DBMS Storage Overview

Values

↓

Records

↓

Blocks

↓

Files

⇣

Memory

Record

- Collection of related data items (called Fields)
- Typically used to store one tuple
- Example: Sells record consisting of
  - bar field
  - beer field
  - price field

Record Metadata

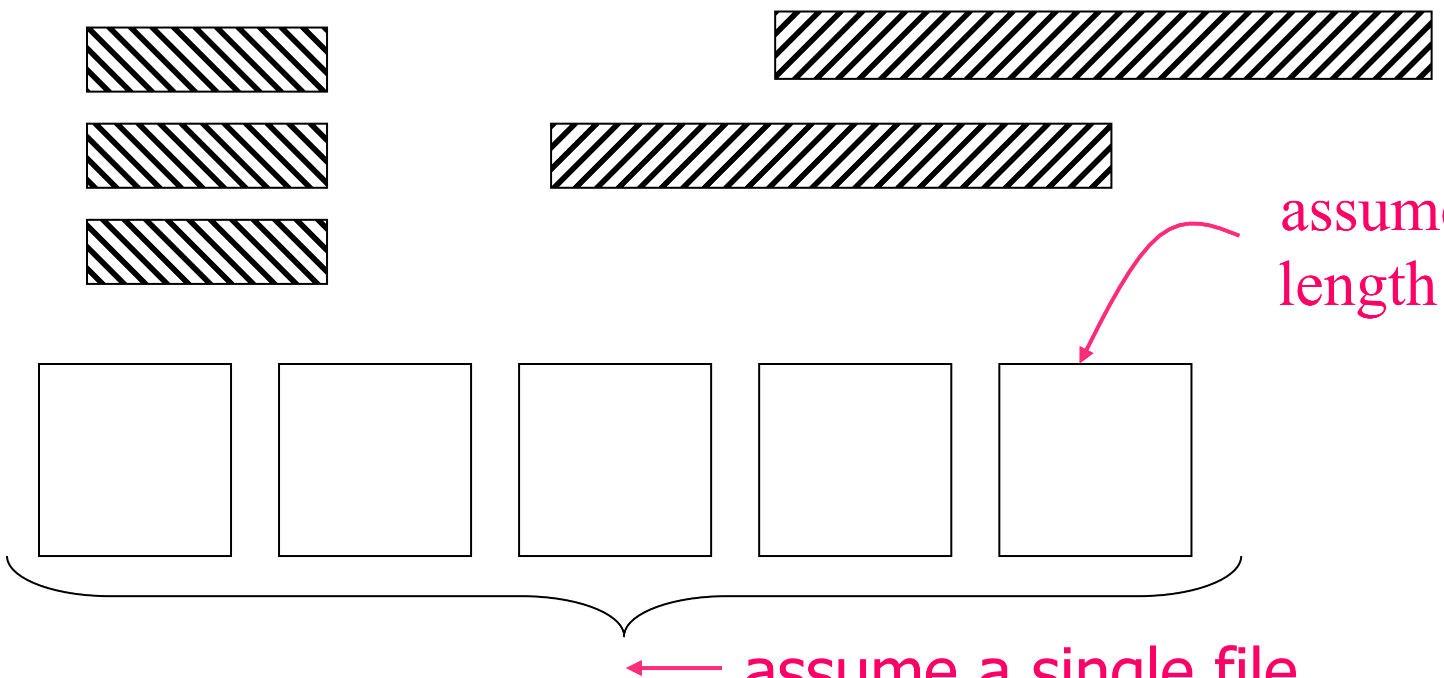
- For fixed-length records, schema contains the following information:
  - Number of fields
  - Type of each field
  - Order in record
- For variable-length records, every record contains this information in its header

Record Header

- Reserved part at the beginning of a record
- Typically contains:
  - Record type (which Schema?)
  - Record length (for skipping)
  - Time stamp (last access)

Files

- Files consist of blocks containing records
- How to place records into blocks?



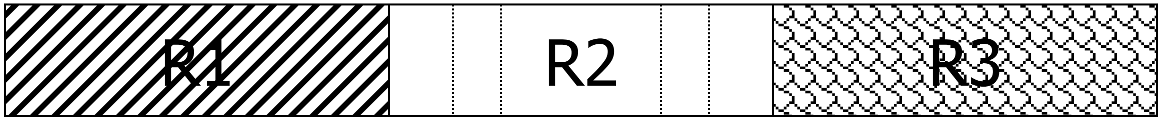
assume fixed length blocks

assume a single file

Files

- Options for storing records in blocks:
  1. Separating records
  2. Spanned vs. unspanned
  3. Sequencing
  4. Indirection

1. Separating Records

Block 

a. no need to separate - fixed size recs.

b. special marker

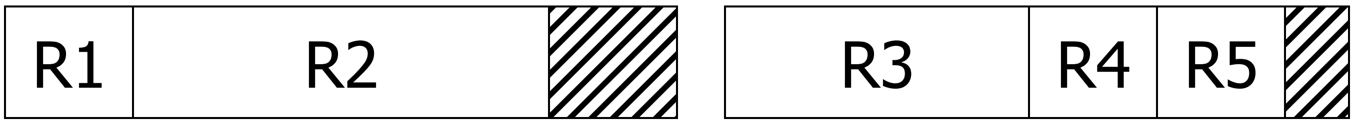
c. give record lengths (or offsets)

   i. within each record

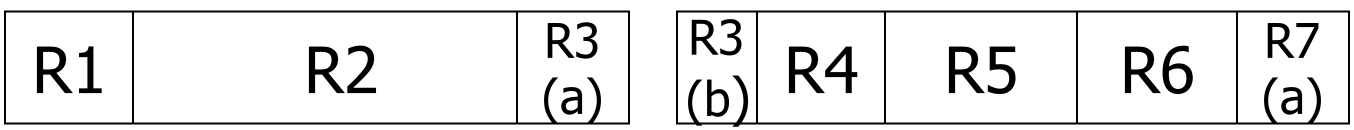
   ii. in block header

2. Spanned vs Unspanned

- Unspanned: records must be in one block



- Spanned: one record in two or more blocks

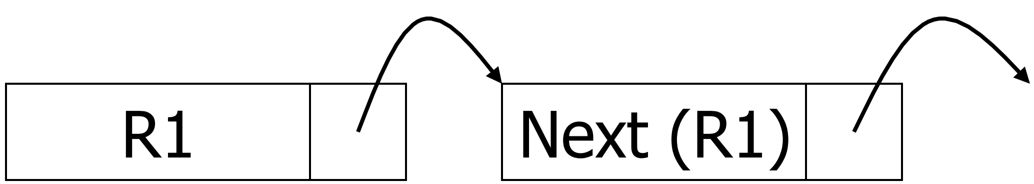


- Unspanned much simpler, but wastes space
- Spanned essential if record size > block size

3. Sequencing

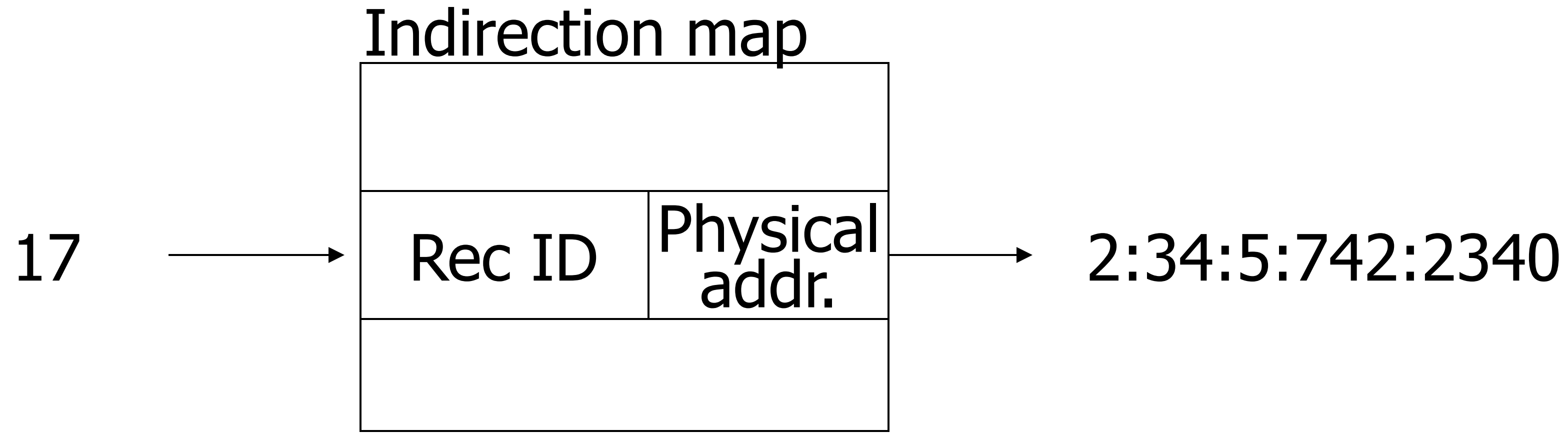
- Ordering records in a file (and in the blocks) by some key value
- Can be used for binary search
- Options:
  a. Next record is physically contiguous

  b. Records are linked



4. Indirection

- How does one refer to records?
  a. Physical address (disk id, cylinder, head, sector, offset in block)
  b. Logical record ids and a mapping table



- Tradeoff between flexibility and cost

Modification of Records

How to handle the following operations on the record level?

1. Insertion
2. Deletion
3. Update

1. Insertion

- Easy case: records not in sequence
  - Insert new record at end of file
  - If records are fixed-length, insert new record in deleted slot
- Difficult case: records are sorted
  - Find position and slide following records
  - If records are sequenced by linking, insert overflow blocks

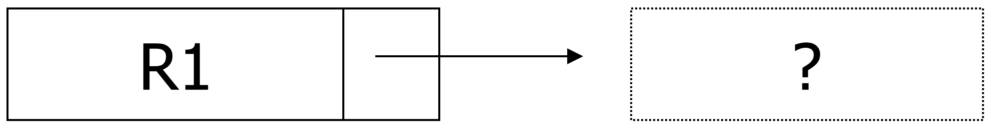
2. Deletion

a. Immediately reclaim space by shifting other records or removing overflows
b. Mark deleted and list as free for re-use

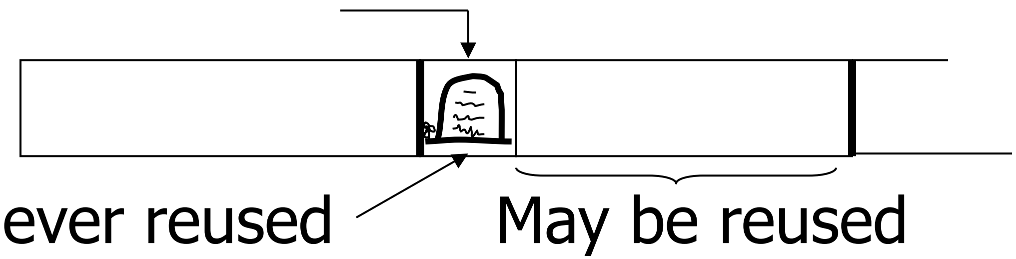
- Tradeoffs:
  - How expensive is immediate reclaim?
  - How much space is wasted?

Problem with Deletion

- Dangling pointers:



- When using physical addresses:



- When using logical addresses:

ID	LOC
7788	

Never reuse ID 7788 nor space in the map

3. Update

- If records are fixed-length and the order is not affected:
  - Fetch the record, modify it, write it back
- Otherwise:
  - Delete the old record
  - Insert the new record overwriting the tombstones from the deletion

Pointer Swizzling

- *Swizzling* = replacement of physical addresses by memory addresses when loading blocks into memory
- Automatic Swizzling: swizzle all addresses when loading a block (need to swizzle all pointer from and to the block)
- Swizzling on Demand: use addresses which are invalid as memory addresses

Data Organizaton

- There are millions of ways to organize the data on disk
- Flexibility Space Utilization

Complexity Performance

Summary 9

More things you should know:

- Memory Hierarchy
- Storage on harddisks
- Values, Records, Blocks, Files
- Storing and modifying records

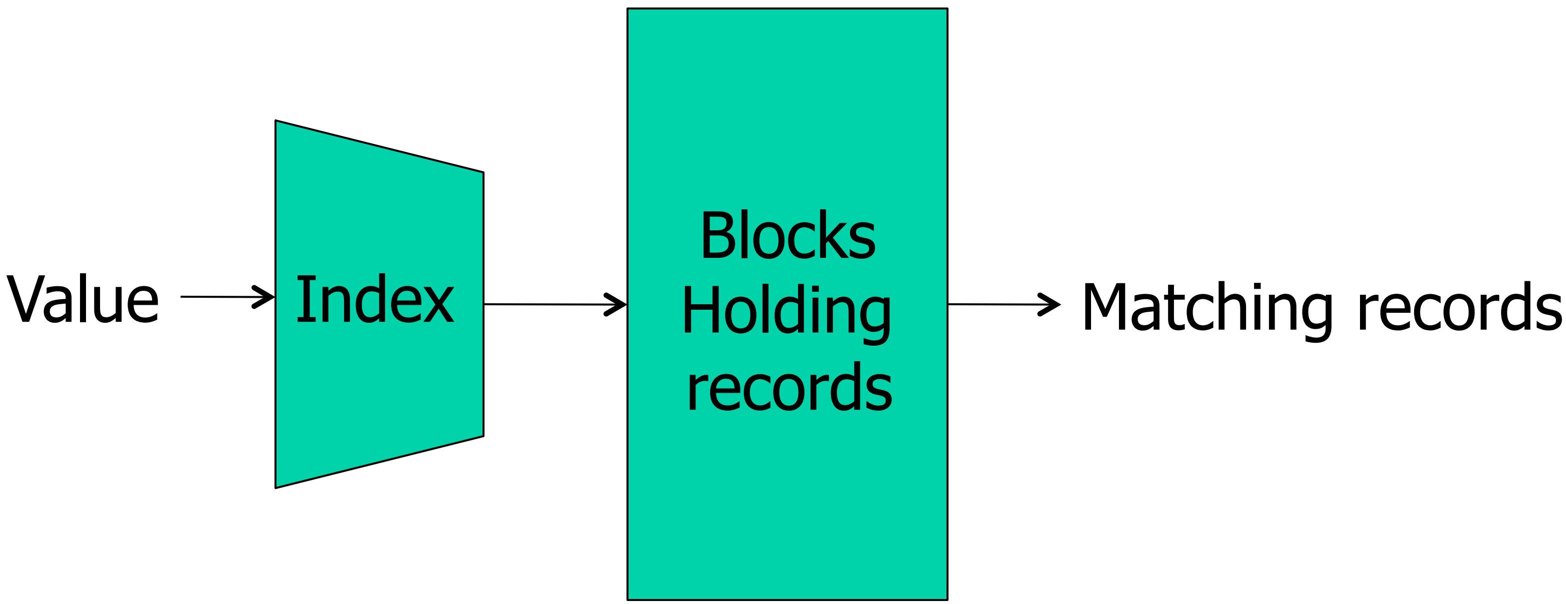
Index Structures

Finding Records

- How do we find the records for a query?
- Example: `SELECT * FROM Sells`
- Need to examine every block in every file
- Group blocks into files by relation!
- Example:
  ```
  SELECT * FROM Sells
     WHERE price = 20;
  ```
- Need to examine every block in the file

