PA152: Efficient Use of DB

5. Hashing

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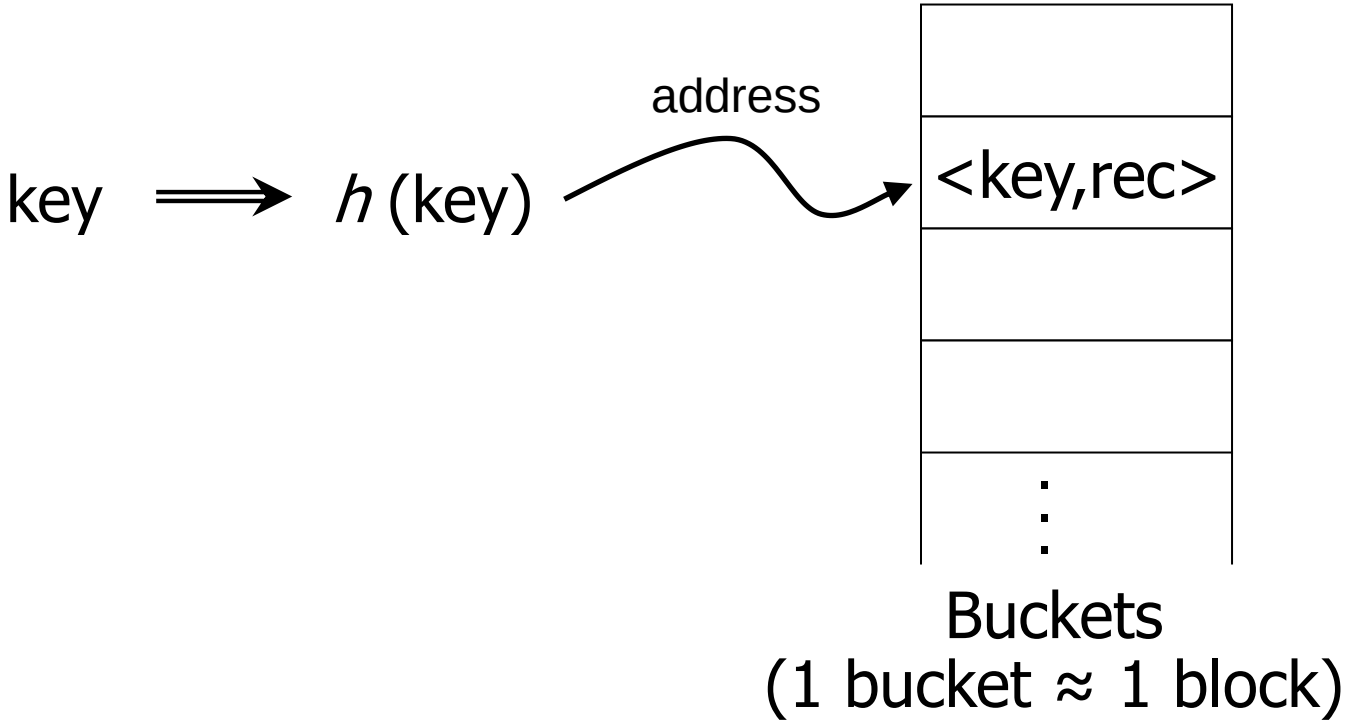
Outline

- Hash index
- Bitmap index
- Multi-attribute indexes
- Grid index

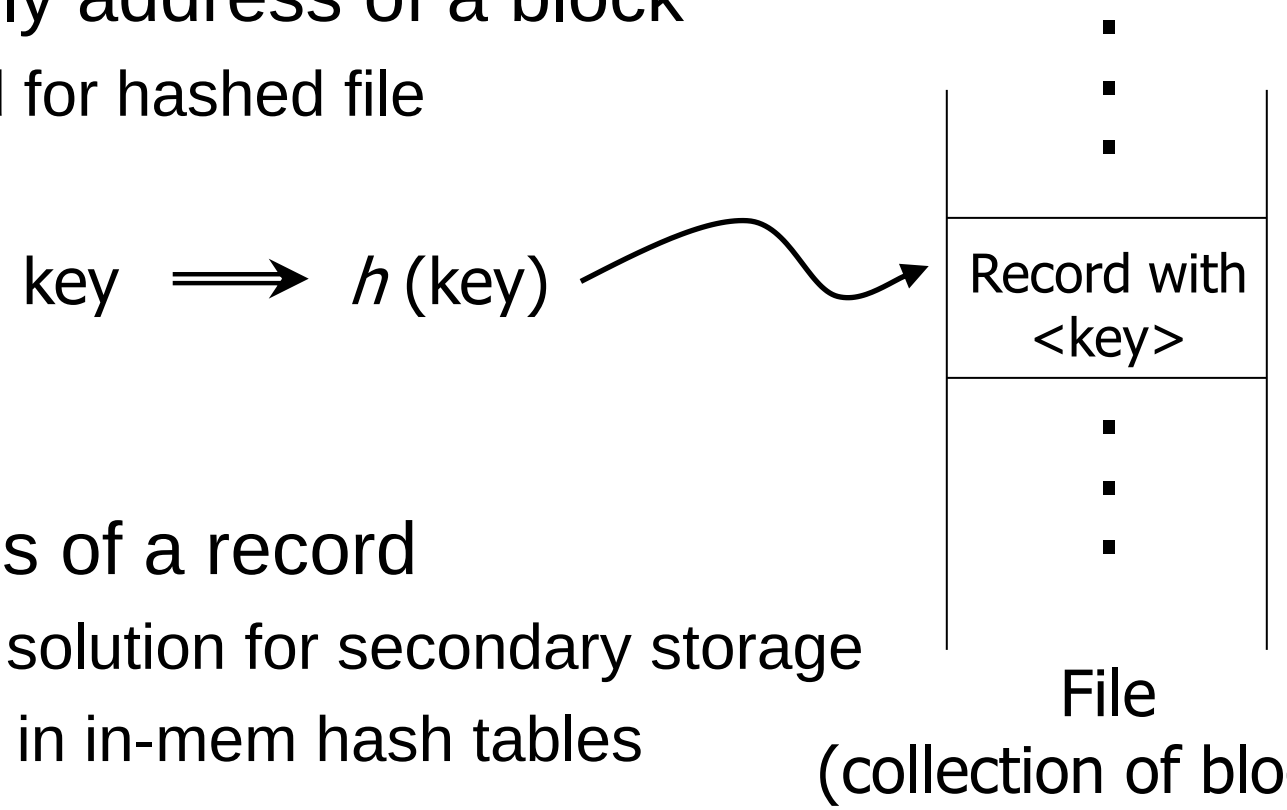
Hashing: Principle

- Key-to-address transformation
  - Based on a function returning an address
    - for an input key value



Variants

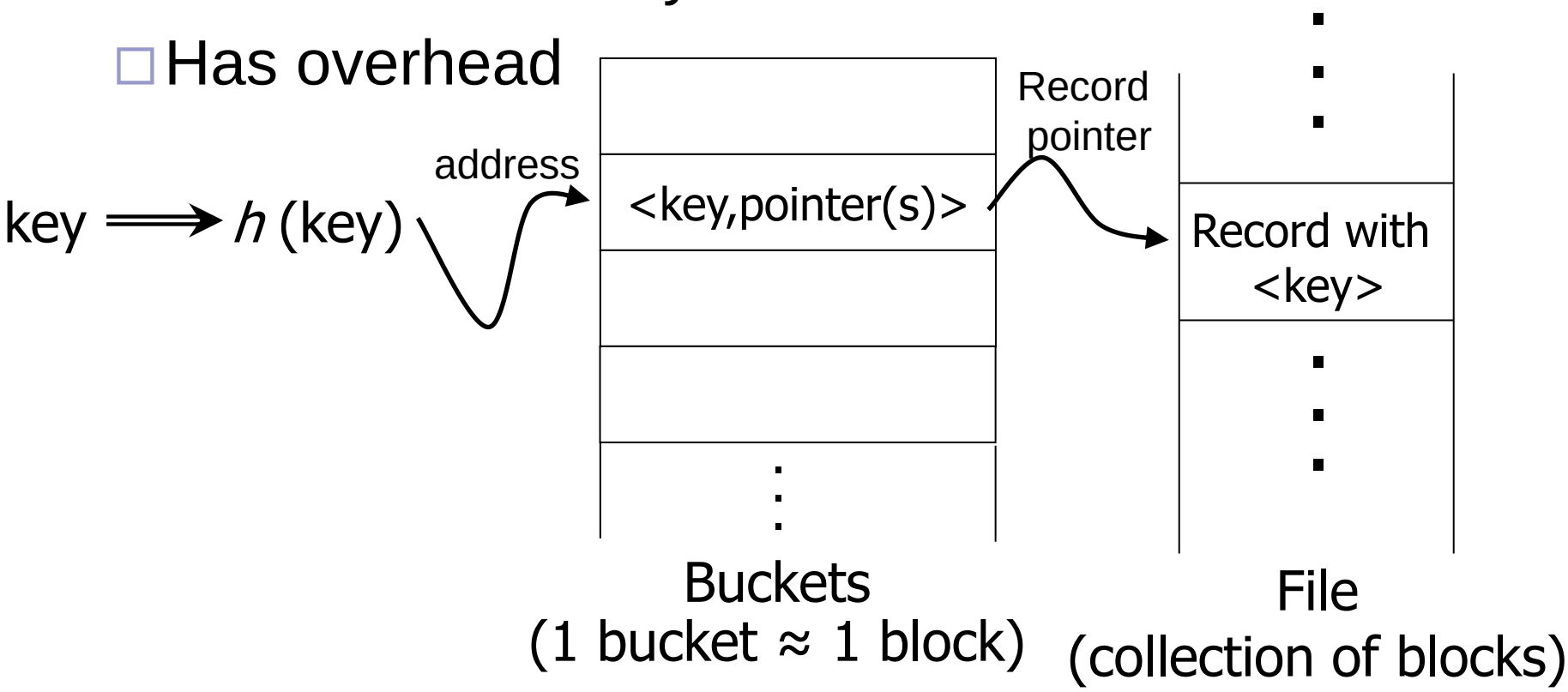
- Direct addressing
  - Typically address of a block
    - Good for hashed file



  - Address of a record
    - Rare solution for secondary storage
    - Used in in-mem hash tables

