.log	fsync(x.log)	6
7	348	4	x.db	fsync(x.log)	7
8	906	5	fs-j	fsync(x.log)	8

Scoreboard

$MMAP_p$	REP_p	$JUMP_p$	$HEAD_p$	$TRAN_p$	total score
0	1	0			
0	0	0			
0	0	0			
0	0	0			
0	0	0			
0	0	1			
1	1	1			
1	0	1			

Alternative to Exhaustive: Pattern-based Ranking

Worker's multi-layer trace

op#	LBA	cmd#	file	syscall	
1	348	1	x.db	msyc(x.db)	1
2	352	2	x.log	fsync(x.log)	2
3	356	2	x.log	fsync(x.log)	3
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7	348	4	x.db	fsync(x.log)	7
8	906	5	fs-j	fsync(x.log)	8

Scoreboard

$MMAP_p$	REP_p	$JUMP_p$	$HEAD_p$	$TRAN_p$	total score
0	1	0	0		
0	0	0	1		
0	0	0	0		
0	0	0	0		
0	0	0	0		
0	0	1	0		
1	1	1	0		
1	0	1	0		

Alternative to Exhaustive: Pattern-based Ranking

Worker's multi-layer trace

op#	LBA	cmd#	file	syscall
1	348	1	x.db	msyc(x.db)
2	352	2	x.log	fsync(x.log)
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7	348	4	x.db	fsync(x.log)
8	906	5	fs-j	fsync(x.log)

Scoreboard

	$MMAP_p$	REP_p	$JUMP_p$	$HEAD_p$	$TRAN_p$	total score
1	0	1	0	0	1	
2	0	0	0	1	1	
3	0	0	0	0	0	
4	0	0	0	0	0	
5	0	0	0	0	0	
6	0	0	1	0	1	
7	1	1	1	0	1	
8	1	0	1	0	1	

Alternative to Exhaustive: Pattern-based Ranking

Worker's multi-layer trace

op#	LBA	cmd#	file	syscall
1	348	1	x.db	msyc(x.db)
2	352	2	x.log	fsync(x.log)
3	356	2	x.log	fsync(x.log)
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6	370	3	x.log	fsync(x.log)
7	348	4	x.db	fsync(x.log)
8	906	5	fs-j	fsync(x.log)

Scoreboard

	$MMAP_p$	REP_p	$JUMP_p$	$HEAD_p$	$TRAN_p$	total score
1	0	1	0	0	1	**2**
2	0	0	0	1	1	**2**
3	0	0	0	0	0	**0**
4	0	0	0	0	0	**0**
5	0	0	0	0	0	**0**
6	0	0	1	0	1	**2**
7	1	1	1	0	1	**4**
8	1	0	1	0	1	**3**

Alternative to Exhaustive: Pattern-based Ranking

Worker's multi-layer trace

op#	LBA	cmd#	file	syscall	
1	348	1	x.db	msyc(x.db)	1
2	352	2	x.log	fsync(x.log)	2
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7	348	4	x.db	fsync(x.log)	7
8	906	5	fs-j	fsync(x.log)	8

Scoreboard

	$MMAP_p$	REP_p	$JUMP_p$	$HEAD_p$	$TRAN_p$	total score
1	0	1	0	0	1	**2**
2	0	0	0	1	1	**2**
3	0	0	0	0	0	**0**
4	0	0	0	0	0	**0**
5	0	0	0	0	0	**0**
6	0	0	1	0	1	**2**
7	1	1	1	0	1	**4**
8	1	0	1	0	1	**3**

1st-rank: 7 ← predicted most error-prone

2nd-rank: 8

3rd-rank: 1 2 6

4th -rank: 3 4 5

Alternative to Exhaustive: Pattern-based Ranking

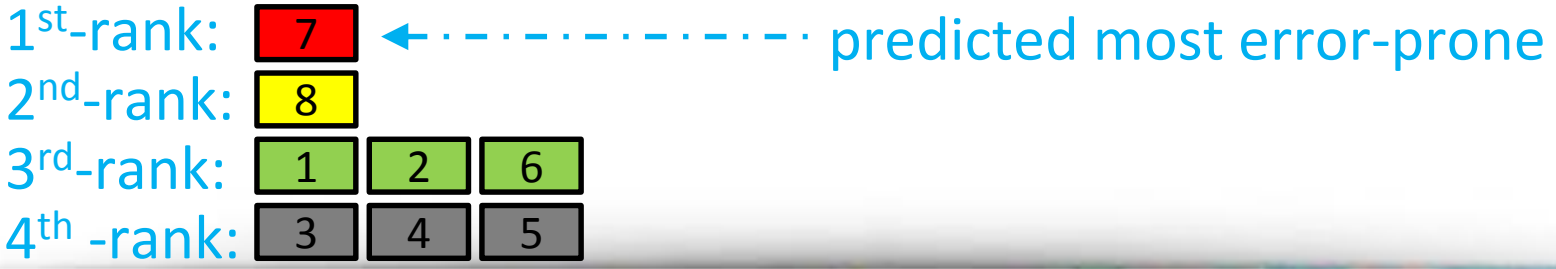
1st-rank: 7 ← predicted most error-prone

