Lecture 15: Indexing

CS348 Spring 2025:
Introduction to Database Management

Guest Lecture: **Chao Zhang**

Sections: 001, 002, 003

Announcements

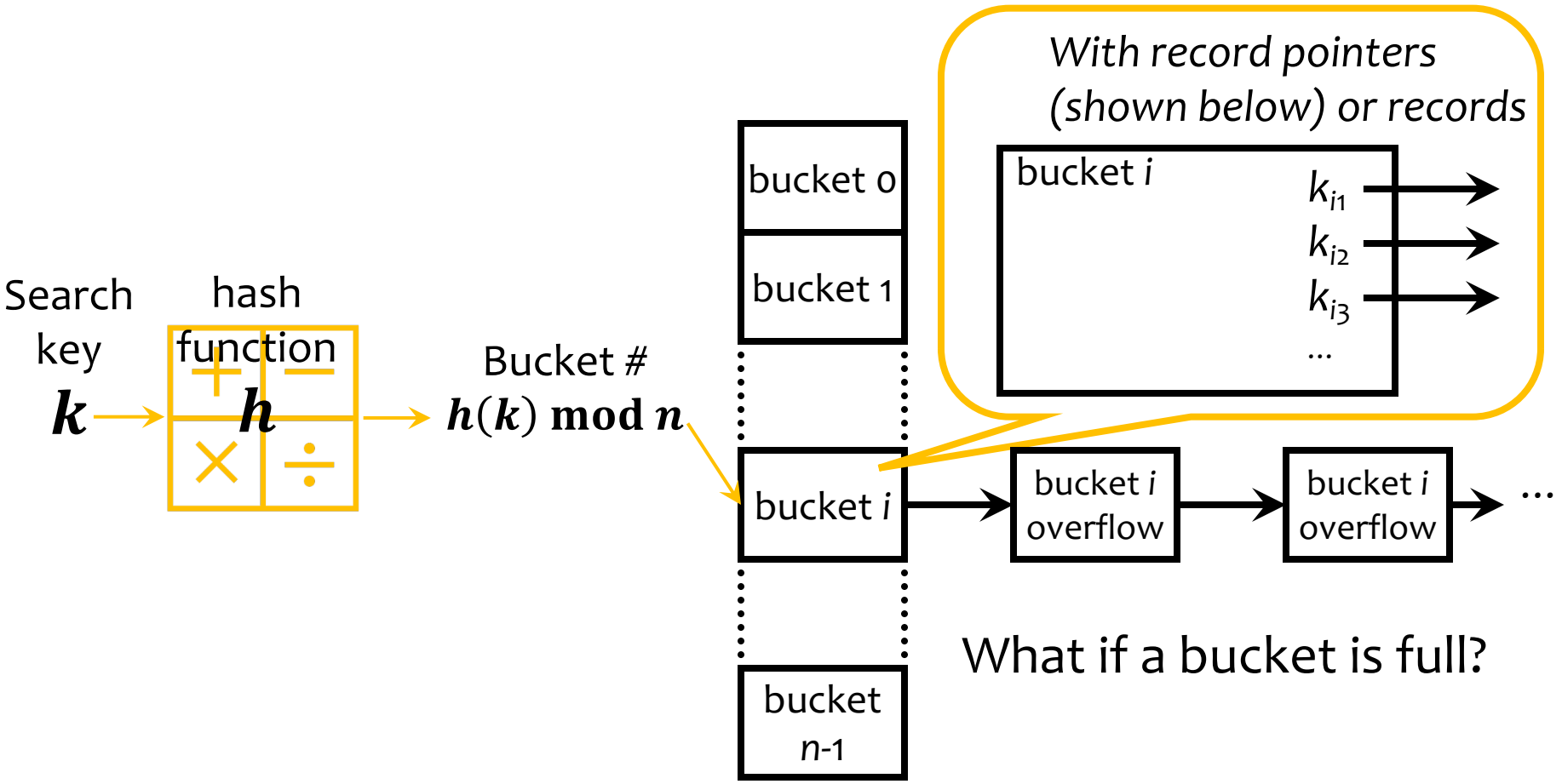
- Midterm exam tomorrow!
  - Time: 4:30 PM – 6:00 PM
  - Location: M3 1006 and STC 0040 (check your room)
  - See the midterm-review lecture

- No class on next Tue, July 1 (Canada day)!

Outline

- Types of indexes:
  - Dense v.s. sparse
  - Clustering v.s. non-clustering
  - Primary v.s. secondary
- Indexing structure
  - ISAM
  - B+-tree
  - Hashing
- How to use index

Static hashing



Performance of static hashing

- Depends on the quality of the hash function
  - Best (hopefully average) case: one I/O
  - Worst case: all keys hashed into one bucket
  - See Knuth vol. 3 for good hash functions
    - Efficiency + uniformity (low collision)
- Rule of thumb: keep utilization at 50%-80%

☞How do we cope with growth?