Variants

- Indirect addressing
  - Used in secondary indexes
  - Has overhead



Hash Function – Examples

- Hash function $h: K \rightarrow A$
  - Key space "*K*"
    - key as a byte-array, e.g., *n* bytes
  - Address space "*A*"
    - *B* buckets
- Examples $h(x_0x_1\ldots x_{n-1}) \rightarrow y$
    - $y = (x_0+x_1+\ldots+x_{n-1}) \bmod B$
    - $y = (x_0*31^{n-1}+x_1*31^{n-2}+\ldots+x_{n-1}) \bmod B$
  - Applicable to variable-length characters

Hash Function

- Properties:
  - Uniform
    - Equal occupation of all buckets
  - Random
    - Low correlation between its input and output
- „Big science“ → special literature
  - Good hash function must be uniform
  - Locality-sensitive hashing
  - Vector quantization, product quantization
  - …

Address Space

- Collection of buckets

- Bucket
  - Capacity larger than 1 record
  - Sort the keys?
    - Yes, if access should be faster
    - Yes, if updates are rare
    - No, if updates are frequent

Terminology

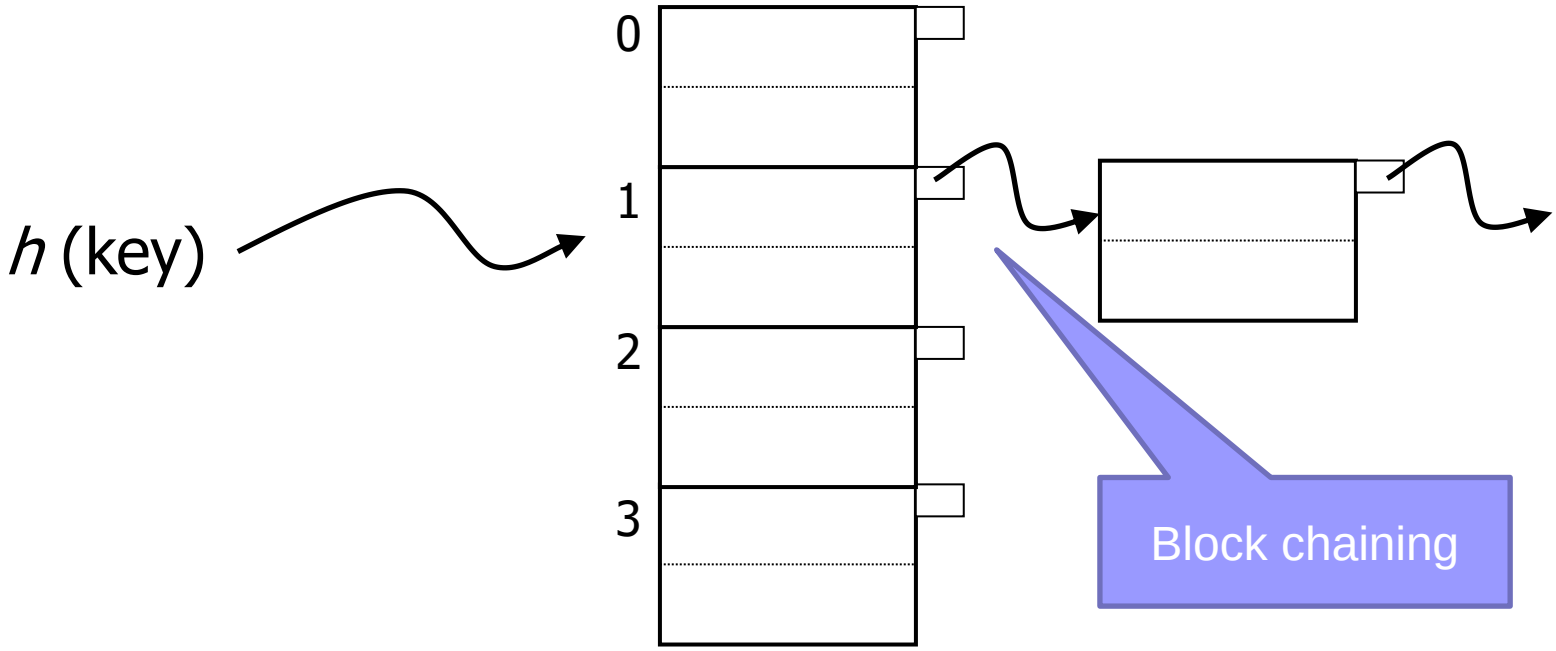
- Hash function
- Collisions
  - in direct addressing, another record present on the returned address
  - in indirect addressing, no problem if more keys/recs can be stored
    - Overflows
      - Bucket capacity is exhausted
      - Overflow blocks
- **Static** vs. **dynamic** hashing
  - Address space cardinality can be modified

Static Hashing: Collision Solutions

- Closed addressing (= open hashing)
  - Returned address is fixed
  - On overflow, allocate a new block (overflow area)
    - and chain overflow blocks
  - Used in secondary memory indexes/files
- Open addressing (= closed hashing)
  - Collision function is introduced
    - Linear, quadratic, double-hashing
  - Used in in-mem hash tables

Example

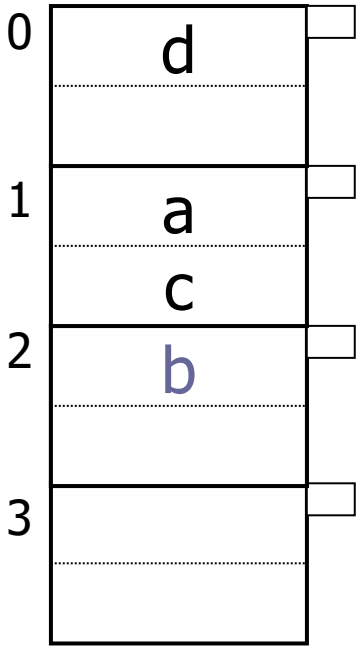
- Static closed addressing
  - Collisions handled by overflow blocks
  - Block capacity = 2 keys



Skip revision…

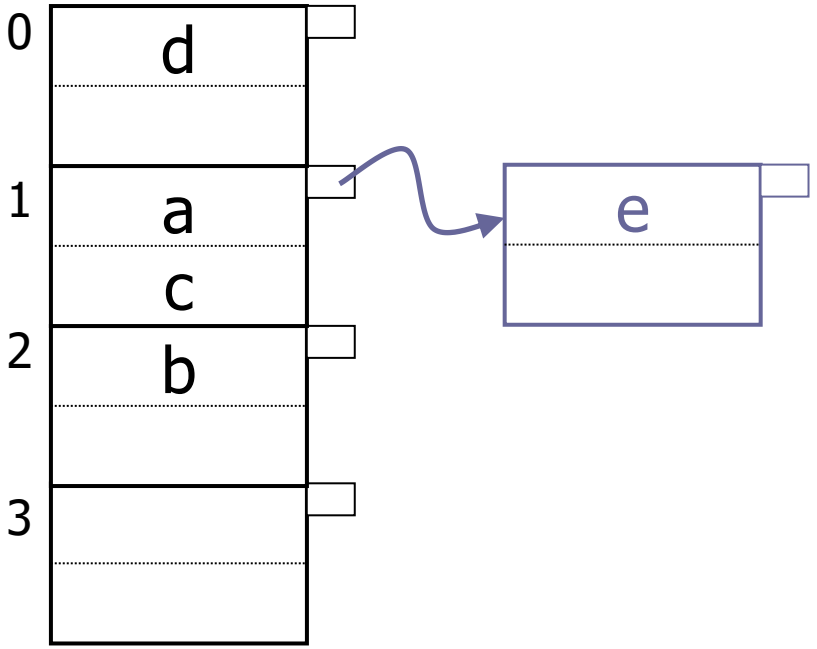
Example: Insert

- *h*(„b“) = 2



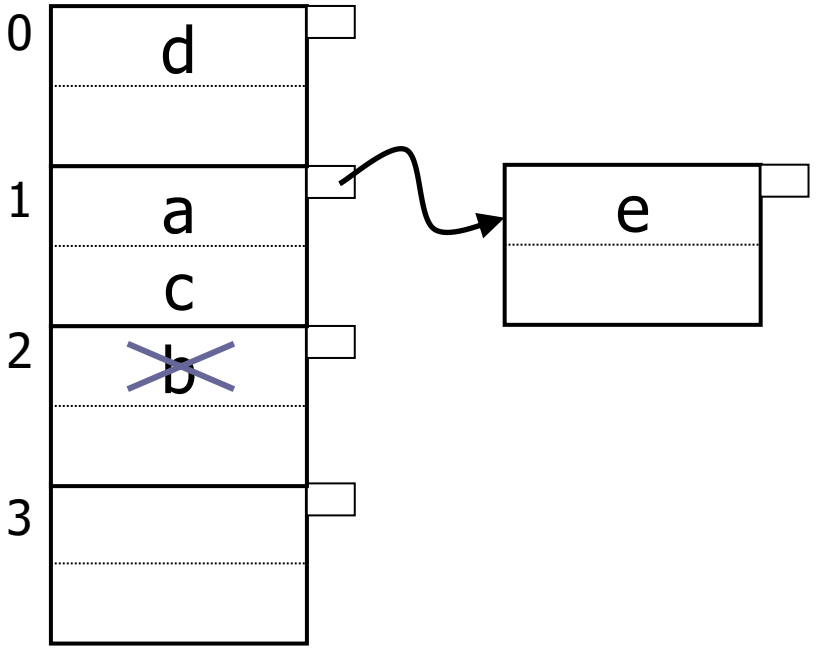
Example: Insert

- *h*(„e“) = 1



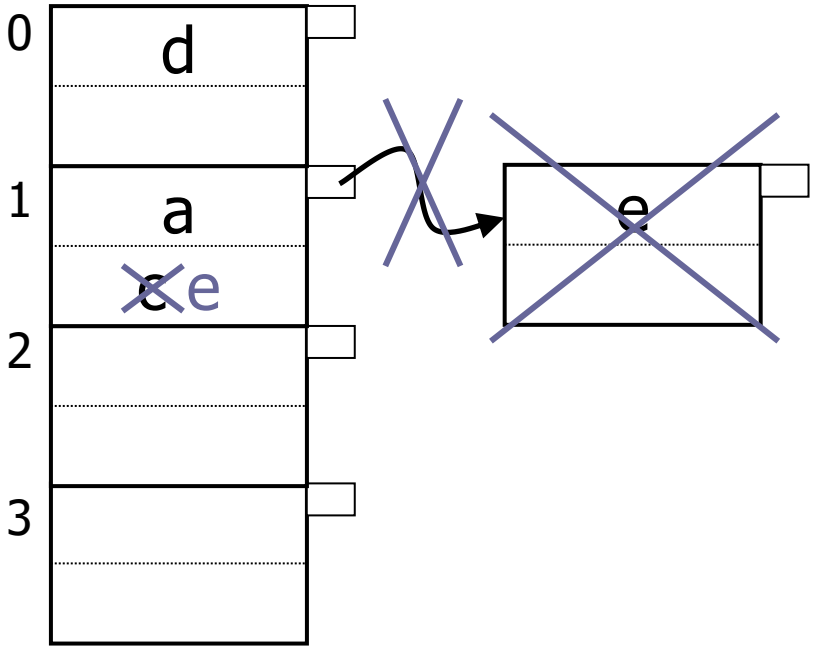
Example: Deletion

- Free overflow blocks up
- Delete „b”