2nd-rank: 8

3rd-rank: 1 2 6

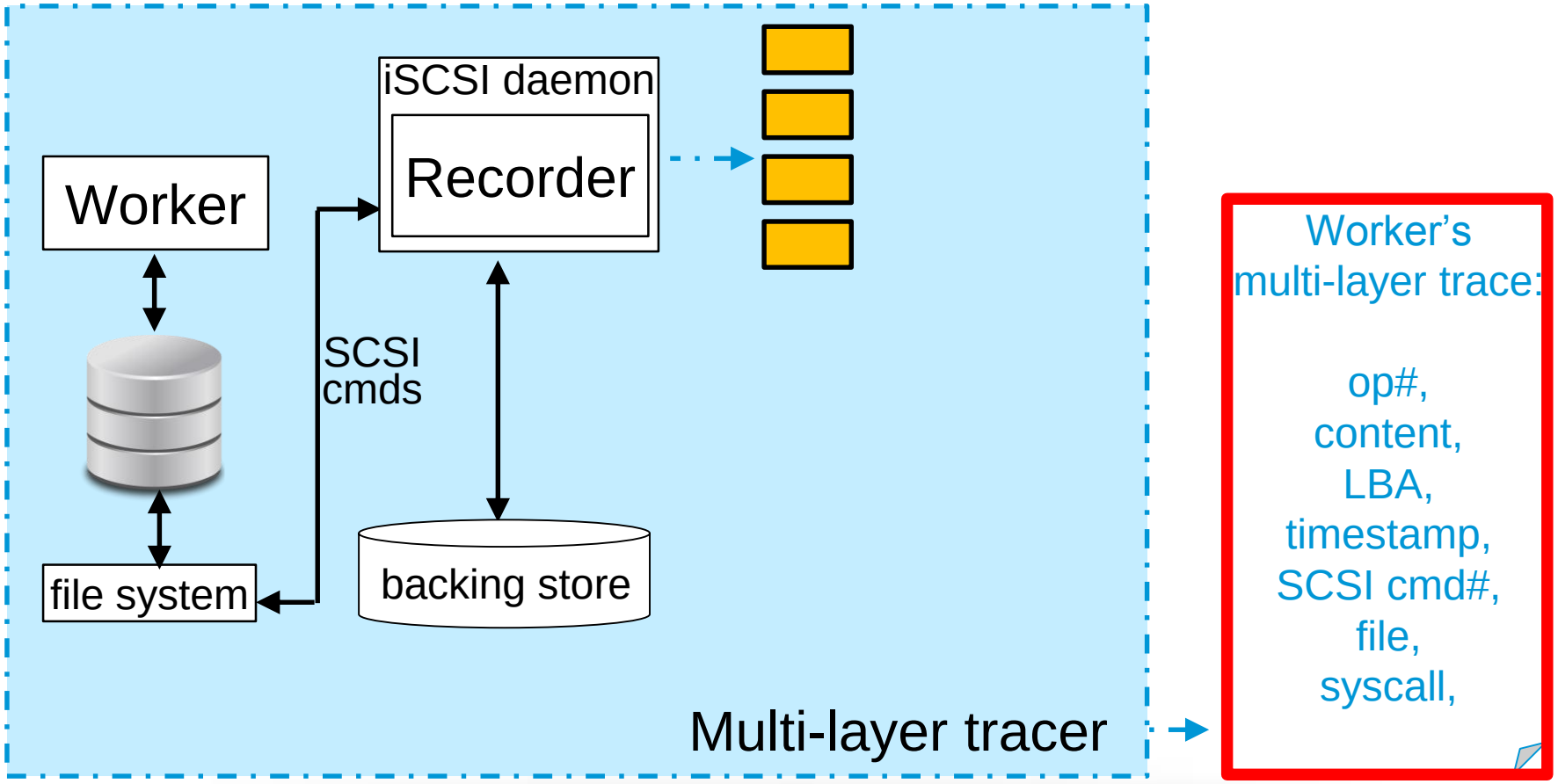
4th -rank: 3 4 5

Alternative to Exhaustive: Pattern-based Ranking

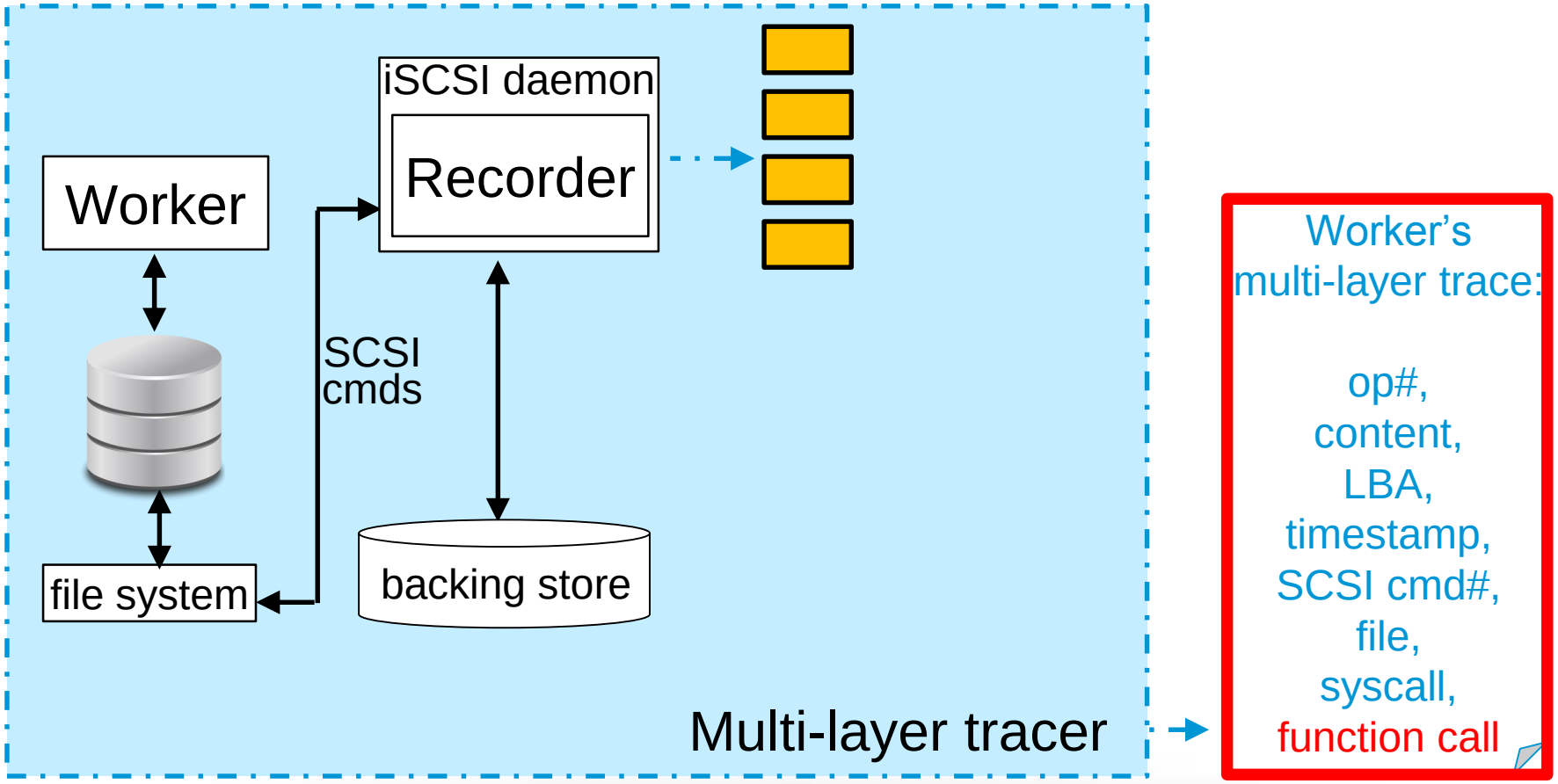


Diagnosis Support

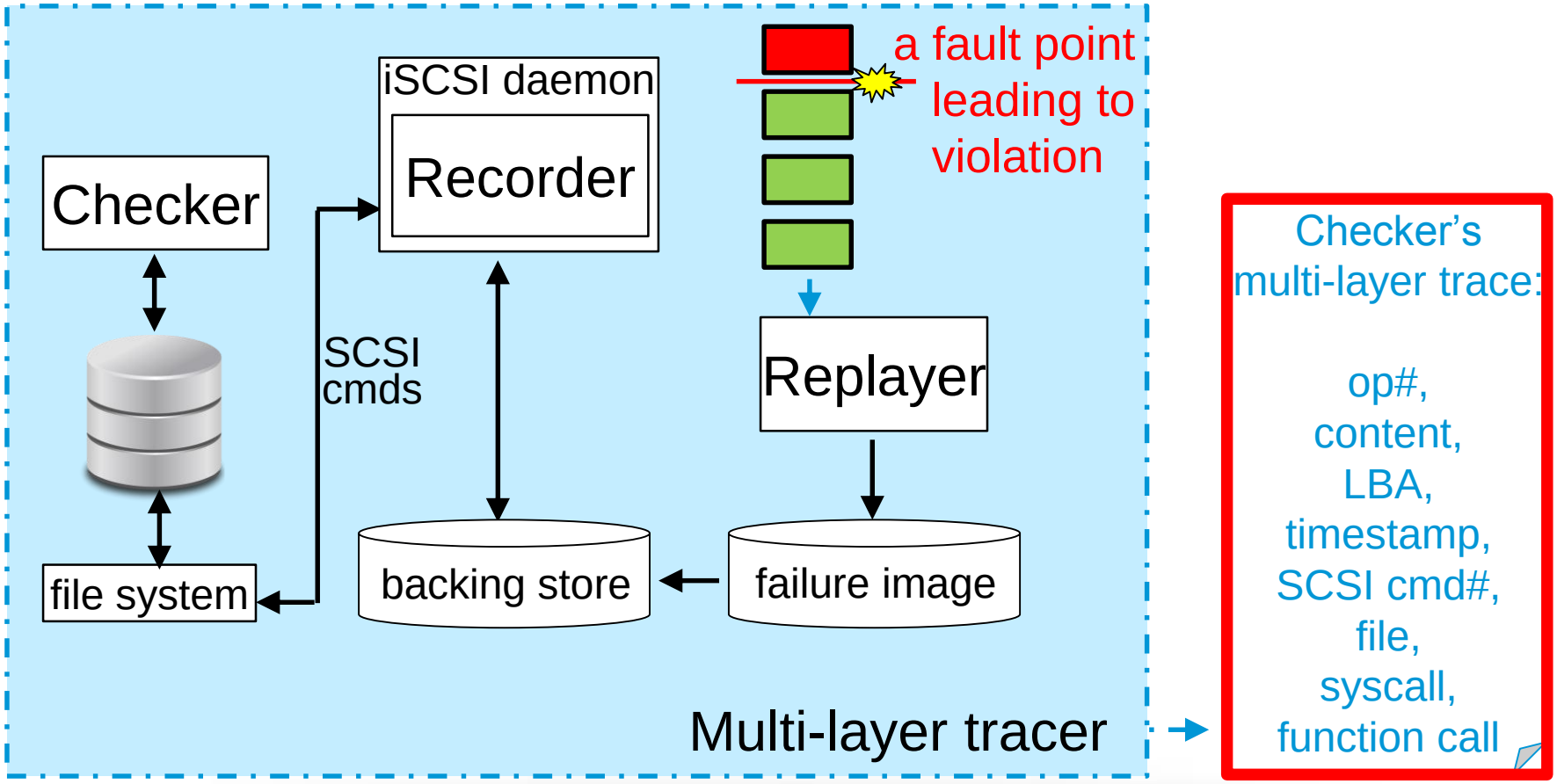
Worker's multi-layer trace helps understand what happened at fault time



Add function-call tracing to disclose more semantics for diagnosis



Enable same tracing during checking to see why recovery didn't work



Results