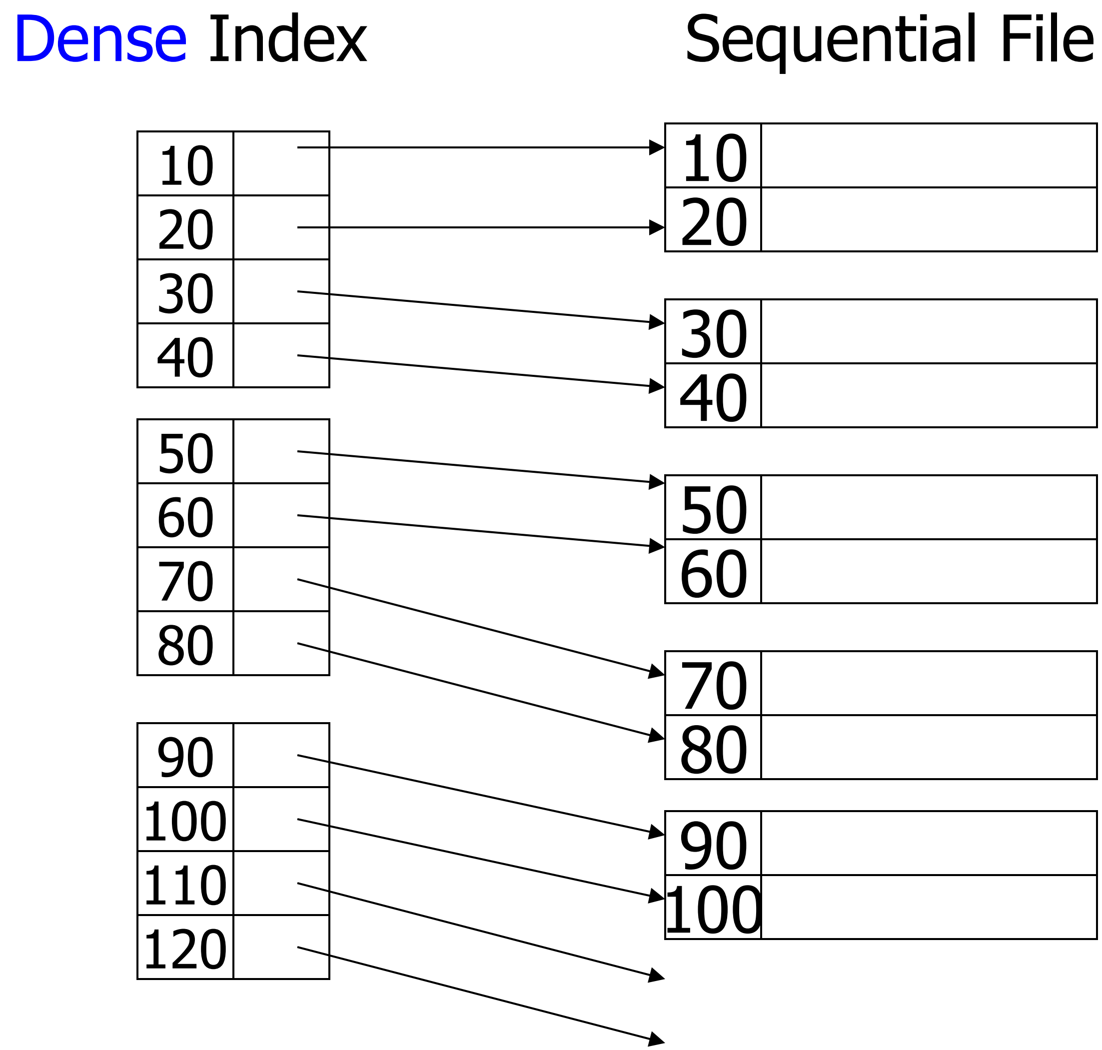
Finding Records

- Use of indexes allows to narrow search to (almost) only the relevant blocks

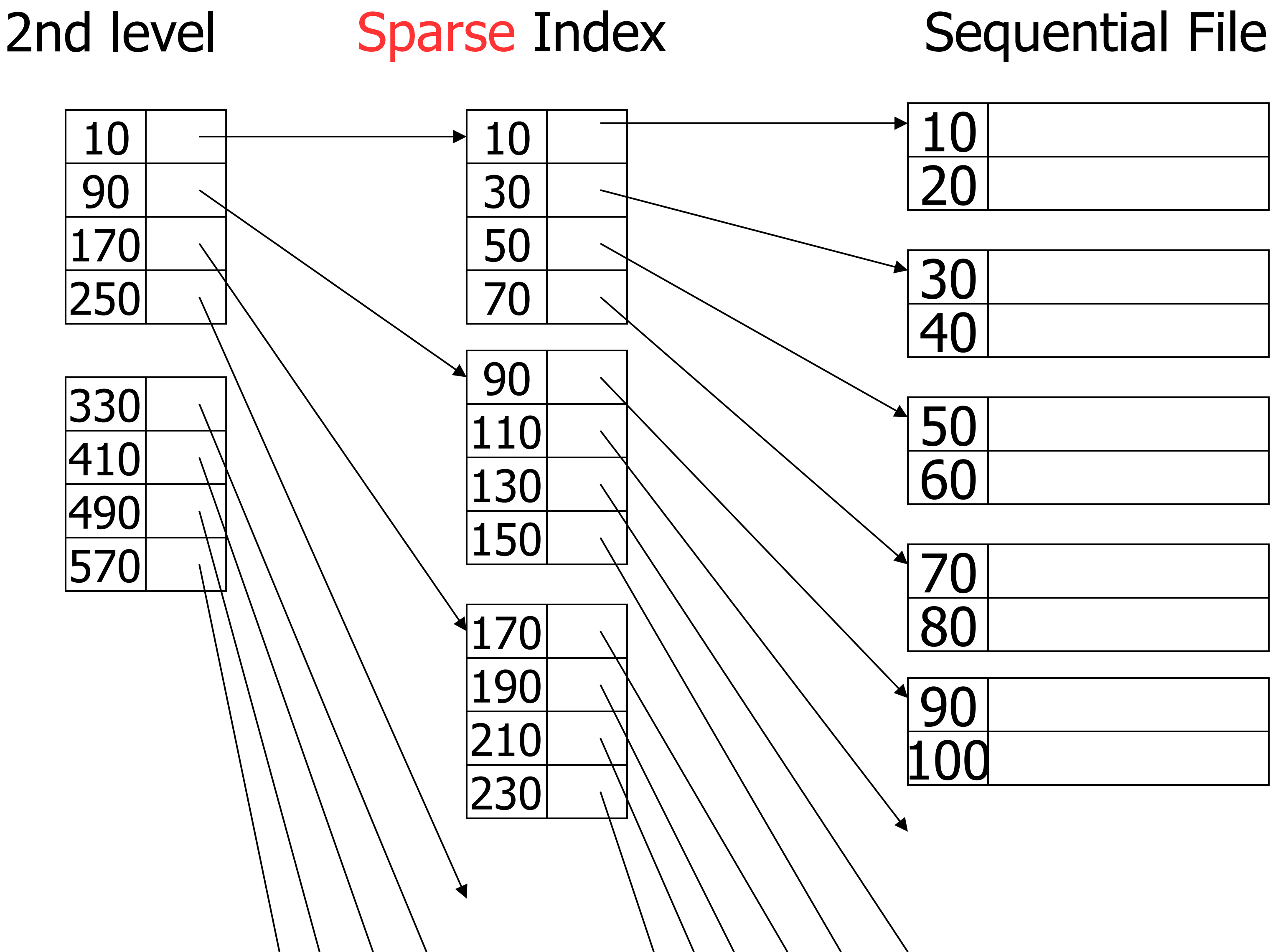


- Indexes can be *dense* or *sparse*

Dense Index

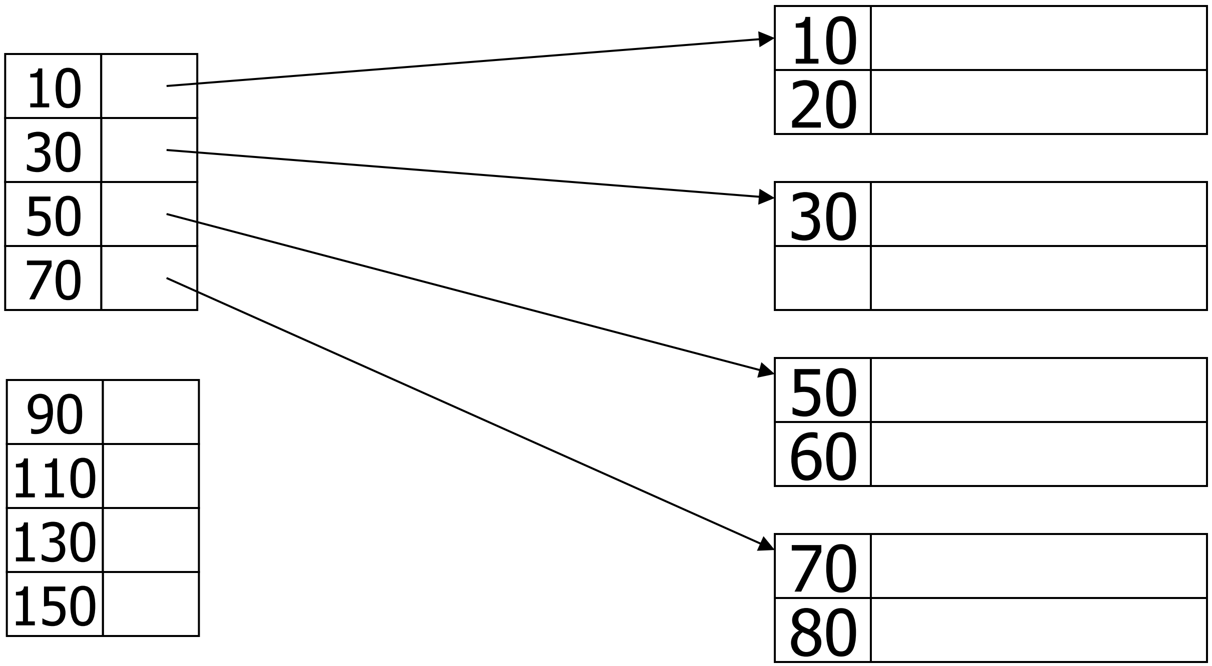

Dense Index
Sequential File
10
20
30
40
50
60
70
80
90
100
110
120
10
20
30
40
50
60
70
80
90
100