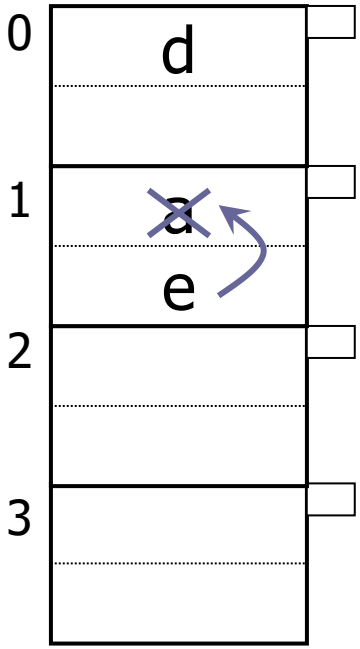
Example: Deletion

- Free overflow blocks up
- Delete „c”



Example: Deletion

- Free overflow blocks up
- Delete „a”



Rule of thumb

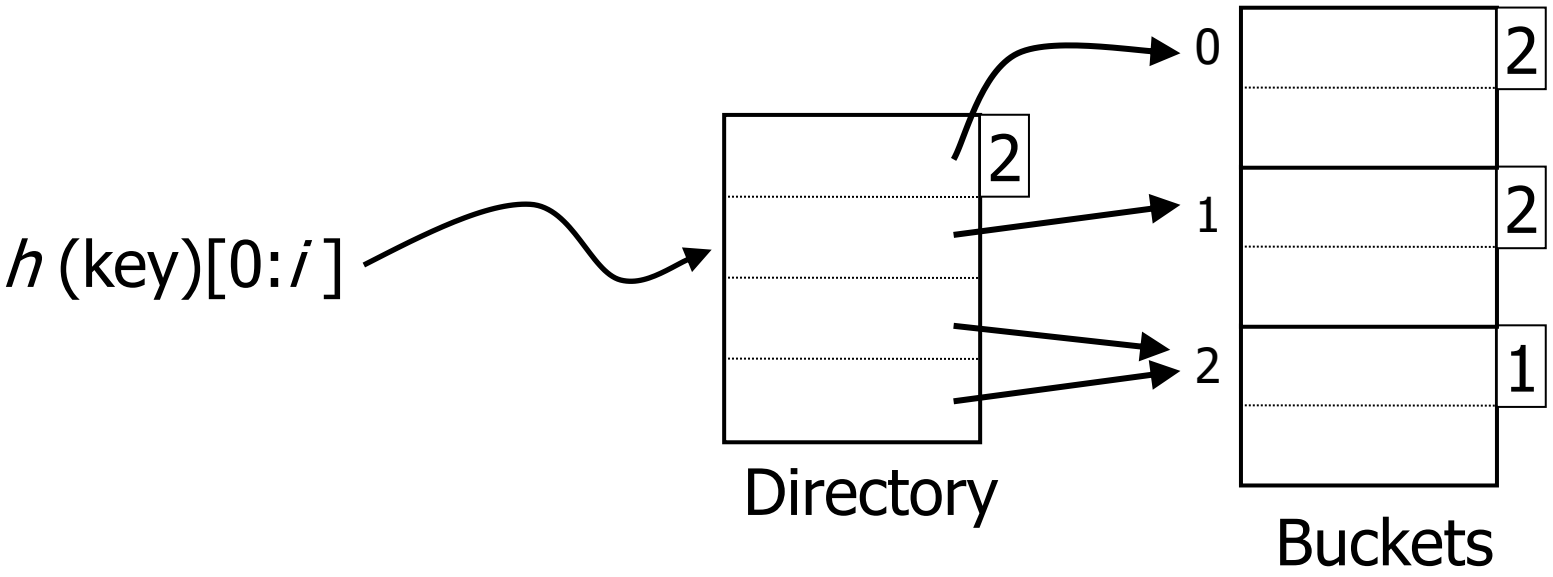
- Keep space utilization btw. 50% and 80%
  - Utilization = # stored keys / max. capacity (in keys)
  - < 50% → wasting space
  - ≥ 80% → too many collisions
    - Overflow areas degrade searching and insertion performance

Dynamic Data

- Static hashing
  - Overflows → (global) reorganization
    - i.e., designing a new hash function
- **Dynamic hashing**
  - Extendible
  - Linear

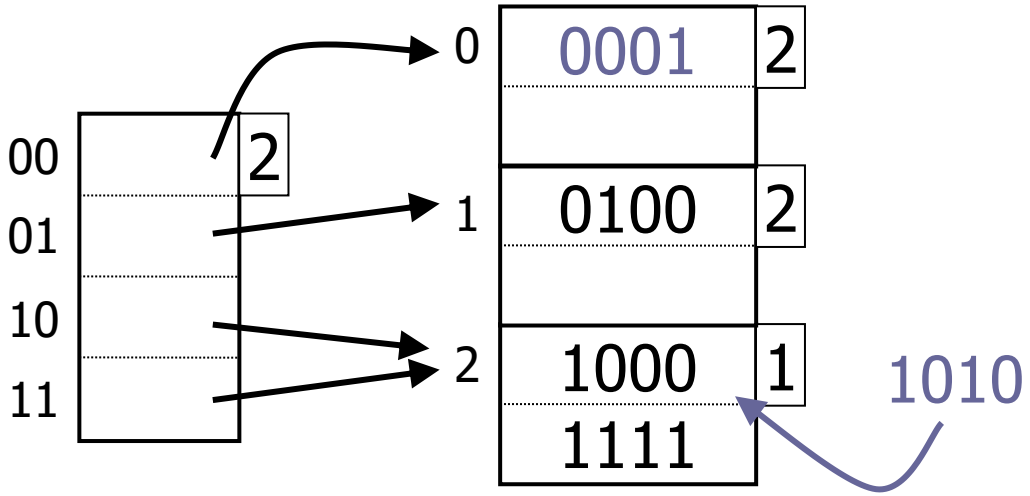
Extendible Hashing

- Idea:
  - Use top *i* of *b* bits output by hash function
  - Indirection added – directory
    - Size is power of 2



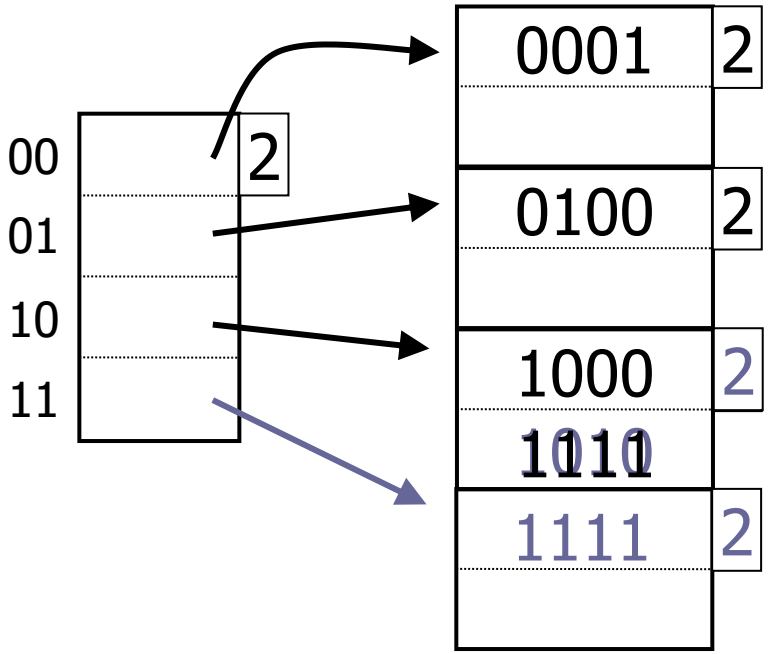
Extendible Hashing: Insertion

- Example: h(x) = x, i.e., identity
- Locate a bucket
  - is free space available?
    - Yes → insert;
    - No → so split the bucket & redistribute its content
- Insert
  - 0001
  - 1010



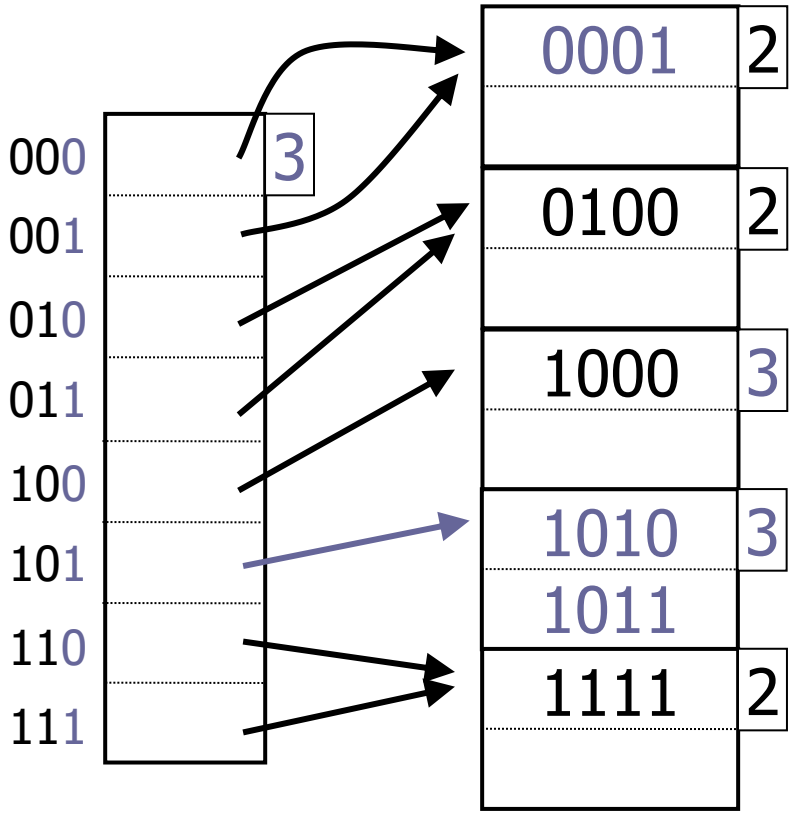
Extendible Hashing: Insertion

- Insert 1010
  - Split bucket



Extendible Hashing: Insertion

- Insert 1011
  - Directory is full → double it (use one more bit)



