Database Applications (15-415)

DBMS Internals- Part XIV
Lecture 25, April 19, 2015

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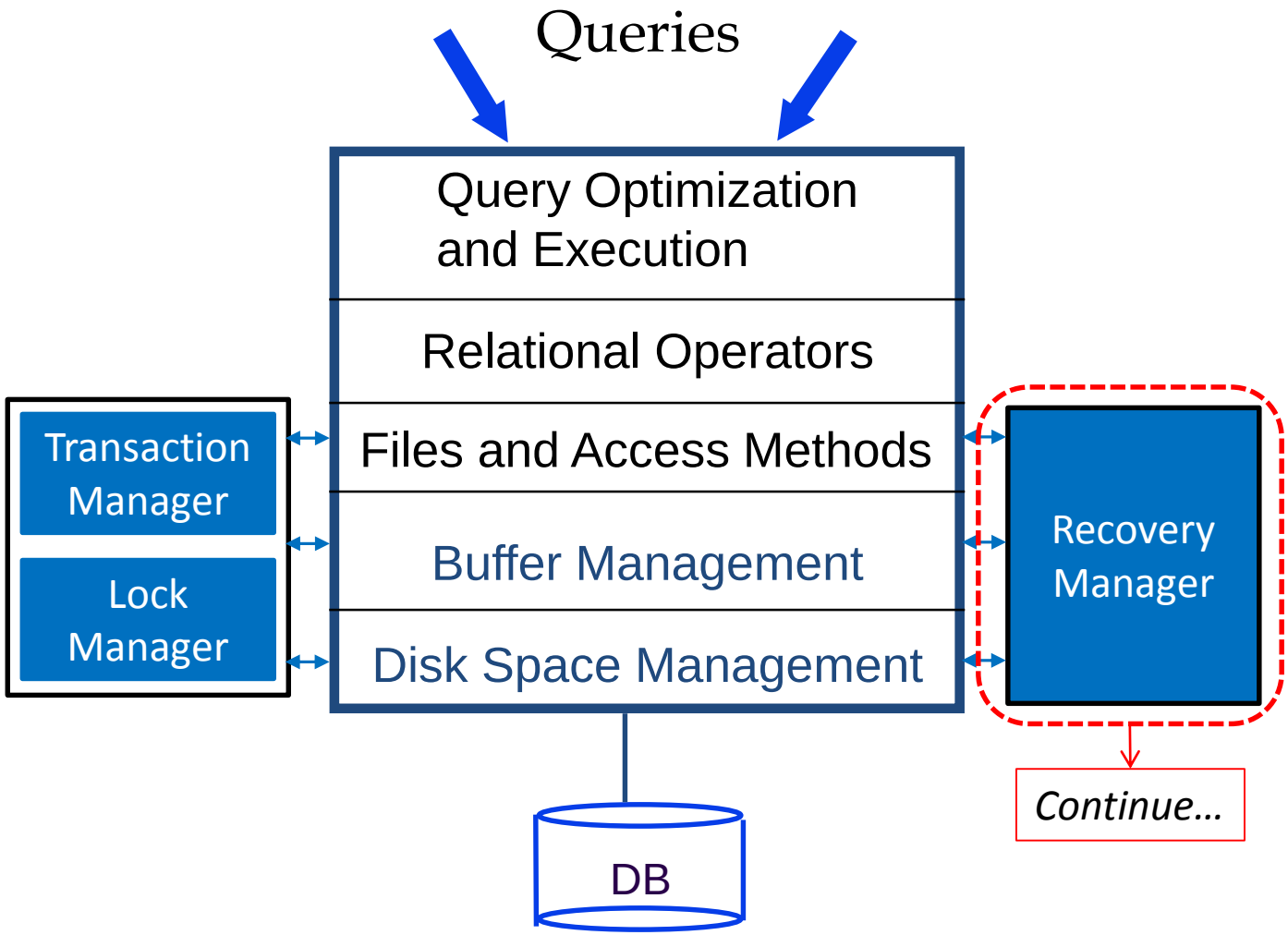
Today…

- Last Session:
  - Recovery Management

- Today's Session:
  - Recovery Management (*Cont'd*)

- Announcements:
  - The final exam is on Monday April 27th, from 8:30AM to 11:30AM in room 1190 (*all materials are included- open book, open notes*)
  - PS5 (the "last" assignment) is due on Thursday, April 23rd by midnight
  - P4: Write a survey on SQL vs. NoSQL databases (*optional*)- due on Friday, April 24th by midnight

DBMS Layers



Logging and the WAL Property

- In order to recover from failures, the recovery manager maintains a *log* of all modifications to the database on *stable storage* (which should survive crashes)

- After a failure, the DBMS "replays" the log to:
  - Redo committed transactions
  - Undo uncommitted transactions

- Caveat: A log record describing a change must be written to stable storage *before* the change is made
  - This is referred to as the *Write-Ahead Log* (*WAL*) *property*

The WAL Protocol

- WAL is the fundamental rule that ensures that a record of every change to the database is available after a crash

- What if a transaction made a change, committed, then a crash occurred (i.e., no log is kept "before" the crash)?
  - The *no-force approach* entails that this change may not have been written to disk before the crash
  - Without a record of this change, there would be no way to ensure that the committed transaction survives the crash
  - Hence, durability cannot be guaranteed!

To guarantee ***durability***, a record for every change must be written to stable storage *before the change is made*

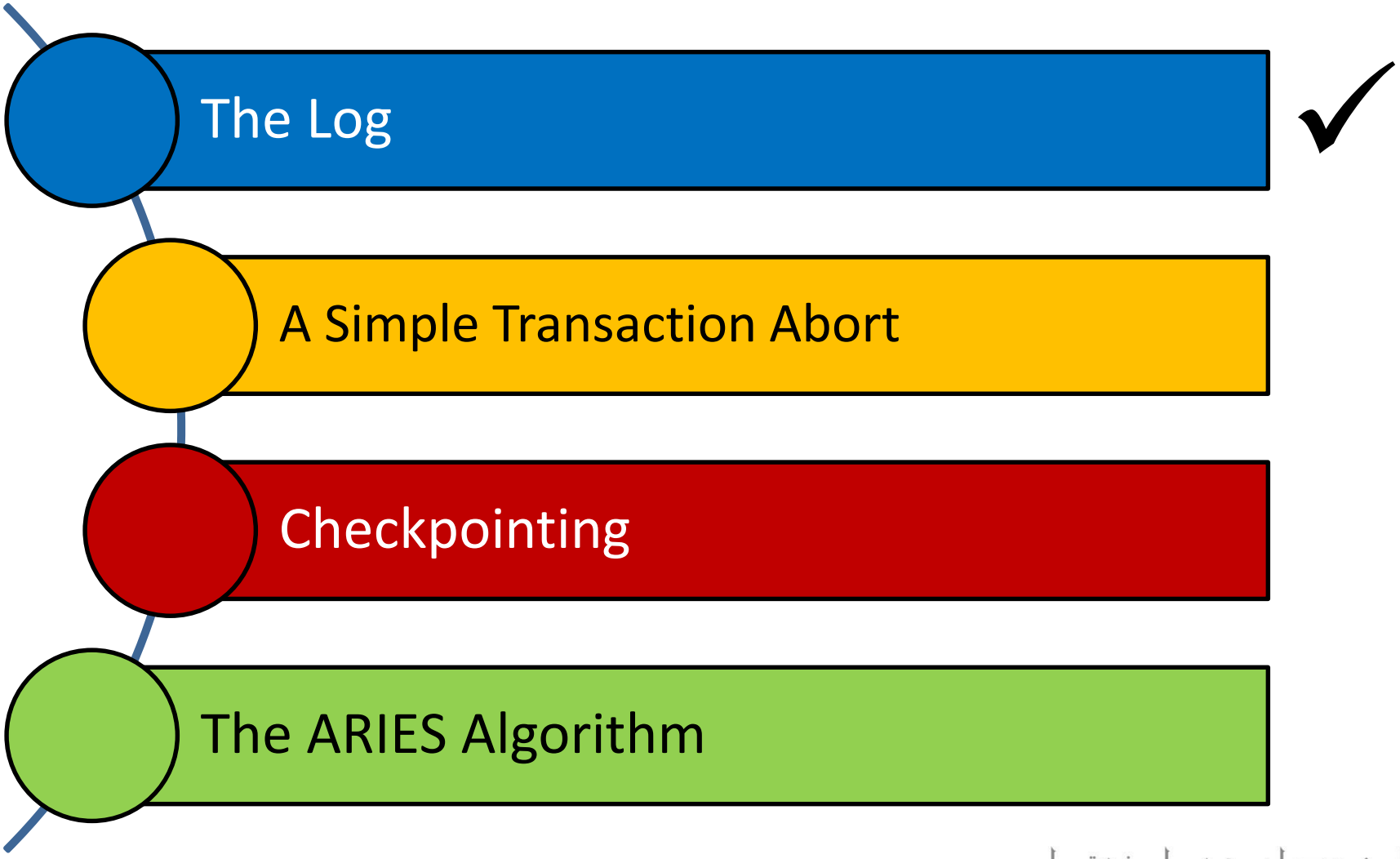
The WAL Protocol (*Cont'd*)

- WAL is the fundamental rule that ensures that a record of every change to the database is available after a crash

- What if a transaction made a change, was progressing, and a crash occurred?
  - The *steal approach* entails that this change may have been written to disk before the crash
  - Without a record of this change, there would be no way to ensure that the transaction can be rolled back (i.e., its effects would be unseen)
  - Hence, atomicity cannot be guaranteed!

To guarantee ***atomicity***, a record for every change must be written to stable storage *before the change is made*

Outline

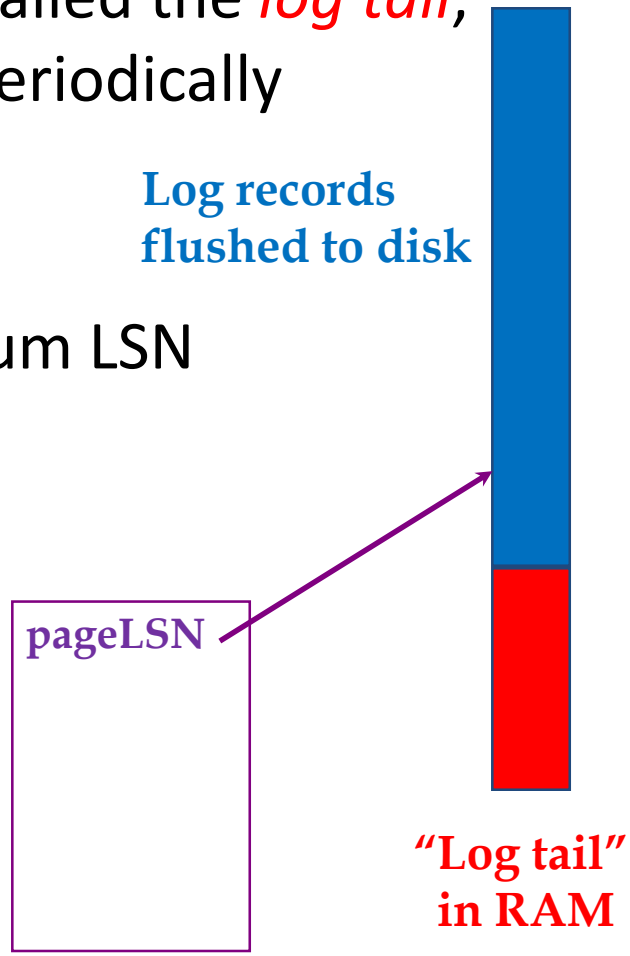


The Log

- The log is *a file of records* stored in stable storage
- Every log record is given a unique id called the Log Sequence Number (LSN)
  - LSNs are assigned in a monotonically increasing order (this is required by the ARIES recovery algorithm- *later*)
- Every page contains the LSN of the *most recent* log record, which describes a change to this page
  - This is called the pageLSN

The Log (*Cont'd*)

- The most recent portion of the log, called the *log tail*, is kept in main memory and *forced* periodically to disk
- The DBMS keeps track of the maximum LSN flushed to disk so far
  - This is called the flushedLSN
- As per the WAL protocol, before a page is written to disk, pageLSN ≤ flushedLSN



When to Write Log Records?

