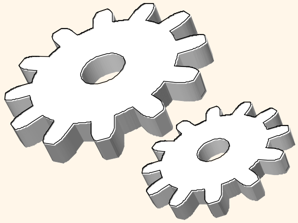
Crash Recovery

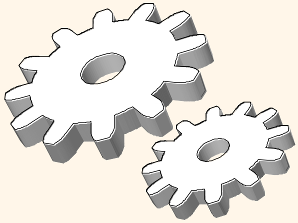
Chapter 18

Review: The ACID properties



- Atomicity: All actions in the Xact happen, or none happen.
- Consistency: If each Xact is consistent, and the DB starts consistent, it ends up consistent.
- Isolation: Execution of one Xact is isolated from that of other Xacts.
- Durability: If a Xact commits, its effects persist.

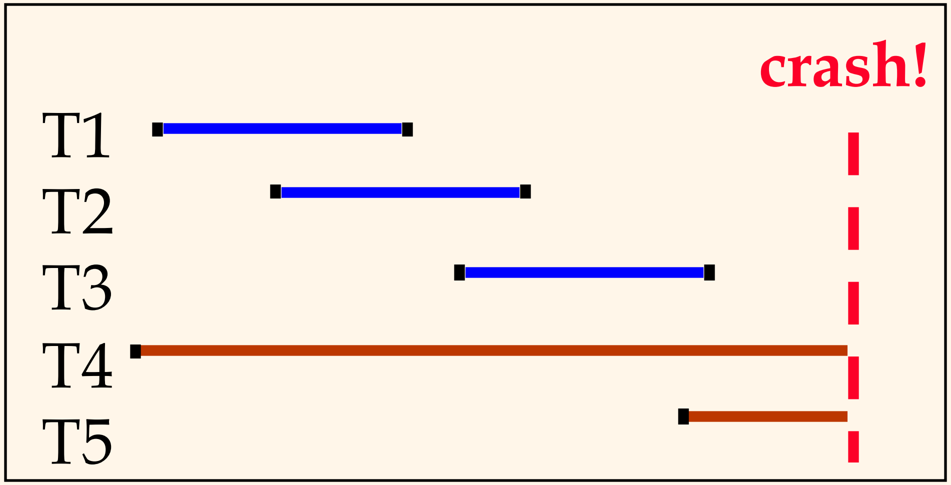
- The **Recovery Manager** guarantees Atomicity & Durability.

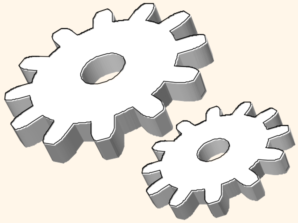


Motivation

- Atomicity:
  - Transactions may abort ("Rollback").
- Durability:
  - What if DBMS stops running? (Causes?)

- Desired Behavior after system restarts:
  - T1, T2 & T3 should be durable.
  - T4 & T5 should be aborted (effects not seen).

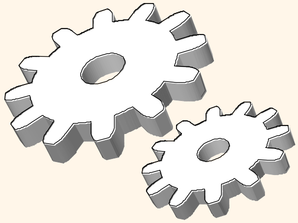




Assumptions

- Concurrency control is in effect.
  - Strict 2PL, in particular.
- Updates are happening “in place”.
  - i.e. data is overwritten on (deleted from) the disk.

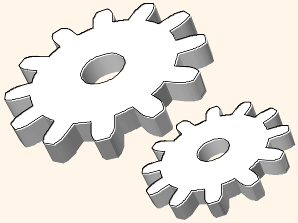
- A simple scheme to guarantee Atomicity & Durability?



Handling the Buffer Pool

- Force every write to disk?
  - Poor response time.
  - But provides durability.
- Steal buffer-pool frames from uncommited Xacts?
  - If not, poor throughput.
  - If so, how can we ensure atomicity?

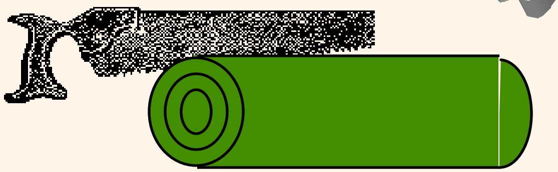
	No Steal	**Steal**
Force	**Trivial**	
No Force		**Desired**



More on Steal and Force

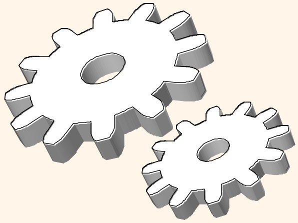
- **STEAL** (why enforcing Atomicity is hard)
  - *To steal frame F:* Current page in F (say P) is written to disk; some Xact holds lock on P.
    - What if the Xact with the lock on P aborts?
    - Must remember the old value of P at steal time (to support UNDOing the write to page P).
- **NO FORCE** (why enforcing Durability is hard)
  - What if system crashes before a modified page is written to disk?
  - Write as little as possible, in a convenient place, at commit time,to support REDOing modifications.

Basic Idea: Logging



- Record REDO and UNDO information, for every update, in a *log*.
  - Sequential writes to log (put it on a separate disk).
  - Minimal info (diff) written to log, so multiple updates fit in a single log page.
- Log: An ordered list of REDO/UNDO actions
  - Log record contains:

    <XID, pageID, offset, length, old data, new data>
  - and additional control info (which we'll see soon).

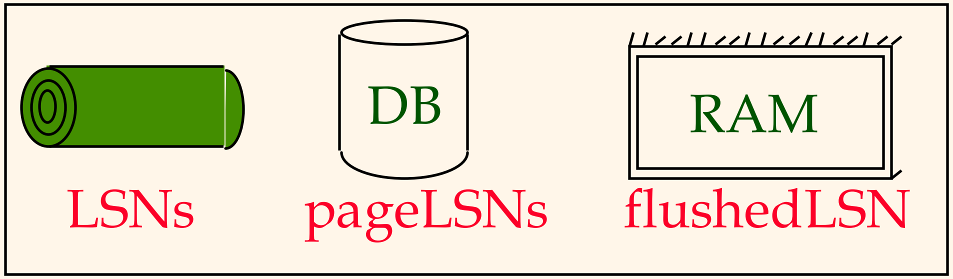


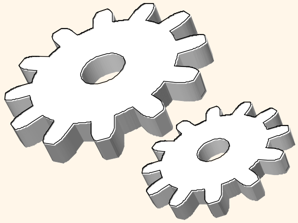
Write-Ahead Logging (WAL)

- The Write-Ahead Logging Protocol:
  - ① Must force the log record for an update *before* the corresponding data page gets to disk.
  - ② Must write all log records for a Xact *before commit*.
- #1 guarantees Atomicity.
- #2 guarantees Durability.