Extendible Hashing: Deletion

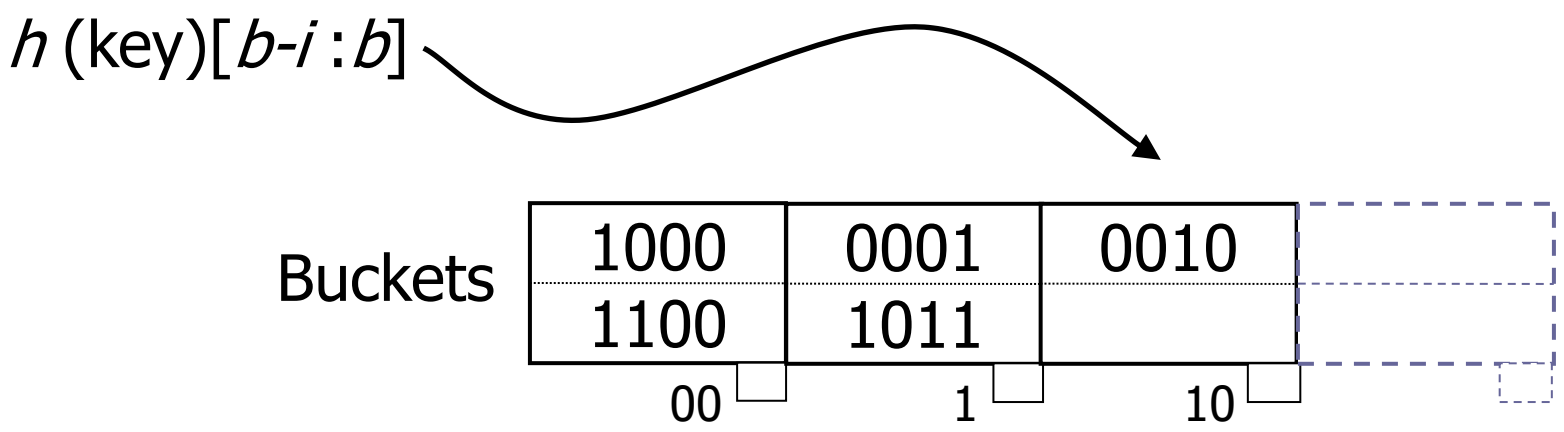
- Delete keys
  - Delete key
  - Bucket gets empty
    - No operation → assume new data arriving
    - Merge neighboring buckets
      - Of the same prefix (shorted by one bit)
      - Directory can shrink too

Extendible Hashing: Summary

- Advantages (over static hashing)
  - Handles growing files
  - Wasting less space
  - Local reorganization
- Disadvantages
  - Indirection
    - Not bad if directory in memory
  - Directory doubles
    - May not fit in memory
    - Number of buckets grows linearly

Linear Hashing

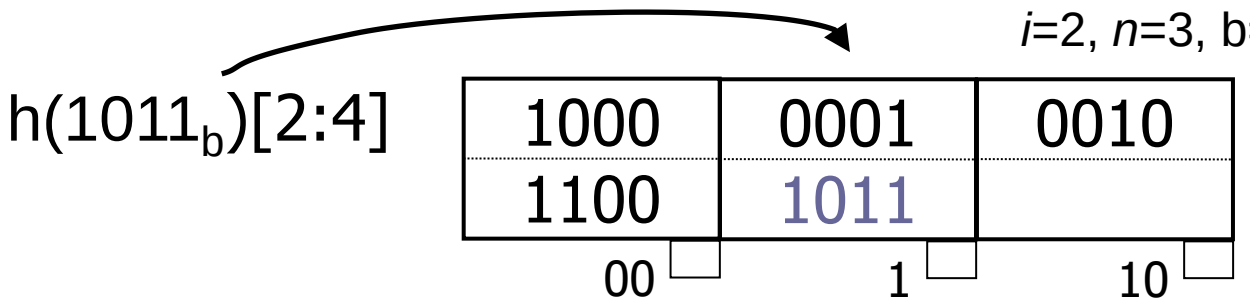
- Idea:
  - Use *i* low order bits of address (of *b* bits)
  - No directory
  - File grows linearly



Linear Hashing: Insertion

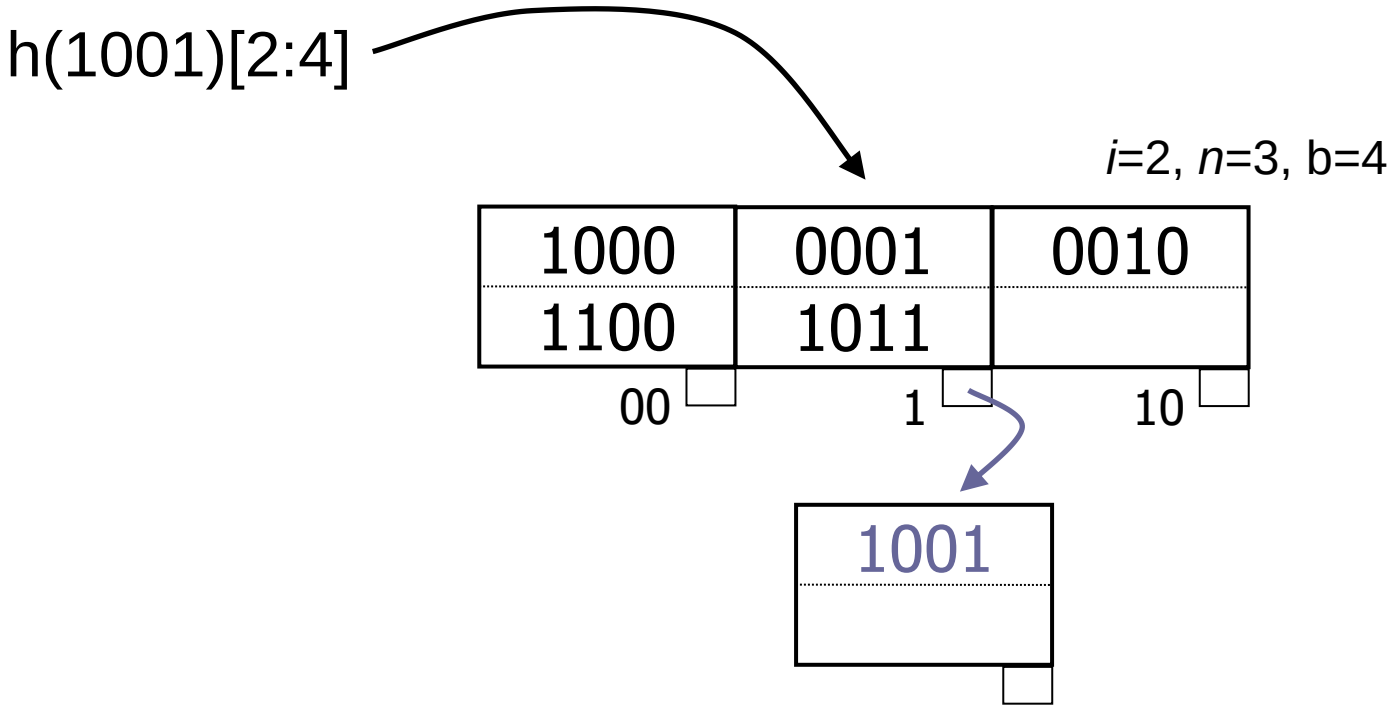
- Parameters:
  - *b* – length of hash address
  - *i* – suffix length => h(k)[*b*-*i*:*b*]
  - *n* – number of allocated buckets
- Insert 1011_b
  - $h(1011_b)[2:4] = 11_b = m$
    - If $m < n$, insert into bucket m
    - Otherwise, insert into bucket $m - 2^{i-1}$

Current parameter values:
i=2, *n*=3, b=4



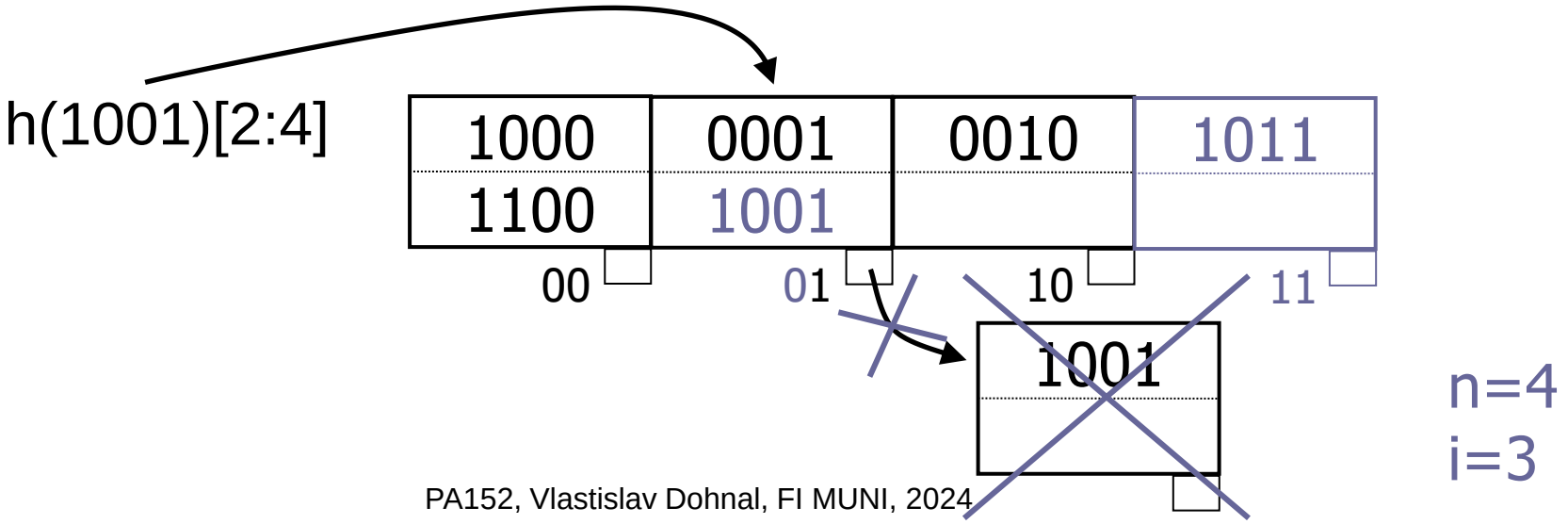
Linear Hashing: Insertion

- Insert 1001
  - h(1001)[2:4] = 01
  - No room → create overflow bucket



Linear Hashing: Bucket Splitting

- Keep track of bucket utilization
  - >80%, then split a bucket (smallest address of ***0****abcd…z*)
    - Add new bucket → address is ***1****abcd...z*
    - Distribute keys from bucket *0abcd…z* and its overflow to buckets *[01]abcd…z*
  - This address ($n - 2^{i-1}$) is always split, i.e., $3\text{-}2^1 = 1$



