CSE544: Principles of Database Systems

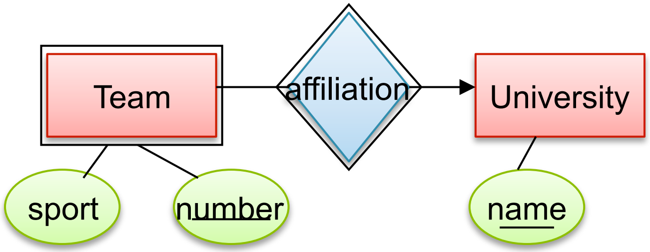
Lectures 3

Storage and Indexes

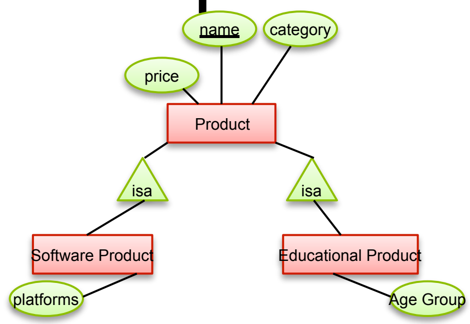
Review of Lecture 2

- What is a many-to-many relationship? What is a many-to-one relationship?

- What is a weak entity set?



- How do we represent IsA relationships in tables?



Review of Lecture 2

- What are *data anomalies?*
- What is a *functional dependency*?
- When is a relation in Boyce-Codd Normal Form?

Where We Are

- Part 1: The relational data model
- Part 2: Database Systems
- Part 3: Transactions
- Part 4: Miscellaneous

Outline

- Storage and Indexes
  – Book: Ch. 8-11, and 20
- Pax paper

The Mechanics of Disk

Mechanical characteristics:

- Rotation speed (5400RPM)
- Number of platters (1-30)
- Number of tracks (<=10000)
- Number of bytes/track(10^5)

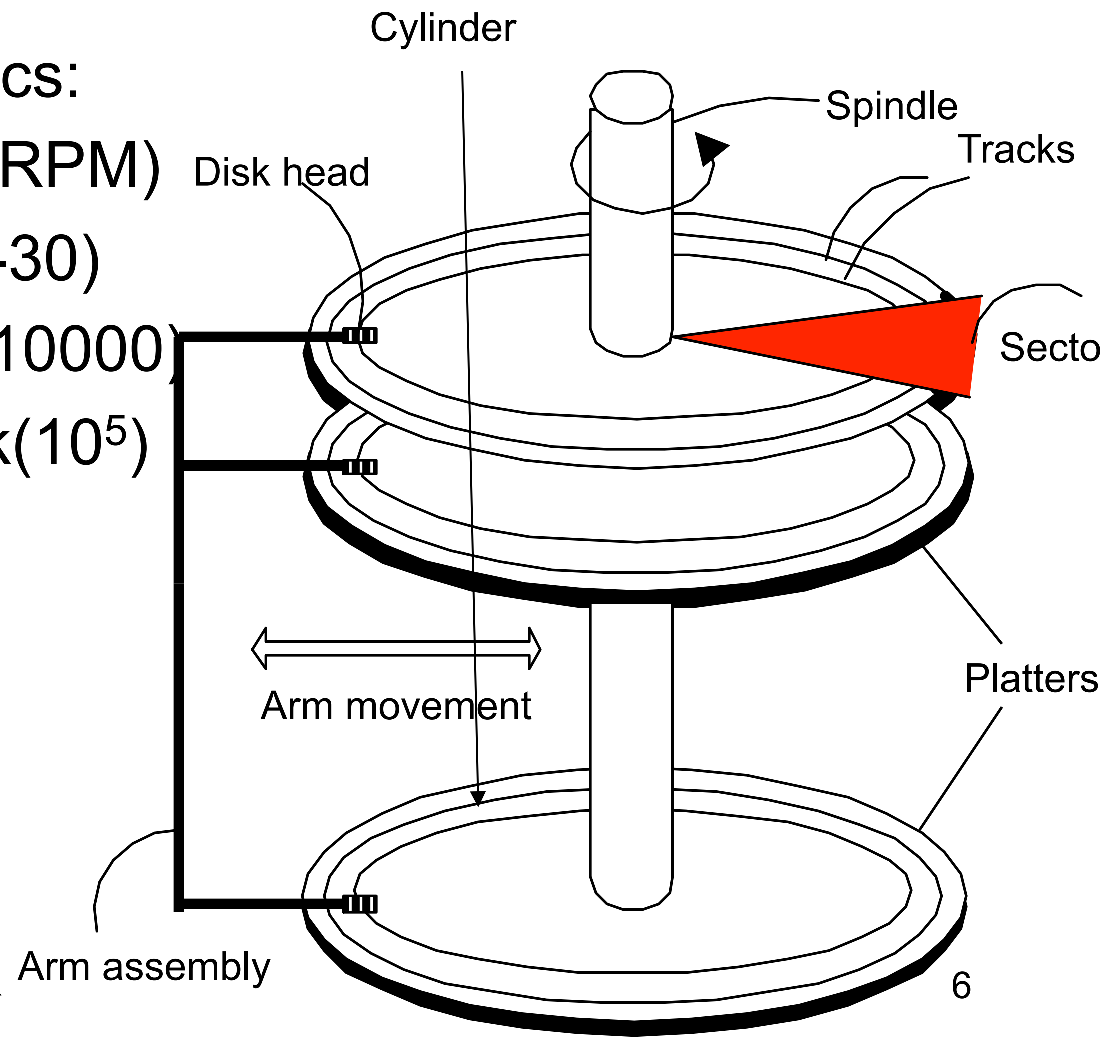
Unit of read or write:

disk block

Once in memory:

page

Typically: 4k or 8k or 16k



Disk Access Characteristics

- Disk latency
  - Time between when command is issued and when data is in memory
  - Equals = seek time + rotational latency
- Seek time = time for the head to reach cylinder
  - 10ms – 40ms
- Rotational latency = time for the sector to rotate
    - Rotation time = 10ms
    - Average latency = 10ms/2
- Transfer time = typically 40MB/s

Basic factoid: disks always read/write an entire block at a time

RAID

Several disks that work in parallel

- Redundancy: use parity to recover from disk failure
- Speed: read from several disks at once

Various configurations (called *levels*):

- RAID 1 = mirror
- RAID 4 = n disks + 1 parity disk
- RAID 5 = n+1 disks, assign parity blocks round robin
- RAID 6 = “Hamming codes”

Storage Model

- DBMS needs spatial and temporal control over storage
  - Spatial control for performance
  - Temporal control for correctness and performance

- For spatial control, two alternatives
  - Use "raw" disk device interface directly
  - Use OS files