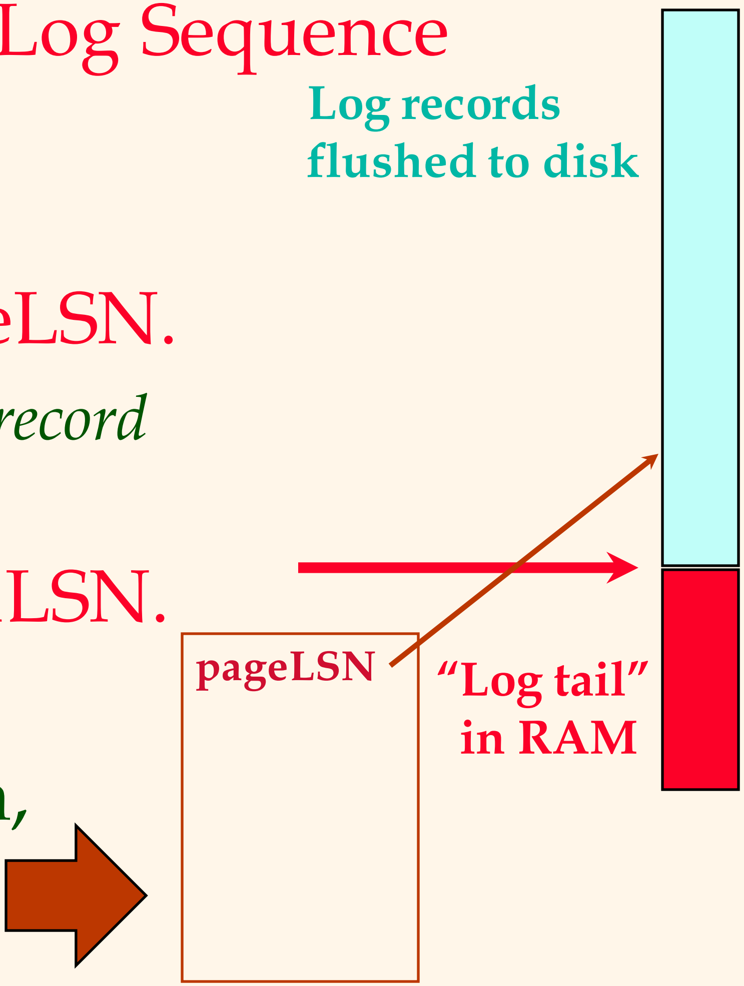
- Exactly how is logging (and recovery!) done?
  - We'll study the ARIES algorithms.

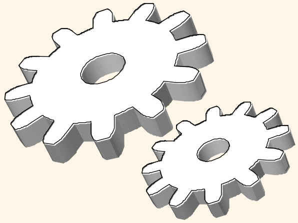
WAL & the Log





- Each log record has a unique Log Sequence Number (LSN).
  - LSNs always increasing.
- Each *data page* contains a pageLSN.
  - The LSN of the most recent *log record* for an update to that page.
- System keeps track of flushedLSN.
  - The max LSN flushed so far.
- WAL: *Before* a page is written,
  - pageLSN ≤ flushedLSN





Log Records

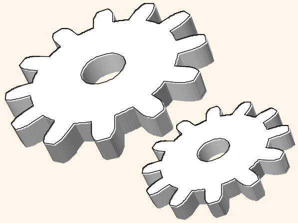
LogRecord fields:

prevLSN
XID
type
pageID
length
offset
before-image
after-image

update records only (pageID, length, offset, before-image, after-image)

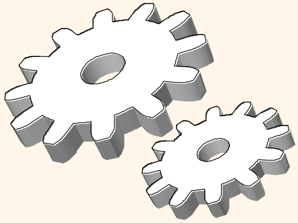
Possible log record types:

- **Update**
- **Commit**
- **Abort**
- **End** (signifies end of commit or abort)
- Compensation Log Records (CLRs)
  - for UNDO actions



Other Log-Related State

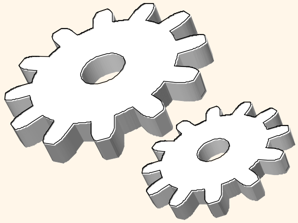
- Transaction Table:
  - One entry per active Xact.
  - Contains XID, status (running/commited/aborted), and lastLSN.
- Dirty Page Table:
  - One entry per dirty page in buffer pool.
  - Contains recLSN -- the LSN of the log record which ***first*** caused the page to be dirty.



Normal Execution of an Xact

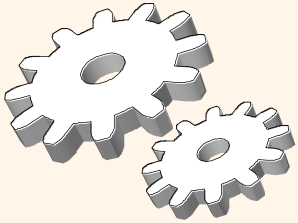
- Series of reads & writes, followed by commit or abort.
  - We will assume that write is atomic on disk.
    - In practice, additional details to deal with non-atomic writes.
- Strict 2PL.
- STEAL, NO-FORCE buffer management, with Write-Ahead Logging.

Checkpointing



- Periodically, the DBMS creates a checkpoint, in order to minimize the time taken to recover in the event of a system crash. Write to log:
  - begin_checkpoint record: Indicates when chkpt began.
  - end_checkpoint record: Contains current *Xact table* and *dirty page table*. This is a \`fuzzy checkpoint':
    - Other Xacts continue to run; so these tables accurate only as of the time of the begin_checkpoint record.
    - No attempt to force dirty pages to disk; effectiveness of checkpoint limited by oldest unwritten change to a dirty page. (So it's a good idea to periodically flush dirty pages to disk!)
  - Store LSN of chkpt record in a safe place (*master* record).

The Big Picture:
What's Stored Where



LogRecords

- prevLSN
- XID
- type
- pageID
- length
- offset
- before-image
- after-image

Data pages

each
with a
pageLSN

master record

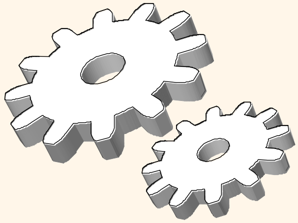
Xact Table

- lastLSN
- status

Dirty Page Table

- recLSN

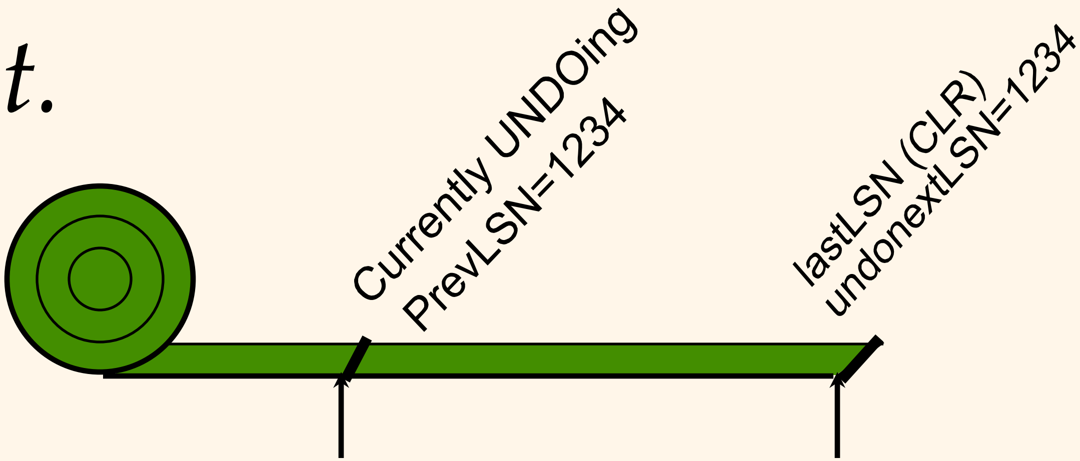
flushedLSN



Simple Transaction Abort

- For now, consider an explicit abort of a Xact.
  - No crash involved.
- We want to “play back” the log in reverse order, UNDOing updates.
  - Get lastLSN of Xact from Xact table.
  - Can follow chain of log records backward via the prevLSN field.
  - Before starting UNDO, write an *Abort* log record.
    - For recovering from crash during UNDO!

Abort, cont.

