CS 525: Advanced Database Organization

04: Indexing

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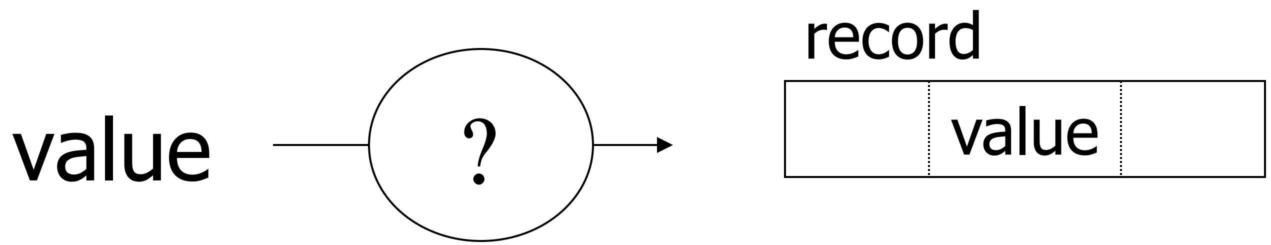
Slides: adapted from a course taught by Hector Garcia-Molina, Stanford InfoLab

IIT College of Science and Letters
ILLINOIS INSTITUTE OF TECHNOLOGY

Part 04

Indexing & Hashing



Query Types:

- **Point queries**:
  - *Input:* value **v** of attribute **A**
  - *Output:* all objects (tuples) with that value in attribute **A**
- **Range queries**:
  - *Input:* value interval **[low,high]** of attr **A**
  - Output: all tuples with a value

    low <= v < high in attribute **A**

Index Considerations:

- Supported Query Types
- Secondary-storage capable
- Storage size
  - Index Size / Data Size
- Complexity of Operations
  - E.g., insert is O(log(n)) worst-case
- Efficient Concurrent Operations?

Topics

- Conventional indexes
- B-trees
- Hashing schemes
- Advanced Index Techniques

Sequential File

10	
20	

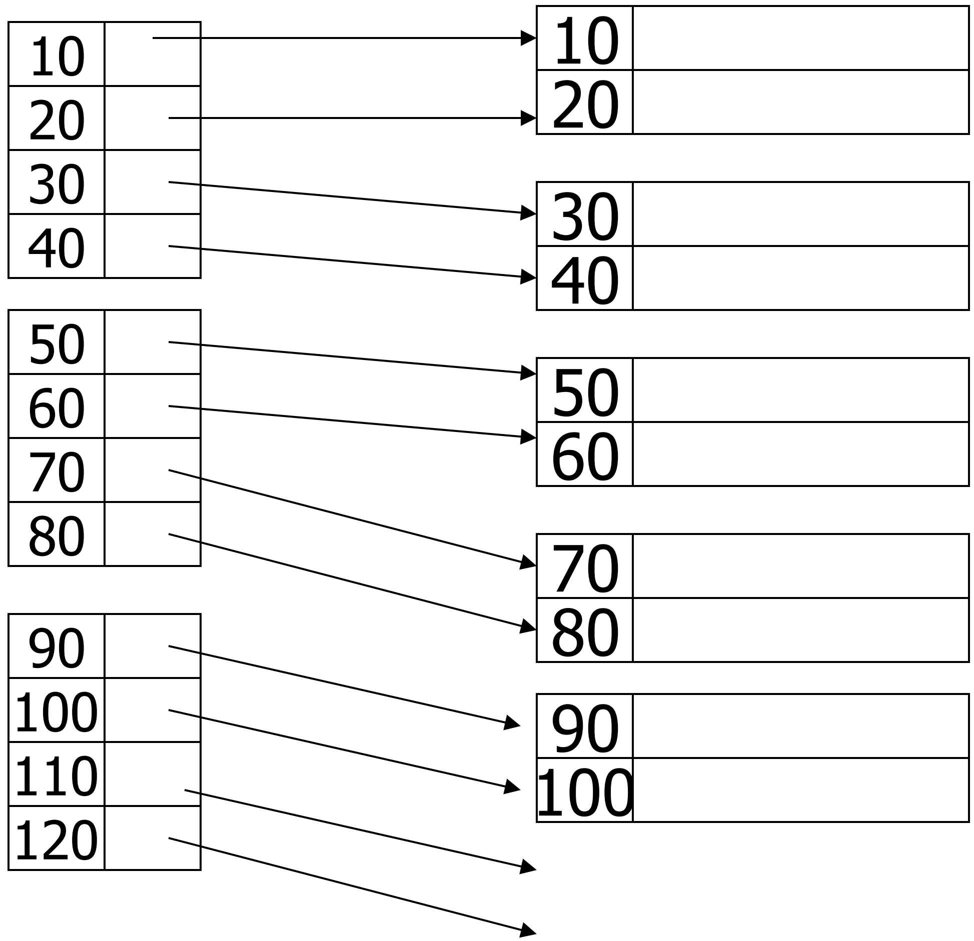
30	
40	

50	
60	

70	
80	

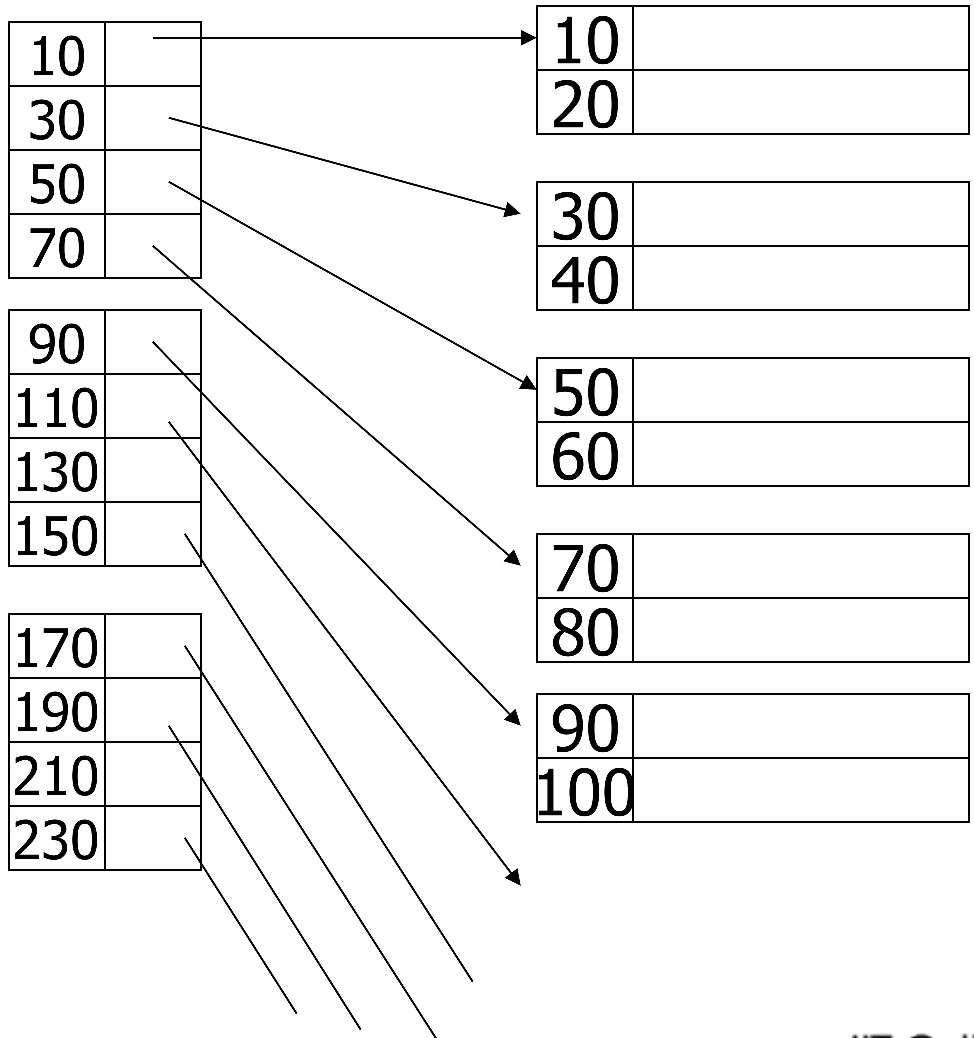
90	
100	

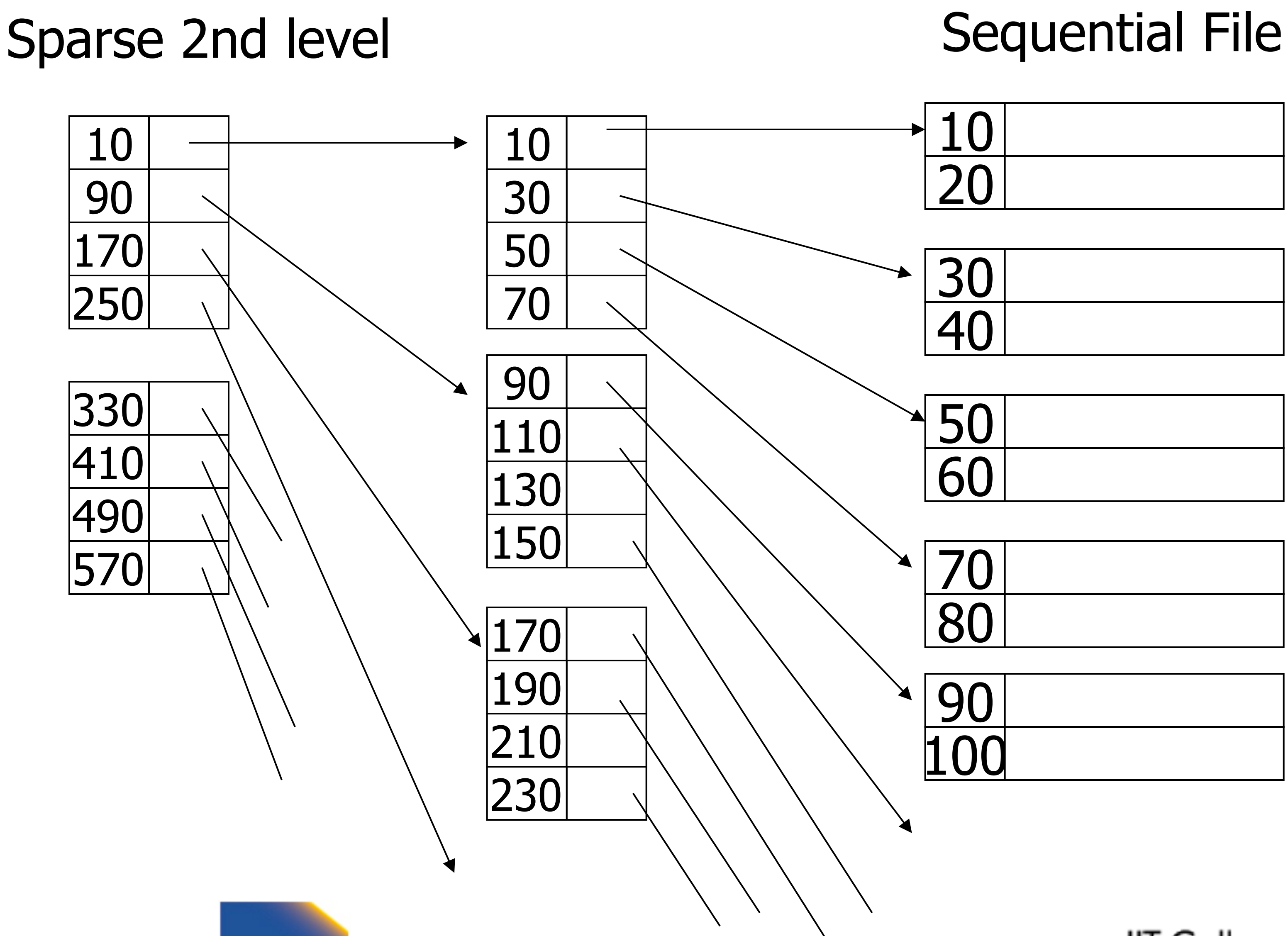
Dense Index Sequential File



Sparse Index

Sequential File




Sparse 2nd level
Sequential File
10
90
170
250
330
410
490
570
10
30
50
70
90
110
130
150
170
190
210
230
10
20
30
40
50
60
70
80
90
100

- Comment:

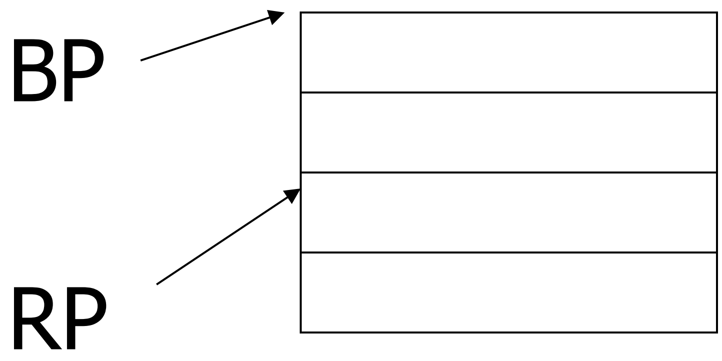
  {FILE,INDEX} may be contiguous
  or not (blocks chained)

Question:

- Can we build a dense, 2nd level index for a dense index?

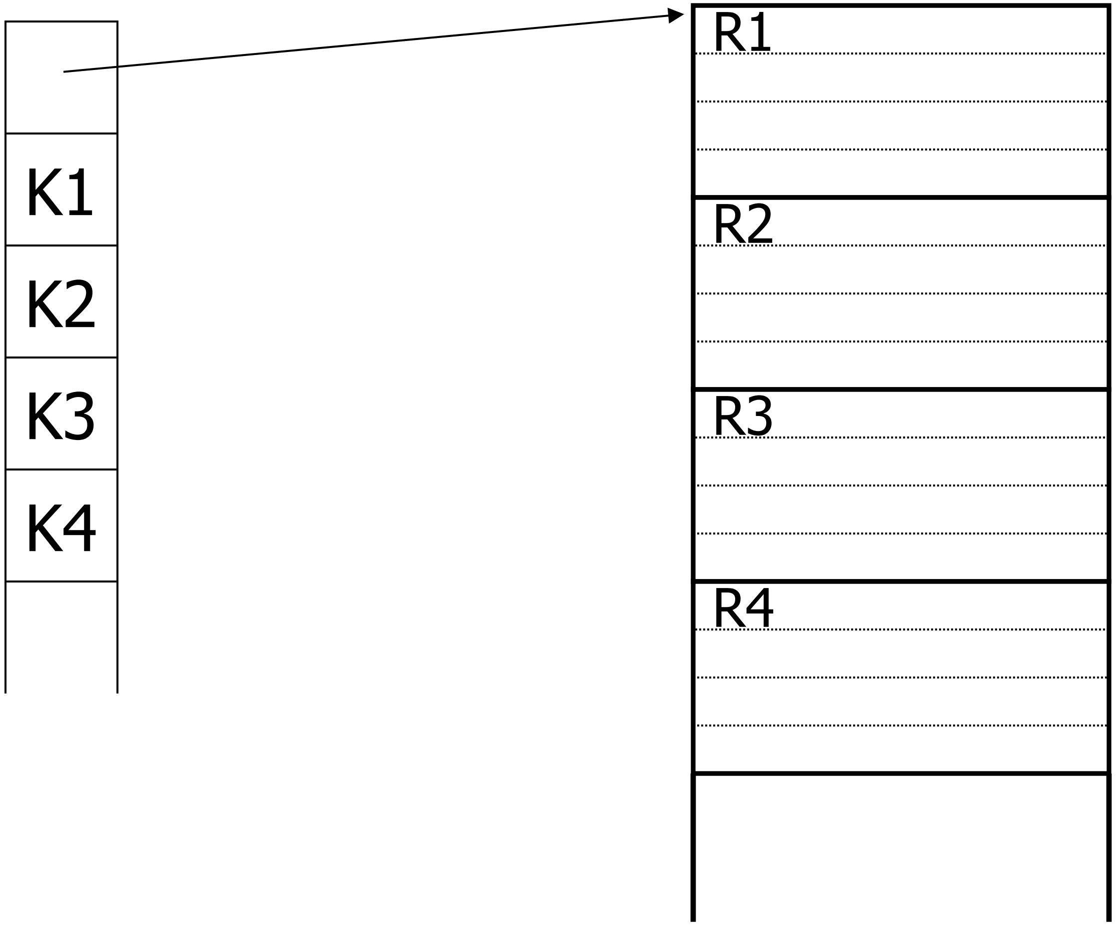
Notes on pointers:

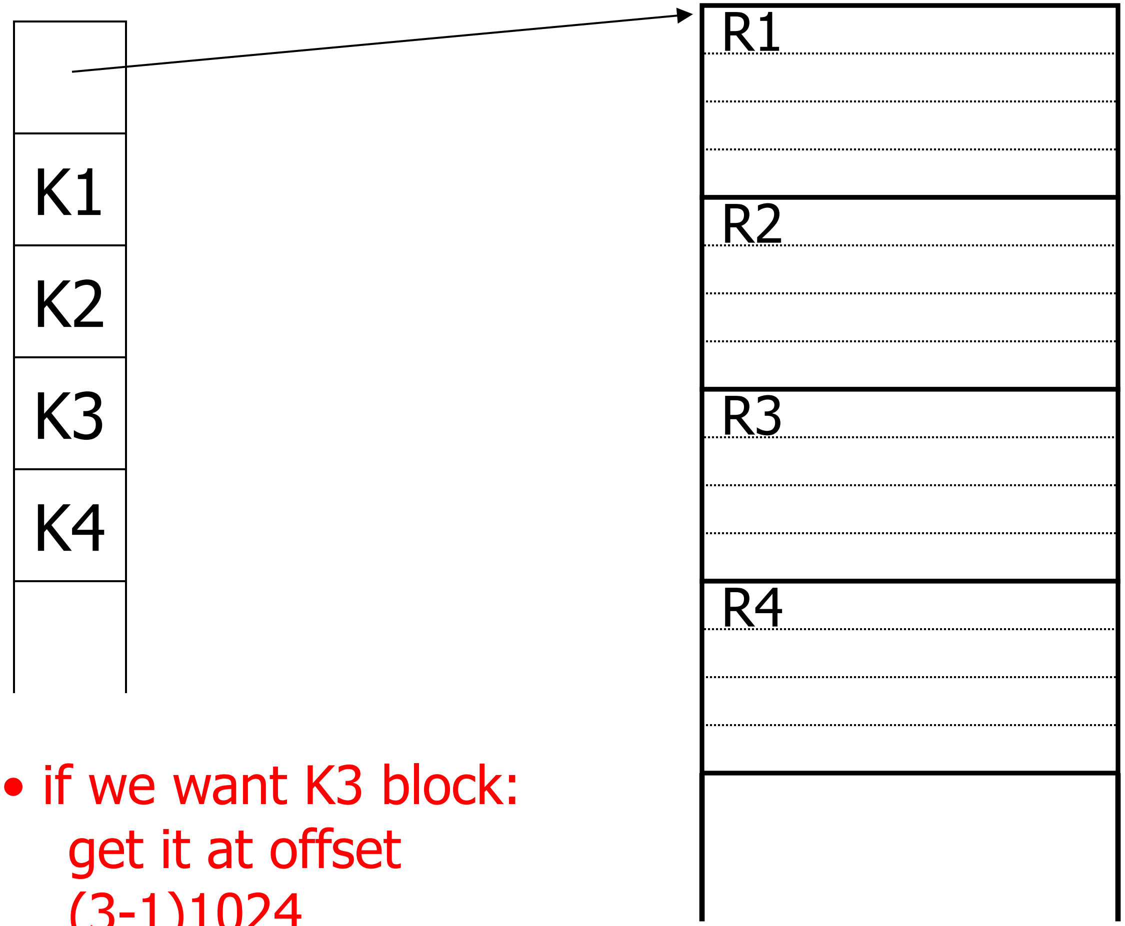
(1) Block pointer (sparse index) can be smaller than record pointer



Notes on pointers:

(2) If file is contiguous, then we can omit pointers (i.e., compute them)


K1
K2
K3
K4
R1
R2
R3
R4



say:
1024 B
per block

- if we want K3 block:
  get it at offset
  (3-1)1024
  = 2048 bytes

Sparse vs. Dense Tradeoff

- Sparse: Less index space per record
  can keep more of index in memory
- Dense: Can tell if any record exists
  without accessing file

(Later:
- sparse better for insertions
- dense needed for secondary indexes)

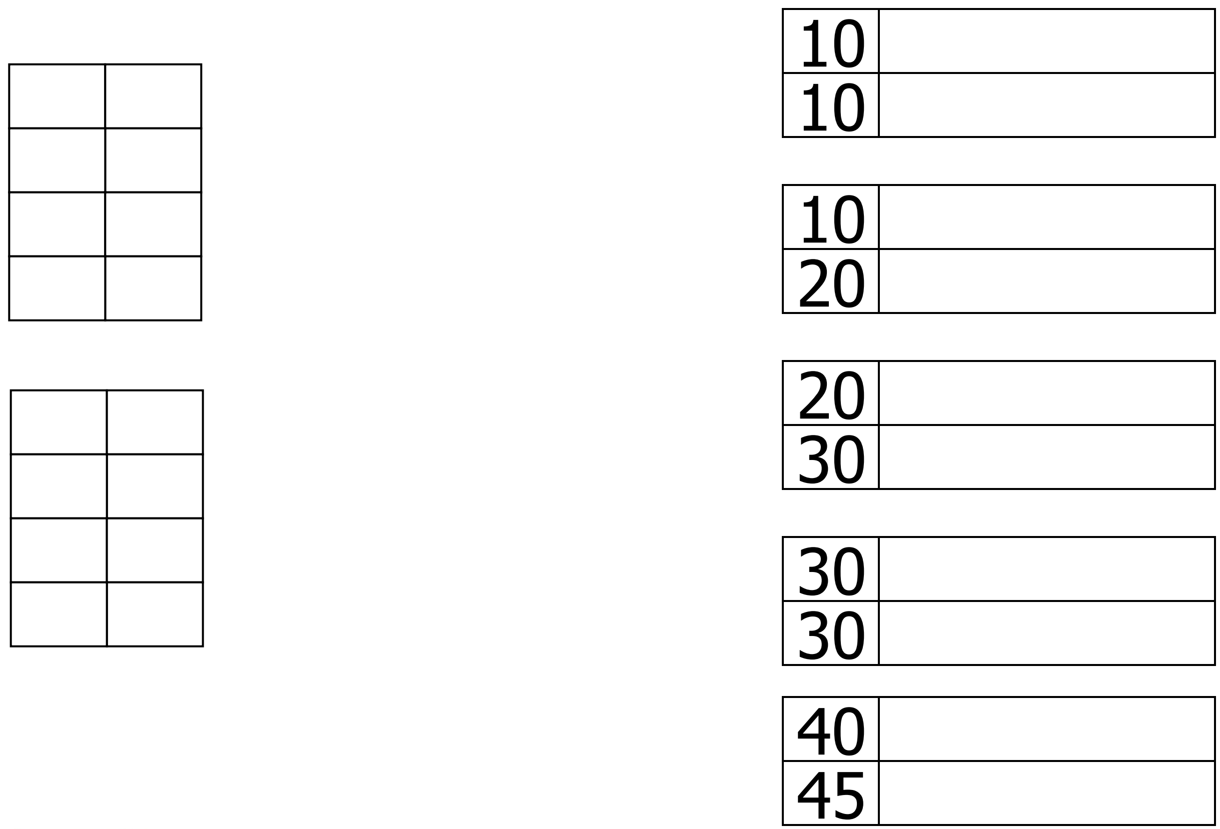
Terms

- Index sequential file
- Search key ($\neq$ primary key)
- Primary index (on Sequencing field)
- Secondary index
- Dense index (all Search Key values in)
- Sparse index
- Multi-level index

Next:

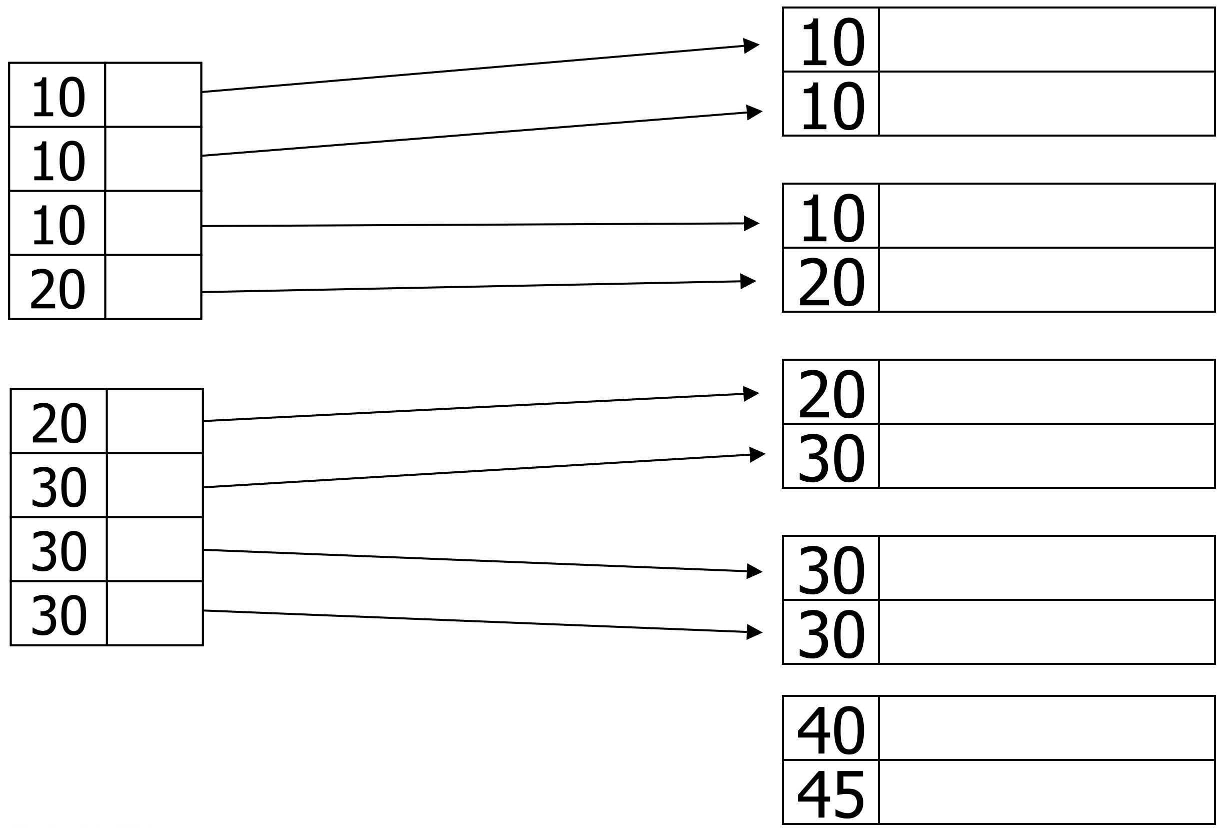
- Duplicate keys
- Deletion/Insertion
- Secondary indexes

Duplicate keys



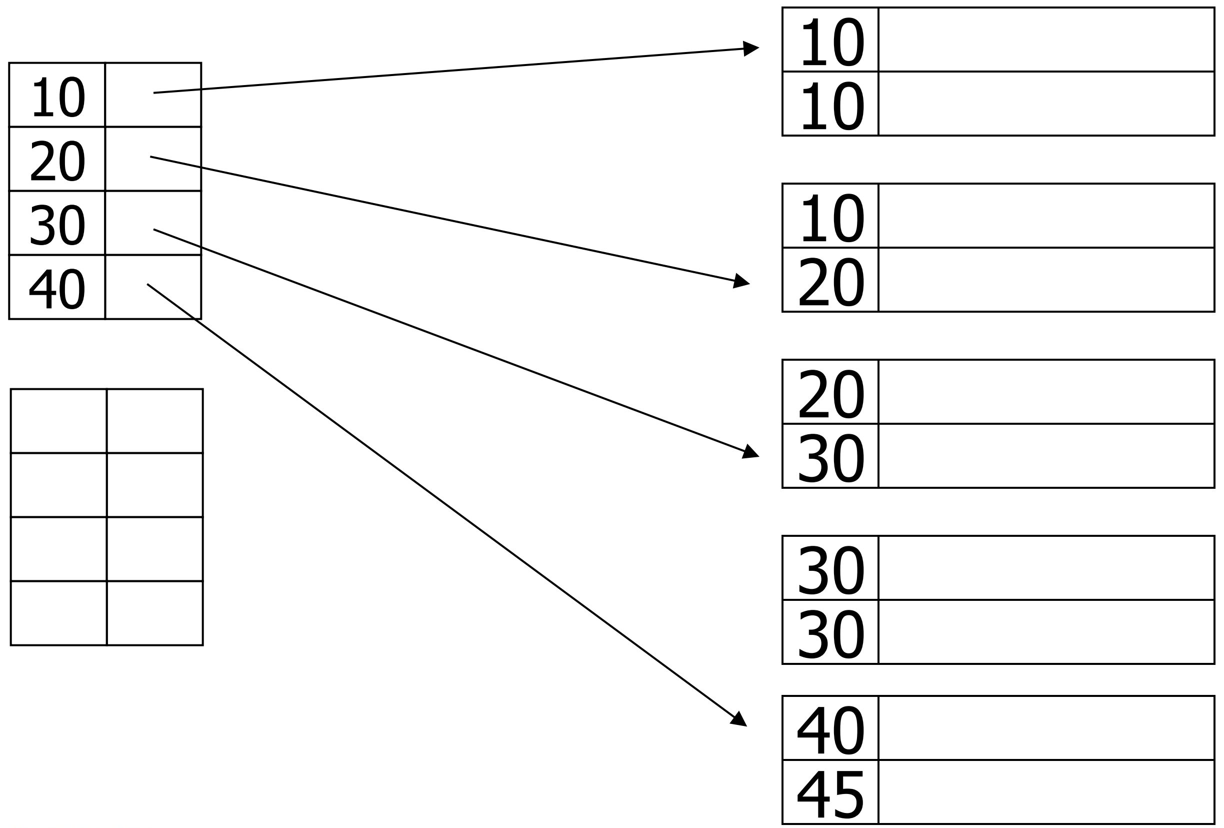
Duplicate keys

Dense index, one way to implement?



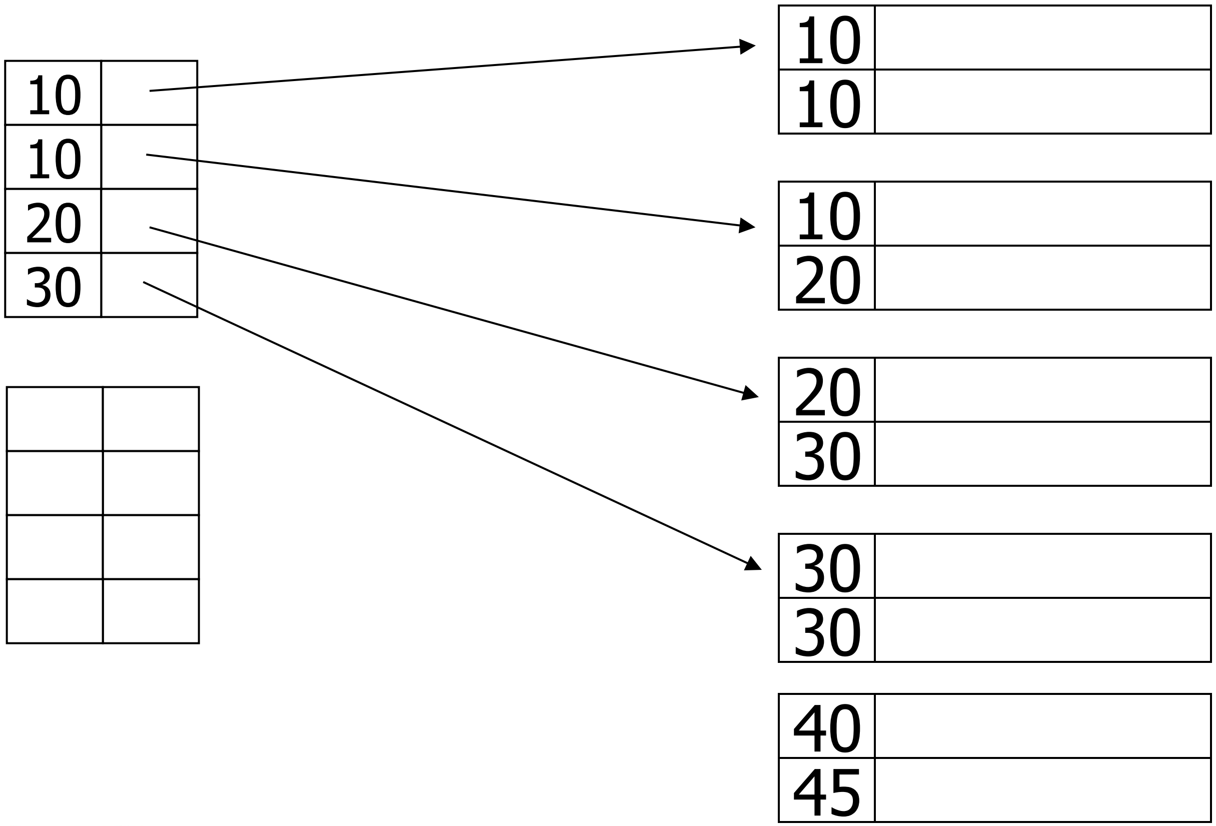
Duplicate keys

Dense index, better way?



Duplicate keys

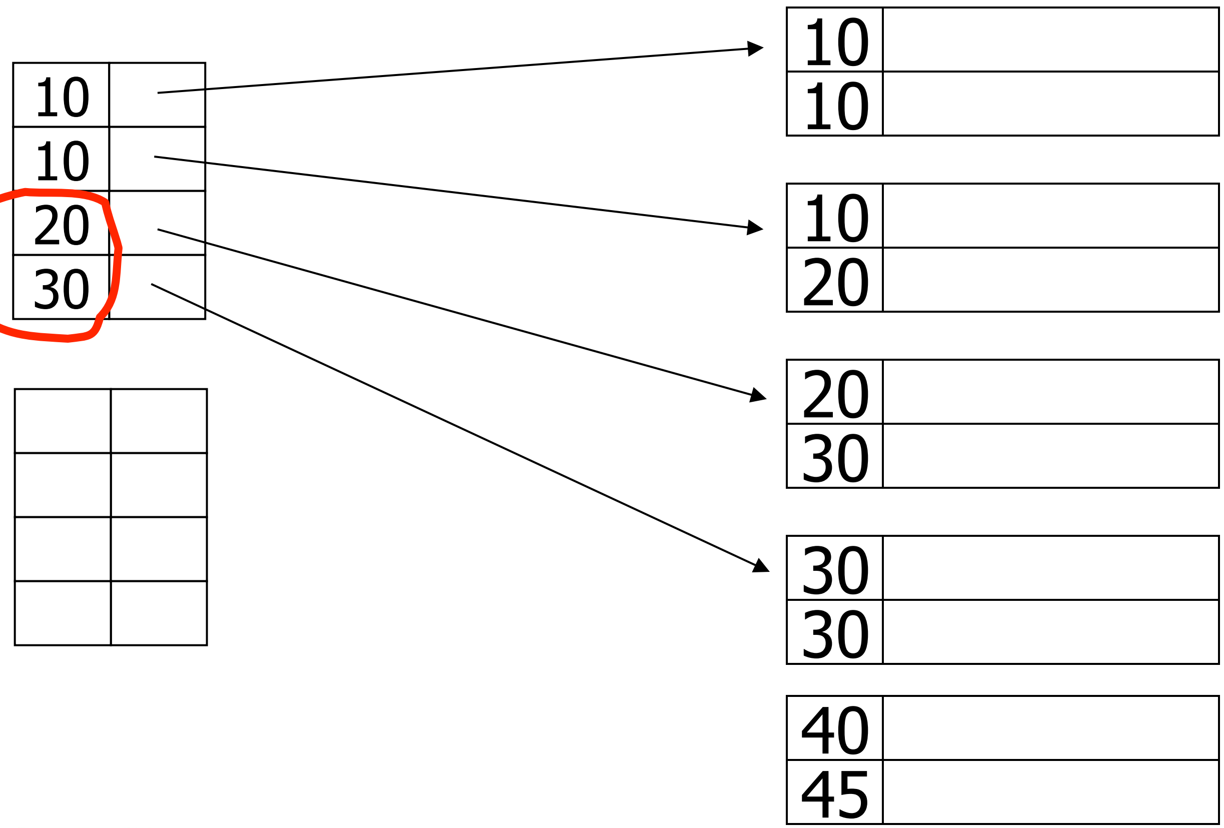
Sparse index, one way?