Experimental Environment

- 8 databases
  - Open-source: TokyoCabinet, MariaDB, LightningDB, SQLite
  - Commercial: KVS-A, SQL-A, SQL-B, SQL-C
- 4 workloads
- 3 file systems
  - ext3, XFS, NTFS
- Several operating systems
  - Linux: RHEL 6, Debian6, Ubuntu 12 LTS
  - Windows 7 Enterprise

Not a single DB can survive all tests

DB	FS	W-1	W-2	W-3	W-4.1	W-4.2	W-4.3	A	C	I	D
TokyoCabinet	ext3	D	D	D	ACD	ACD	ACD	0.15%	0.14%	0	16.05%
	XFS	--	D	D	ACD	D	ACD	<0.01%	0.01%	0	4.38%
MariaDB	ext3	D	D	D	D	D	D	0	0	0	1.36%
	XFS	D	D	D	D	D	D	0	0	0	0.49%
LightningDB	ext3	--	--	--	--	--	D	0	0	0	0.05%
	XFS	--	--	--	--	--	--	0	0	0	0
SQLite	ext3	D	D	--	D	D	D	0	0	0	19.15%
	XFS	--	--	D	D	D	D	0	0	0	10.60%
KVS-A	ext3	--	--	Hang	--	--	--	0	0	0	0
	XFS	--	--	--	--	--	--	0	0	0	0
SQL-A	ext3	D	D	D	D	D	D	0	0	0	3.31%
	XFS	D	D	D	D	D	D	0	0	0	0.92%
SQL-B	ext3	D	D	CD	CD	CD	CD	0	8.96%	0	3.24%
	XFS	CD	D	CD	CD	CD	CD	0	7.77%	0	3.90%
SQL-C	NTFS	D	D	D	D	D	D	0	0	0	8.08%