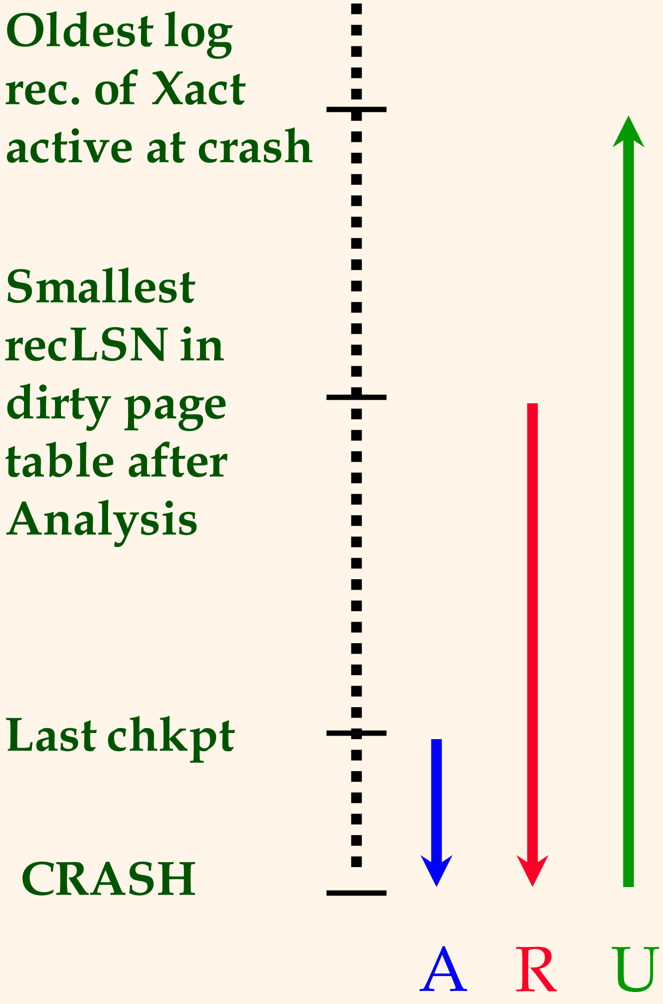


- To perform UNDO, must have a lock on data!
  - No problem!
- Before restoring old value of a page, write a CLR:
  - You continue logging while you UNDO!!
  - CLR has one extra field: undonextLSN
    - Points to the next LSN to undo (i.e. the prevLSN of the record we're currently undoing).
  - CLRs *never* Undone (but they might be Redone when repeating history: guarantees Atomicity!)
- At end of UNDO, write an "end" log record.

Transaction Commit

- Write commit record to log.
- All log records up to Xact's lastLSN are flushed.
  - Guarantees that flushedLSN ≥ lastLSN.
  - Note that log flushes are sequential, synchronous writes to disk.
  - Many log records per log page.
- Commit() returns.
- Write end record to log.

Crash Recovery: Big Picture



Oldest log rec. of Xact active at crash

Smallest recLSN in dirty page table after Analysis

Last chkpt

CRASH

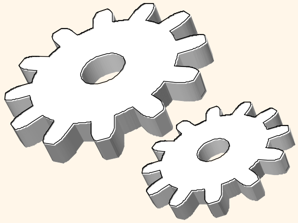
A R U

- Start from a checkpoint (found via master record).
- Three phases. Need to:
  - Figure out which Xacts committed since checkpoint, which failed (Analysis).
  - REDO ***all*** actions.
    - (repeat history)
  - UNDO effects of failed Xacts.

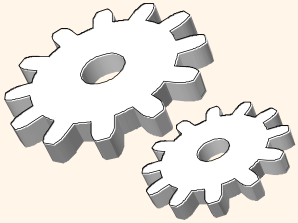
Recovery: The Analysis Phase

- Reconstruct state at checkpoint.
  - via end_checkpoint record.
- Scan log forward from checkpoint.
  - End record: Remove Xact from Xact table.
  - Other records: Add Xact to Xact table, set lastLSN=LSN, change Xact status on commit.
  - Update record: If P not in Dirty Page Table,
    - Add P to D.P.T., set its recLSN=LSN.

Recovery: The REDO Phase



- We *repeat History* to reconstruct state at crash:
  - Reapply *all* updates (even of aborted Xacts!), redo CLRs.
- Scan forward from log rec containing smallest recLSN in D.P.T. For each CLR or update log rec LSN, REDO the action unless:
  - Affected page is not in the Dirty Page Table, or
  - Affected page is in D.P.T., but has recLSN > LSN, or
  - pageLSN (in DB) ≥ LSN.
- To REDO an action:
  - Reapply logged action.
  - Set pageLSN to LSN. No additional logging!



Recovery: The UNDO Phase

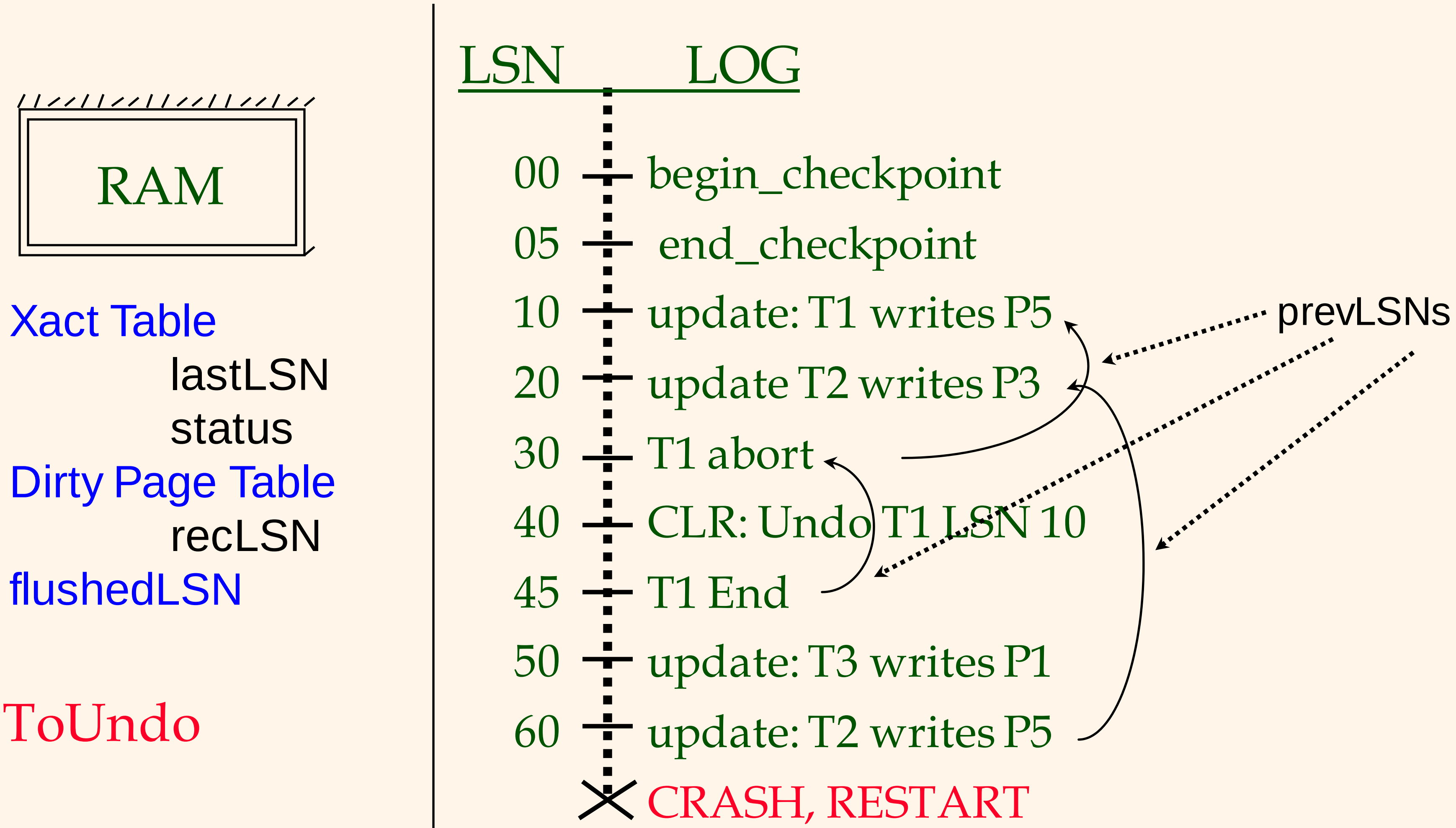
ToUndo={ l | l a lastLSN of a “loser” Xact}

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.

