ΕΛΛΗΝΙΚΗ ΔΗΜΟΚΡΑΤΙΑ
ΠΑΝΕΠΙΣΤΗΜΙΟ ΚΡΗΤΗΣ

Συστήματα Διαχείρισης Βάσεων Δεδομένων

Διάλεξη 3η: Access methods: Hash Indexes

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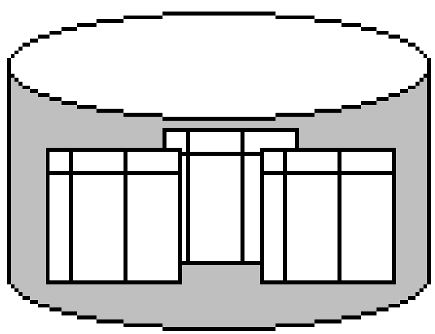
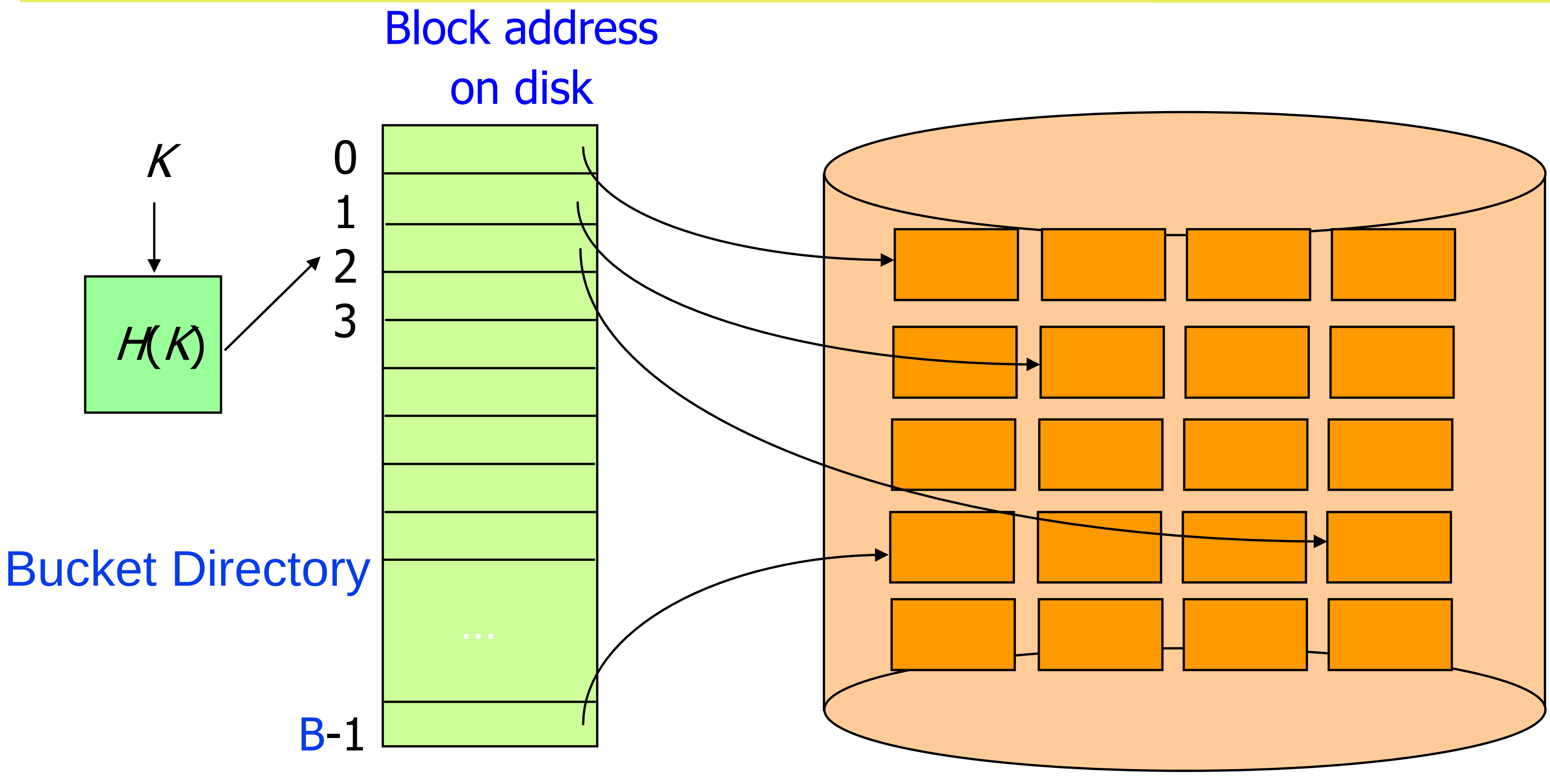
ACCESS METHODS: HASH INDEXES



Hash-based Indexes

- Hash Tables
  - frequently used as main-memory data structures
  - idea: use a hash function **h** taking as input a (hash) key and returning an integer in the range `[0,...,B-1]`; **B** is the number of available buckets
  - organization: a bucket array indexed `[0,...,B-1]` stores the headers of **B** linked lists; if a record has a search key **K**, then it will be stored in the list for the bucket numbered **h(K)**
- Hash Tables in Secondary Storage vs main-memory:
  - Bucket is a unit of storage containing one or more records, typically a disk block
    - Records (or pointers) are placed in the block returned by the hash function
    - Chains of overflow blocks may be added to buckets to accommodate more records
  - Bucket array (directory) consists of block addresses rather than pointers to lists

Hash Tables in Secondary Storage



- Hash file has relative bucket numbers 0 through **B**–1
- Map logical bucket numbers to physical disk block addresses

How do we Choose a Hashing Function ?

- The hash function used should be such that the resulting integer appears to be a random function of the search key
  - thus, buckets will have more or less equal numbers of records and the average time to locate a record will be improved
  - but still one bucket may receive more records than another because some values are more "popular" than others (data skewing)
- Typical hash functions perform computation on the internal binary representation of the search-key
- A function commonly used to hash on integer-valued keys is `K mod B`, which yields an integer in the range 0 to **B**−1
  - **B** is often chosen to be a prime number
  - in certain cases it is convenient to use a power of 2
- For character string keys, characters may be treated as integers (integers are summed up, divided by **B**, and the remainder of the division is taken as the result of the hash function)

Choice of Good Hash Functions

- Desired property: expected number of record keys/bucket is the same for all buckets (uniform distribution) and is relatively small; ideally all buckets consist of only one page
  - B must be large enough to minimize the occurrence of overflow chains
  - B must not be so large that bucket occupancy is small and too much space is wasted
- The worst hash function maps all search-key values to the same bucket
  - this makes access time proportional to the number of search-key values in the file
- Potentially good hash functions: division or multiplication

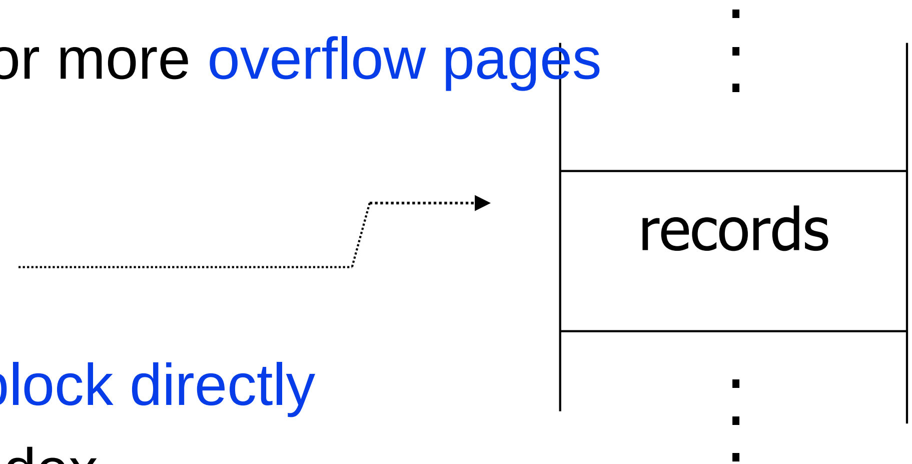
  `h(K) = (a*K + a') mod B,`

  `h(K) = [ fractional-part-of ( K * ϕ ) ] * B,`
  - ϕ: golden ratio (0.6180339887 = (sqrt(5)-1)/2)
  - advantage: B (size of hash table) need not be a prime number but ϕ must be irrational
  - Read Knuth Vol. 3 for more on good hashing functions

Hash Tables in Secondary Storage: Two Alternatives

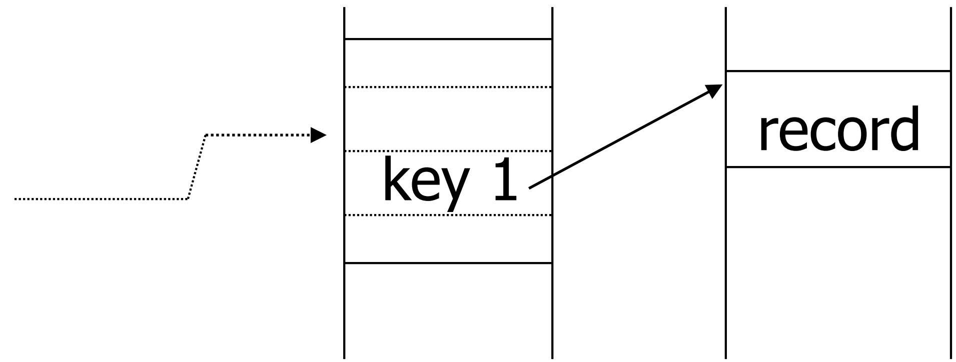
- Index is a collection of buckets
  - Bucket = primary page plus zero or more overflow pages

(1) key -> h(key)



❶ Hash value determines the storage block directly to implement a clustered primary index

(2) key -> h(key)

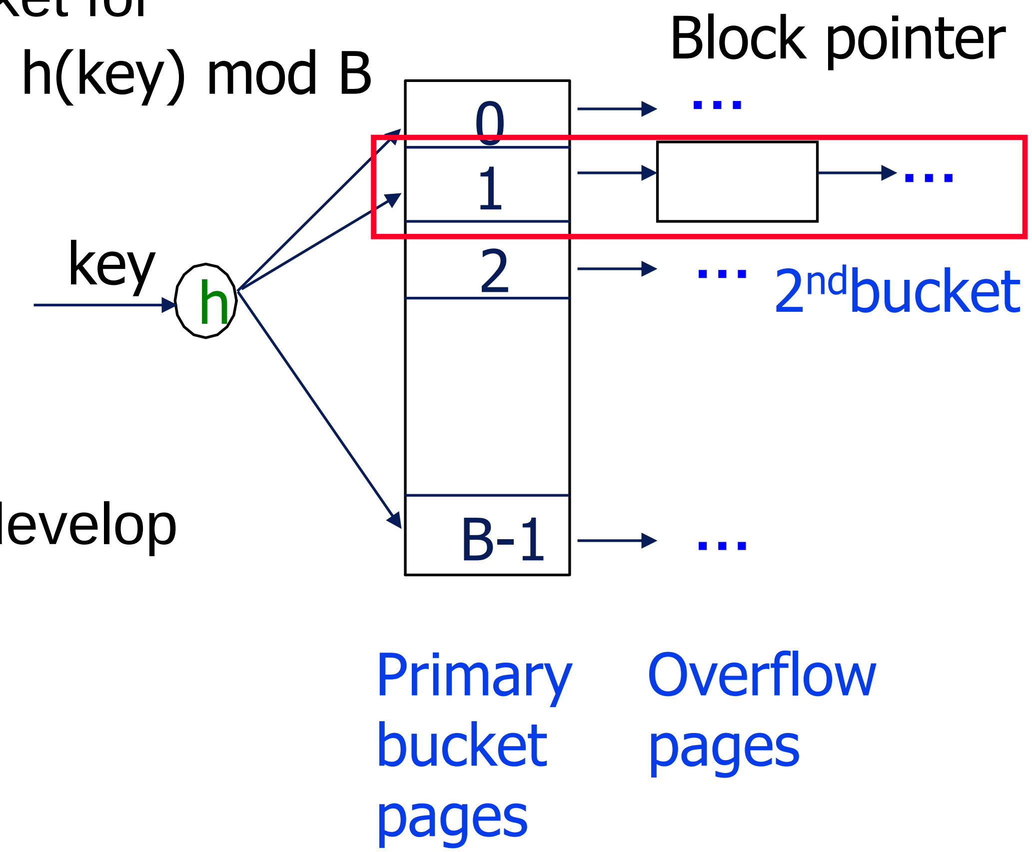


❷ Records located indirectly via index buckets for a secondary index

Index File

Static Hash Tables

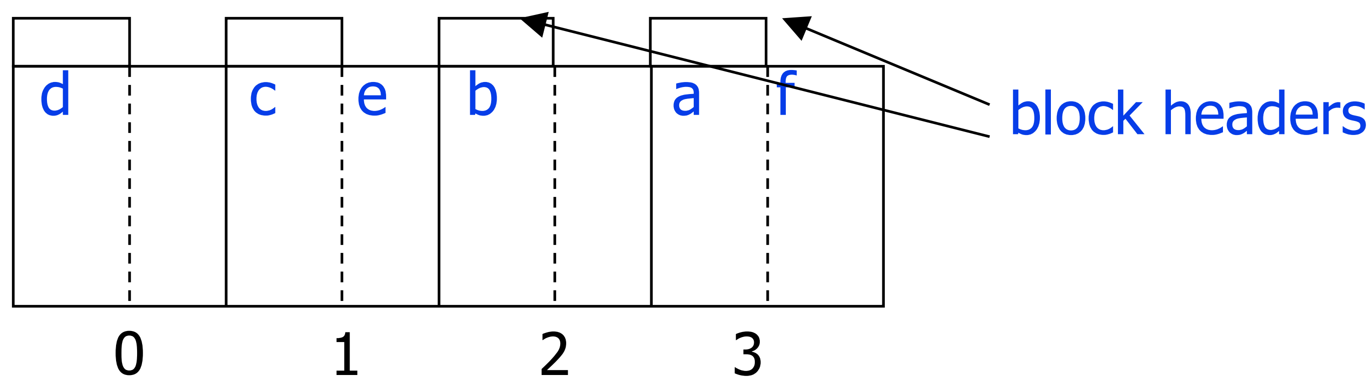
- Buckets contain data entries
  - Buckets of records, not pointers
  - Need to search within the bucket for the record with the key
- One primary page per bucket
  - Fixed, allocated sequentially
  - Additional overflow pages
- Fixed number of buckets
  - File grows
    - Long overflow chains can develop
    - Performance degrade
  - File shrinks
    - Space wastage
- Rehash file periodically