Strawman solution

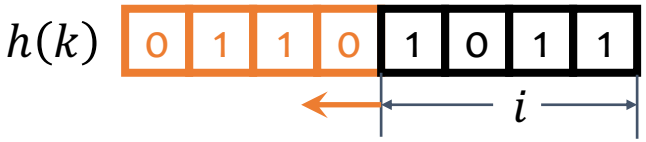
Rehash the whole table — using a new hash function, or at least changing n in $\bmod n$ to the new number of buckets

- Entries in an old bucket may show up across many different new buckets, causing lots of I/Os
- Cost of (re)building a giant hash table on external storage ≈ sorting (later in this course)

☞Is it possible to reduce data movement?

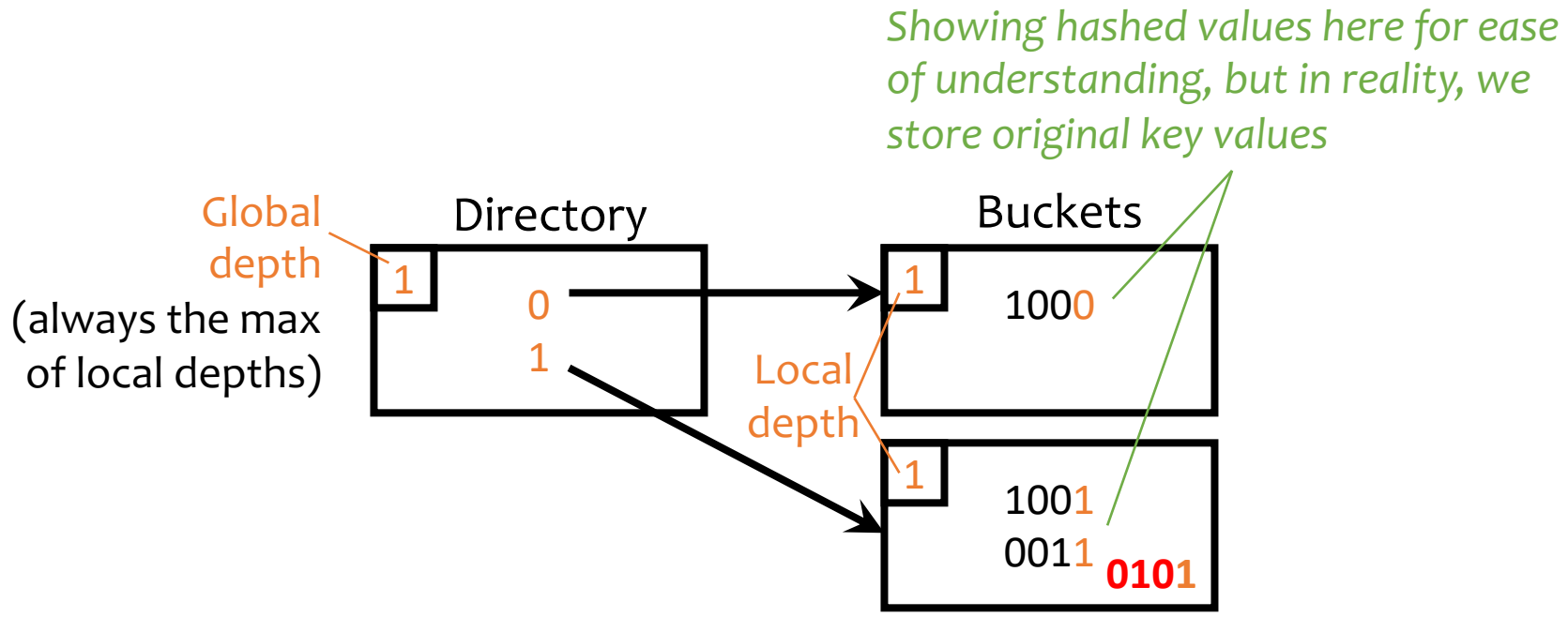
Extensible hashing

- Idea 1: have hash function h output a large number of bits, but only use the lowest i bits, and dynamically increase i as needed