Example of Recovery



RAM

Xact Table
- lastLSN
- status

Dirty Page Table
- recLSN

flushedLSN

ToUndo

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

prevLSNs

Example: Crash During Restart!

RAM

Xact Table

lastLSN

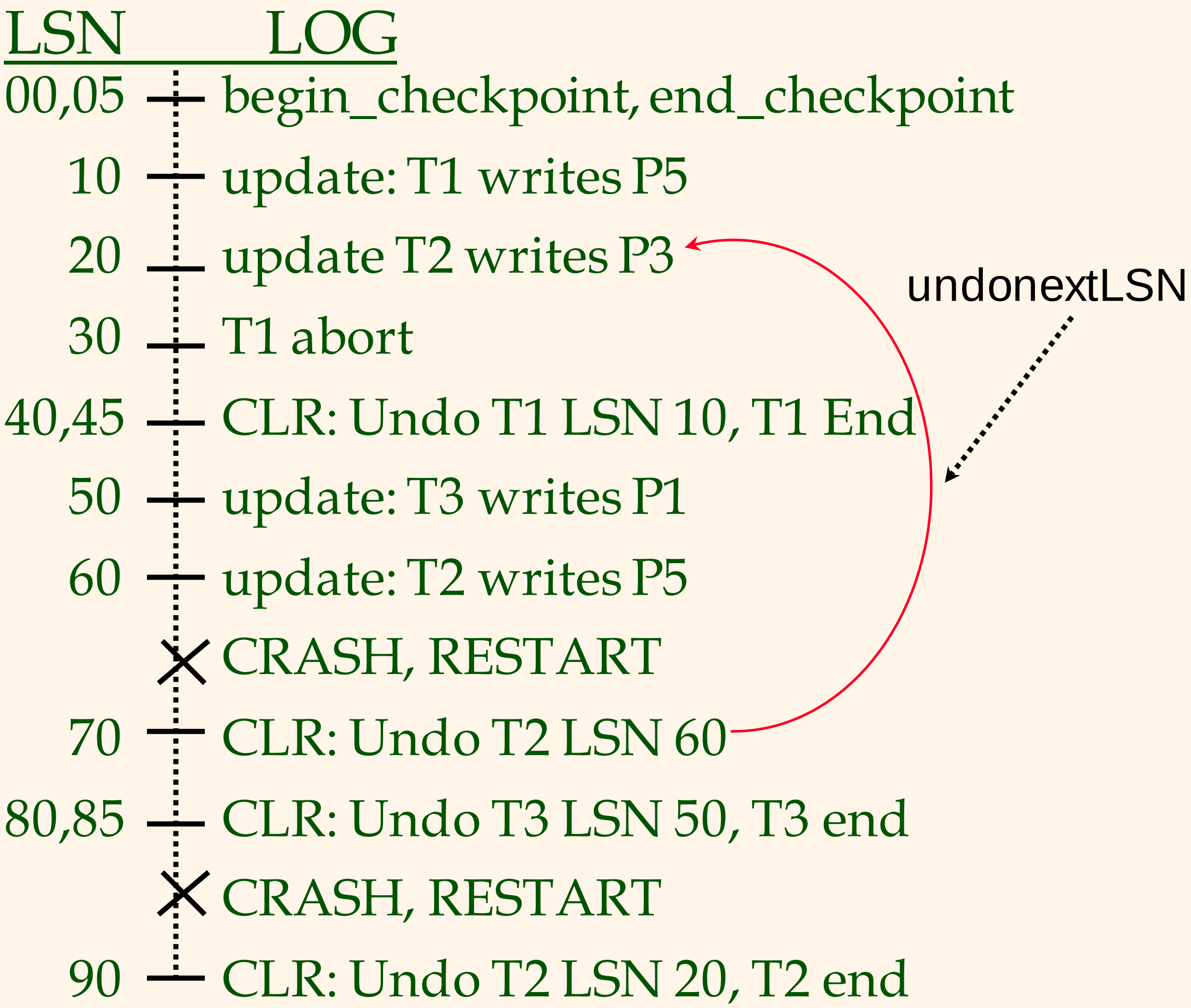
status

Dirty Page Table

recLSN

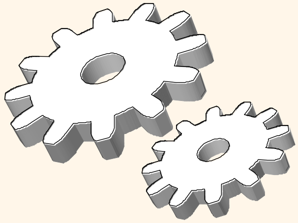
flushedLSN

ToUndo



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

undonextLSN



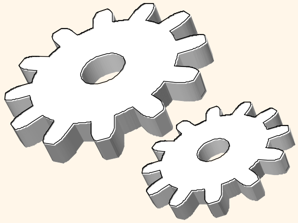
Additional Crash Issues

- What happens if system crashes during Analysis? During REDO?
- How do you limit the amount of work in REDO?
  - Flush asynchronously in the background.
  - Watch “hot spots”!
- How do you limit the amount of work in UNDO?
  - Avoid long-running Xacts.

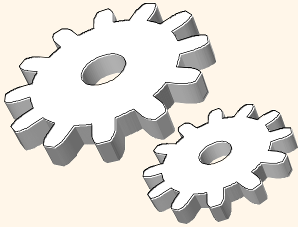
Summary of Logging/Recovery

- Recovery Manager guarantees Atomicity & Durability.
- Use WAL to allow STEAL/NO-FORCE w/o sacrificing correctness.
- LSNs identify log records; linked into backwards chains per transaction (via prevLSN).
- pageLSN allows comparison of data page and log records.

Summary, Cont.

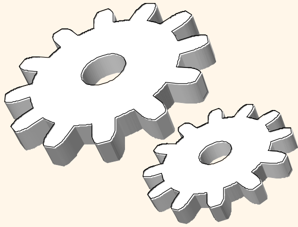


- Checkpointing: A quick way to limit the amount of log to scan on recovery.
- Recovery works in 3 phases:
  - Analysis: Forward from checkpoint.
  - Redo: Forward from oldest recLSN.
  - Undo: Backward from end to first LSN of oldest Xact alive at crash.
- Upon Undo, write CLRs.
- Redo “repeats history”: Simplifies the logic!