Duplicate keys

Sparse index, one way?

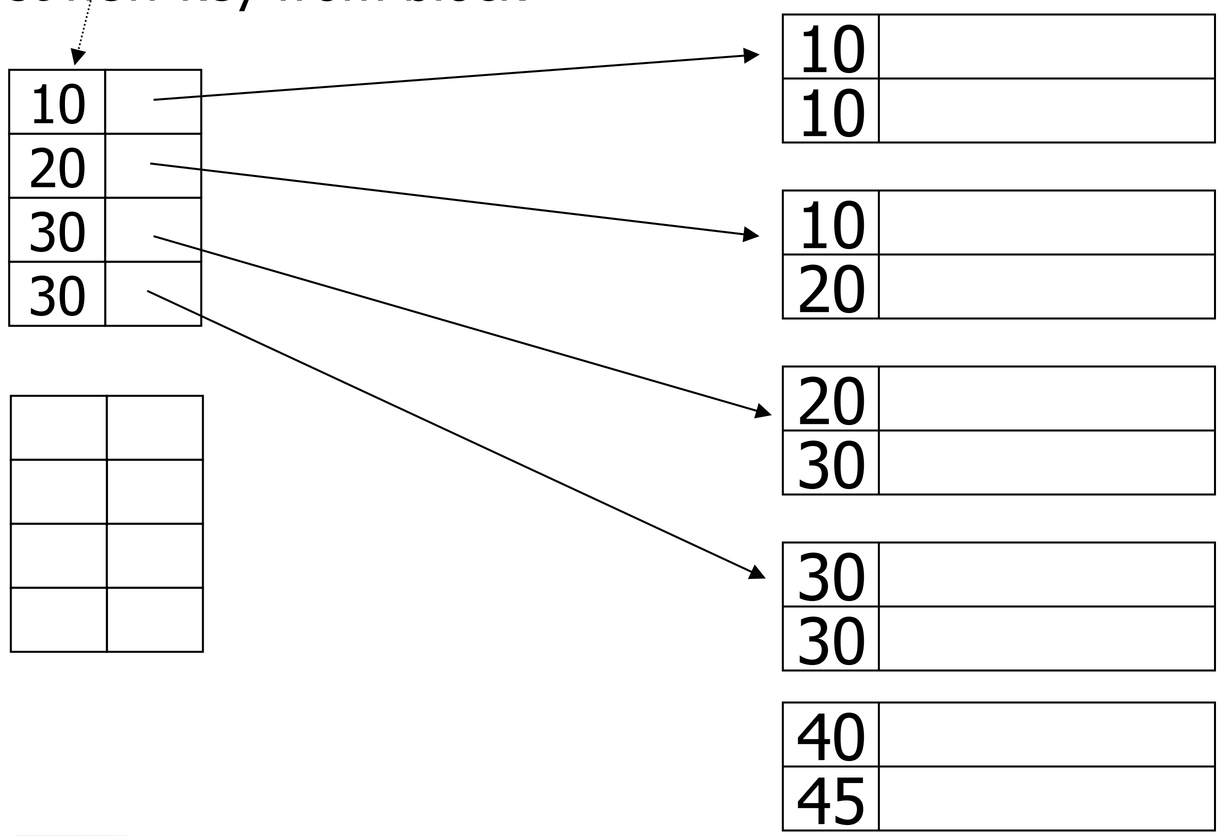
careful if looking for 20 or 30!



Duplicate keys

Sparse index, another way?

– place first new key from block

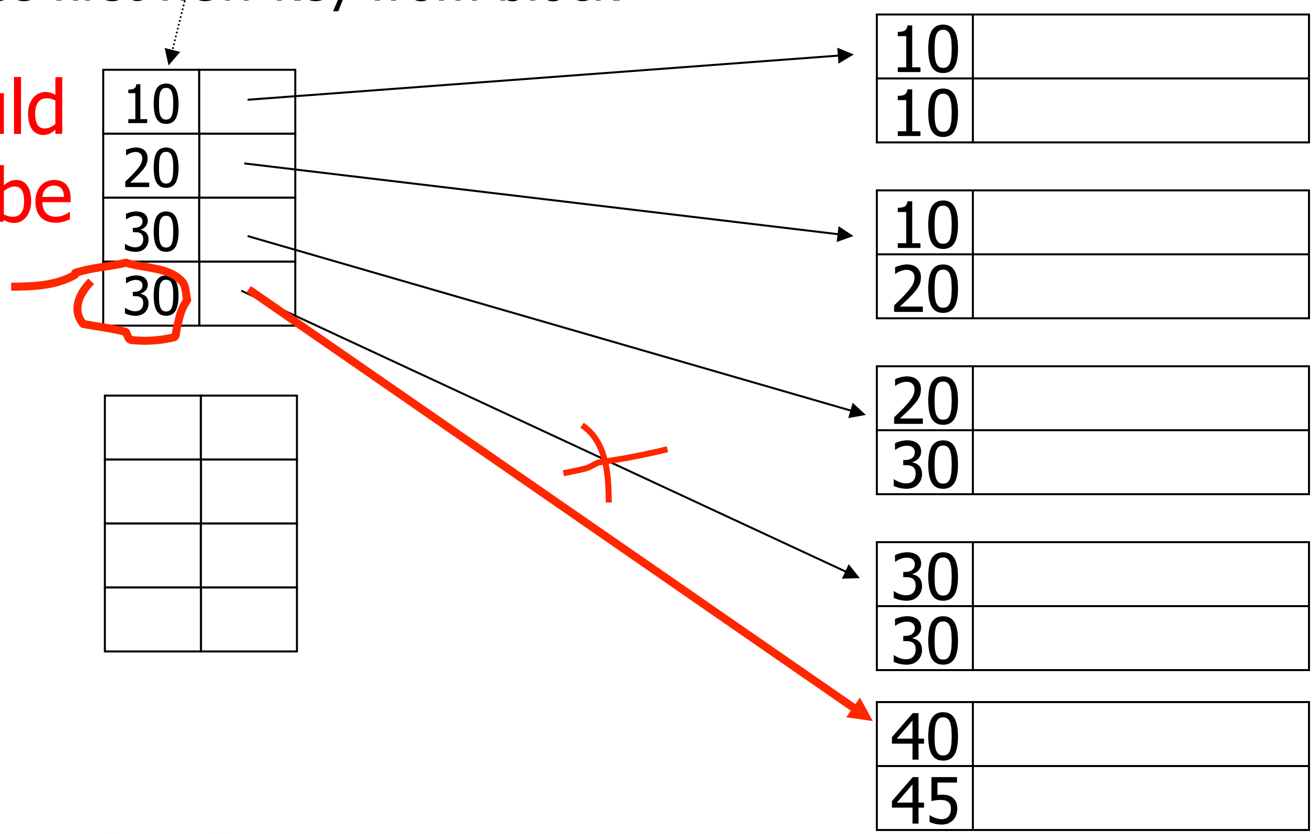


Duplicate keys

Sparse index, another way?

– place first new key from block

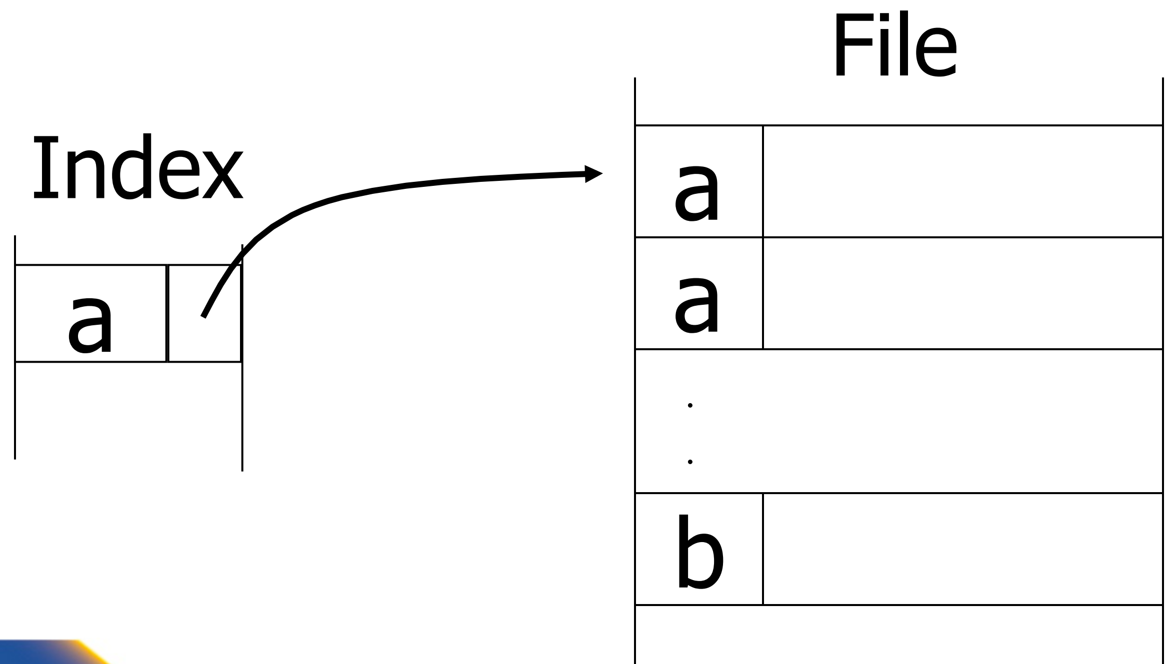
should this be 40?