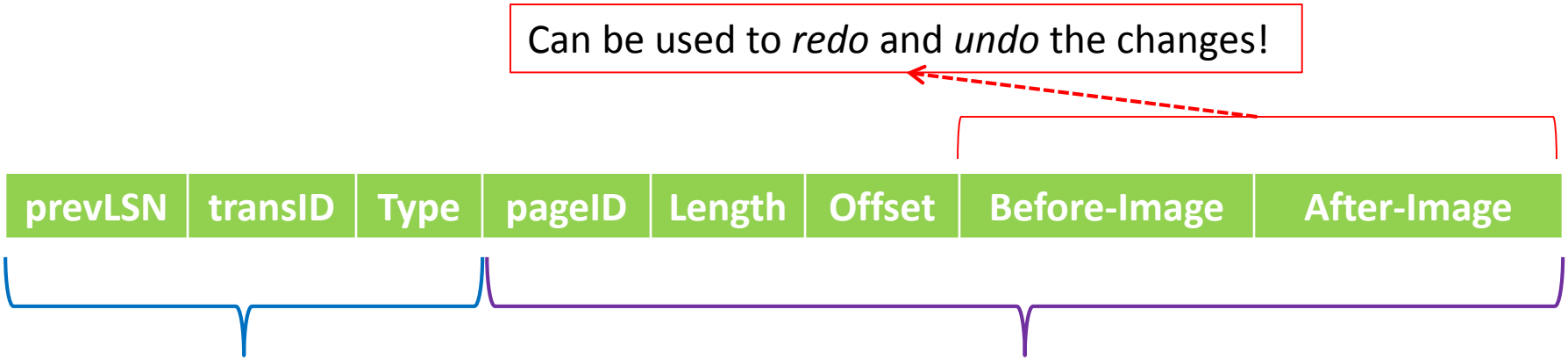
- A log record is written after:
  - Updating a Page
    - An *update log record* is appended to the log tail
    - The pageLSN of the page is set to the LSN of the update log record
  - Committing a Transaction
    - A *commit log record* is appended to the log tail
    - The log tail is written to stable storage, up to and including the commit log record
  - Aborting a Transaction
    - An *abort log record* is appended to the log tail
    - An undo is initiated for this transaction

When to Write Log Records?

- A log record is written after:
  - Ending (Aborting or Committing) a Transaction:
    - Additional steps are completed (*later*)
    - An *end log record* is appended to the log tail
  - Undoing an Update
    - When the action (described by an update log record) is undone, a *compensation log record* (CLR) is appended to the log tail
    - CLR describes the action taken to undo the action recorded in the corresponding update log record

Log Records

- The fields of a log record are usually as follows:



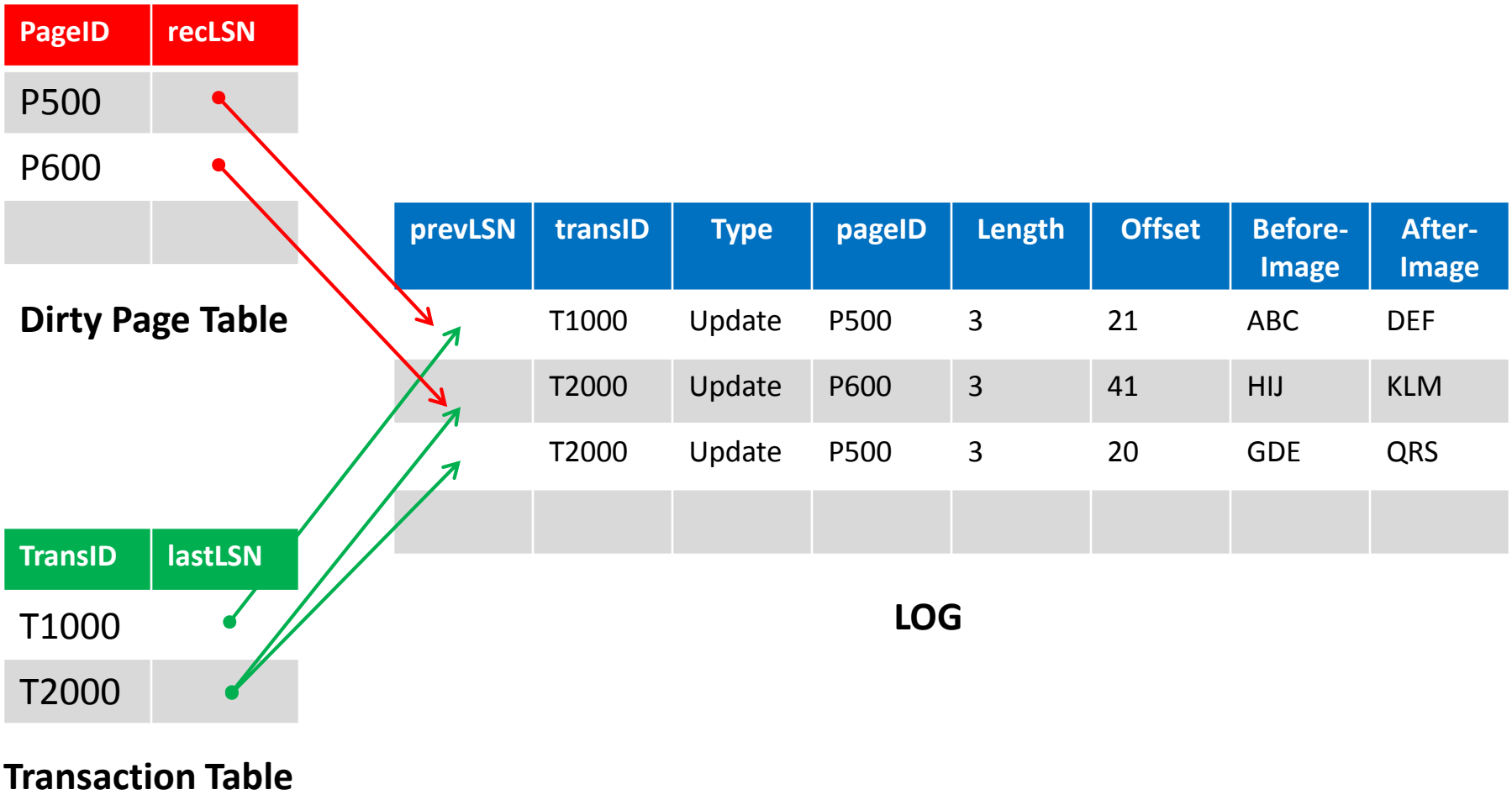
- Fields common to *all* log records:
  - Update Log Records
  - Commit Log Records
  - Abort Log Records
  - End Log Records
  - Compensation Log Records

Additional Fields for only the Update Log Records

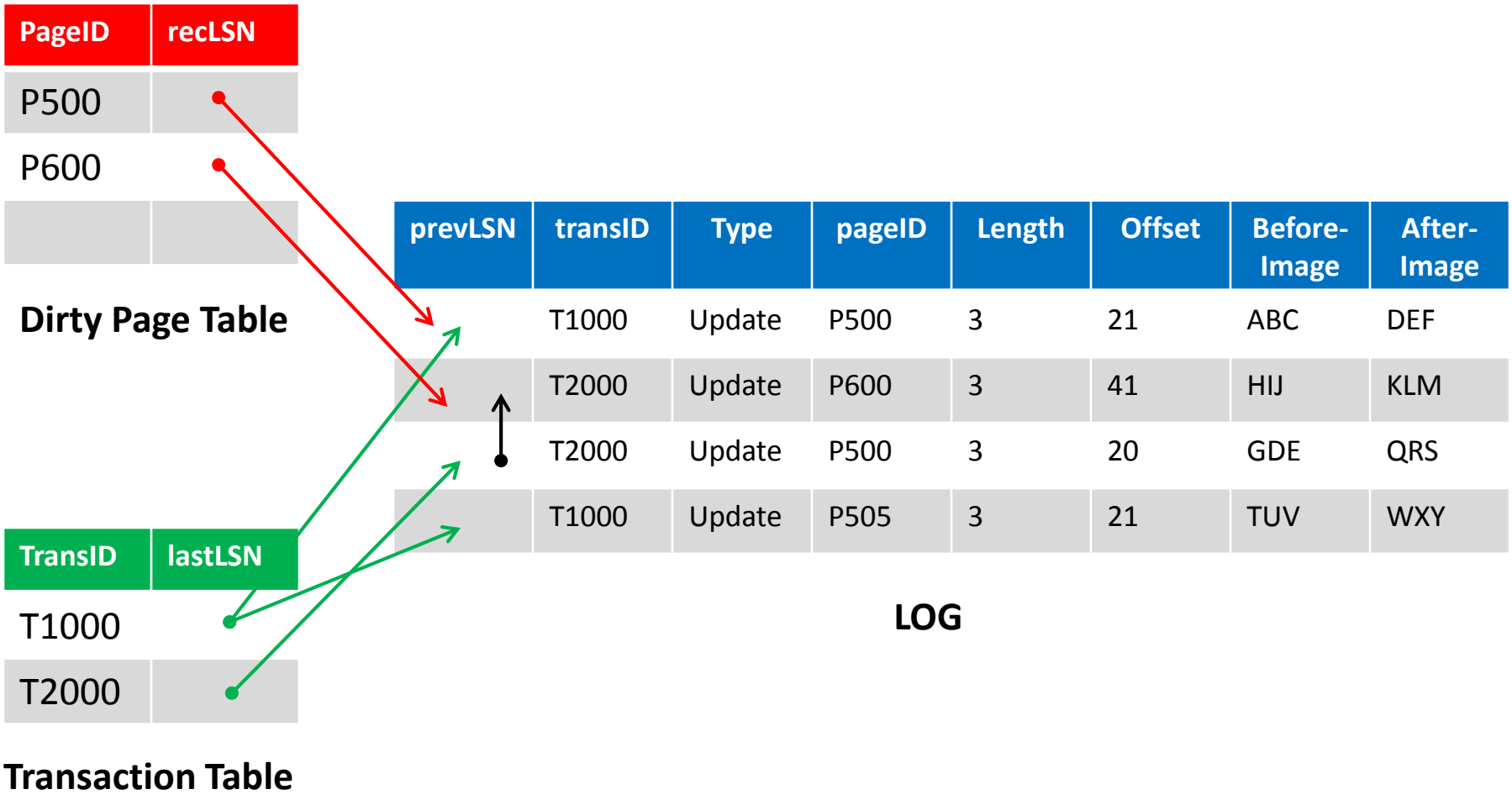
Other Recovery-Related Structures

- In addition to the log, the following two tables are maintained:
  - The Transaction Table
    - One entry ***E*** for each active transaction
    - ***E*** fields are:
      - *Transaction ID*
      - *Status*, which can be "*Progress*", "*Committed*" or "*Aborted*"
      - *lastLSN*, which is the most recent log record for this transaction
  - The Dirty Page Table
    - One entry ***E'*** for each dirty page in the buffer pool
    - ***E'*** fields are:
      - *Page ID*
      - *recLSN*, which is the LSN of the first log record that caused the page to become dirty