Hash-Based Indexes

Chapter 11

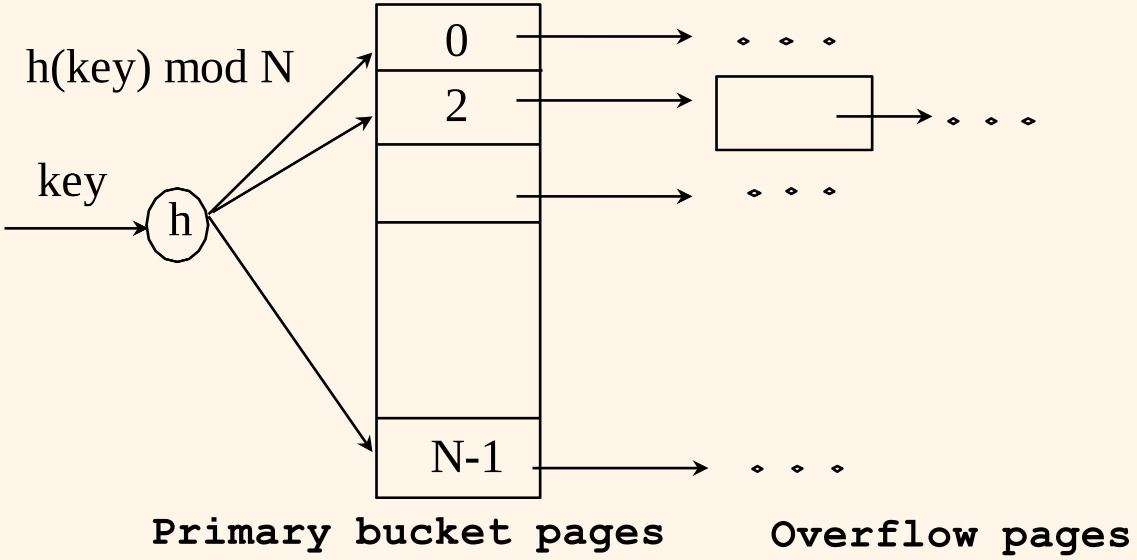


Introduction

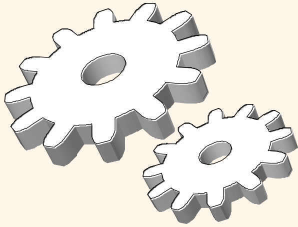
- *As for any index, 3 alternatives for data entries* **k***:
  - Data record with key value **k**
  - <**k**, rid of data record with search key value **k**>
  - <**k**, list of rids of data records with search key **k**>
  - Choice orthogonal to the *indexing technique*
- *Hash-based* indexes are best for *equality selections*. ***Cannot*** support range searches.
- Static and dynamic hashing techniques exist; trade-offs similar to ISAM vs. B+ trees.

Static Hashing

- # primary pages fixed, allocated sequentially, never de-allocated; overflow pages if needed.
- **h**(*k*) mod M = bucket to which data entry with key *k* belongs. (M = # of buckets)

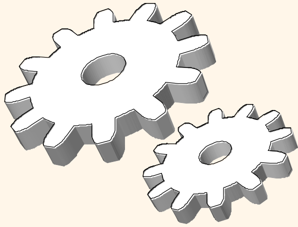


Static Hashing (Contd.)



- Buckets contain *data entries*.
- Hash fn works on *search key* field of record *r*. Must distribute values over range 0 ... M-1.
  - **h**(*key*) = (a * *key* + b) usually works well.
  - a and b are constants; lots known about how to tune **h**.
- Long overflow chains can develop and degrade performance.
  - *Extendible* and *Linear Hashing*: Dynamic techniques to fix this problem.

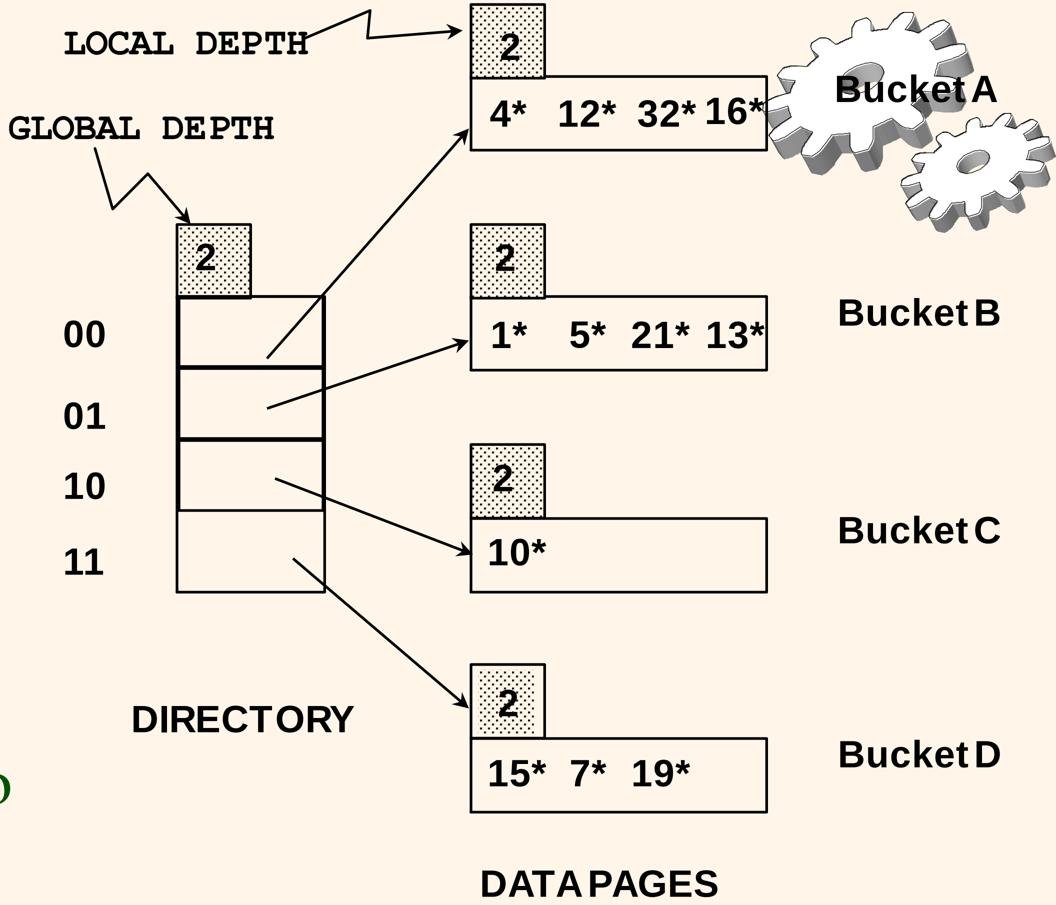
Extendible Hashing



- Situation: Bucket (primary page) becomes full. Why not re-organize file by *doubling* # of buckets?
  - Reading and writing all pages is expensive!
  - *Idea*: Use *directory of pointers to buckets*, double # of buckets by *doubling the directory,* splitting just the bucket that overflowed!
  - Directory much smaller than file, so doubling it is much cheaper. Only one page of data entries is split. *No overflow page*!
  - Trick lies in how hash function is adjusted!