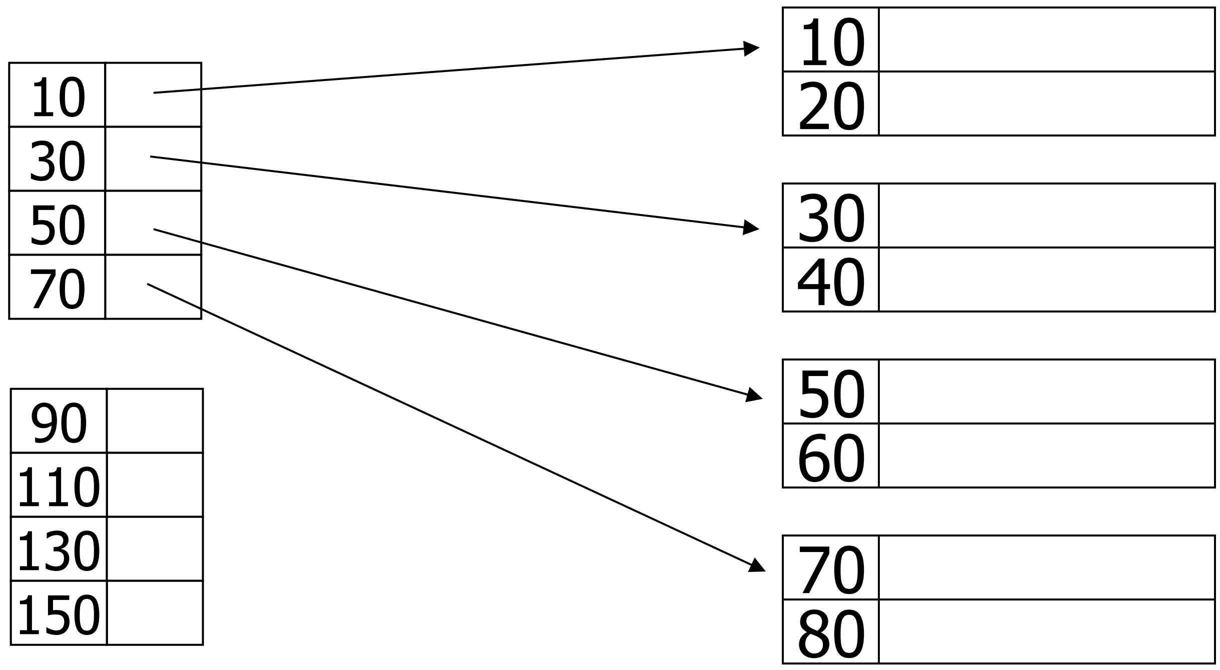
Summary

Duplicate values, primary index

- Index may point to first instance of each value only

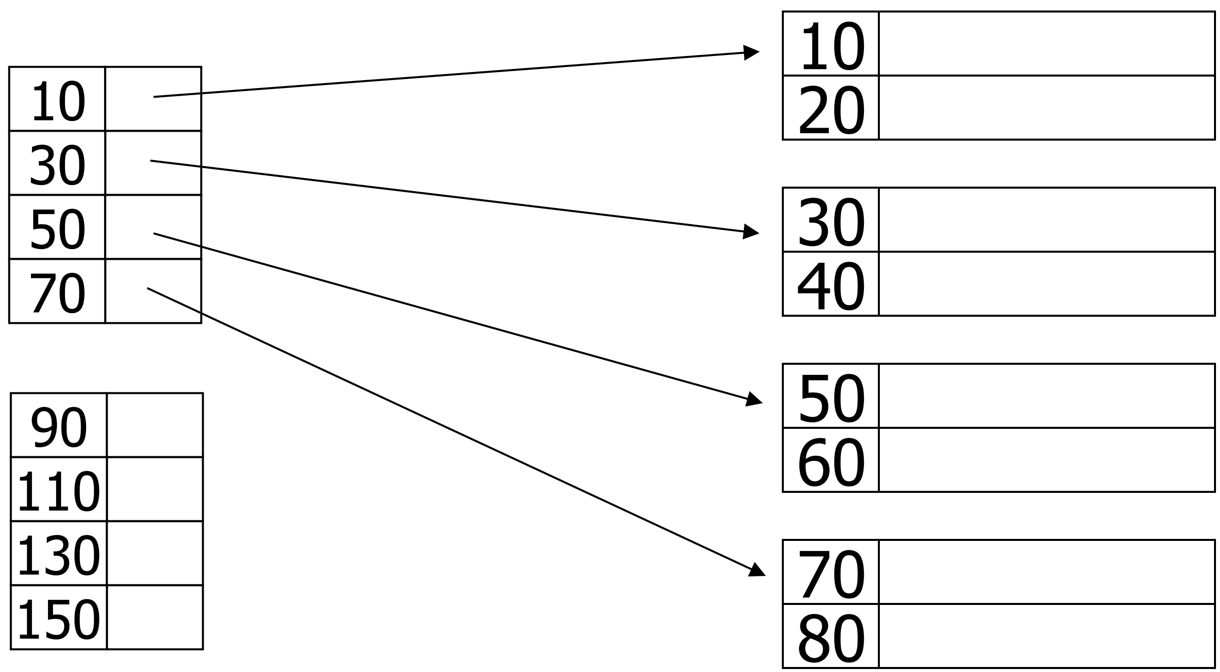


Deletion from sparse index



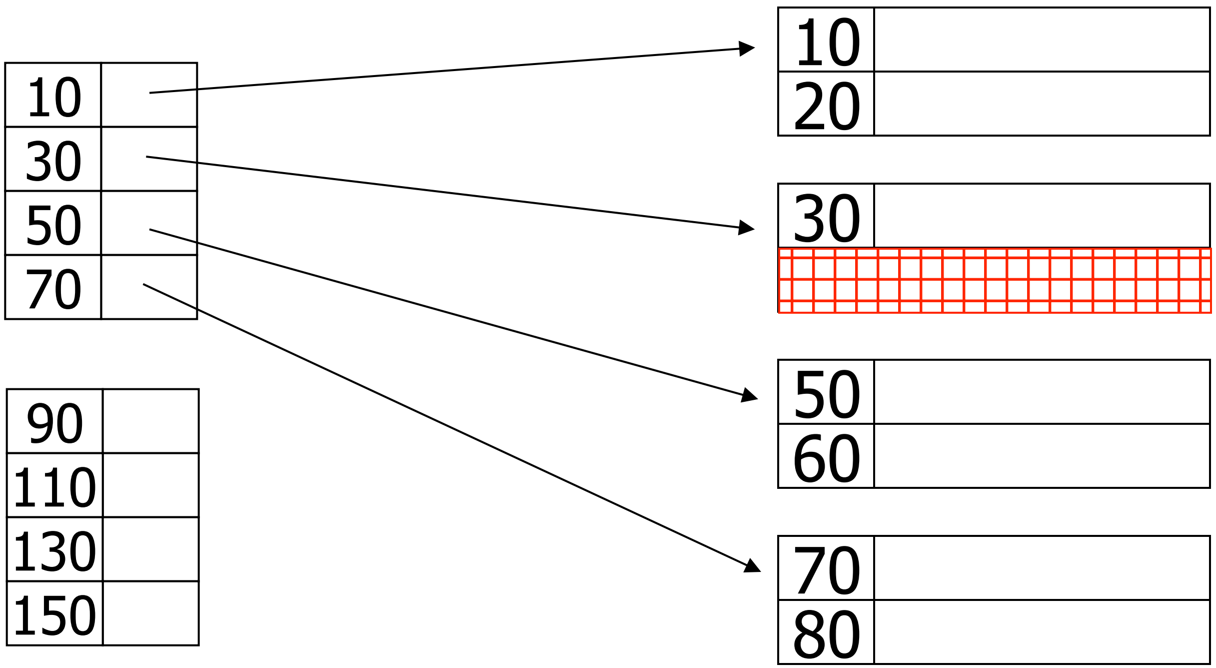
Deletion from sparse index

– delete record 40



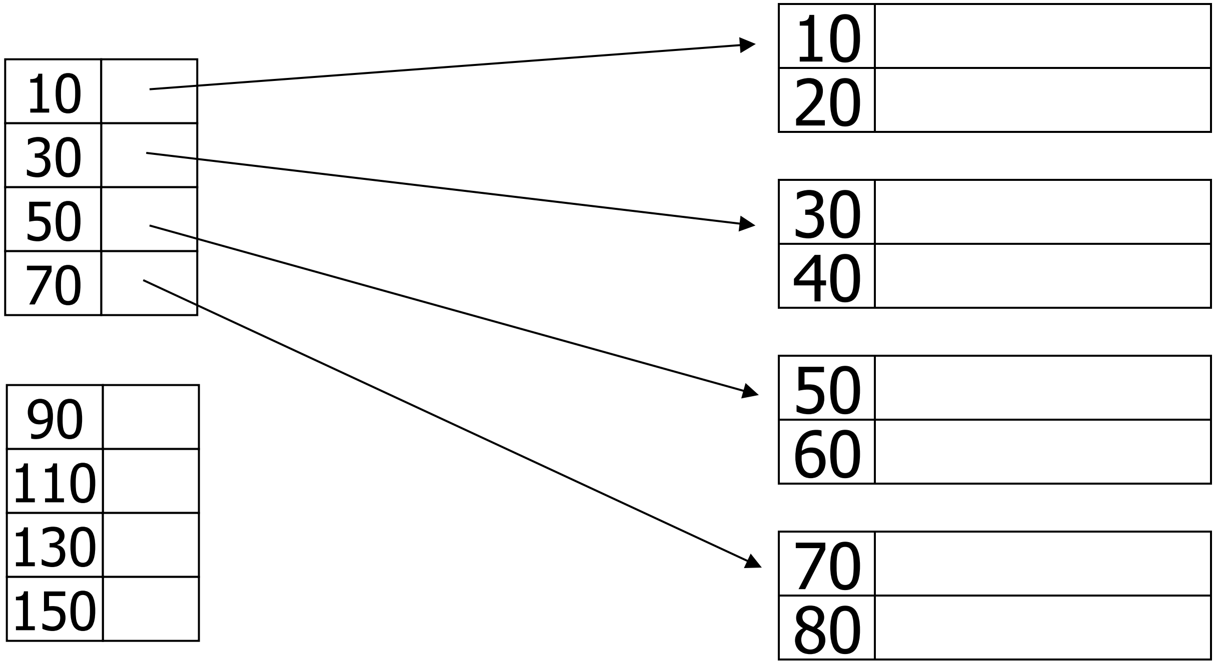
Deletion from sparse index

– delete record 40



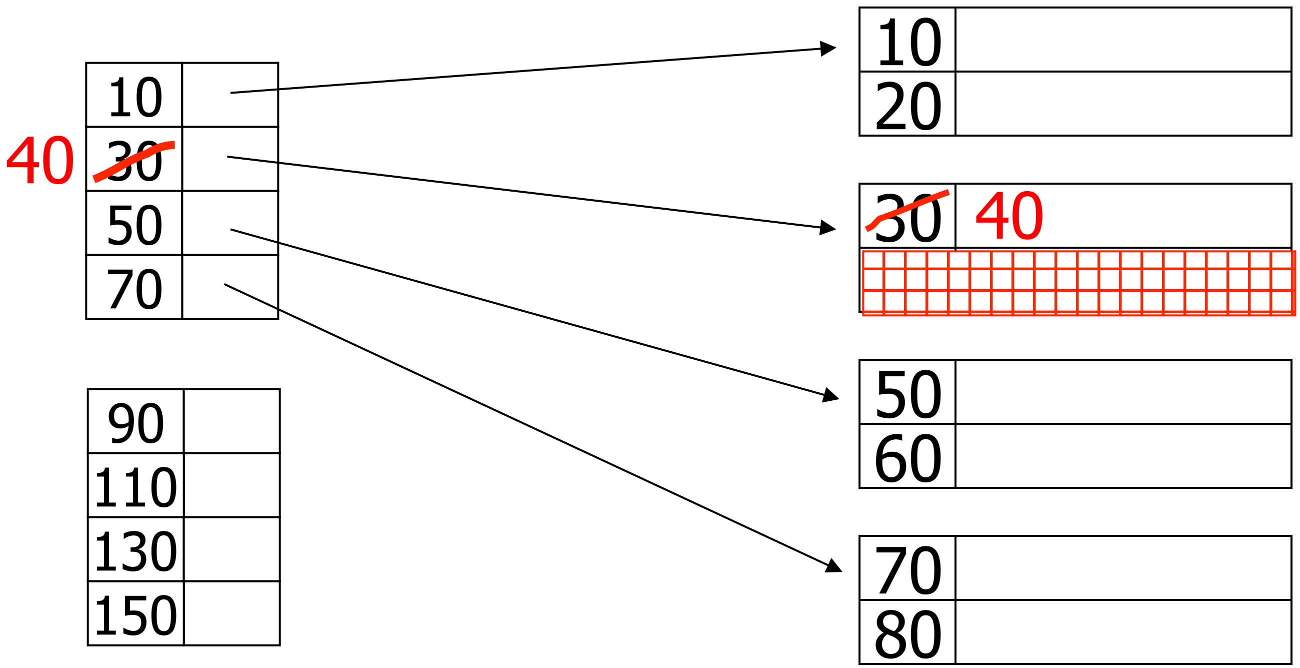
Deletion from sparse index

– delete record 30



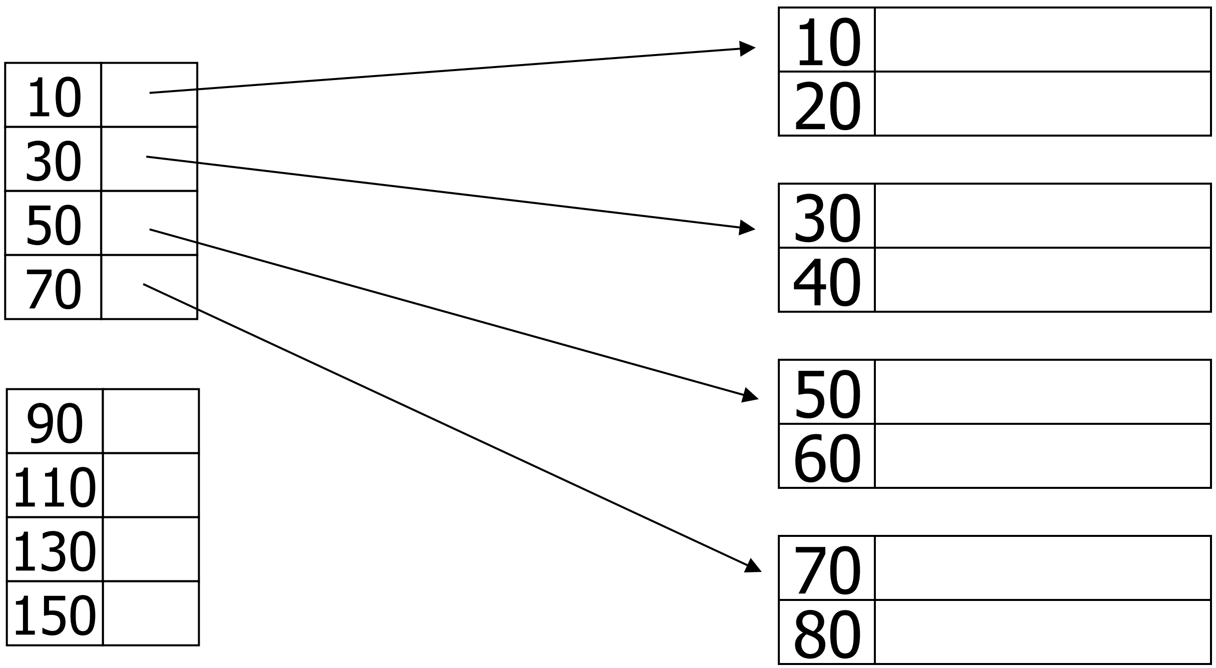
Deletion from sparse index

– delete record 30



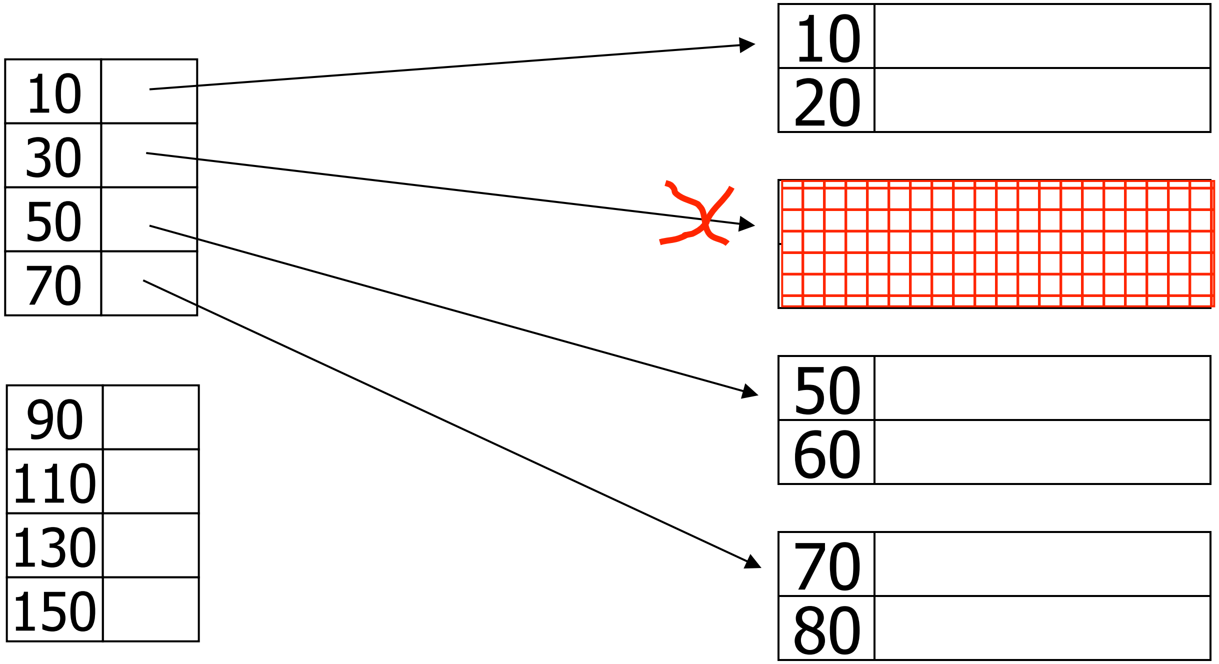
Deletion from sparse index

– delete records 30 & 40



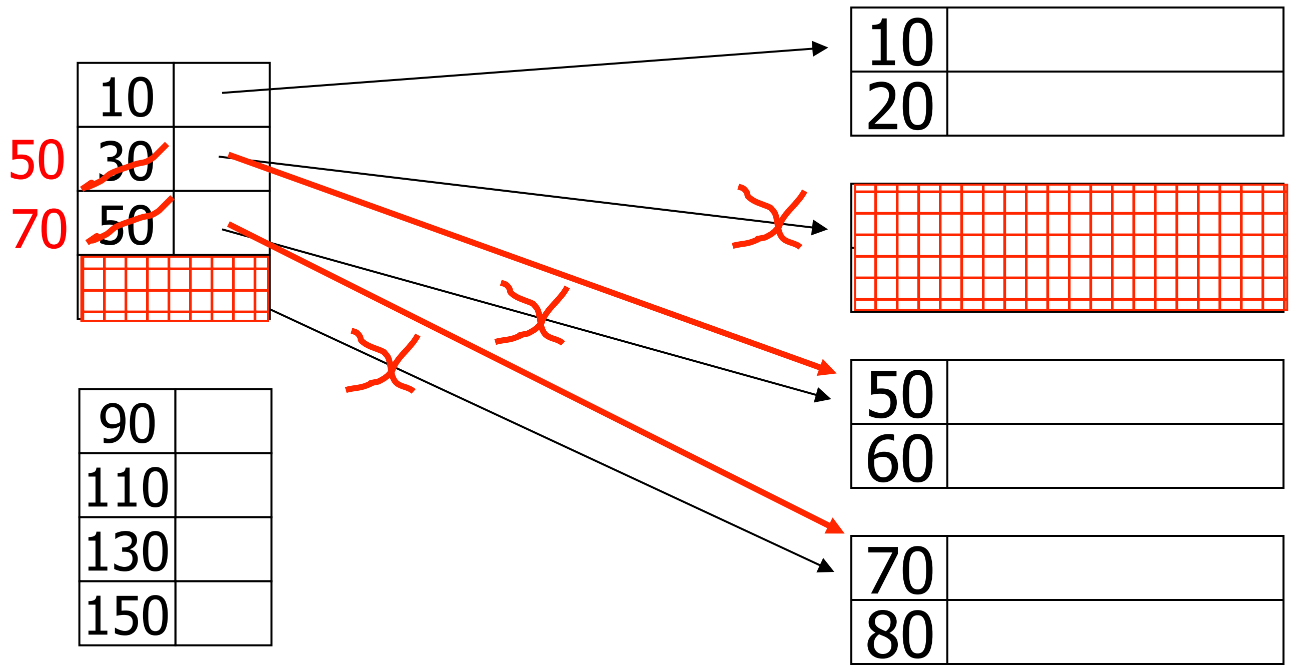
Deletion from sparse index

– delete records 30 & 40

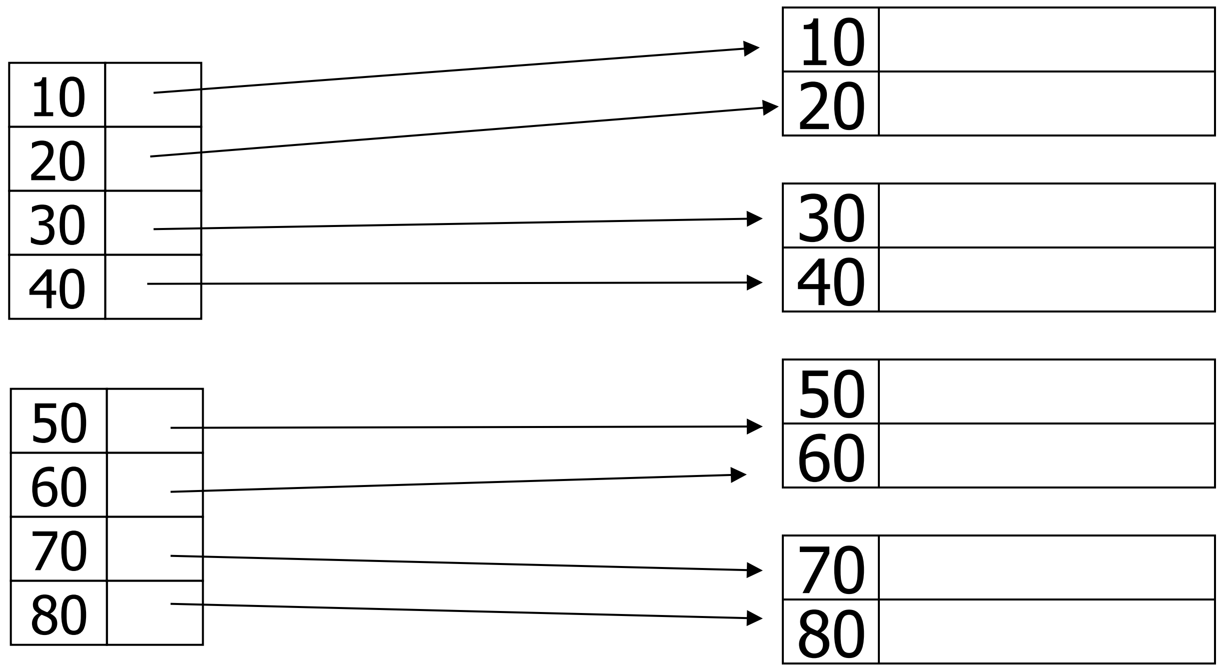


Deletion from sparse index

– delete records 30 & 40

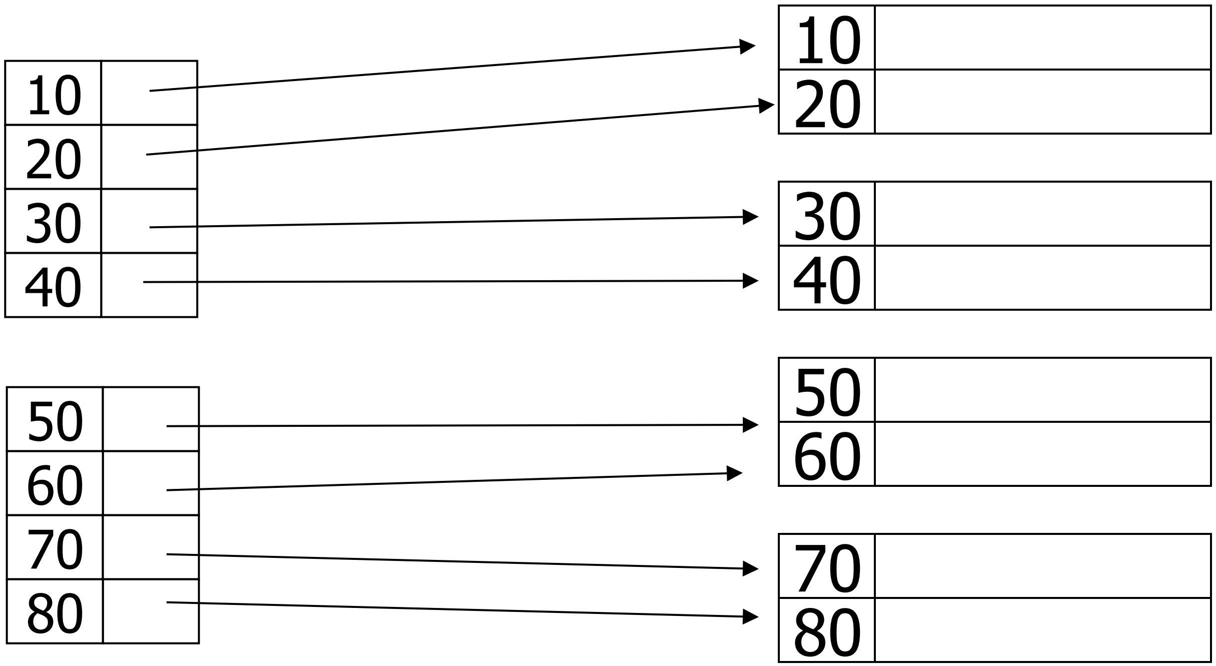


Deletion from dense index



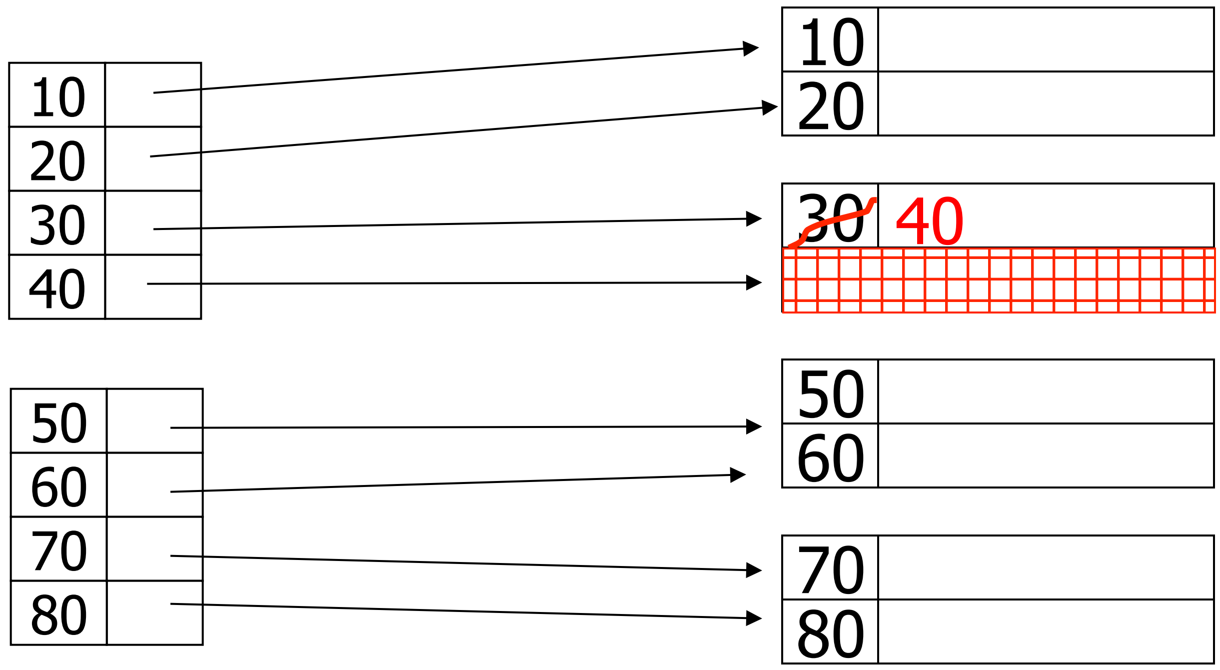
Deletion from dense index

– delete record 30



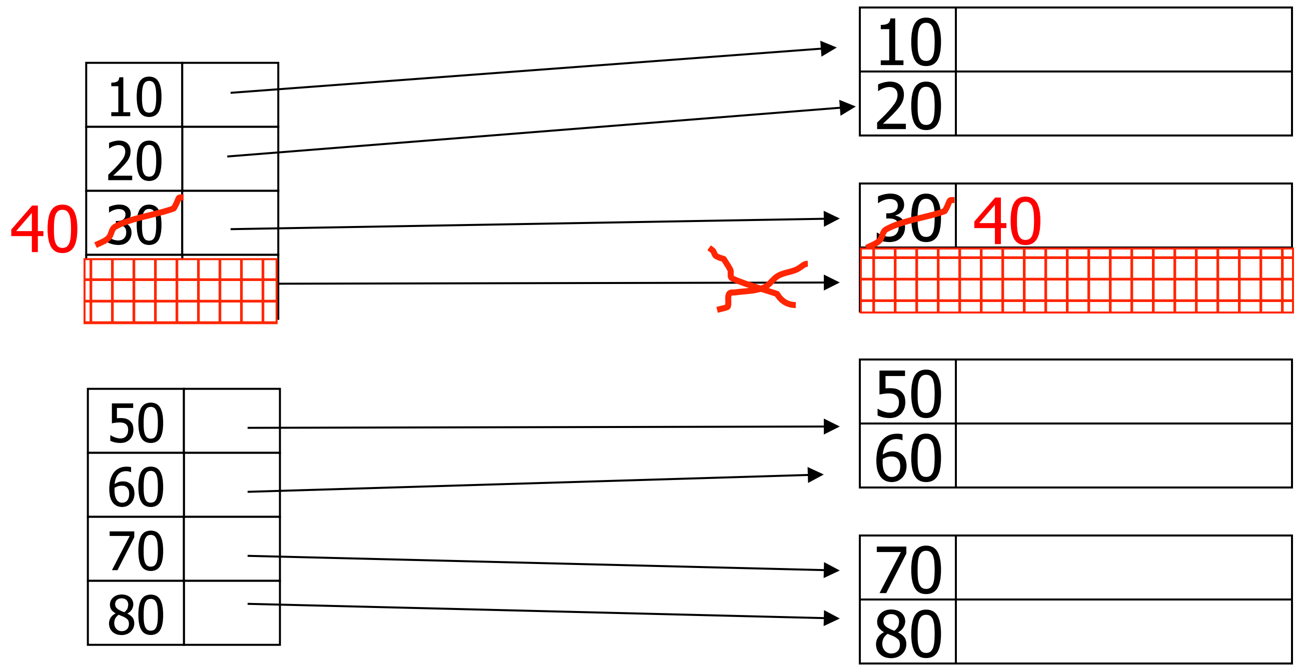
Deletion from dense index

– delete record 30

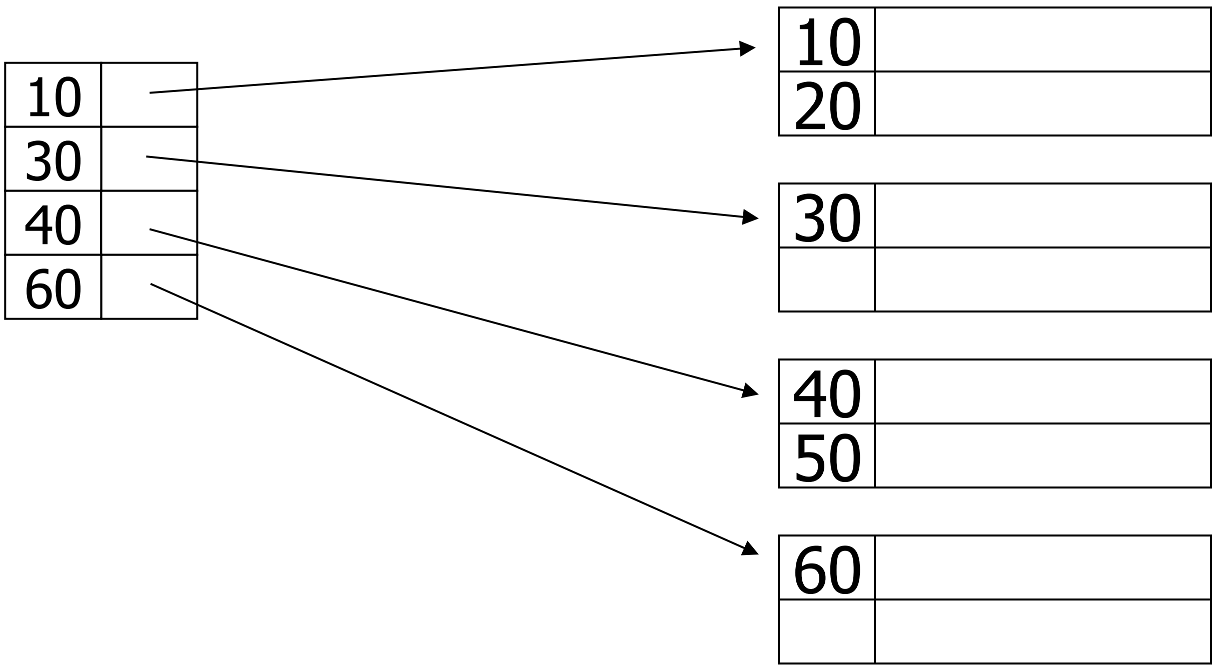


Deletion from dense index

– delete record 30

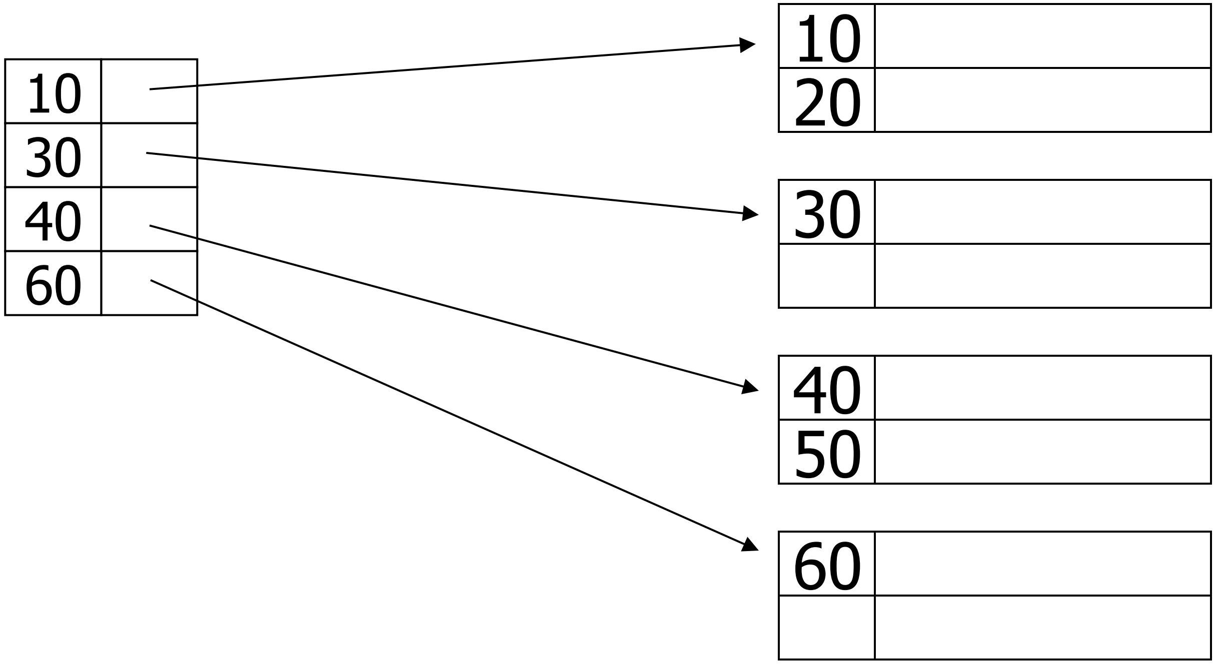


Insertion, sparse index case



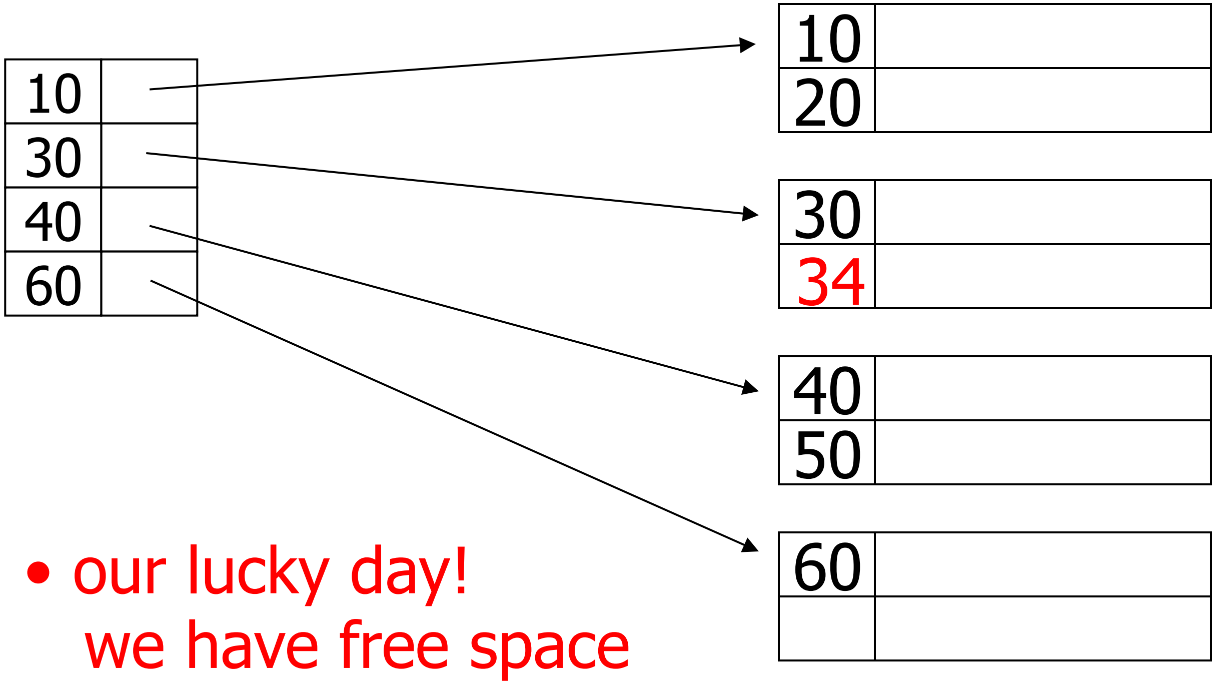
Insertion, sparse index case

– insert record 34



Insertion, sparse index case

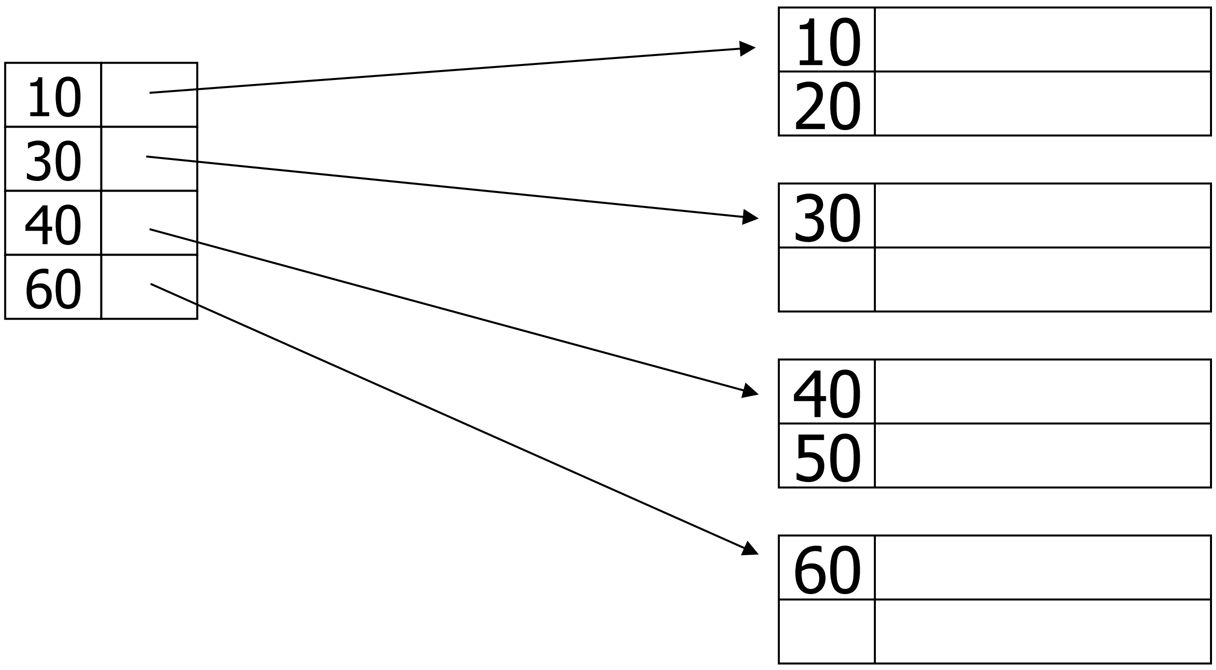
– insert record 34



- our lucky day!
  we have free space
  where we need it!

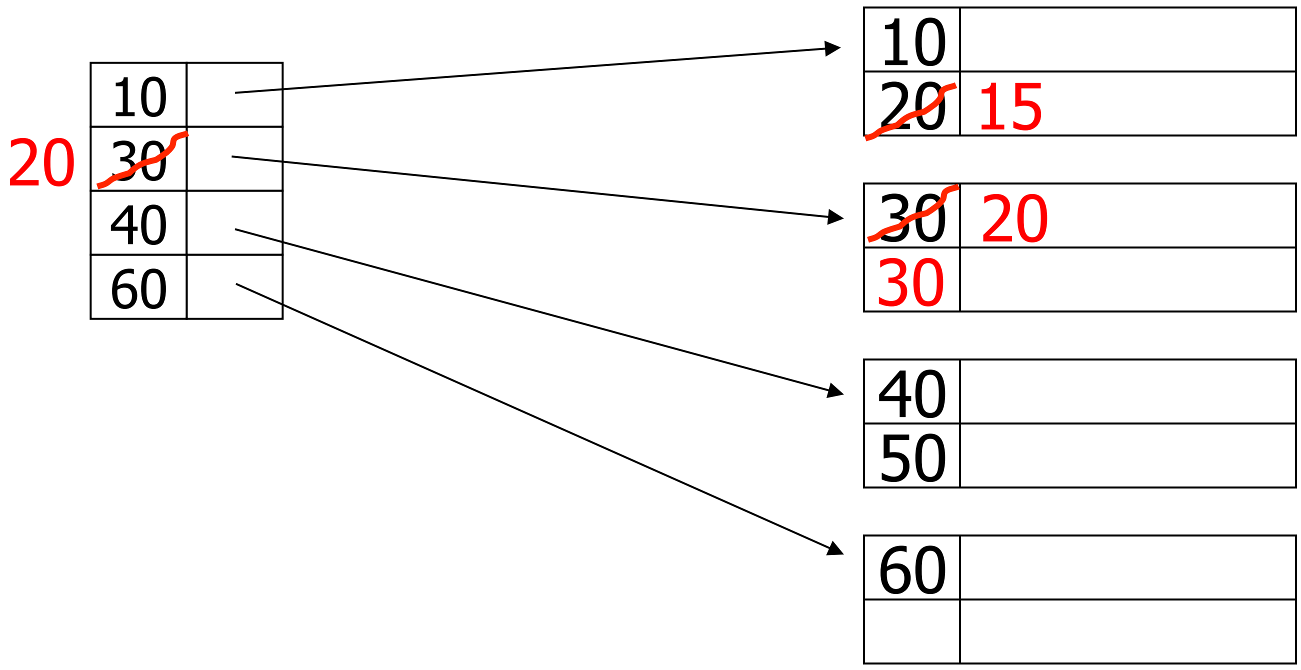
Insertion, sparse index case

– insert record 15



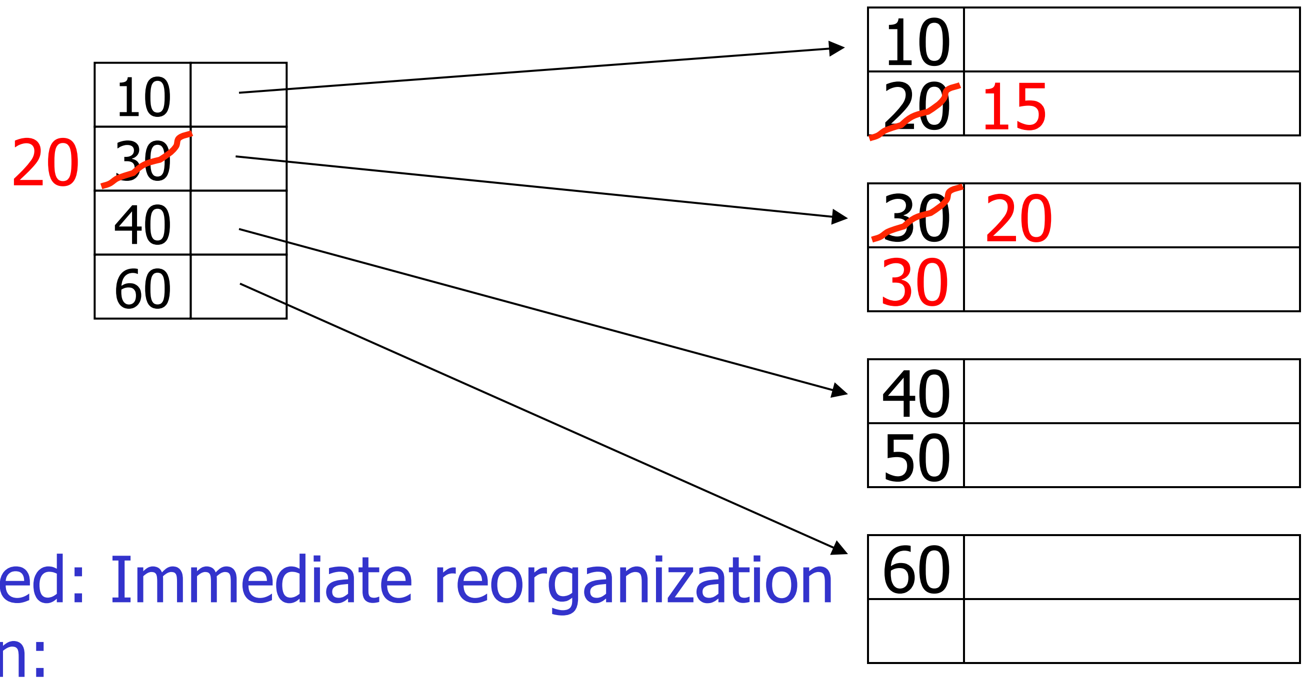
Insertion, sparse index case

– insert record 15



Insertion, sparse index case

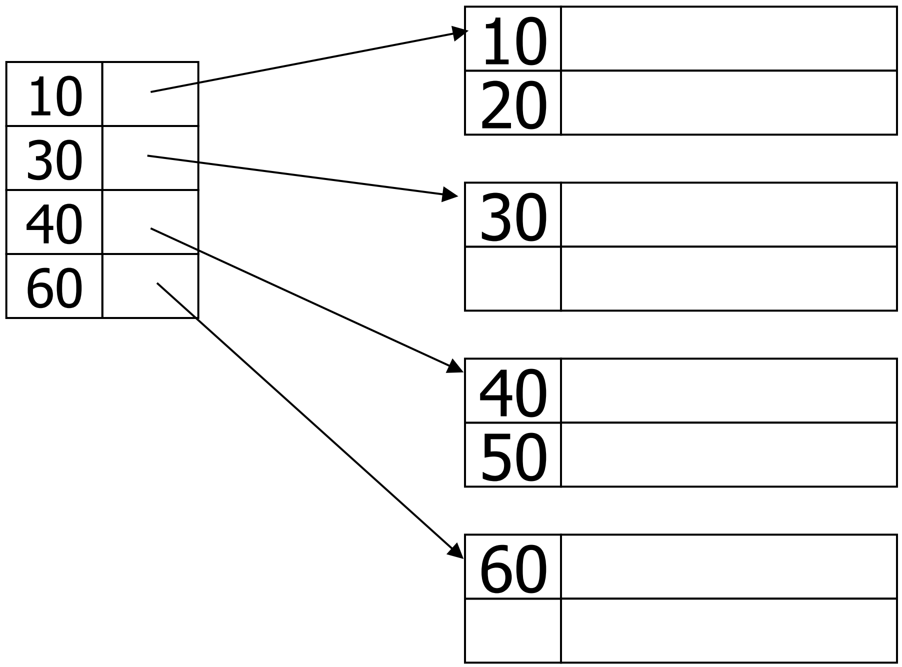
– insert record 15



- Illustrated: Immediate reorganization
- Variation:
  - insert new block (chained file)
  - update index

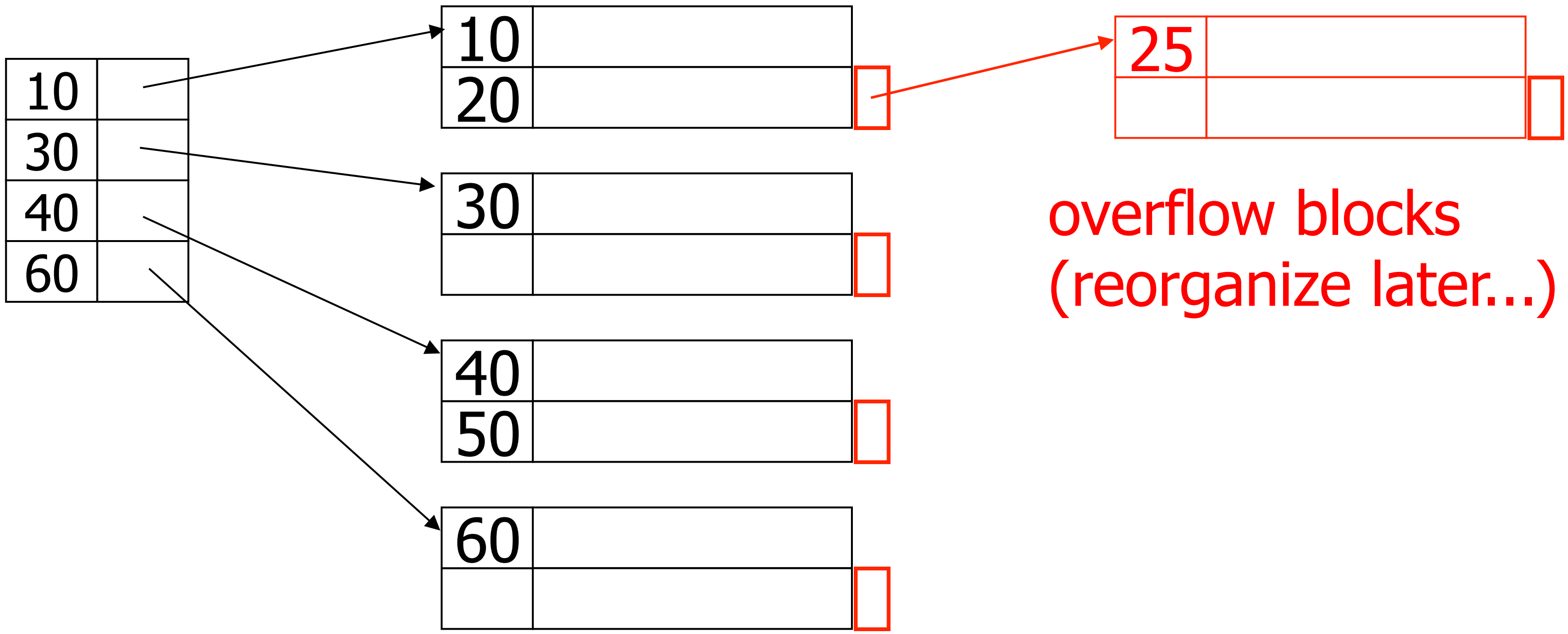
Insertion, sparse index case

– insert record 25



Insertion, sparse index case

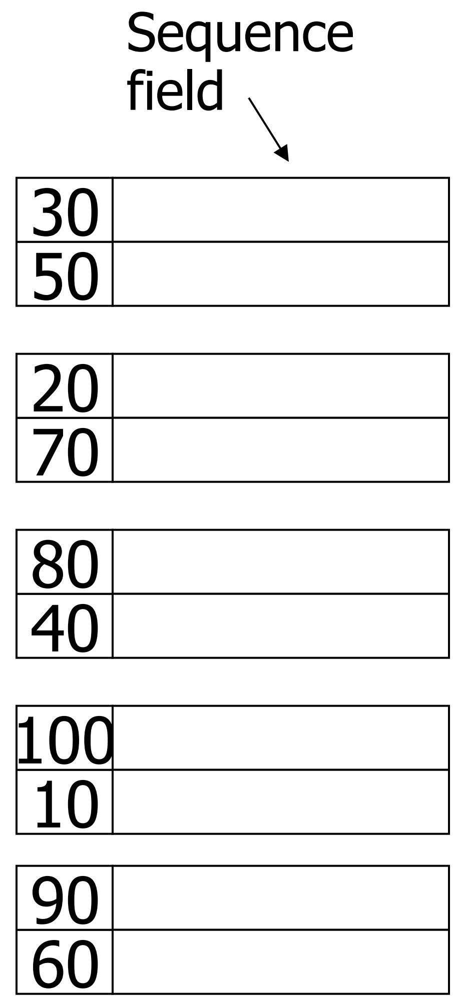
– insert record 25



Insertion, dense index case

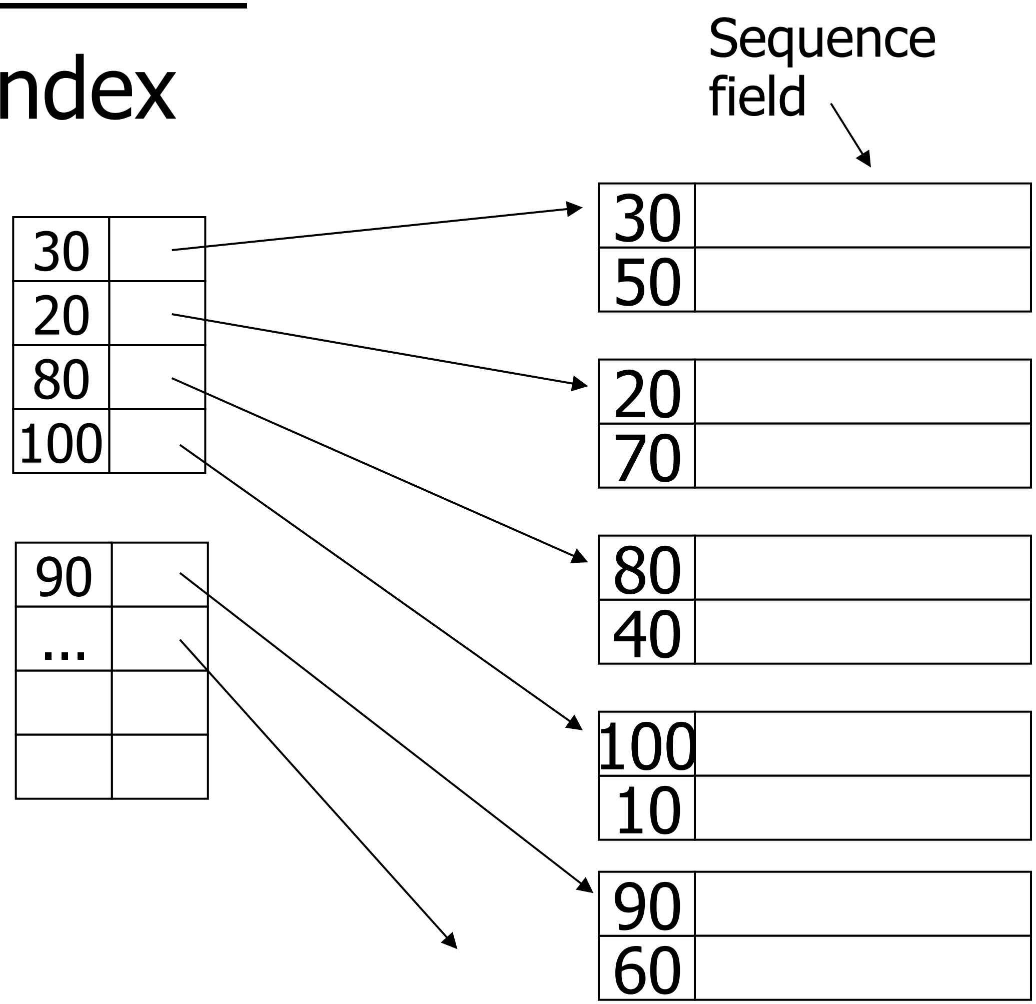
- Similar
- Often more expensive . . .