Sparse Index



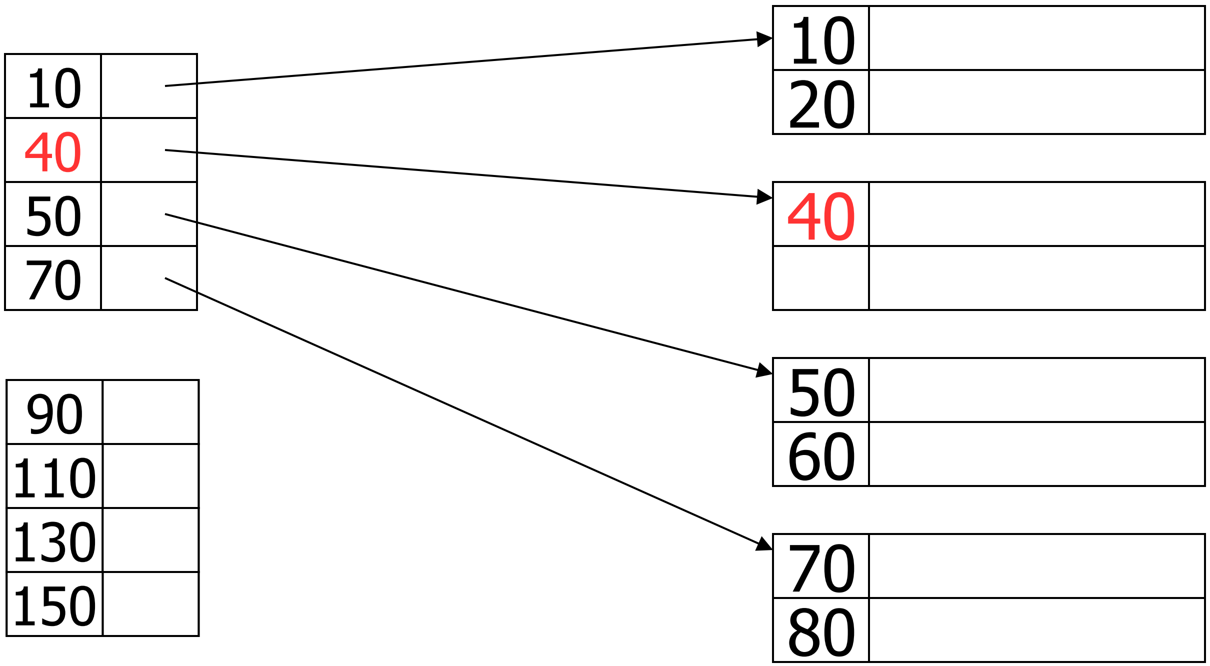
Deletion from Sparse Index

- Delete 40



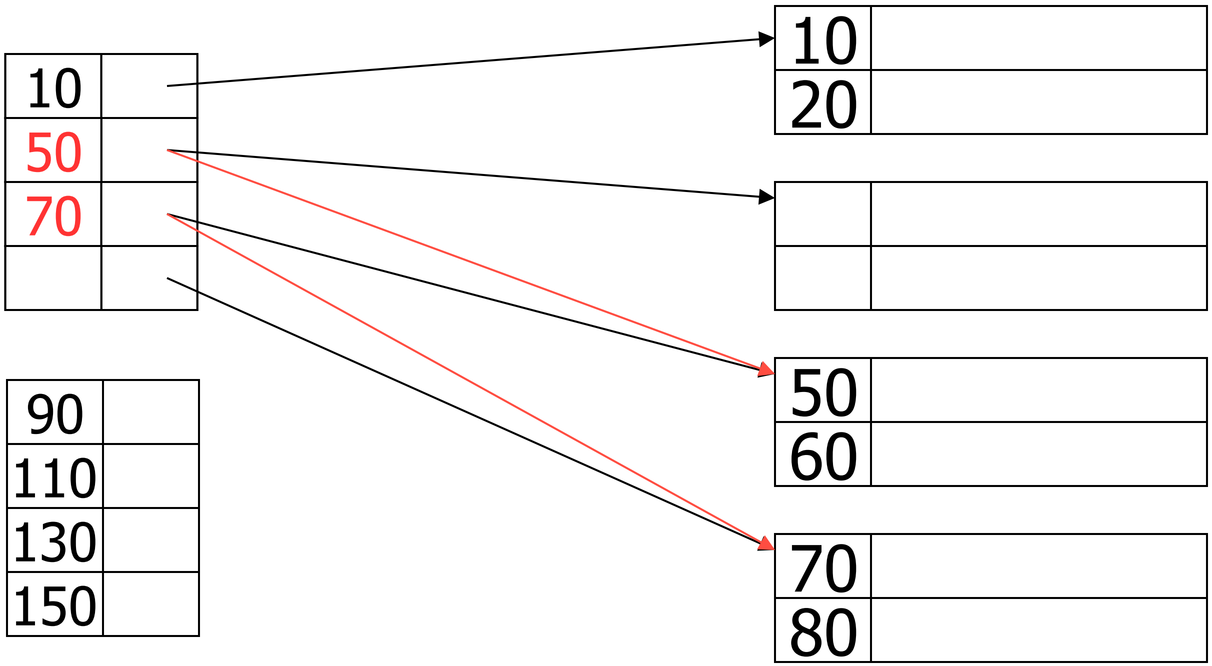
Deletion from Sparse Index

- Delete 30



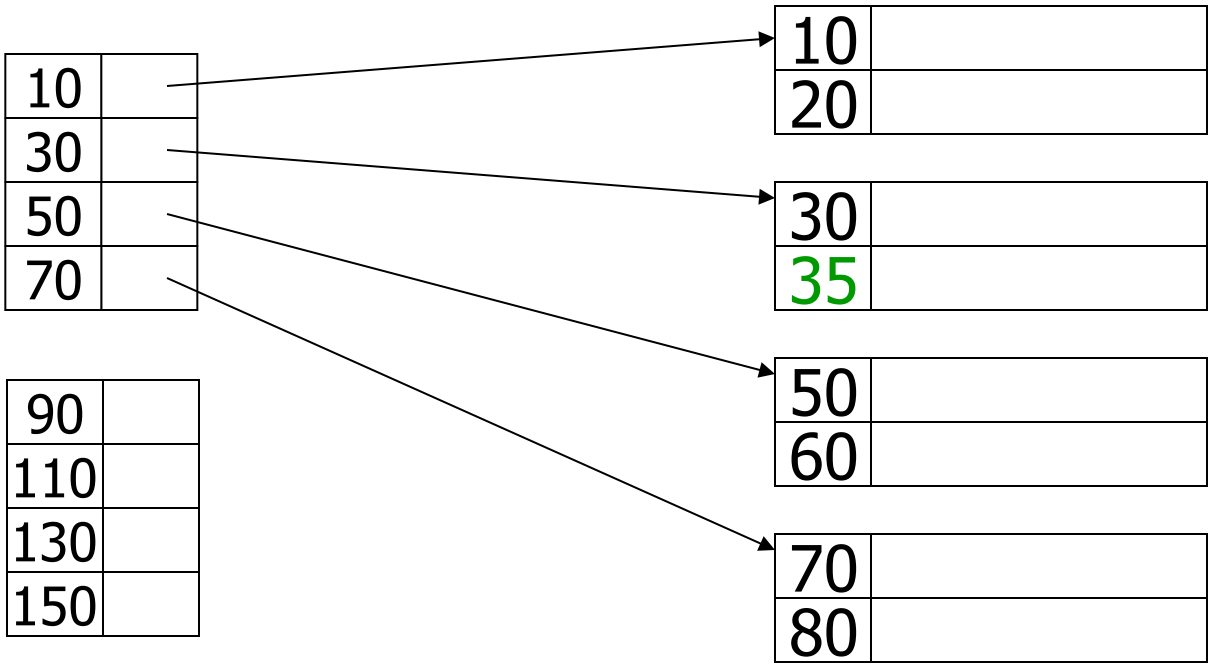
Deletion from Sparse Index

- Delete 30 & 40



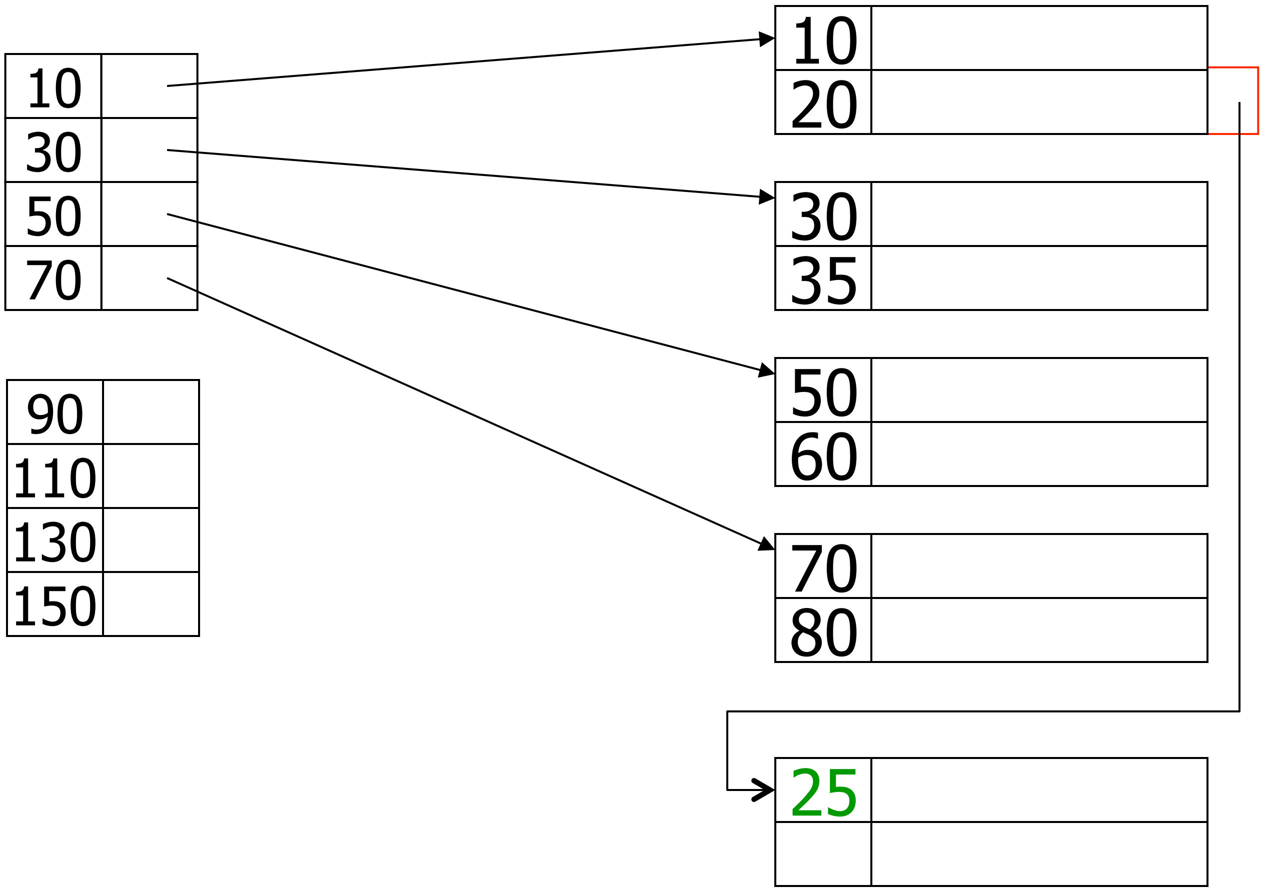
Insertion into Sparse Index

- Insert 35



Insertion into Sparse Index

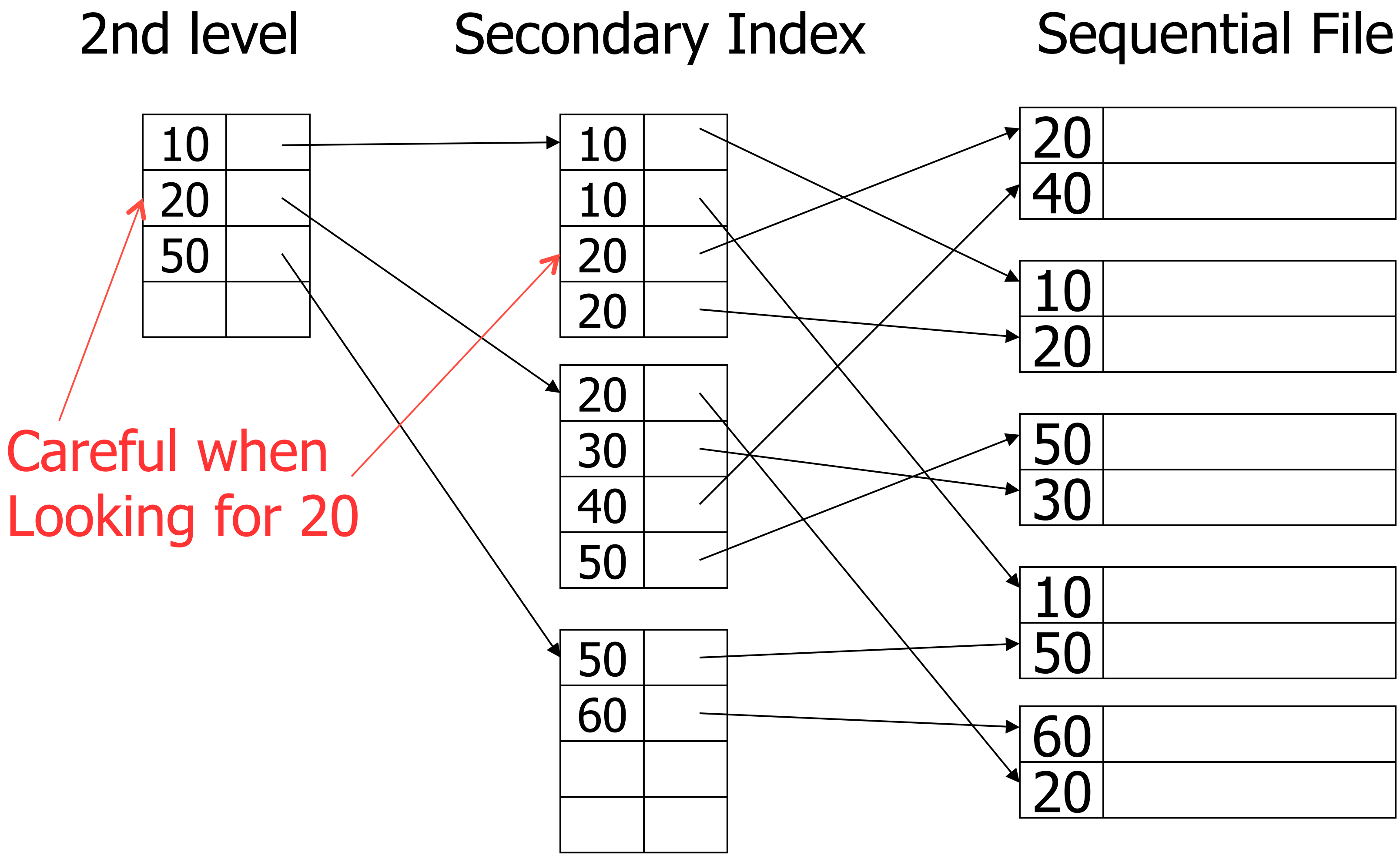
- Insert 25



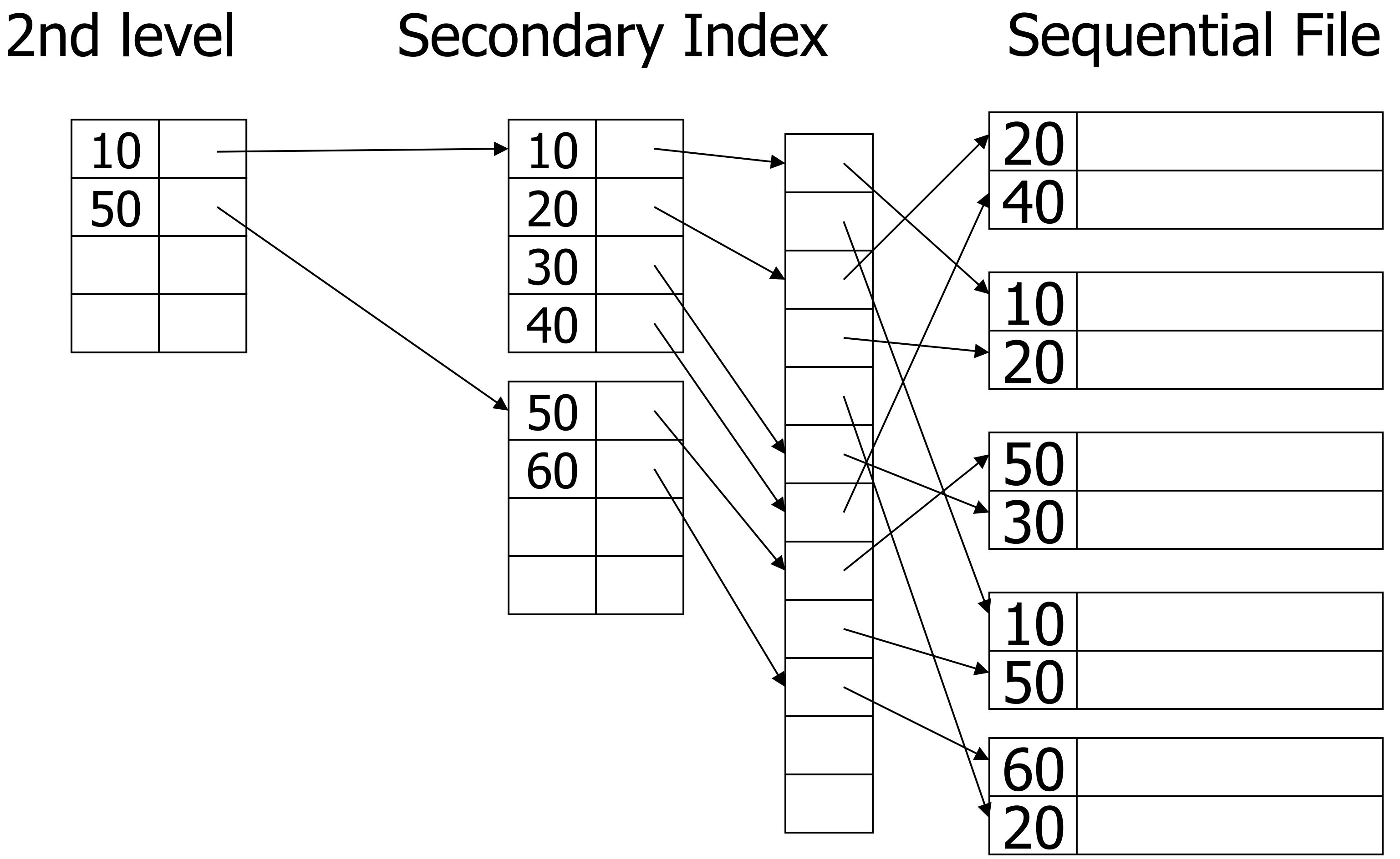
Sparse vs Dense

- Sparse uses less index space per record (can keep more of index in memory)
- Sparse allows multi-level indexes
- Dense can tell if record exists without accessing it
- Dense needed for secondary indexes
- Primary index = order of records in storage
- Secondary index = impose different order