Spatial Control
Using “Raw” Disk Device Interface

- **Overview**
  - DBMS issues low-level storage requests directly to disk device
- **Advantages**
  - DBMS can ensure that important queries access data sequentially
  - Can provide highest performance
- **Disadvantages**
  - Requires devoting entire disks to the DBMS
  - Reduces portability as low-level disk interfaces are OS specific
  - Many devices are in fact “virtual disk devices”

Spatial Control Using OS Files

- **Overview**
  - DBMS creates one or more very large OS files
- **Advantages**
  - Allocating large file on empty disk can yield good physical locality
- **Disadvantages**
  - OS can limit file size to a single disk
  - OS can limit the number of open file descriptors
  - But these drawbacks have mostly been overcome by modern OSs

Commercial Systems

- Most commercial systems offer both alternatives
  - Raw device interface for peak performance
  - OS files more commonly used

- In both cases, we end-up with a DBMS file abstraction implemented on top of OS files or raw device interface

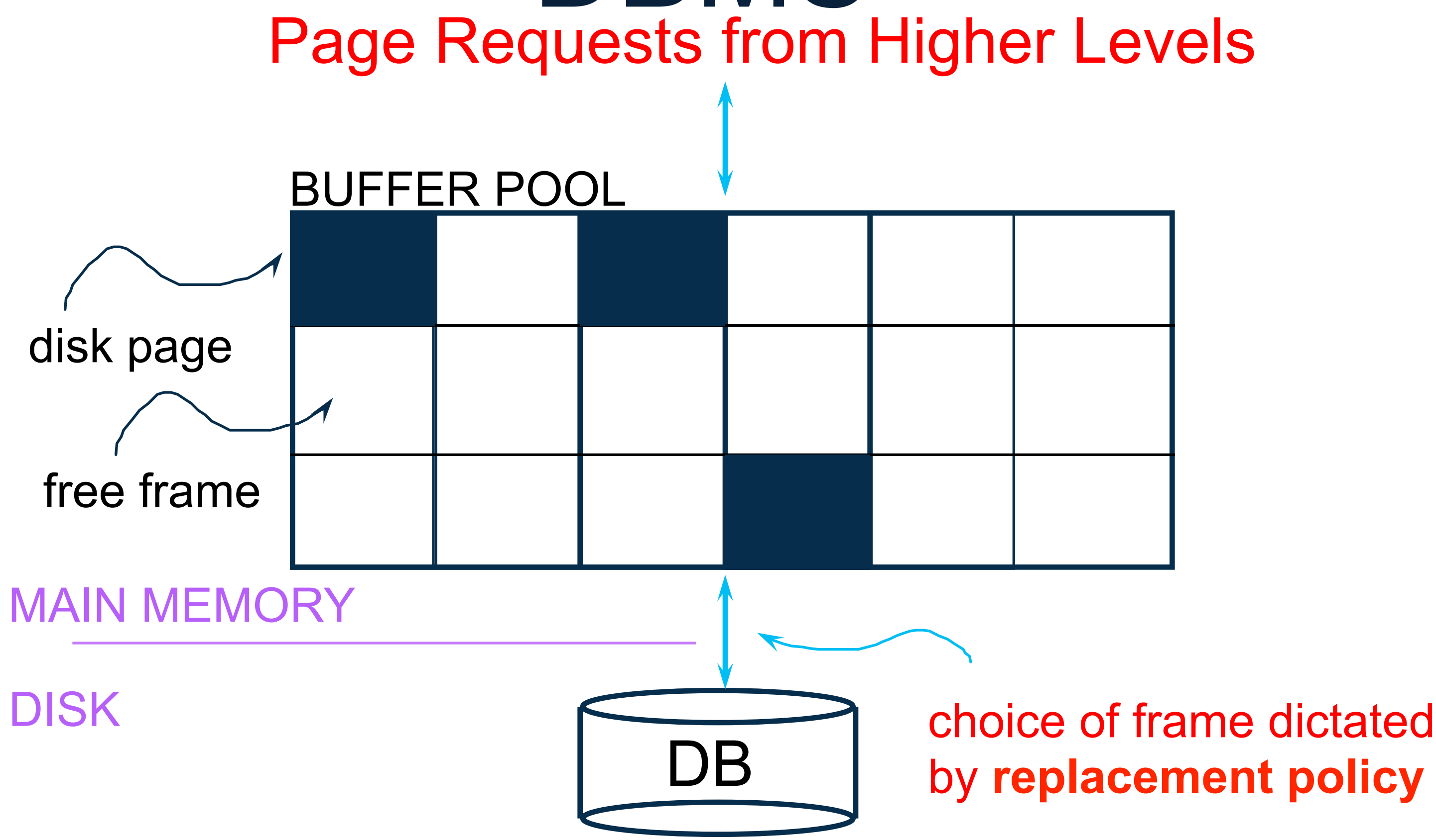
File Types

The data file can be one of:

- Heap file
  - Set of records, partitioned into blocks
  - Unsorted
- Sequential file
  - Sorted according to some attribute(s) called *key*

Note: “key” here means something else than “primary key”

Buffer Management in a DBMS



- Data must be in RAM for DBMS to operate on it!
- Table of <frame#, pageid> pairs is maintained

Buffer Manager

Needs to decide on page replacement policy

- LRU
- Clock algorithm

Both work well in OS, but not always in DB

Enables the higher levels of the DBMS to assume that the needed data is in main memory.

Arranging Pages on Disk

A disk is organized into blocks (a.k.a. pages)

- blocks on same track, followed by
- blocks on same cylinder, followed by
- blocks on adjacent cylinder

A file should (ideally) consists of sequential blocks on disk, to minimize seek and rotational delay.

For a sequential scan, pre-fetching several pages at a time is a big win!