Linear Hashing

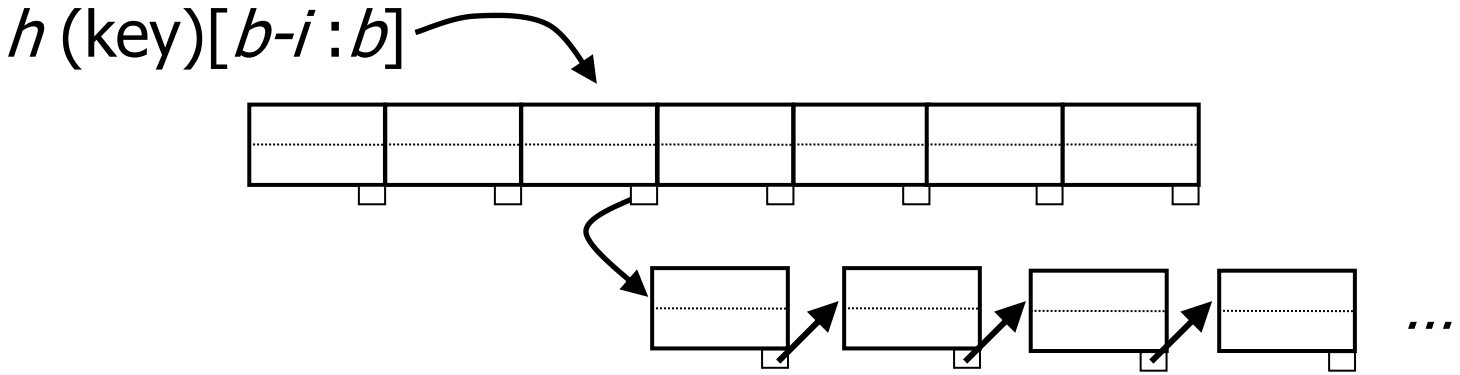
- Inserting new keys
  - May lead to overflow buckets
  - Utilization exceeding 80%
    - Do the bucket split
    - The bucket being split may differ from the overflowing one!
  - After allocating 2^i-*th* bucket, increment *i*
    - i.e., the bucket count exceeds 2^i -1

Linear Hashing: Summary

- Advantages (over static hashing)
  - Handles growing files
  - Less wasted space
  - Local reorganization
  - No indirection like extendible hashing
- Disadvantages
  - Overflow chains

Linear Hashing: Example

- „Bad“ data
  - Last x bits do not distinguish keys



  - One bucket “stores” all data; others are empty
    - Utilization is decreased by split
      - → need to track the length of overflow blocks!

Hashing vs. Indexing: Query Types

- Hashing
  - Good for exact match
    SELECT … WHERE a=5
- Indexing
  - Good for range search
    SELECT … WHERE a>5

- What if cardinality of ``a'' is low?

Bitmap (raster) index

- Attribute *X* has got *h* unique values
- Collection of *h* bit arrays
  - One array (vector) per value
  - Array length is equal to # records (*n*)
- Good for attributes with „few“ values
  - Up to 10% of records
- Queries:
  - WHERE a = 5 OR a = 7

Bitmap index: Example

- Relation *R*(*F*,*G*)

F	*G*
30	foo
30	bar
40	baz
50	foo
40	bar
30	baz
34	foo

- Bitmap index on *G*

Value	*Vector*
foo	1001001
bar	0100100
baz	0010010

Bitmap index: Summary

- Disadvantages
  - Storage demands
    - If *key* is the primary key, then
      $n(n + log_2 n)$ bits
    - Many records with the same value (many 1's) or too many records in general
      - Compress to the bit vector of blocks (instead of records)
  - Record updates
    - New value $\rightarrow$ add new array
    - New record $\rightarrow$ extend all arrays

Bitmap index: Summary

- Advantages
  - Fast bit operations (AND, OR)
  - Applicable to “range” queries
  - Easy to combine multiple indexes together
    - which are typically single-attribute indexes

Bitmap index: Compression

- Reduce individual arrays
  - Few 1's, many 0's
  - ends with one
  - trailing zeros are omitted
    - Can be filled up to # records

- Run-Length Encoding (RLE)
  - Split to blocks
    - Sequence of "*i*" zeros followed by *one*
  - Encode "*i*" binary
  - Code for "*i*" :
    „number length + number itself“

Bitmap index: RLE

- Example of compression – 24 bits
  - Sequence: 0000 0000 0000 0110 0010 0000
    - 13x zeros, 1x one
    - 0x zero, 1x one
    - 3x zero, 1x one
    - 5x zero followed by nothing… → ignore
  - Binary:
    - $13_d \rightarrow 1101_b$
    - $0_d \rightarrow 0_b$
    - $3_d \rightarrow 11_b$
  - RLE code:
    - Sequence of „blocks“:
      - Binary number length in prefix code, binary number itself
    - Code: 111011010010 11

Bitmap index: RLE

- Example of decompression
  - Code 11101101001011
  - Split into block and decompress…
    - Binary number length:
      - bit count (ones followed by one zero)
    - 1110 1101 0 0 1011
  - Decoding parts
    - 1110 1101 → 0000 0000 0000 01
    - 0 0 → 1
    - 1011 → 0001
  - Resulting sequence:
    - 0000 0000 0000 0110 001
    - Missing trailing zeros filled up to # records

Bitmap index: Operations

- Bit operations
  - AND, OR
- RLE strings
  - Decompression is easy
  - No need to decompress
    - More complex implementation, but possible
    - AND: sum of "*i*"'s in codes must match
    - OR: by analogy…
    - 1110110100 1011 OR/AND 1101011101001010

Bitmap index: Implementation

- Issues for efficient use:
  1. Locate bit arrays for the passed key value
  2. Having the array, how to get records?
  3. Updating records, how to update index?

Bitmap index: Solutions

- Ad 1: (Locate bit arrays for the passed key value)
  - We have a bit array for each key value
    - B^+-tree for keys
    - Pointers to arrays in leaves
  - Storing bit arrays
    - records of variable length
- Ad 2: (Having the array, how to get records?)
  - Get record *r* (ordinal number of record)
    - Secondary index for record numbers
    - Array of pointers to records (replacement of bit arrays)
    - List of block occupations in the number of records

Bitmap index: Solutions

- Ad 3: (Updating records, how to update index?)
  - Record numbers fixed (not seq. file / sec. index)
    - Delete record
      → tombstone in file and
      clear a bit in the corresponding array
    - Insert record
      → append to end of file (a new record number)
      → append bit 1 to the corresponding bit array
      → if not existing, create new one

Bitmap index: Solutions

- Ad 3: (Updating records, how to update index?)
  - Record numbers are not fixed
    - Reorganize all arrays (delete 1 bit)
    - Update array of pointers to records
    - Rarely used

Bitmaps – data (TPC-H)

Settings:

```
lineitem ( L_ORDERKEY, L_PARTKEY , L_SUPPKEY, L_LINENUMBER,
     L_QUANTITY, L_EXTENDEDPRICE ,
     L_DISCOUNT, L_TAX , L_RETURNFLAG, L_LINESTATUS ,
     L_SHIPDATE, L_COMMITDATE,
     L_RECEIPTDATE, L_SHIPINSTRUCT ,
     L_SHIPMODE , L_COMMENT );
```

```
create bitmap index b_lin_2 on lineitem(l_returnflag);
create bitmap index b_lin_3 on lineitem(l_linestatus);
create bitmap index b_lin_4 on lineitem(l_linenumber);
```

- 100000 rows ; cold buffer
- Dual Pentium II (450MHz, 512KB), 512 MB RAM, 3x18GB drives (10000RPM), Windows 2000.

Bitmaps -- queries

Queries:

- 1 attribute

```
select count(*) from lineitem where l_returnflag = 'N';
```

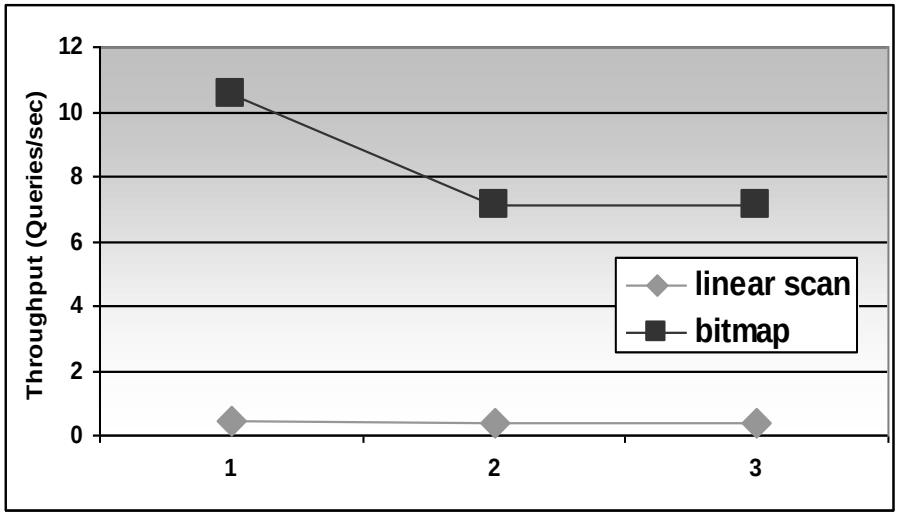
- 2 attributes

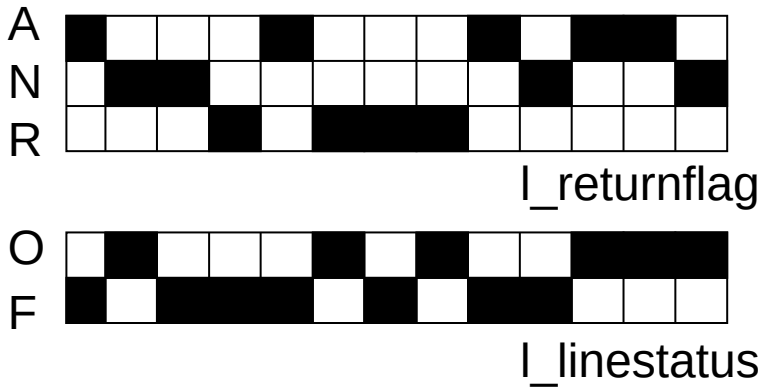
```
select count(*) from lineitem where l_returnflag = 'N' and
  l_linenumber > 3;
```

- 3 attributes

```
select count(*) from lineitem where l_returnflag =
   'N' and l_linenumber > 3 and l_linestatus = 'F';
```

Bitmaps





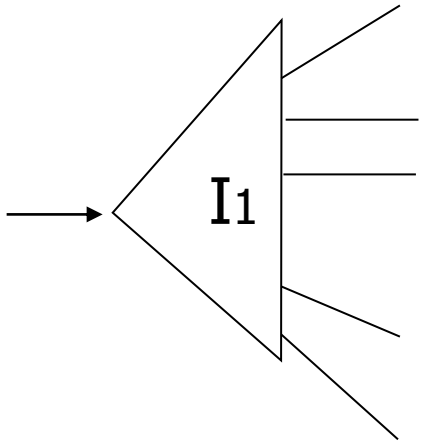
- Order of magnitude improvement compared to table scan.
- Bitmaps are best suited for multiple conditions on several attributes, each having a low selectivity.