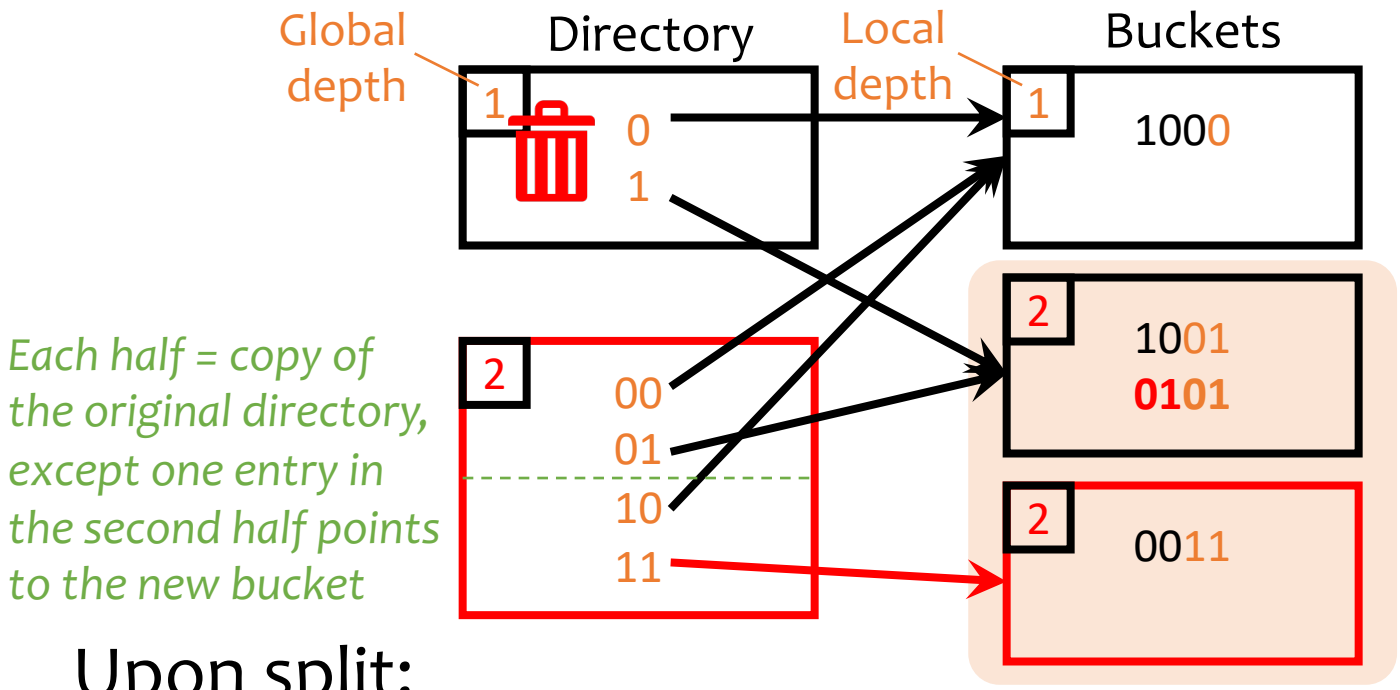
  - E.g., $h_4(k) = 1011$, then $h_5(k)$ is either 01011 or 11011 ⇒ contents in one old bucket can only go to two new buckets!
- Problem: $++i$ doubles the number of buckets!
- Idea 2: use a directory
  - Only split overflowing buckets
  - But double the directory size
  - Many directory entries can point to the same bucket

Extensible hashing example – 1



- Insert k with $h(k) = \mathbf{0101}$
- Bucket too full? Split (next slide)
  - Allowing some overflow is also fine (and sometimes necessary)

Extensible hashing example – 2

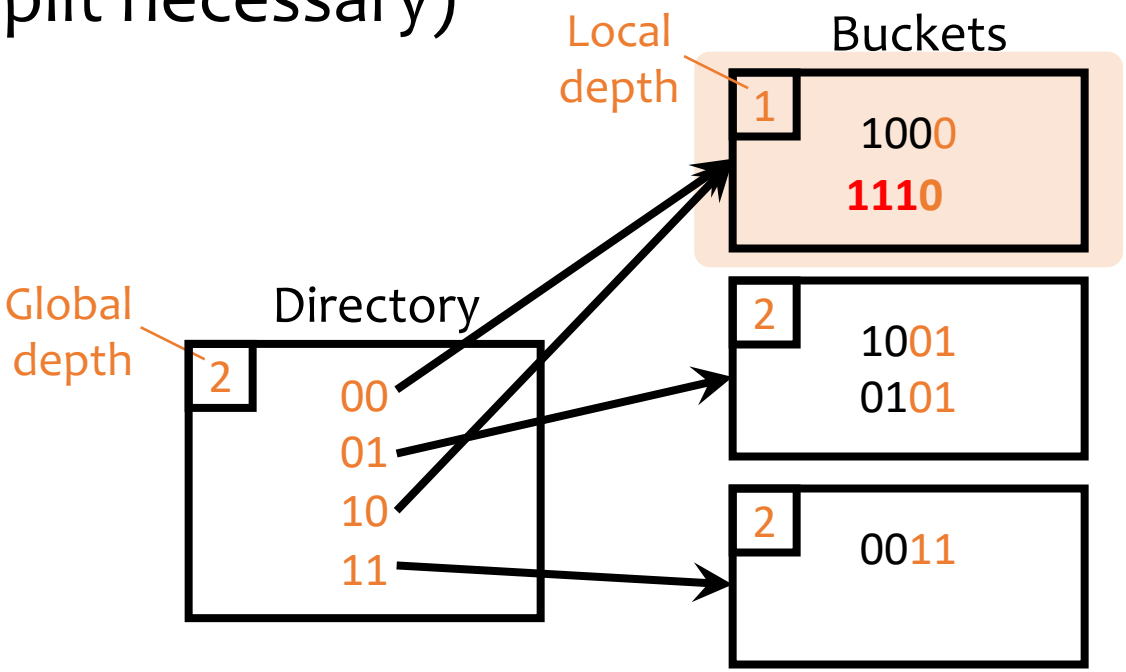


Upon split:

- ++local depth, redistribute contents, and ++global depth (double the directory size) if necessary

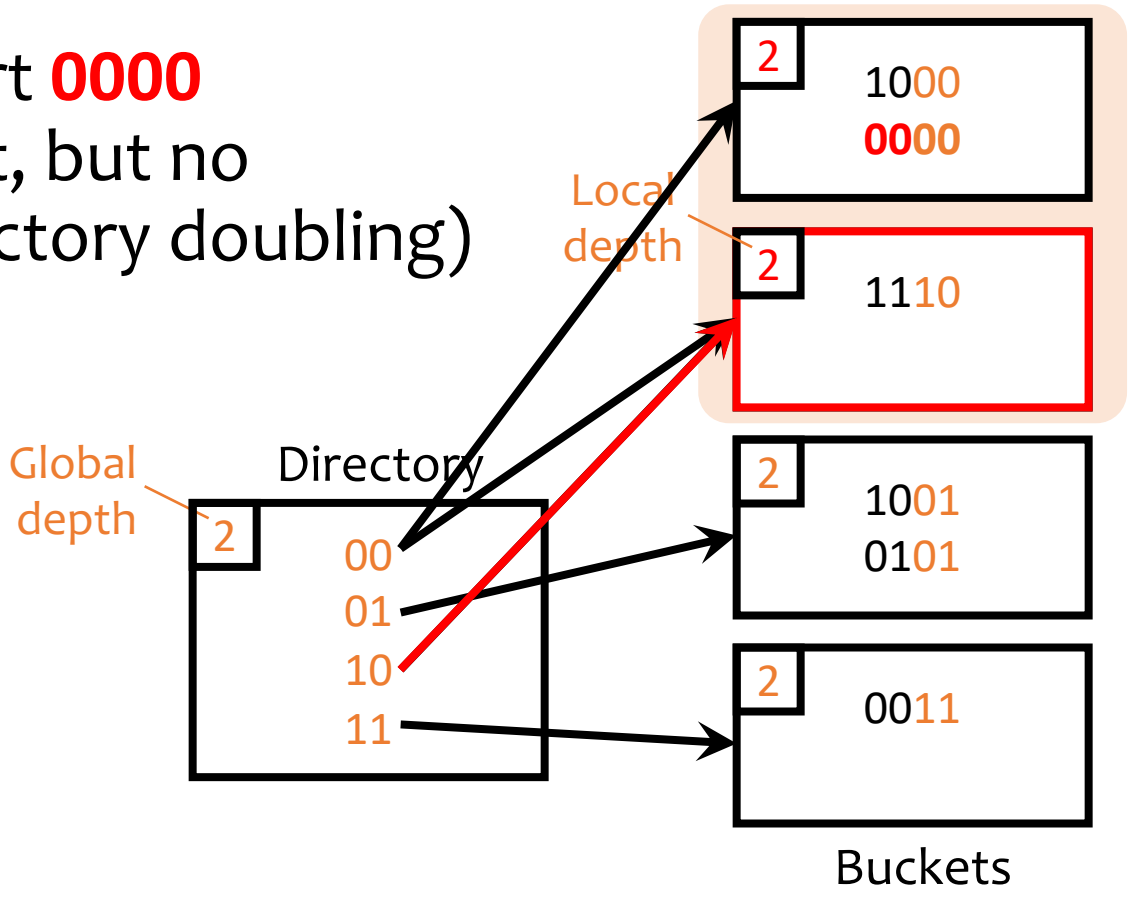
Extensible hashing example – 3

- Insert **1110**
  (no split necessary)