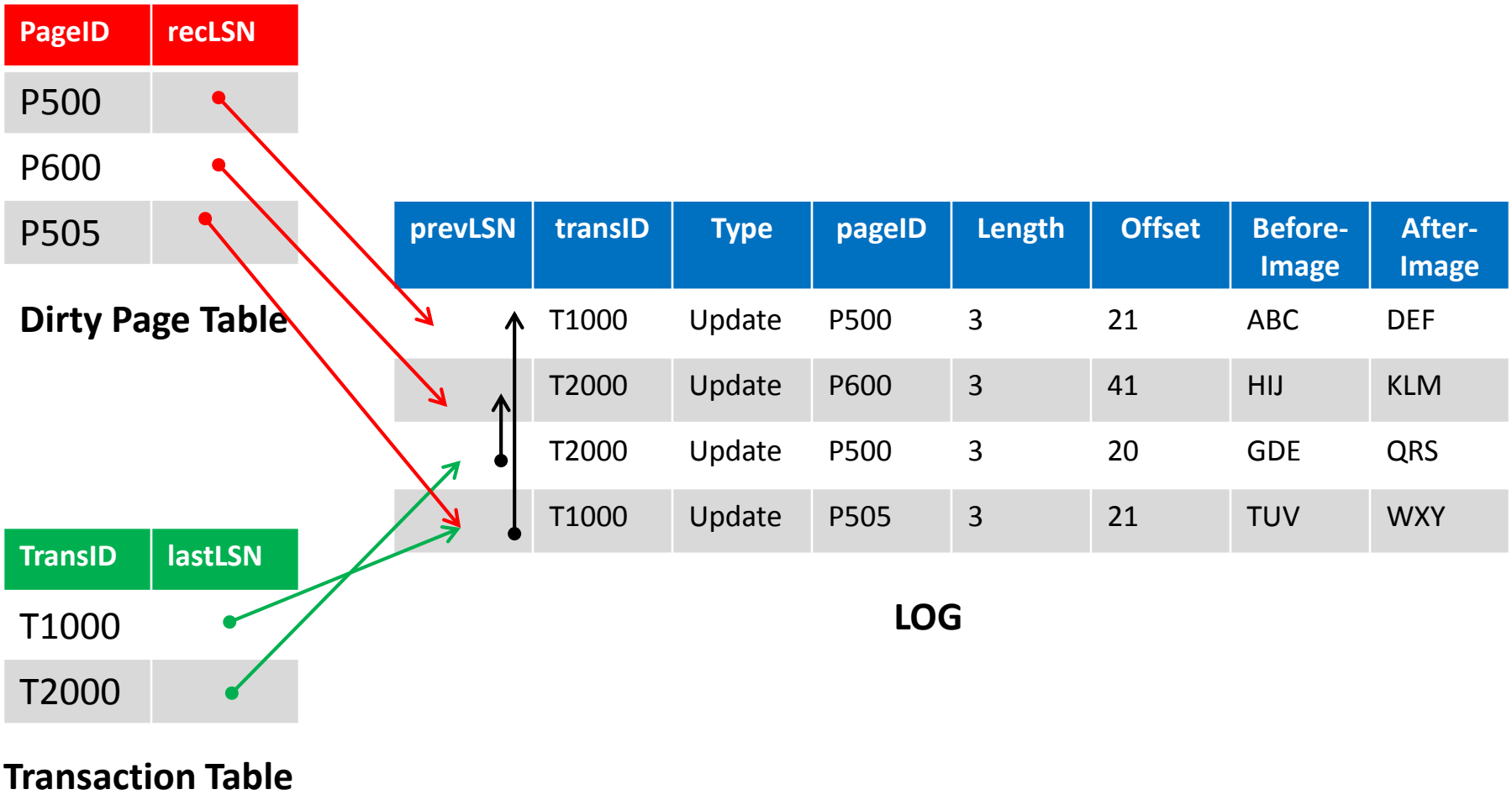
An Example


PageID
recLSN
P500
P600
Dirty Page Table
prevLSN
transID
Type
pageID
Length
Offset
Before-Image
After-Image
T1000
Update
P500
3
21
ABC
DEF
T2000
Update
P600
3
41
HIJ
KLM
T2000
Update
P500
3
20
GDE
QRS
LOG
TransID
lastLSN
T1000
T2000
Transaction Table

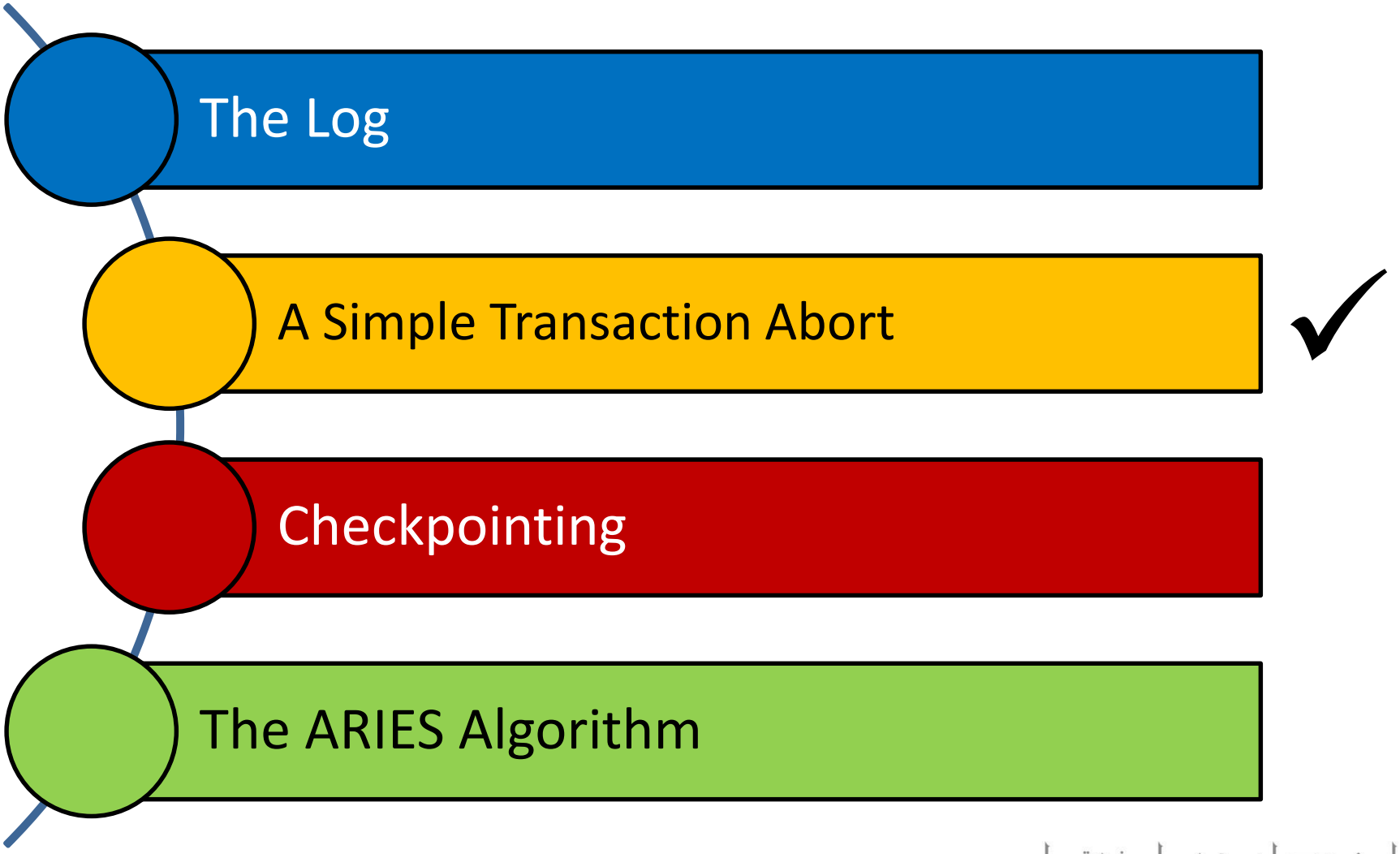
An Example


PageID
recLSN
P500
P600
Dirty Page Table
TransID
lastLSN
T1000
T2000
Transaction Table
prevLSN
transID
Type
pageID
Length
Offset
Before-Image
After-Image
T1000 Update P500 3 21 ABC DEF
T2000 Update P600 3 41 HIJ KLM
T2000 Update P500 3 20 GDE QRS
T1000 Update P505 3 21 TUV WXY
LOG

An Example


PageID
recLSN
P500
P600
P505
Dirty Page Table
TransID
lastLSN
T1000
T2000
Transaction Table
prevLSN
transID
Type
pageID
Length
Offset
Before-Image
After-Image
T1000 Update P500 3 21 ABC DEF
T2000 Update P600 3 41 HIJ KLM
T2000 Update P500 3 20 GDE QRS
T1000 Update P505 3 21 TUV WXY
LOG

Outline



A Simple Transaction Abort

- For now, let us consider an "explicit" abort of a transaction ***T***
  - That is, no system crash is involved

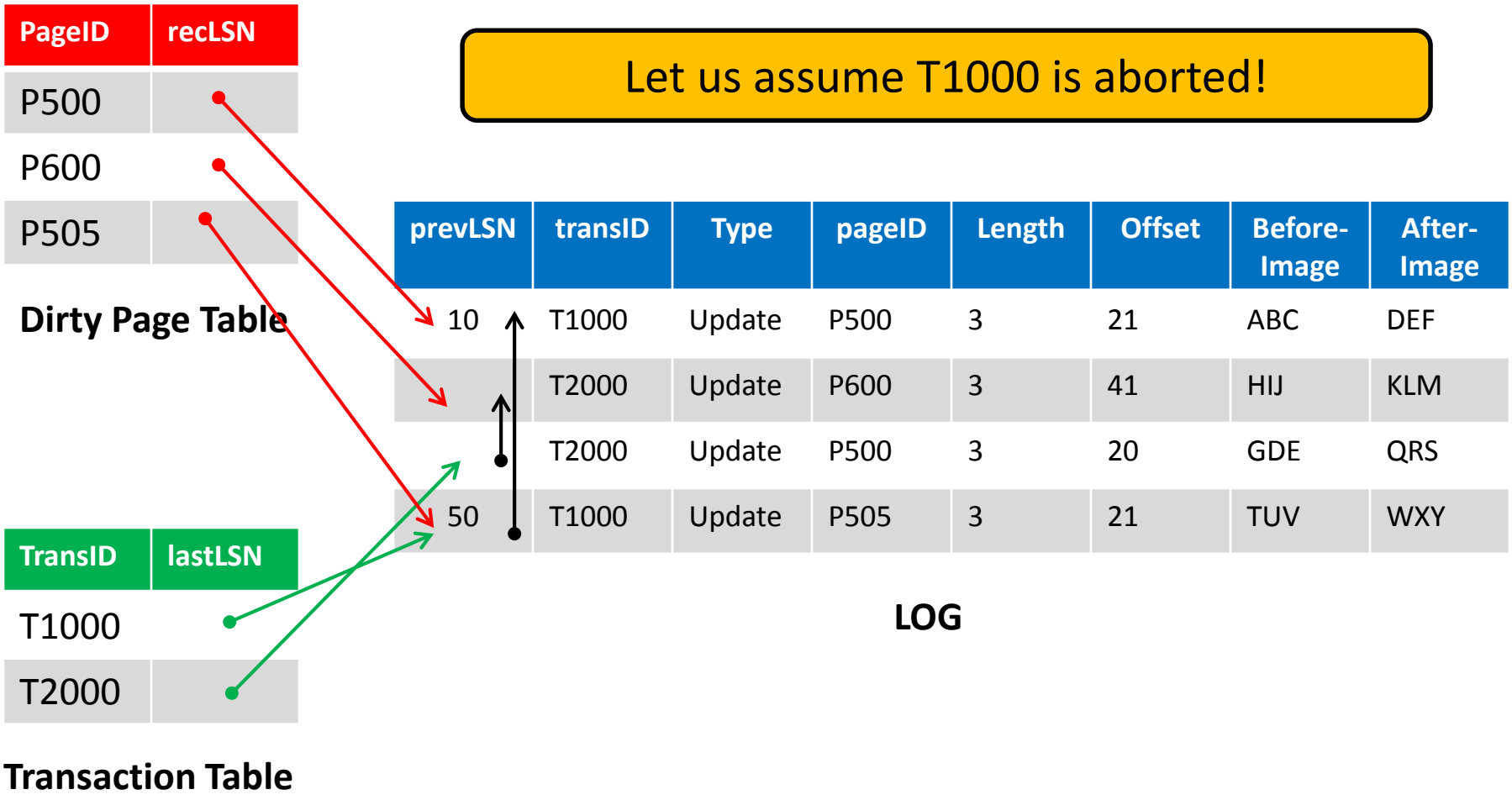
- We want to "play back" the log in reverse order, *undoing* ***T***'s updates
  - Step 1: We get the *lastLSN* of ***T*** from the Transaction table