Multi-key / Composite index

- Index on multiple attributes
- Motivation:
  SELECT name, salary FROM emp
  WHERE dept='Toys' AND salary < 10000
- Alternatives:
  a) Index on one attribute + filtering
  b) Combine two indexes + intersection of candidate record pointers
  c) Index in index
  d) Concatenation of key values into one

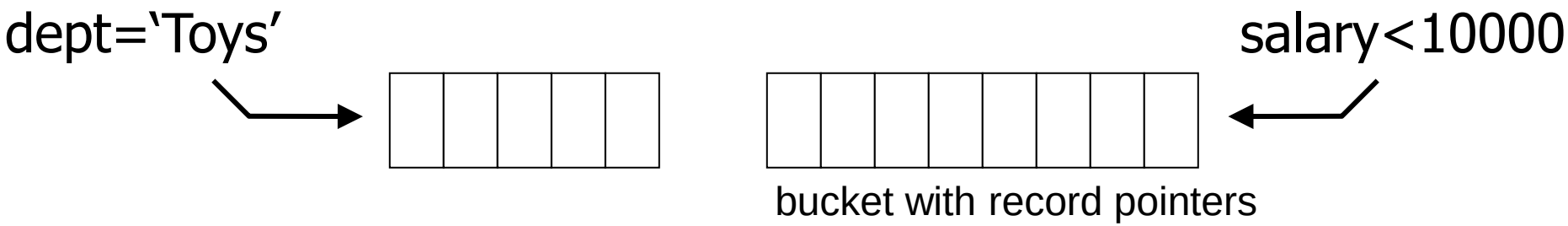
Index on one attribute

- SELECT name, salary FROM emp
  WHERE dept='Toys' AND salary < 10000
- Index on *dept*
  - Filter found records using *salary* < *10000*



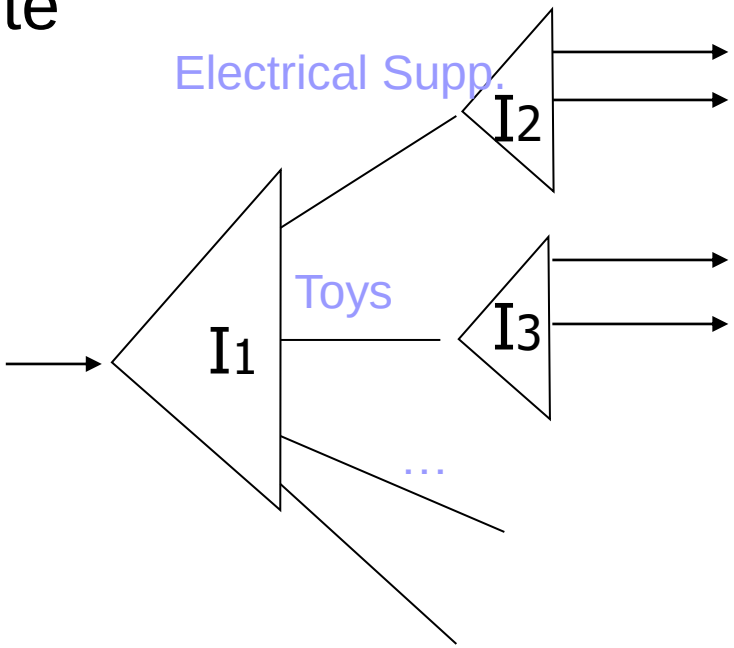
Combining Indexes

- Index on *dept*
- Index on *salary*
- Each index returns a list of candidate records
  - Intersection of lists → query result



Index in index

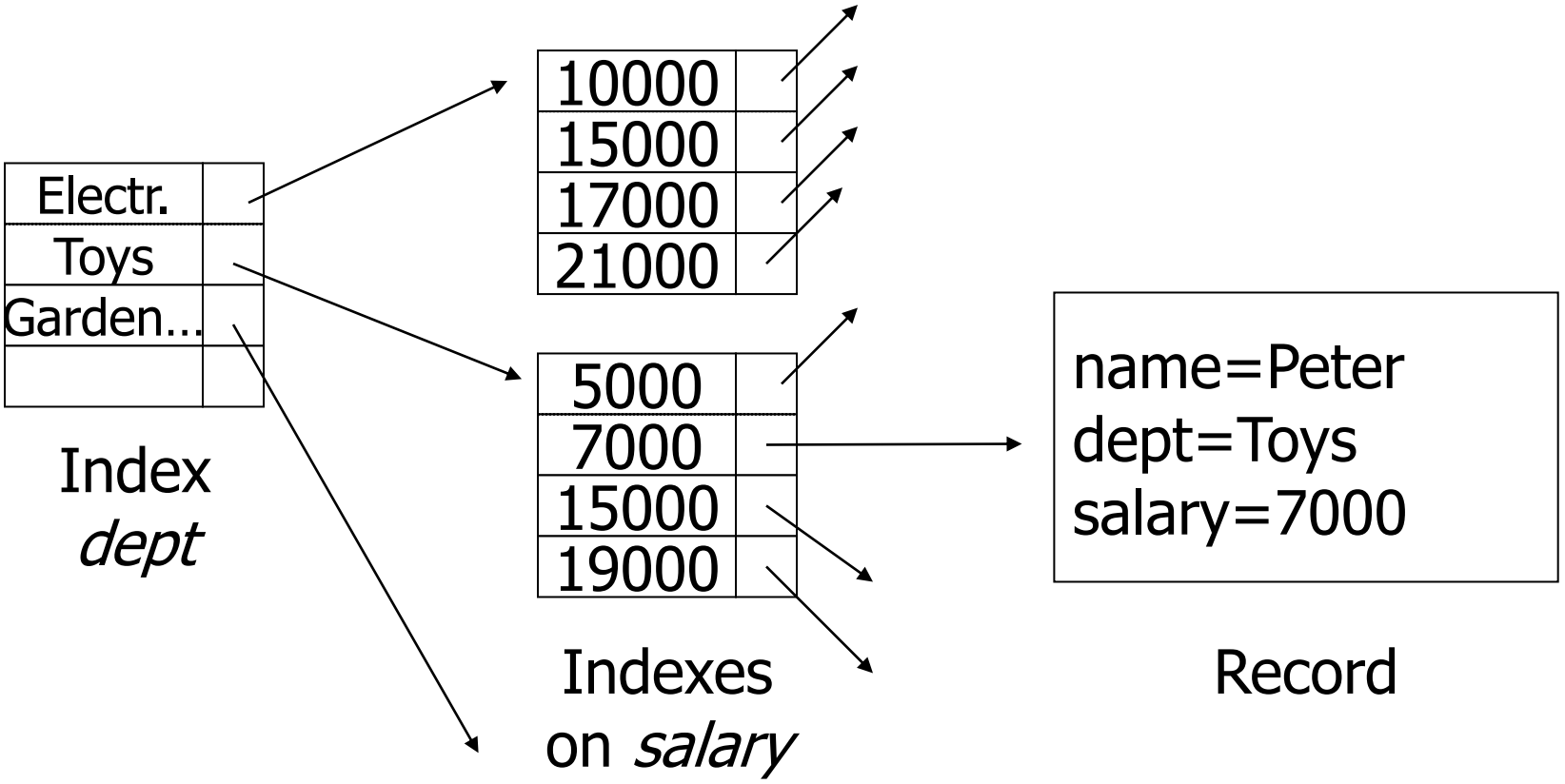
- Index on the first attribute
  - In leaves, pointers to embedded indexes on 2nd attribute



  - I_1 on *dept*
  - I_x, x=2..k on *salary*
    - I_2 contains only records having the same dept. value (Electrical Supp.)

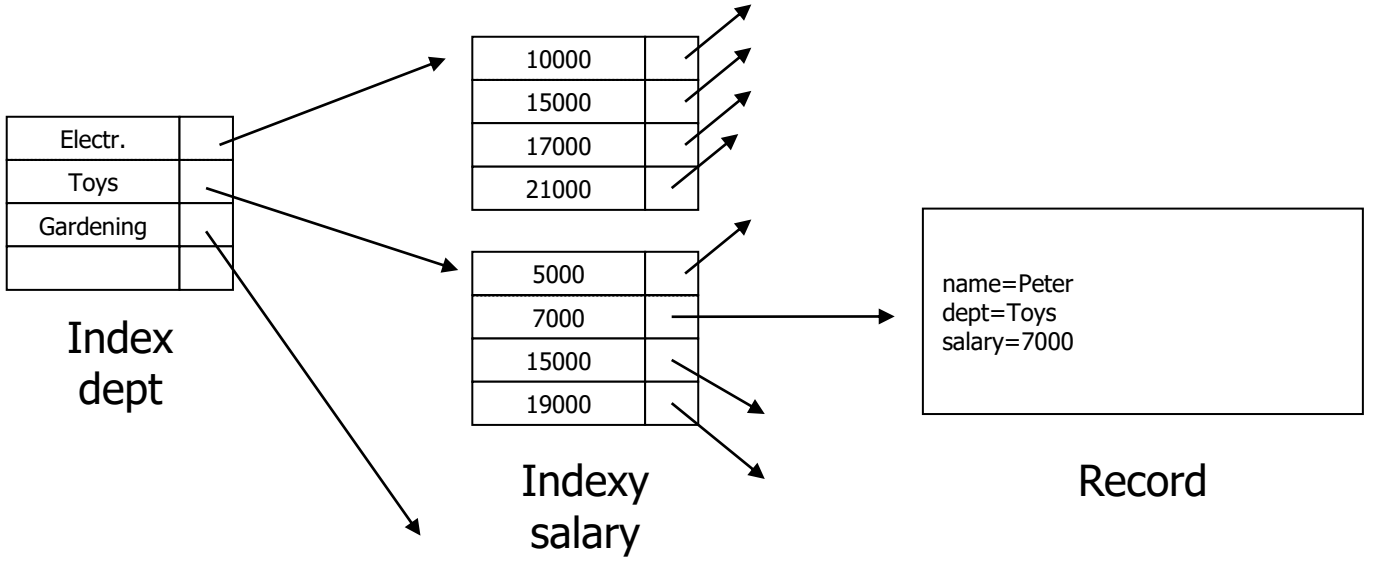
Index in index: Example

- SELECT name, salary FROM emp
  WHERE dept='Toys' AND salary < 10000



Index in index

- What queries can use this solution?
  - SELECT name, salary FROM emp WHERE
    a) dept = ‘Toys’ AND salary ≥ 10000
    b) dept = ‘Toys’
    c) salary = 10000