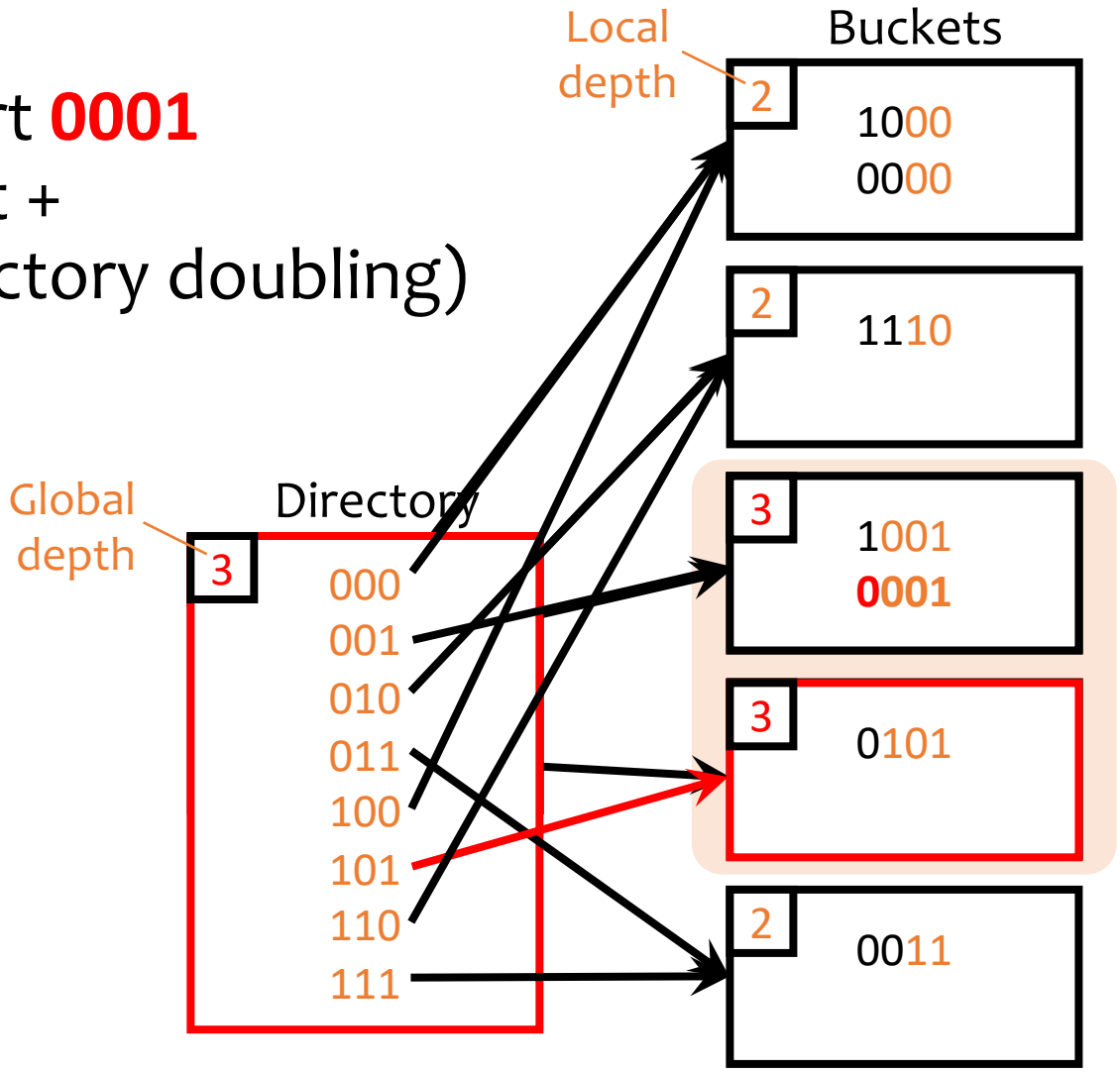
Extensible hashing example – 4

- Insert **0000** (split, but no directory doubling)



Extensible hashing example - 5

- Insert **0001** (split + directory doubling)



Extensible hashing – deletions

Just the reverse of insertions

- If the bucket becomes too empty:
  - Merge with "sibling" (differing only on the leading bit)
    - Adjust any pointer from the directory as needed
  - – – local depth
  - If possible, – – global depth and half the directory
    - Invariant: global depth = max of all local depths

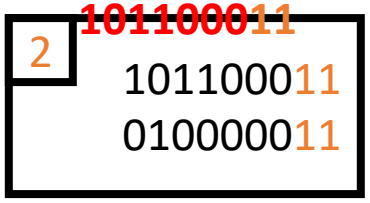
Summary of extensible hashing

Pros:

- Handles growing/shrinking indexes
- No full reorganization

Cons:

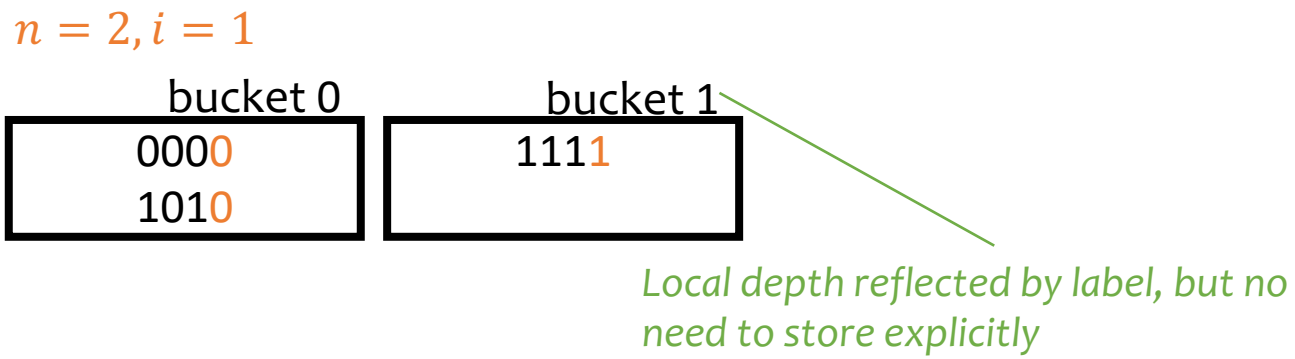
- One more level of indirection through the directory
- Directory size still doubles/halves
- There are cases when doubling may not be enough