Issues

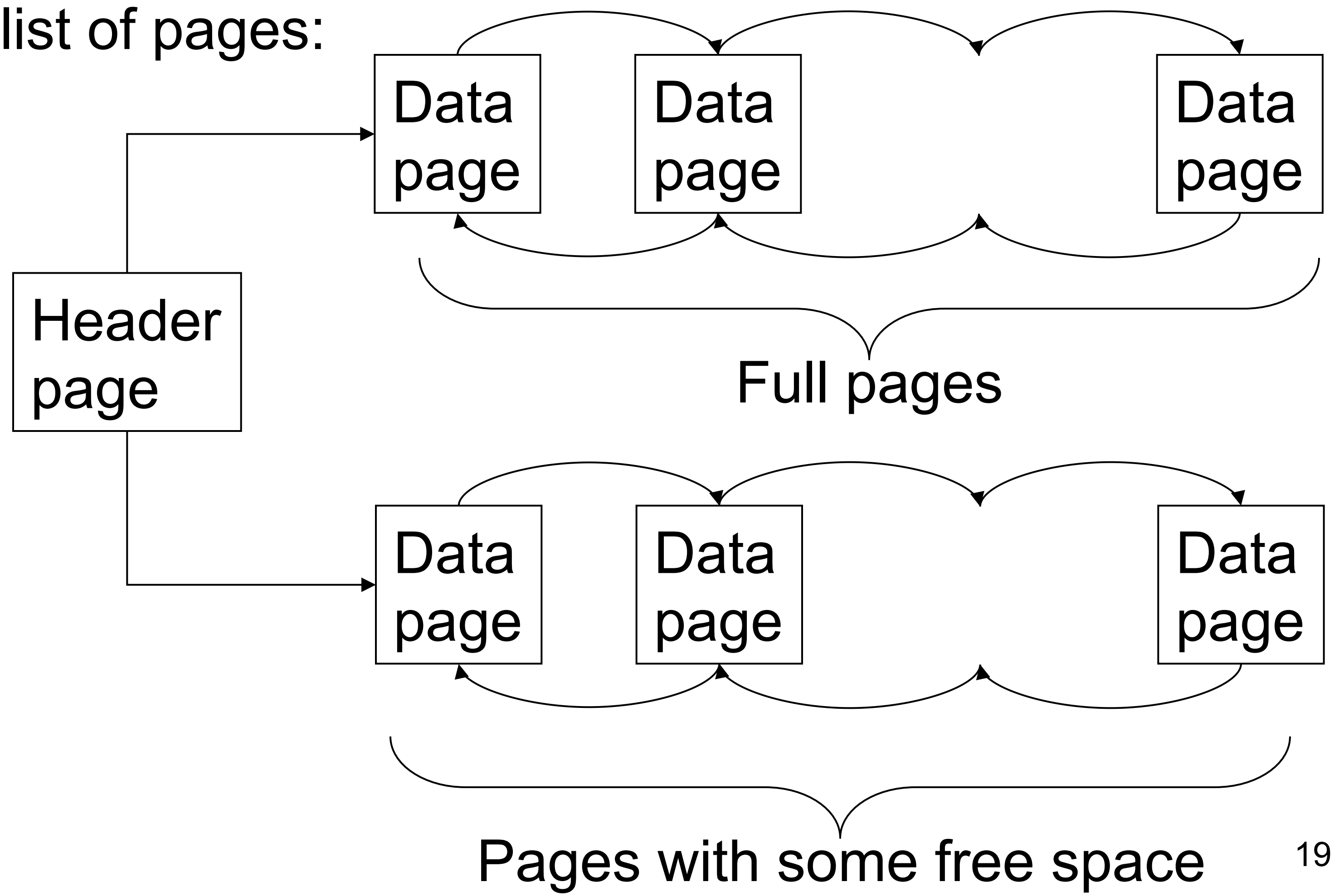
- Managing free blocks
- File Organization
- Represent the records inside the blocks
- Represent attributes inside the records

Managing Free Blocks

- Linked list of free blocks
- Or bit map

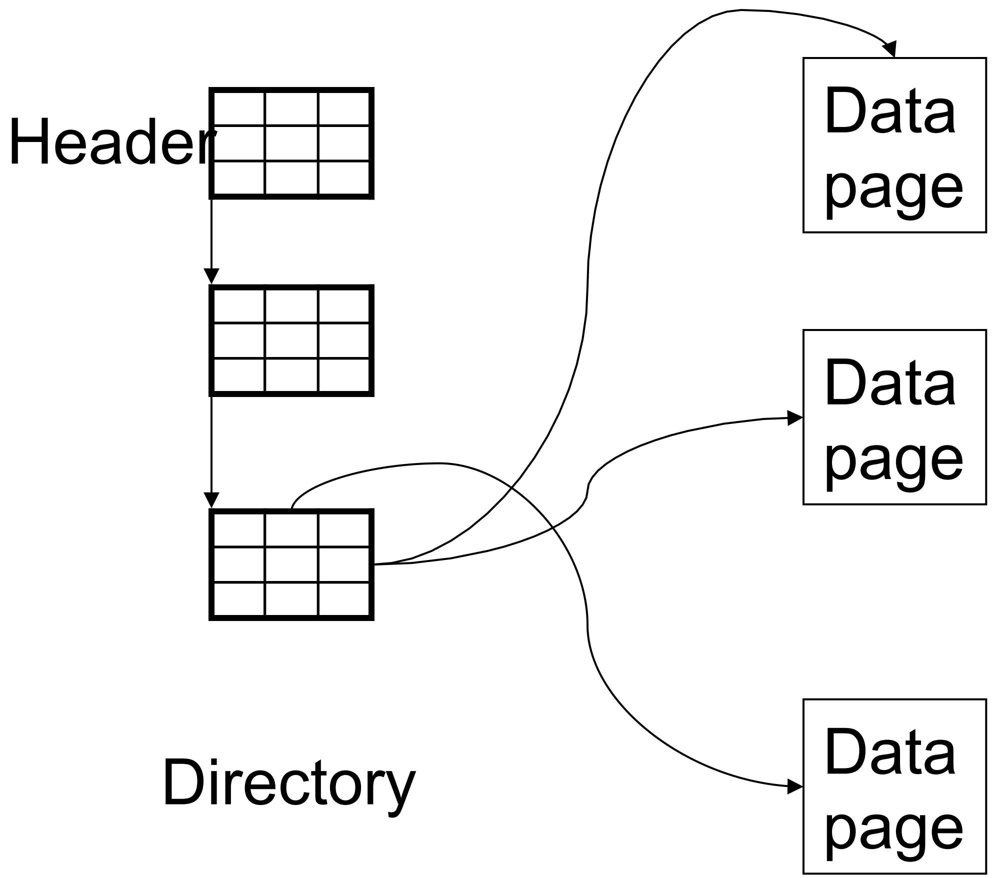
File Organization

Linked list of pages:



File Organization

Better: directory of pages



Page Formats

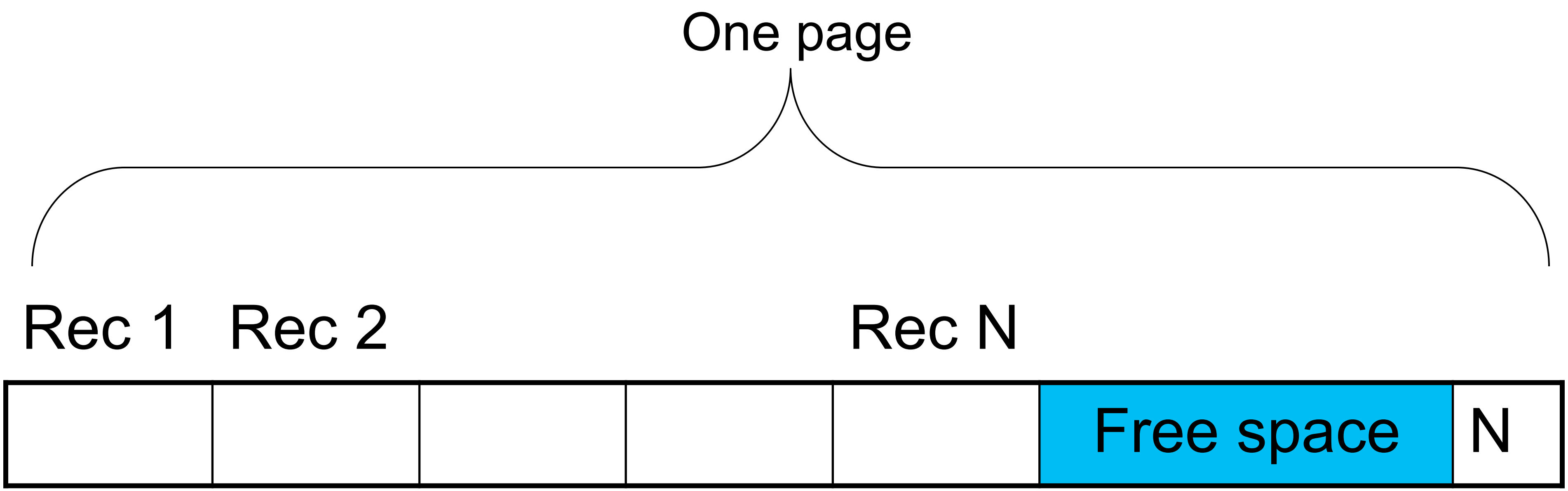
Issues to consider

- 1 page = fixed size (e.g. 8KB)
- Records:
  - Fixed length
  - Variable length
- Record id = RID
  - Typically RID = (PageID, SlotNumber)

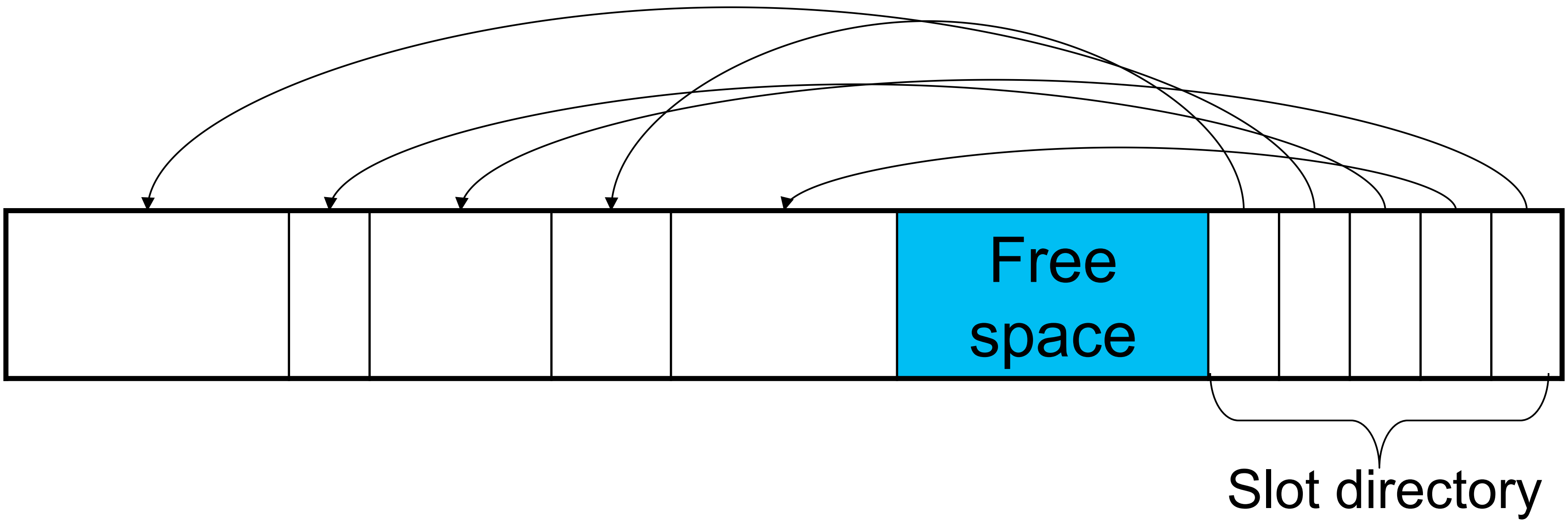
Why do we need RID's in a relational DBMS ?

Page Formats

Fixed-length records: packed representation



Page Formats



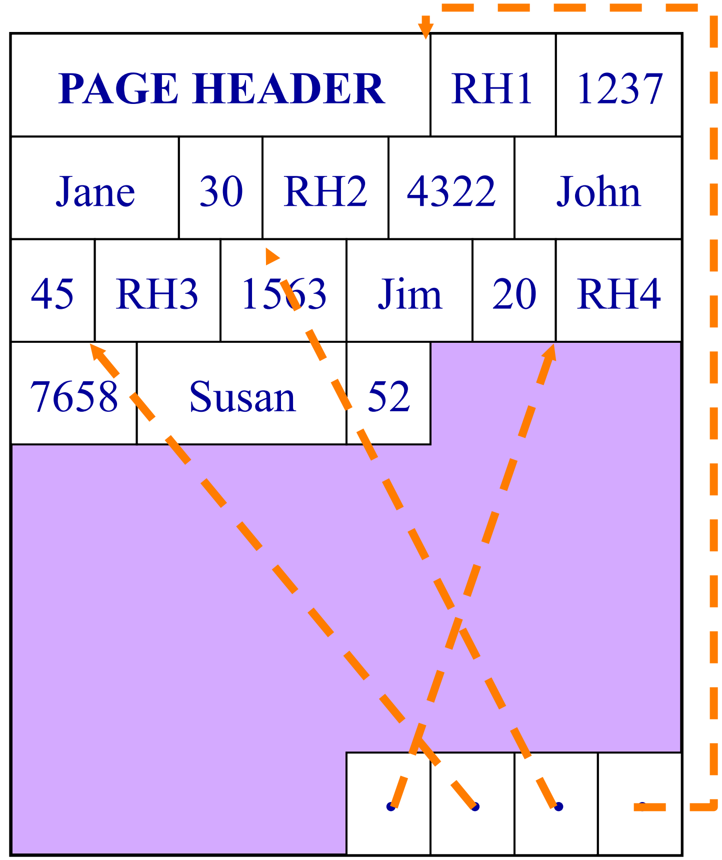
Variable-length records

Current Scheme: Slotted Pages

Formal name: NSM (N-ary Storage Model)