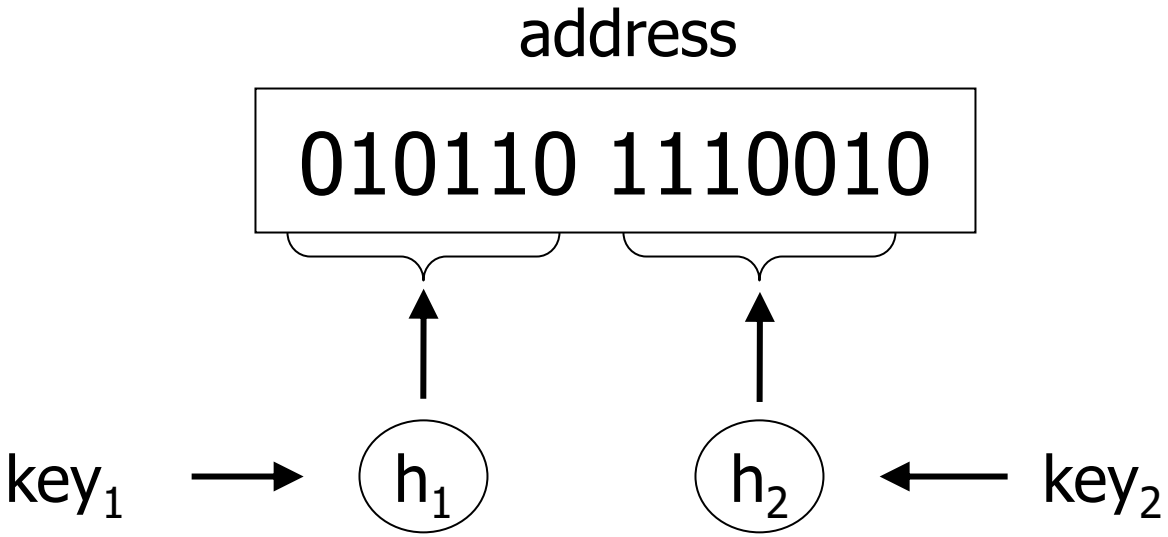


Concatenation of key values

- Analogous to an index on one attribute
  - Key values are merged
    - String concatenation, number multiplication, …
- Indexing
  - used in PostgreSQL
- Hashing
  - Partitioned hash function

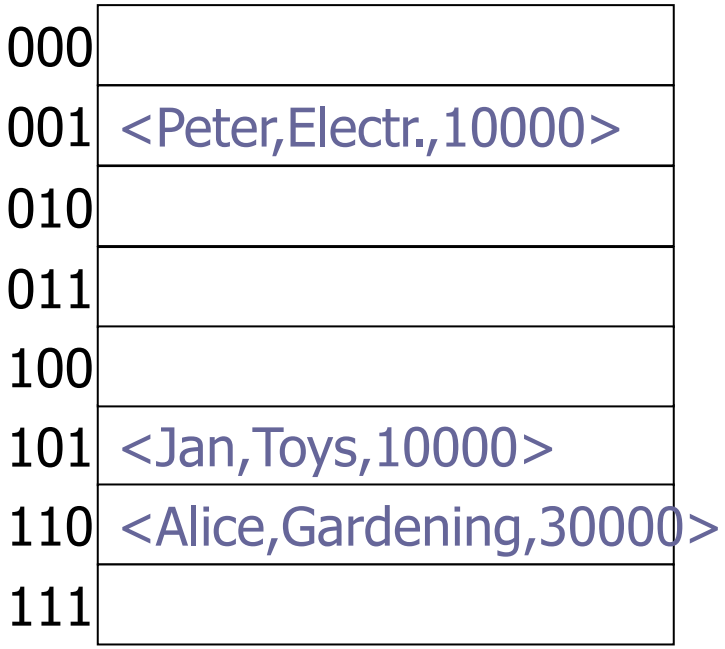
Partitioned hash function

- Idea:
  - Two keys
  - Two hash functions
  - One address



Partitioned hash function: Example

- Dept
  - h_1(Electr.)=0
  - h_1(Toys) =1
  - h_1(Gardening) =1
- Salary
  - h_2(10000) =01
  - h_2(20000) =11
  - h_2(30000) =10
  - h_2(40000) =00
- Records to insert
  - <Peter,Electr.,10000>
  - <Jan,Toys,10000>
  - <Alice,Gardening,30000>



Partitioned hash function: Example

- Dept
  - h_1(Electr.)=0
  - h_1(Toys) =1
  - h_1(Gardening) =1
- Salary
  - h_2(10000) =01
  - h_2(20000) =11
  - h_2(30000) =10
  - h_2(40000) =00
- Find
  - employess in Toys dept. with salary of 40000.

000	<Pavel,…><Lukáš,…>
001	<Peter,…>
010	<Marie,…>
011	
100	<Anna,…>
101	<Jan,…>
110	<Alice,…>
111	<Veronika,…>

Partitioned hash function: Example

- Dept
  - h_1(Electr.)=0
  - h_1(Toys) =1
  - h_1(Gardening) =1
- Salary
  - h_2(10000) =01
  - h_2(20000) =11
  - h_2(30000) =10
  - h_2(40000) =00
- Find
  - employees with salary 30000

000	<Pavel,…><Lukáš,…>
001	<Peter,…>
010	<Marie,…>
011	
100	<Anna,…>
101	<Jan,…>
110	<Alice,…>
111	<Veronika,…>

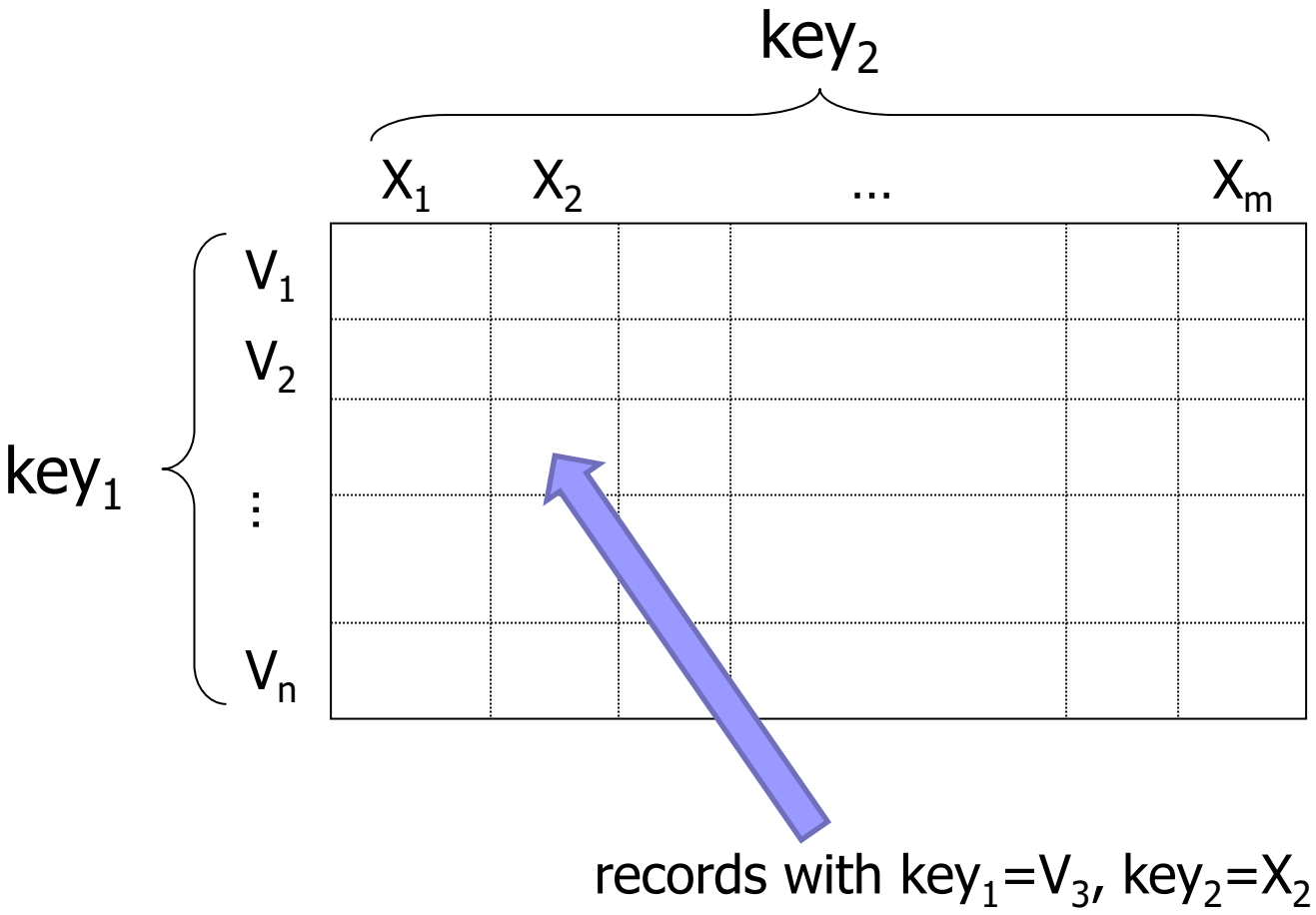
Partitioned hash function: Example

- Dept
  - h_1(Electr.)=0
  - h_1(Toys) =1
  - h_1(Gardening) =1
- Salary
  - h_2(10000) =01
  - h_2(20000) =11
  - h_2(30000) =10
  - h_2(40000) =00
- Find
  - employes in Toys dept.