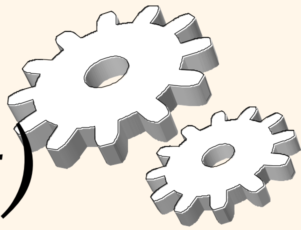
Example

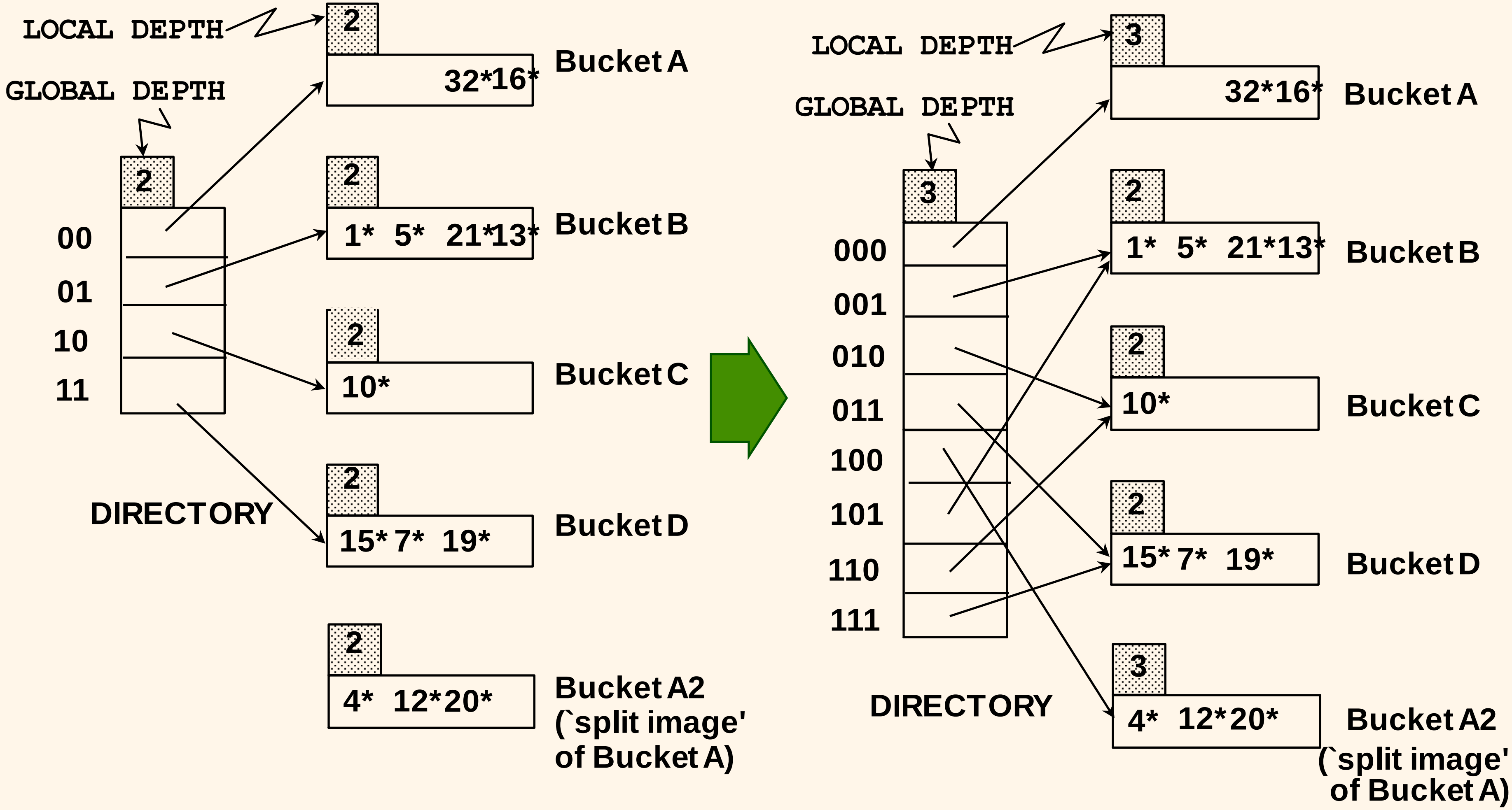
- Directory is array of size 4.
- To find bucket for *r*, take last `*global depth*' # bits of **h**(*r*); we denote *r* by **h**(*r*).
  - If **h**(*r*) = 5 = binary 101, it is in bucket pointed to by 01.



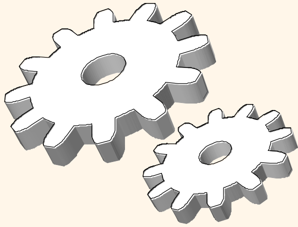
- **Insert**: If bucket is full, *split* it (*allocate new page, re-distribute*).
- *If necessary*, double the directory. (As we will see, splitting a bucket does not always require doubling; we can tell by comparing *global depth* with *local depth* for the split bucket.)

*Insert **h**(r)=20 (Causes Doubling)*



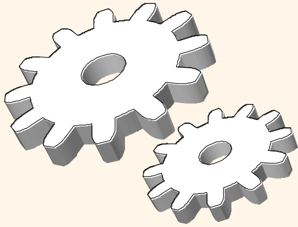


Points to Note

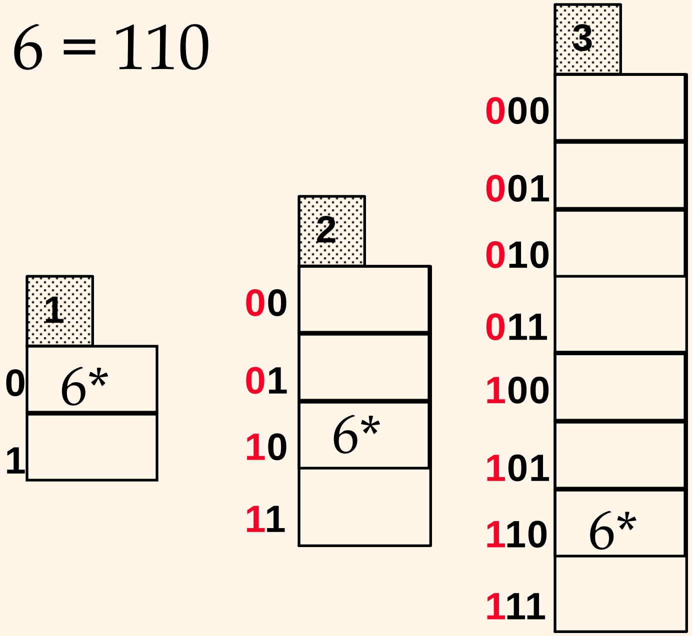


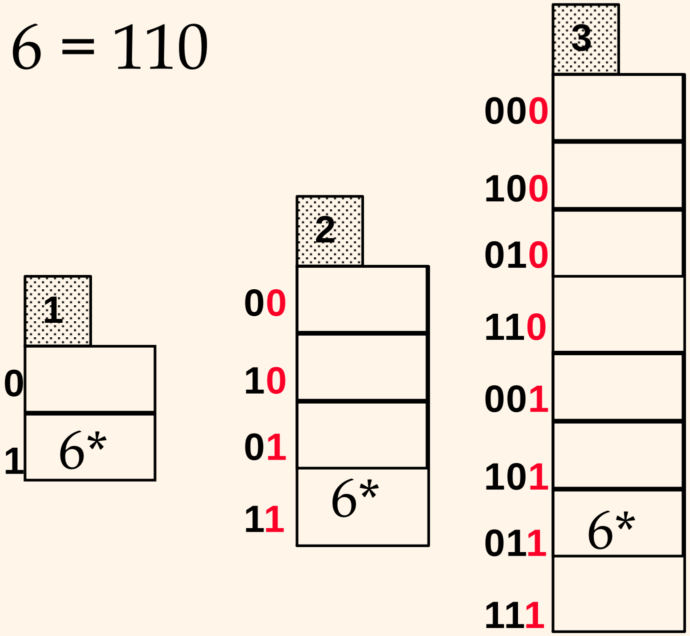
- 20 = binary 10100. Last **2** bits (00) tell us *r* belongs in A or A2. Last **3** bits needed to tell which.
  - *Global depth of directory*: Max # of bits needed to tell which bucket an entry belongs to.
  - *Local depth of a bucket*: # of bits used to determine if an entry belongs to this bucket.
- When does bucket split cause directory doubling?
  - Before insert, *local depth* of bucket = *global depth*. Insert causes *local depth* to become > *global depth*; directory is doubled by *copying it over* and `fixing' pointer to split image page. (Use of least significant bits enables efficient doubling via copying of directory!)

Directory Doubling



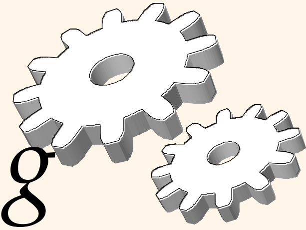
Why use least significant bits in directory?
⬄ Allows for doubling via copying!





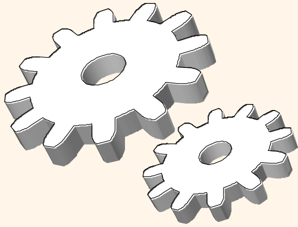
Least Significant vs. Most Significant

Comments on Extendible Hashing



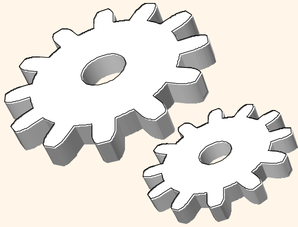
- If directory fits in memory, equality search answered with one disk access; else two.
    - 100MB file, 100 bytes/rec, 4K pages contains 1,000,000 records (as data entries) and 25,000 directory elements; chances are high that directory will fit in memory.
    - Directory grows in spurts, and, if the distribution *of hash values* is skewed, directory can grow large.
    - Multiple entries with same hash value cause problems!
- **Delete**: If removal of data entry makes bucket empty, can be merged with `split image'. If each directory element points to same bucket as its split image, can halve directory.