Durability violation is most common

DB	FS	W-1	W-2	W-3	W-4.1	W-4.2	W-4.3	A	C	I	D
TokyoCabinet	ext3	D	D	D	ACD	ACD	ACD	0.15%	0.14%	0	16.05%
	XFS	--	D	D	ACD	D	ACD	<0.01%	0.01%	0	4.38%
MariaDB	ext3	D	D	D	D	D	D	0	0	0	1.36%
	XFS	D	D	D	D	D	D	0	0	0	0.49%
LightningDB	ext3	--	--	--	--	--	D	0	0	0	0.05%
	XFS	--	--	--	--	--	--	0	0	0	0
SQLite	ext3	D	D	--	D	D	D	0	0	0	19.15%
	XFS	--	--	D	D	D	D	0	0	0	10.60%
KVS-A	ext3	--	--	Hang	--	--	--	0	0	0	0
	XFS	--	--	--	--	--	--	0	0	0	0
SQL-A	ext3	D	D	D	D	D	D	0	0	0	3.31%
	XFS	D	D	D	D	D	D	0	0	0	0.92%
SQL-B	ext3	D	D	CD	CD	CD	CD	0	8.96%	0	3.24%
	XFS	CD	D	CD	CD	CD	CD	0	7.77%	0	3.90%
SQL-C	NTFS	D	D	D	D	D	D	0	0	0	8.08%

Some violations are difficult to trigger

DB	FS	W-1	W-2	W-3	W-4.1	W-4.2	W-4.3	A	C	I	D
TokyoCabinet	ext3	D	D	D	ACD	ACD	ACD	0.15%	0.14%	0	16.05%
	XFS	--	D	D	ACD	D	ACD	<0.01%	0.01%	0	4.38%
MariaDB	ext3	D	D	D	D	D	D	0	0	0	1.36%
	XFS	D	D	D	D	D	D	0	0	0	0.49%
LightningDB	ext3	--	--	--	--	--	D	0	0	0	0.05%
	XFS	--	--	--	--	--	--	0	0	0	0
SQLite	ext3	D	D	--	D	D	D	0	0	0	19.15%
	XFS	--	--	D	D	D	D	0	0	0	10.60%
KVS-A	ext3	--	--	Hang	--	--	--	0	0	0	0
	XFS	--	--	--	--	--	--	0	0	0	0
SQL-A	ext3	D	D	D	D	D	D	0	0	0	3.31%
	XFS	D	D	D	D	D	D	0	0	0	0.92%
SQL-B	ext3	D	D	CD	CD	CD	CD	0	8.96%	0	3.24%
	XFS	CD	D	CD	CD	CD	CD	0	7.77%	0	3.90%
SQL-C	NTFS	D	D	D	D	D	D	0	0	0	8.08%

Some violations are difficult to trigger

DB	FS	W-1	W-2	W-3	W-4.1	W-4.2	W-4.3	A	C	I	D
TokyoCabinet	ext3	D	D	D	ACD	ACD	ACD	0.15%	0.14%	0	16.05%
	XFS	--	D	D	ACD	D	ACD	<0.01%	0.01%	0	4.38%
MariaDB	ext3	D	D	D	D	D	D	0	0	0	1.36%
	XFS	D	D	D	D	D	D	0	0	0	0.49%
LightningDB	ext3	--	--	--	--	--	D	0	0	0	0.05%
	XFS	--	--	--	--	--	--	0	0	0	0
SQLite	ext3	D	D	--	D	D	D	0	0	0	19.15%
	XFS	--	--	D	D	D	D	0	0	0	10.60%
KVS-A	ext3	--	--	Hang	--	--	--	0	0	0	0
	XFS	--	--	--	--	--	--	0	0	0	0
SQL-A	ext3	D	D	D	D	D	D	0	0	0	3.31%
	XFS	D	D	D	D	D	D	0	0	0	0.92%
SQL-B	ext3	D	D	CD	CD	CD	CD	0	8.96%	0	3.24%
	XFS	CD	D	CD	CD	CD	CD	0	7.77%	0	3.90%
SQL-C	NTFS	D	D	D	D	D	D	0	0	0	8.08%

Case Study: A TokyoCabinet Bug

- Failure symptoms

  faults injected in a region of operations cause:

  - A violation: a transaction is partially committed

  - D violation: some rows are irretrievable

  - C violation: retrievable rows by range query and point queries are different

Case Study: A TokyoCabinet Bug

Why recovery didn't work?

```
...
tchdbopenimpl(x.tcb)
...
open(x.tcb) = 3
read(x.tcb) = 256
//op#, LBA,  content, file
op#1, 480, ...100..., x.tcb

tcbdbget()
...
```

Checker's trace when ACID violations were found

```
...
tchdbopenimpl(x.tcb)
...
open(x.tcb) = 3
read(x.tcb) = 256
//op#, LBA,  content, file
op#1, 480, ...101..., x.tcb
tchdbwalrestore()
tcbdbget()
...
```

Checker's trace when no violation was found

Delta Debugging
[Zeller, SIGSOFT'02/FSE-10]