R

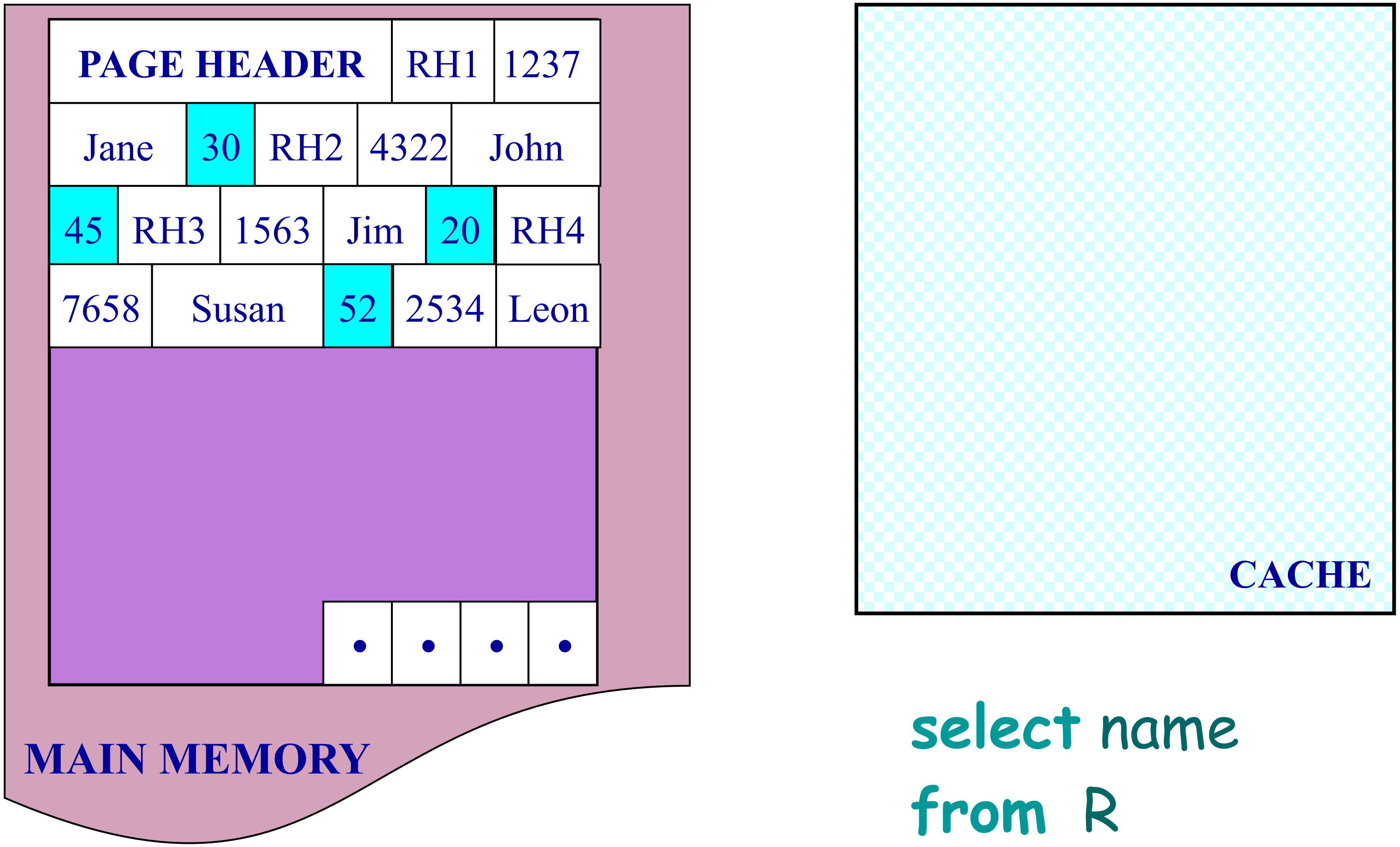
RID	SSN	Name	Age
1	1237	Jane	30
2	4322	John	45
3	1563	Jim	20
4	7658	Susan	52
5	2534	Leon	43
6	8791	Dan	37



- Records are stored sequentially
- Offsets to start of each record at end of page

Ailamaki VLDB'01 http://research.cs.wisc.edu/multifacet/papers/vldb01_pax_talk.ppt

Predicate Evaluation using NSM



select name
from R
where age > 50

NSM pushes non-referenced data to the cache

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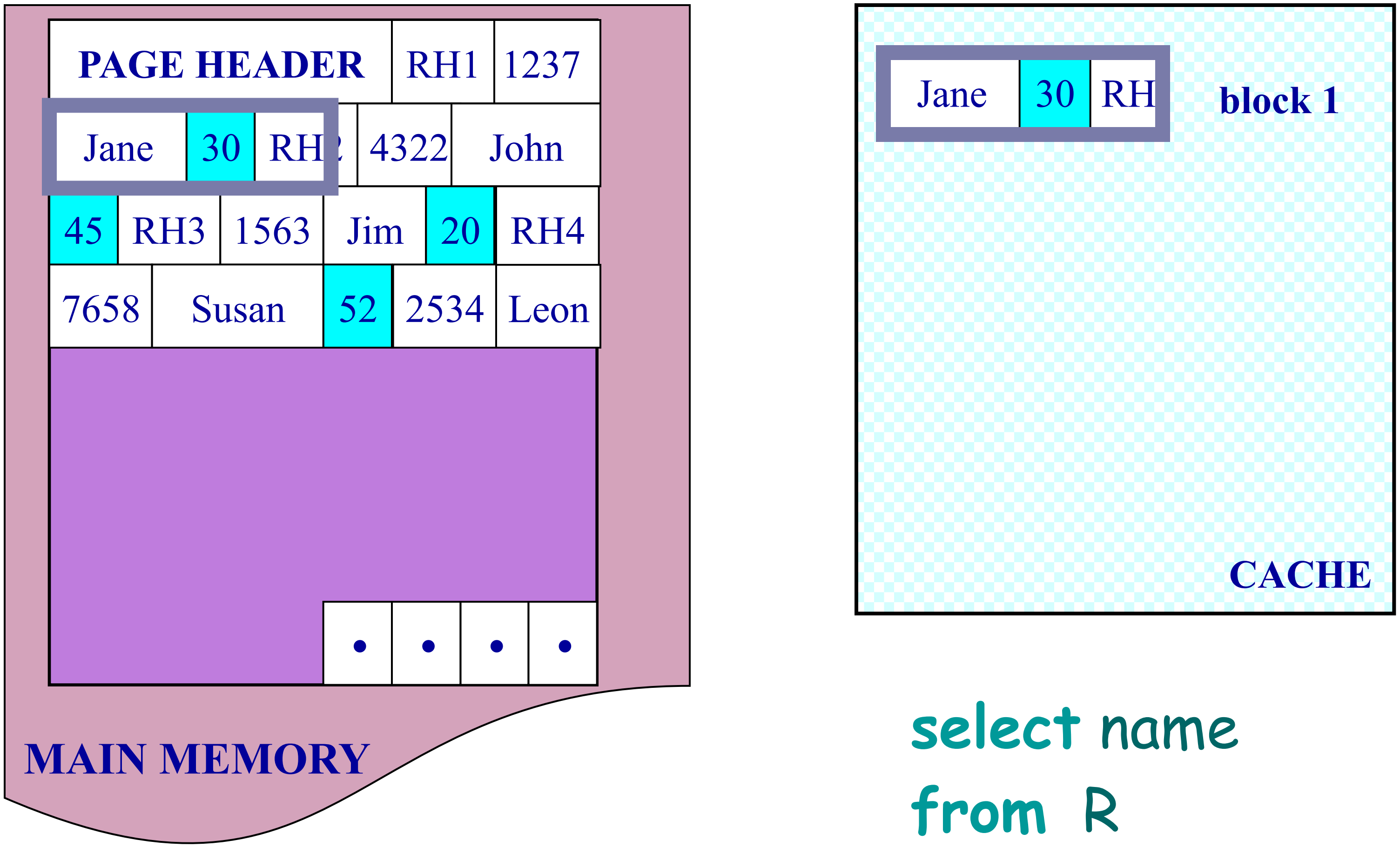