Linear Hashing



- This is another dynamic hashing scheme, an alternative to Extendible Hashing.
- LH handles the problem of long overflow chains without using a directory, and handles duplicates.
- *Idea*: Use a family of hash functions $\mathbf{h}_0$, $\mathbf{h}_1$, $\mathbf{h}_2$, ...
  - $\mathbf{h}_i(key) = \mathbf{h}(key) \bmod (2^i N)$; N = initial # buckets
  - **h** is some hash function (range is *not* 0 to N-1)
  - If $N = 2^{d0}$, for some *d0*, $\mathbf{h}_i$ consists of applying **h** and looking at the last *di* bits, where $di = d0 + i$.
  - $\mathbf{h}_{i+1}$ doubles the range of $\mathbf{h}_i$ (similar to directory doubling)

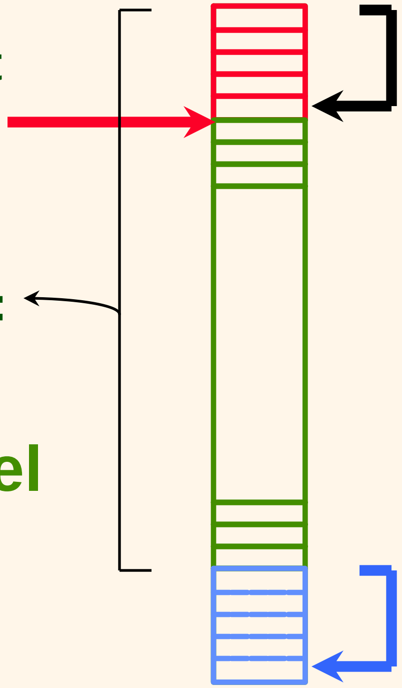
Linear Hashing (Contd.)



- Directory avoided in LH by using overflow pages, and choosing bucket to split round-robin.
  - Splitting proceeds in \`rounds'. Round ends when all N_R initial (for round R) buckets are split. Buckets 0 to *Next-1* have been split; *Next* to N_R yet to be split.
  - Current round number is *Level*.
  - **Search:** To find bucket for data entry r, find $\mathbf{h}_{Level}(r)$:
    - If $\mathbf{h}_{Level}(r)$ in range \`*Next* to N_R', r belongs here.
    - Else, r could belong to bucket $\mathbf{h}_{Level}(r)$ or bucket $\mathbf{h}_{Level}(r) + N_R$; must apply $\mathbf{h}_{Level+1}(r)$ to find out.

Overview of LH File

- In the middle of a round.



Bucket to be split

Next

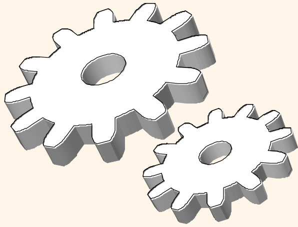
Buckets that existed at the beginning of this round: this is the range of

h_{Level}

Buckets split in this round: If h_{Level} (search key value) is in this range, must use $h_{Level+1}$ (search key value) to decide if entry is in `split image' bucket.

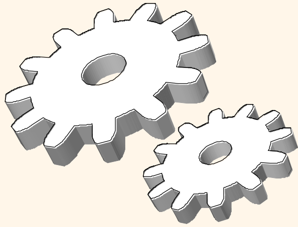
`split image' buckets: created (through splitting of other buckets) in this round

Linear Hashing (Contd.)

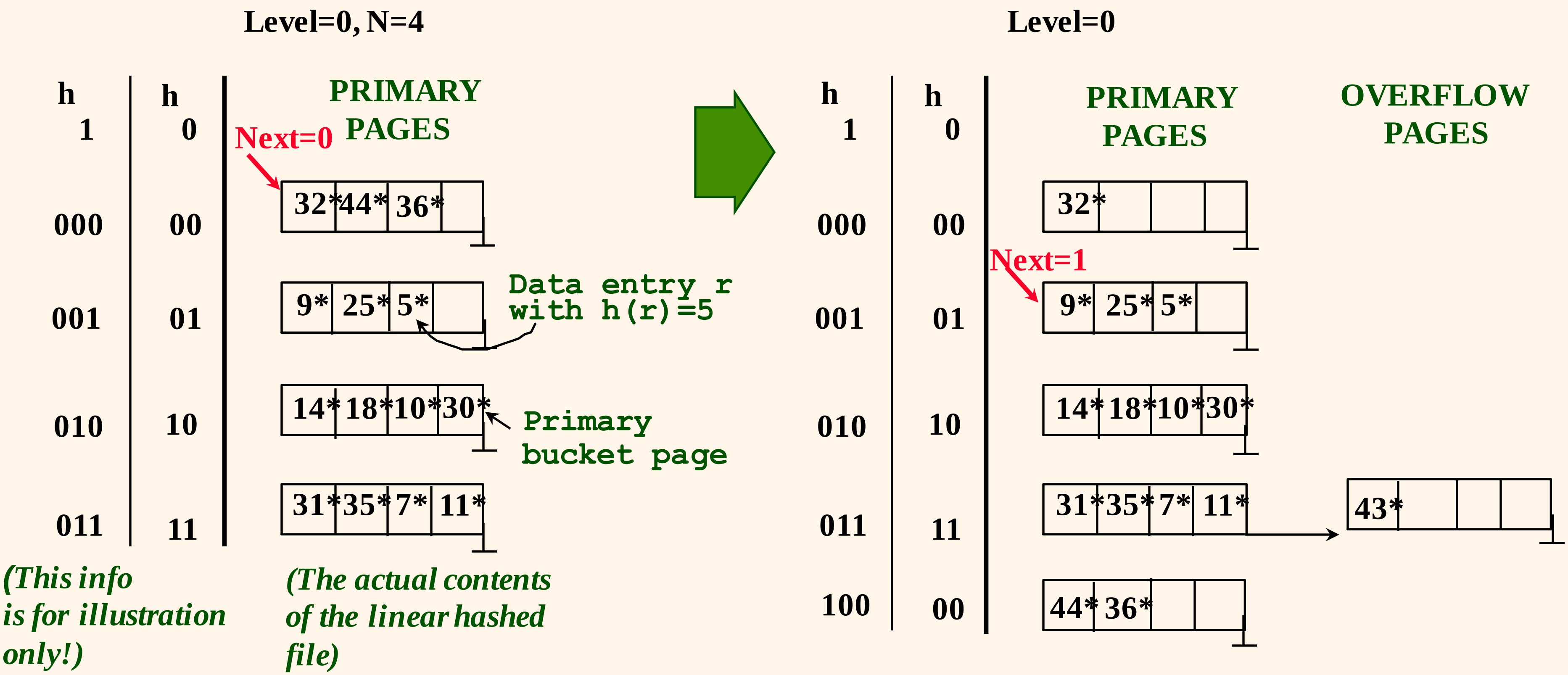


- **Insert**: Find bucket by applying $\mathbf{h}_{Level}$ / $\mathbf{h}_{Level+1}$:
  - If bucket to insert into is full:
    - Add overflow page and insert data entry.
    - (*Maybe*) Split *Next* bucket and increment *Next*.
- Can choose any criterion to `trigger' split.
- Since buckets are split round-robin, long overflow chains don't develop!
- Doubling of directory in Extendible Hashing is similar; switching of hash functions is *implicit* in how the # of bits examined is increased.