Secondary Index

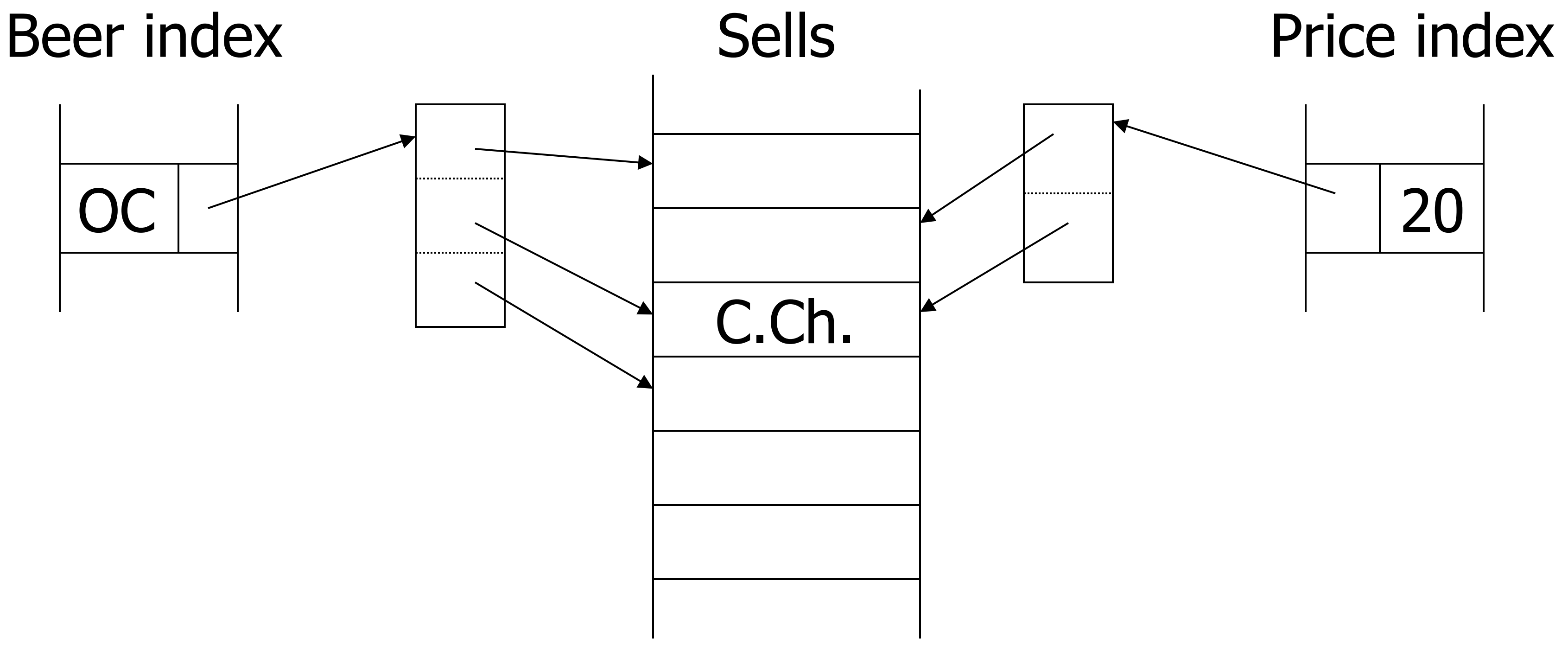


Secondary Index



Combining Indexes

- SELECT * FROM Sells WHERE beer = "Od.Cl." AND price = "20"

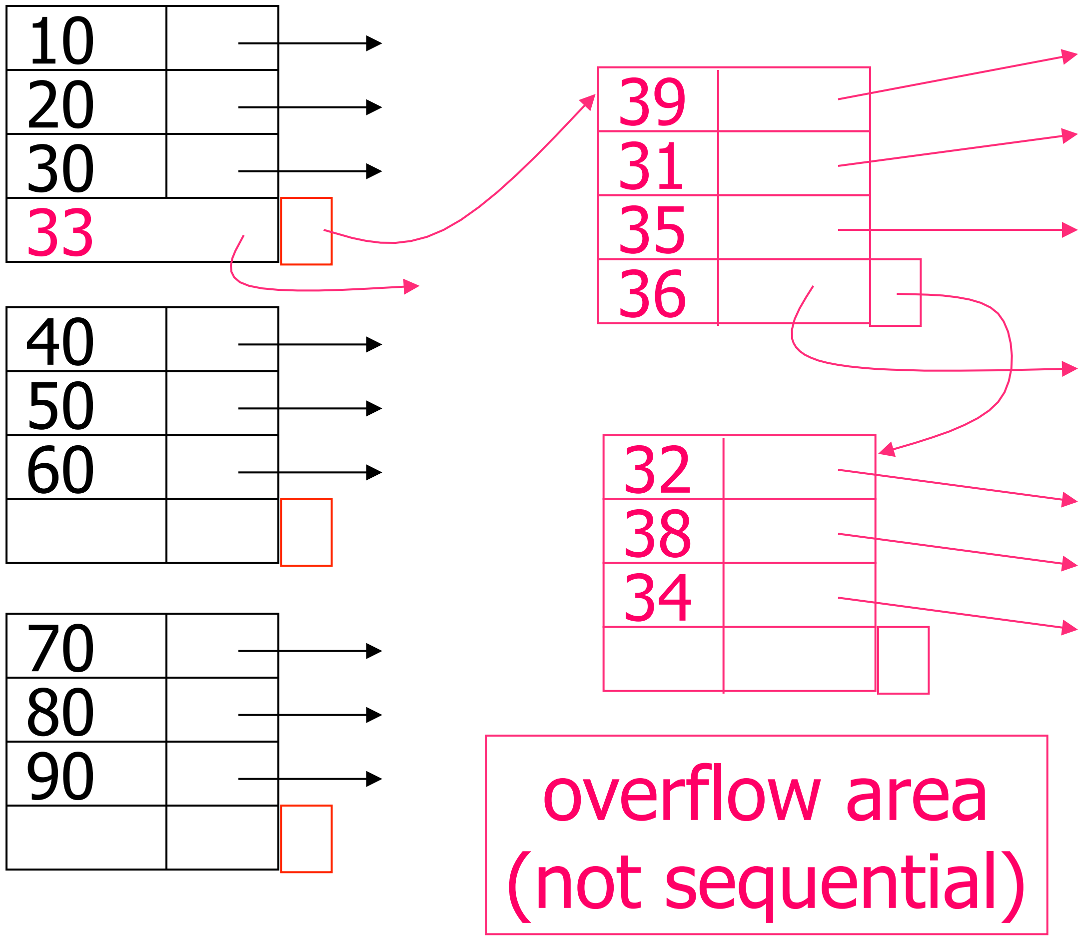


- Just intersect buckets in memory!

Conventional Indexes

- Sparse, Dense, Multi-level, ...
- Advantages:
  - Simple
  - Sequential index is good for scans
- Disadvantage:
  - Inserts expensive
  - Lose sequentiality and balance

Example: Unbalanced Index



B+Trees

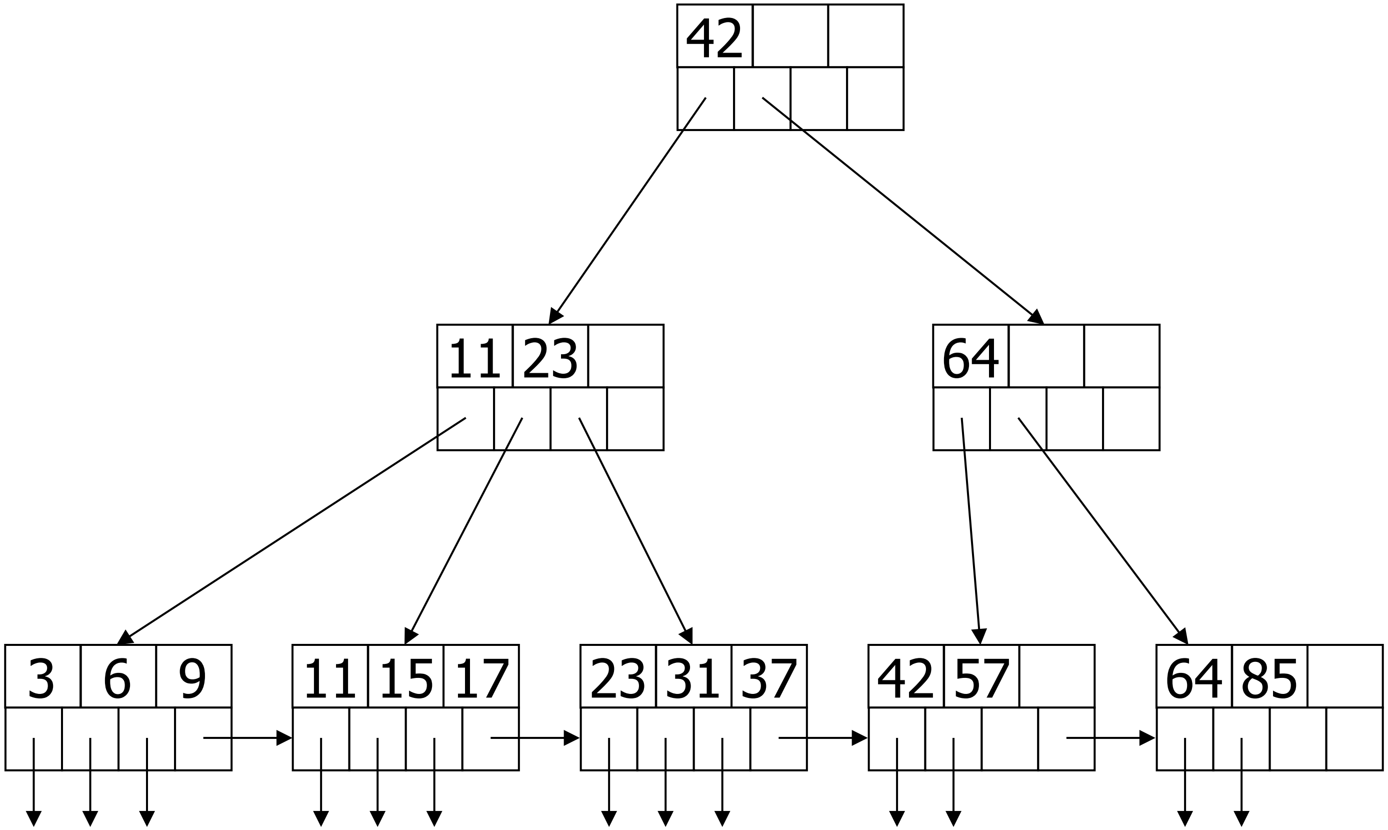
Idea

- Conventional indexes are fixed-level
- Give up sequentiality of the index in favour of balance
- B+Tree = variant of B-Tree
- Allows index tree to grow as needed
- Ensures that all blocks are between half used and completely full

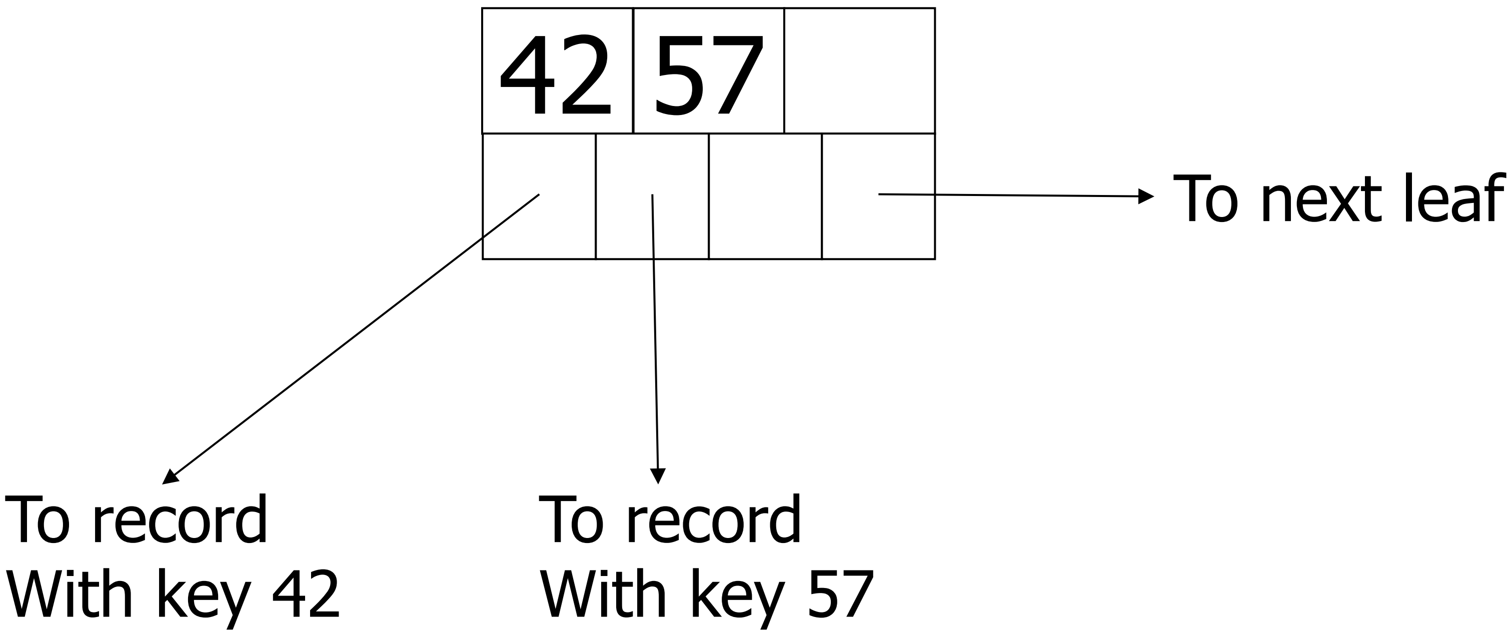
Characteristics

- Parameter n determines number of keys and pointers per node
- Key size 4 and pointer size 8 allows for maximal $n = 340 \quad (4n + 8(n+1) < 4096)$
- Leafs contain at least n/2 key-pointer pairs to records and a pointer to the next leaf
- Interior nodes contain at least (n-1)/2 keys and at least n/2 pointers to other nodes
- No restrictions for the root node