Secondary indexes



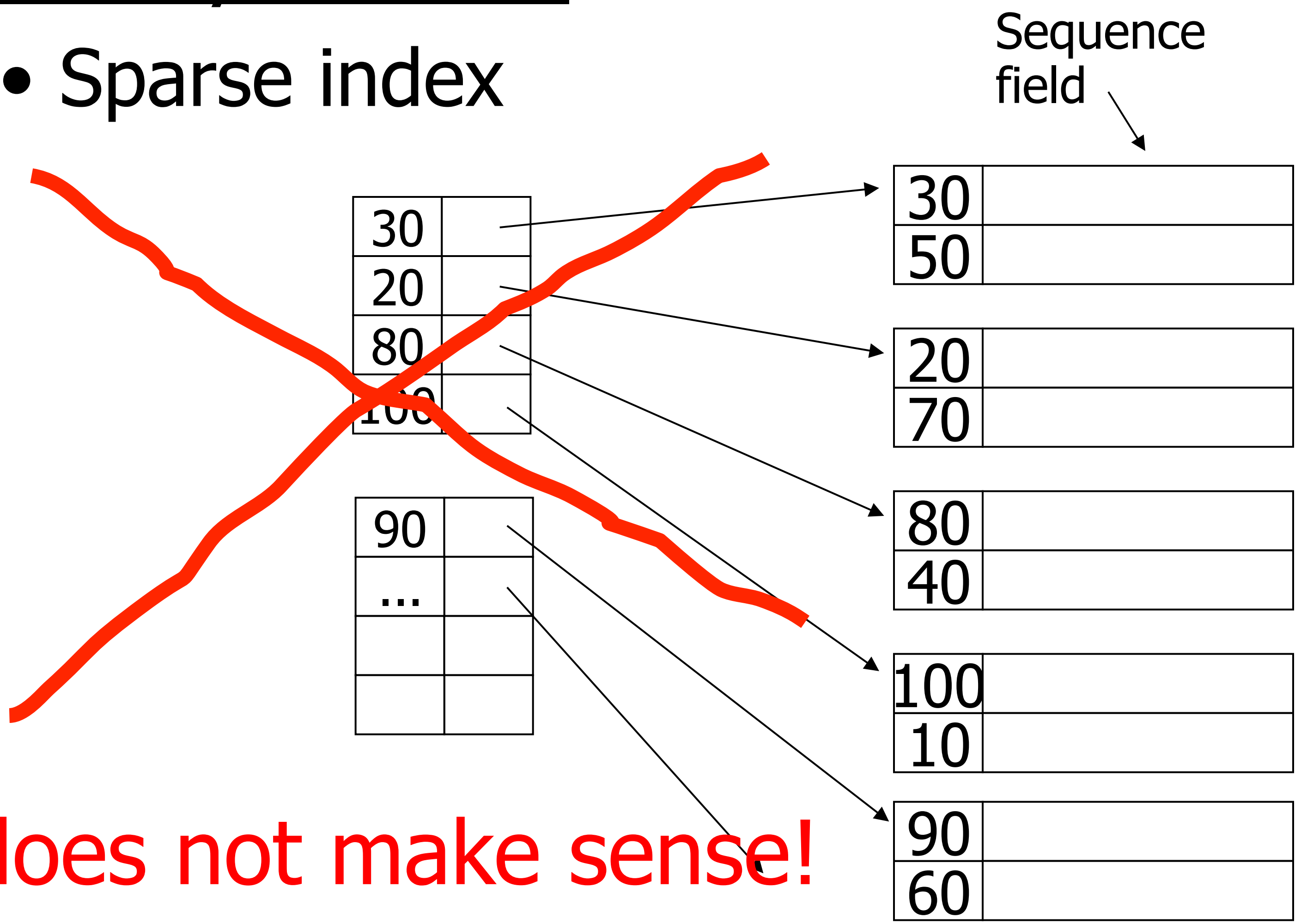
Secondary indexes

- Sparse index



Secondary indexes

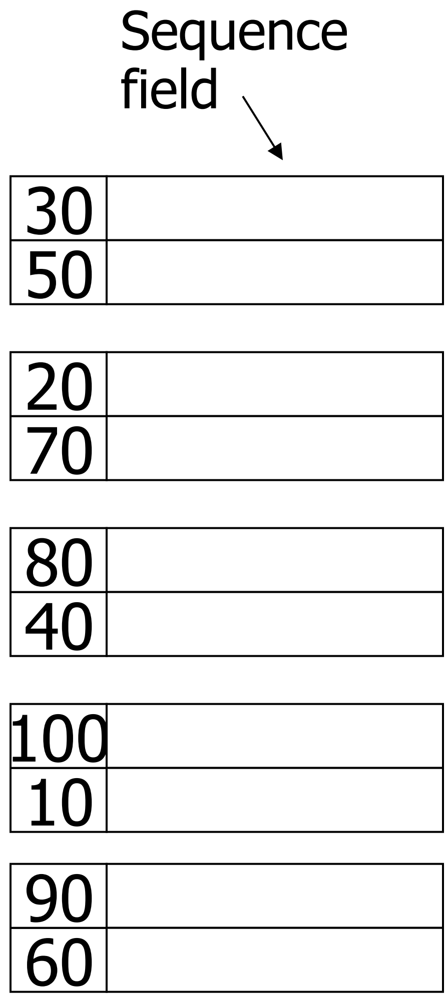
- Sparse index



does not make sense!

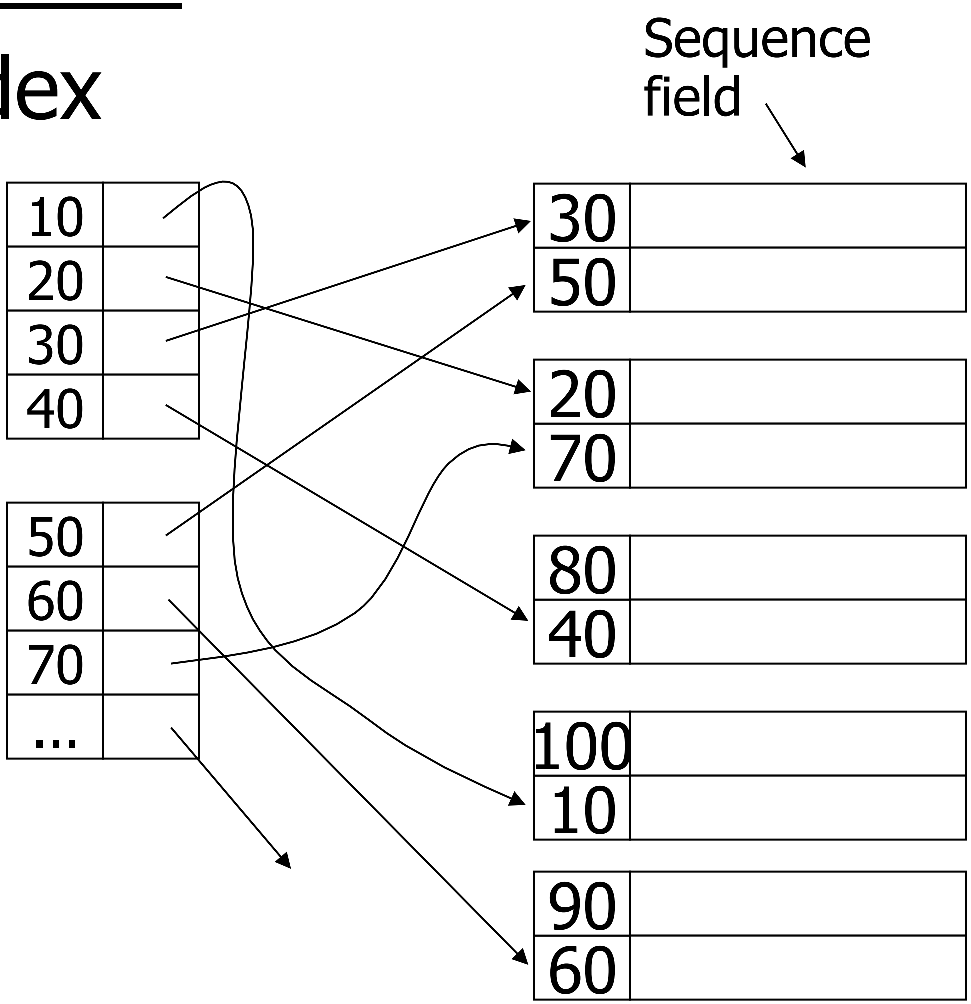
Secondary indexes

- Dense index



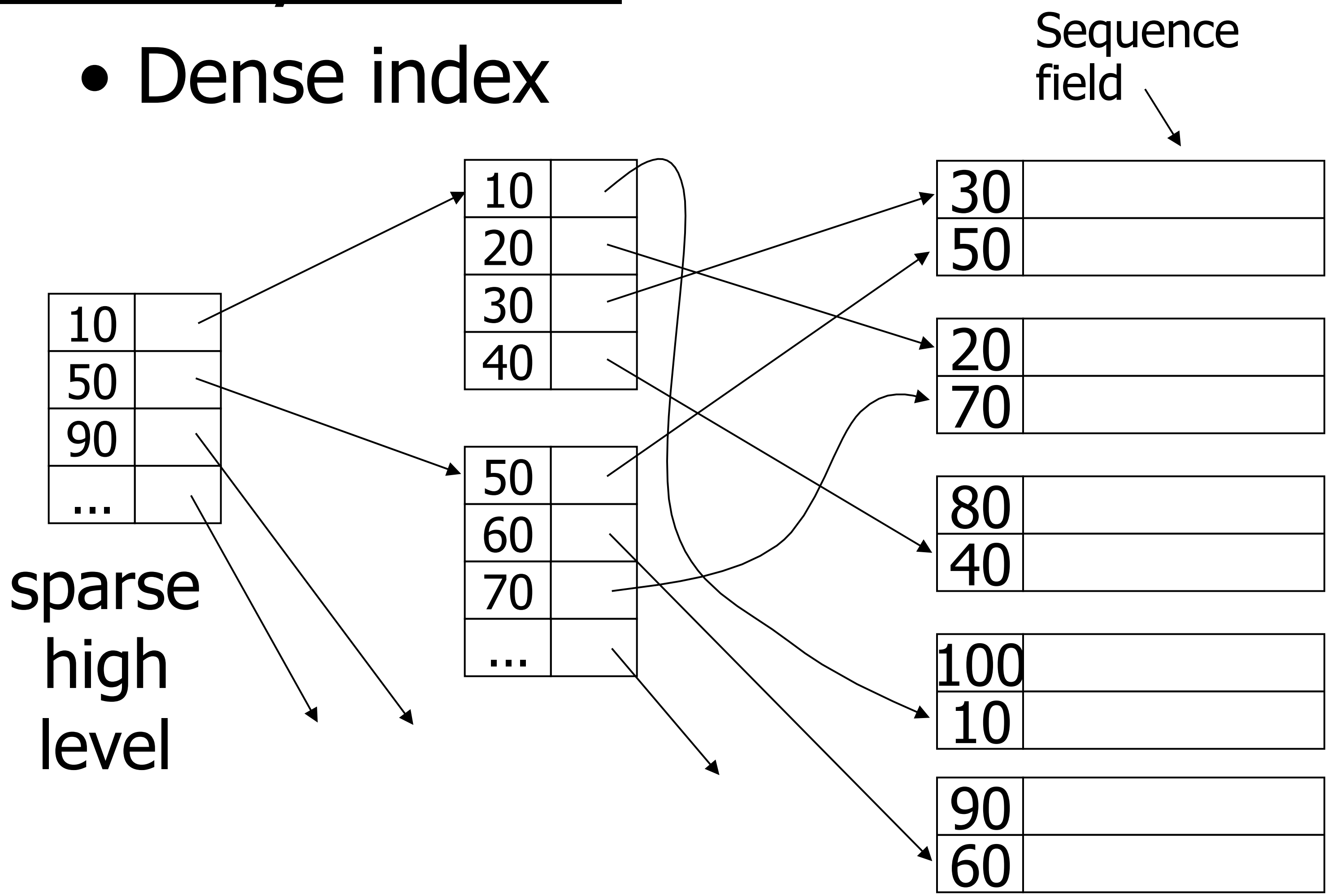
Secondary indexes

- Dense index



Secondary indexes

- Dense index



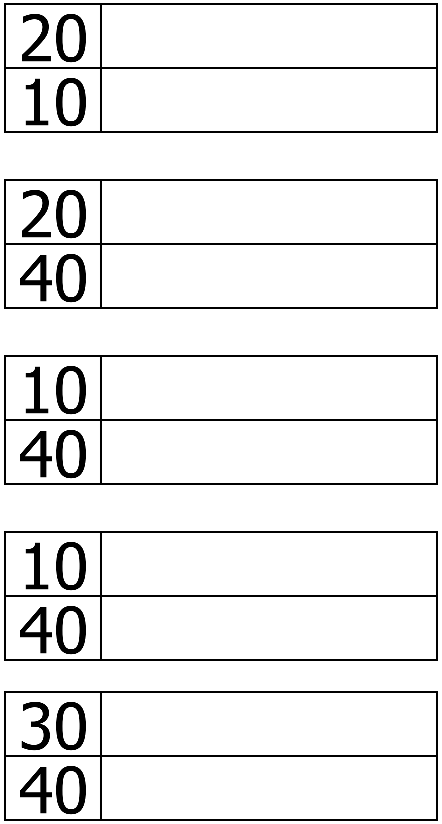
With secondary indexes:

- Lowest level is dense
- Other levels are sparse

Also: Pointers are record pointers

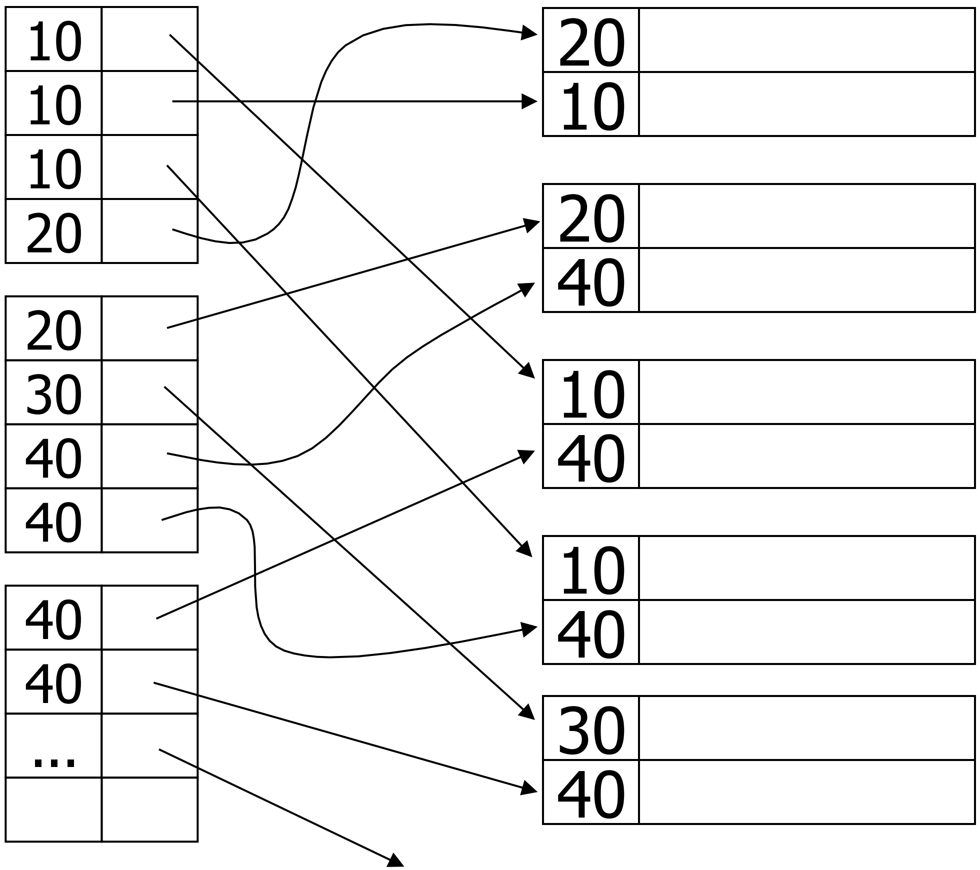
(not block pointers; not computed)

Duplicate values & secondary indexes



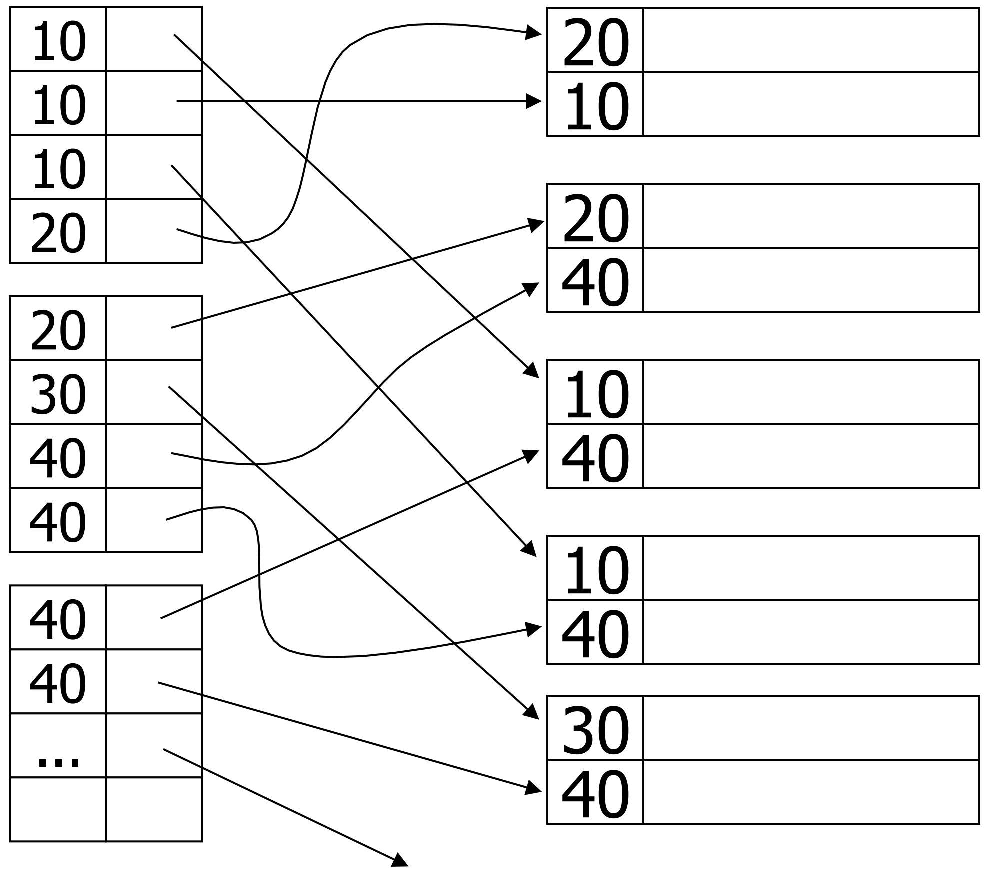
Duplicate values & secondary indexes

one option...



Duplicate values & secondary indexes

one option...

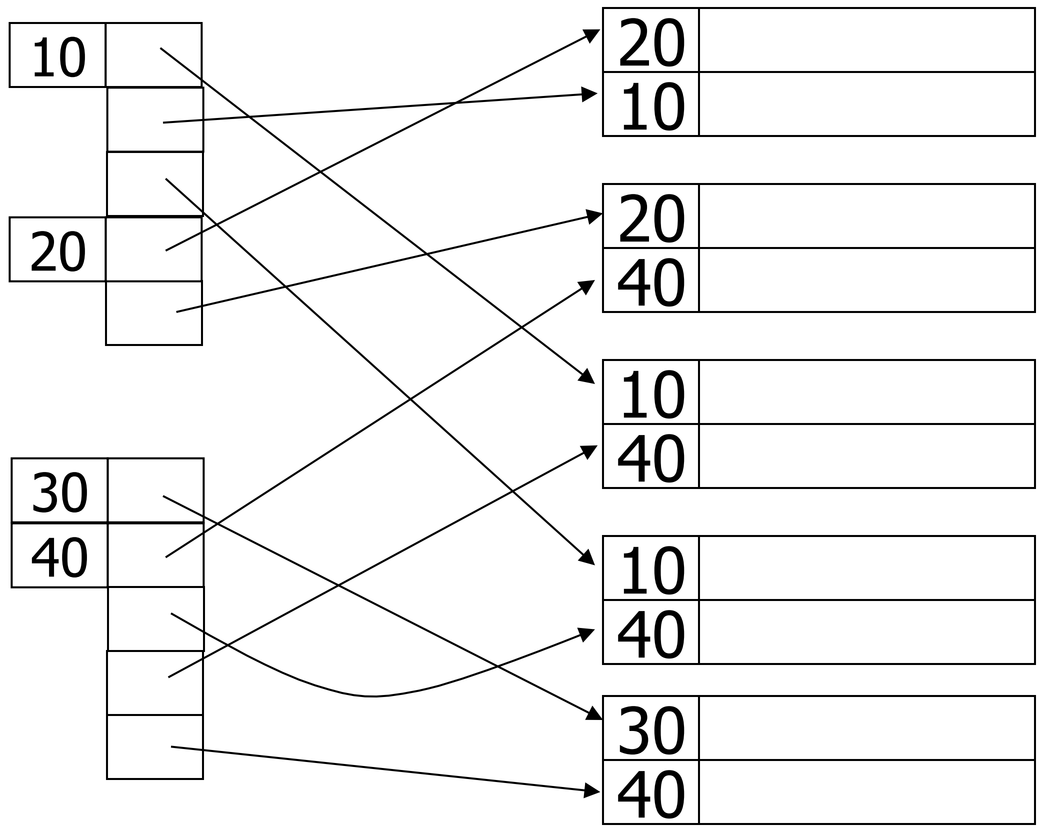


Problem:
excess overhead!

- disk space
- search time

Duplicate values & secondary indexes

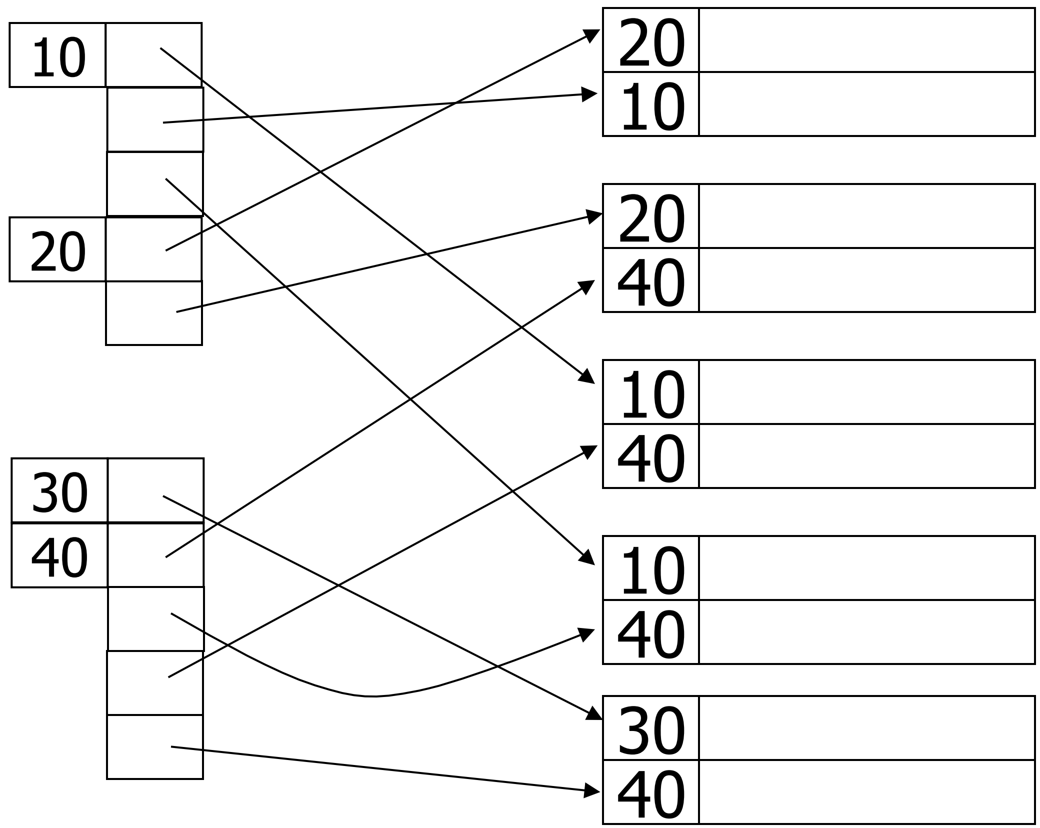
another option...



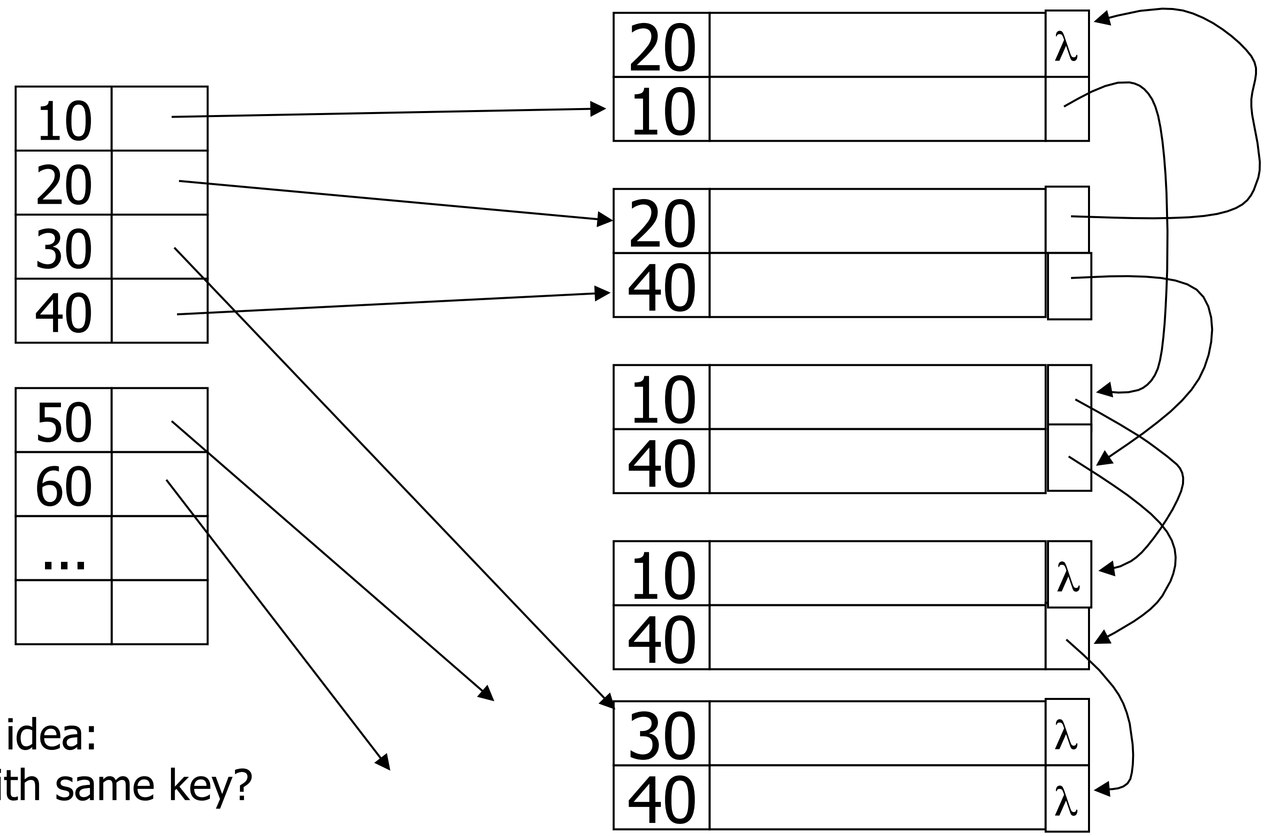
Duplicate values & secondary indexes

another option...

Problem: variable size records in index!

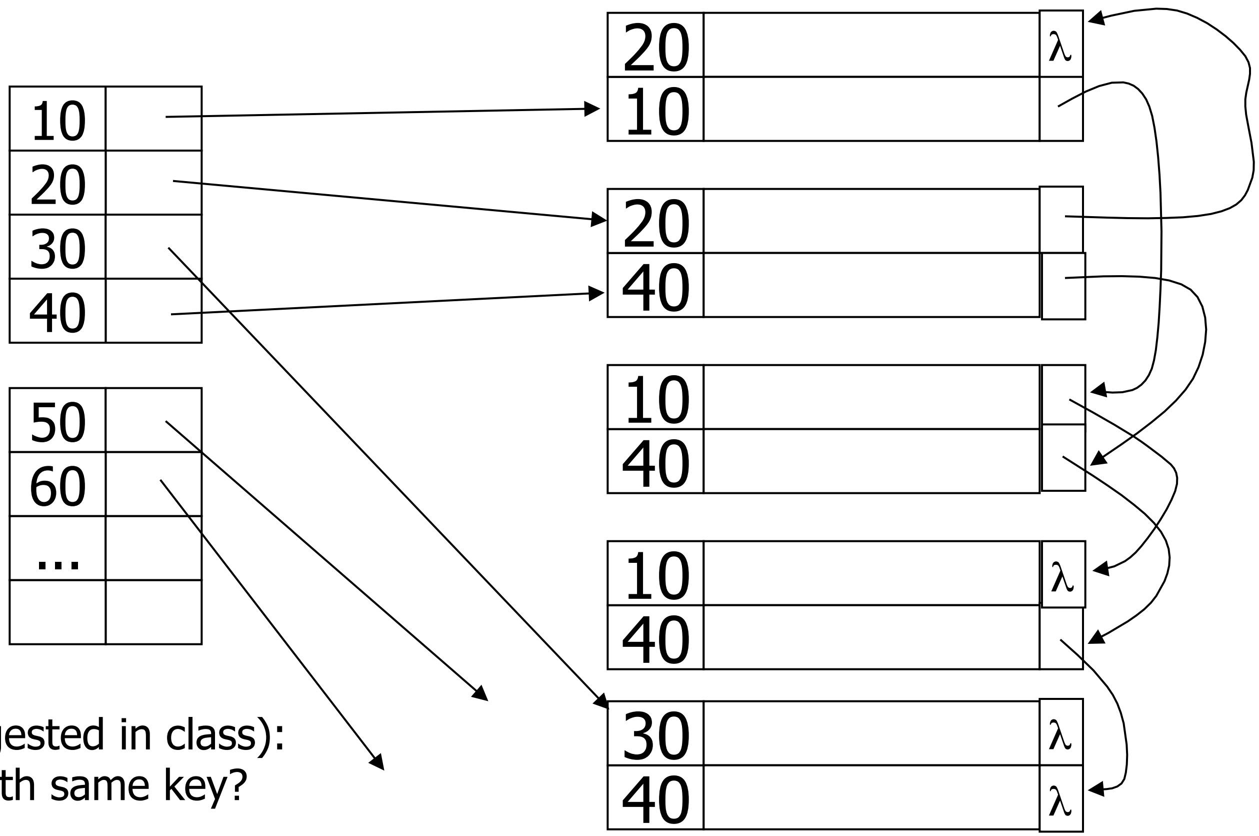


Duplicate values & secondary indexes



Another idea:
Chain records with same key?

Duplicate values & secondary indexes

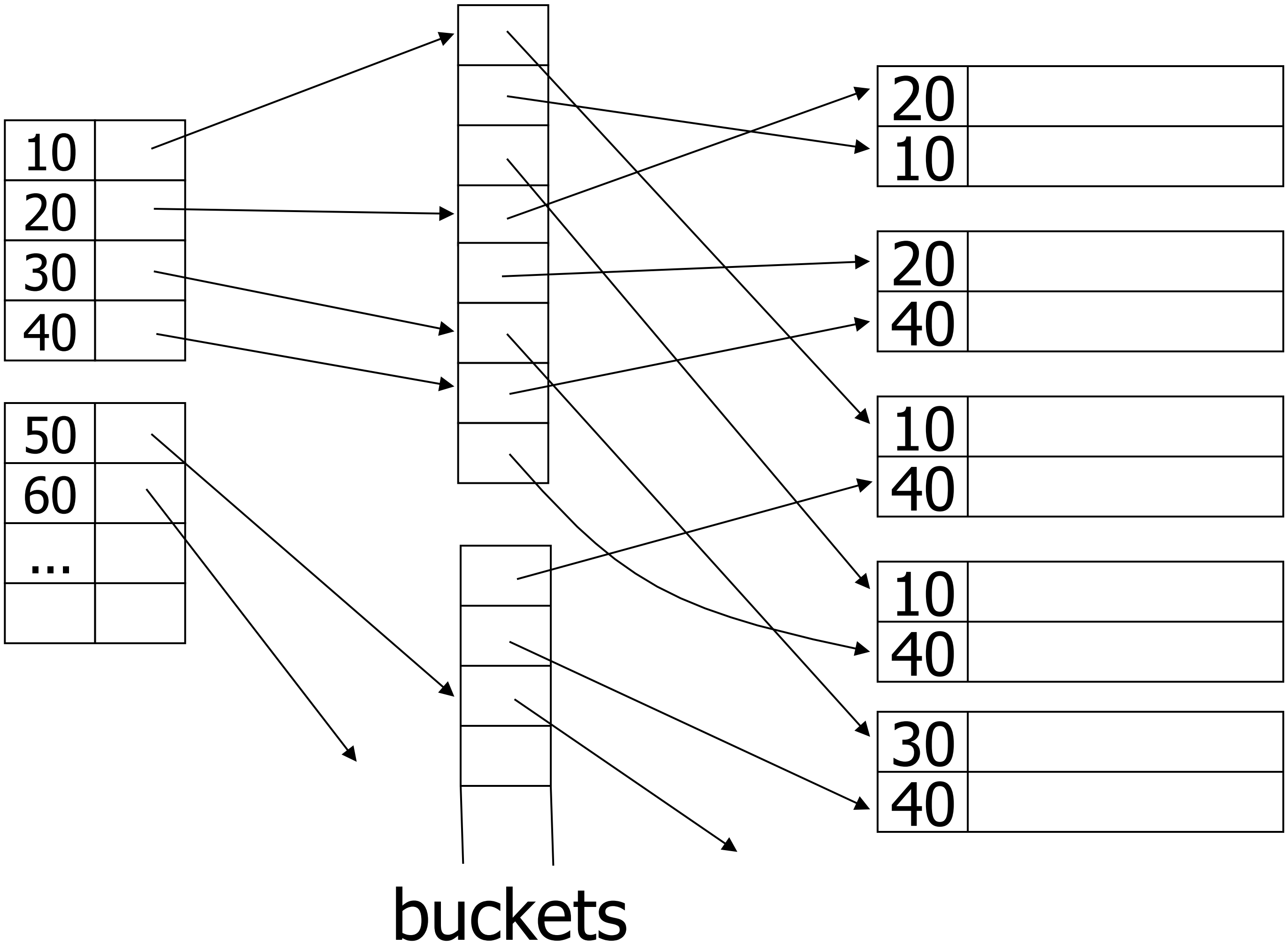


Another idea (suggested in class):
Chain records with same key?