Static Hash Tables

- Each bucket is identified by an address **a**
  - Bucket at address **a** contains all index entries with search key v such that **h(v)=a**
- Assumption: the address of the first block for bucket i is known
  - may use a main-memory directory of pointers to blocks
  - alternatively, the first block for each bucket may be placed in fixed, consecutive locations on disk
- Example: h:{a,b,c,d,e,f} → {0,1,2,3}

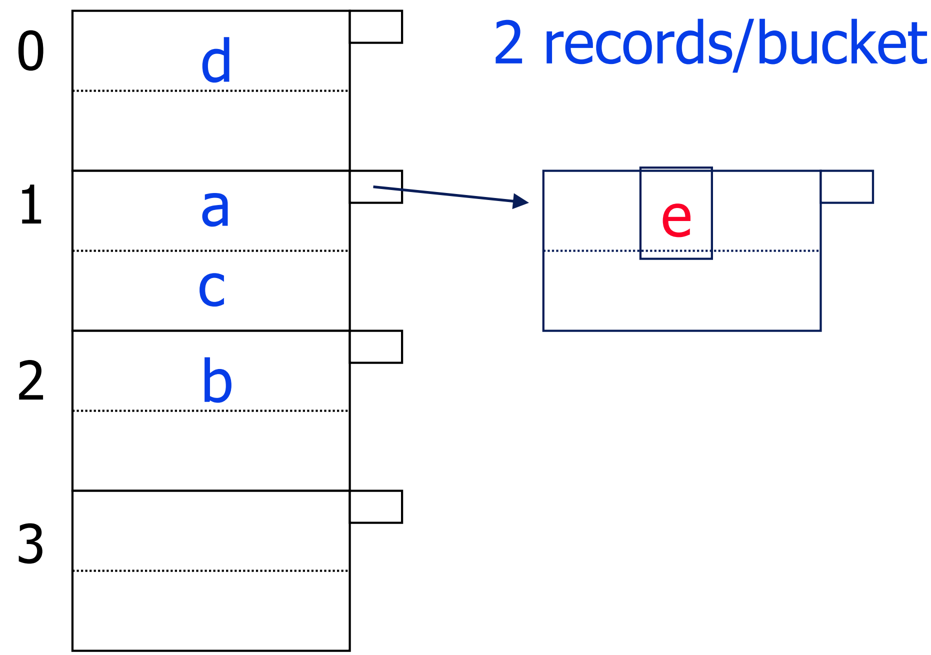
  h(a) = h(f) = 3, h(b) = 2, h(c) = h(e) = 1, h(d) = 0



Inserting into Static Hash Tables

- To insert record with key K:
  - compute h(K)
  - if bucket h(K) has space, insert the record in the block
  - if not, insert it into one of the overflow blocks associated with the bucket
  - if none of them has space, add a new overflow block and store the record there

INSERT:
h(a) = 1
h(b) = 2
h(c) = 1
h(d) = 0



Insert: h(e) = 1

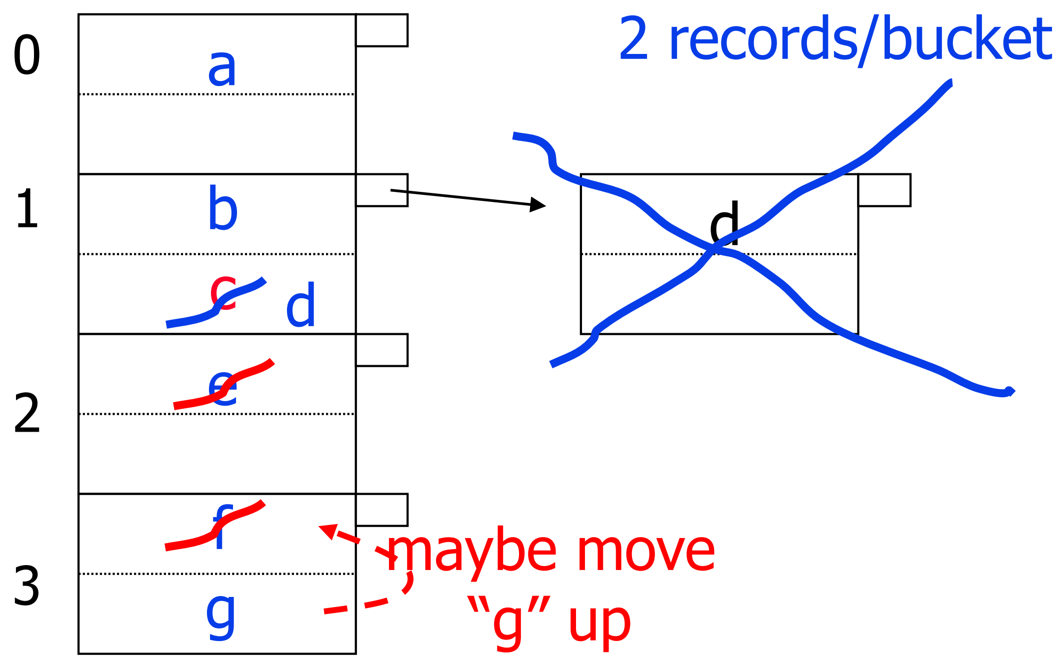
Deleting from Static Hash Tables

- If record with search key K is to be deleted:
  - search bucket h(K) for records with value K
  - delete record(s) found
  - optionally consolidate blocks on a chain after deletion
    - not always a good idea to merge blocks of a chain: repeated insertions / deletions may cause blocks to be created / destroyed at each step

Delete:

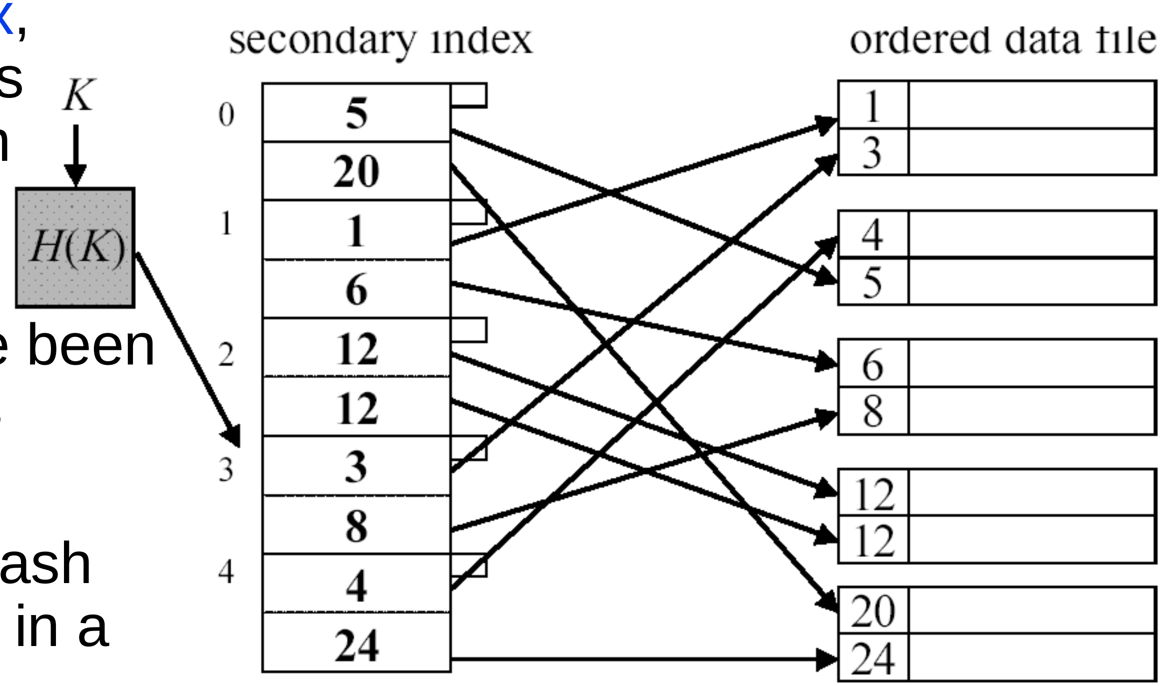
e
f

c



Applications of Hash Tables

- Hashing can be used for both primary and secondary indexes
- For a clustered primary index, no separate index structure is required as the hash function dictates the physical organization of the file
  - The examples so far have been clustered primary indexes
- For a secondary index, the hash function computes a location in a secondary index file
  - This location contains a bucket of physical addresses of records that hash to this logical location



How Full should Buckets be?

- Space utilization:

$$\textit{utilization} = \frac{\text{\# keys used in a bucket}}{\text{total \# keys that fit in a block}}$$

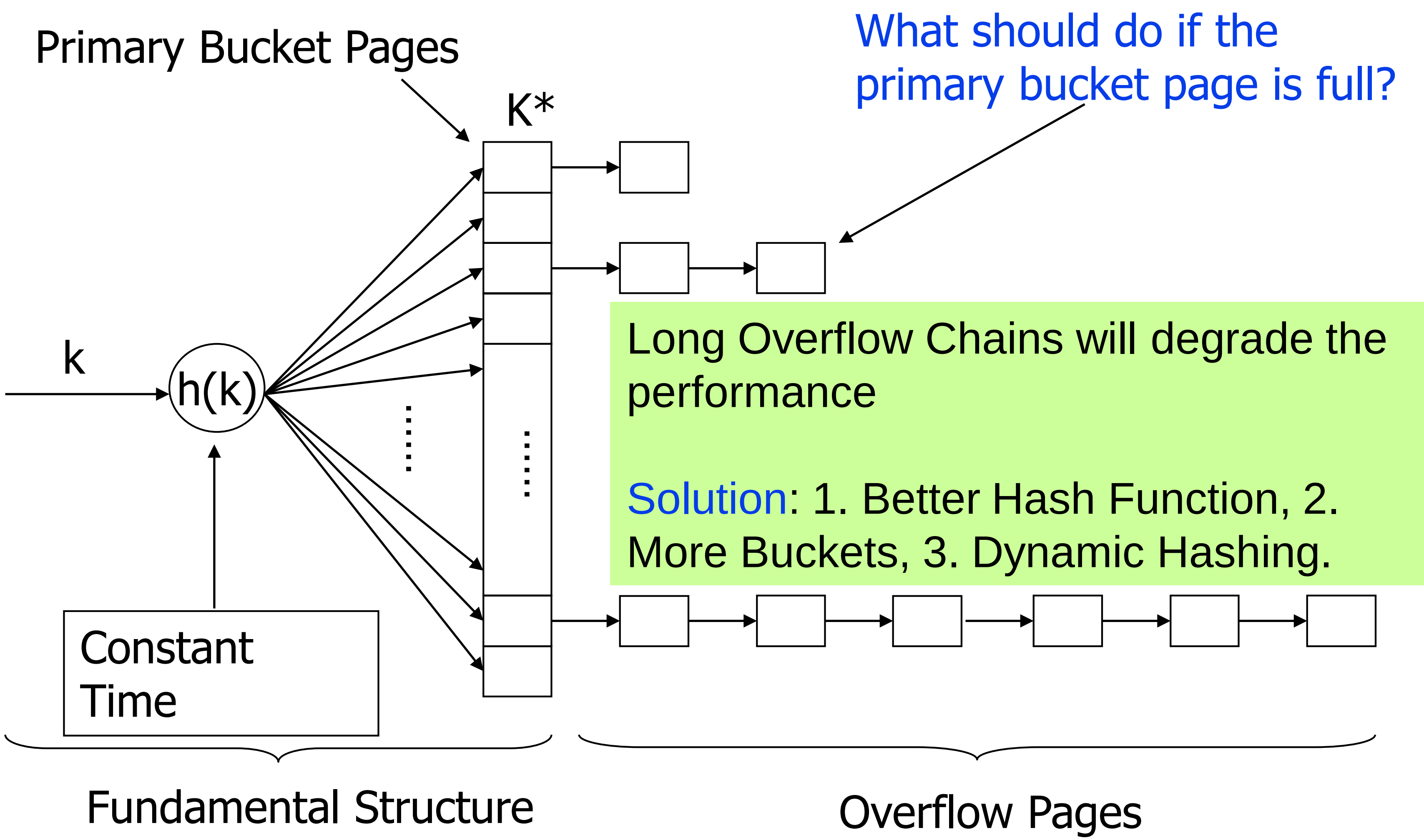
  - If too small: wasting space
  - If too big, overflows significant