Linear hashing

- No extra indirection through a directory
  - Fix the splitting/growth order
  - Use some extra math to figure out the right bucket
- Grow only when utilization (avg. # entries per bucket / max # entries per block) exceeds a given threshold

n: # of primary buckets (not counting overflow blocks)
$i = \lceil \log_2 n \rceil$: # of hash bits in use (global depth)
threshold = 85% (a range of the buckets may use $i - 1$ bits)

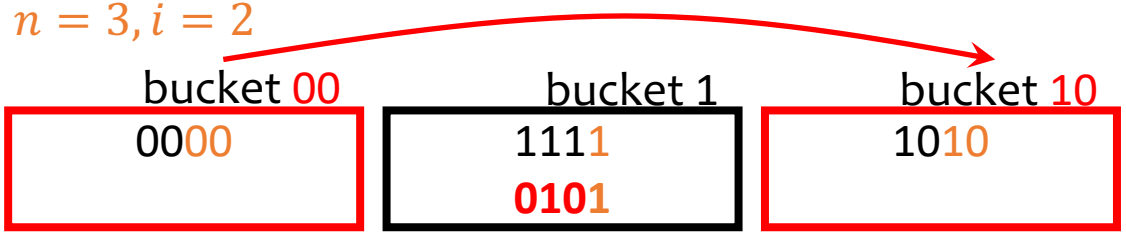


Linear hashing example – 1

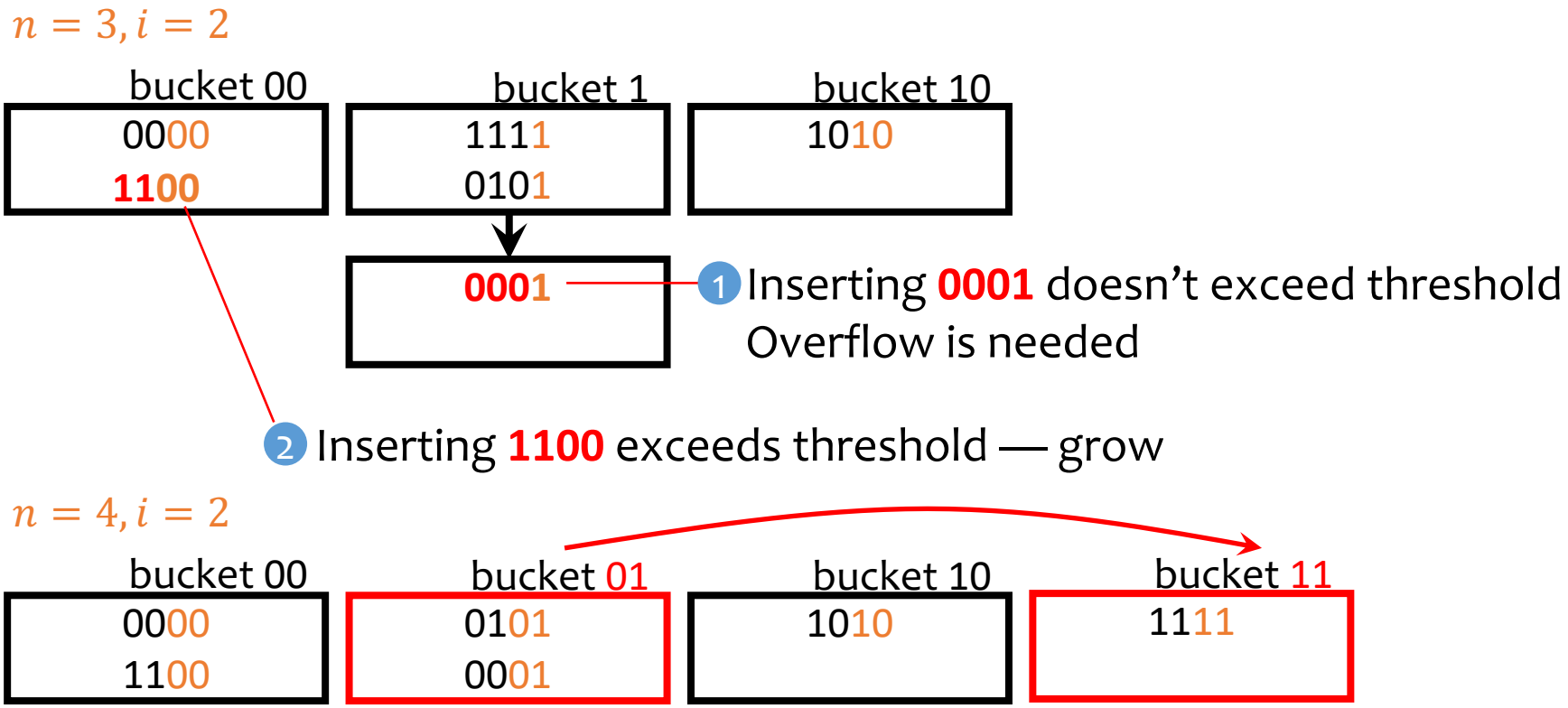
$n = 2, i = 1$

- Split the first bucket with the lowest depth — it's always the bucket $n - 2^{\lfloor \log_2 n \rfloor}$ (0-based index)
  - Often not the bucket you are inserting into!
- File grows *linearly* at the end (hence the name)