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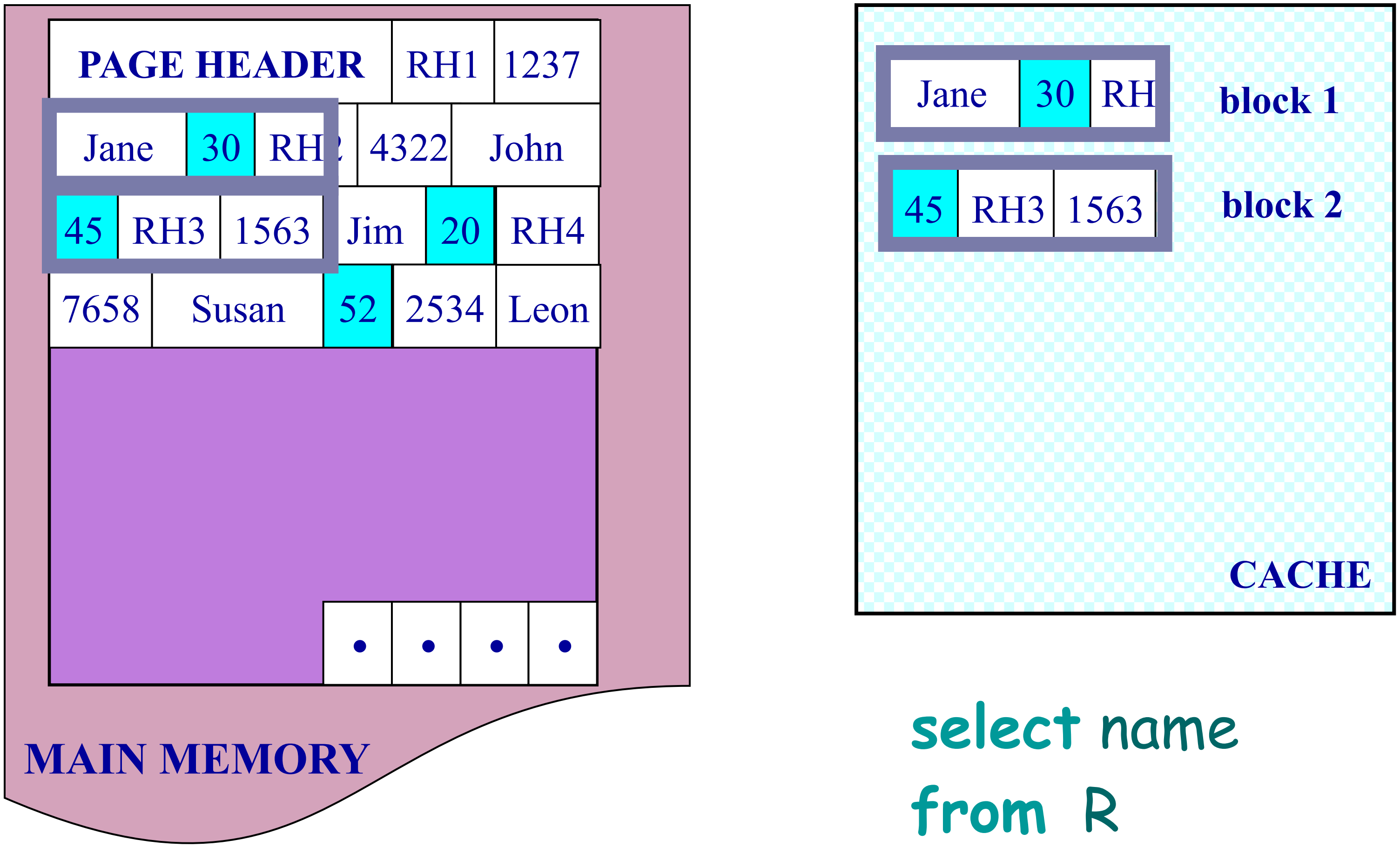

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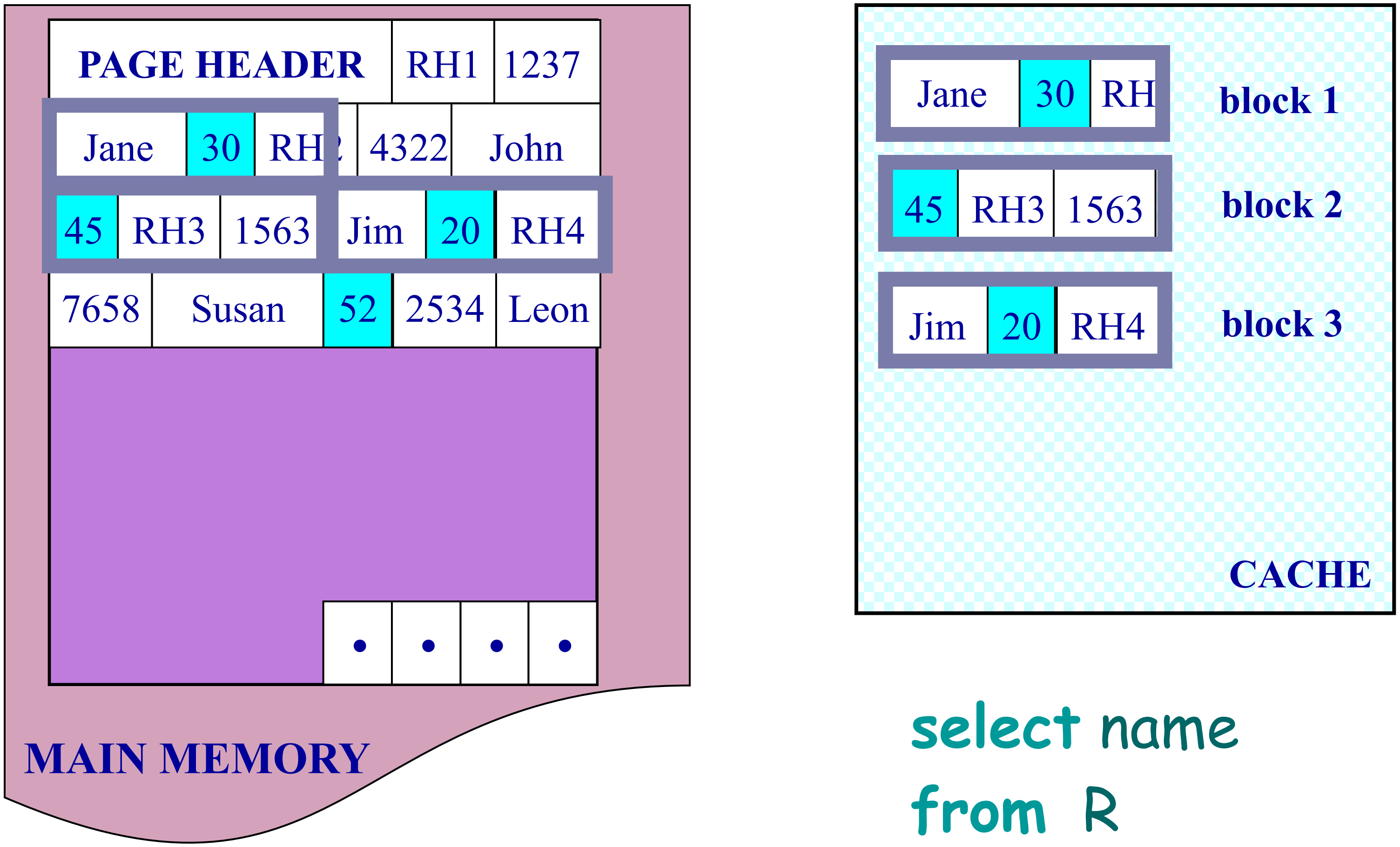