- A good space utilization:
  - depends on how good the hash function is
  - Rule of thumb: usually between 50% and 80%
    - If U < 50%, space is underutilized
    - if U > 80%, overflows become significant

Efficiency of Static Hash Tables

- Searching for a key v:
  - ❶ Evaluate *h(v)*
  - ❷ Fetch bucket at *h(v)*
  - ❸ Search bucket
- In an ideal case, we have enough buckets so that each bucket consists of a single block
  - Lookup: one disk I/O
  - Insert / Delete: two disk I/O's
- In such a case, static hash tables (fixed **B**) perform better than simple dense or sparse indexes, or even B+-trees
- Dynamically growing files produce overflow chains, which negate the efficiency of the hashing algorithm
  - many blocks per chain may need to be searched
  - hence, `#blocks/bucket` should be as low as possible

Static Hash Tables



Long Overflow Chains will degrade the performance

Solution: 1. Better Hash Function, 2. More Buckets, 3. Dynamic Hashing.

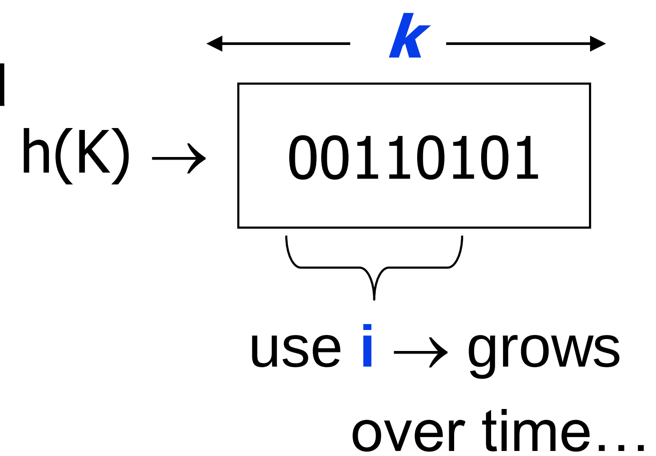
Dynamic Hash Tables

- Bucket (primary page) becomes full
  - Why not re-organize the file by doubling # of buckets?
    - Reading and writing all pages is expensive!
- Idea: the hash file size can grow and shrink "on the fly" in response to the size of the data
  - **B** is allowed to vary
  - Trick lies in how hash function is adjusted!
- Two types of dynamic hashing:
  - Extensible: uses a directory that grows or shrinks depending on the data distribution
    - No overflow buckets
  - Linear: No directory
    - Splits buckets in linear order, uses overflow buckets

Extensible Hashing

- First Idea
  - Use a family of hash functions based on **h**:
    $h_k(key) = h(key) \bmod 2^k$
    - The range of hash function has to be extended to accommodate additional buckets (use a sequence of **k** bits of **h(key)** for some large **k**, e.g., 32)
  - At any given time a unique hash, h_k, is used depending on the number of times buckets have been split
    - bucket addresses use fewer bits (say **i** bits from the beginning of the sequence); hence, directory will have 2^i entries
    - each bucket stores **j**, indicating the number of bits used for placing the records in this block ($j \leq i$)

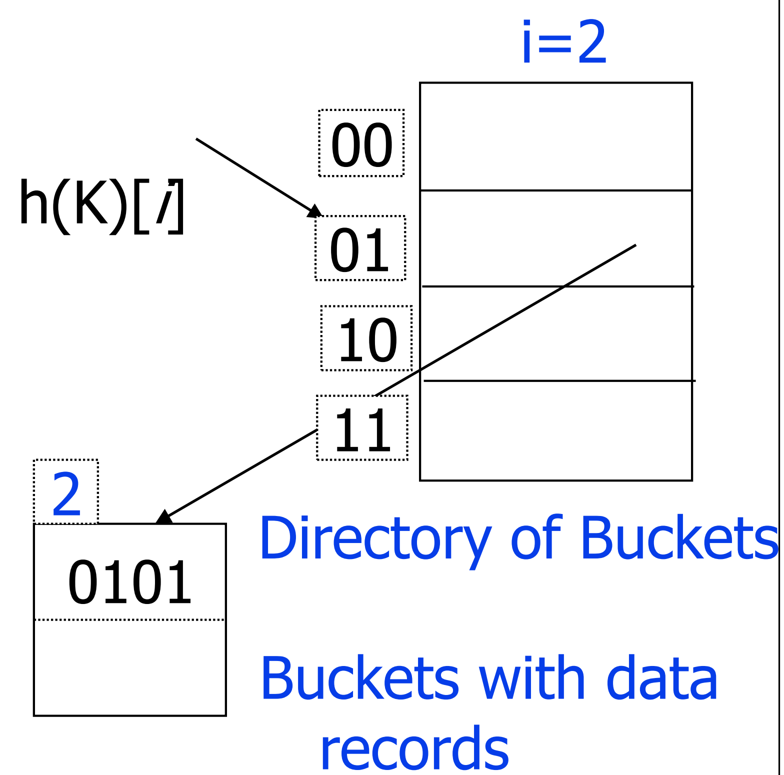
Use **i** of **k** bits output by hash function



Extensible Hashing

- Second Idea:
  - Use directory of pointers to bucket blocks, i.e., introduce a level of indirection
  - The directory's size is a power of 2 and may vary;
    - 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
  - Certain buckets may share a block (if the total number of records of the buckets fit in a block)

Use directory of pointers



For simplicity, "0101" represents a record whose key is hashed to "0101"

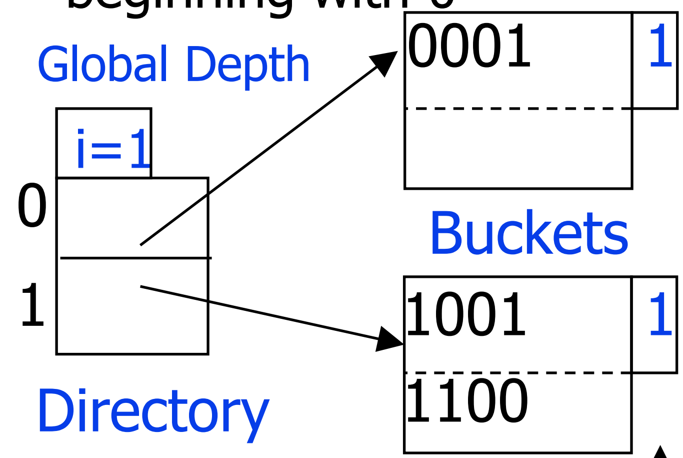
Alternative ❷

Extensible Hashing

- Global depth of directory (i)
  - First i bits of a binary number to tell which bucket an entry belongs to
  - Number of bits needed to express total number of buckets
  - E.g., i=2=>4 buckets; i=3=>8 buckets
  - Increase i by 1 after a directory split
  - Distribute entries across a bucket and its split image based on i th bit
- Local depth of bucket (j)
  - Hash values of data entries in bucket agree on the first j bits
  - Increase j by 1 after a bucket split
  - Assign new j to split image
  - If bucket with local depth j = global depth i is split, then double the directory

- Example: k=4,i=1

Holds records whose key hashes to a sequence beginning with 0

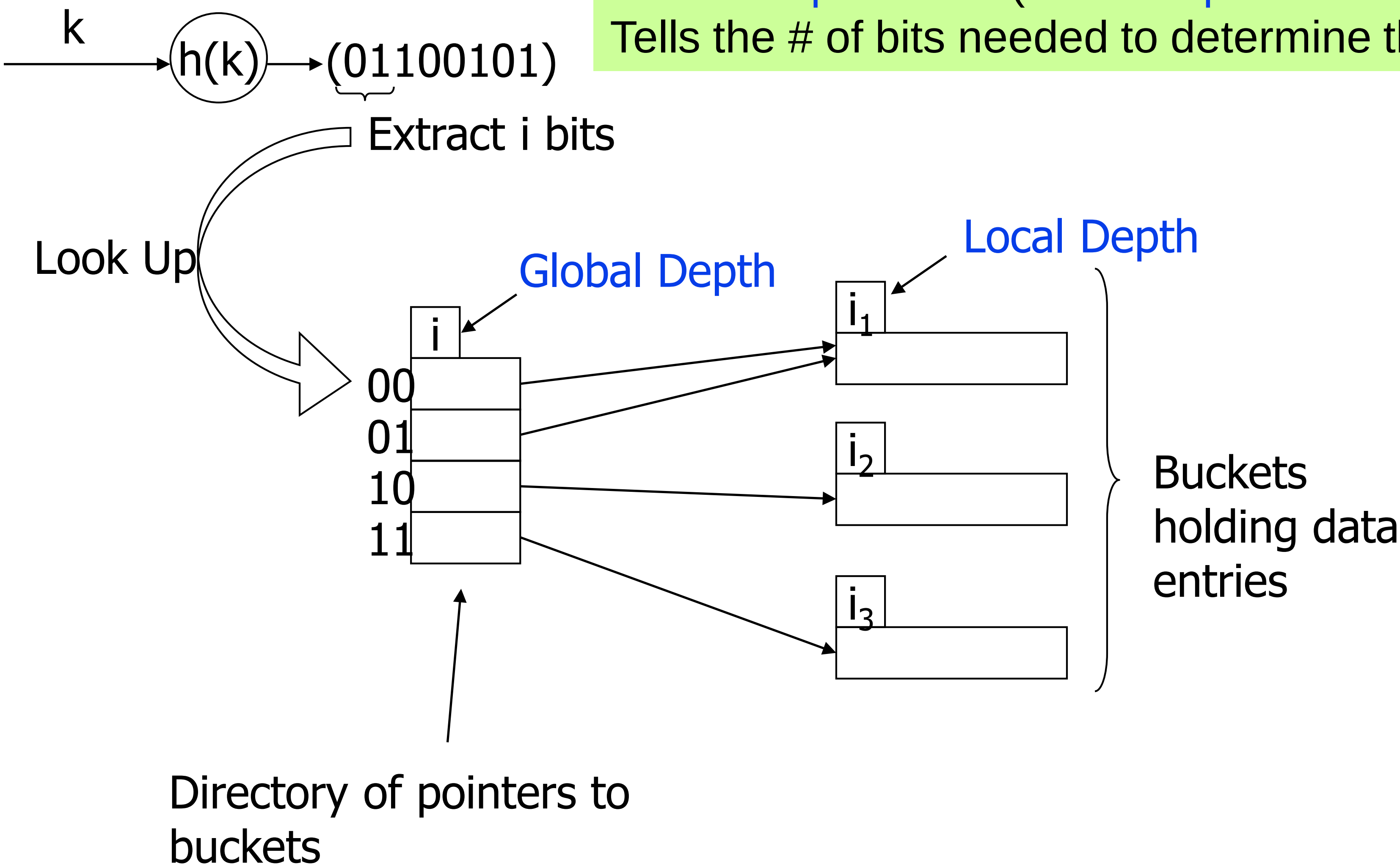


Holds records whose key hashes to a sequence beginning with 1

Local Depth: Number of bits used to determine membership of records in block

Extensible Hashing

Global Depth = max(Local Depth of all buckets)
Tells the # of bits needed to determine the address



Insertion into Extensible Hash Tables

- To insert a record with key **K**:
  - compute **h(K)**; take the first i bits of the sequence returned and follow the pointer in the directory indexed by these i bits (global depth), leading to block **b**
  - if there is room, place record in **b**
  - if not, then, let j be the local depth stored in the block header **b**:
    1. If **j < i** (local < global), then:
       a) Split **b** in two
       b) Distribute records in **b** to the two blocks based on the value of the (j+1)-st bit: those with 0 stay in **b** and those with 1 go to the new block
       c) Update header of each block with the split image j+1
       d) Adjust pointers in directory so that entries point to the correct block depending on their (j+1)-st bit