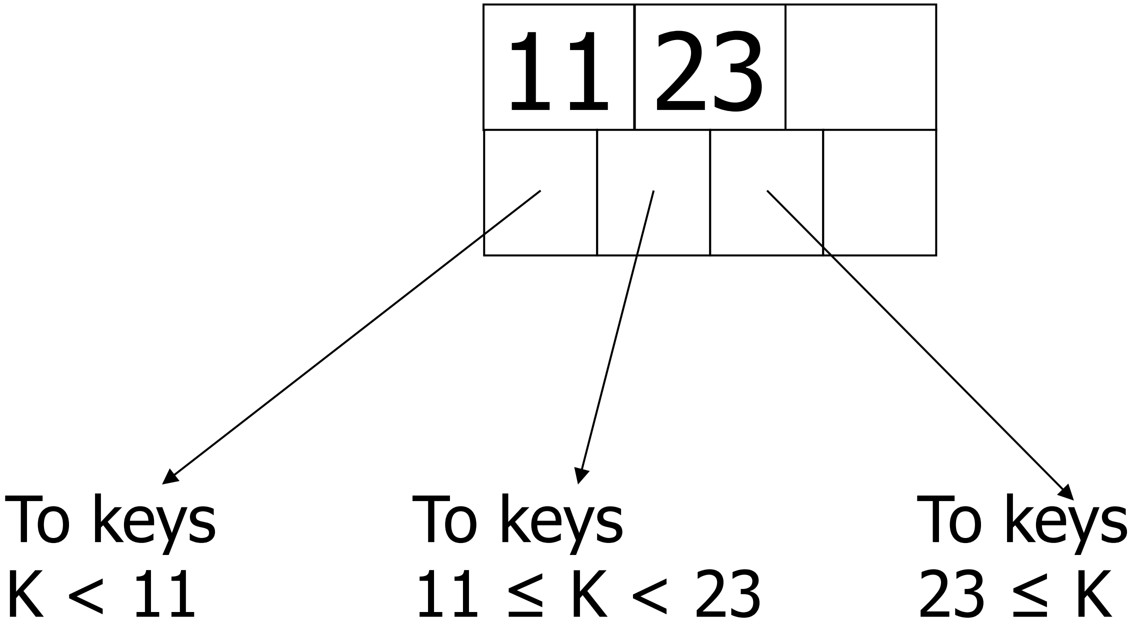
Example: B+Tree (n=3)



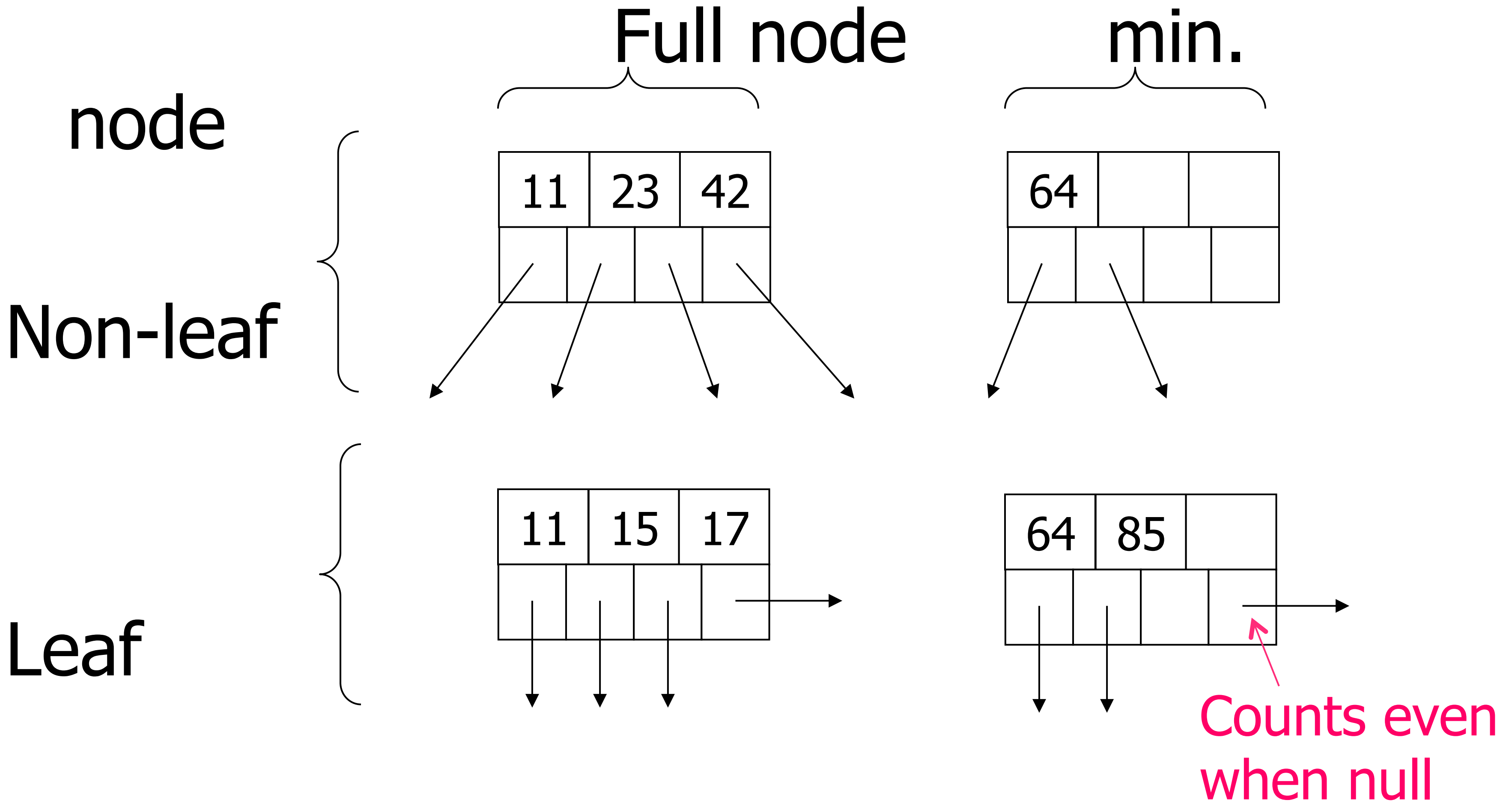
Example: Leaf node



Example: Interior node



Restrictions

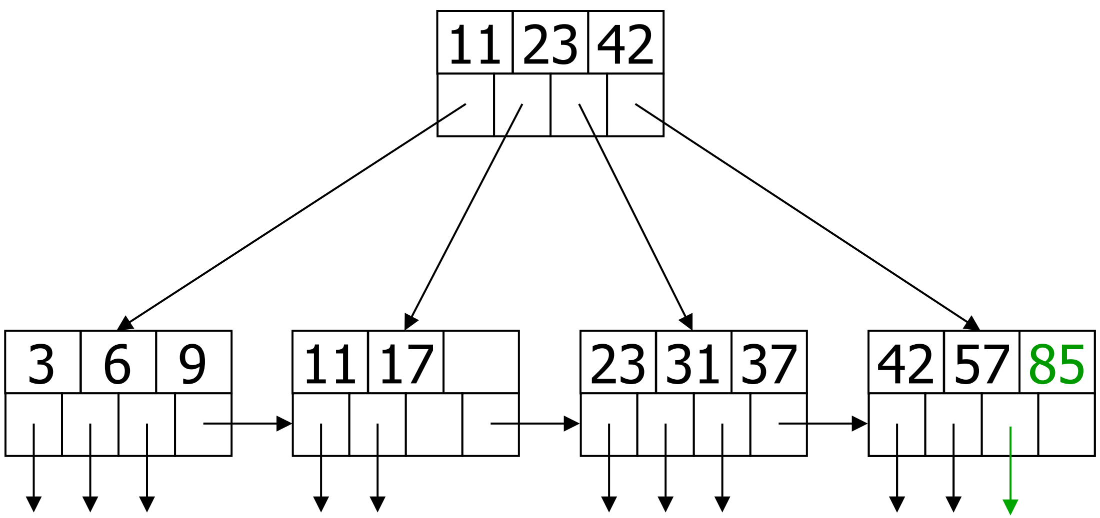


Insertion

- If there is place in the appropriate leaf, just insert it there
- Otherwise:
  - Split the leaf in two and divide the keys
  - Insert the smallest value reachable through the right node into the parent node
  - Recurse until there is enough room
- Special case: Splitting the root results in a new root