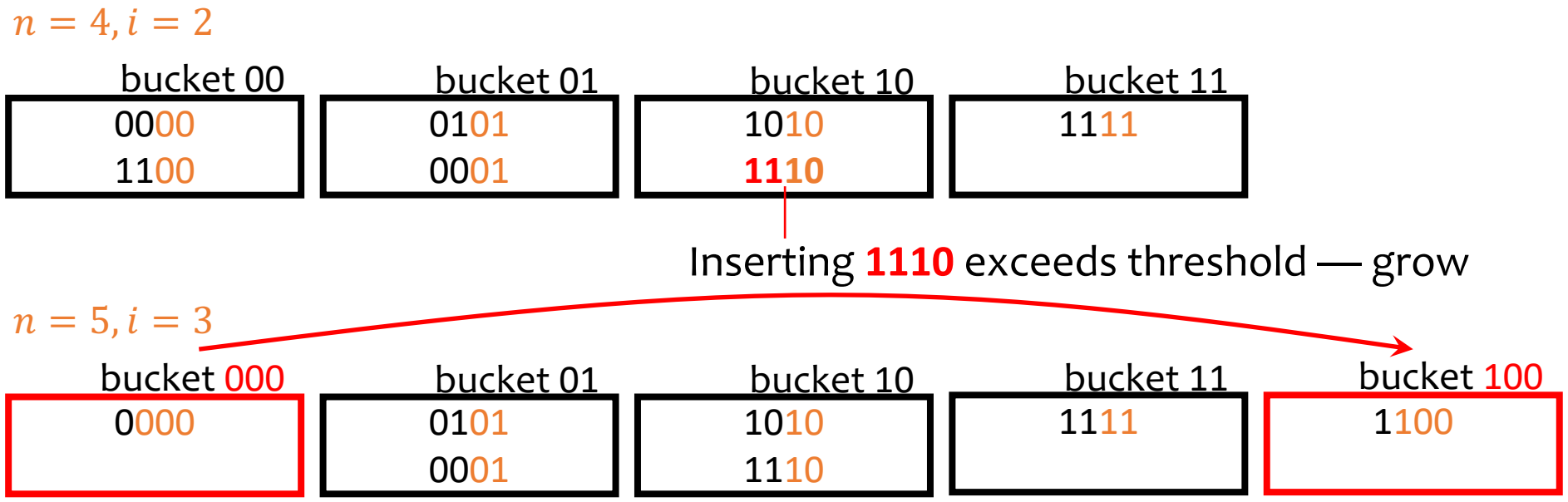
$n = 3, i = 2$



Linear hashing example – 2



Linear hashing example – 3



Look up **1110**

- Bucket **110** doesn't exist, so go to bucket **10**

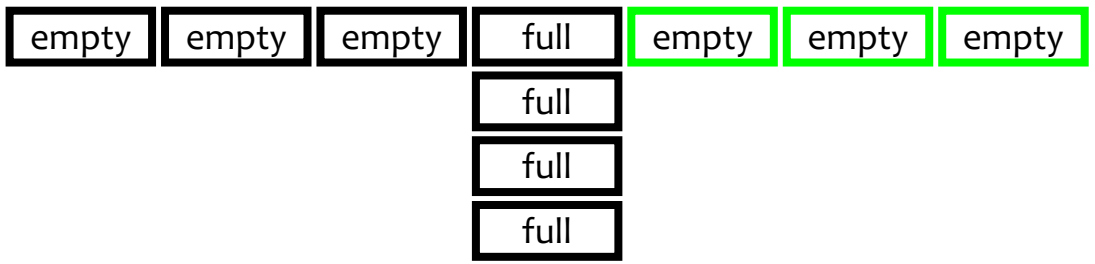
Summary of linear hashing

Pros:

- Handles growing/shrinking indexes
- No full reorganization
- No extra level of indirection (beats extensible hashing)

Cons:

- Still has overflow chains, and may not split them right away because buckets must be split in sequence



Hash indexes vs. B$^+$-trees

- Hashing is faster on average, but the worst case can be bad
- B$^+$-tree's worst-case performance guarantees rely on fewer assumptions, and in practice these trees are not very tall
- Hashing destroys order, but B$^+$-trees provide ordering and support range scans

☞We will come back to sorting vs. hashing again in query processing

Outline

- Types of indexes:
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  - Clustering v.s. non-clustering
  - Primary v.s. secondary
- Indexing structure
  - ISAM
  - B+-tree
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- How to use index

Multi-attribute indices

- Index on several attributes of the same relation.
  - CREATE INDEX NameIndex ON User(LastName,FirstName);

tuples (or tuple pointers) are organized first by Lastname. Tuples with a common lastname are then organized by Firstname.