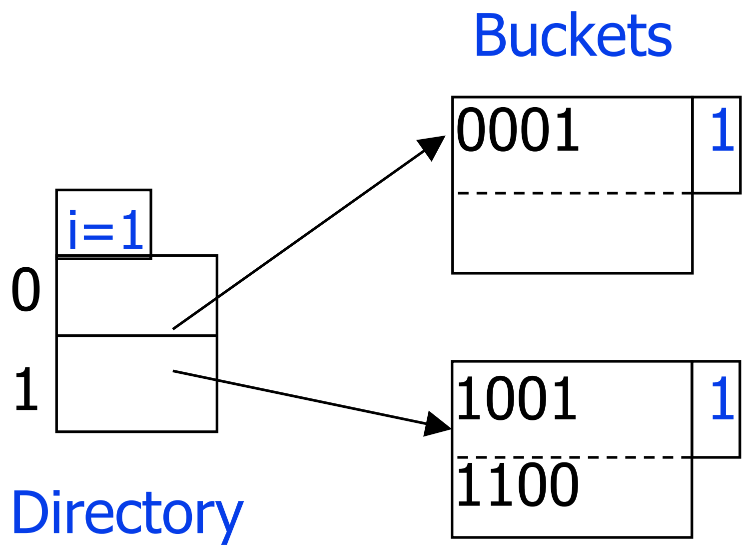
Insertion into Extensible Hash Tables

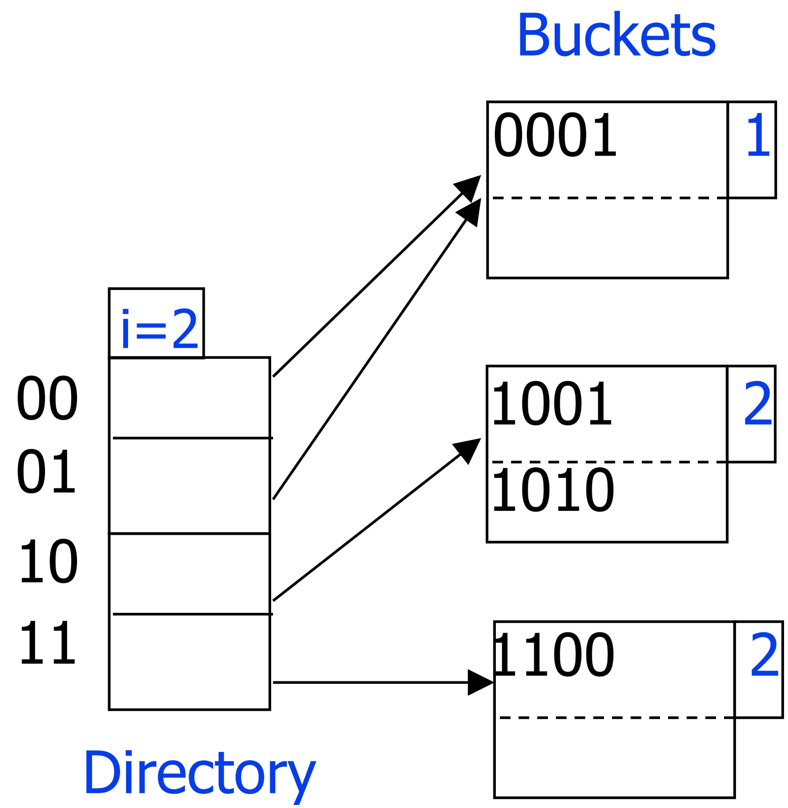
- It may so happen, that examining the `j`-th bit may send all records to one block
  - In this case, the process is repeated with the next higher value of the split image `j`

2. If **`j = i`** (local = global), then:
   a) increment `i` by 1; double the size of the directory so it now has 2^{i+1} entries
   b) let **`w`** be a sequence of `i` bits indexing the entries of the previous directory
      - Then w_0 and w_1 each point to the same block that **`w`** pointed to (entries share the block but the block hasn't changed)
   c) As in case 1, split **`b`** (since **`i>j`**)

Insertion into Extensible Hash Tables

- Example: insert record with value hashing to 1010 in the table

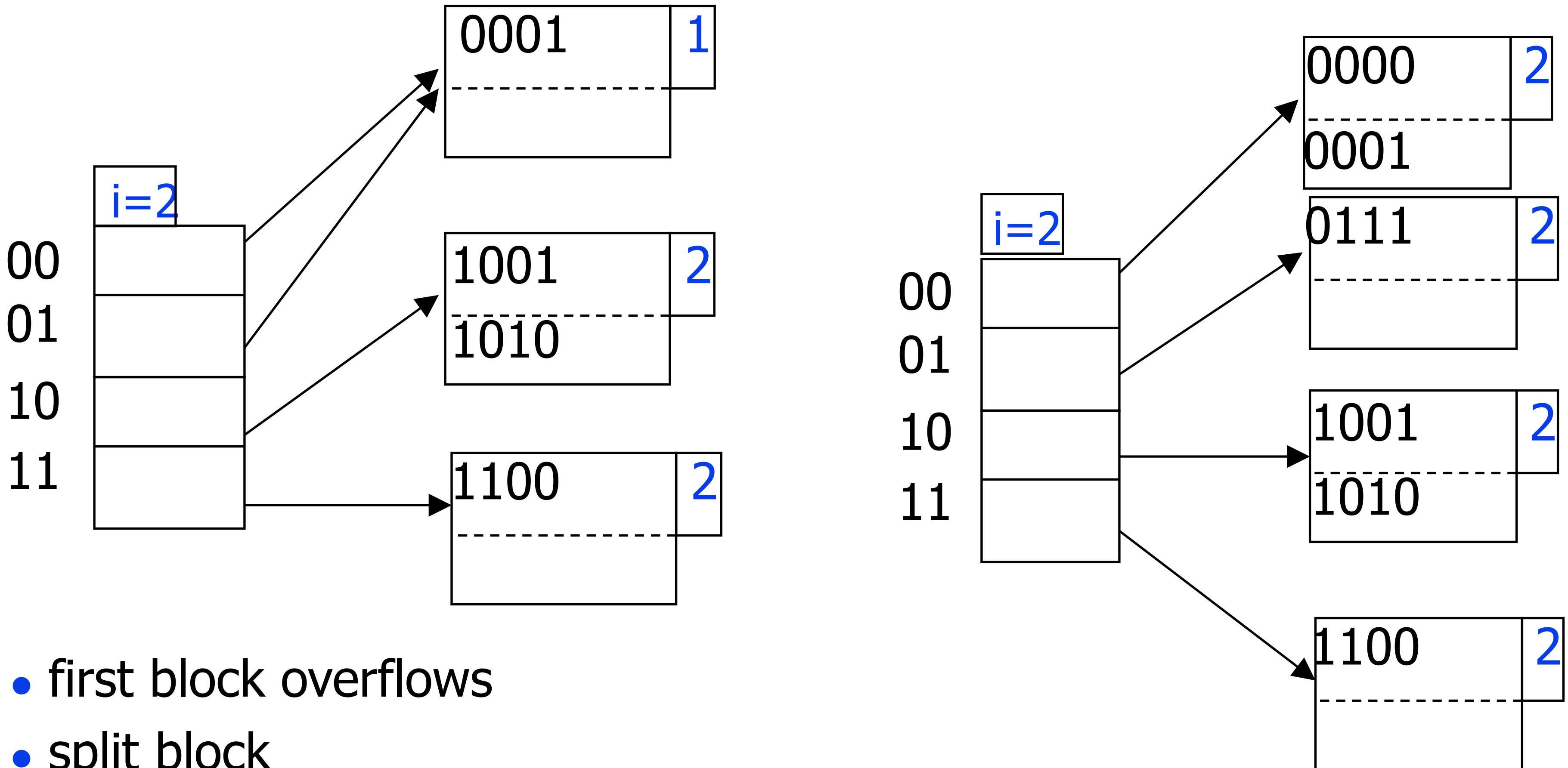




- record must go on the 2nd block
- block is full and must be split
- `j = i = 1; i++`

Insertion into Extensible Hash Tables

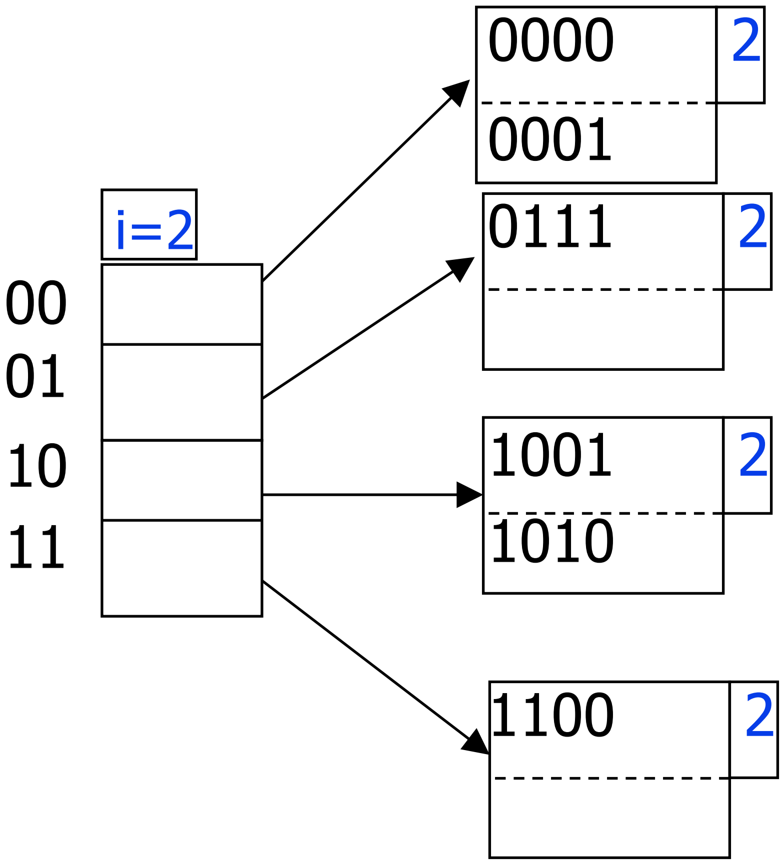
- Example: insert records with values hashing to 0000 and 0111