000	<Pavel,…><Lukáš,…>
001	<Peter,…>
010	<Marie,…>
011	
100	<Anna,…>
101	<Jan,…>
110	<Alice,…>
111	<Veronika,…>

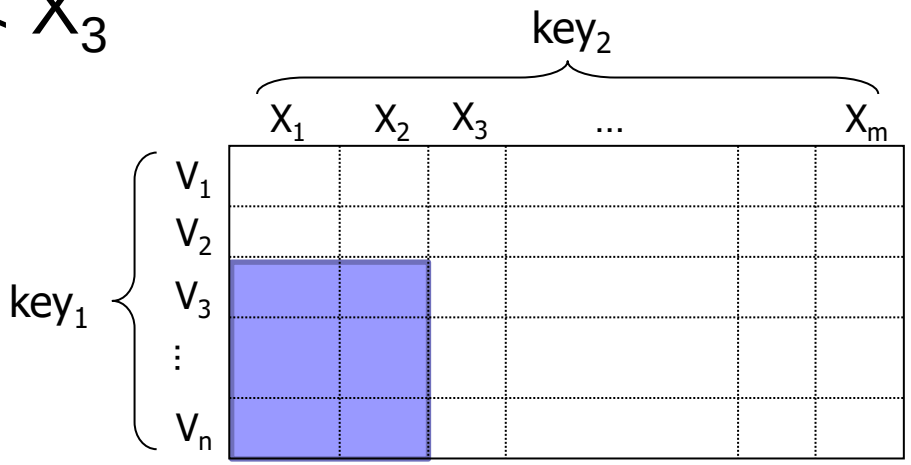
Grid Index: another multi-key index

- Idea:



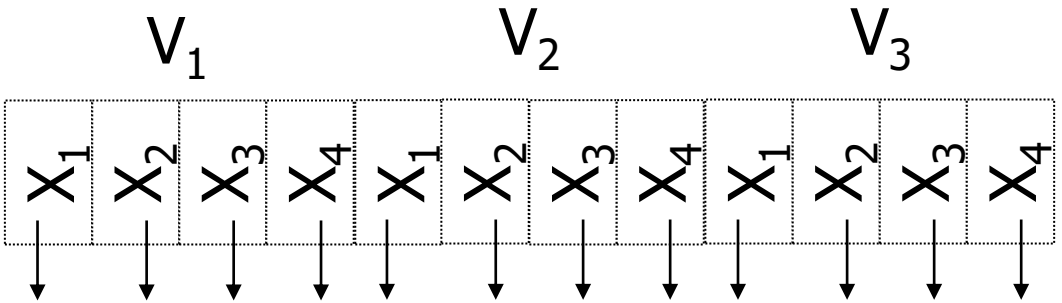
Grid Index: Properties

- Efficient for exact match queries
  - $key_1 = V_i$ and $key_2 = X_j$
  - $key_1 = V_i$
  - $key_2 = X_j$
- Range queries
  - $key_1 \geq V_3$ and $key_2 < X_3$
    - Rectangular area



Grid Index: Implementation

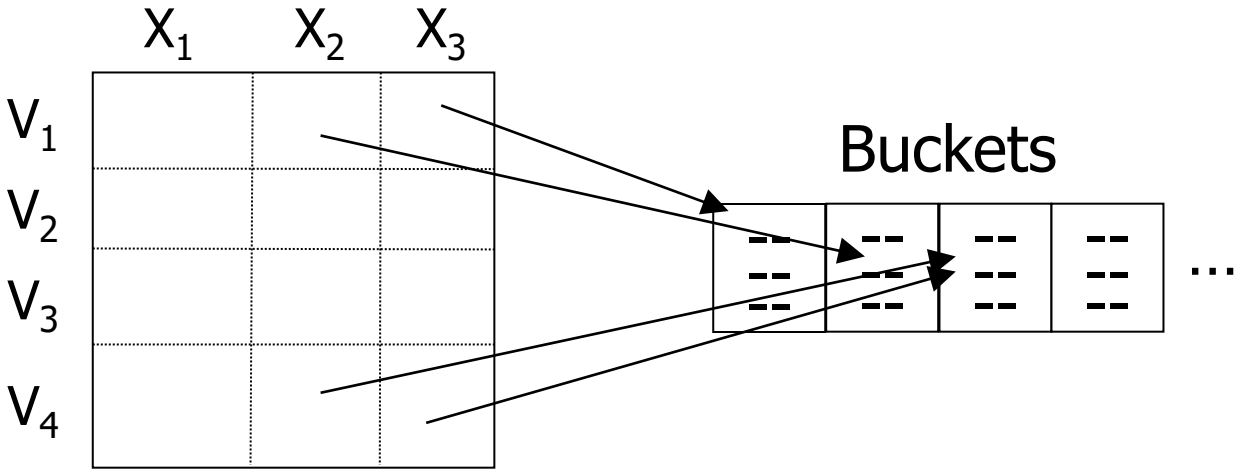
- How to store grid on disk?
  - one-dimensional array



  - Tradeoff: grid dimensions vs. cell capacity
- Disadvantage
  - Grid dimensions must be fixed
    - They are needed to calculate position of cell $<V_x,X_y>$.
  - Limited cell capacity

Grid Index: Implementation

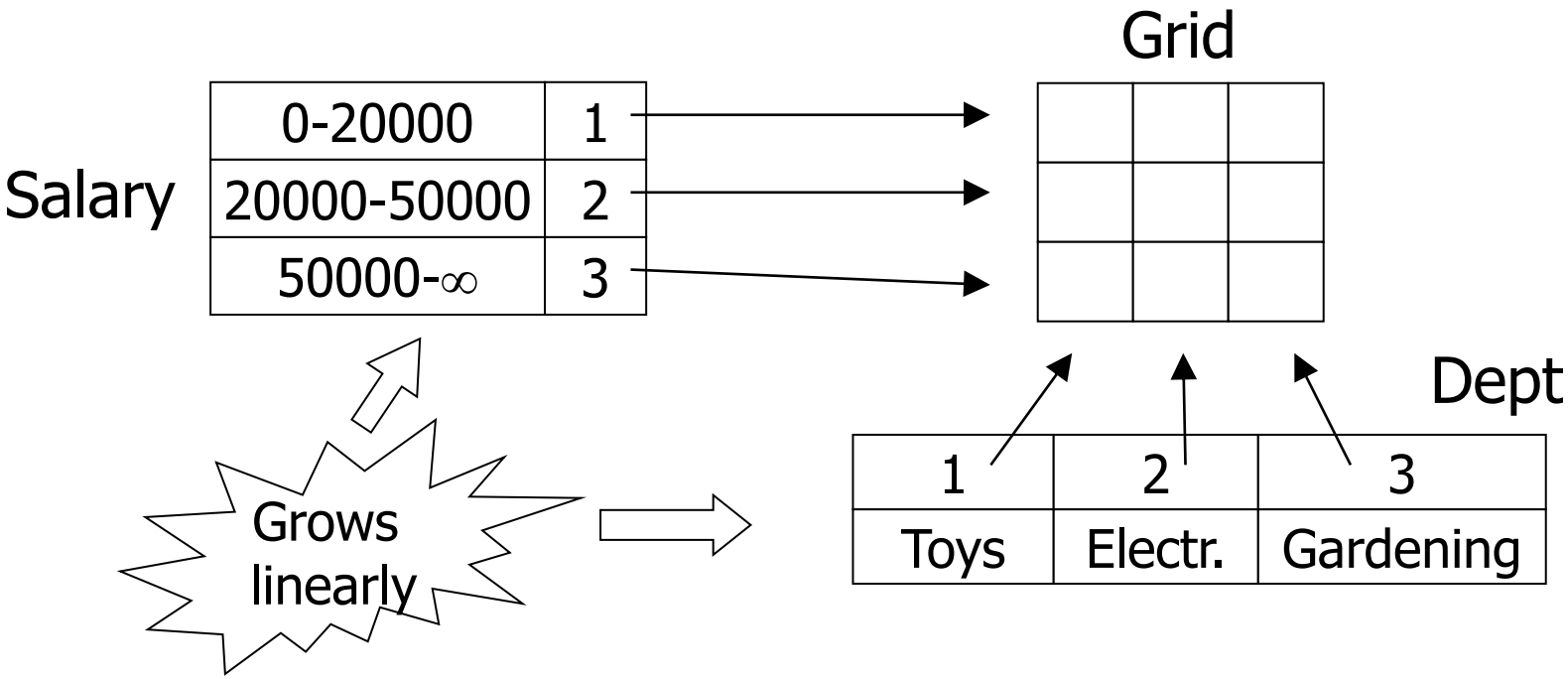
- Use buckets, i.e., indirection
  - Grid cell points to a bucket



- Grid is fixed-sized
  - Overhead with indirection
  - Allows allocating buckets linearly.

Grid Index: Defining Grid

- Analysis of data and query types
  - Find out dimensions of the grid
  - Value on an axis can be an interval → binning
    - E.g., numeric domains



Grid Index: Summary

- Advantages
  - Good for multikey indexing
- Disadvantages
  - Grid size is fixed; may waste space
    - Alternative is a hierarchical grid
  - Choice of grid intervals (quantization)
    $\rightarrow$ uniform data distribution

Index Design Guidelines

- Good selectivity (i.e., low selectivity)
  - Fraction of matching rows is small
- “Short” attribute values
  - Increase tree fan-out
- On “join” attributes

- Prefer more single-attribute indexes
  - for one multi-attribute one
- Few indexes on highly-updated tables
- No indexes on tiny tables

Lecture's Takeaways

- Techniques of hashing
- Recall handling duplicate keys
  - i.e., multiple records with the same key value.
- Alternative indexes
  - Bitmap index
    - do not mix up with bitmap scan in Pg's explain plan
  - Grid index
- Multi-attribute indexes and query predicates
- Further terms (follows…)

Further Terminology

- Clustered index
  - = index-sequential file / B^+-file
  - Records are stored in leaf nodes and cannot be accessed in any other way (than by this index)
- Non-clustered index
  - = secondary index / B^+-tree
- Covering index
  - Query can be fully answered using the index only
    - i.e., records are not accessed.
  - MS SQL Server: *Index with included columns*
    - Not a multi-attribute index, but leaf node values are enriched with values of the included cols.
- Indexed view
  - materialized view with clustered index
- Multidim. data and indexes (R-trees, Quad Trees, kd-trees)