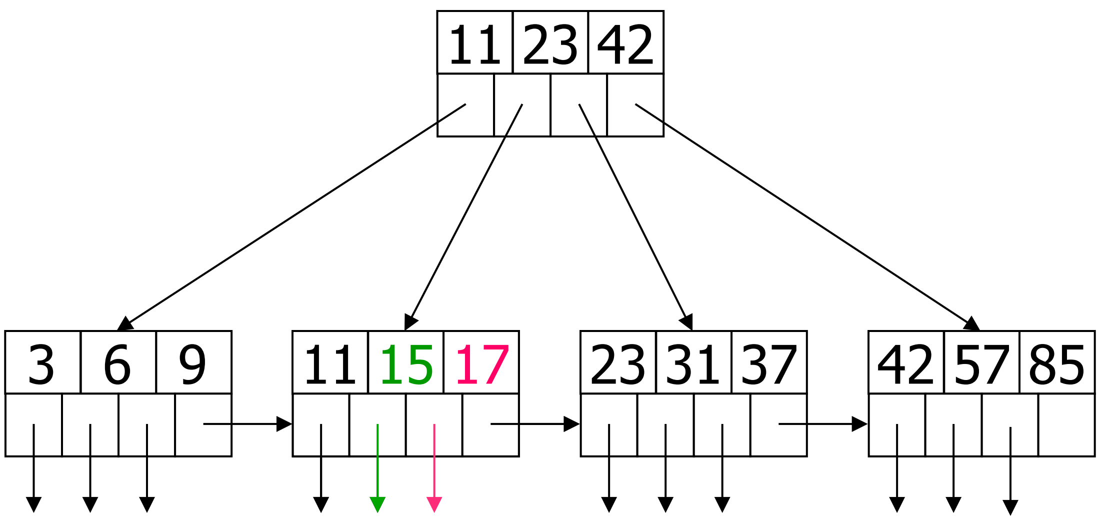
Example: Insertion

- Insert 85



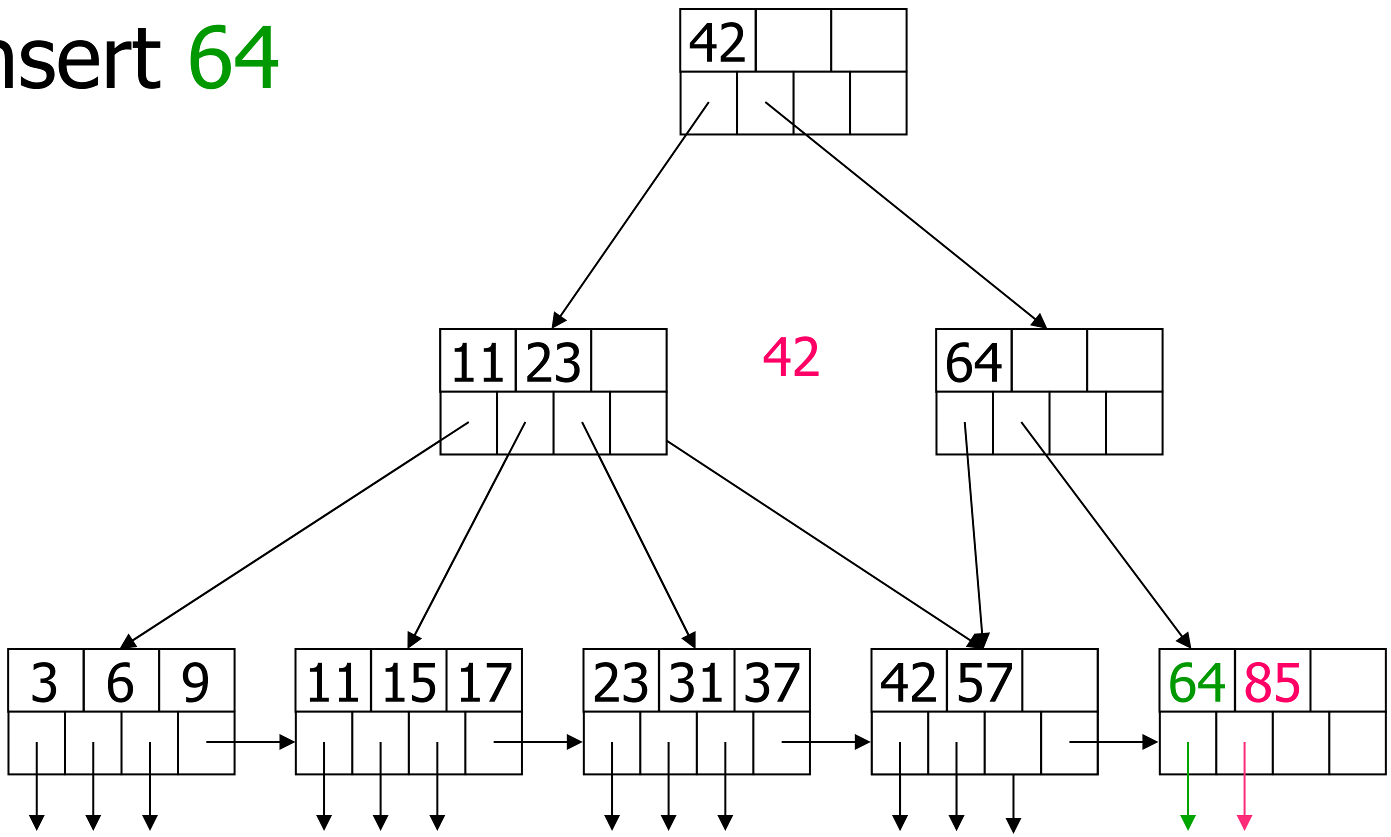
Example: Insertion

- Insert 15



Example: Insertion

- Insert 64

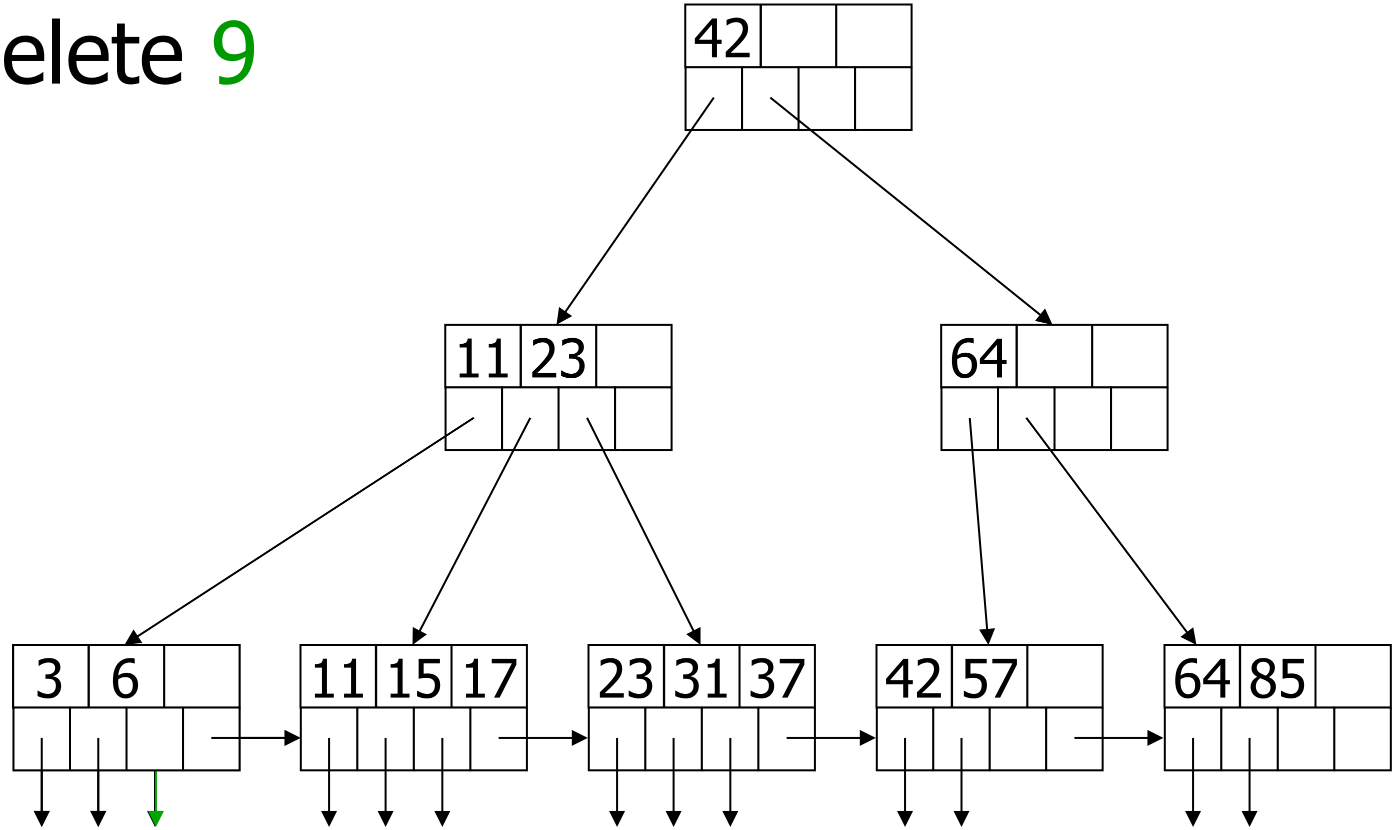


Deletion

- If there are enough keys left in the appropriate leaf, just delete the key
- Otherwise:
  - If there is a direct sibling with more than minimum key, steal one!
  - If not, join the node with a direct sibling and delete the smallest value reachable through the former right sibling from its parent
- Special case: If the root contains only one pointer after deletion, delete it