Problems:

- Need to add fields to records
- Need to follow chain to know records

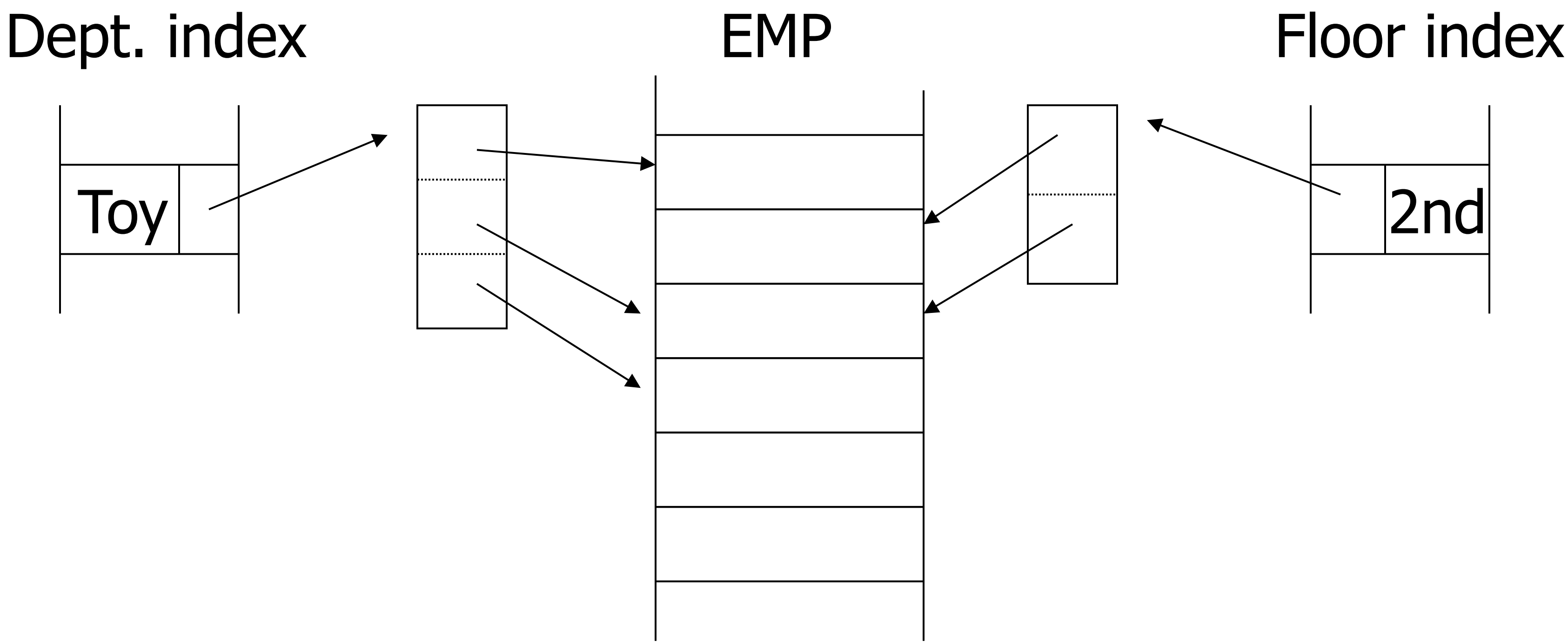
Duplicate values & secondary indexes



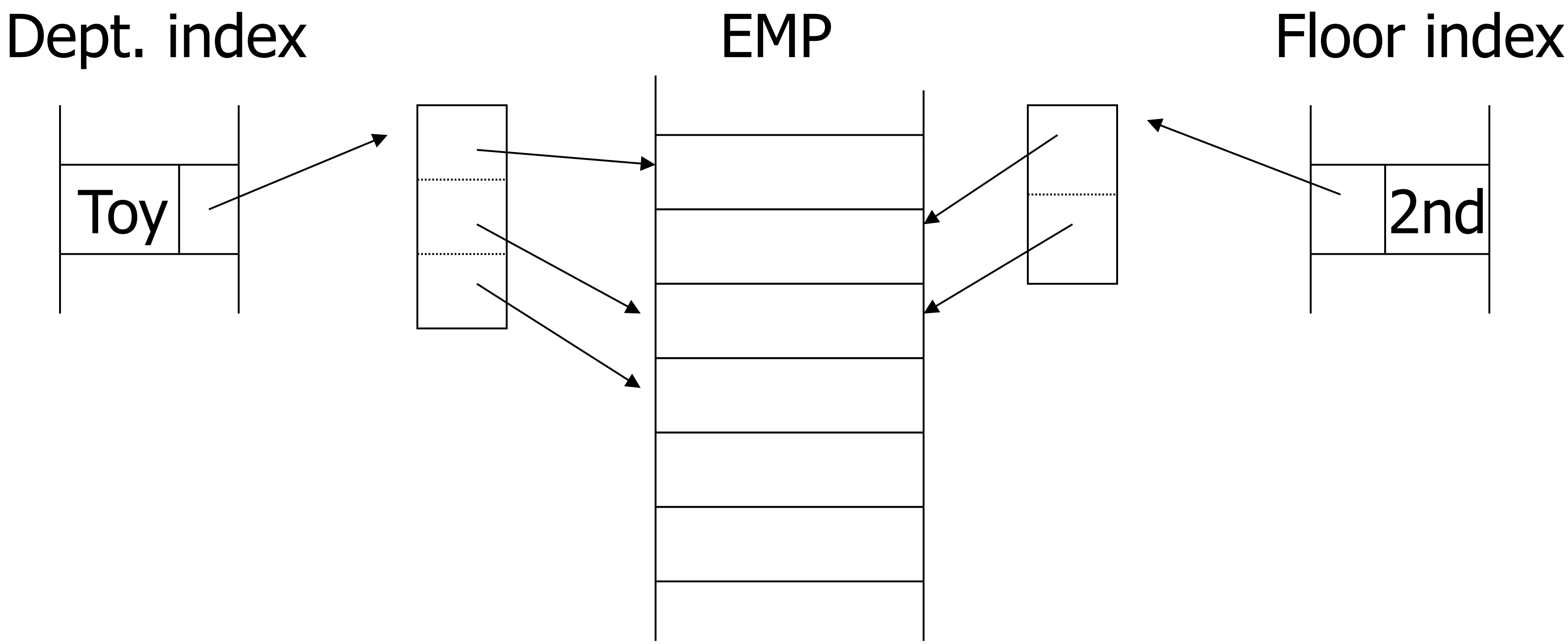
Why "bucket" idea is useful

Indexes	Records
Name: primary	EMP (name,dept,floor,...)
Dept: secondary	
Floor: secondary	

Query: Get employees in (Toy Dept) $\wedge$ (2nd floor)



Query: Get employees in (Toy Dept) $\wedge$ (2nd floor)



→ Intersect toy bucket and 2nd Floor bucket to get set of matching EMP's

This idea used in text information retrieval

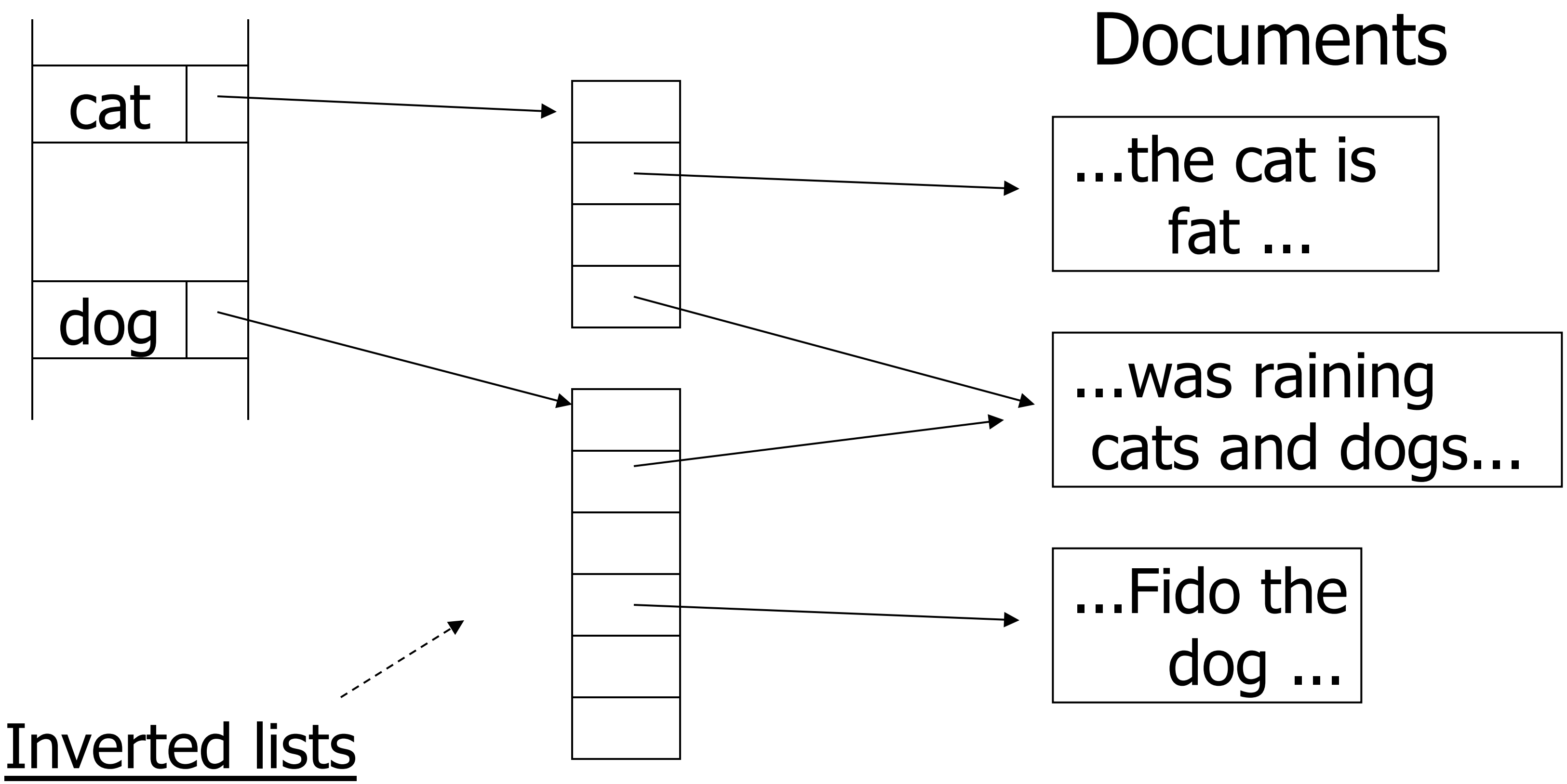
Documents

...the cat is fat ...

...was raining cats and dogs...

...Fido the dog ...

This idea used in text information retrieval



IR QUERIES

- Find articles with “cat” and “dog”
- Find articles with “cat” or “dog”
- Find articles with “cat” and not “dog”

Summary so far

- Conventional index
  - Basic Ideas: sparse, dense, multi-level…
  - Duplicate Keys
  - Deletion/Insertion
  - Secondary indexes
    - Buckets of Postings List

Conventional indexes

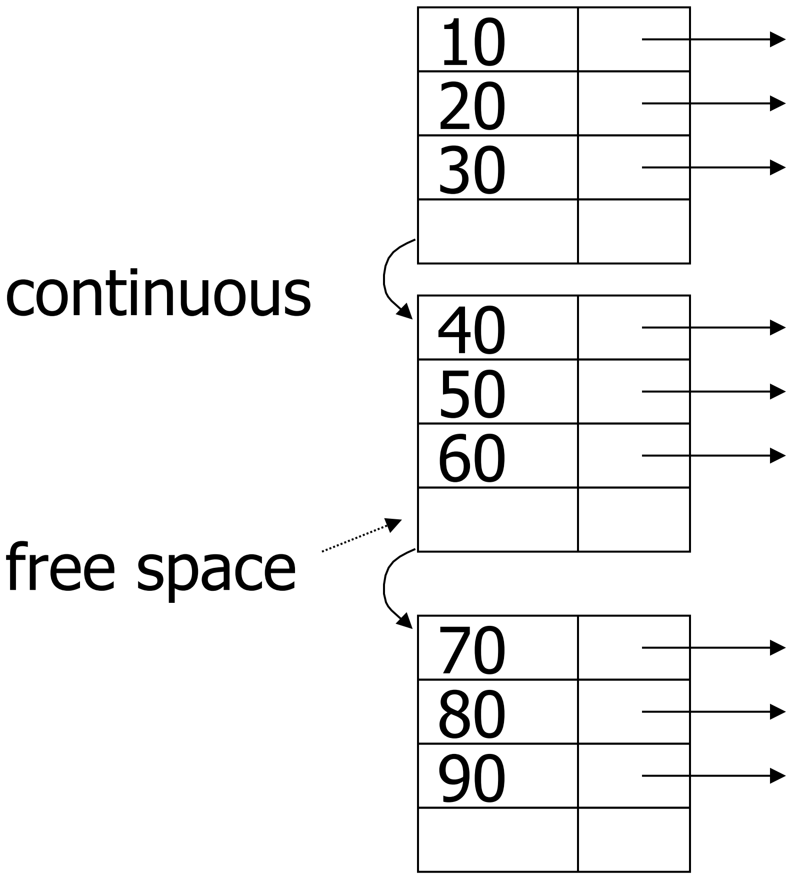
Advantage:

- Simple
- Index is sequential file
  good for scans

Disadvantage:

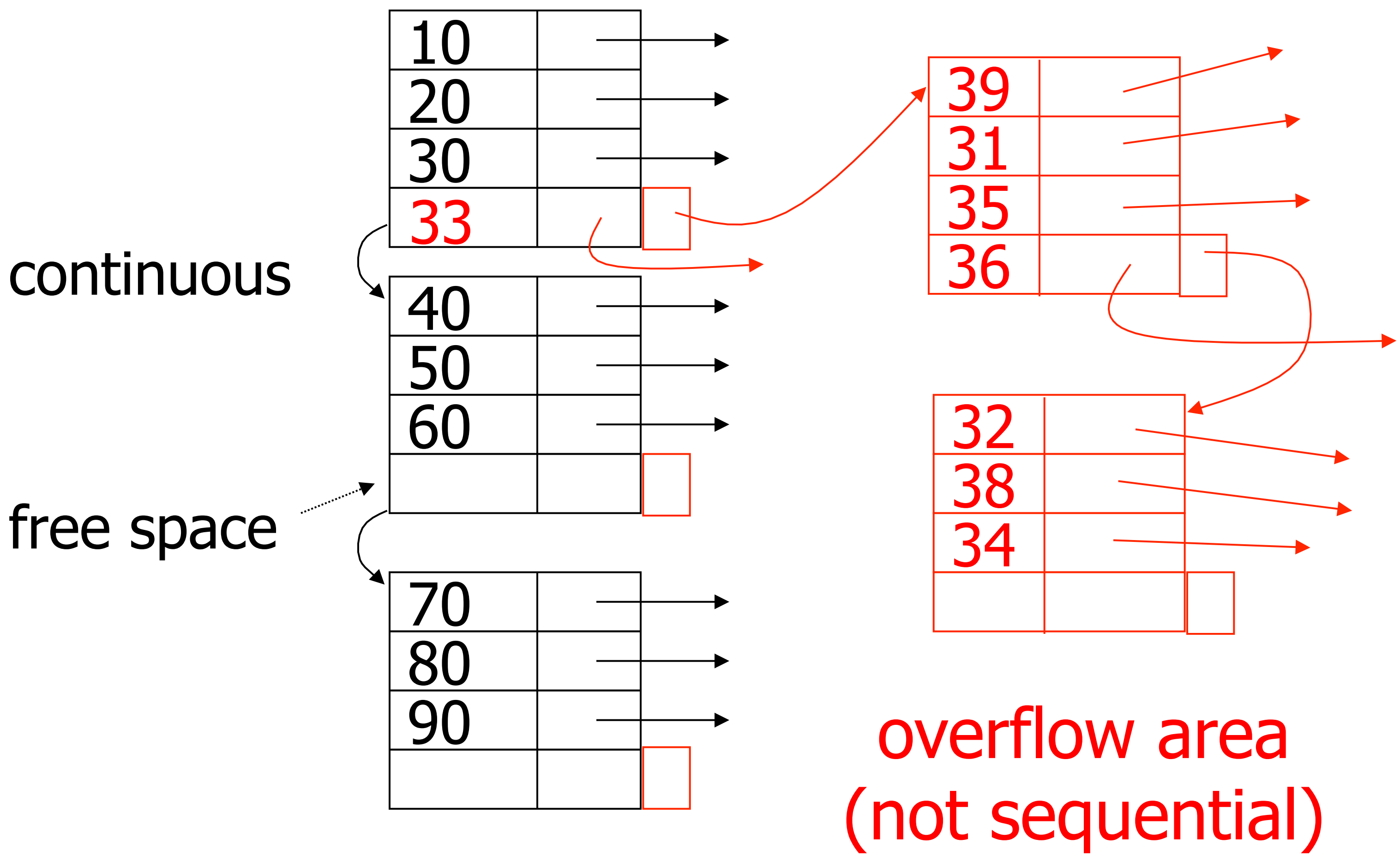
- Inserts expensive, and/or
- Lose sequentiality & balance

Example Index (sequential)



Example

Index (sequential)



Outline:

- Conventional indexes
- B-Trees $\Rightarrow$ NEXT
- Hashing schemes
- Advanced Index Techniques

- NEXT: Another type of index
  - Give up on sequentiality of index
  - Try to get “balance”

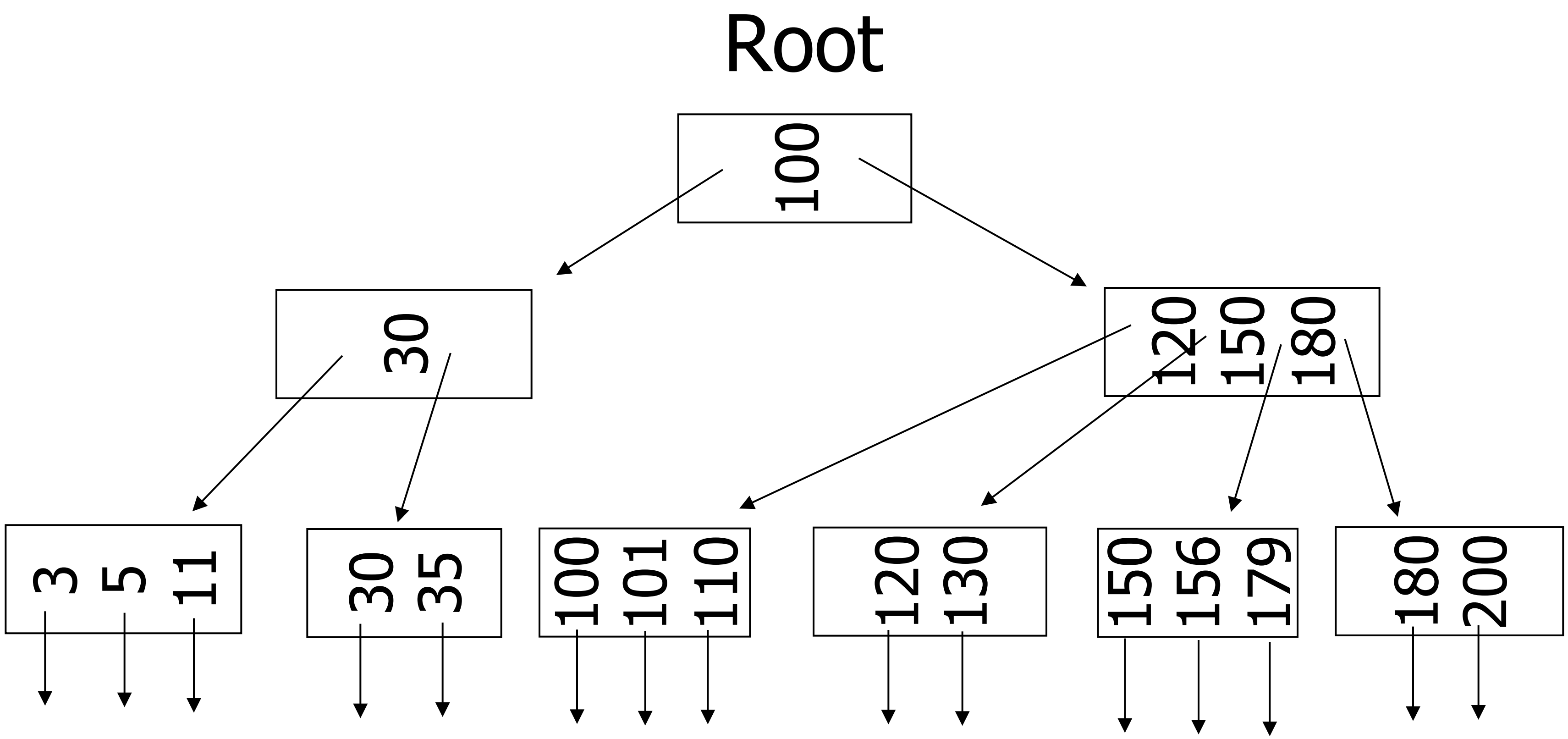
B+-tree Motivation

- Tree indices are pretty efficient
  - E.g., binary search tree
    - Average case O(log(n)) lookup
- However
  - Unclear how to map to disk (index larger than main memory, loading partial index)
  - Worst-case O(n) lookup

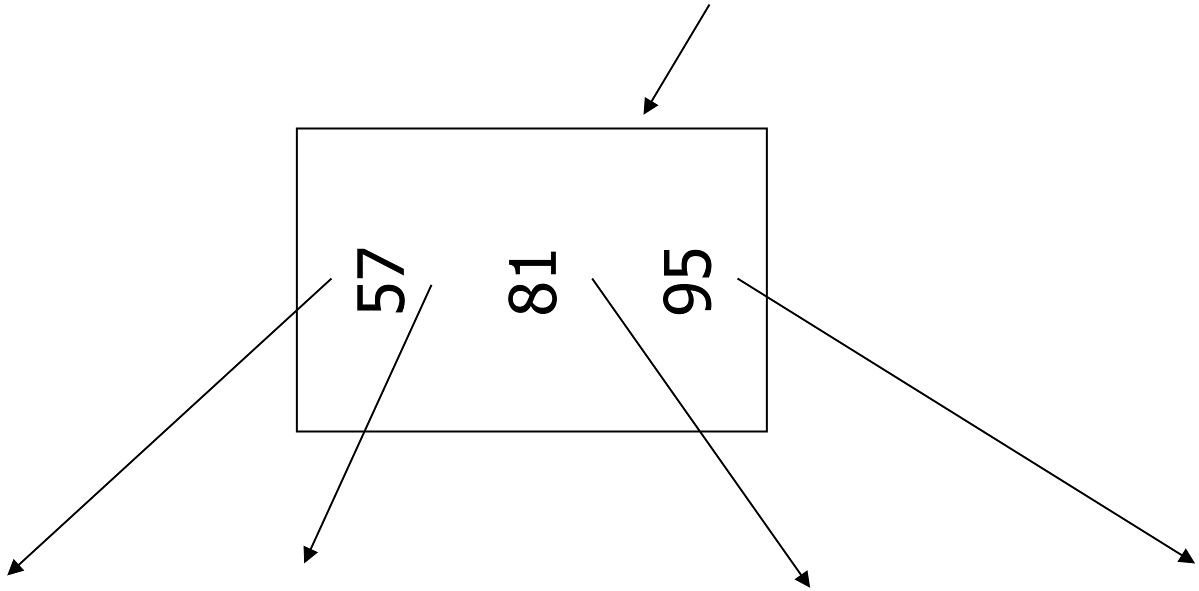
B+-tree Properties

- Large nodes:
  - Node size is multiple of block size
    - -> small number of levels
    - -> simple way to map index to disk
    - -> many keys per node
- Balance:
  - Require all nodes to be more than X% full
  - -> for n records guaranteed only logarithmically many levels
  - -> log(n) worst-case performance

B+Tree Example n=3

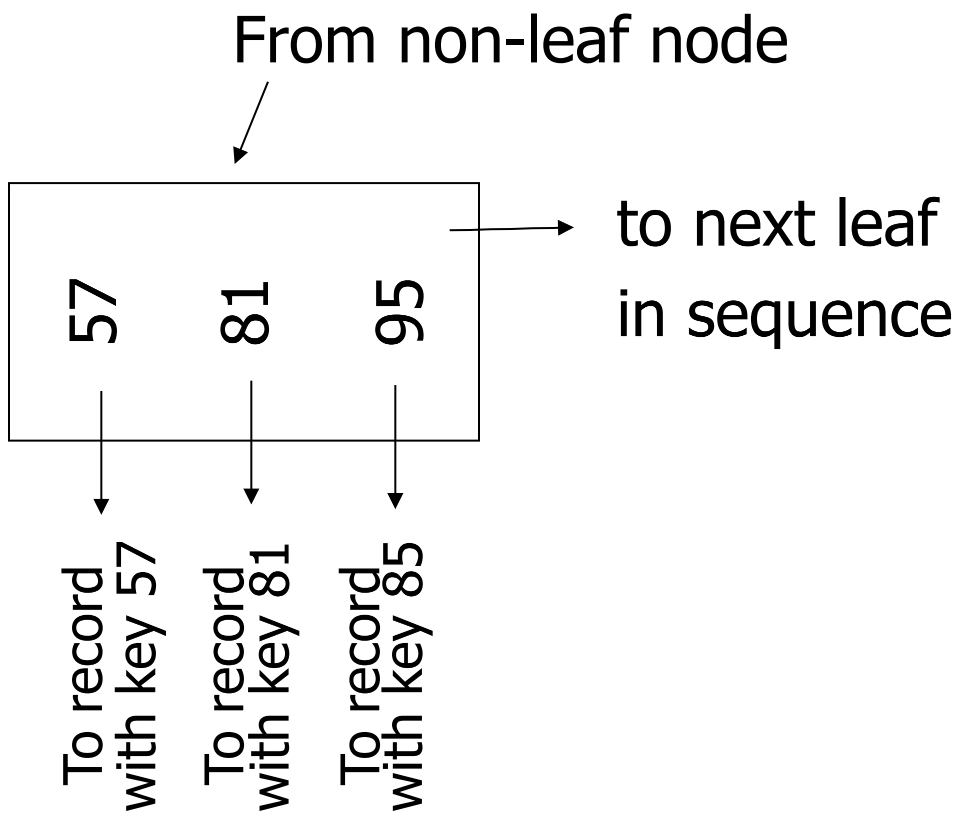


Sample non-leaf



to keys	to keys	to keys	to keys
< 57	57≤ k<81	81≤k<95	≥95

Sample leaf node:



In textbook's notation n=3

Leaf:

Non-leaf:

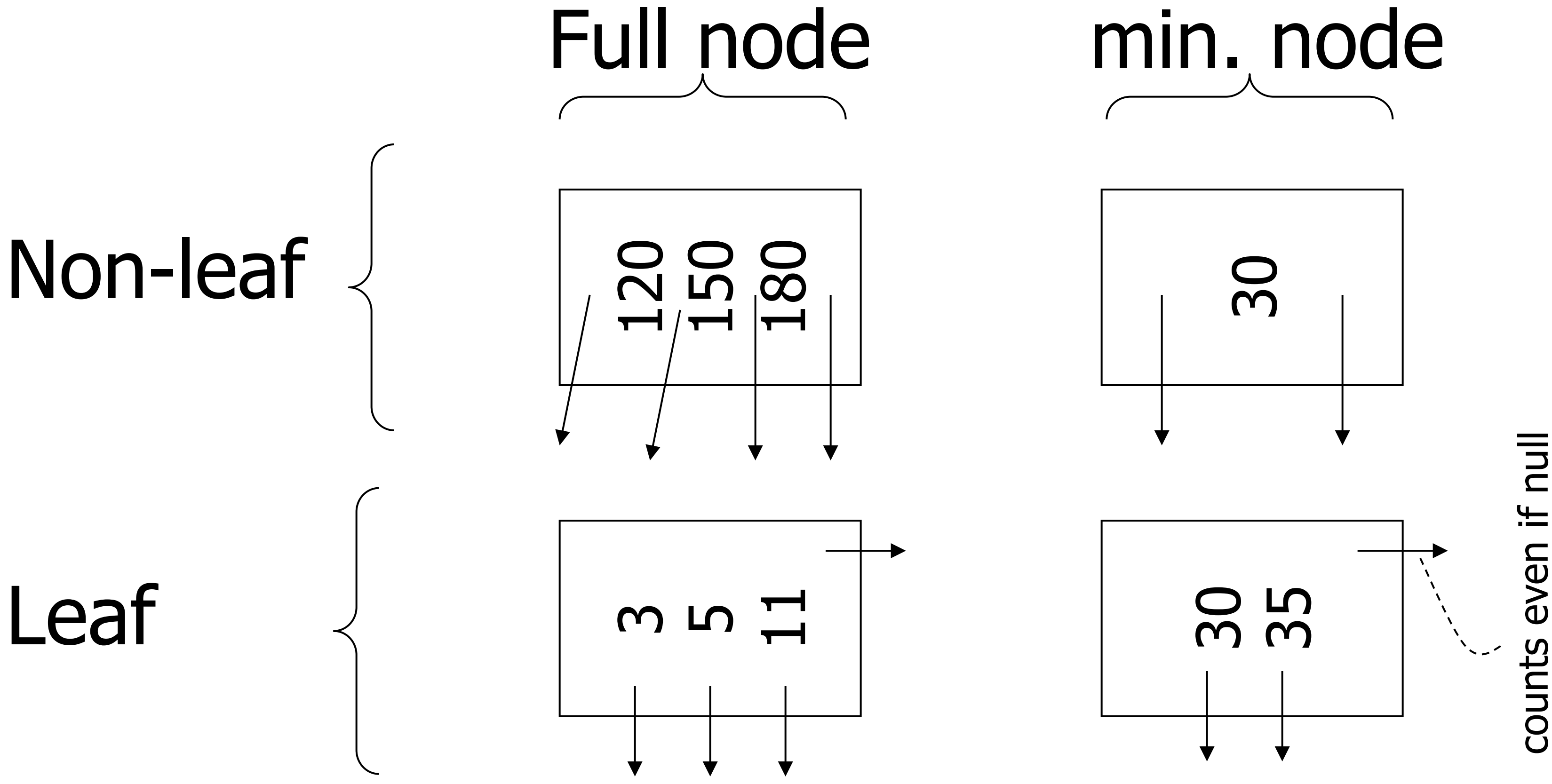
Size of nodes: $\left\{ \begin{array}{l} \text{n+1 pointers} \\ \text{n keys} \end{array} \right.$ <u>(fixed)</u>

Don't want nodes to be too empty

- Use at least (balance)

Non-leaf: $\lceil (n+1)/2 \rceil$ pointers

Leaf: $\lfloor (n+1)/2 \rfloor$ pointers to data n=3


Full node
min. node
Non-leaf
Leaf
120
150
180
30
3
5
11
30
35
counts even if null

B+tree rules tree of order *n*

(1)All leaves at same lowest level
(balanced tree)

-> guaranteed worst-case complexity for operations on the index

(2) Pointers in leaves point to records
except for "sequence pointer"

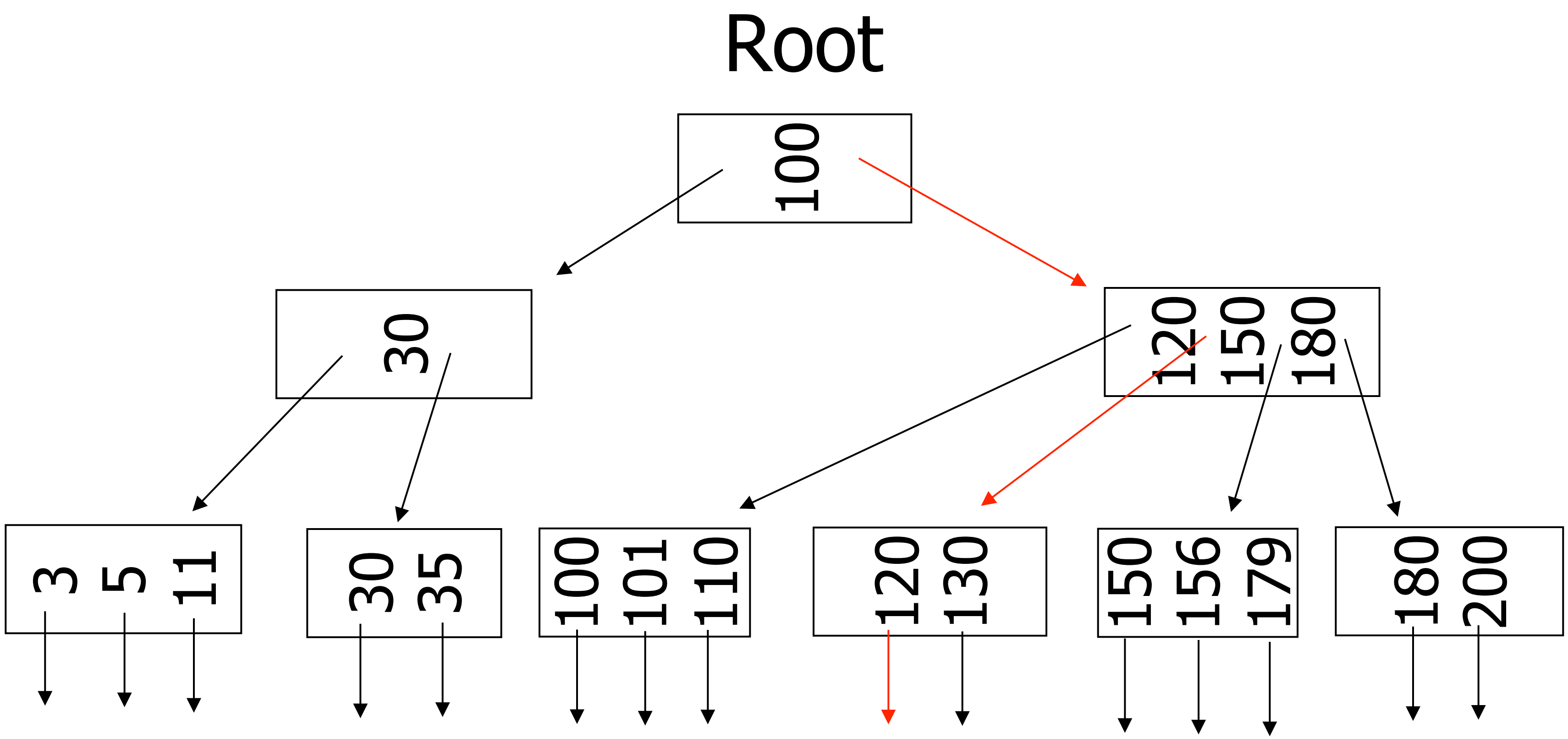
(3) Number of pointers/keys for B+tree

	Max ptrs	Max keys	Min ptrs→data	Min keys
Non-leaf (non-root)	n+1	n	$\lceil (n+1)/2 \rceil$	$\lceil (n+1)/2 \rceil - 1$
Leaf (non-root)	n+1	n	$\lfloor (n+1)/2 \rfloor$	$\lfloor (n+1)/2 \rfloor$
Root	n+1	n	1	1

Search Algorithm

- Search for key **k**
- Start from root until leaf is reached
- For current node find i so that
  - Key[i] <= **k** < Key[i + 1]
  - Follow i+1th pointer
- If current node is leaf return pointer to record or fail (no such record in tree)

Search Example **k= 120** n=3



Remarks Search

- If **n** is large, e.g., 500
- Keys inside node are sorted
- -> use binary search to find **I**
- Performance considerations
  - – Linear search $O(n)$
  - – Binary search $O(\log_2(n))$