  - Step 2: We lock the corresponding data to be undone (we can use strict 2PL)

A Simple Transaction Abort (*Cont'd*)

- Step 3: before restoring an old value of a page, we write a respective *Compensation Log Record* (CLR)
  - CLR has one extra field, that is, *undoNextLSN*, which points to the next LSN to undo
    - That is, the *prevLSN* of the record we are currently undoing
  - CLRs are *never* undone (but they might be Redone)
- Step 4: repeat steps 2 and 3 by following a *chain* of log records backward via the *prevLSN* field
- Last Step: at the end of UNDO, write an *end log record*

An Example


PageID
recLSN
P500
P600
P505
Dirty Page Table
Let us assume T1000 is aborted!
prevLSN
transID
Type
pageID
Length
Offset
Before-Image
After-Image
10
T1000
Update
P500
3
21
ABC
DEF
T2000
Update
P600
3
41
HIJ
KLM
T2000
Update
P500
3
20
GDE
QRS
50
T1000
Update
P505
3
21
TUV
WXY
LOG
TransID
lastLSN
T1000
T2000
Transaction Table

An Example

PageID	recLSN
P500	
P600	
P505	

Dirty Page Table

TransID	lastLSN
T1000	
T2000	

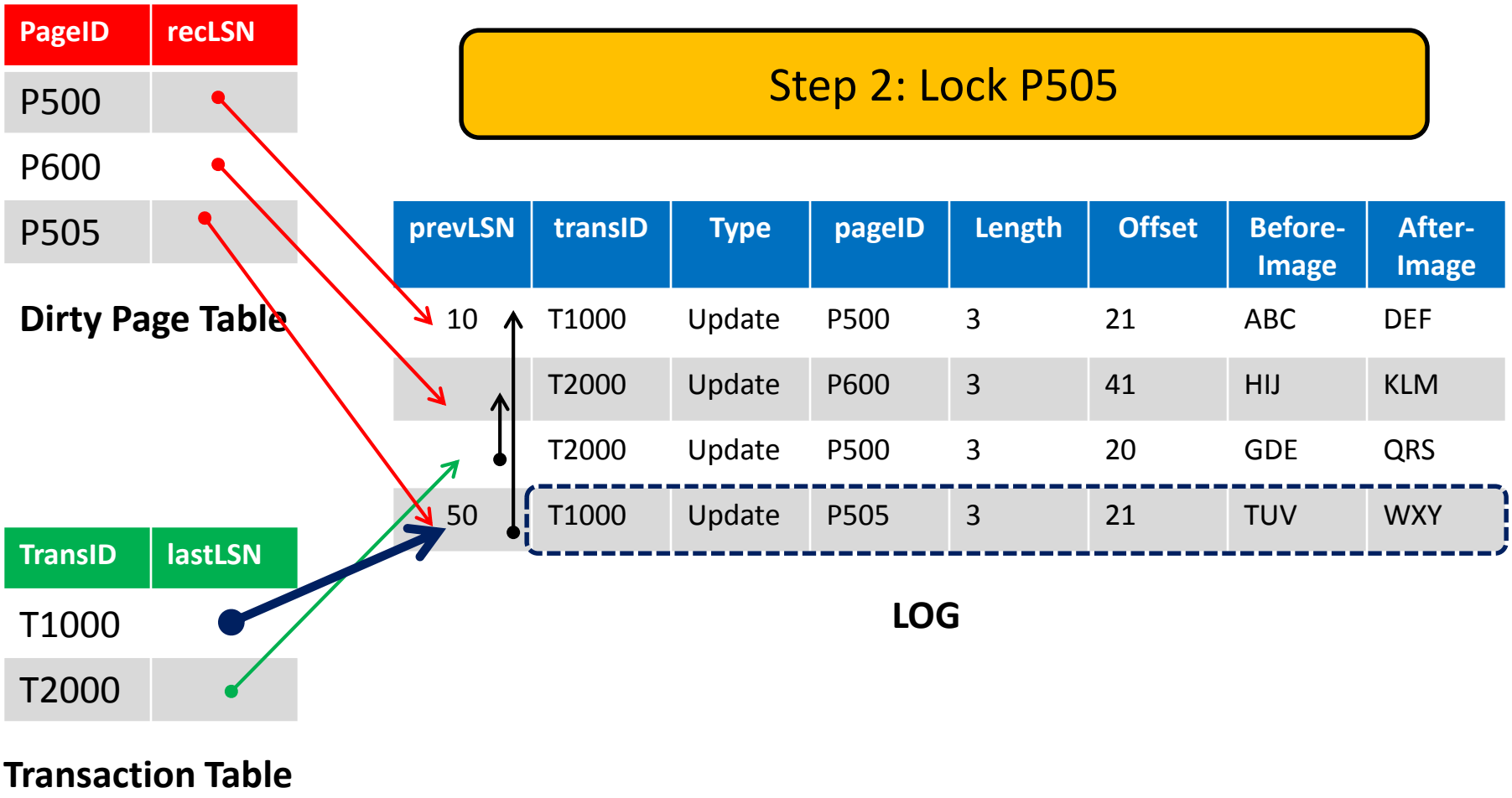
Transaction Table

Step 1: Get the lastLSN of T1000 from the Transaction table

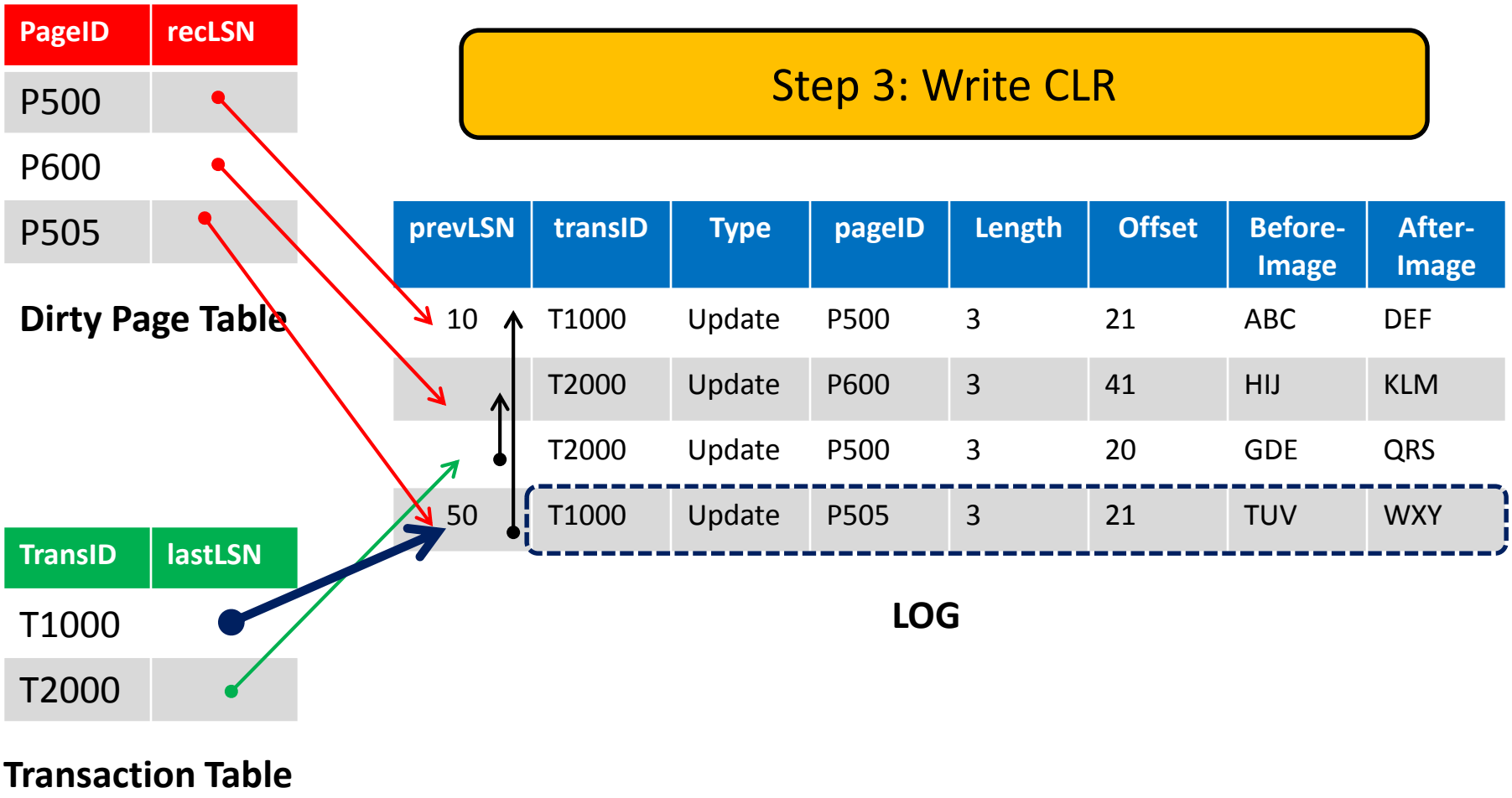
prevLSN	transID	Type	pageID	Length	Offset	Before-Image	After-Image
10	T1000	Update	P500	3	21	ABC	DEF
	T2000	Update	P600	3	41	HIJ	KLM
	T2000	Update	P500	3	20	GDE	QRS
50	T1000	Update	P505	3	21	TUV	WXY