Example of Linear Hashing



- On split, **$h_{Level+1}$** is used to re-distribute entries.



Level=0, N=4

h_1	h_0	PRIMARY PAGES
000	00	32* 44* 36*
001	01	9* 25* 5*
010	10	14* 18* 10* 30*
011	11	31* 35* 7* 11*

Next=0

Data entry r with h(r)=5

Primary bucket page

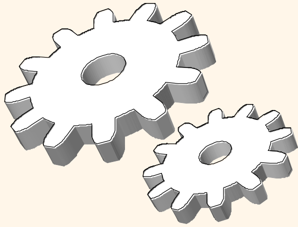
(This info is for illustration only!)

(The actual contents of the linear hashed file)

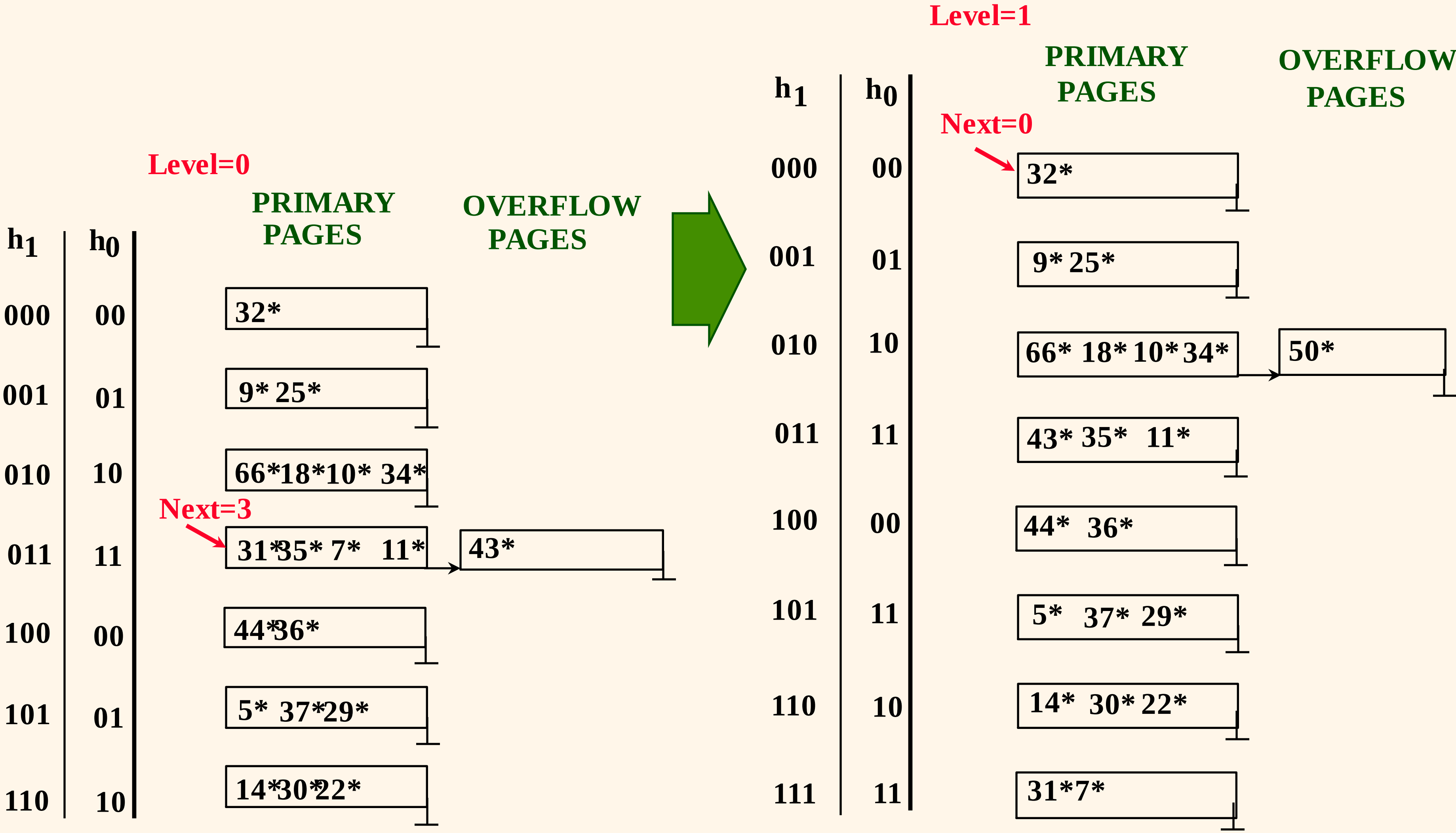
Level=0

h_1	h_0	PRIMARY PAGES	OVERFLOW PAGES
000	00	32*	
001	01	9* 25* 5*	
010	10	14* 18* 10* 30*	
011	11	31* 35* 7* 11*	43*
100	00	44* 36*	

Next=1



Example: End of a Round



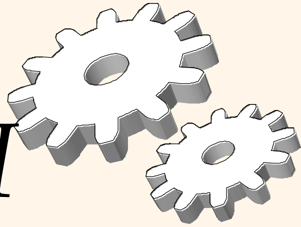
Level=0

h1	h0	PRIMARY PAGES	OVERFLOW PAGES
000	00	32*	
001	01	9* 25*	
010	10	66*18*10* 34*	
011	11	Next=3 31*35* 7* 11*	43*
100	00	44*36*	
101	01	5* 37*29*	
110	10	14*30*22*	

Level=1

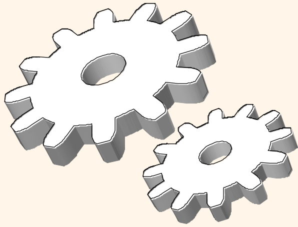
h1	h0	PRIMARY PAGES	OVERFLOW PAGES
000	00	Next=0 32*	
001	01	9* 25*	
010	10	66* 18* 10* 34*	50*
011	11	43* 35* 11*	
100	00	44* 36*	
101	11	5* 37* 29*	
110	10	14* 30* 22*	
111	11	31*7*	

LH Described as a Variant of EH



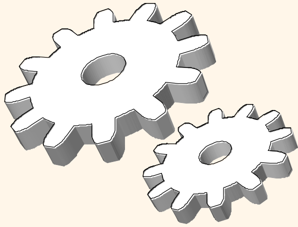
- The two schemes are actually quite similar:
  - Begin with an EH index where directory has *N* elements.
  - Use overflow pages, split buckets round-robin.
  - First split is at bucket 0. (Imagine directory being doubled at this point.) But elements <1,*N*+1>, <2,*N*+2>, ... are the same. So, need only create directory element *N*, which differs from 0, now.
    - When bucket 1 splits, create directory element *N*+1, etc.
- So, directory can double gradually. Also, primary bucket pages are created in order. If they are *allocated* in sequence too (so that finding i'th is easy), we actually don't need a directory! Voila, LH.

Summary



- Hash-based indexes: best for equality searches, cannot support range searches.
- Static Hashing can lead to long overflow chains.
- Extendible Hashing avoids overflow pages by splitting a full bucket when a new data entry is to be added to it. (*Duplicates may require overflow pages.*)
  - Directory to keep track of buckets, doubles periodically.
  - Can get large with skewed data; additional I/O if this does not fit in main memory.

Summary (Contd.)



- Linear Hashing avoids directory by splitting buckets round-robin, and using overflow pages.
  - Overflow pages not likely to be long.
  - Duplicates handled easily.
  - Space utilization could be lower than Extendible Hashing, since splits not concentrated on `dense' data areas.
    - Can tune criterion for triggering splits to trade-off slightly longer chains for better space utilization.
- For hash-based indexes, a *skewed* data distribution is one in which the *hash values* of data entries are not uniformly distributed!