Insert into B+tree

(a) simple case
- space available in leaf

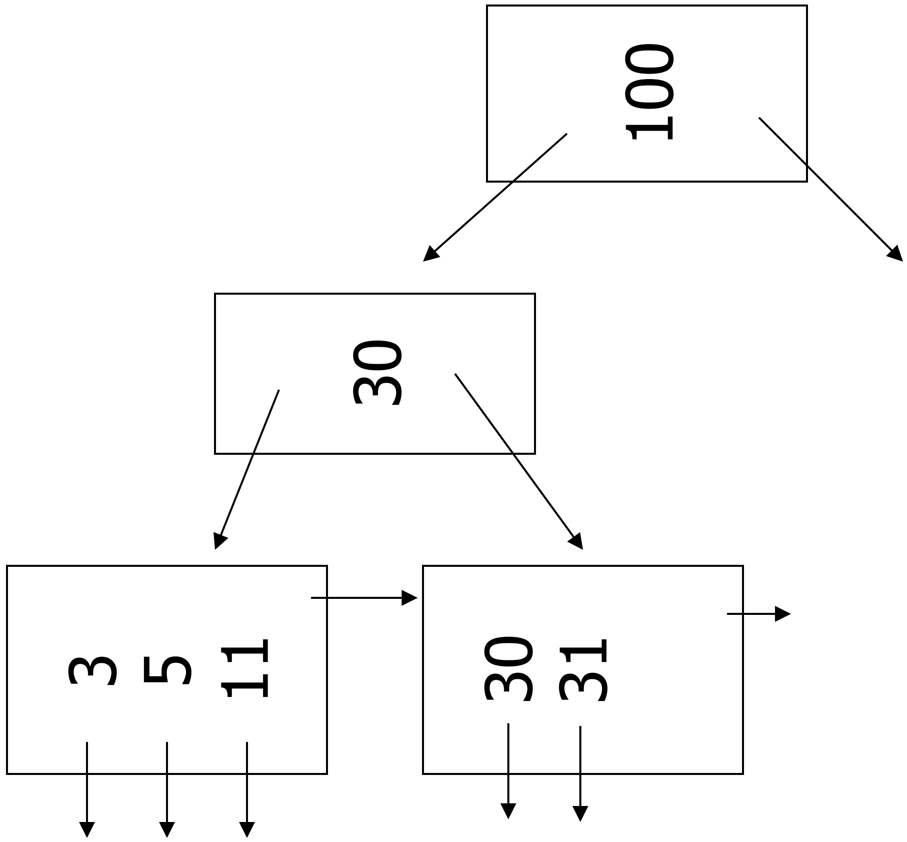
(b) leaf overflow

(c) non-leaf overflow

(d) new root

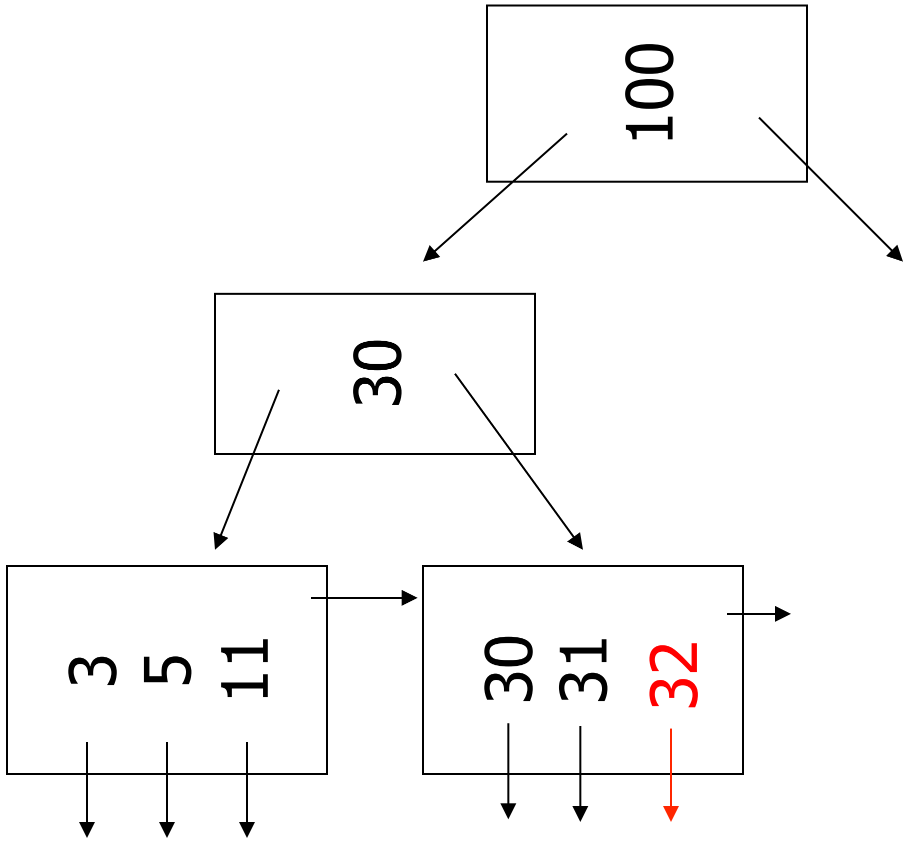
(a) Insert key = 32

n=3



(a) Insert key = 32

n=3



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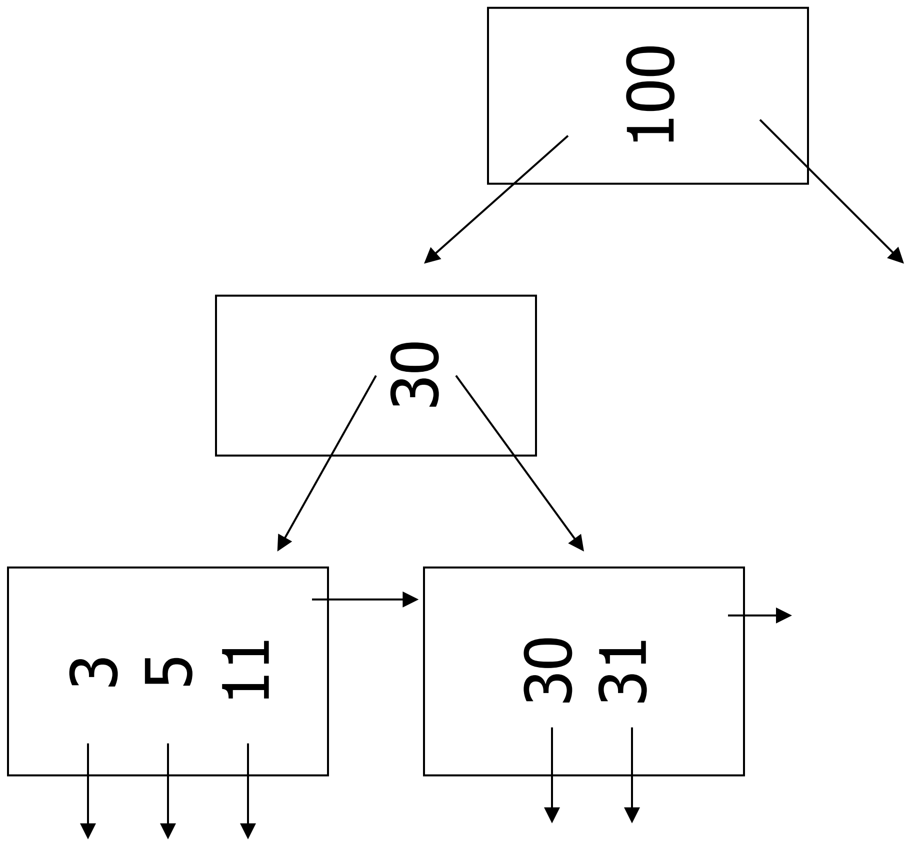
(a) Insert key = 7

n=3



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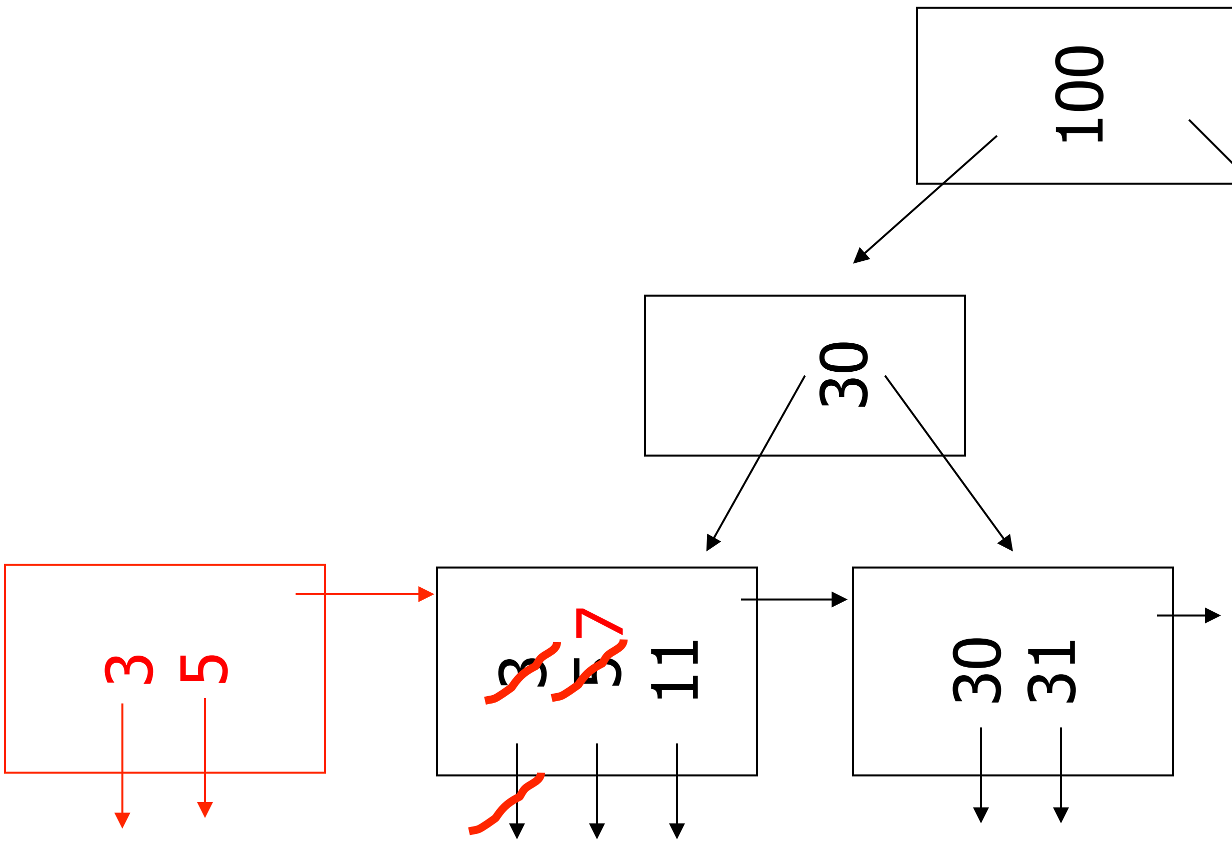

(a) Insert key = 7

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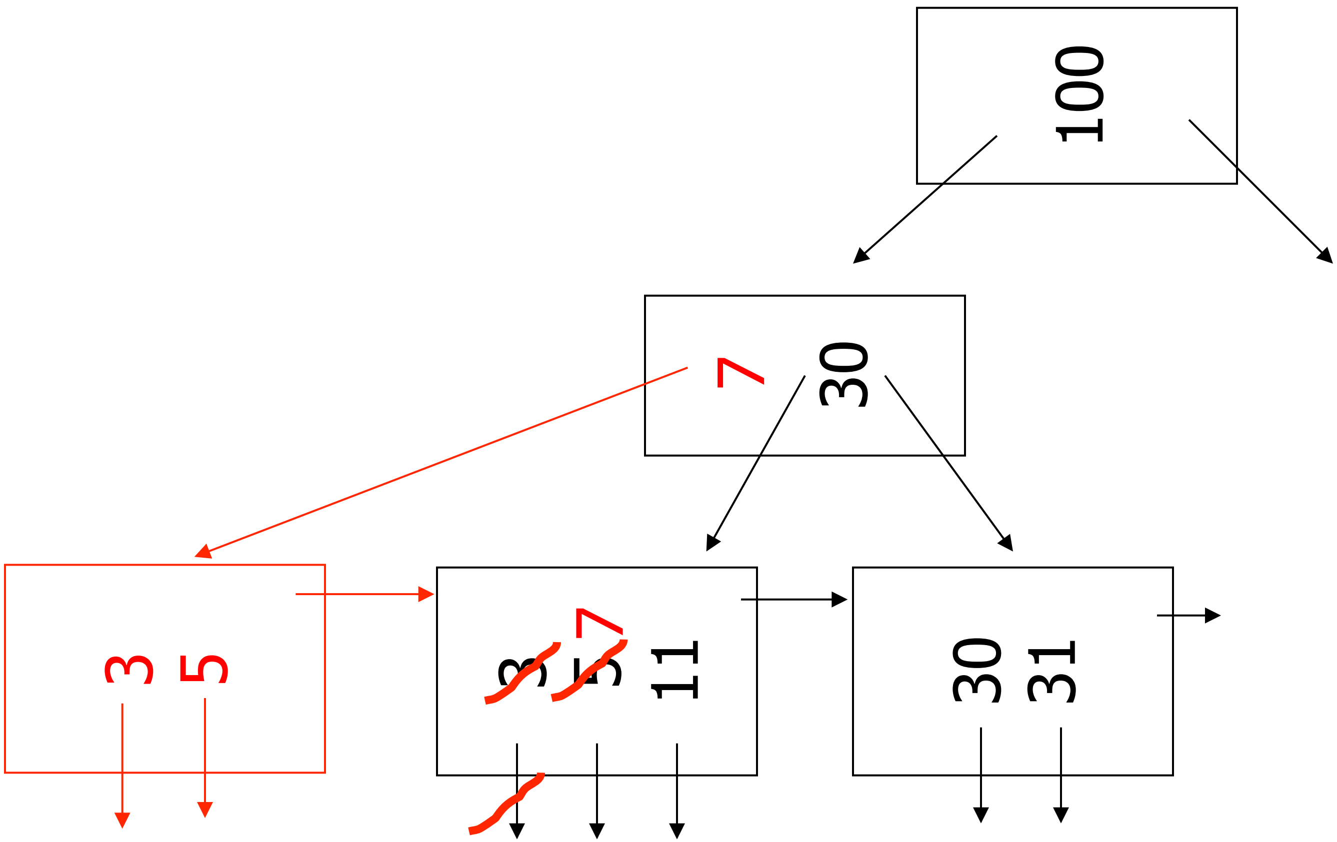
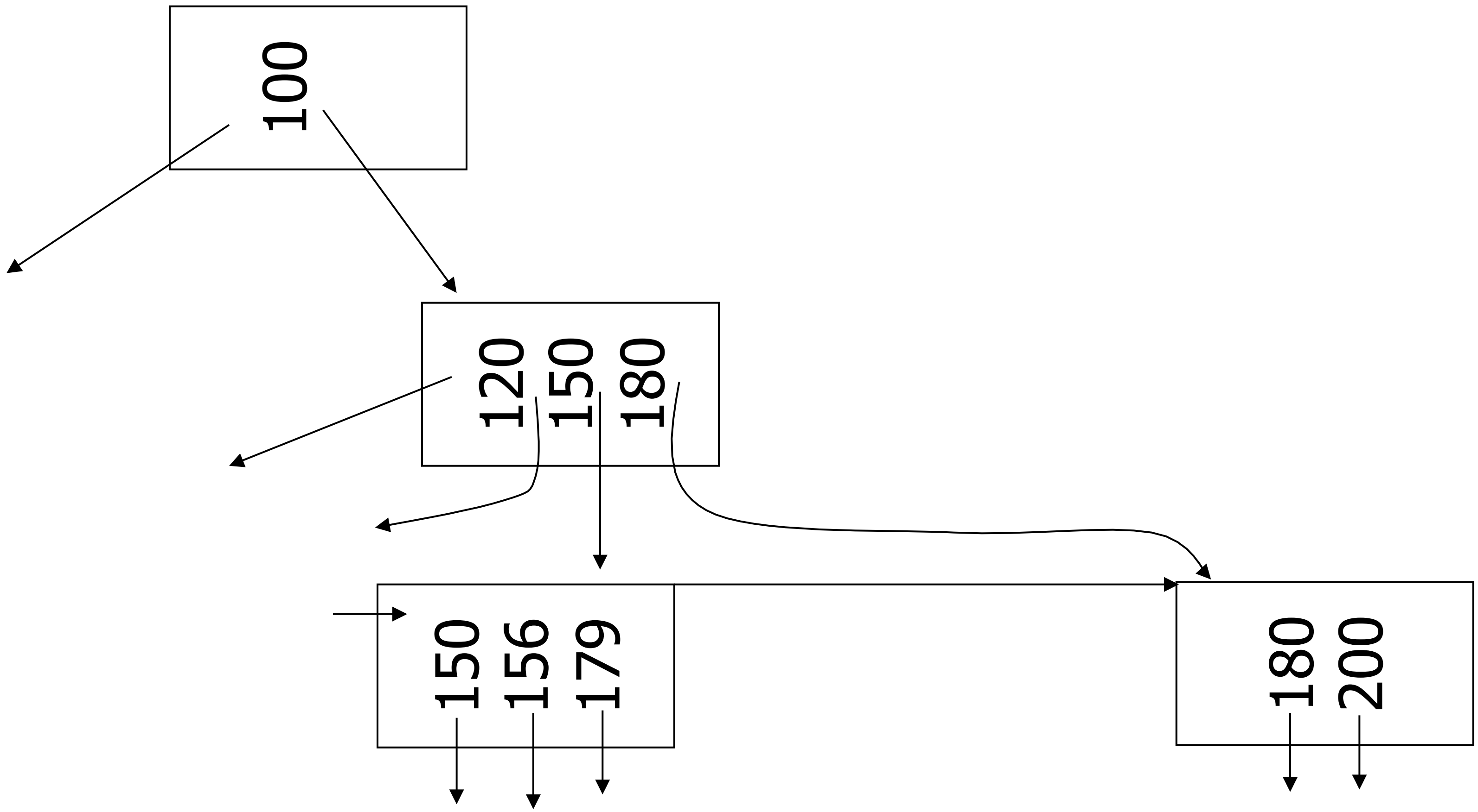


(c) Insert key = 160

n=3



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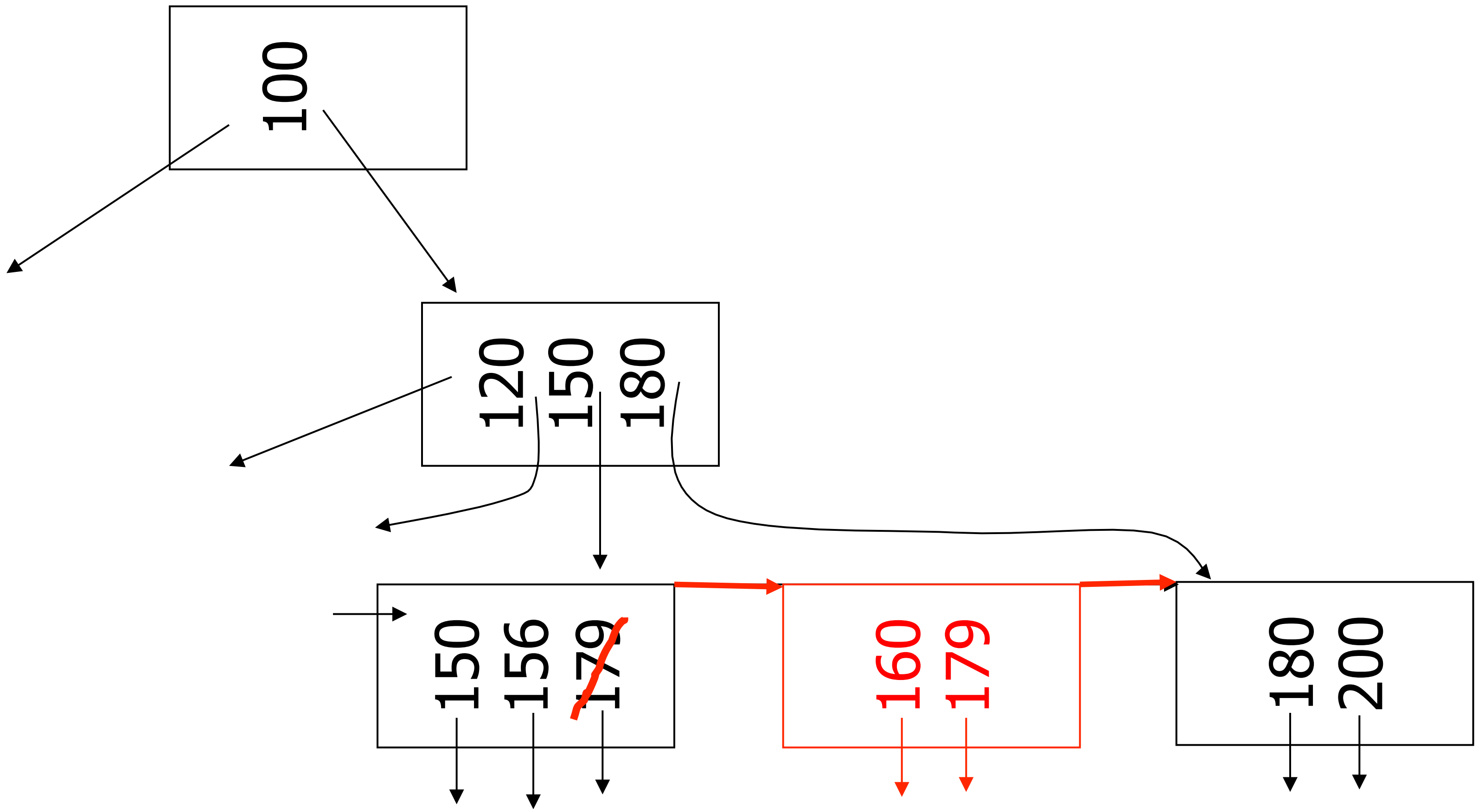
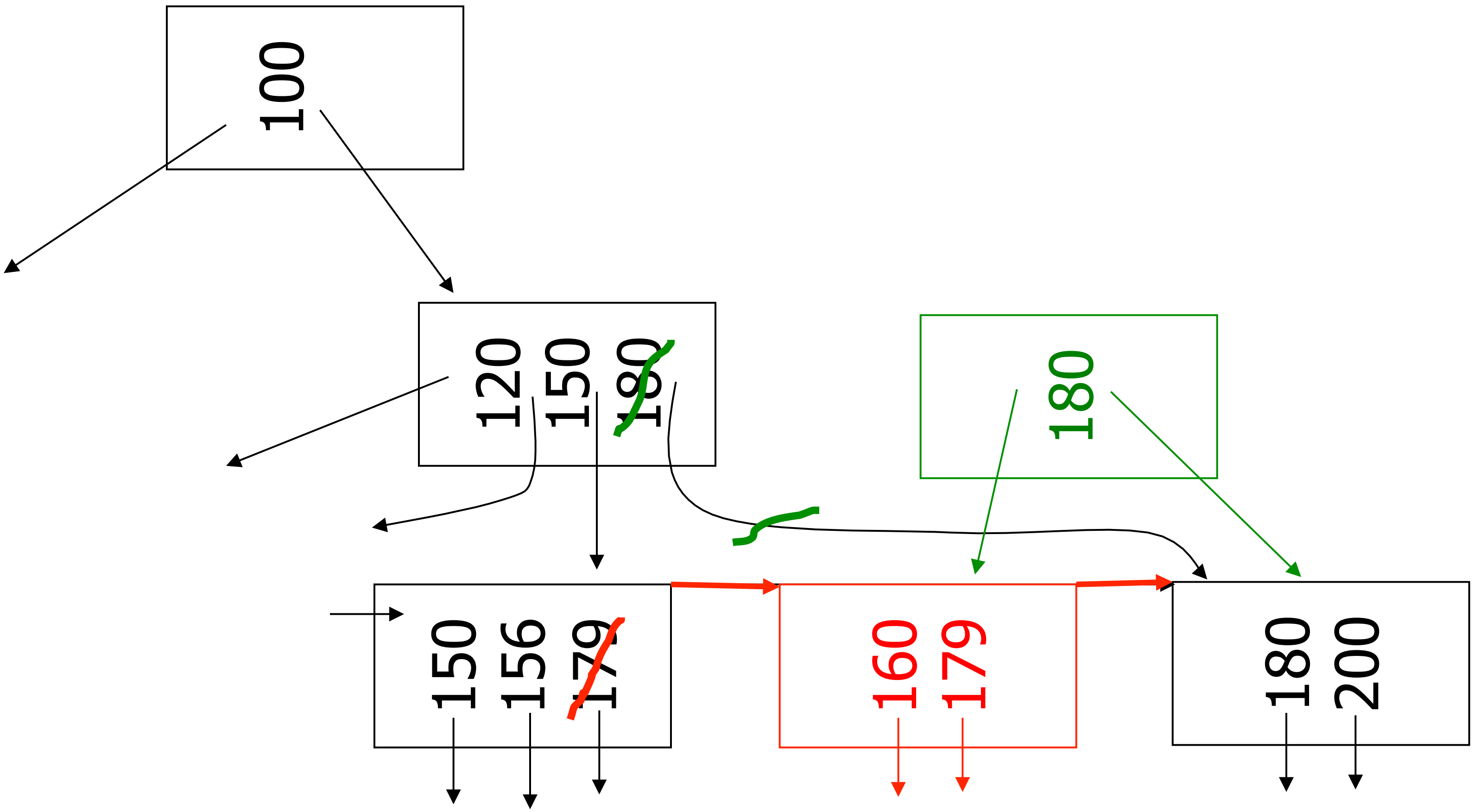
(c) Insert key = 160

n=3



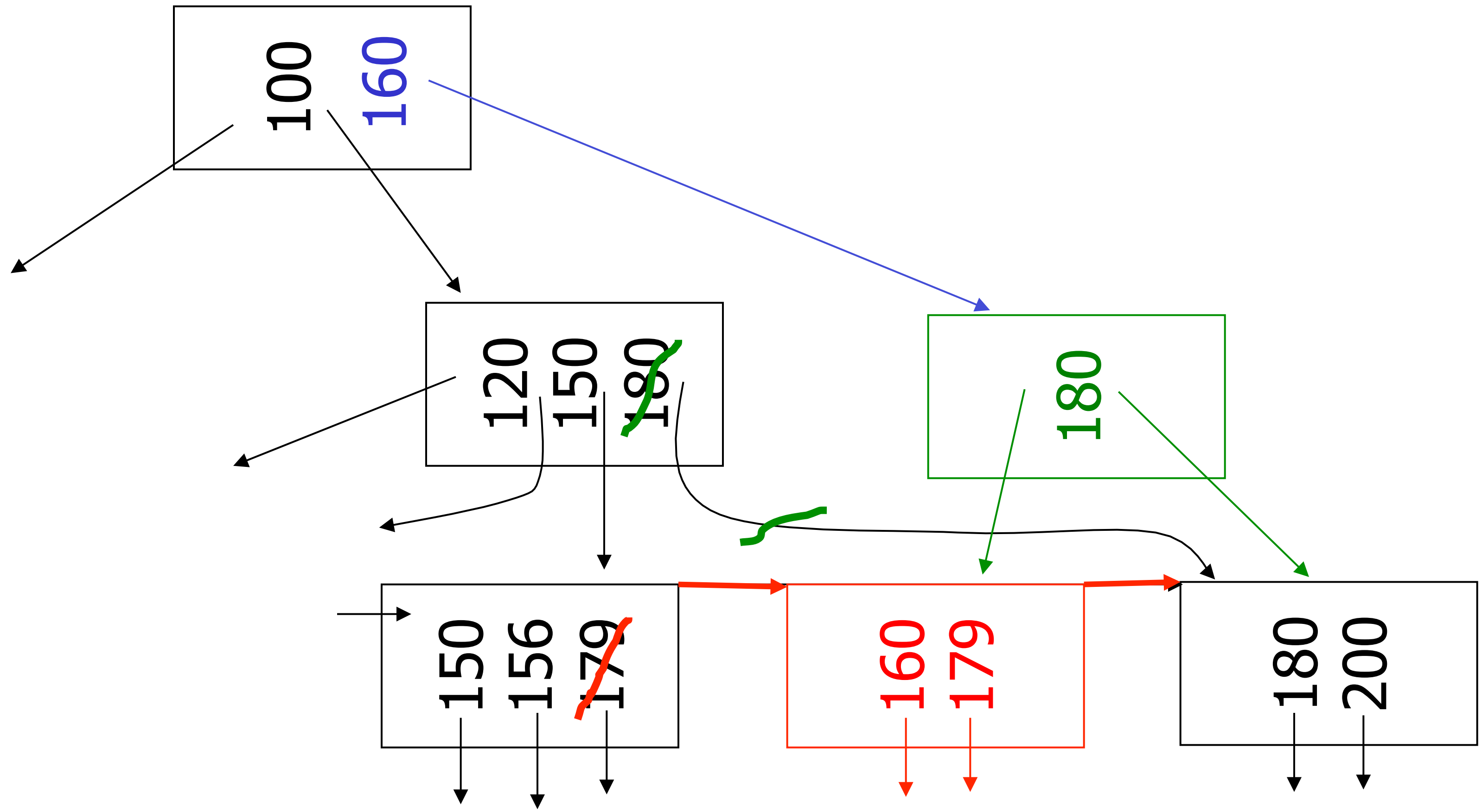
(c) Insert key = 160

n=3



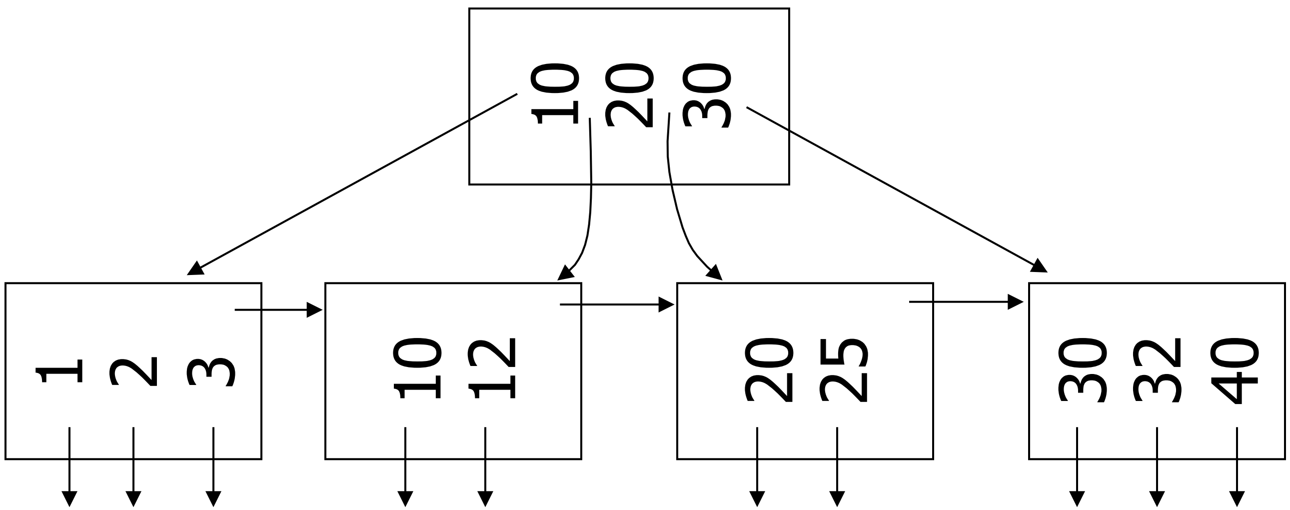
(c) Insert key = 160

n=3



(d) New root, insert 45

n=3



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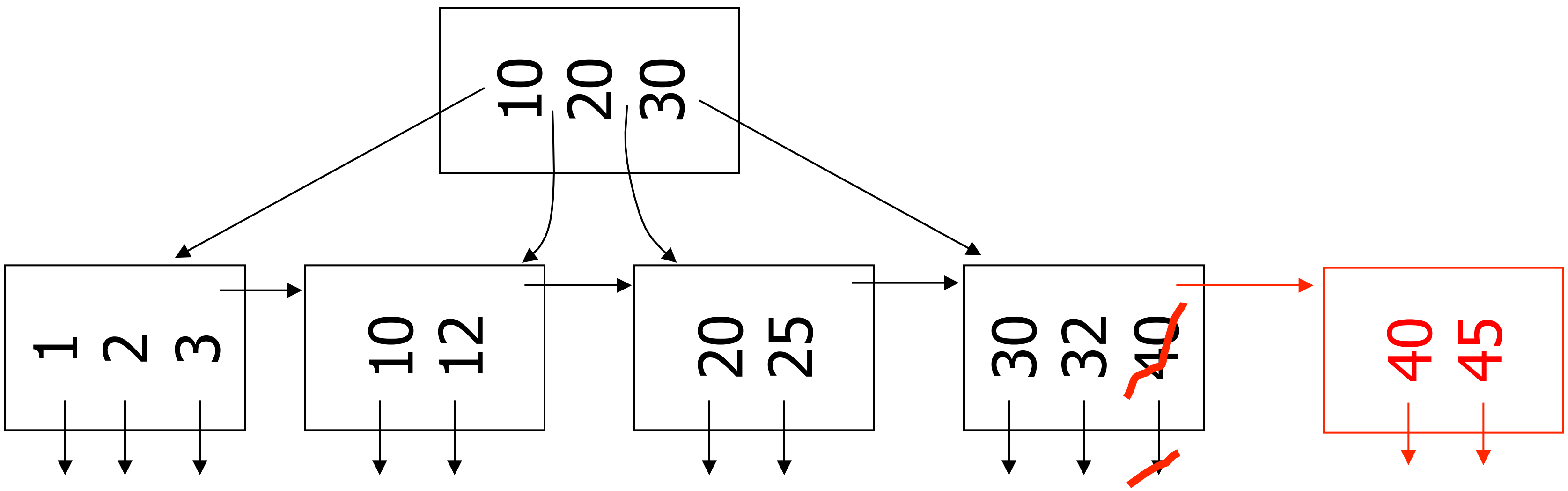

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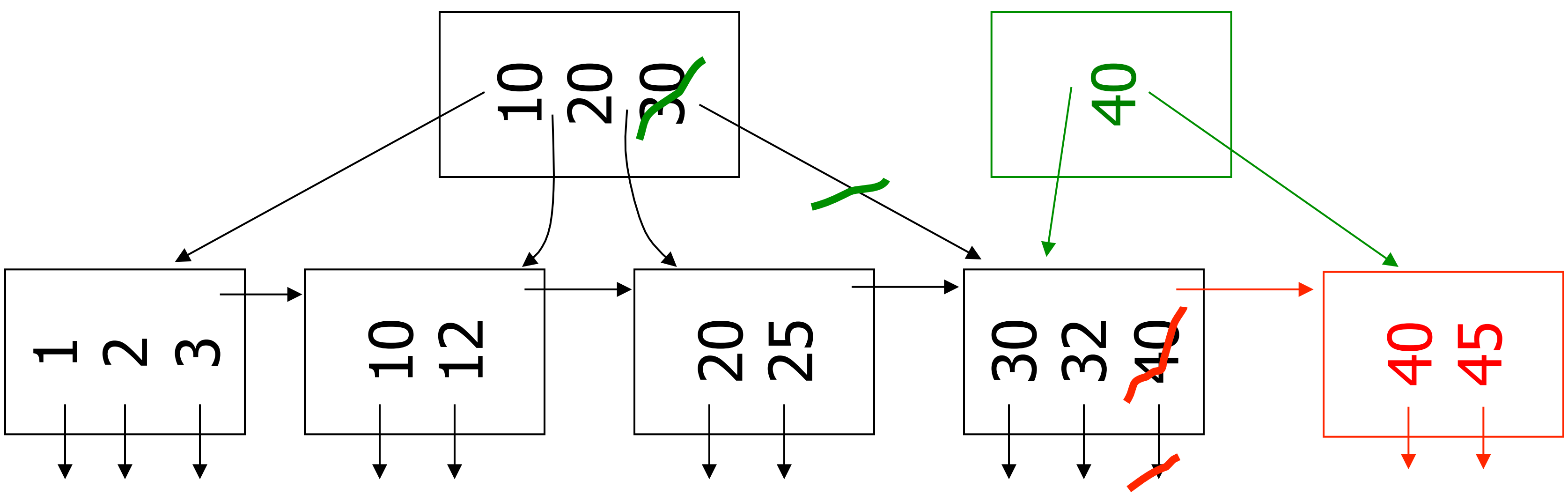

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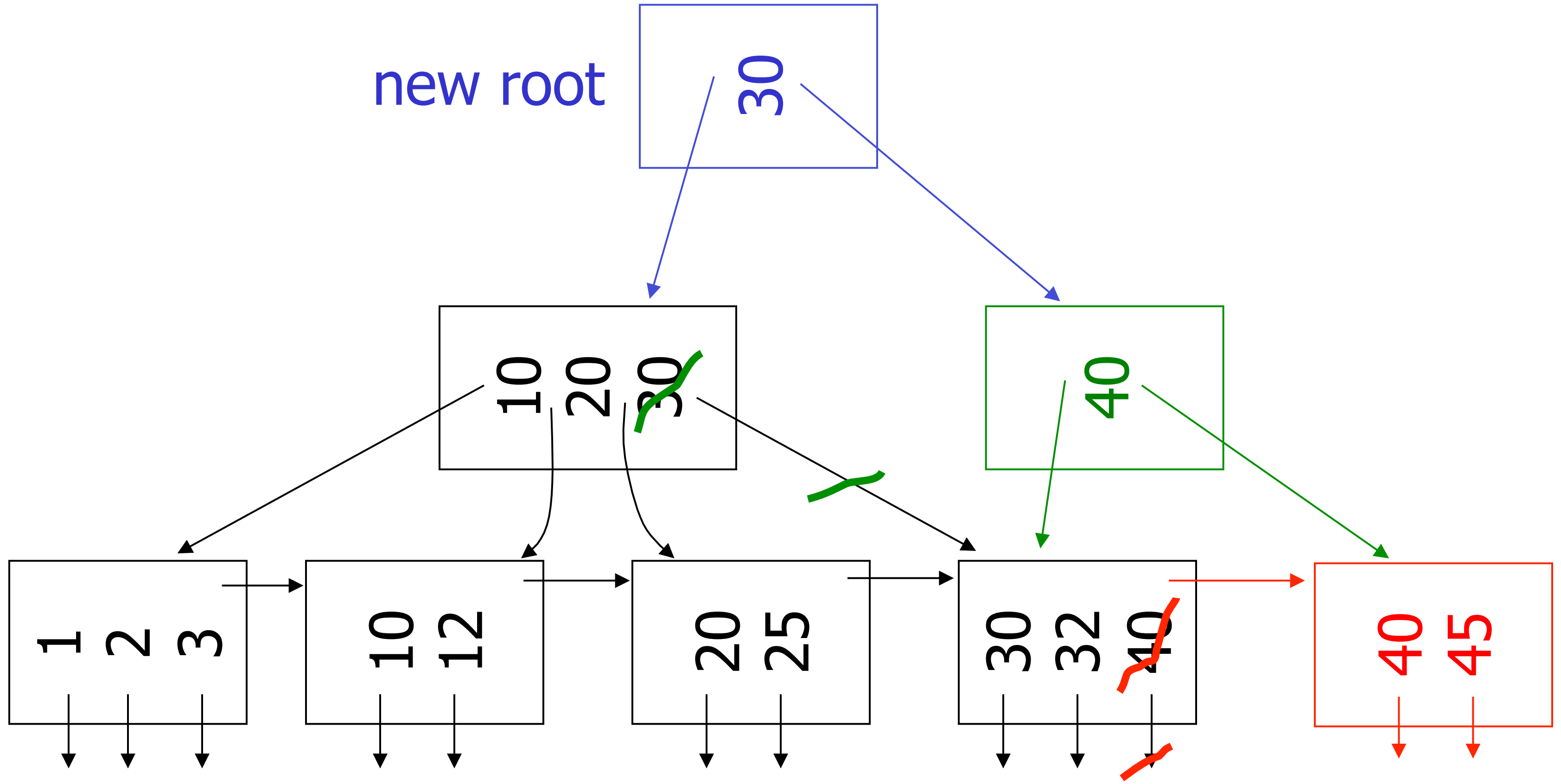


Insertion Algorithm

- Insert Record with key **k**
- Search leaf node for **k**
  - Leaf node has at least one space
    - Insert into leaf
  - Leaf is full
    - Split leaf into two nodes (new leaf)
    - Insert new leaf's smallest key into parent

Insertion Algorithm cont.