- This index would be *useful* for these queries:
  - **select * from** User **where** Lastname = 'Smith'
  - **select * from** User **where** Lastname = 'Smith' and Firstname='John'

- This index would be not *useful* at all for this query:
  - **select * from** User **where** Firstname='John'

Index-only plan

- For example:
  - SELECT firstname, pop FROM User WHERE pop > '0.8' AND firstname = 'Bob';
  - non-clustering index on (firstname, pop)

- A (non-clustered) index contains all the columns needed to answer the query without having to access the tuples in the base relation.
  - Avoid one disk I/O per tuple
  - The index is much smaller than the base relation

Physical design guidelines for indices

- Don’t index unless the performance increase outweighs the update overhead
- Attributes mentioned in WHERE clauses are candidates for index search keys
- Multi-attribute search keys should be considered when a WHERE clause contains several conditions; or it enables index-only plans

Physical design guidelines for indices

- Choose indexes that benefit as many queries as possible

- Each relation can have at most one clustering scheme; therefore choose it wisely
  - Target important queries that would benefit the most
    - Range queries benefit the most from clustering
  - A multi-attribute index that enables an index-only plan does not benefit from being clustered

Case study

User (*uid* int, *name* string, *age* int, *pop* float)
Group (*gid* string, *name* string, *date* DATE)
Member (*uid* int, *gid* string)

- Common queries
  1. List the name, pop of users in a particular age range
  2. List the uid, age, pop of users with a particular name
  3. List the average pop of each age
  4. List all the group info, ordered by their starting date
  5. List the average pop of a particular group given the group name
- Pick a set of clustering/non-clustering indexes for these set of queries (without worrying too much about storage and update cost)

Case study

User (*uid* int, *name* string, *age* int, *pop* float)
Group (*gid* string, *name* string, *date* DATE)
Member (*uid* int, *gid* string)

A clustering index on User(age)

A non-clustering index on User(name)

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A non-clustering index on User(age, pop) → index-only plan

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A clustering index on User(age)

A non-clustering index on User(name)

A clustering index on Group(date)

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A join between User(uid, …,pop) , Member(uid,gid), Group(gid, name)

A clustering index on Group(date)

(i) Search gid by a particular name
→ Clustering/non-clustering index on Group(name)?

(ii) Search uid by a particular gid
→ Clustering/non-clustering index on Member(gid)?

(iii) Search pop by a particular uid
→ Clustering/non-clustering index on User(uid)?

Non-clustering, as we already have a clustered index on Group(date)

If many other queries need a clustering index on Group(name), we may reconsider!

Case study

User (*uid* int, *name* string, *age* int, *pop* float)
Group (*gid* string, *name* string, *date* DATE)
Member (*uid* int, *gid* string)

- Common q

A non-clustering index on User(age, pop) → index-only plan

A clustering index on User(age)

A non-clustering index on User(name)

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A join between User(uid, …,pop) , Member(uid,gid), Group(gid, name)

A clustering index on Group(date)

(i) Search gid by a particular name
→ Non-clustering index on Group(name)

(ii) Search uid by a particular gid
→ Clustering/non-clustering index on Member(gid)?

Clustering -> all records of the same gid are clustered

(iii) Search pop by a particular uid
→ Clustering/non-clustering index on User(uid)?

Or clustering index on Member(gid,uid)

Case study

User (*uid* int, *name* string, *age* int, *pop* float)
Group (*gid* string, *name* string, *date* DATE)
Member (*uid* int, *gid* string)

- Common q

A non-clustering index on User(age, pop) → index-only plan

A clustering index on User(age)

A non-clustering index on User(name)

1. List the name, pop users in a particular age range
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A join between User(uid, …,pop) , Member(uid,gid), Group(gid, name)

A clustering index on Group(date)

(i) Search gid by a particular name
→ Non-clustering index on Group(name)

(ii) Search uid by a particular gid
→ Clustering index on Member(gid)

(iii) Search pop by a particular uid
→ Clustering/non-clustering index on User(uid)?

Or non-clustering index on User(uid, pop) → index-only plan, if without worrying about storage/update cost

Non-clustering, as we already have a clustering index on User(age)

Summary

- Types of indexes:
  - Dense v.s. sparse
  - Clustering v.s. non-clustering
  - Primary v.s. secondary
- Indexing structure
  - ISAM
  - B+-tree
  - Hashing
- How to use index
  - Use multi-attribute indices
  - Index-only plan
  - General guideline

What is next?

DBMS Internals:

- Storage: records, blocks, and files
- Indexing
- Query processing & optimization