Case Study: A TokyoCabinet Bug

Why recovery didn't work?

```
...
tchdbopenimpl(x.tcb)
...
open(x.tcb) = 3
read(x.tcb) = 256
//op#, LBA,  content, file
op#1, 480, ...100..., x.tcb
//no tchdbwalrestore()
tcbdbget()
...
```

Checker's trace when ACID violations were found

```
...
tchdbopenimpl(x.tcb)
...
open(x.tcb) = 3
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op#1, 480, ...101..., x.tcb
tchdbwalrestore()
tcbdbget()
...
```

Checker's trace when no violation was found

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//op#, LBA,  content, file
op#1, 480, ...100..., x.tcb
//no tchdbwalrestore()
tcbdbget()
...
```

Checker's trace when ACID violations were found

```
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tchdbopenimpl(x.tcb)
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Checker's trace when no violation was found

Delta Debugging
[Zeller, SIGSOFT'02/FSE-10]

Case Study: A TokyoCabinet Bug

What happened at fault time?

Worker's trace
around the bug-triggering
fault points #30 - #90

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mmap(8192, x.tcb, 0)
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fsync(x.tcb.wal)
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Why recovery didn't work?

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msync mmap'ed pages to disk

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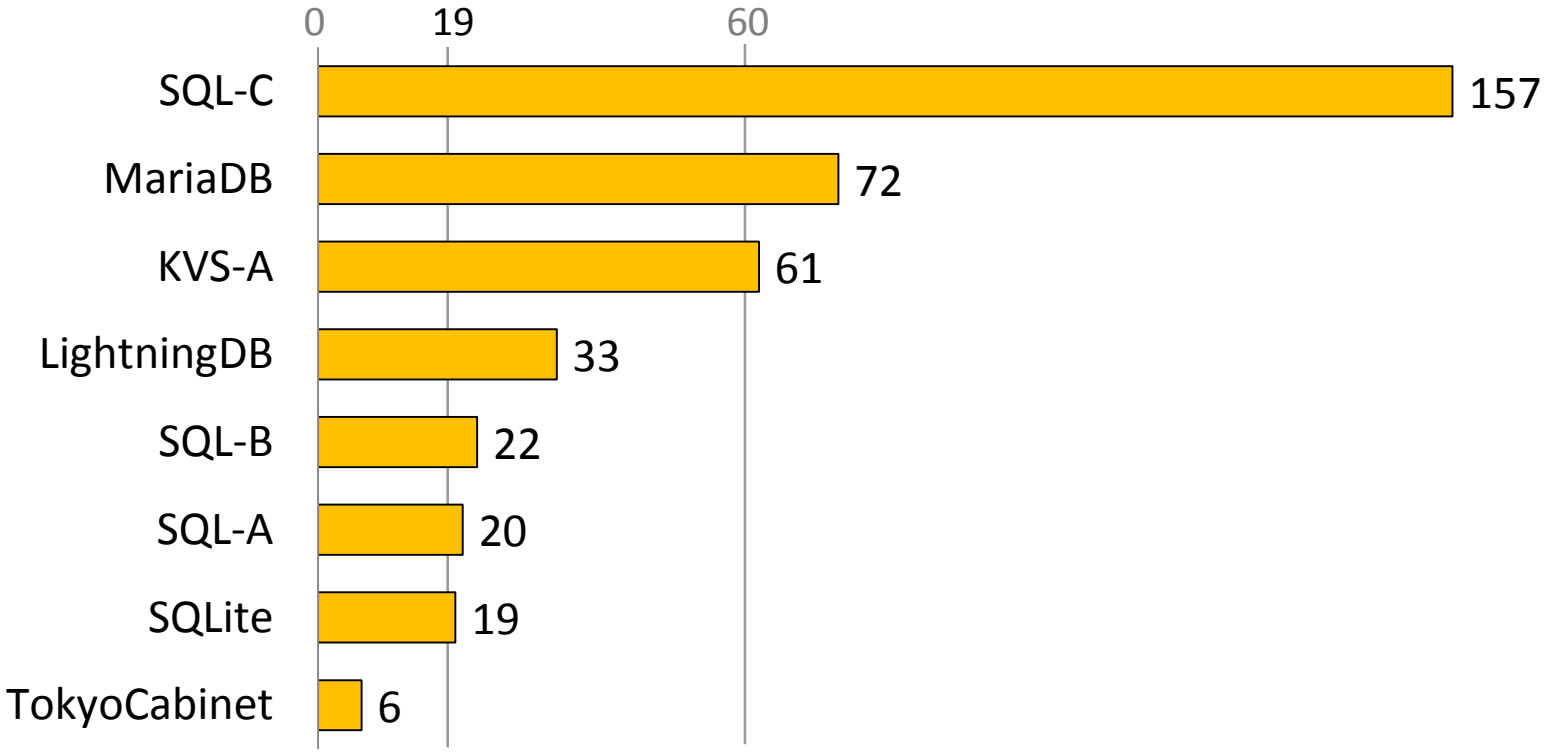
Unintended update!
fsync on **x.tcb.wal**
but data block goes to **x.tcb**