LOG

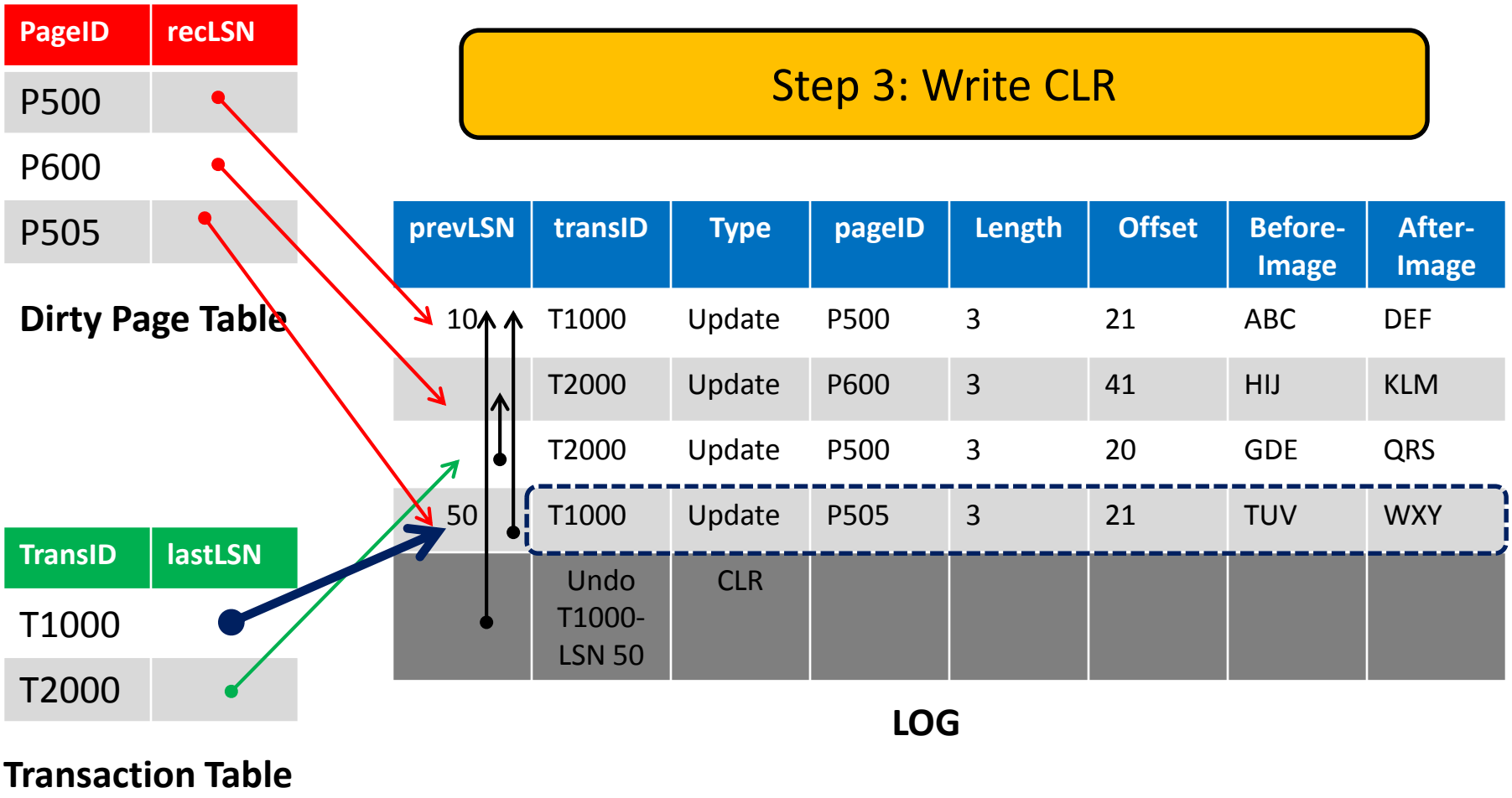
An Example


PageID
recLSN
P500
P600
P505
Dirty Page Table
Step 2: Lock P505
prevLSN
transID
Type
pageID
Length
Offset
Before-Image
After-Image
10
T1000
Update
P500
3
21
ABC
DEF
T2000
Update
P600
3
41
HIJ
KLM
T2000
Update
P500
3
20
GDE
QRS
50
T1000
Update
P505
3
21
TUV
WXY
LOG
TransID
lastLSN
T1000
T2000
Transaction Table

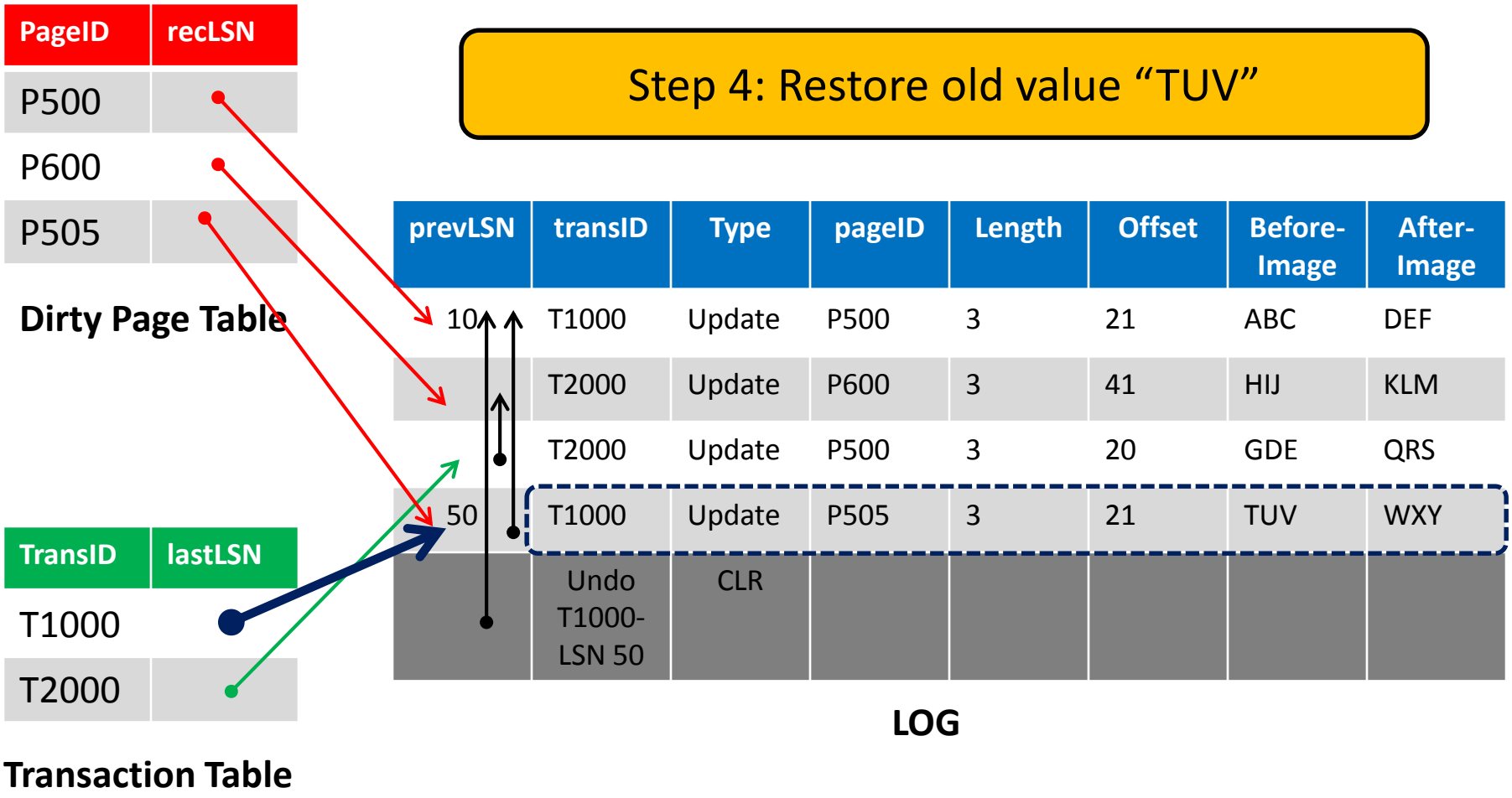
An Example


PageID
recLSN
P500
P600
P505
Dirty Page Table
Step 3: Write CLR
prevLSN
transID
Type
pageID
Length
Offset
Before-Image
After-Image
10
T1000
Update
P500
3
21
ABC
DEF
T2000
Update
P600
3
41
HIJ
KLM
T2000
Update
P500
3
20
GDE
QRS
50
T1000
Update
P505
3
21
TUV
WXY
LOG
TransID
lastLSN
T1000
T2000
Transaction Table

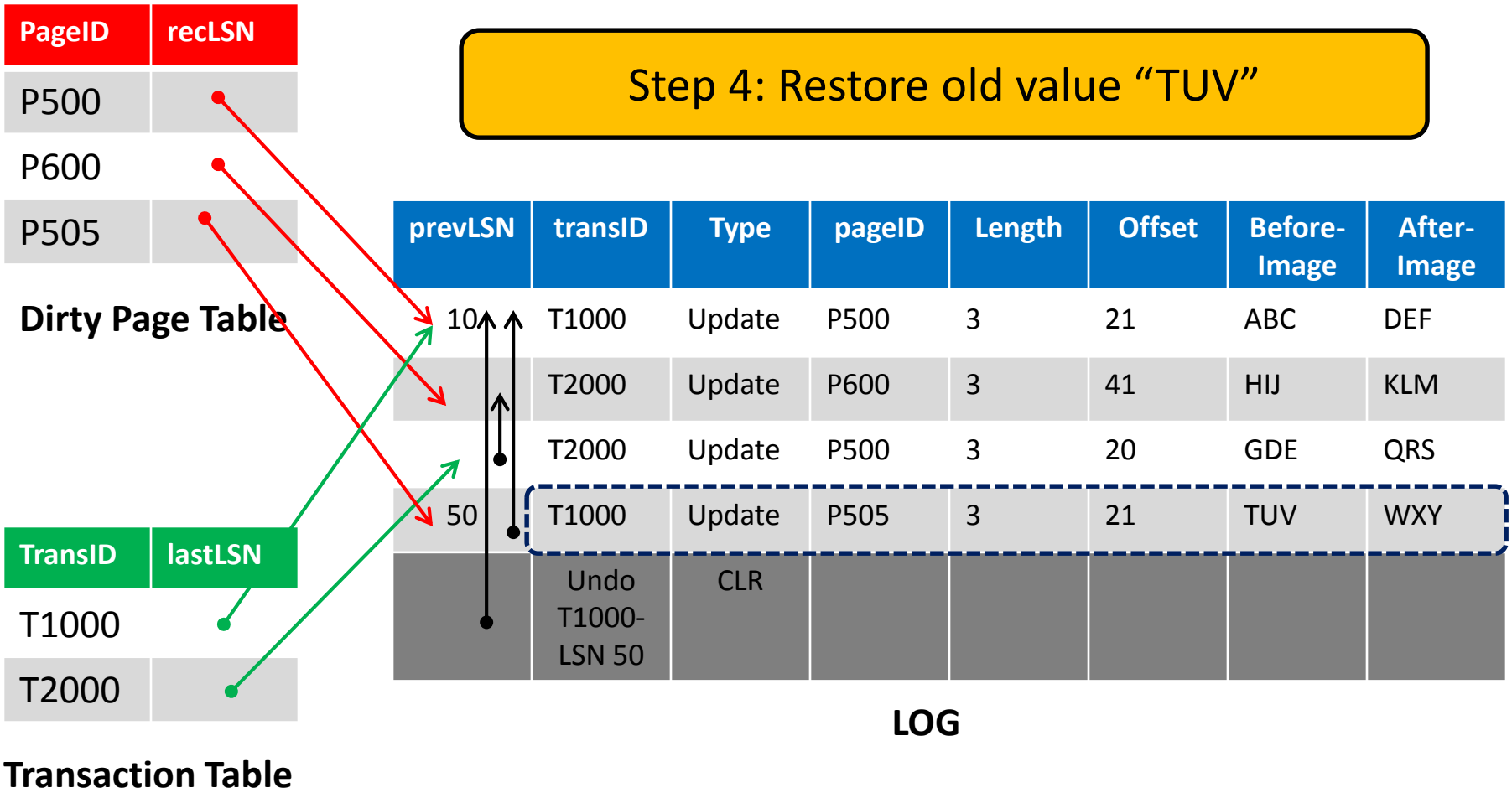
An Example


PageID
recLSN
P500
P600
P505
Dirty Page Table
Step 3: Write CLR
prevLSN
transID
Type
pageID
Length
Offset
Before-Image
After-Image
10
T1000
Update
P500
3
21
ABC
DEF
T2000
Update
P600
3
41
HIJ
KLM
T2000
Update
P500
3
20
GDE
QRS
50
T1000
Update
P505
3
21
TUV
WXY
Undo T1000-LSN 50
CLR
LOG
TransID
lastLSN
T1000
T2000
Transaction Table