- Non-leaf node is full
  - Split parent
  - Insert median key into parent
- Root is full
  - Split root
  - Create new root with two pointers and single key

- -> B-trees grow at the root

Deletion from B+tree

(a) Simple case - no example

(b) Coalesce with neighbor (sibling)

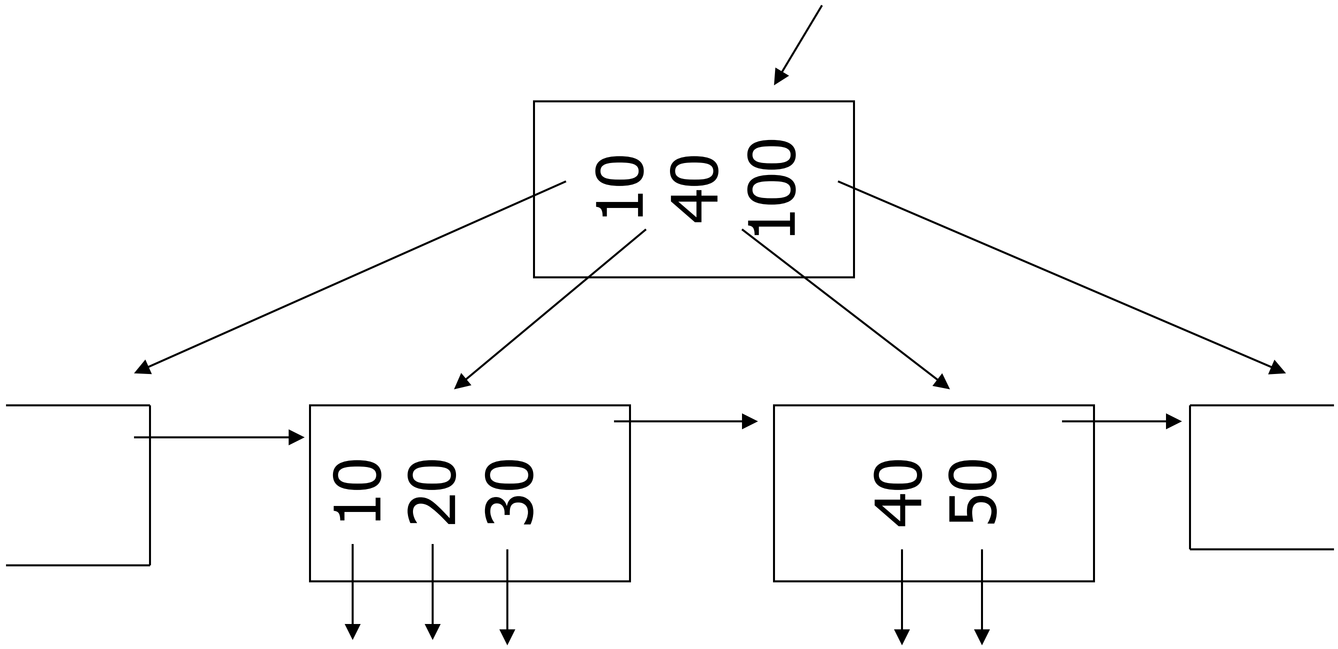
(c) Re-distribute keys

(d) Cases (b) or (c) at non-leaf

(b) Coalesce with sibling

– Delete 50

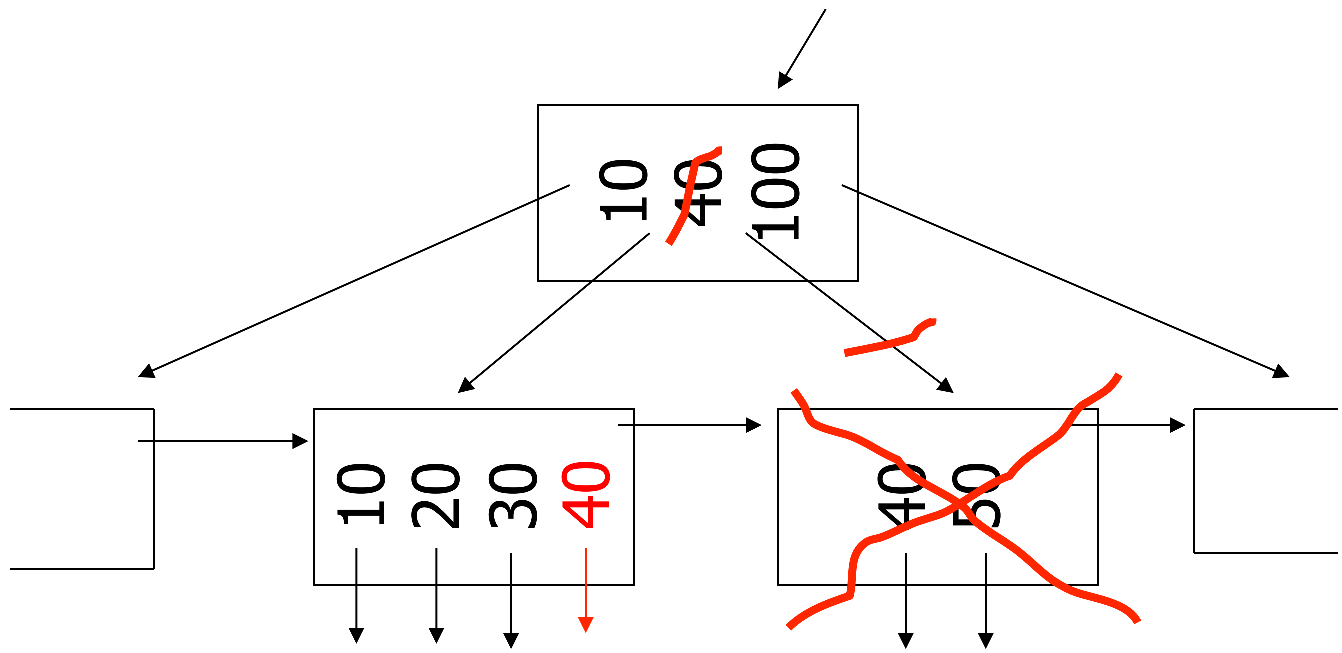
n=4



(b) Coalesce with sibling

– Delete 50

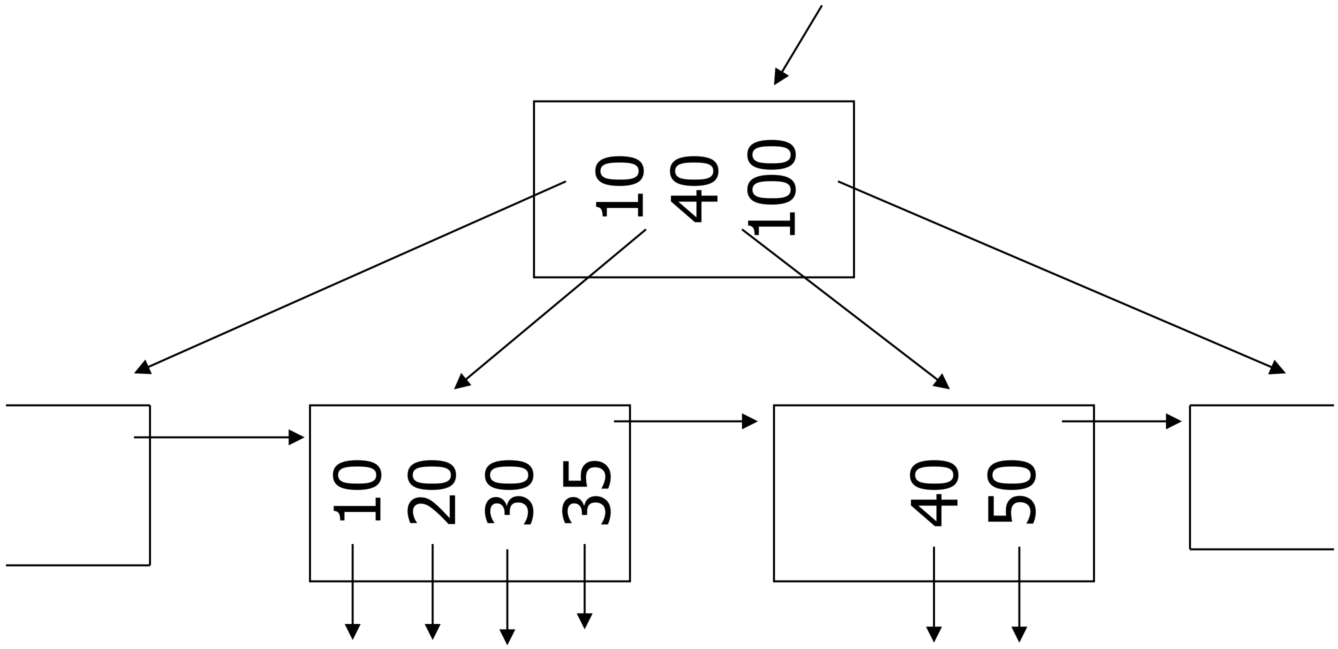
n=4



(c) Redistribute keys

– Delete 50

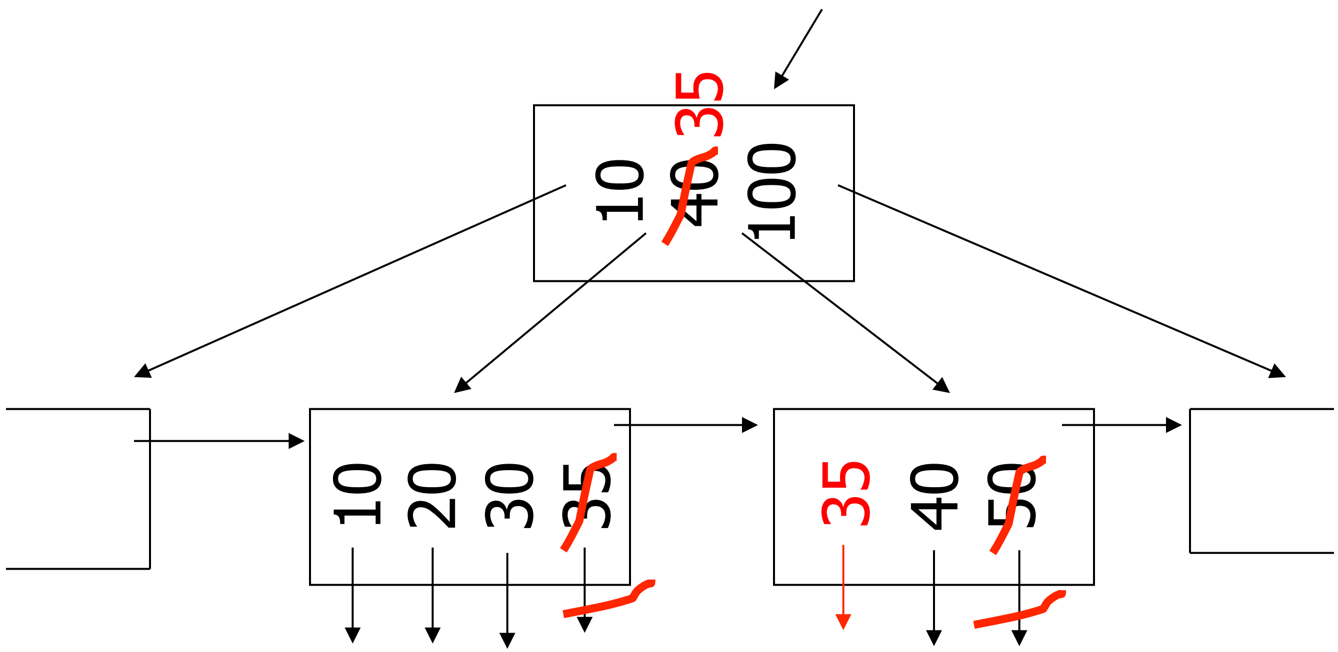
n=4



(c) Redistribute keys

– Delete 50

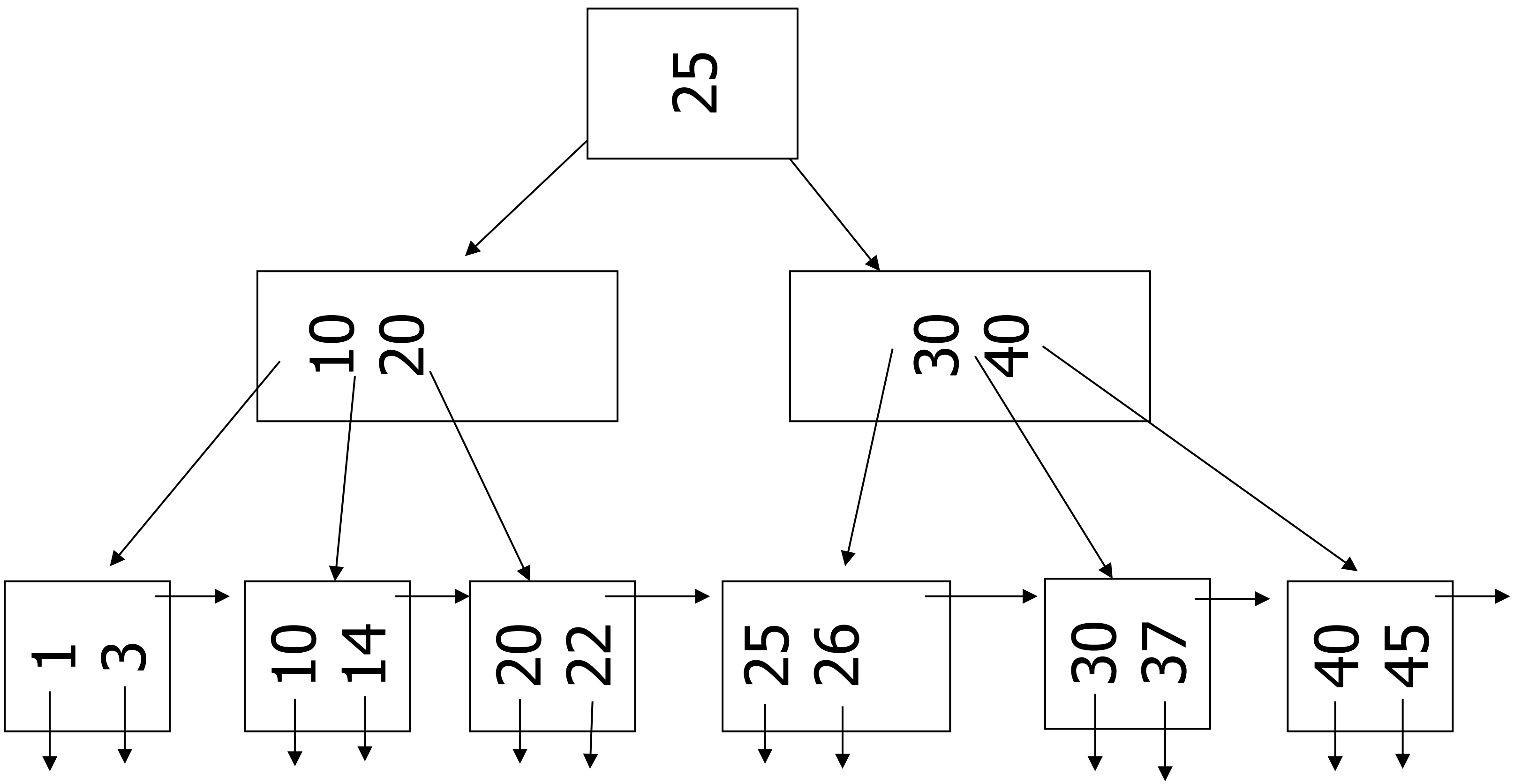
n=4



(d) Non-leaf coalese

– Delete 37

n=4



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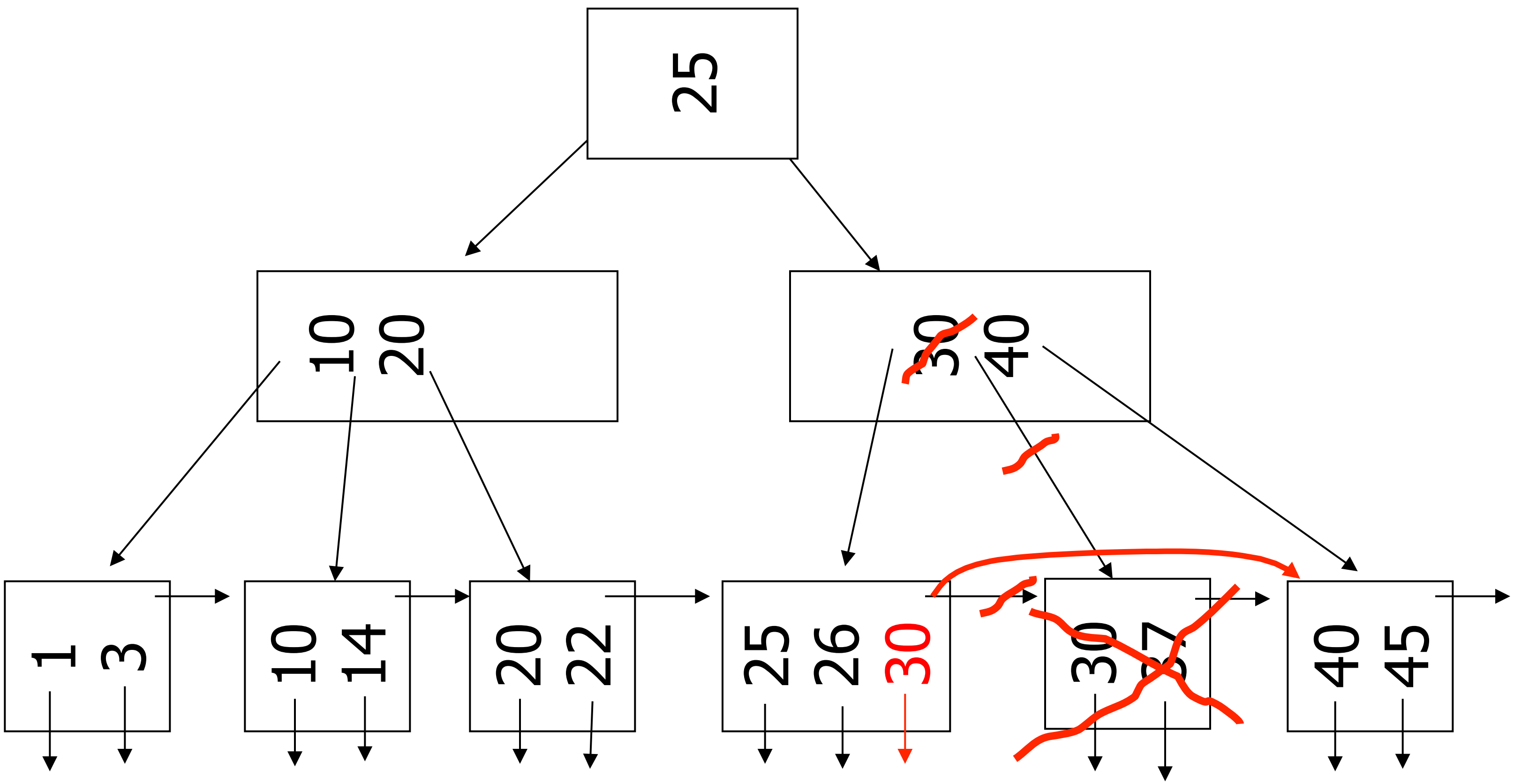
n=4



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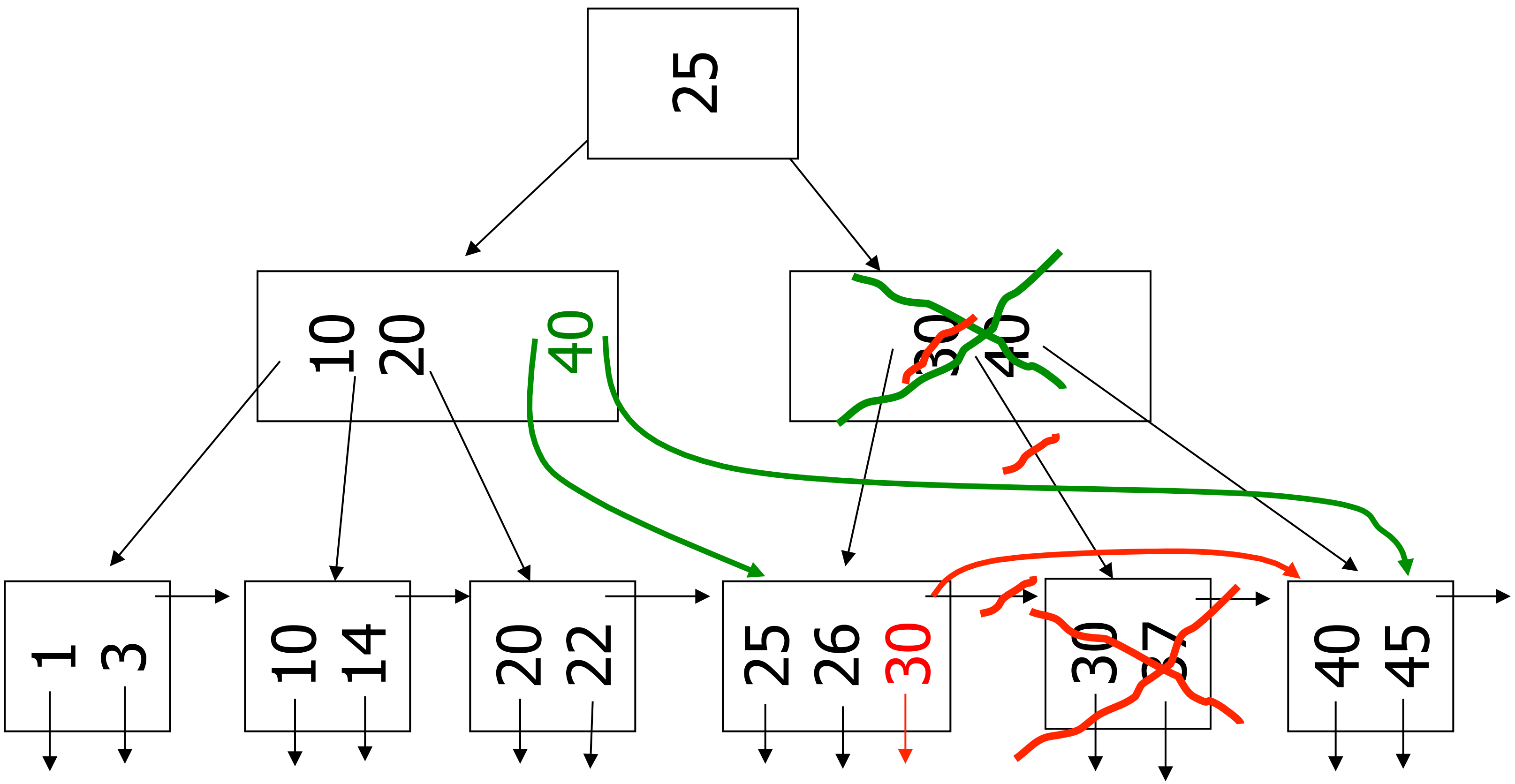
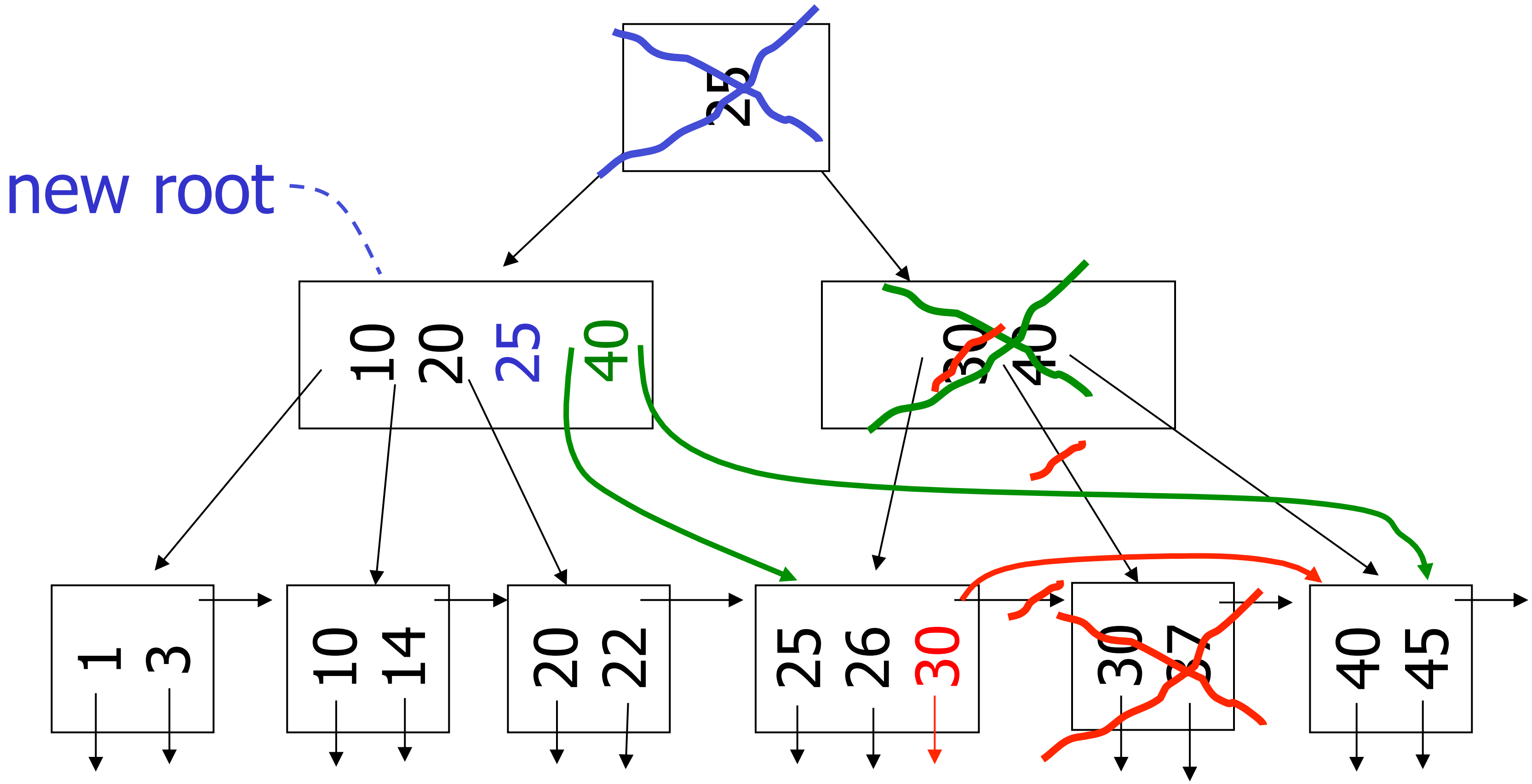
n=4



(d) Non-leaf coalese

– Delete 37

n=4



Deletion Algorithm

- Delete record with key **k**
- Search leaf node for **k**
  - Leaf has more than min entries
    - Remove from leaf
  - Leaf has min entries
    - Try to borrow from sibling
  - One direct sibling has more min entries
    - Move entry from sibling and adapt key in parent

Deletion Algorithm cont.