Intended update:
msync mmap'ed pages to disk

Patterns reduce required test points greatly while achieving similar coverage



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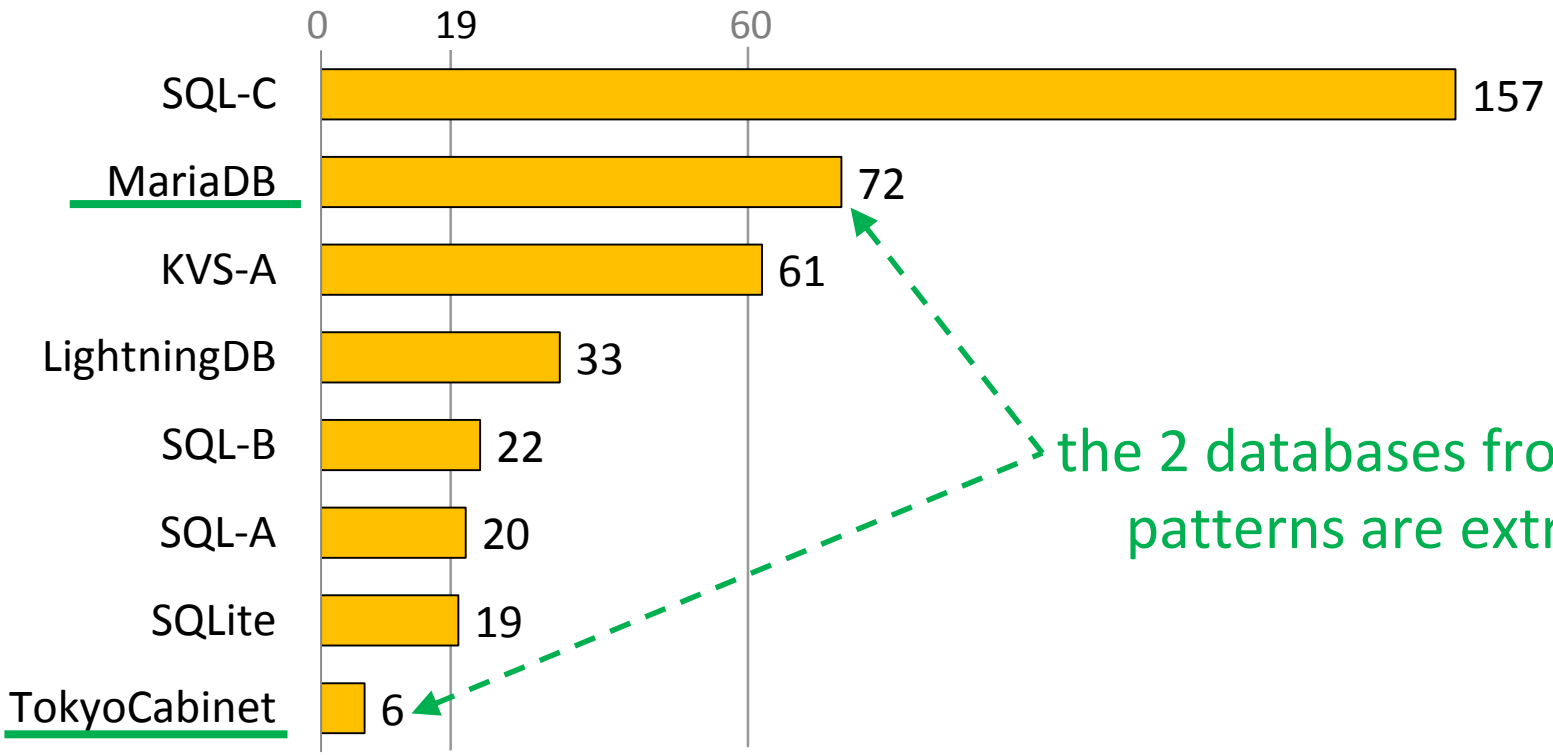