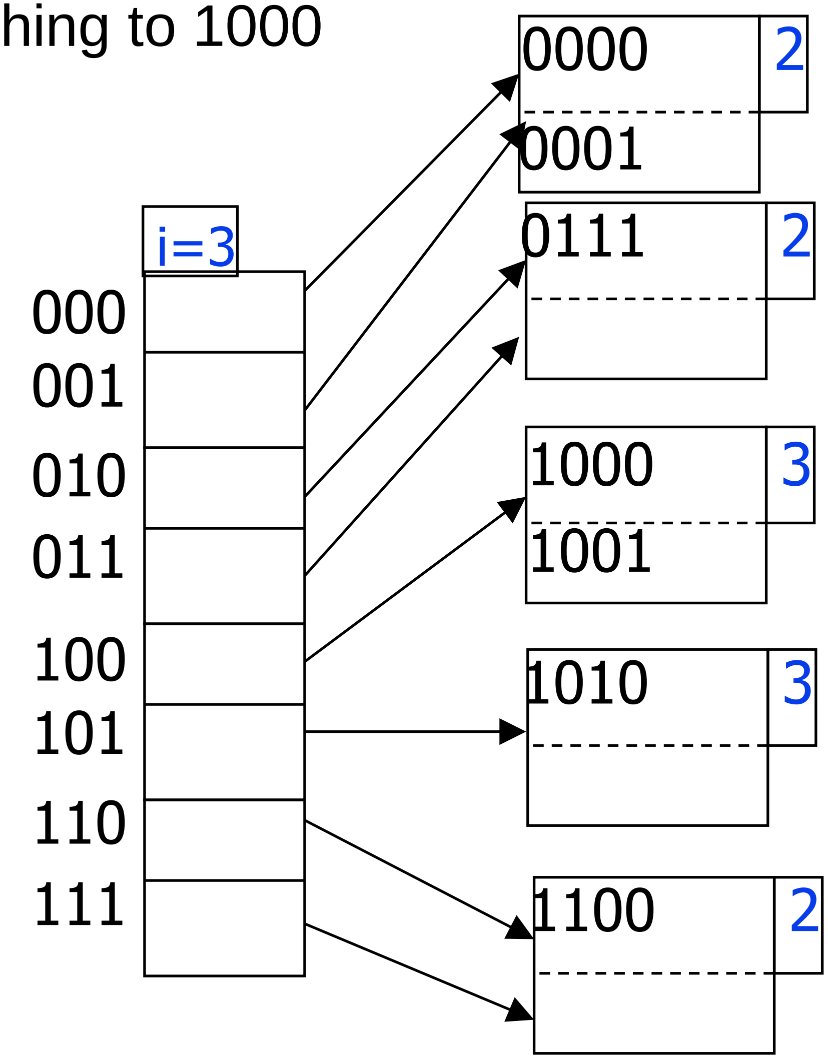


- first block overflows
- split block
- `j < i; j++`

Insertion into Extensible Hash Tables

- Example: insert record with value hashing to 1000





- block for 10 overflows
- `j = i = 2; i++`

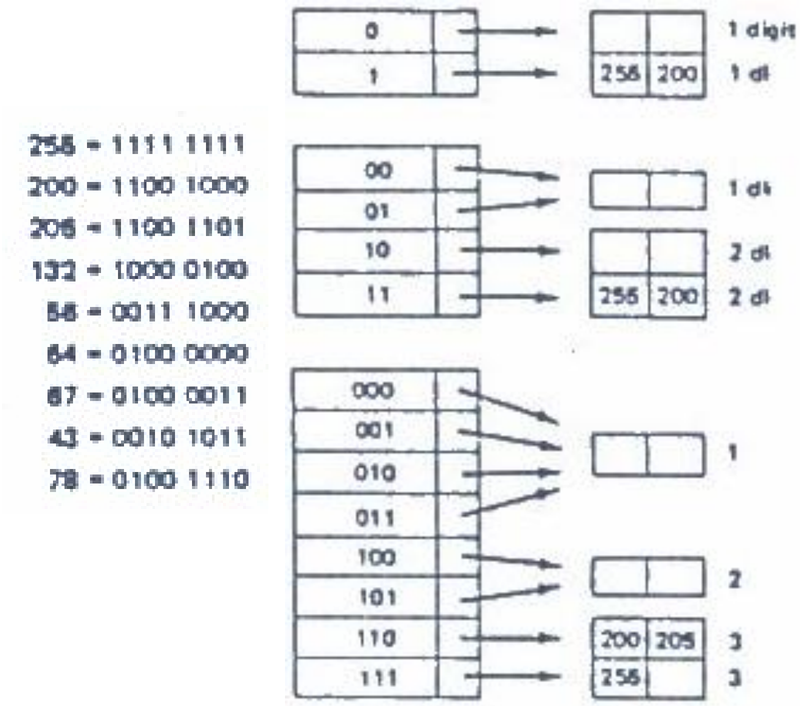
Deletion from Extensible Hash Tables

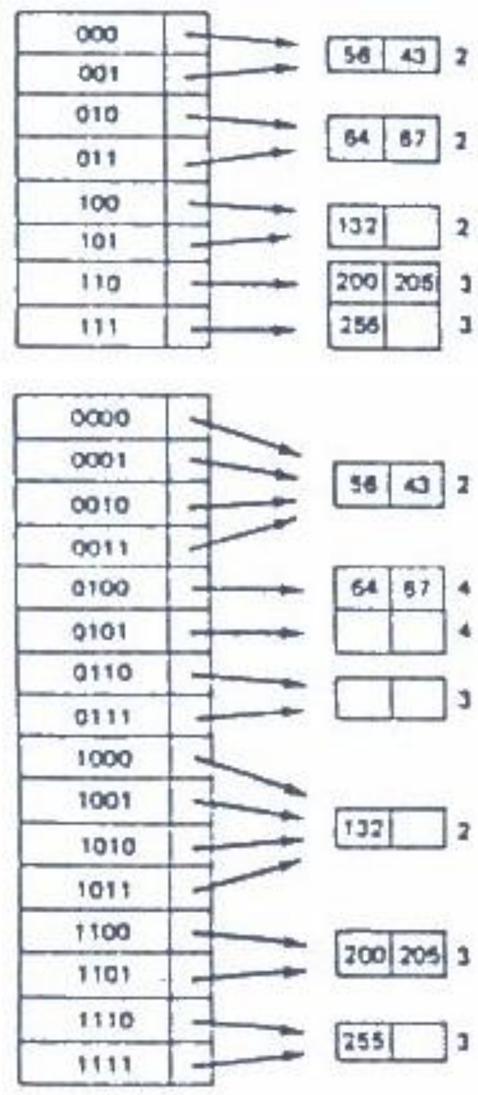
- To delete record with key **K**:
  - remove data entry from bucket
  - if bucket is empty
    - merge bucket with its split image
    - decrease local depth
    - If each directory element points to the same bucket as its split image
      - Halve directory
      - Reduce global depth

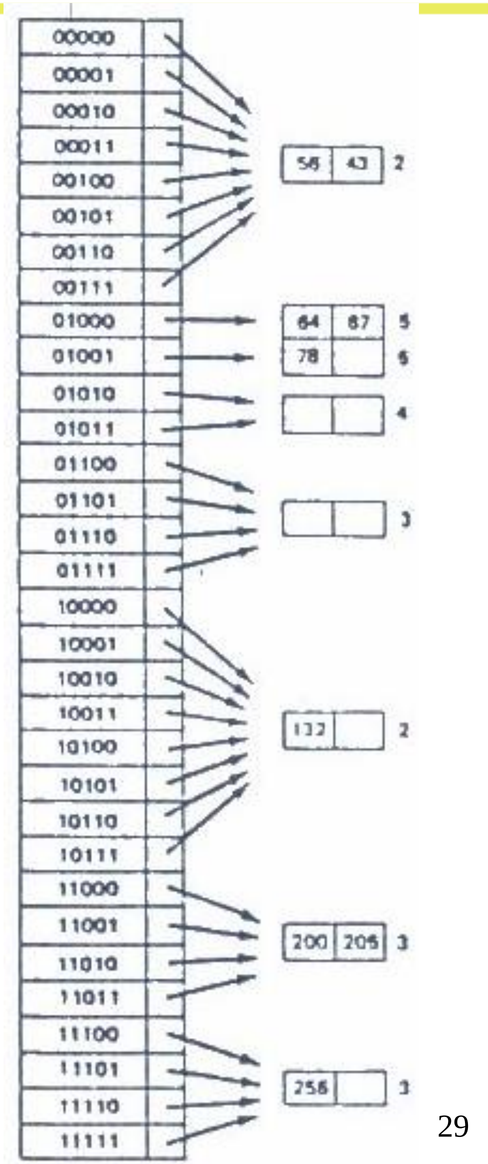
Analysis of Extensible Hash Tables

- With uniform distributed addresses, all the buckets tend to fill up at the same time => split at the same time (Periodic and fluctuating)
  - As buffer fills up to 90%
  - After a concentrated series of splits drops to under 50%
- Space utilization of the bucket
  - R (# of records), b (block size), B (# of Blocks)
  - Utilization = R / b*B
  - Average utilization ~ln 2 (natural logarithm) = 0.69 ==> 69%
    - recall normal B+-tree: 67%, B+-tree with redistribution: 85 %
- Space utilization for the directory
  - How large a directory should we expect to have, given an expected number of keys?
    - estimated directory size = $3.92/b*R^{(1+1/b)}$ Flajolet (1983)
  - Overall Load Factor (LF) of the file below 2 seeks, 75%~80% utilization Litwin (1980)
    - LF: The number of records in the file divided by the number of places for the records in the primary area

A Pathological Case







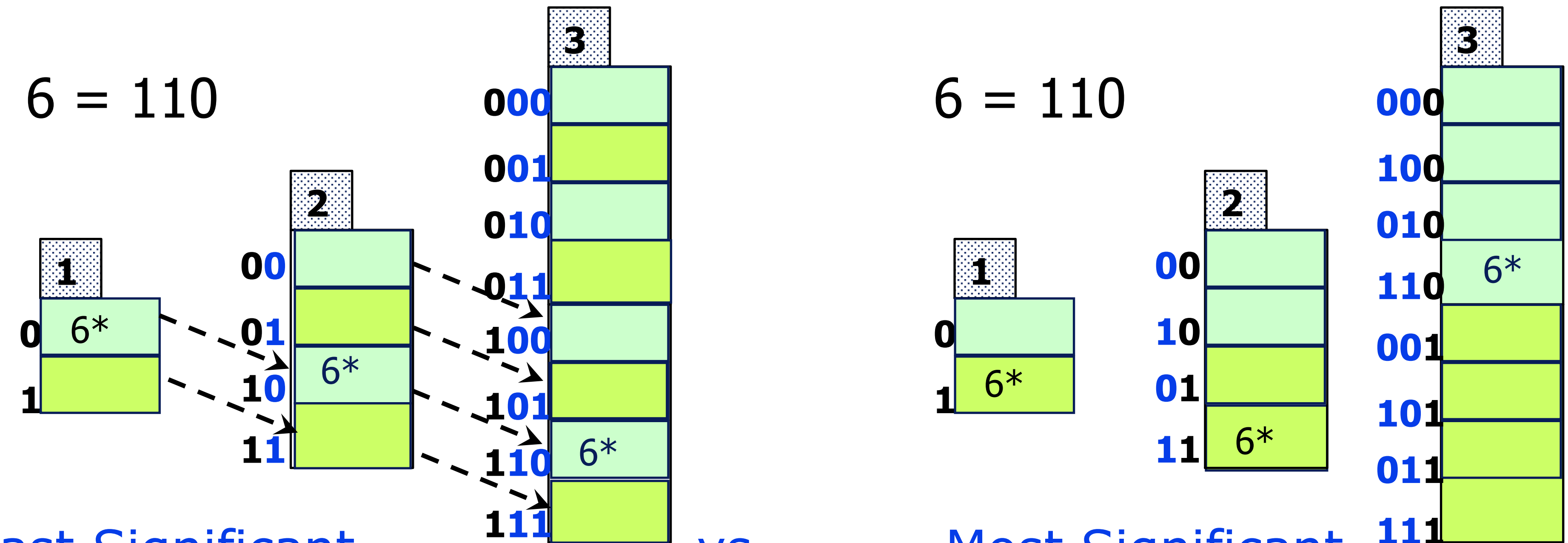
- A pathological case: We need a 32-entry table for 9 records
  - Buckets are labeled with the number of digits used. The bucket factor is 2

Efficiency of Extensible Hash Tables

- Example: 100MB file, 100 bytes/record, 4K pages contains 1.000.000 records (as data entries) and 25.000 directory entries
  - chances are high that directory will fit in memory
    - With 80% utilization the directory size will be
      - 1.2 * 25.000 * 100 = 3.000.000 = 3M
- Pros:
  - equality search can be answered with only one I/O to locate the record
  - if the size of the bucket directory is small enough to be kept in main memory no disk I/O is required to look-up the directory
- Cons:
  - when the size of the bucket directory is doubled (if `i` is already large), it may no longer fit in main memory
  - if the number of records per block is small, block splitting may occur earlier than actually required
- Can we do better? (smoother growth of bucket directories)
  - In Linear Hashing, buckets are split from left to right, regardless of which one overflowed (simple, but it works!!)

Directory Doubling: Least vs. Most Significant Bits

- 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
- Use of least (vs most) significant bits enables efficient directory doubling via copying!
  - doubled by copying it over and `fixing' pointer to split image page

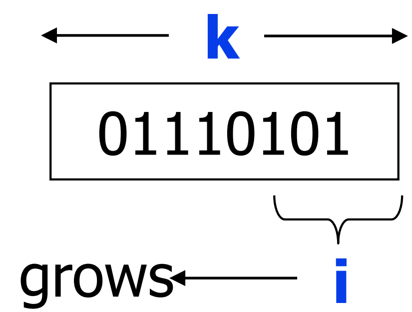


Least Significant vs. Most Significant

Linear Hashing

- Handles the problem of long overflow chains (chaining approach) without using a directory, while it also handles duplicates
- First Idea: Use a family of hash functions h_0, h_1, h_2, ...
  - Initial number of buckets **B**
  - $h_k(key) = h(key) \bmod (\mathbf{B} * 2^k)$
  - **h** is some hash function
    - range is not 0 to **B**-1
  - If $\mathbf{B} = 2^{d0}$, for some d_0, h_i consists of applying **h** and looking at the last d_i bits, where $d_i = d_0 + i$
  - h_{i+1} doubles the range of h_i
    - Eg. **B** = 32 = 2^5, $h_0 = h \bmod 32$, $d_1 = d_0 + 1 = 6$, $h_1 = h \bmod (32 * 2)$

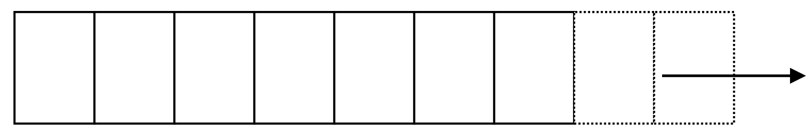
Use **i** low order bits of hash



Linear Hashing

- Second Idea: Split buckets in 'round-robin'
  - Counter `Level` indicate current round number (initially 0)
  - Bucket to split denoted by `Next` (initially bucket 0 or first bucket)
  - $B_{Level} = 2^{Level} B$ = # buckets in file at the beginning of round `Level`
    - # buckets at beginning of round 0, denoted by B_0 is B
  - Round ends when all B_{Level} buckets have been split