- Both direct siblings have min entries
  - Merge with one sibling
  - Remove node or sibling from parent
  - ->recursive deletion
- Root has two children that get merged
  - Merged node becomes new root

B+tree deletions in practice

- Often, coalescing is <u>not</u> implemented
  - Too hard and not worth it!
  - Assumption: nodes will fill up in time again

Comparison: B-trees vs. static indexed sequential file

Ref #1: Held & Stonebraker
"B-Trees Re-examined"
CACM, Feb. 1978

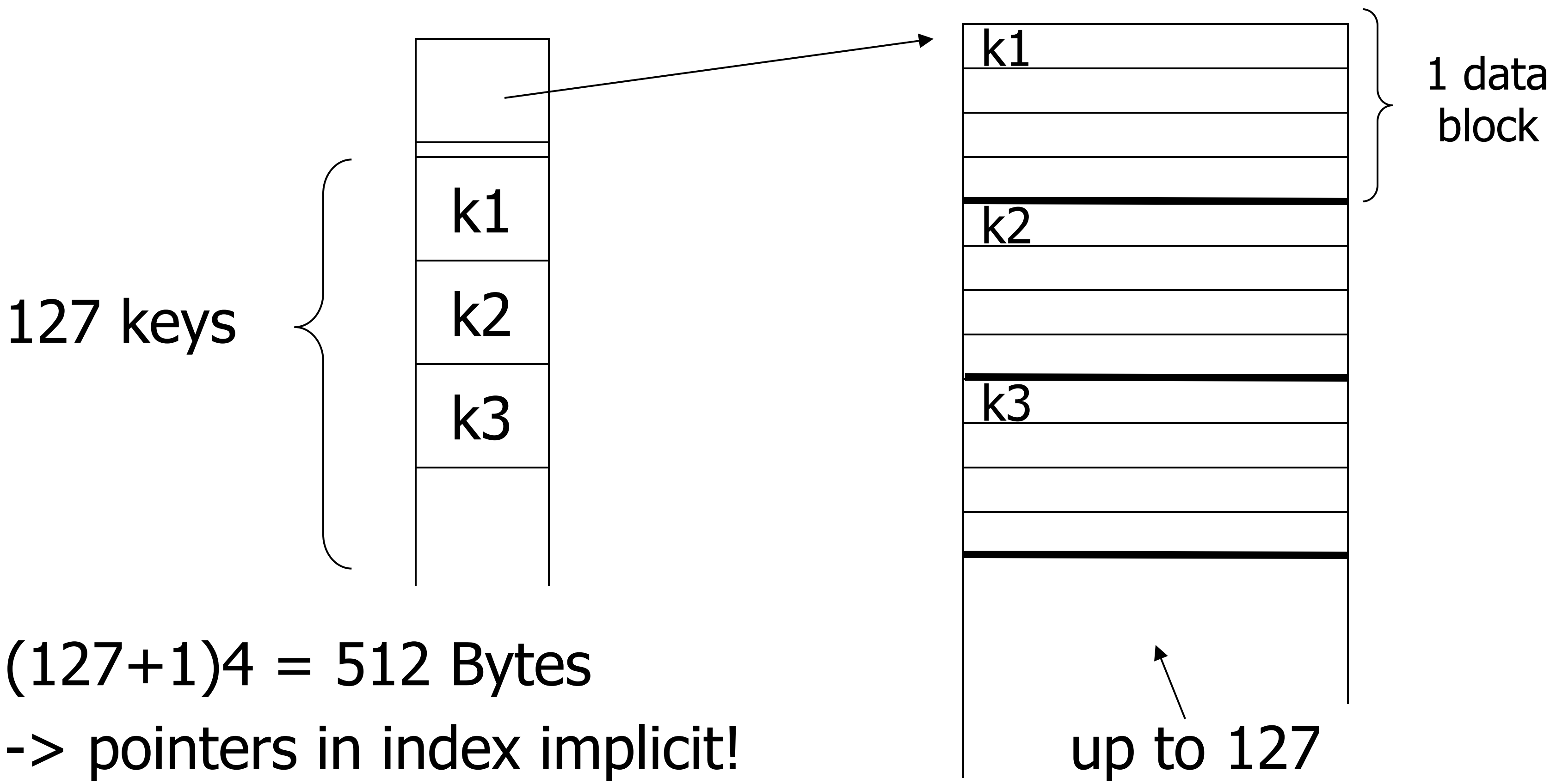
Ref # 1 claims:

- Concurrency control harder in B-Trees
- B-tree consumes more space

For their comparison:

block = 512 bytes
key = pointer = 4 bytes
4 data records per block

Example: 1 block static index

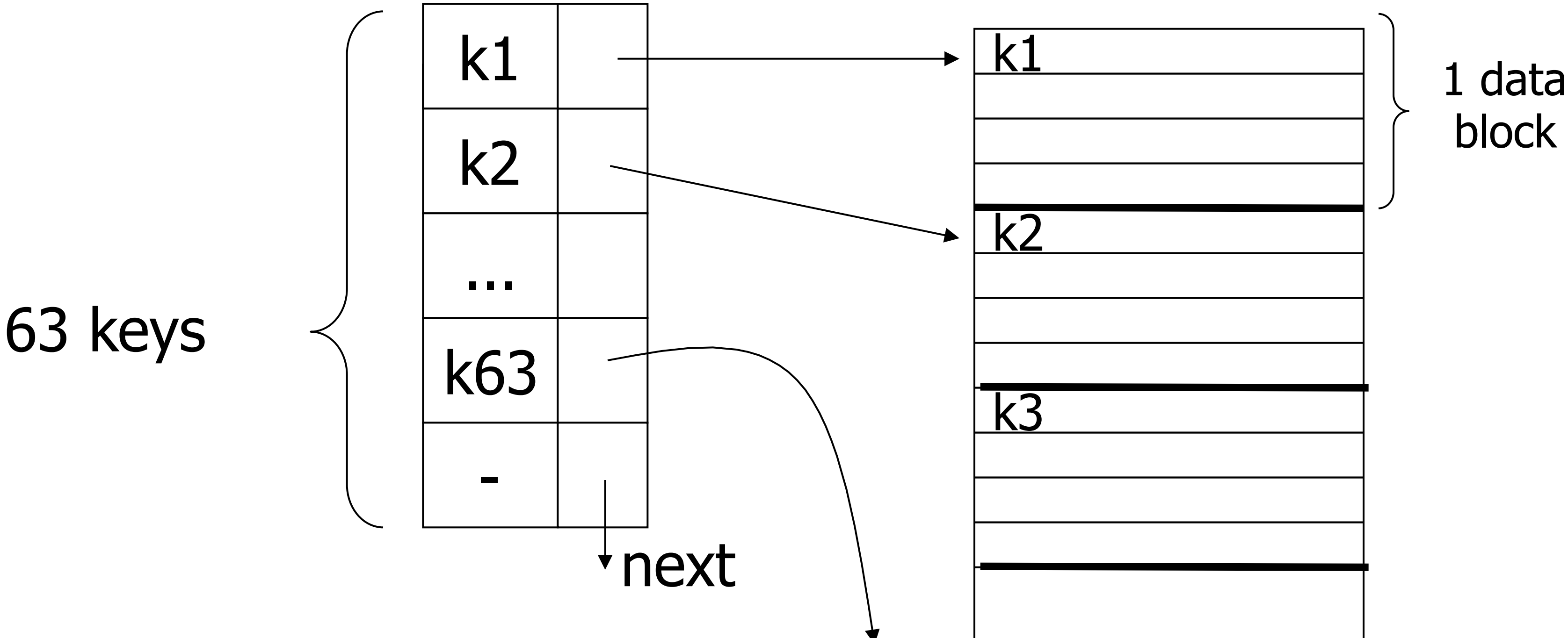


(127+1)4 = 512 Bytes

-> pointers in index implicit!

up to 127 blocks

Example: 1 block B-tree



63x(4+4)+8 = 512 Bytes

-> pointers needed in B-tree blocks because index is not contiguous

up to 63 blocks

Size comparison Ref. #1

Static Index # data blocks	height	B-tree # data blocks	height
2 -> 127	2	2 -> 63	2
128 -> 16,129	3	64 -> 3968	3
16,130 -> 2,048,383	4	3969 -> 250,047	4
		250,048 -> 15,752,961	5

Ref. #1 analysis claims

- For an 8,000 block file,

  after 32,000 inserts

  after 16,000 lookups

  ⇒ Static index saves enough accesses to allow for reorganization

Ref. #1 analysis claims

- For an 8,000 block file,
  - after 32,000 inserts
  - after 16,000 lookups

$\Rightarrow$ Static index saves enough accesses to allow for reorganization

Ref. #1 conclusion $\Rightarrow$ Static index better!!

Ref #2: M. Stonebraker, "Retrospective on a database system," TODS, June 1980

Ref. #2 conclusion ⇒ B-trees better!!

Ref. #2 conclusion → B-trees better!!

- DBA does not know <u>when</u> to reorganize
- DBA does not know <u>how full</u> to load pages of new index

Ref. #2 conclusion → B-trees better!!

- Buffering
  - B-tree: has fixed buffer requirements
  - Static index: must read several overflow blocks to be efficient (large & variable size buffers needed for this)

- Speaking of buffering…
  Is LRU a good policy for B+tree buffers?

- Speaking of buffering…

  Is LRU a good policy for B+tree buffers?

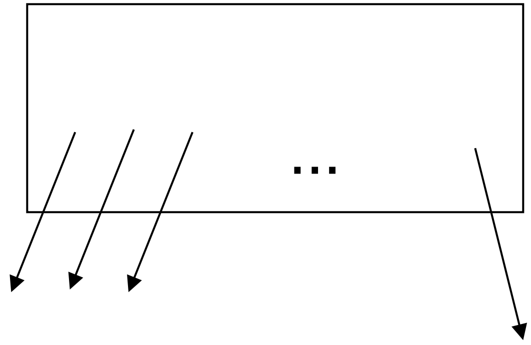
→ Of course not!

→ Should try to keep root in memory at all times

(and perhaps some nodes from second level)

Interesting problem:

For B+tree, how large should *n* be?



n is number of keys / node

Sample assumptions:

(1) Time to read node from disk is
(S+Tn) msec.

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(2) Once block in memory, use binary search to locate key: $(a + b \text{ LOG}_2\ n)$ msec.

For some constants a,b; Assume $a << S$

Sample assumptions:

(1) Time to read node from disk is
($S+Tn$) msec.

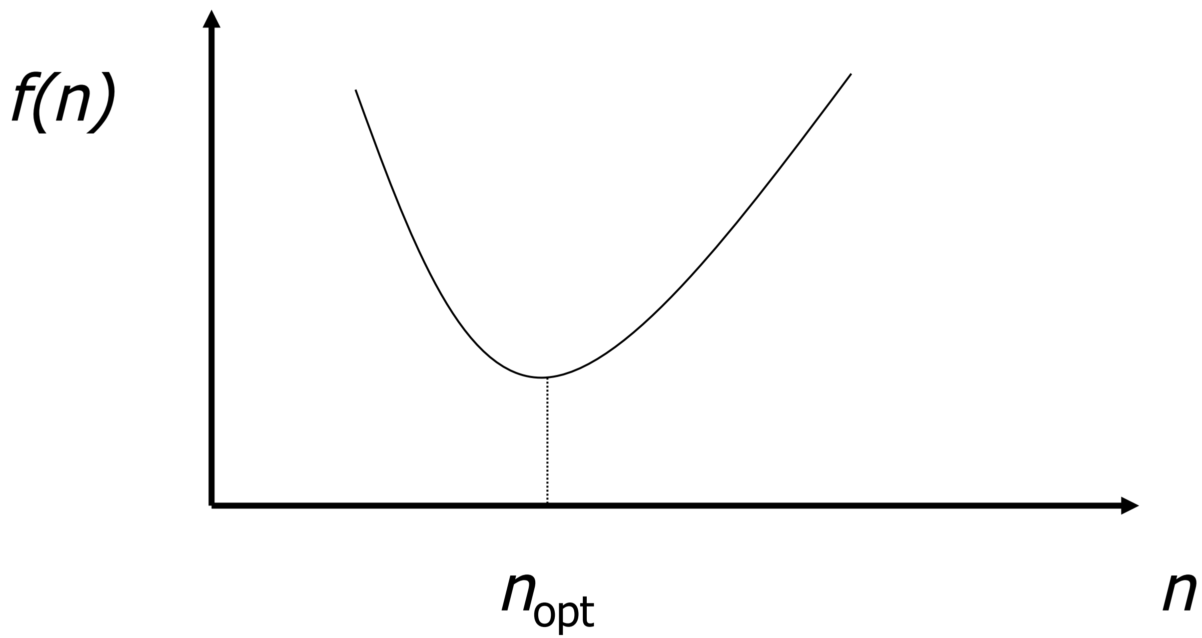
(2) Once block in memory, use binary
search to locate key:
($a + b \text{ LOG}_2\ n$) msec.

For some constants *a,b;* Assume a << S

(3) Assume B+tree is full, i.e.,
nodes to examine is $\text{LOG}_n N$
where N = # records

- Can get:

  $f(n)$ = time to find a record



- FIND n_{opt} by $f'(n) = 0$

  Answer is n_{opt} = "few hundred"

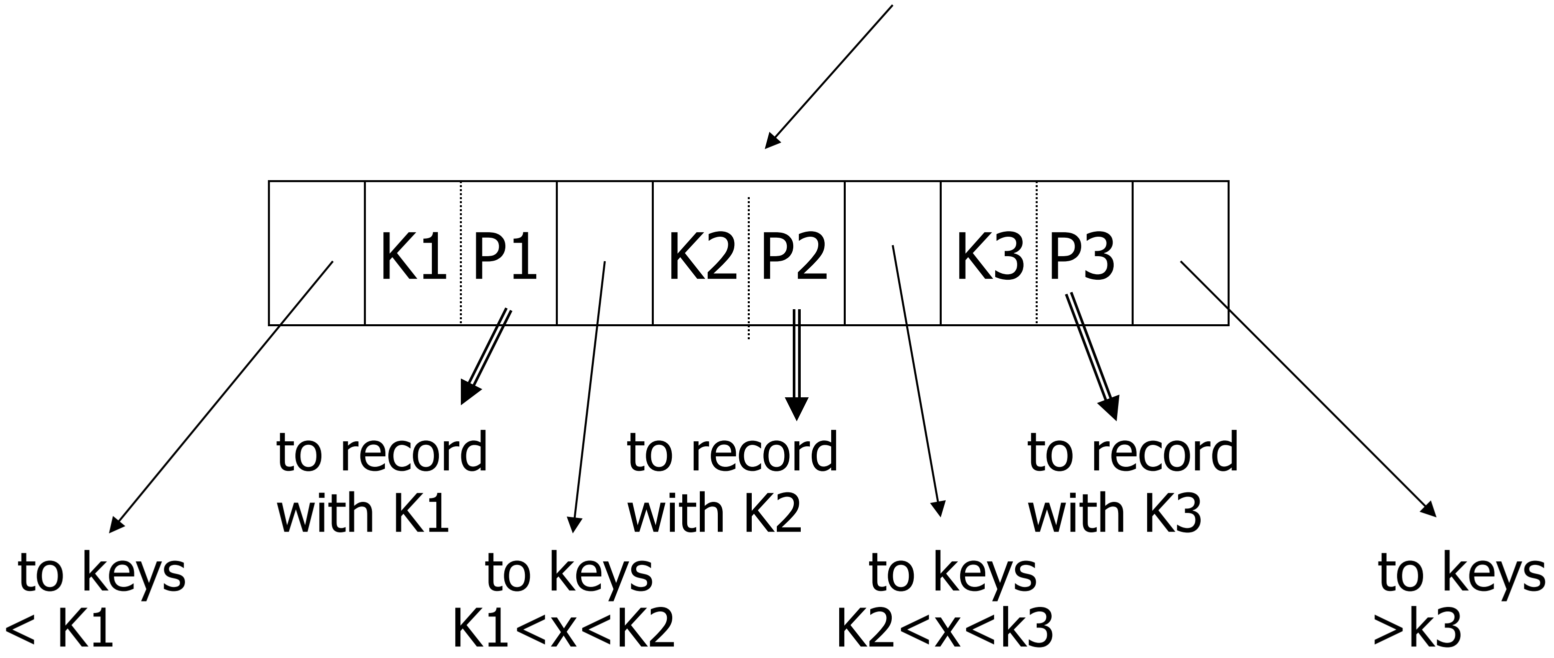
- FIND n_{opt} by $f'(n) = 0$

  Answer is n_{opt} = "few hundred"

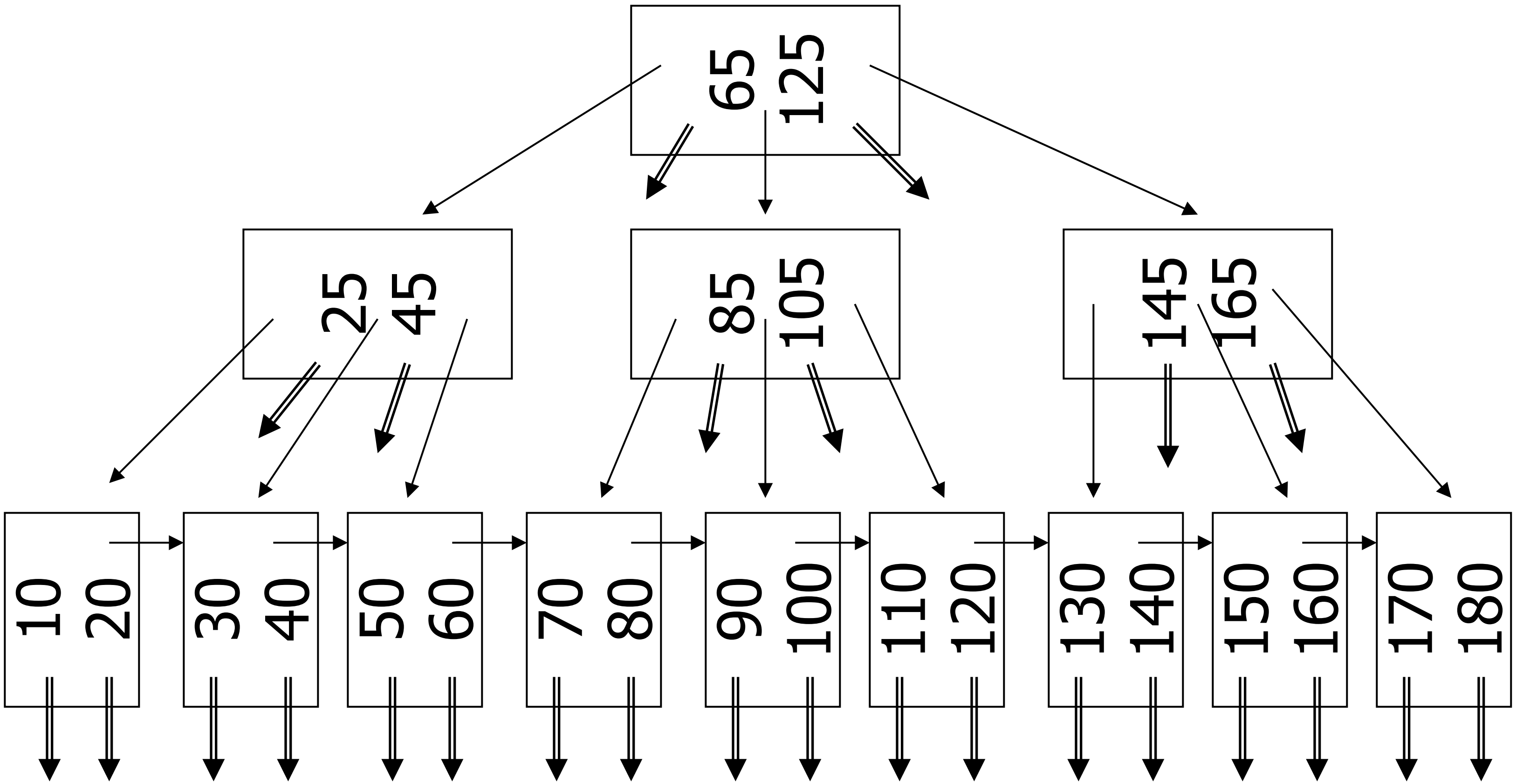
- What happens to n_{opt} as
  - Disk gets faster?
  - CPU get faster?
  - Memory hierarchy?

Variation on B+tree: B-tree (no +)

- Idea:
  - Avoid duplicate keys
  - Have record pointers in non-leaf nodes

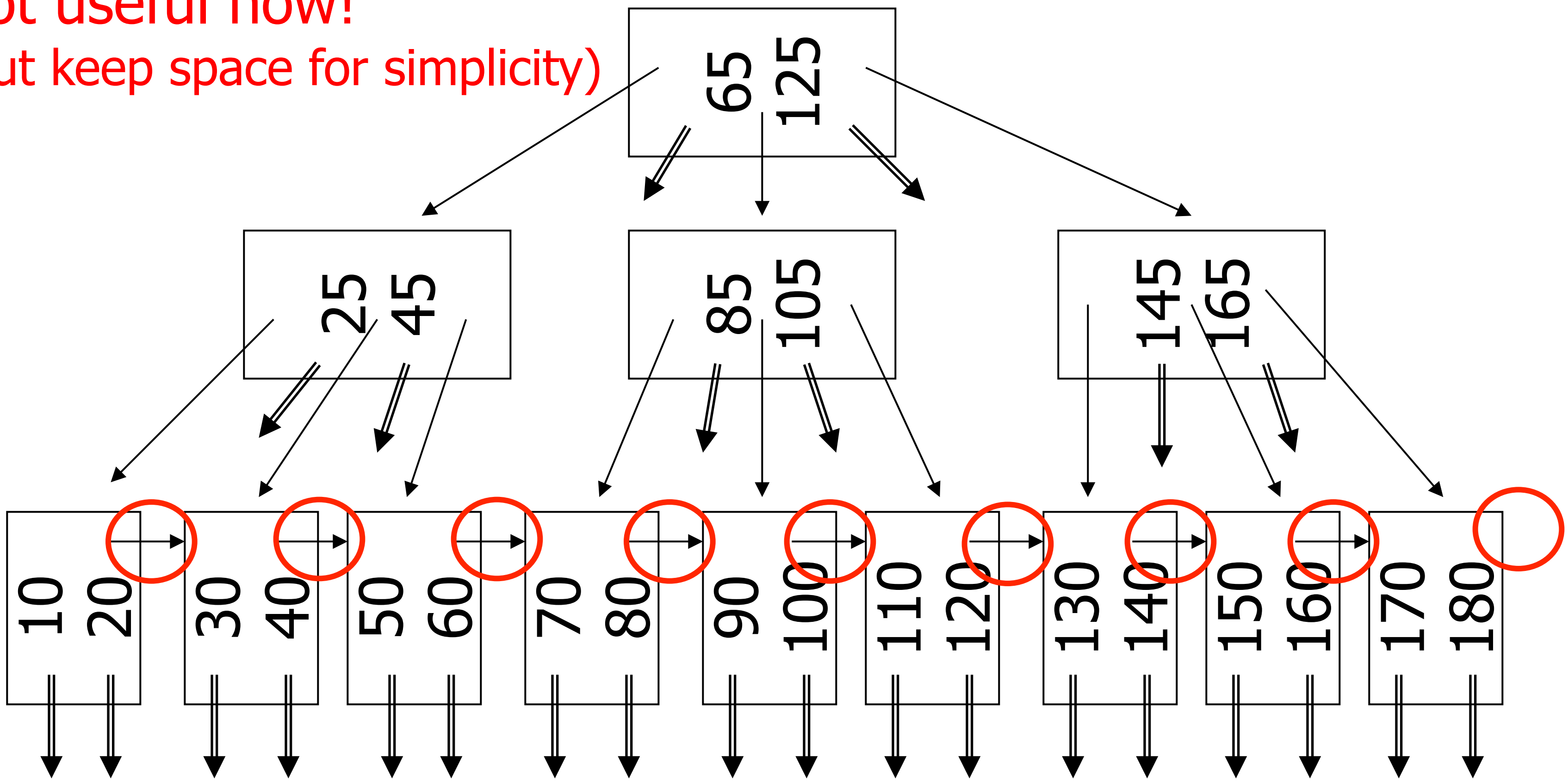

K1 P1
K2 P2
K3 P3
to record
with K1
to record
with K2
to record
with K3
to keys
< K1
to keys
K1<x<K2
to keys
K2<x<k3
to keys
>k3

B-tree example   n=2



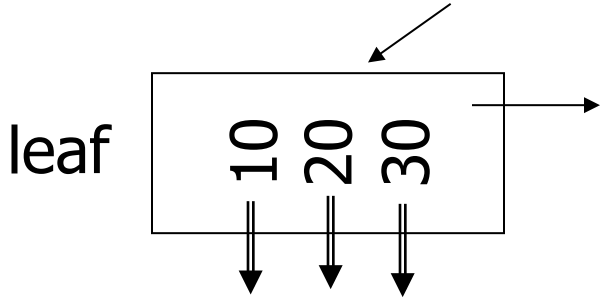
B-tree example n=2

- sequence pointers not useful now!
  (but keep space for simplicity)



Note on inserts

- Say we insert record with key = 25

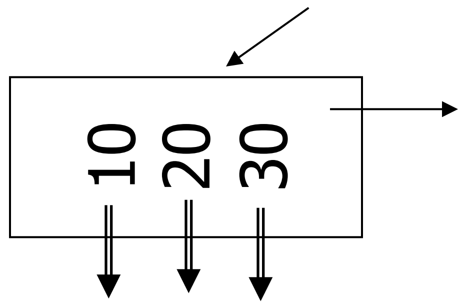


n=3

Note on inserts

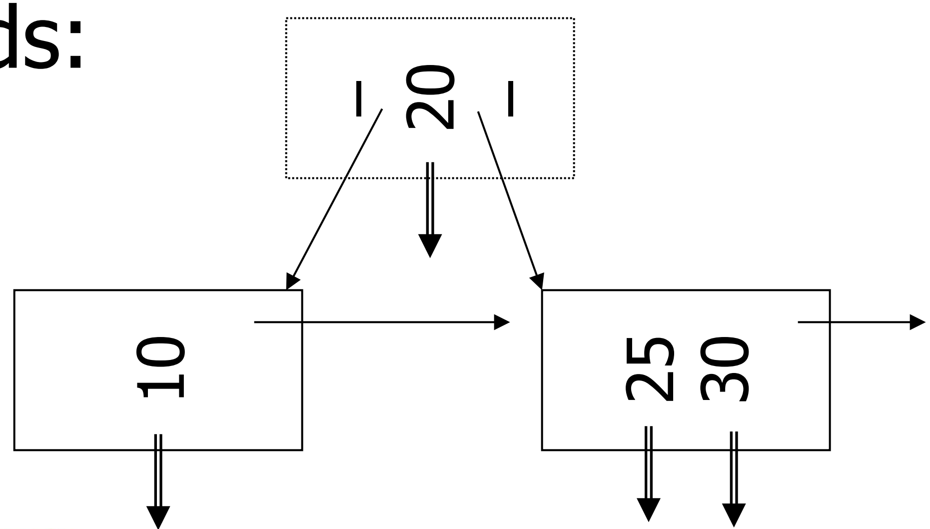
- Say we insert record with key = 25

leaf



n=3

- Afterwards:



So, for B-trees:

	MAX			MIN		
	Tree Ptrs	Rec Ptrs	Keys	Tree Ptrs	Rec Ptrs	Keys
Non-leaf non-root	n+1	n	n	$\lceil(n+1)/2\rceil$	$\lceil(n+1)/2\rceil$-1	$\lceil(n+1)/2\rceil$-1
Leaf non-root	1	n	n	1	$\lfloor n/2\rfloor$	$\lfloor n/2\rfloor$
Root non-leaf	n+1	n	n	2	1	1
Root Leaf	1	n	n	1	1	1

Tradeoffs:

☺ B-trees have faster lookup than B+trees

☹ in B-tree, non-leaf & leaf different sizes

☹ in B-tree, deletion more complicated

Tradeoffs:

☺ B-trees have faster lookup than B+trees

☹ in B-tree, non-leaf & leaf different sizes

☹ in B-tree, deletion more complicated

➨ B+trees preferred!

<u>But note:</u>

- If blocks are fixed size

  (due to disk and buffering restrictions)

  Then lookup for B+tree is
  <u>actually better!!</u>

Example:

- Pointers 4 bytes
- Keys 4 bytes
- Blocks 100 bytes (just example)
- Look at full 2 level tree

B-tree:

Root has 8 keys + 8 record pointers
+ 9 son pointers
= 8x4 + 8x4 + 9x4 = 100 bytes

B-tree:

Root has 8 keys + 8 record pointers
+ 9 son pointers
= 8x4 + 8x4 + 9x4 = 100 bytes

Each of 9 sons: 12 rec. pointers (+12 keys)
= 12x(4+4) + 4 = 100 bytes

B-tree:

Root has 8 keys + 8 record pointers
+ 9 son pointers
= 8x4 + 8x4 + 9x4 = 100 bytes

Each of 9 sons: 12 rec. pointers (+12 keys)
= 12x(4+4) + 4 = 100 bytes

2-level B-tree, Max # records =
12x9 + 8 = 116

B+tree:

Root has 12 keys + 13 son pointers

= 12x4 + 13x4 = 100 bytes

B+tree:

Root has 12 keys + 13 son pointers

= 12x4 + 13x4 = 100 bytes

Each of 13 sons: 12 rec. ptrs (+12 keys)

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B+tree:

Root has 12 keys + 13 son pointers

= 12x4 + 13x4 = 100 bytes

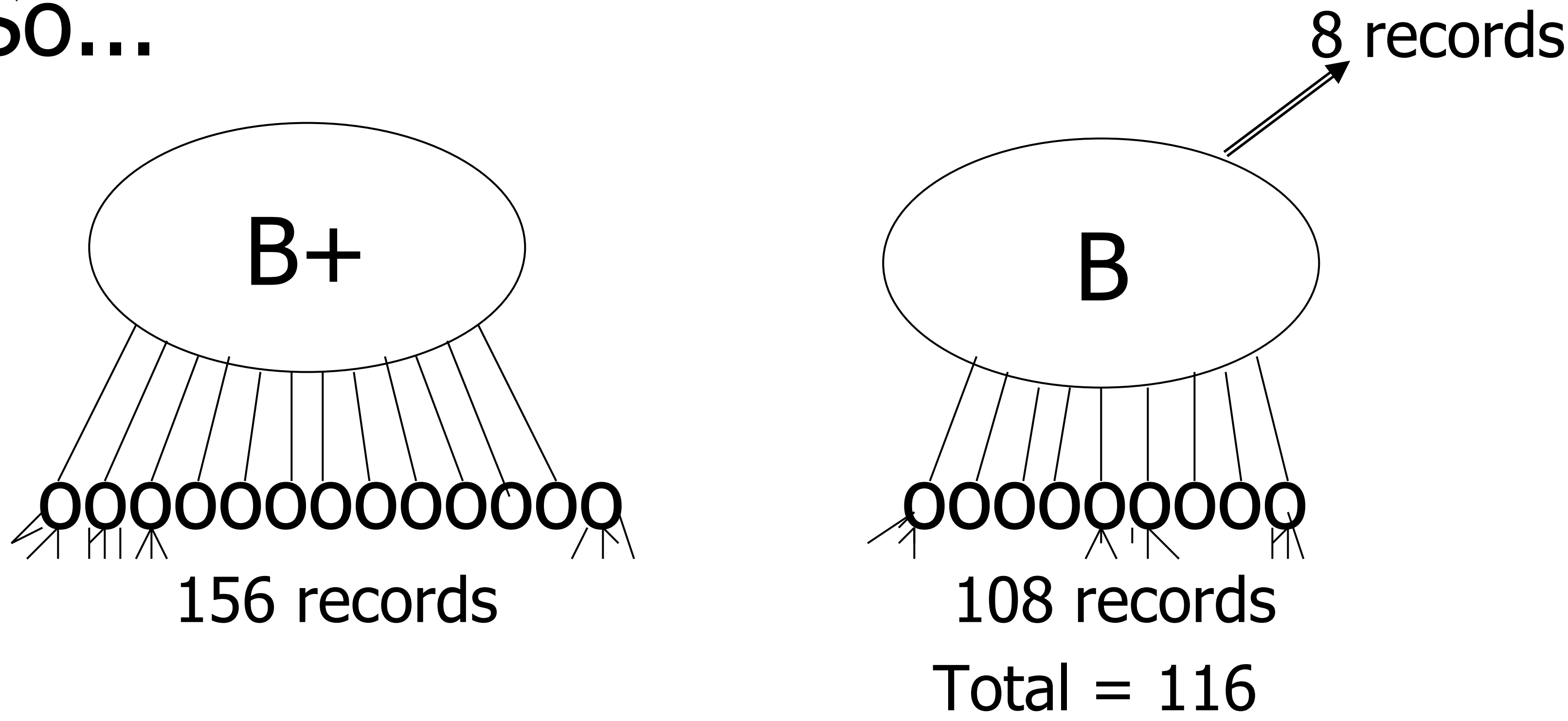
Each of 13 sons: 12 rec. ptrs (+12 keys)

= 12x(4 +4) + 4 = 100 bytes

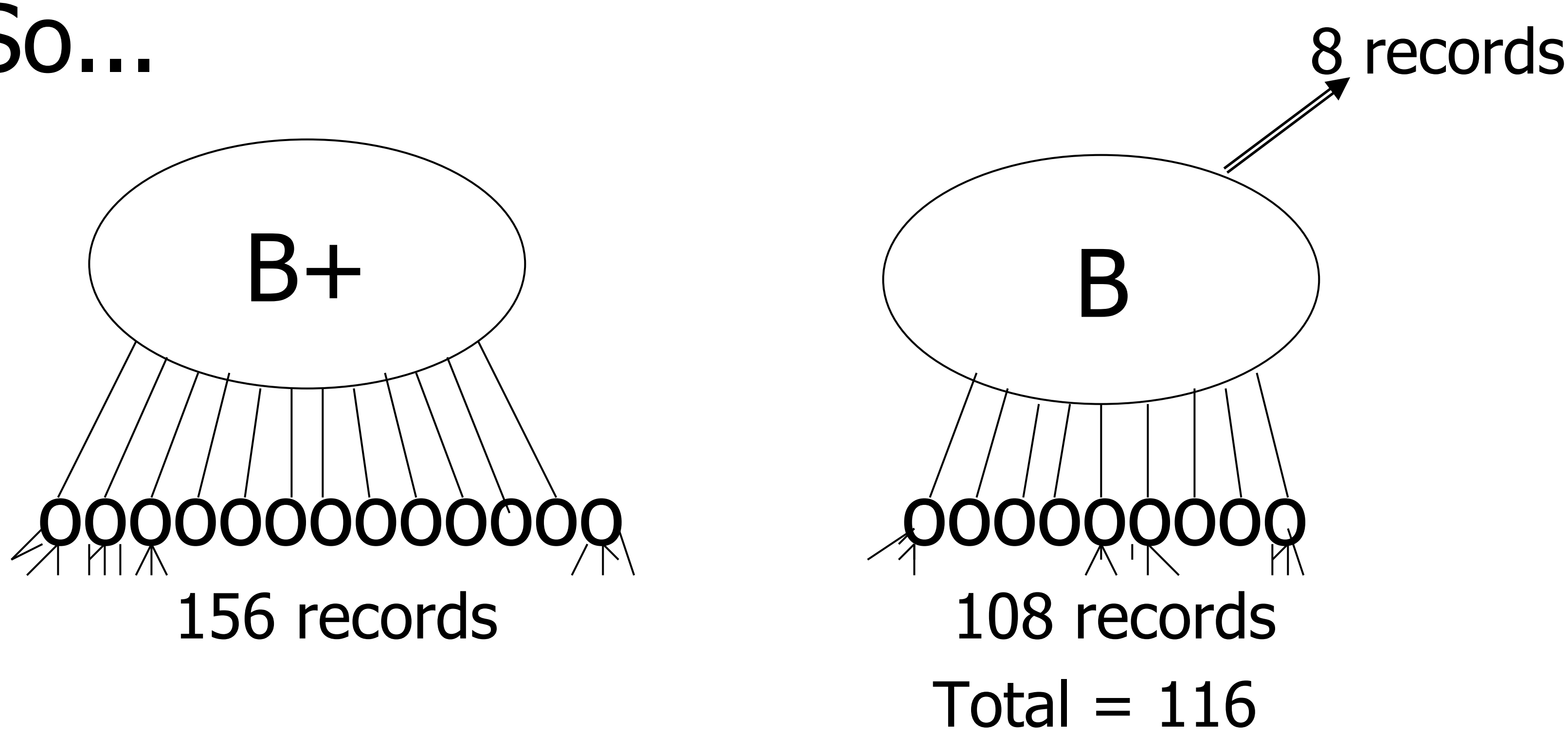
2-level B+tree, Max # records

= 13x12 = 156

So...


8 records
B+
B
oooooooooooooo
ooooooooo
156 records
108 records
Total = 116

So...



- <u>Conclusion:</u>
  - For fixed block size,
  - B+ tree is better because it is <u>bushier</u>

Additional B-tree Variants

- B*-tree
  - Internal notes have to be 2/3 full

An Interesting Problem…

- What is a good index structure when:
  - records tend to be inserted with keys that are larger than existing values?
    (e.g., banking records with growing data/time)
  - we want to remove older data

One Solution: Multiple Indexes

- Example: I1, I2

day	days indexed I1	days indexed I2
10	1,2,3,4,5	6,7,8,9,10
11	11,2,3,4,5	6,7,8,9,10
12	11,12,3,4,5	6,7,8,9,10
13	11,12,13,4,5	6,7,8,9,10

- advantage: deletions/insertions from smaller index
- disadvantage: query multiple indexes

Another Solution (Wave Indexes)

day	I1	I2	I3	I4
10	1,2,3	4,5,6	7,8,9	10
11	1,2,3	4,5,6	7,8,9	10,11
12	1,2,3	4,5,6	7,8,9	10,11, 12
13	13	4,5,6	7,8,9	10,11, 12
14	13,14	4,5,6	7,8,9	10,11, 12
15	13,14,15	4,5,6	7,8,9	10,11, 12
16	13,14,15	16	7,8,9	10,11, 12

- advantage: no deletions
- disadvantage: approximate windows

Concurrent Access To B-trees

- Multiple processes/threads accessing the B-tree
  - Can lead to corruption
- Serialize access to complete tree for updates
  - Simple
  - Unnecessary restrictive
  - Not feasible for high concurrency

Lock Nodes

- One solution
  - **Read** and **exclusive** locks
  - Safe and unsafe updates of nodes
    - **Safe:** No ancestor of node will be effected by update
    - **Unsafe:** Ancestor may be affected
    - Can be determined locally
      - E.g., deletion is safe is node has more than n/2

	Read	Write
Read	X	-
Write	-	-

Lock Nodes

- Reading
  - Use standard search algorithm
  - Hold lock on current node
  - Release when navigating to child
- Writing
  - Lock each node on search for key
  - Release all locks on parents of node if the node is safe

Improvements?

- Try locking only the leaf for update
  - Let update use read locks and only lock leaf node with write lock
  - If leaf node is unsafe then use previous protocol
- Many more locking approaches have been proposed

Outline/summary

- Conventional Indexes
  - Sparse vs. dense
  - Primary vs. secondary
- B trees
  - B+trees vs. B-trees
  - B+trees vs. indexed sequential
- Hashing schemes --> Next
- Advanced Index Techniques