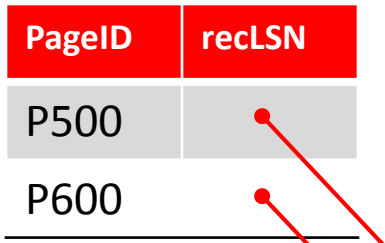
An Example


PageID
recLSN
P500
P600
P505
Dirty Page Table
Step 4: Restore old value “TUV”
prevLSN
transID
Type
pageID
Length
Offset
Before-Image
After-Image
10
T1000
Update
P500
3
21
ABC
DEF
T2000
Update
P600
3
41
HIJ
KLM
T2000
Update
P500
3
20
GDE
QRS
50
T1000
Update
P505
3
21
TUV
WXY
Undo T1000-LSN 50
CLR
LOG
TransID
lastLSN
T1000
T2000
Transaction Table

An Example

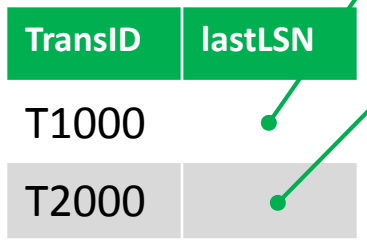

PageID
recLSN
P500
P600
P505
Dirty Page Table
Step 4: Restore old value “TUV”
prevLSN
transID
Type
pageID
Length
Offset
Before-Image
After-Image
10
T1000
Update
P500
3
21
ABC
DEF
T2000
Update
P600
3
41
HIJ
KLM
T2000
Update
P500
3
20
GDE
QRS
50
T1000
Update
P505
3
21
TUV
WXY
Undo T1000-LSN 50
CLR
LOG
TransID
lastLSN
T1000
T2000
Transaction Table

An Example



PageID	recLSN
P500	
P600	

Dirty Page Table



TransID	lastLSN
T1000	
T2000	

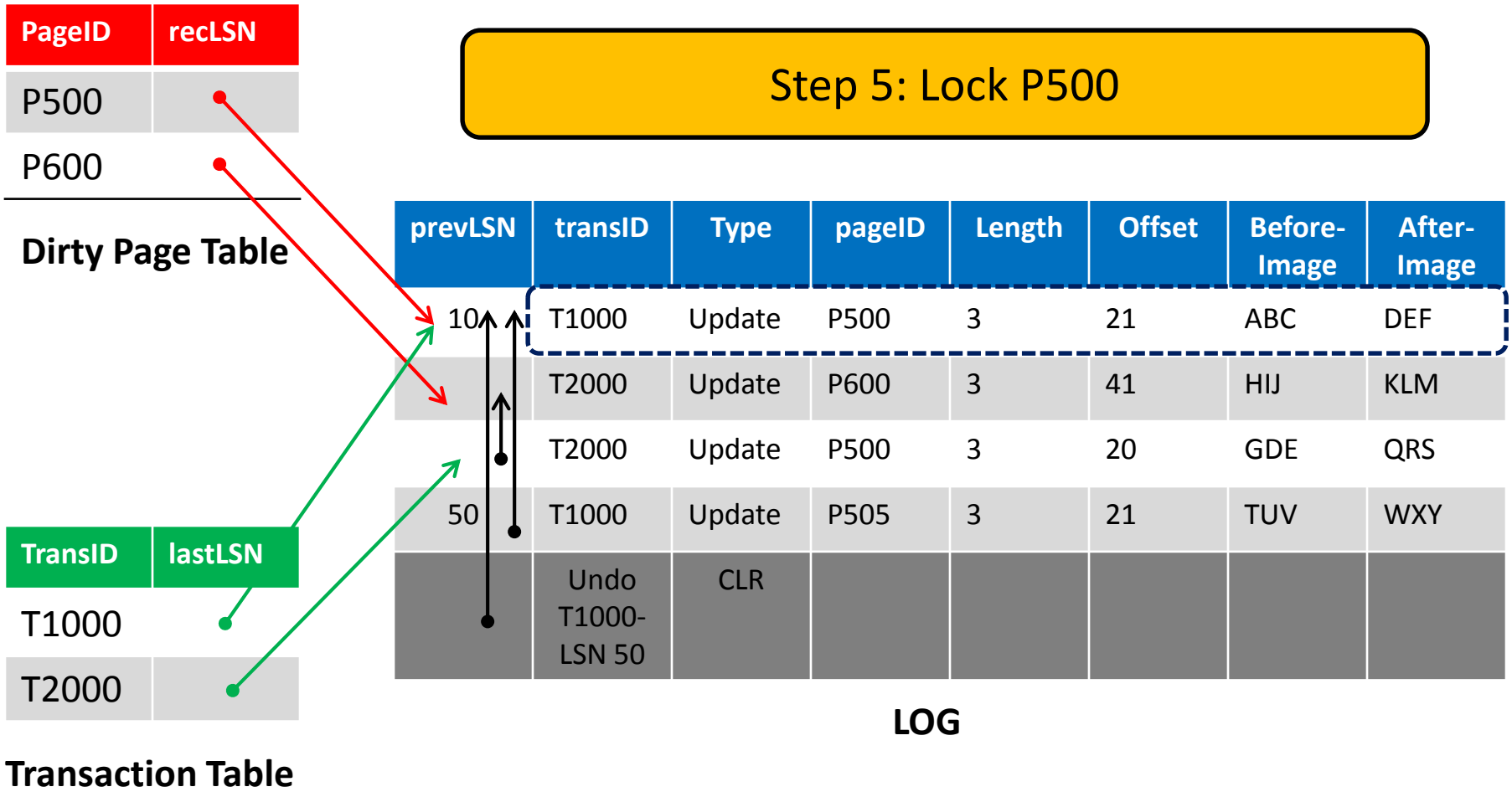
Transaction Table

Step 4: Restore old value “TUV”

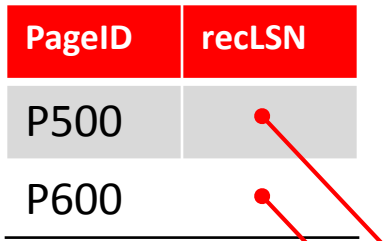
prevLSN	transID	Type	pageID	Length	Offset	Before-Image	After-Image
10	T1000	Update	P500	3	21	ABC	DEF
	T2000	Update	P600	3	41	HIJ	KLM
	T2000	Update	P500	3	20	GDE	QRS
50	T1000	Update	P505	3	21	TUV	WXY
	Undo T1000-LSN 50	CLR					

LOG

An Example

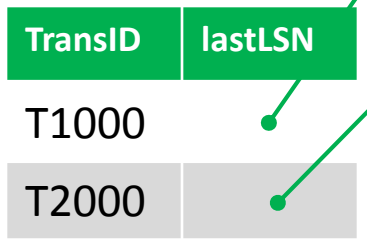

PageID
recLSN
P500
P600
Dirty Page Table
Step 5: Lock P500
prevLSN
transID
Type
pageID
Length
Offset
Before-Image
After-Image
10
T1000
Update
P500
3
21
ABC
DEF
T2000
Update
P600
3
41
HIJ
KLM
T2000
Update
P500
3
20
GDE
QRS
50
T1000
Update
P505
3
21
TUV
WXY
Undo T1000-LSN 50
CLR
LOG
TransID
lastLSN
T1000
T2000
Transaction Table

An Example



PageID	recLSN
P500	
P600	

Dirty Page Table



TransID	lastLSN
T1000	
T2000	

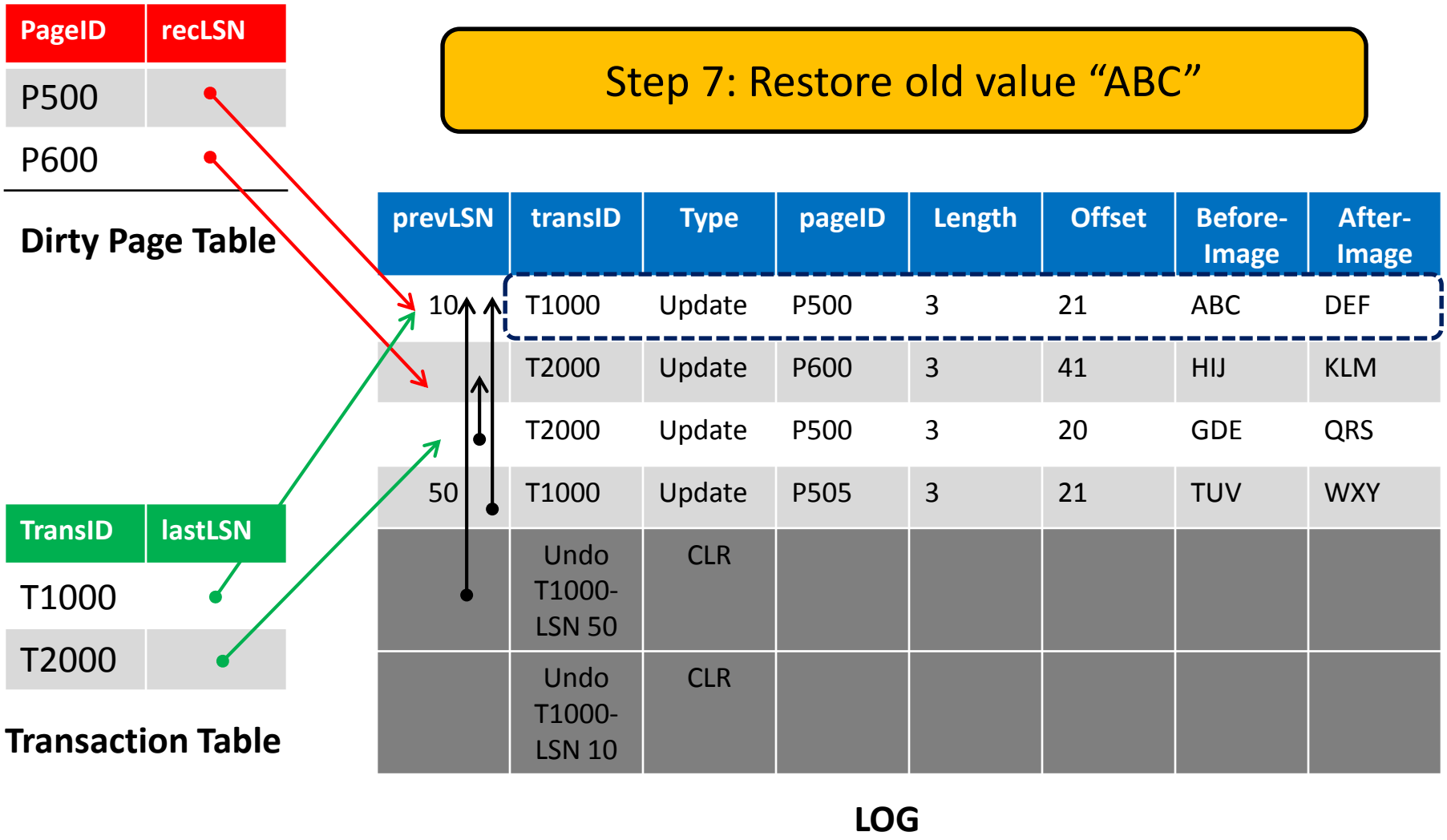
Transaction Table

Step 6: Write CLR

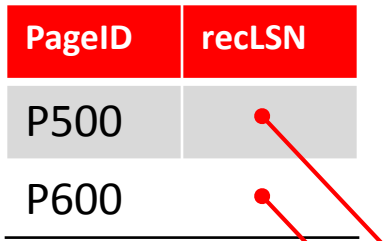
prevLSN	transID	Type	pageID	Length	Offset	Before-Image	After-Image
10	T1000	Update	P500	3	21	ABC	DEF
	T2000	Update	P600	3	41	HIJ	KLM
	T2000	Update	P500	3	20	GDE	QRS
50	T1000	Update	P505	3	21	TUV	WXY
	Undo T1000-LSN 50	CLR					
	Undo T1000-LSN 10	CLR					