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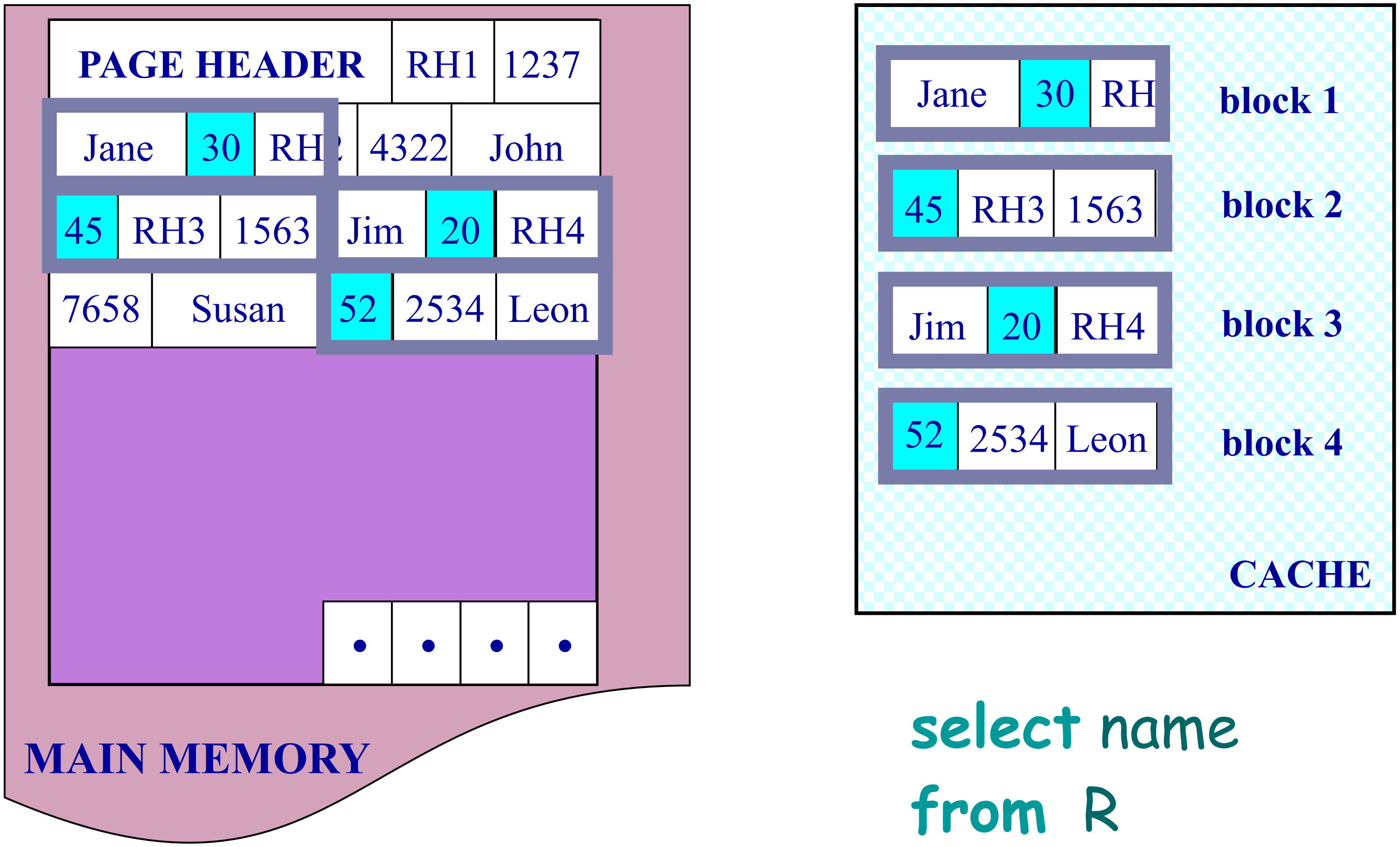

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Need New Data Page Layout

- Eliminates unnecessary memory accesses
- Improves inter-record locality
- Keeps a record's fields together
- Does not affect I/O performance