The size of the table will grow gradually, but not double in size



Record blocks

Linear Hashing

- During round number `Level`, only hash functions h_{Level} and $h_{Level+1}$ are used, so at any given point in a round, we have:
  - buckets that have been split (0 to `Next`-1)
  - buckets that are yet to be split (`Next` to $B_{level}-1$)
  - buckets created by splits in this round (B_{Level} to $2B_{Level}-1 < B_{level+1}$)

Linear Hashing

- In the middle of a round

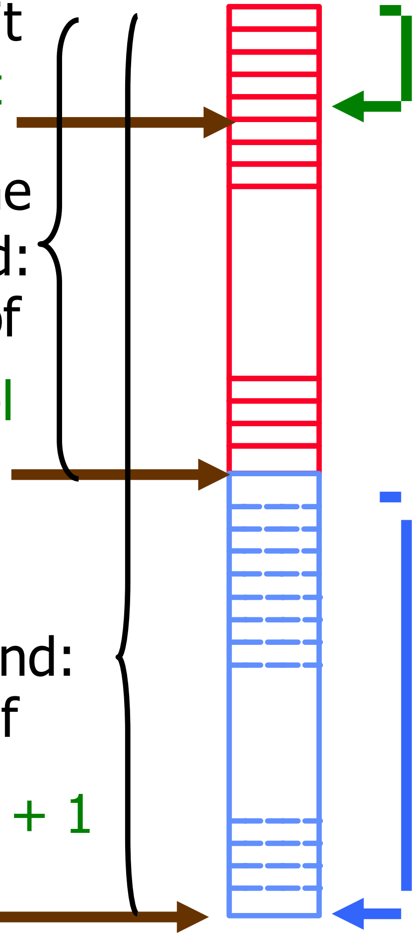
Bucket to be split
Next

Buckets that existed at the beginning of this round: this is the range of h_{Level}

B_{Level}

Buckets available at the beginning of the next round: this is the range of $h_{Level+1}$

$2B_{Level}-1$



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

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

Searching Linear Hash Tables

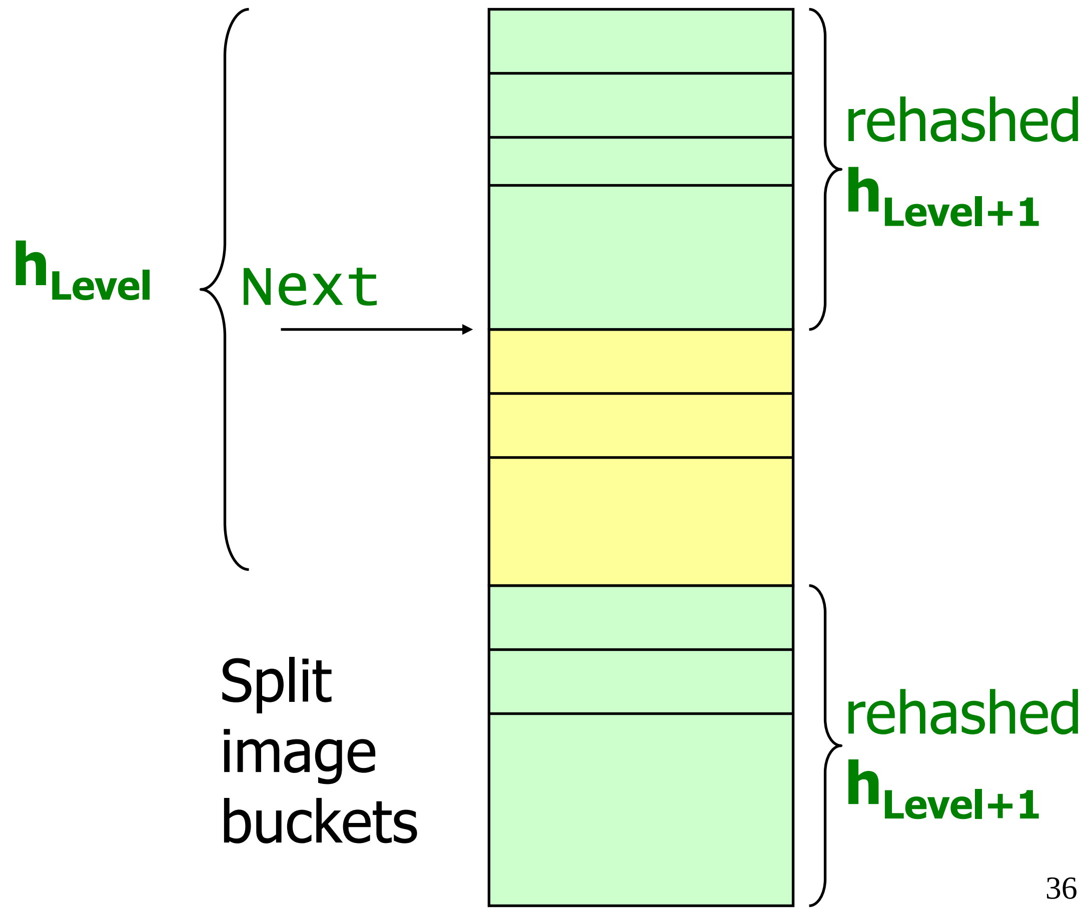
- To find bucket for data entry **K**:

active hash table buckets are those in $\mathbf{h}_{Lavel}$'s range: [0 .. 2^{Level} **B**– 1]

1. Apply hash function $\mathbf{h}_{Level}$ to search key $\mathbf{h}_{Level}(\mathbf{K})$

2. If it leads to an unsplit bucket **b** (bucket Next to $\mathbf{B}_{Level}$)
   - look for **K** there

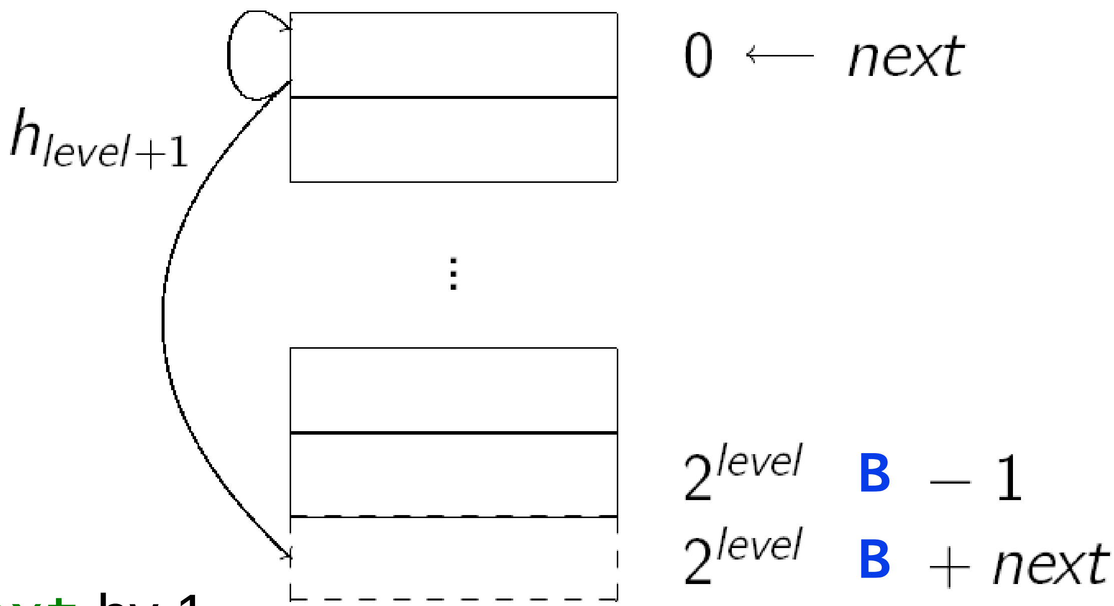
3. If it leads to a split bucket **b** (bucket 0 to Next-1), **K** can be in b or bucket b + B_{Level}
   - apply $\mathbf{h}_{Level+1}(\mathbf{K})$ to find out



Linear Hashing: Bucket Splitting

- Allocate a new bucket, append it to the hash table (its position will be 2^{Level} **B** + Next)

- Re-distribute the entries in bucket Next by rehashing them via $h_{Level+1}$ (some entries remain in bucket Next, some go to bucket **B***2^{Level}+Next)

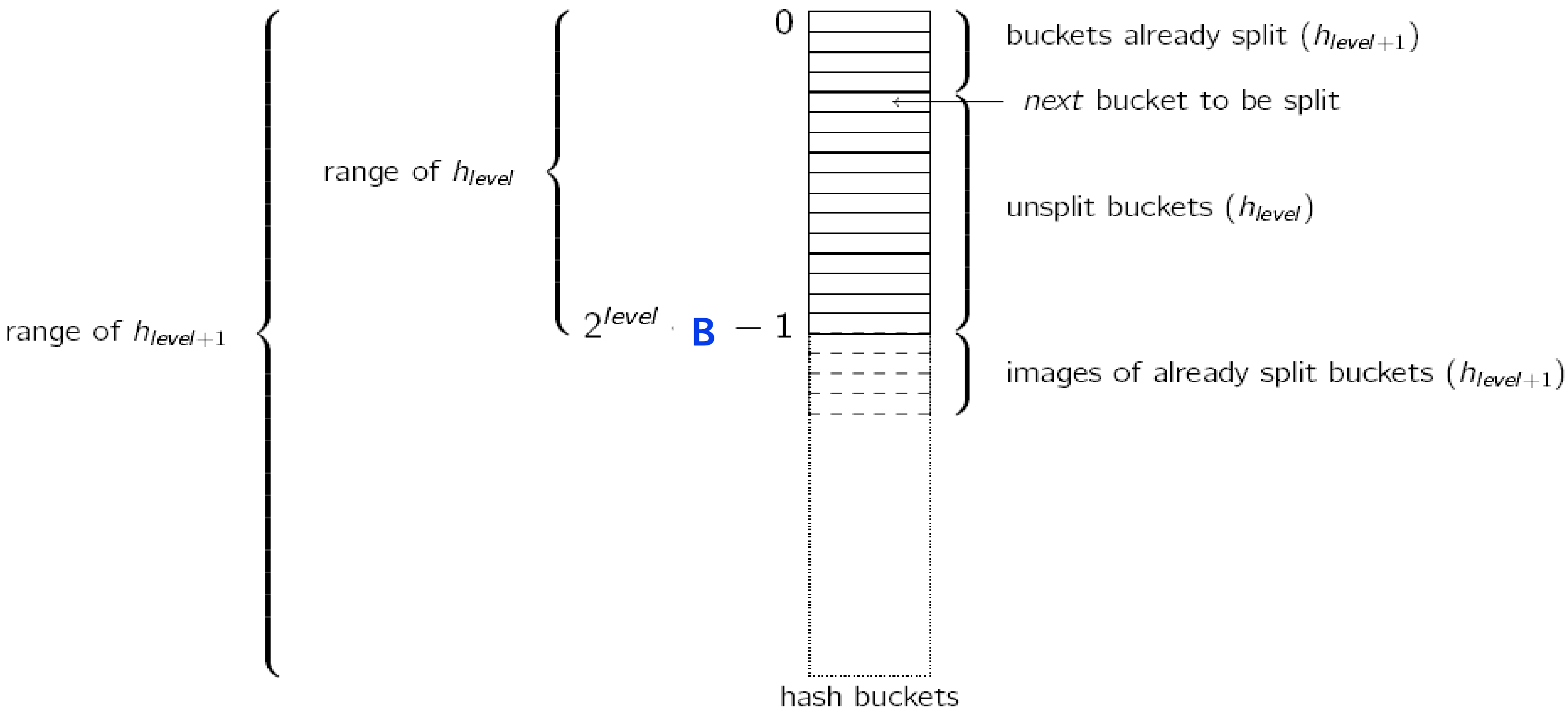


- increment Next by 1

Linear Hashing: Rehashing

- Hashing via h_{Level} has to take care of Next's position:

h_{Level}(key) = { < Next: we hit an already split bucket, rehash
>= Next: we hit a yet unsplit bucket, bucket found



Linear Hashing: Split Rounds

- A bucket split increments `Next` by 1 to mark the next bucket to be split

- How would you propose to handle the situation if `Next` is incremented beyond the last current hash table position, i.e., `Next` $> 2^{Level}B - 1$?
  - If `Next` $> 2^{Level}B - 1$, all buckets in the current hash table are hashed via $h_{Level+1}$ (see previous slides)
  - Linear hashing thus proceeds in a round-robin fashion:
    - If `Next` $> 2^{Level}B - 1$, then
      - increment level by 1,
      - reset next to 0 (start splitting from the hash table top again)

- In general, an overflowing bucket is not split immediately, but—due to round-robin splitting—no later than in the following round