LOG

An Example

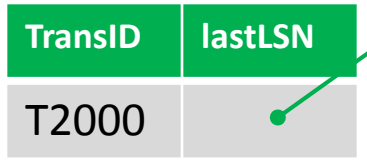

PageID
recLSN
P500
P600
Dirty Page Table
TransID
lastLSN
T1000
T2000
Transaction Table
Step 7: Restore old value “ABC”
prevLSN
transID
Type
pageID
Length
Offset
Before-Image
After-Image
10
T1000
Update
P500
3
21
ABC
DEF
T2000
Update
P600
3
41
HIJ
KLM
T2000
Update
P500
3
20
GDE
QRS
50
T1000
Update
P505
3
21
TUV
WXY
Undo T1000-LSN 50
CLR
Undo T1000-LSN 10
CLR
LOG

An Example



PageID	recLSN
P500	
P600	

Dirty Page Table



TransID	lastLSN
T2000	

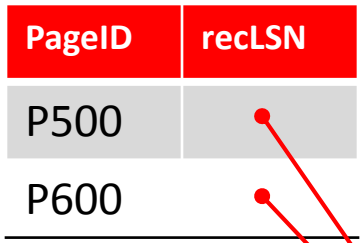
Transaction Table

Step 7: Restore old value “ABC”

prevLSN	transID	Type	pageID	Length	Offset	Before-Image	After-Image
10	T1000	Update	P500	3	21	ABC	DEF
	T2000	Update	P600	3	41	HIJ	KLM
	T2000	Update	P500	3	20	GDE	QRS
50	T1000	Update	P505	3	21	TUV	WXY
	Undo T1000-LSN 50	CLR					
	Undo T1000-LSN 10	CLR					

LOG

An Example



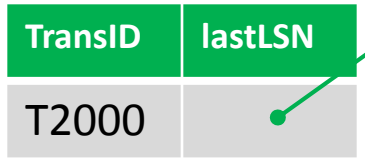
PageID	recLSN
P500	
P600	

Dirty Page Table

Step 7: Restore old value “ABC”

prevLSN	transID	Type	pageID	Length	Offset	Before-Image	After-Image
10	T1000	Update	P500	3	21	ABC	DEF
	T2000	Update	P600	3	41	HIJ	KLM
	T2000	Update	P500	3	20	GDE	QRS
50	T1000	Update	P505	3	21	TUV	WXY
	Undo T1000-LSN 50	CLR					
	Undo T1000-LSN 10	CLR					

LOG



TransID	lastLSN
T2000	

Transaction Table

An Example

PageID	recLSN
P500	
P600	

Dirty Page Table

TransID	lastLSN
T2000	

Transaction Table

Step 8: Write an end log record

prevLSN	transID	Type	pageID	Length	Offset	Before-Image	After-Image
10	T1000	Update	P500	3	21	ABC	DEF
	T2000	Update	P600	3	41	HIJ	KLM
	T2000	Update	P500	3	20	GDE	QRS
50	T1000	Update	P505	3	21	TUV	WXY
	Undo T1000-LSN 50	CLR					
	Undo T1000-LSN 10	CLR					

LOG

An Example

PageID	recLSN
P500	
P600	

Dirty Page Table

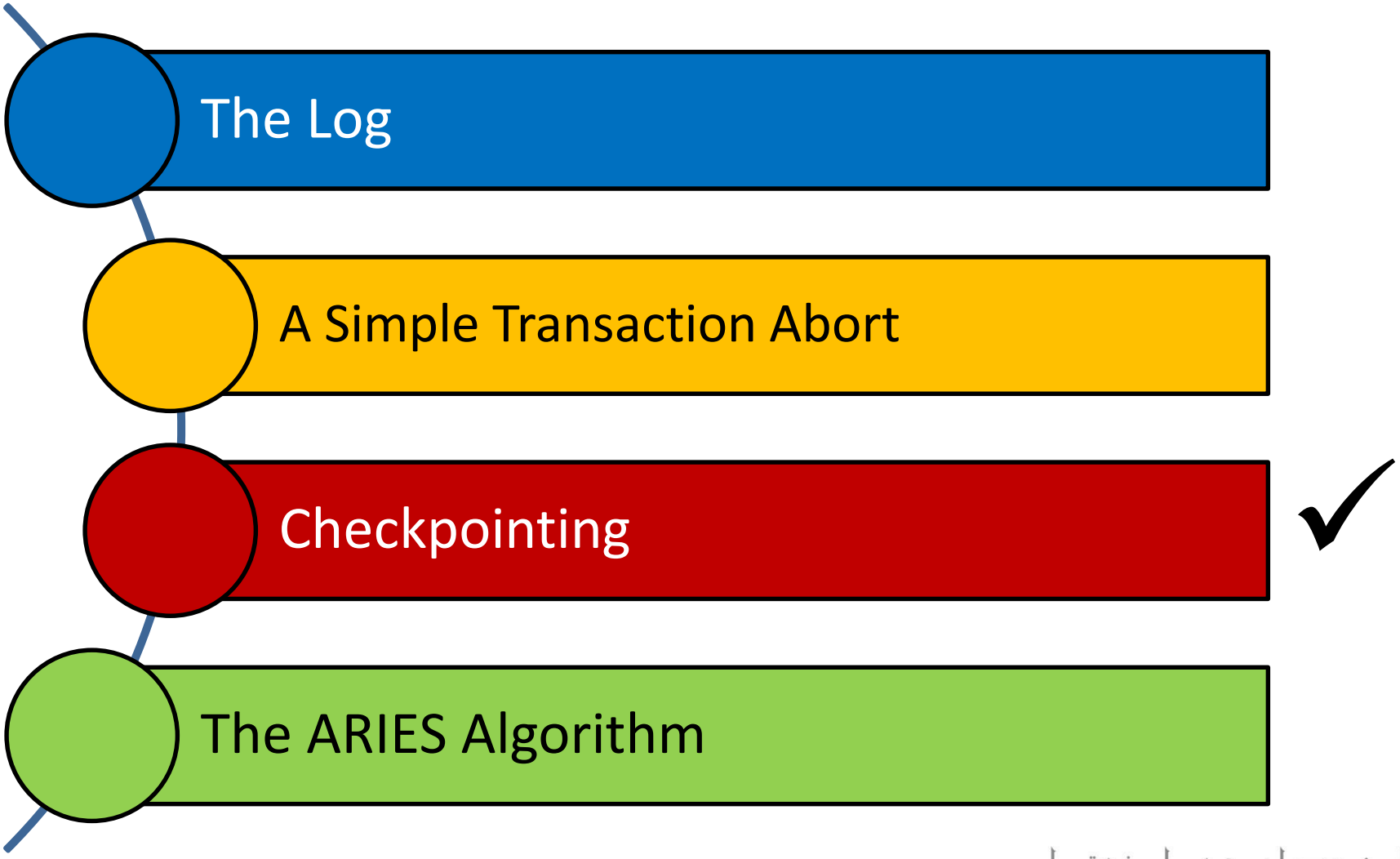
TransID	lastLSN
T2000	

Transaction Table

Step 8: Write an end log record

prevLSN	transID	Type	pageID	Length	Offset	Before-Image	After-Image
10	T1000	Update	P500	3	21	ABC	DEF
	T2000	Update	P600	3	41	HIJ	KLM
	T2000	Update	P500	3	20	GDE	QRS
50	T1000	Update	P505	3	21	TUV	WXY
	Undo T1000-LSN 50	CLR					
	Undo T1000-LSN 10	CLR					
	T1000 End-LSN 10	END					

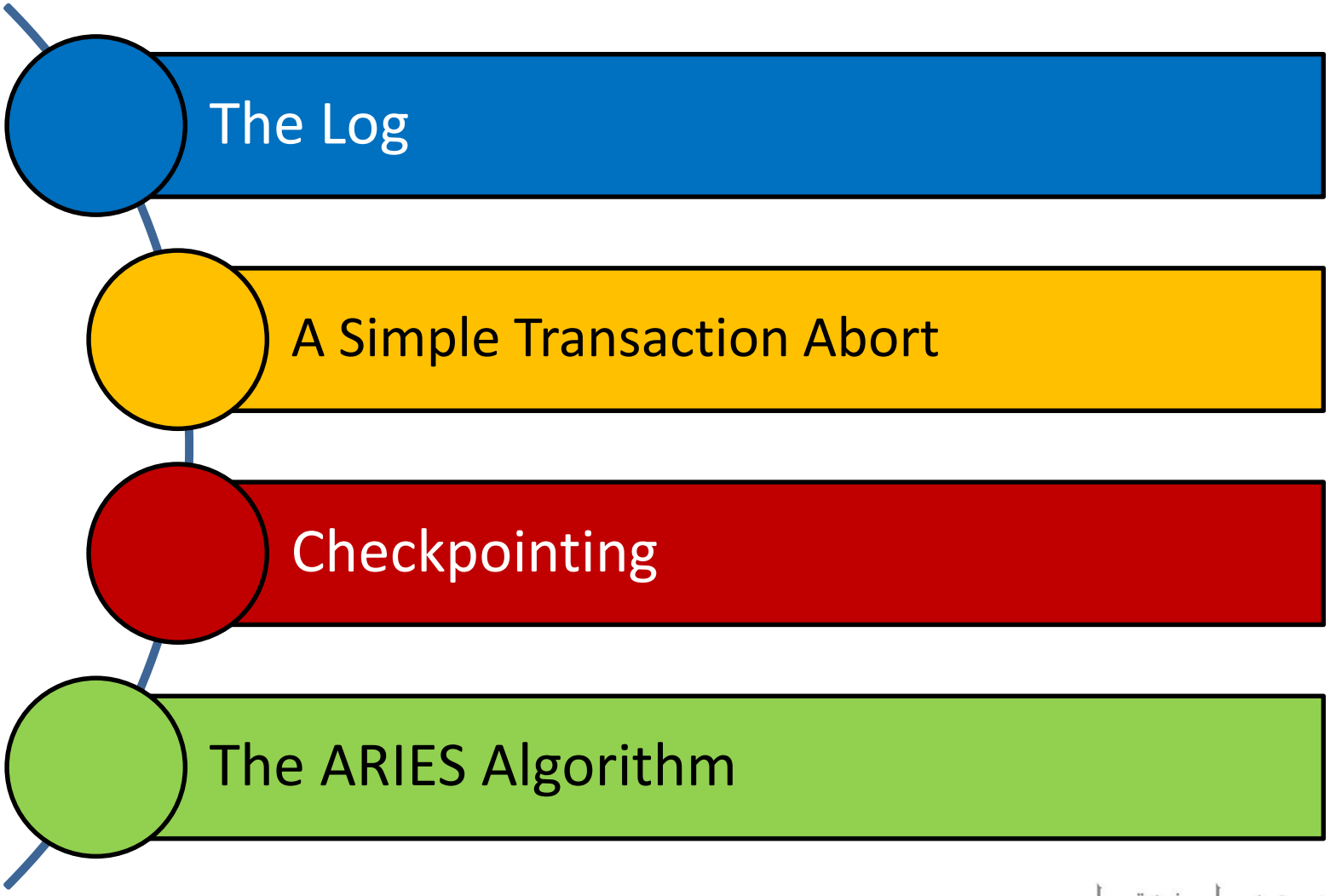
Outline



Checkpointing

- To reduce the amount of work to do during recovery, DBMSs typically take *checkpoints*
- A checkpoint is like a *snapshot of a DBMS state*
- A checkpoint can be taken by writing to the log:
  - A begin_checkpoint record
    - This indicates the start of the checkpoint
  - An end_checkpoint record
    - This indicates the end of the checkpoint
    - It includes the contents of the Transaction and the Dirty Page tables
  - A master record
    - This contains the LSN of the begin_checkpoint record