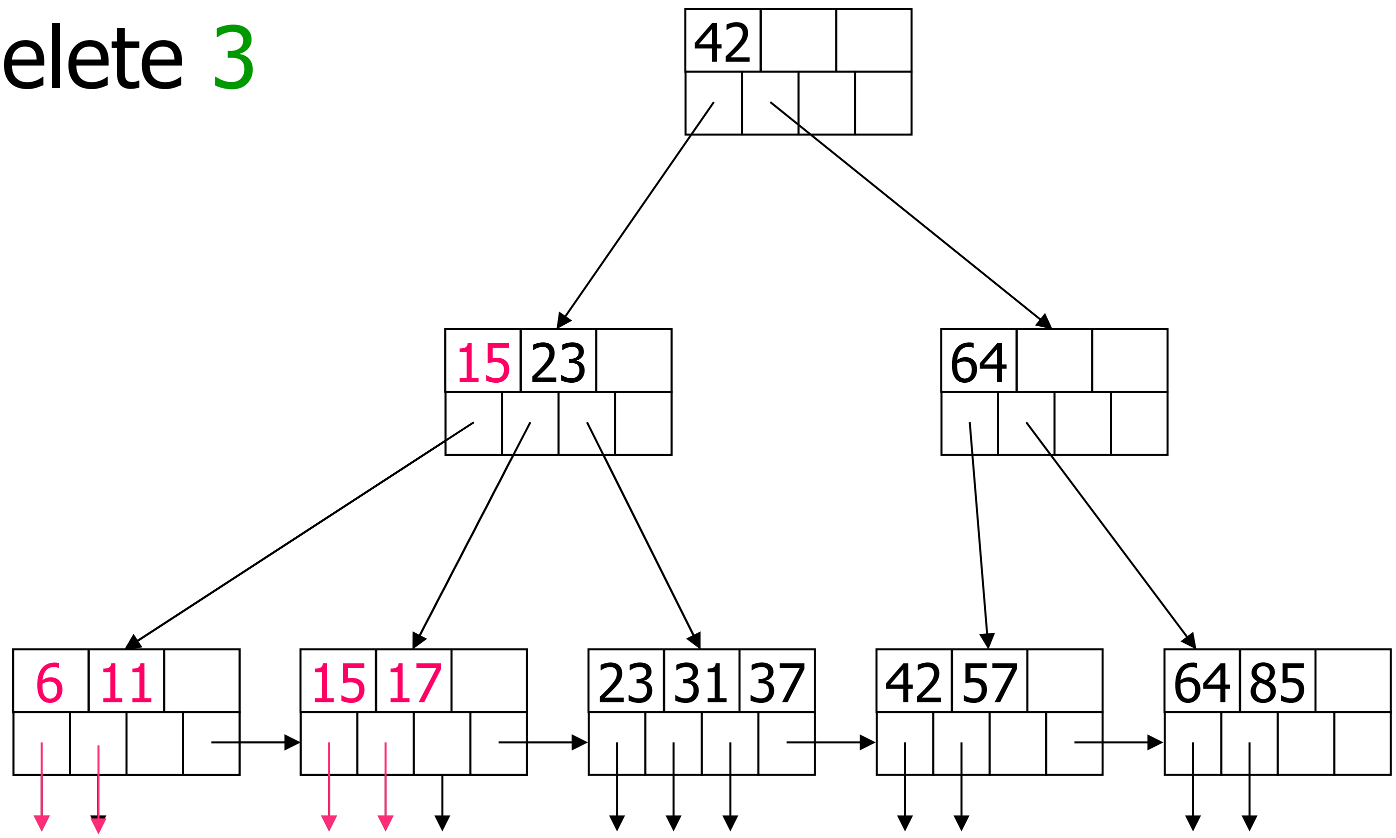
Example: Deletion

- Delete 9



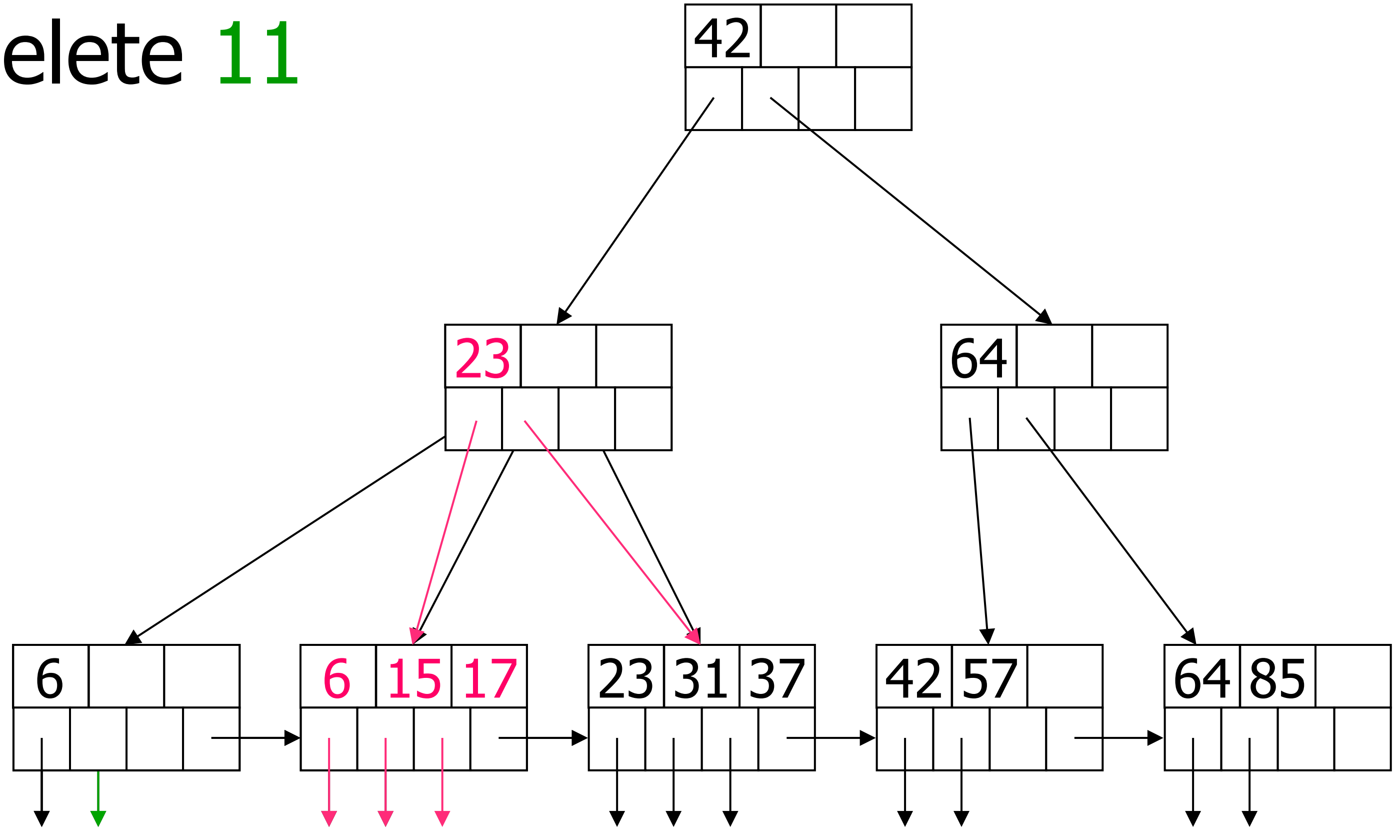
Example: Deletion

- Delete 3



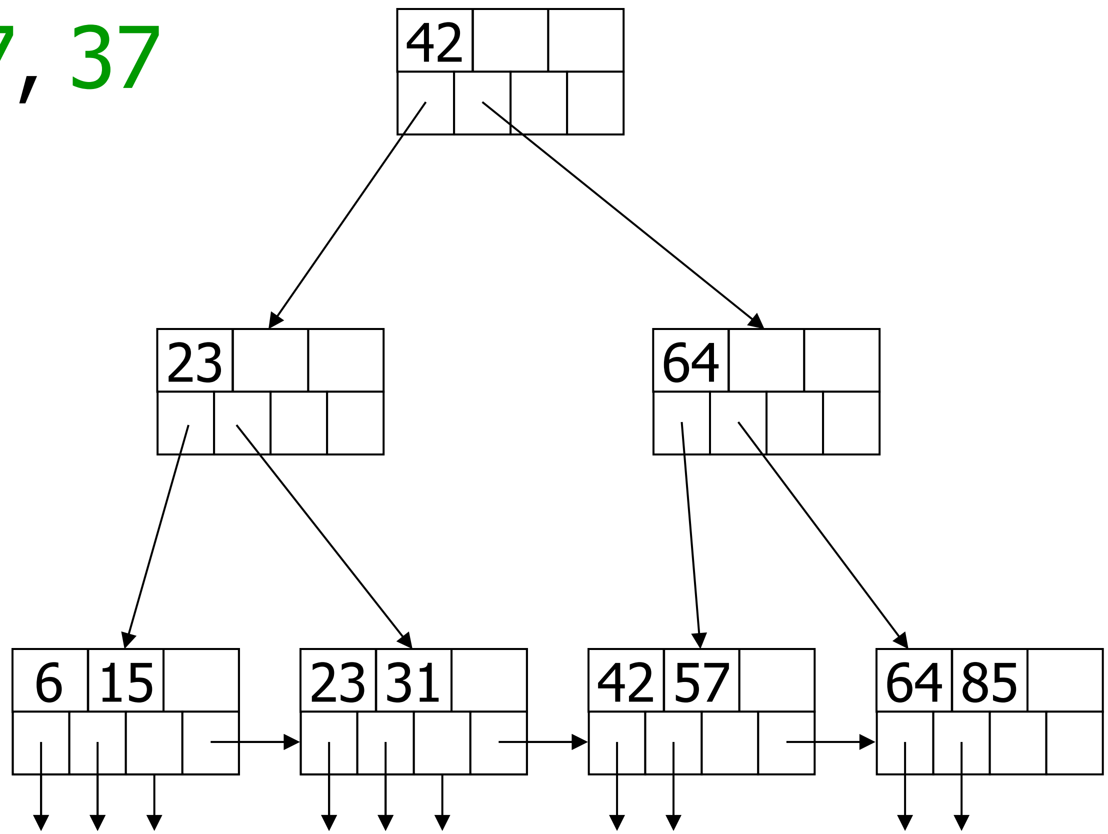
Example: Deletion

- Delete 11



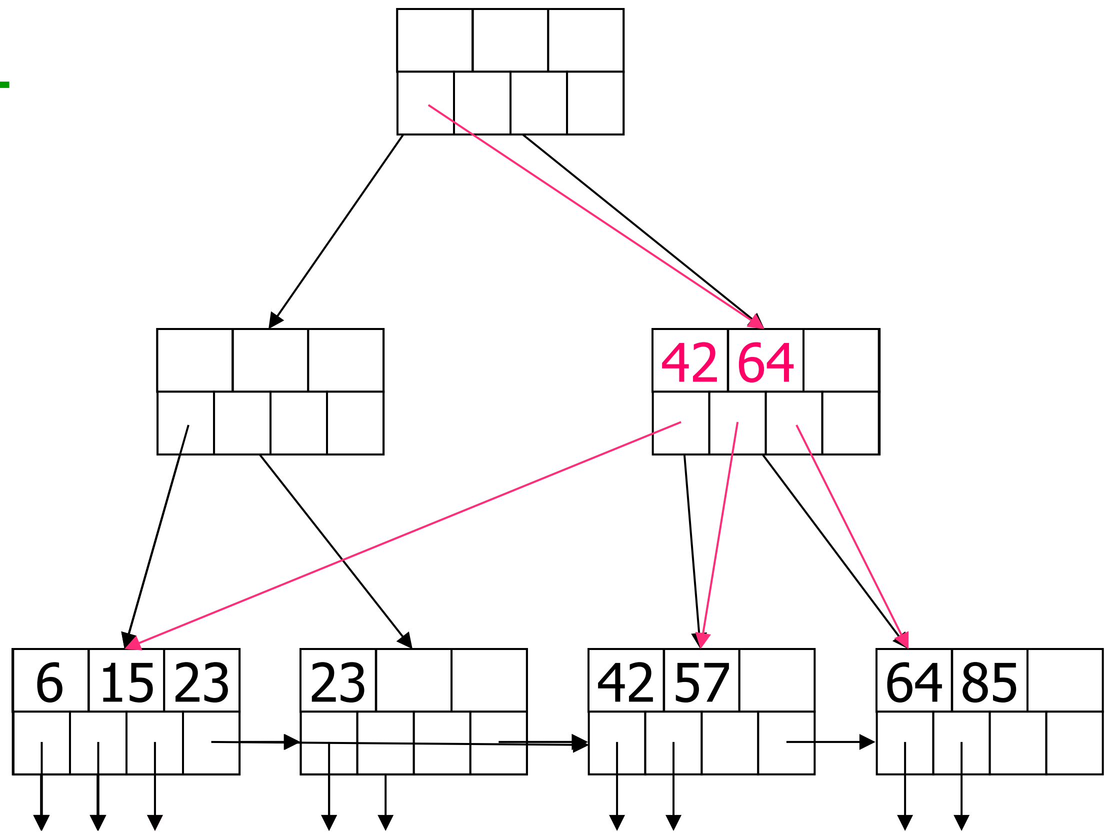
Example: Deletion

- Delete 17, 37



Example: Deletion

- Delete 31



Efficiency

- Need to load one block for each level!
- With n = 340 and an average fill of 255 pointers, we can index 255^3 = 16.6 million records in only 3 levels
- There are at most 342 blocks in the first two levels
- First two levels can be kept in memory using less than 1.4 Mbyte
- Only need to access one block!

Range Queries

- Queries often restrict an attribute to a range of values
- Example:

```
SELECT * FROM Sells
WHERE price > 20;
```

- Records are found efficiently by searching for value 20 and then traversing the leafs
- Can also be used if there is both an upper and a lower limit

Summary 10

More things you should know:

- Dense Index, Sparse Index
- Multi-Level Indexes
- Primary vs Secondary Index
- Structure of B+Trees
- Insertion and Deletion in B+Trees

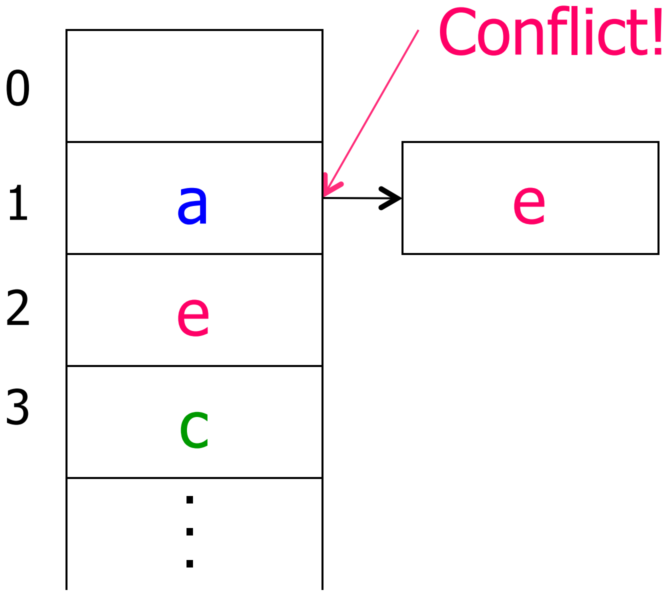
Hash Tables

Hash Table in Primary Storage

- Main parameter B = number of buckets
- Hash function h maps key to numbers from 0 to B-1
- Bucket array indexed from 0 to B-1
- Each bucket contains exactly one value
- Strategy for handling conflicts

Example: B = 4

- Insert c (h(c) = 3)
- Insert a (h(a) = 1)
- Insert e (h(e) = 1)
- Alternative 1:
  - Search for free bucket, e.g. by Linear Probing
- Alternative 2:
  - Add overflow bucket



Hash Function

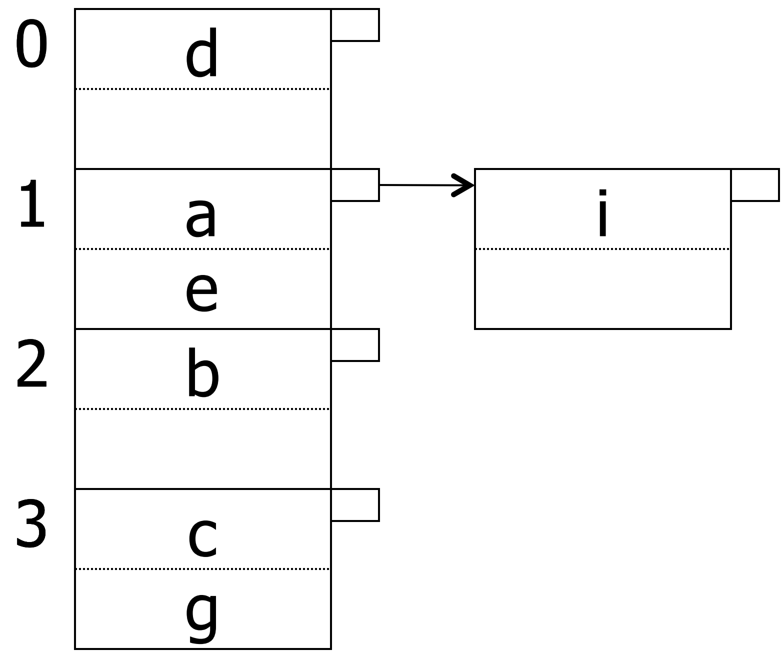
- Hash function should ensure hash values are equally distributed
- For integer key K, take h(K) = K modulo B
- For string key, add up the numeric values of the characters and compute the remainder modulo B
- For really good hash functions, see *Donald Knuth, The Art of Computer Programming: Volume 3 – Sorting and Searching*

Hash Table in Secondary Storage

- Each bucket is a block containing *f* key-pointer pairs
- Conflict resolution by probing potentially leads to a large number of I/Os
- Thus, conflict resolution by adding overflow buckets
- Need to ensure we can directly access bucket *i* given number *i*

Example: Insertion, B=4, f=2

- Insert a
- Insert b
- Insert c
- Insert d
- Insert e
- Insert g
- Insert i



Efficiency

- Very efficient if buckets use only one block: one I/O per lookup
- Space utilization is #keys in hash divided by total #keys that fit
- Try to keep between 50% and 80%:
  - < 50% wastes space
  - > 80% significant number of overflows

Dynamic Hashing

- How to grow and shrink hash tables?
- Alternative 1:
  - Use overflows and reorganizations
- Alternative 2:
  - Use dynamic hashing
  - Extensible Hash Tables
  - Linear Hash Tables

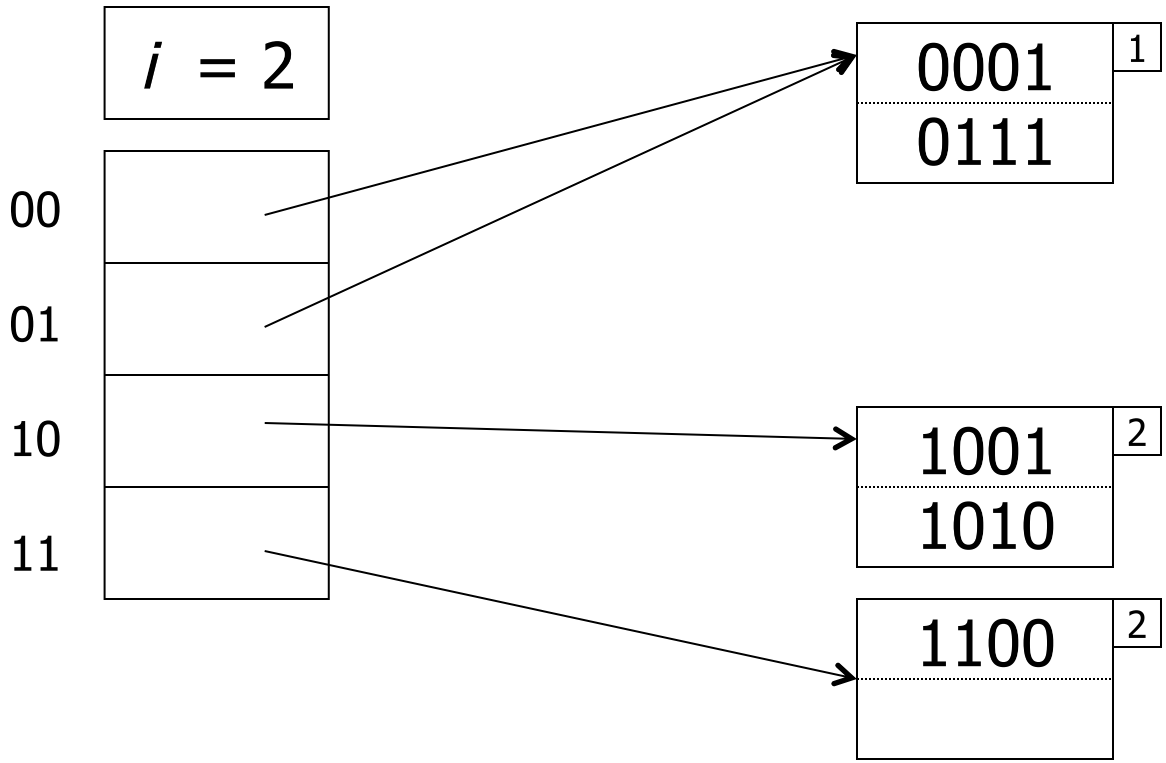
Extensible Hash Tables

- Hash function computes sequence of k bits for each key

$$k = 8 \ \boxed{\underbrace{001}_{i\,=\,3}10101}$$

- At any time, use only the first i bits
- Introduce indirection by a pointer array
- Pointer array grows and shrinks (size 2^i)
- Pointers may share data blocks (store number of bits used for block in j)

Example: k = 4, f = 2



Insertion

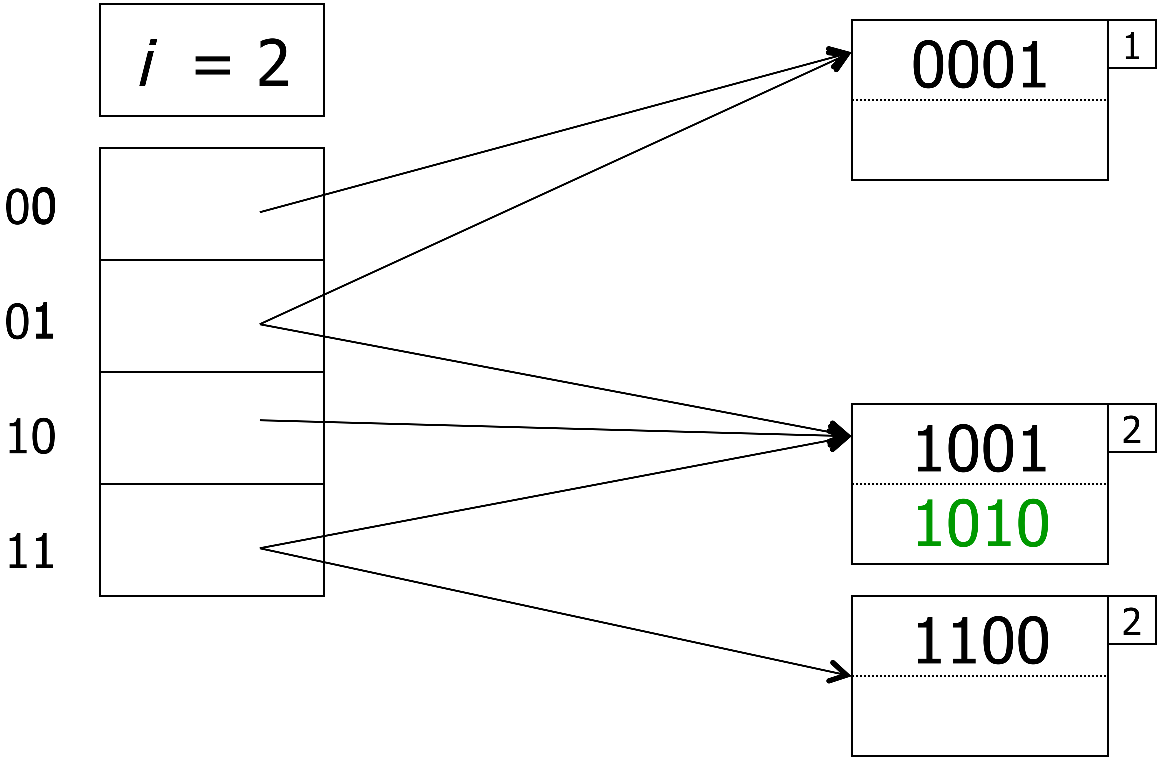
- Find destination block B for key-pointer pair
- If there is room, just insert it
- Otherwise, let *j* denote the number of bits used for block B
- If j = i, increment i by 1:
  - Double the length of the bucket array to 2^{i+1}
  - Adjust pointers such that for old bit strings w, w0 and w1 point to the same bucket
  - Retry insertion

Insertion

- If $j < i$, add a new block B`:
  - Key-pointer pairs with $(j+1)$st bit = 0 stay in B
  - Key-pointer pairs with $(j+1)$st bit = 1 go to B`
  - Set number of bits used to $j+1$ for B and B`
  - Adjust pointers in bucket array such that if for all w where previously w0 and w1 pointed to B, now w1 points to B`
  - Retry insertion