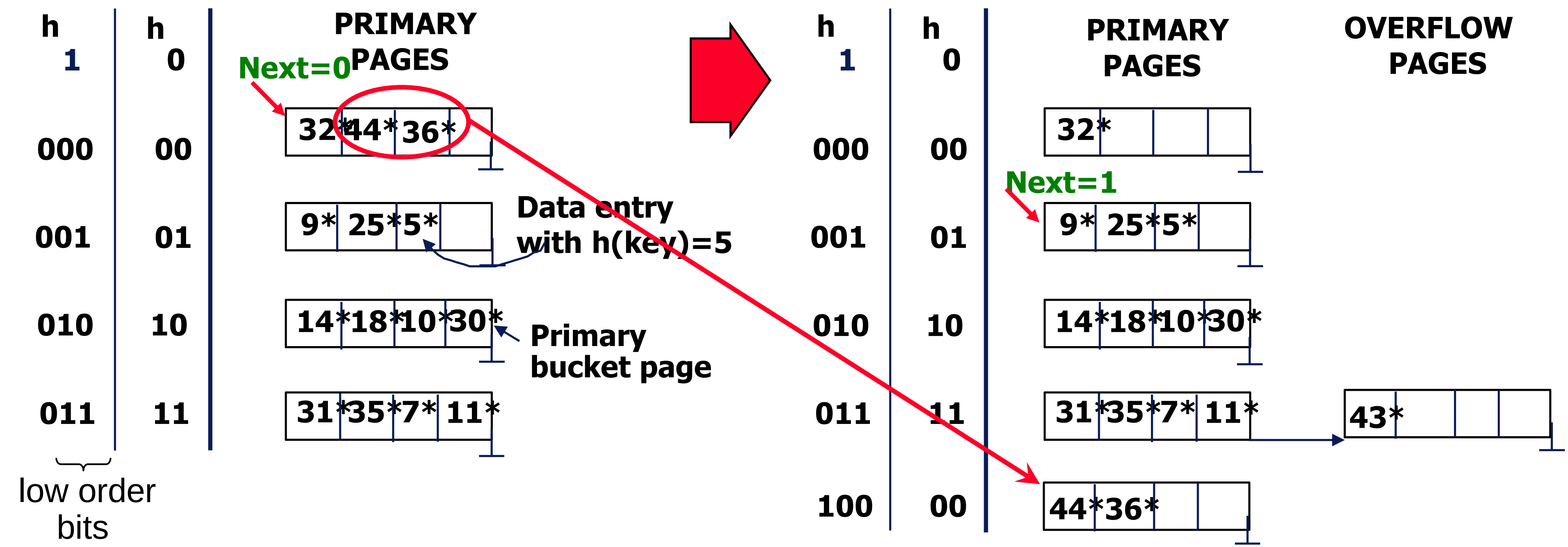
Insertion into Linear Hash Tables

- To insert a data entry **K**:
  - Locate bucket by applying $h_{Level}(K)$ or $h_{Level+1}(K)$
    - If bucket is full
    - Add overflow page and insert data entry
    - (Maybe) Split bucket `Next`
      - Hash function $h_{Level+1}$ redistributes entries between bucket `Next` and bucket `Next` + B_{Level}
      - Increment pointer `Next`
- Buckets are split round-robin, long overflow chains don't occur
  - in general, the spitted bucked is not the bucket which triggered the split!
  - each bucket may use overflow pages
- Choose any criterion to `trigger' split
  - insertions filled a primary bucket page beyond c % capacity,
  - or the overflow chain of a bucket grew longer than p pages, or . . .
- We will examine, in the sequel, the first growth method

Example of Linear Hashing

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

Level=0, B=4, primary bucket capacity = 4 **Level=0, Insert record such that $h0(key)=43=101011_2$**



(This info is for Illustration only!)

(The actual contents of the linear hashed file)

Example: End of a Round

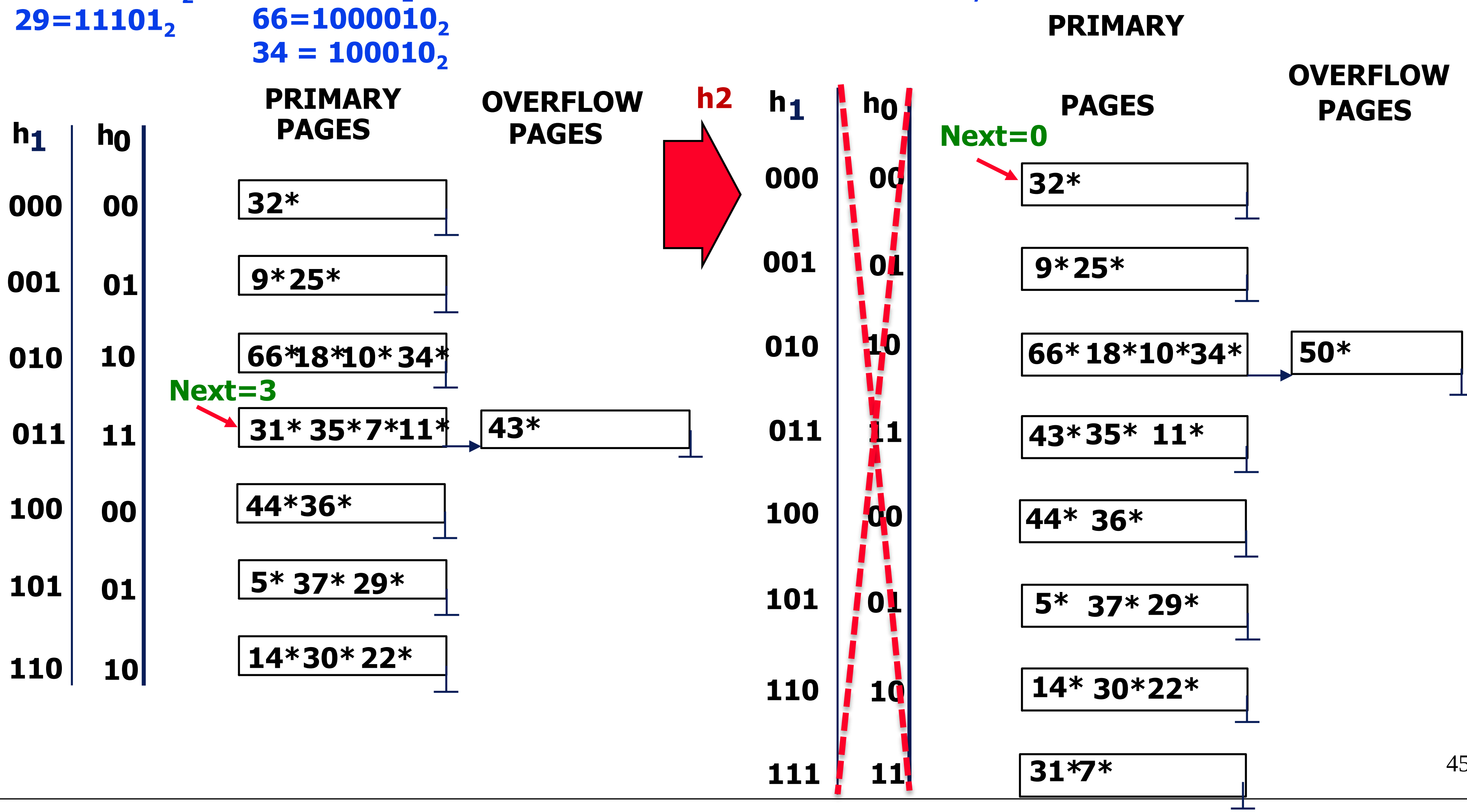
Level=0 , Insert records such that $h_0(k)$

$37=100101_2$ $22=10110_2$

$29=11101_2$ $66=1000010_2$

$34 = 100010_2$

Level=1 , B=8



Analysis of Linear Hashing

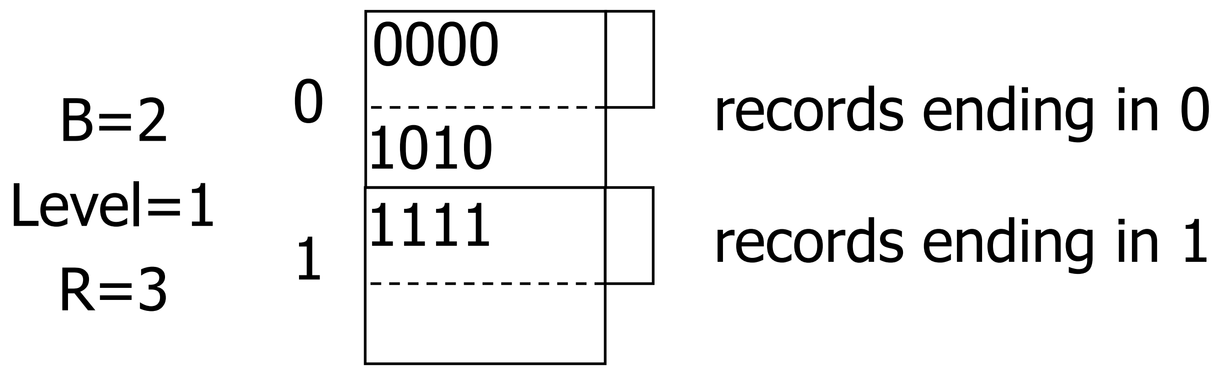
- **B**: the current number of bucket blocks in use (at round number `Level`)
  - As the table grows, the initial # of bucket blocks is increased but it may not always be a power of 2
- **`Level`**: the # bits of **`h(k)`** used to address buckets is $\lfloor \log_2 B \rfloor$ (low-order bits)
- **R**: number of records stored in hash table
  - initially 0 and increased as records are added
- Utilization of the hash table is the number of stored records divided by the number of possible storage places = **R** / **B** * c (#entries/block)
  - ratio **R**/**B** limited so that the average number of records per bucket is a fixed fraction of the number of records that fit in one block
  - overflow blocks are permitted, but the average number of overflow per bucket will be <= 1
- We will use this ratio to determine when to grow or shrink the hash table
  - grow when **R**/**B** >= 90% and shrink when **R**/**B** <= 75%
  - we will use the average value of 85% as the threshold for growth

Insertion into Linear Hash Tables: Alternative Algo

- To insert record with key K:
  - Compute $h(K)=b$ and determine the i-bit rightmost ($b=a_1a_2...a_i$) sequence of $h(K)$ to use as the bucket number
    - If $b<B$ the bucket with number b exists and the record is placed there
    - If $B \leq b < 2^i$, then the bucket does not exist and we have to place the record in bucket $b-2^{i-1}$ (this is the bucket we would obtain if a_1 changed to 0)
      - If the bucket we add has number $1a_2...a_i$, then we split the bucket numbered $0a_2...a_i$ and divide the records depending on their last i bits
    - If $B>2^i$ then i is incremented by 1 (leading 0 is added)
  - Each time an insertion need to be performed, we examine the ratio R/B and if it is too high, we increase B by 1 (R the # of records in hash table)

Linear Hashing Occupancy Example

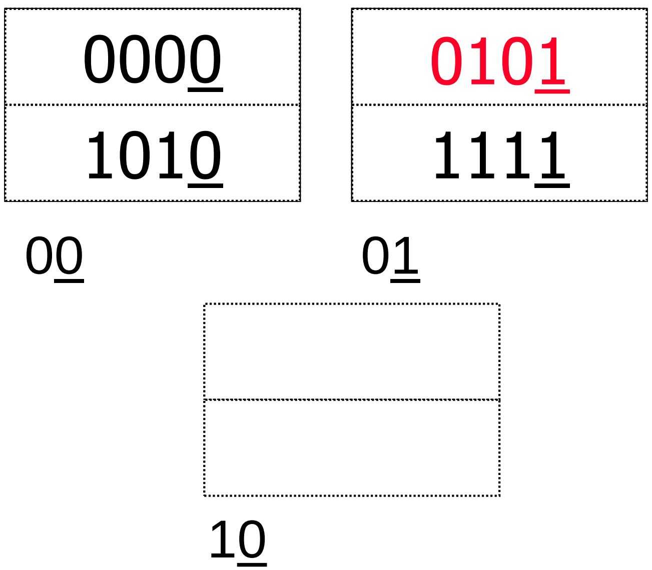
- Example: B=2, Level=1, assume **h** produces 4-bit sequences (k=4)



- If **R** <=1.7**B**, and block holds 2 records then on the average, occupancy c of a bucket does not exceed 85% (i.e., ≤ 1.7/2) of the block capacity

Linear Hashing: Second Example

- Example: 2 keys/block, R=3, B=2, Level =1 assume **h** produces 4-bit sequences (k=4)



- insert 0101
- now R=4 >1.7B (**R**/**B** = 2)
→ B++ Level++
→ get new bucket 10 and distribute keys between buckets 00 and 10

Rule

Rule

If h(k)[i] $= (a_1 \ldots a_i)_2 <$ B, then
look at bucket h(k)[i];
else
look at bucket h(k)[i] $- 2^{i-1} = (0a_2 \ldots a_i)_2$