Outline

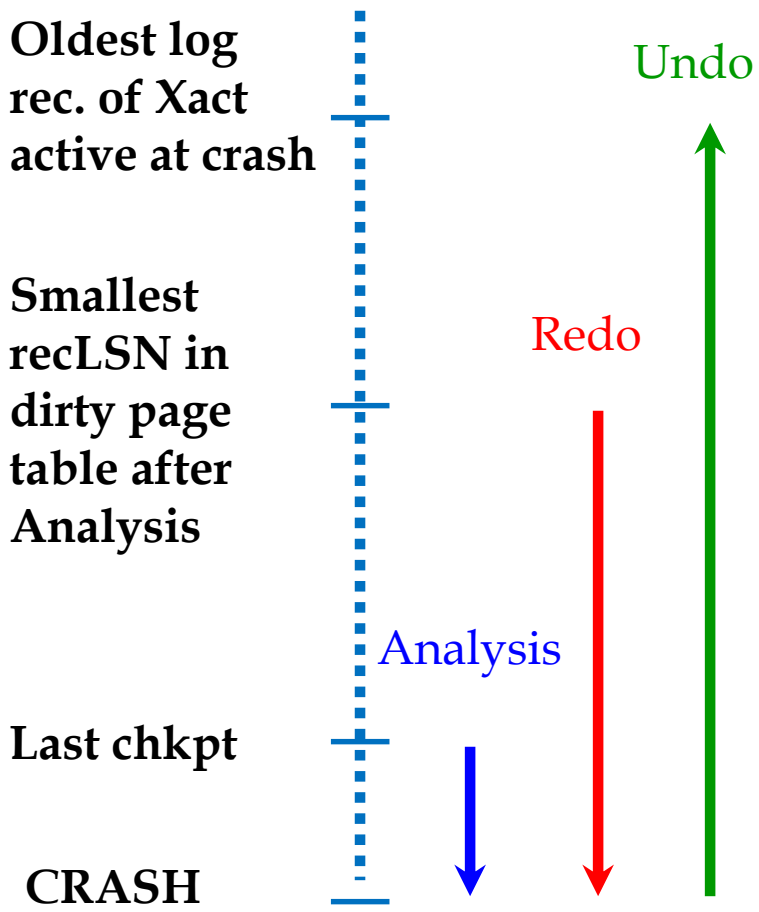


Recovering From a System Crash: ARIES

- We will study the ARIES algorithm for recovering from system crashes
- ARIES is designed to work with a steal, no-force approach
- When the recovery manager is invoked after a crash, restart proceeds in three phases:
  - Analysis
  - Redo
  - Undo

Recovering From a System Crash: ARIES

- The Analysis Phase:
  - Identifies dirty pages in the buffer pool and active transactions at the time of the crash
- The Redo Phase:
  - Redoes *all* actions
- The Undo Phase:
  - Undoes the actions of transactions that were active and did not commit



ARIES: The Analysis Phase

- The Analysis phase encompasses two main steps:
  - Step 1: Reconstruct state (i.e., Dirty Page and Transaction tables) via the *end_checkpoint* record, after the most recent *begin_checkpoint* record
  - Step 2: Scan the log in the forward direction, starting after the checkpoint
    - If an *end log record* is encountered
      - Remove the corresponding transaction from the Transaction table

ARIES: The Analysis Phase

- The Analysis phase encompasses two main steps:
  - Step 2 (*Cont'd*):
    - If any other record is encountered
      - Add the corresponding transaction to the Transaction table (*if it is not already there*)
      - Set lastLSN to the LSN of the record
      - Set status to ***C*** for committed transactions, or to ***U*** (i.e., Undo), otherwise
    - When an *update log record* is encountered
      - If the recorded page, ***P***, is not in the Dirty Page table
        - Add ***P*** to the Dirty Page table and set its recLSN to the LSN of the log record

ARIES: The Analysis Phase

- At the end of the Analysis phase:
  - The Transaction table contains an “accurate” list of all transactions that were active at the time of the crash
  - The Dirty Page table contains all pages that were dirty at the time of the crash
    - These pages may contain some pages that were written to disk (why?)– Not a Problem!

ARIES: The Redo Phase

- During the Redo phase, ARIES reapplies the updates of "all" transactions (i.e., *committed* and *aborted*)
  - This paradigm is referred to as *Repeating History*

- The Redo phase scans forward until the end of the log, and redoes every action unless:
  - The affected page is not in the Dirty Page table
  - The affected page is in the Dirty Page table, but its recLSN > the current record's LSN
  - The pageLSN of the affected page >= the current record's LSN

Wouldn't checking this be enough?

ARIES: The Redo Phase

- During the Redo phase, ARIES reapplies the updates of "all" transactions (i.e., *committed* and *aborted*)
  - This paradigm is referred to as *Repeating History*

- The Redo phase scans forward until the end of the log, and redoes every action unless:
  - The affected page is not in the Dirty Page table
  - The affected page is in the Dirty Page table, but its recLSN > the current record's LSN
  - The pageLSN of the affected page >= the current record's LSN

***YES**, but it requires retrieving the page from the disk, thus made last!*

ARIES: The Redo Phase

- If the logged action must be redone:
  - The logged action is reapplied
  - The pageLSN on the page is set to the LSN of the redone log record
    - No additional record is written at this time!

ARIES: The Undo Phase

- This phase will undo the actions of all transactions that were active before the crash
  - These transactions are referred to as *loser transactions* and were identified by the Analysis phase

- The Undo phase:
  - Considers the set of lastLSN values for all loser transactions
    - This is denoted as the ToUndo set

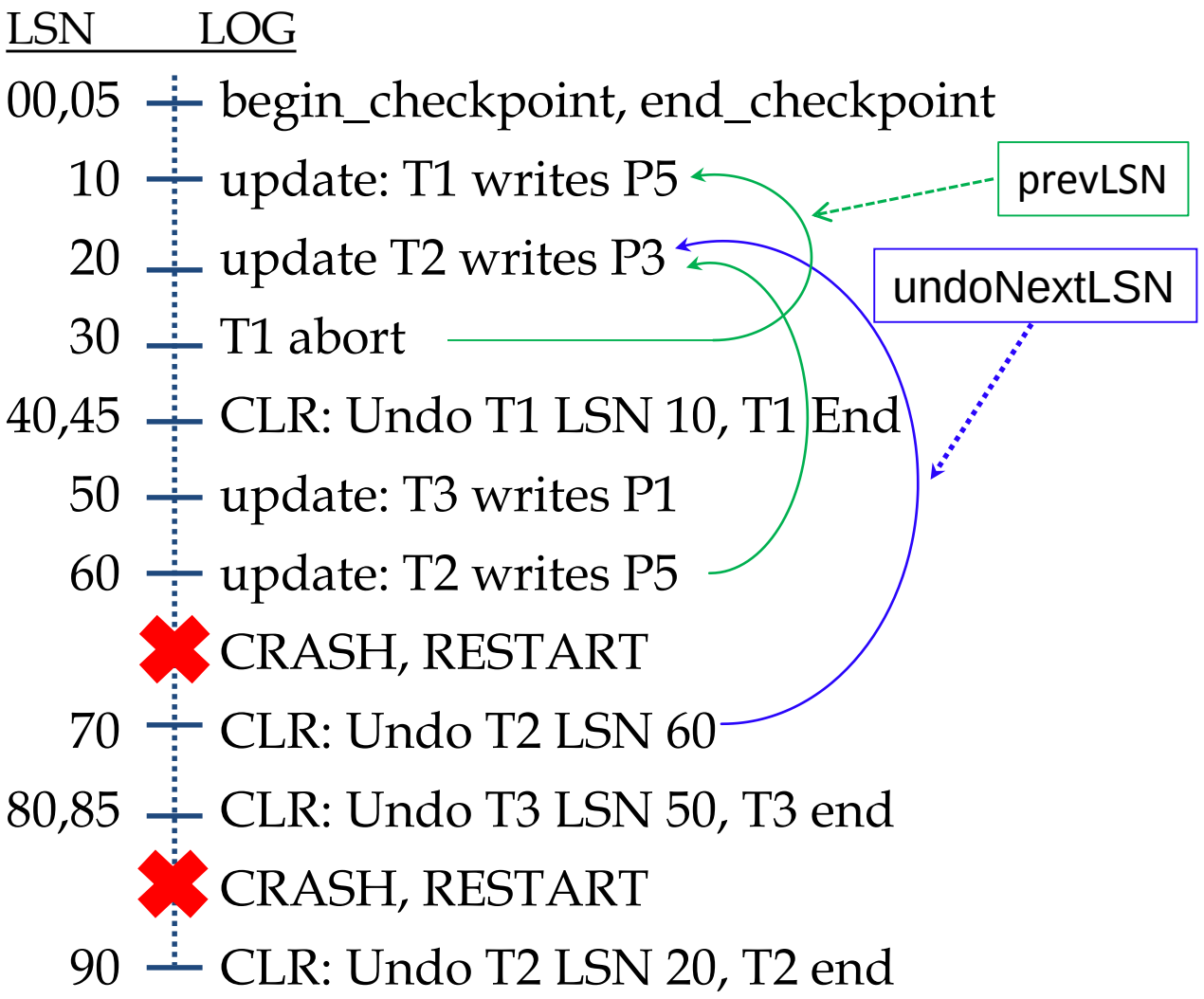
  - Repeatedly chooses the *largest* (i.e., the most recent) LSN value in ToUndo and processes it, until ToUndo is empty

ARIES: The Undo Phase

- In particular, the Undo phase proceeds as follows:

Repeat:
    Choose largest LSN among ToUndo
    If this LSN is a CLR and undoNextLSN==NULL
        Write an End record for this Xact
    If this LSN is a CLR, and undoNextLSN != NULL
        Add undonextLSN to ToUndo
    Else this LSN is an update
        Undo the update
        Write a CLR
        Add prevLSN to ToUndo
Until ToUndo is empty

An Example


LSN
LOG
00,05
begin_checkpoint, end_checkpoint
10
update: T1 writes P5
20
update T2 writes P3
30
T1 abort
40,45
CLR: Undo T1 LSN 10, T1 End
50
update: T3 writes P1
60
update: T2 writes P5
CRASH, RESTART
70
CLR: Undo T2 LSN 60
80,85
CLR: Undo T3 LSN 50, T3 end
CRASH, RESTART
90
CLR: Undo T2 LSN 20, T2 end
prevLSN
undoNextLSN

Additional Crash Issues

- What happens if the system crashes while "Restart" is in the Analysis phase?
  - All the work done is lost!
  - On a second Restart, the Analysis phase starts afresh

- What happens if the system crashes while "Restart" is in the Redo phase?
  - Restart starts again with the Analysis phase then the Redo phase
  - But, some of the changes made during Redo may have been written to disk
    - The update log records that were done the first time around will not be redone a second time (why?)

Summary

- Recovery Manager guarantees Atomicity & Durability
- WAL is used to allow STEAL/NO-FORCE without sacrificing correctness
- LSNs identify log records; linked into backwards chains per transaction (via prevLSN)
- pageLSNs allow comparisons of data pages and log records

Summary

- Checkpointing: A quick way to limit the amount of log to scan on recovery

- Recovery works in 3 phases:
  - Analysis: Forward from checkpoint
  - Redo: Forward from oldest recLSN
  - Undo: Backward from end to first LSN of oldest transaction alive at crash

- Upon Undo, write CLRs

- Redo “repeats history”: Simplifies the logic!

Next Class

The NoSQL Movement!