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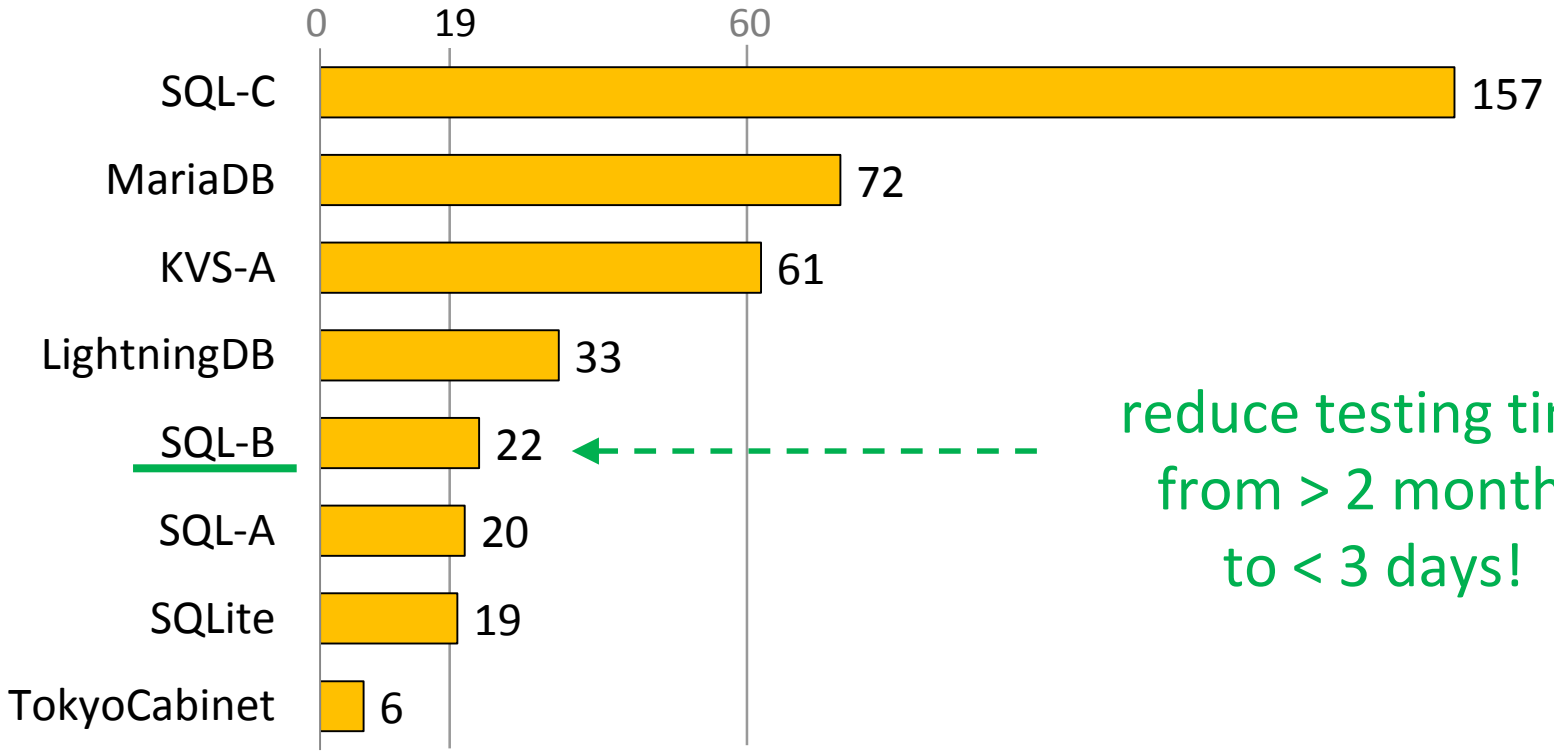

Conclusions & Future Work

- A wake-up call

  - traditional testing methodology may not be enough for today's complex storage systems

  - thorough testing requires purpose-built workloads and intelligent fault injection techniques

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  - thorough testing requires purpose-built workloads and intelligent fault injection techniques

- Different layers in OS can help in different ways

  - iSCSI: fault injection w/ high portability & high fidelity

  - LBA & syscall: generic behavior patterns

  - combined multi-layer info: clear whole picture of complicated scenarios

Conclusions & Future Work

- We should bridge the gaps of understanding/assumptions!

between
DB & OS

between
User & DB

Conclusions & Future Work

- We should bridge the gaps of understanding/assumptions!

Pop Quiz: true or false?

between DB & OS	“mmap'ed files are not updated until msync()”	
	“file-length update are persistent after fdatasync()”	
between User & DB	“durability is provided by the default configuration”	
	“transactions are durable after COMMIT”	

Conclusions & Future Work

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Pop Quiz: true or false?

between DB & OS	“mmap'ed files are not updated until msync()”	false
	“file-length update are persistent after fdatasync()”	
between User & DB	“durability is provided by the default configuration”	
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Conclusions & Future Work

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Pop Quiz: true or false?

between DB & OS	“mmap'ed files are not updated until msync()”	false
	“file-length update are persistent after fdatasync()”	depends!
between User & DB	“durability is provided by the default configuration”	depends!
	“transactions are durable after COMMIT”	depends!

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Pop Quiz: true or false?

between DB & OS	“mmap'ed files are not updated until msync()”	false
	“file-length update are persistent after fdatasync()”	depends!
between User & DB	“durability is provided by the default configuration”	depends!
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Thank you!