Linear Hashing: Second Example

-> R=4, B=3, Level =2;

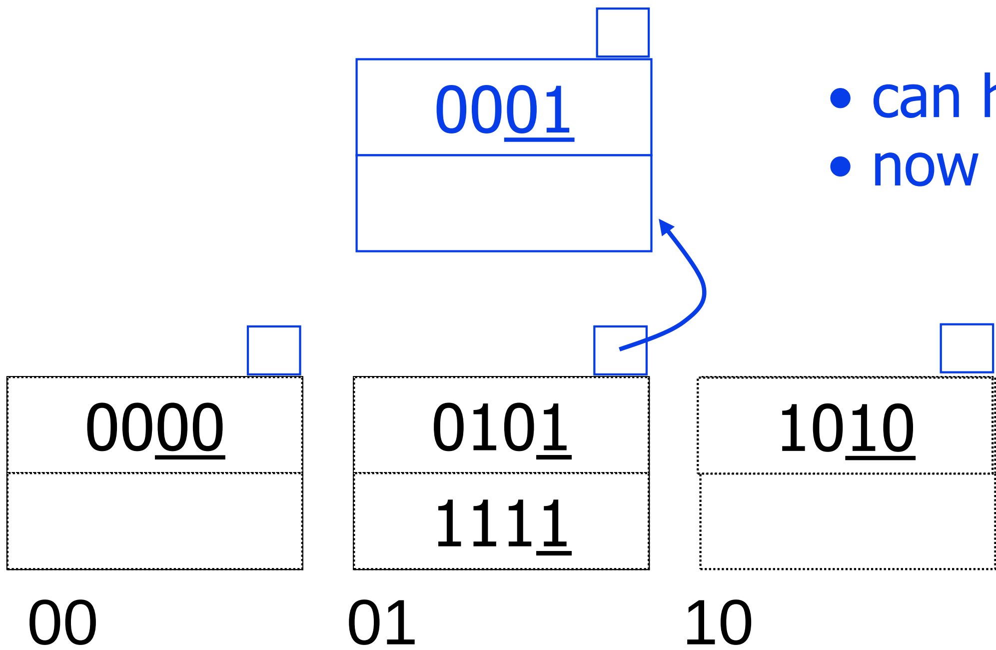
distribute keys between buckets 00 and 10:

00	01	10
0000	0101	1010
~~1010~~	1111	

- now R=4 <1.7B (**R**/**B** = 1.33) !

Linear Hashing: Second Example

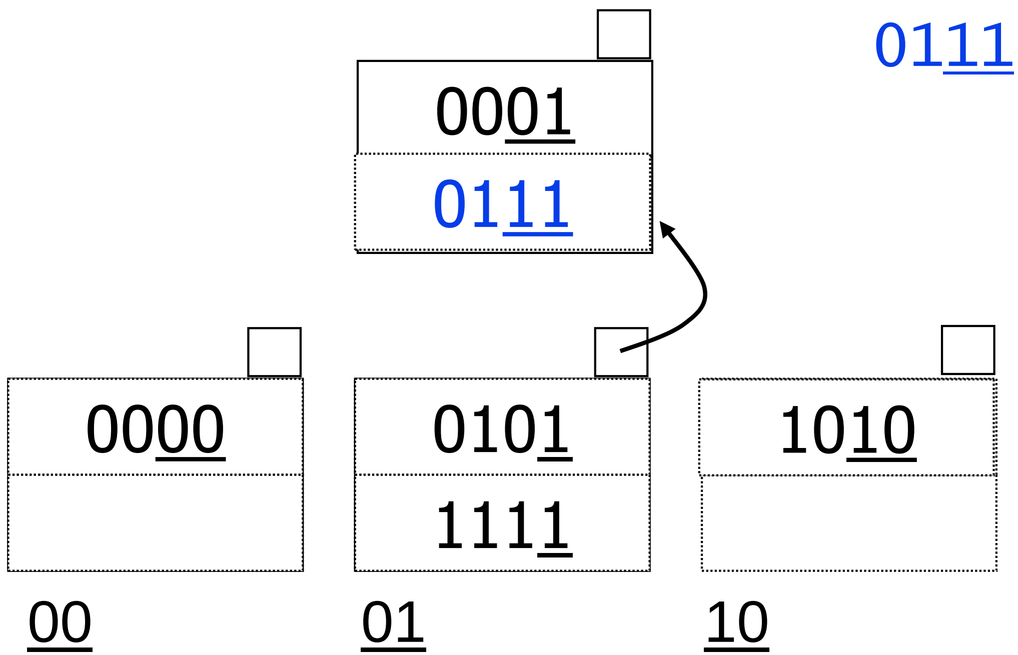
R=4, B=3, Level =2; insert 0001:



- can have overflow chains!
- now **R**/**B** becomes 5/3 < 1.7

Linear Hashing: Second Example

R=5, B=3, Level =2



- insert 0111
- bucket 11 not in use

→ redirect to 01

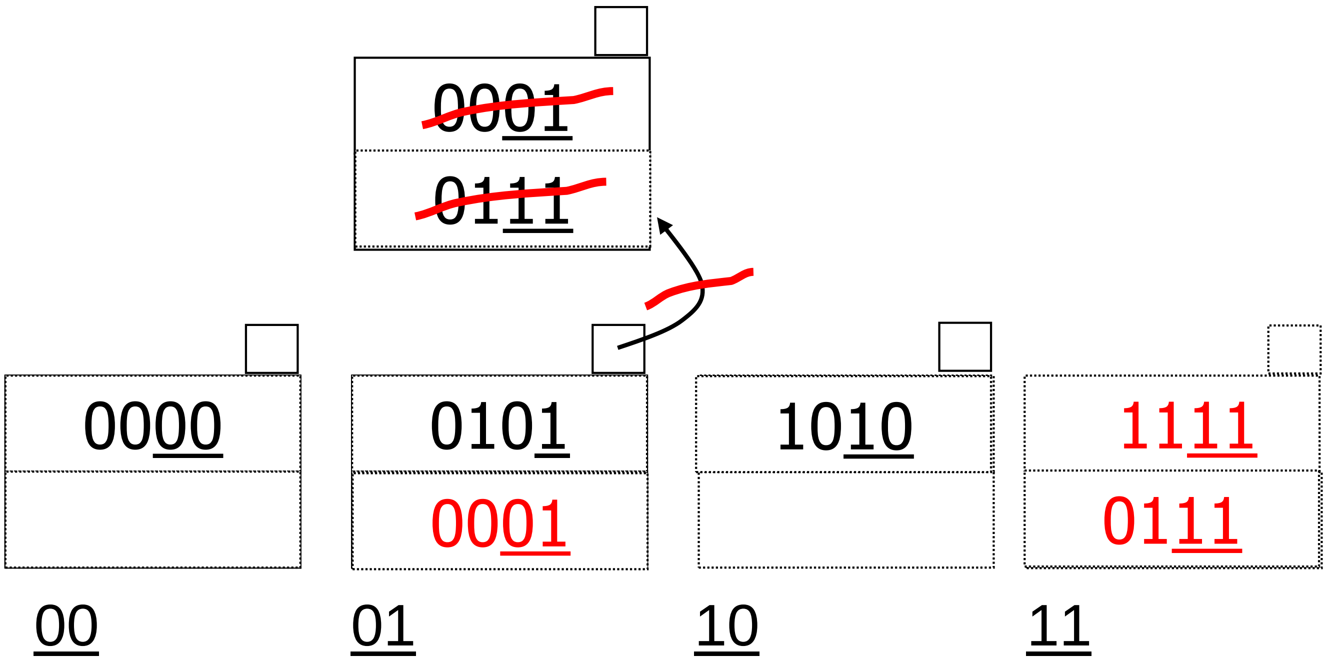
- now R=6 > 1.7B
  → get new bucket 11

Rule

If h(k)[i] = $(a_1 \ldots a_i)_2$ < B, then
look at bucket h(k)[i];
else
look at bucket h(k)[i] – $2^{i-1} = (0a_2 \ldots a_i)_2$

Linear Hashing: Second Example

R=6, B=4, Level =2; distribute keys between 01 and 11

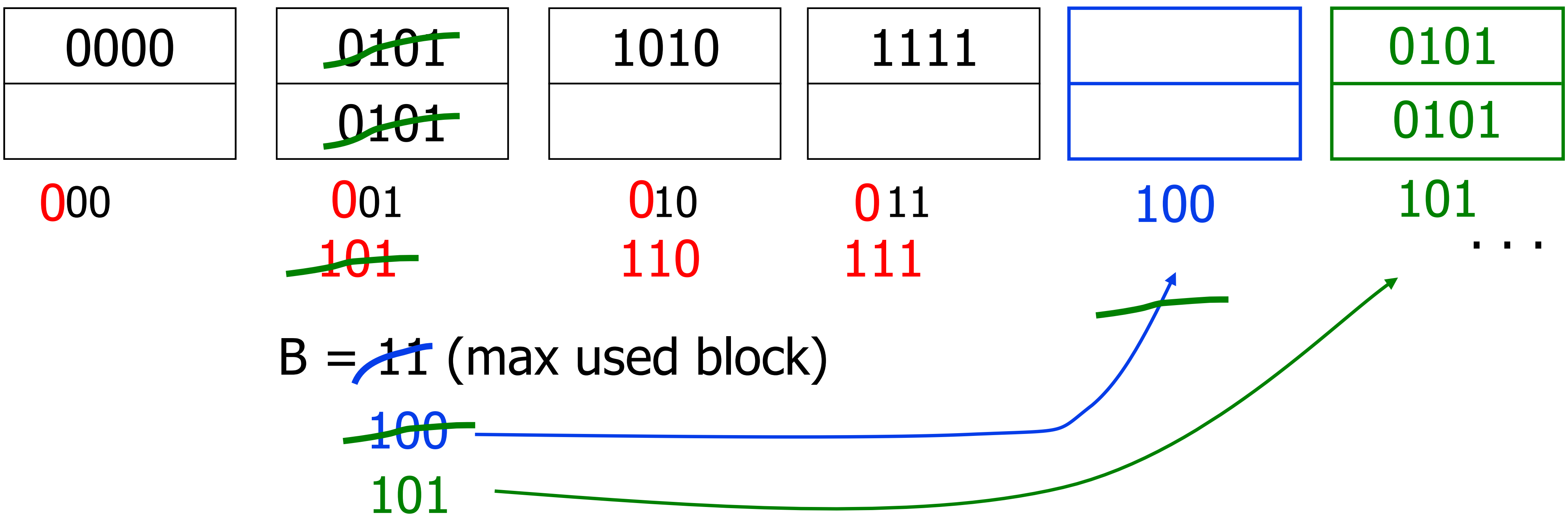


Overflow block no longer needed !

Linear Hashing: Second Example

Example Continued: How to grow beyond this?

```
B++
Level++ (2) 3
```



Linear vs. Extensible Hashing

- Two schemes are quite similar
  - Imagine Linear Hashing (LH) has a directory with elements 0 to **B**-1
  - First split at bucket 0, add directory element **B**
    - Imagine entire directory doubled at this point
    - Elements <1,**B**+1>, <2,**B**+2>, ... are the same
    - Only create directory element **B**, which differs from 0, now
  - Second split at bucket 1, create directory element **B**+1
  - So, directory can double gradually
    - Also, primary bucket pages are created in order
    - If they are allocated in sequence too, then finding bucket **i** is easy
    - Thus, we actually don't need a directory!
- LH is recommended when main storage is at a premium since it requires no directory
  - Particularly useful in a small computer environment
- EH could be useful if sufficient main memory is available to hold the directory
  - Doubling and halving the directory size is expensive

Hashing vs. B+ trees

- In a typical DBMS, you will find support for B+ trees as well as hash-based indexing structures
  - Cost of periodic re-organization
  - Relative frequency of insertions and deletions
  - Is it desirable to optimize average access time at the expense of worst-case access time?
- In a B+ tree, to locate a record with key k means to compare k with other keys k' organized in a (tree-shaped) search data structure
- Hash indexes use the bits of k itself (independent of all other stored records and their keys) to find the location of the associated record
- Hash indexes: best for equality searches, cannot support range searches (also known as scatter storage)
  - True, but they can be used to answer range queries in O(1+Z/B) I/Os, where Z is the number of results (Alstrup et all 2001; Brodal et all 2004)
- Although hash indexes supports multiple attribute keys, cannot support partial key search

References

- Based on slides from:
  - R. Ramakrishnan and J. Gehrke
  - H. Garcia Molina
  - J. Hellerstein
  - L. Mong Li
  - P. Kilpeläinen
  - R. Lawrence
  - M. H. Scholl

Τέλος Ενότητας

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ΕΣΠΑ 2007-2013
πρόγραμμα για την ανάπτυξη
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Σημειώματα

Σημείωμα αδειοδότησης

Σημείωμα Αναφοράς

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