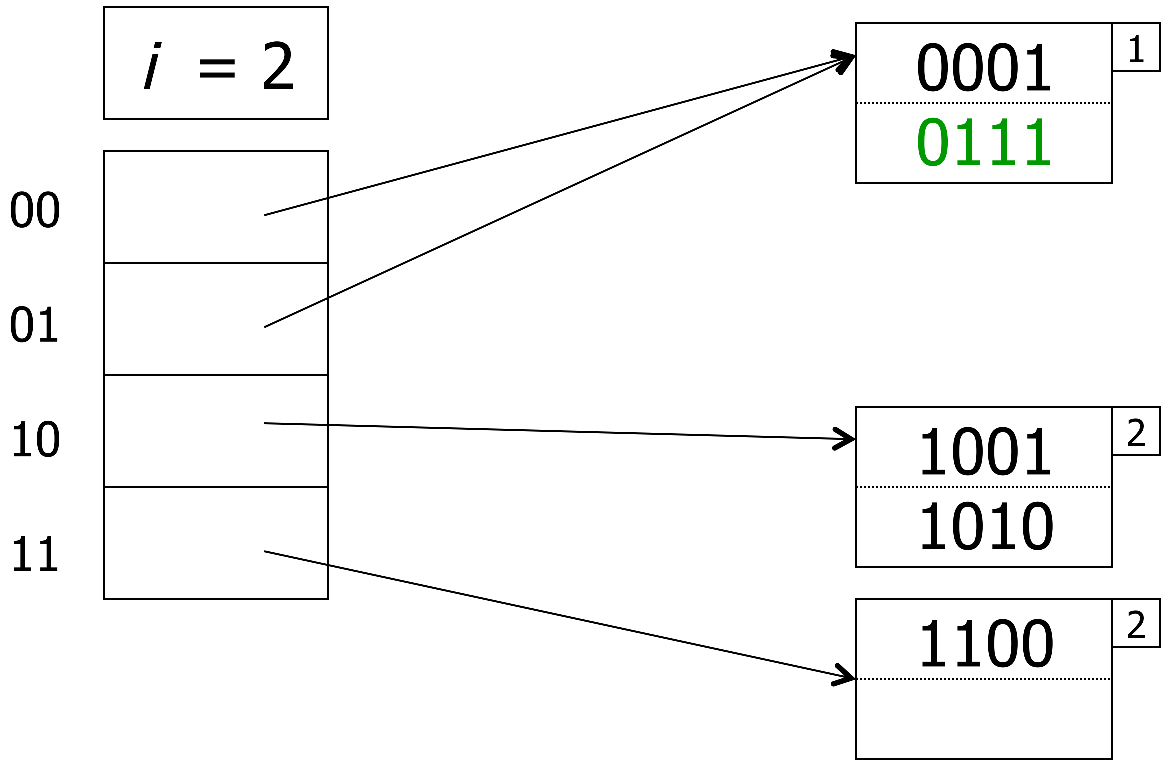
Example: Insert, k = 4, f = 2

- Insert 1010



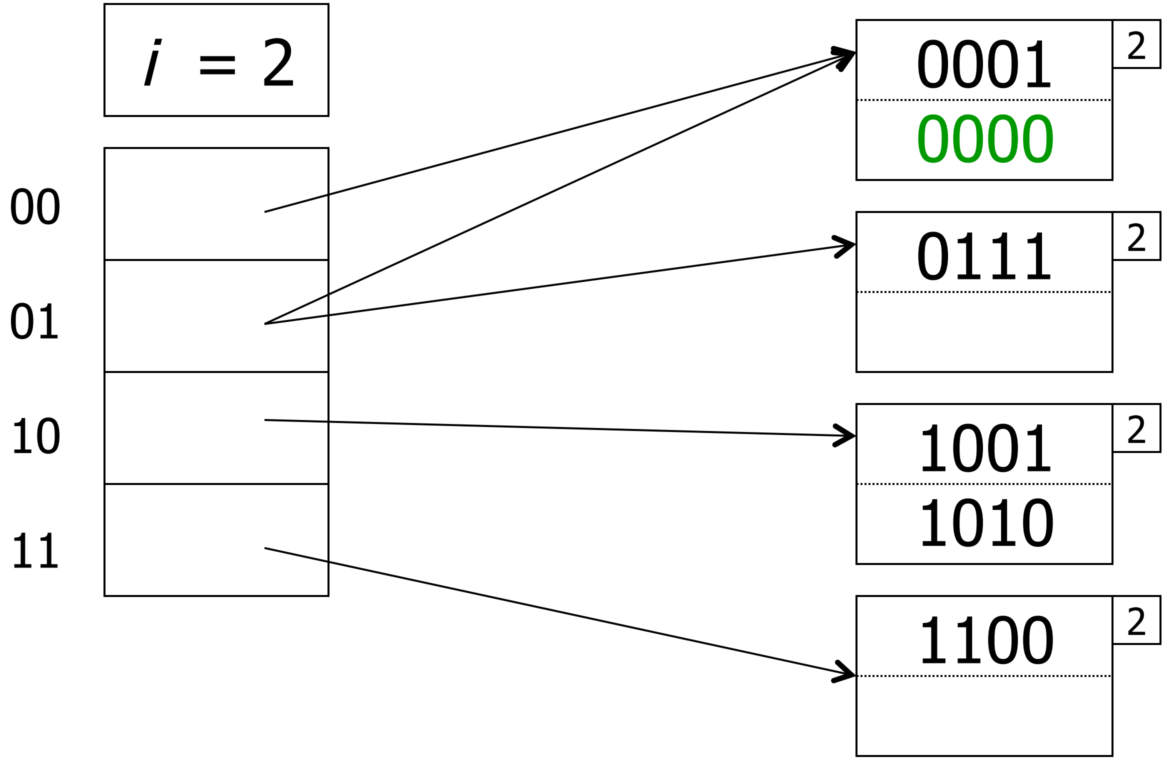
Example: Insert, k = 4, f = 2

- Insert 0111



Example: Insert, k = 4, f = 2

- Insert 0000

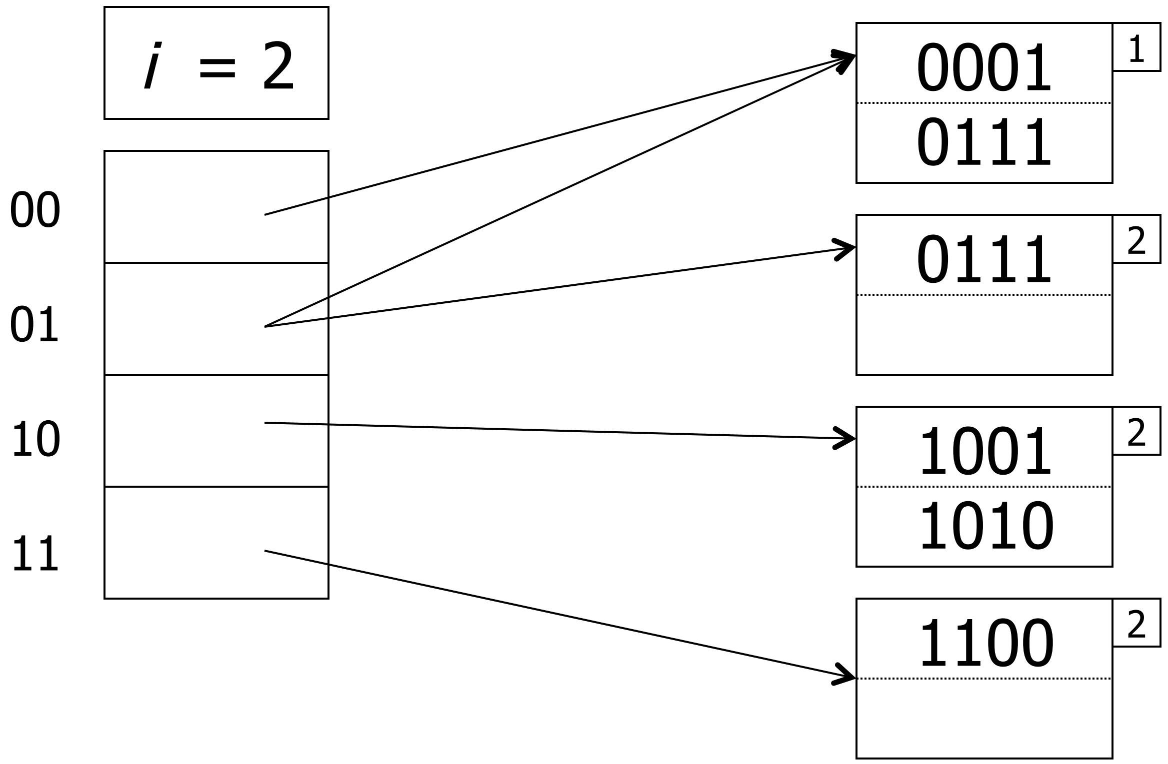


Deletion

- Find destination block B for key-pointer pair
- Delete the key-pointer pair
- If two blocks B referenced by w0 and w1 contain at most *f* keys, merge them, decrease their j by 1, and adjust pointers
- If there is no block with $j = i$, reduce the pointer array to size 2^{i-1} and decrease i by 1

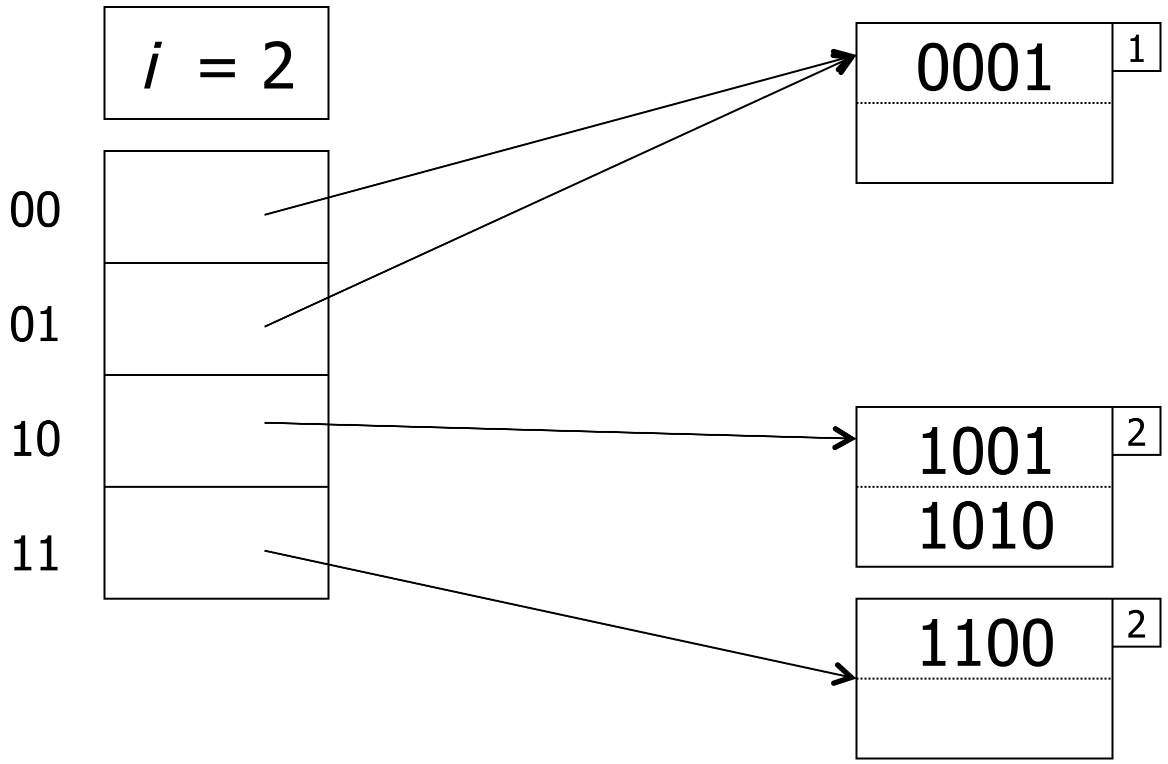
Example: Delete, k = 4, f = 2

- Delete 0000



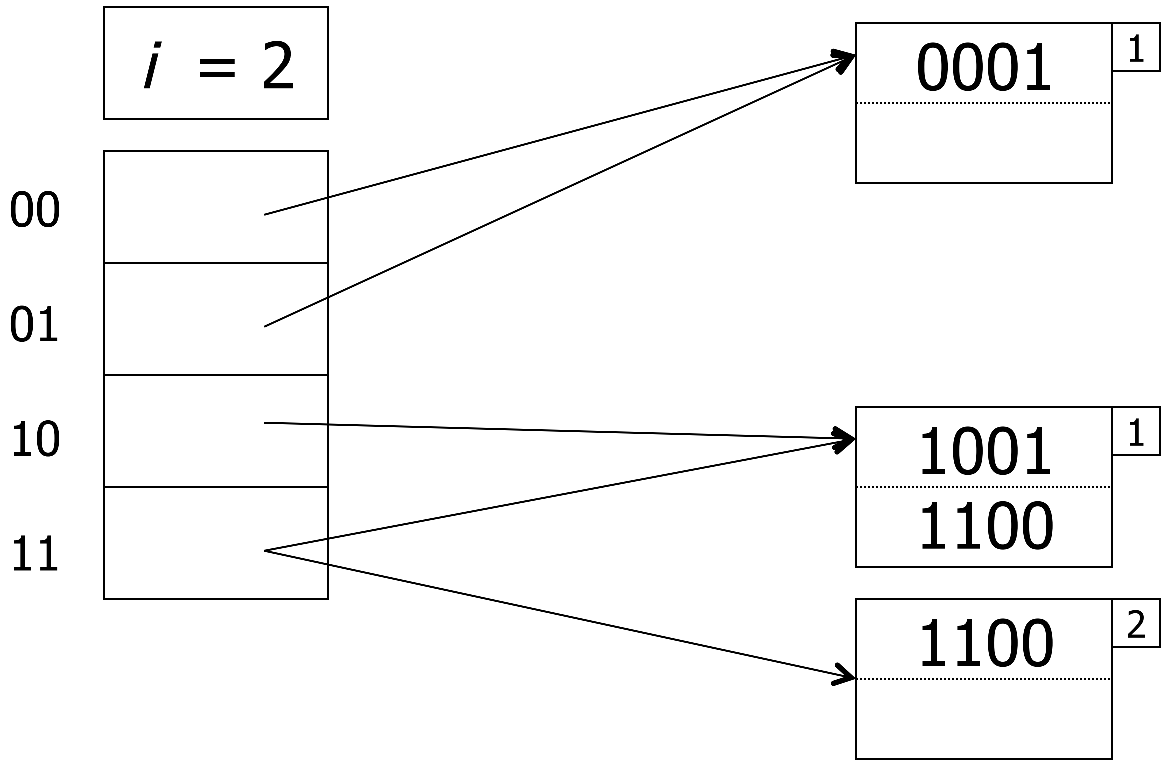
Example: Delete, k = 4, f = 2

- Delete 0111



Example: Delete, k = 4, f = 2

- Delete 1010



Efficiency

- As long as pointer array fits into memory and hash function behaves nicely, just need one I/O per lookup
- Overflows can still happen if many key-pointer pairs hash to the same bit string
- Solve by adding overflow blocks