and, most importantly, is…

low-implementation-cost, high-impact

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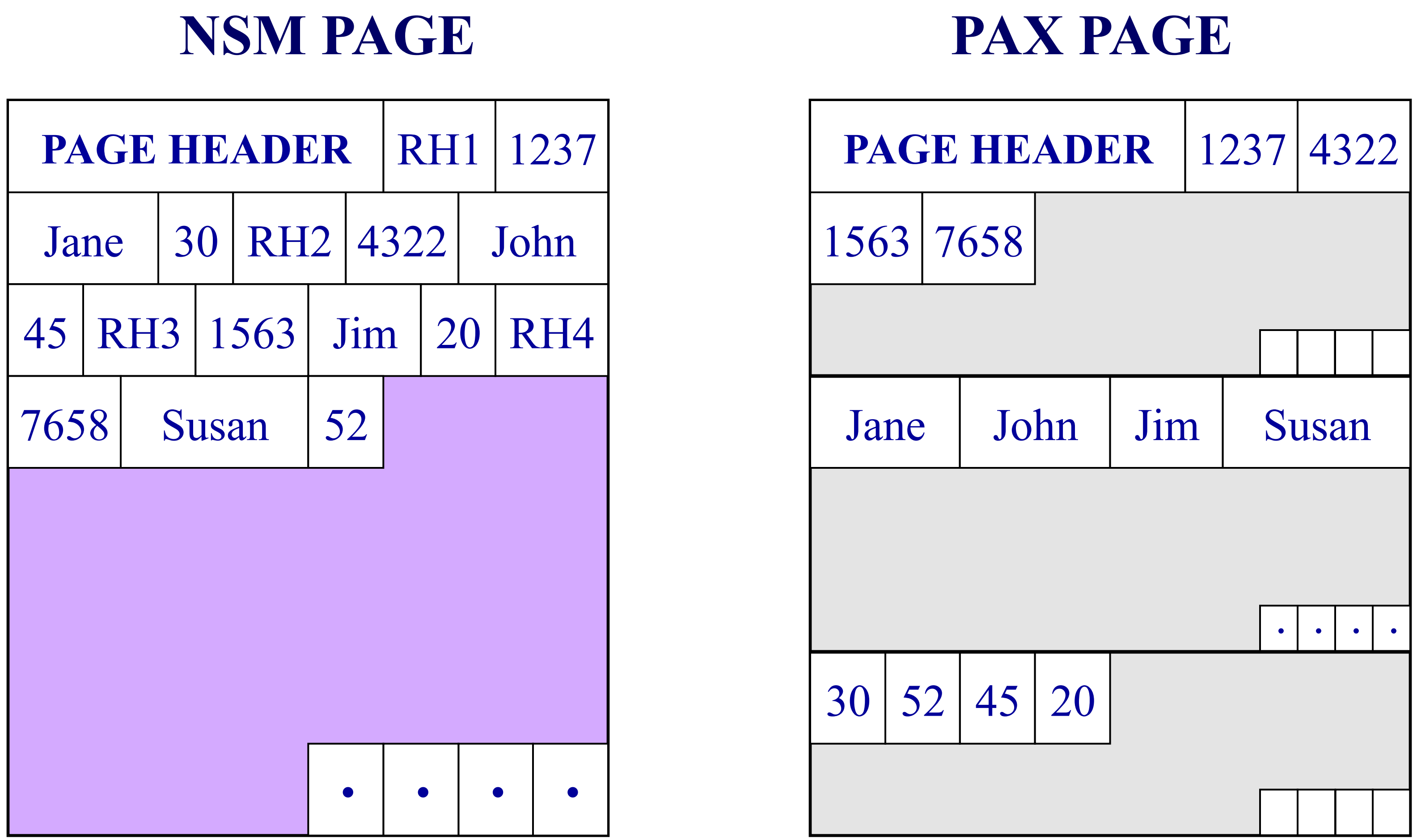
Partition Attributes Across (PAX)



Partition data *within* the page for spatial locality

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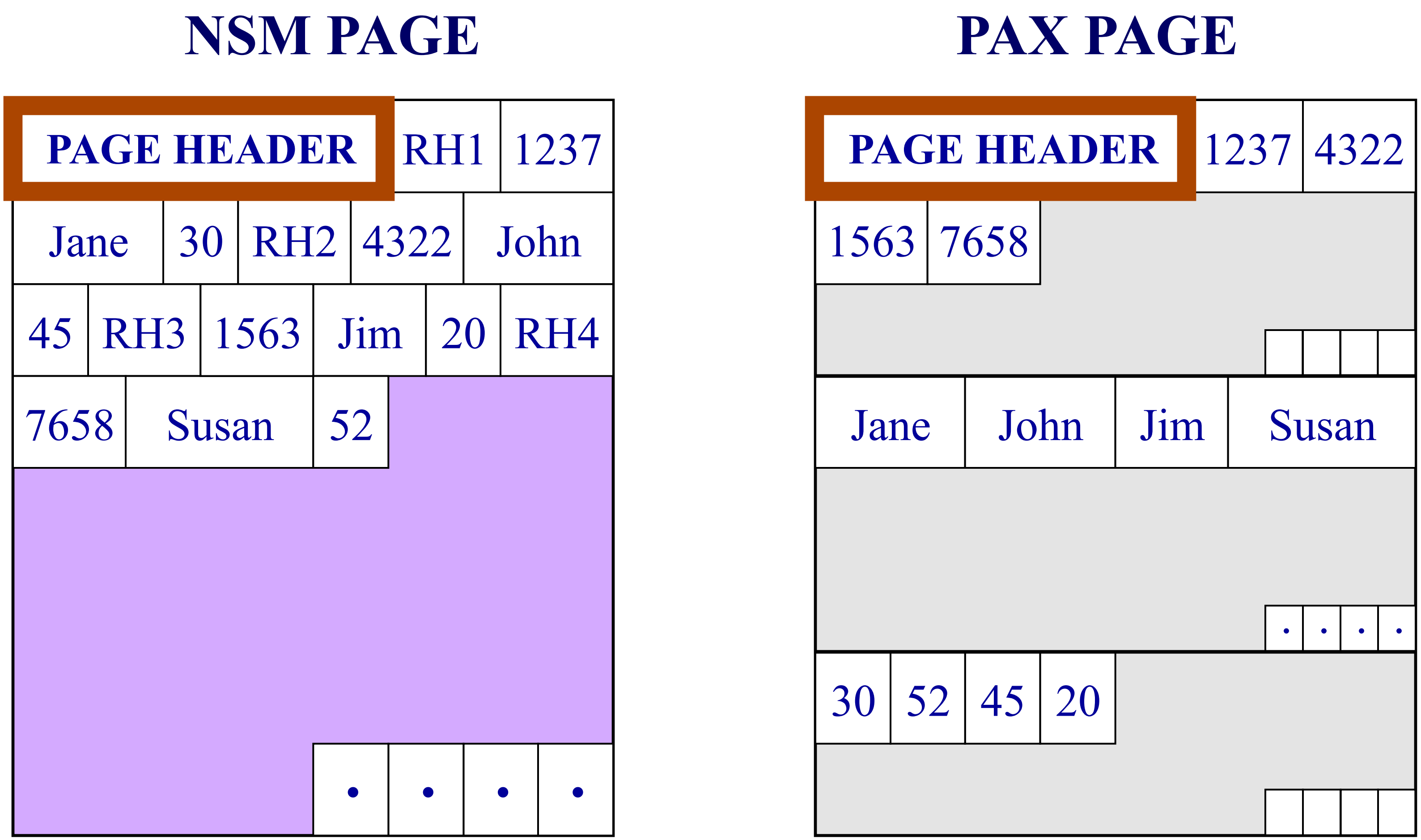

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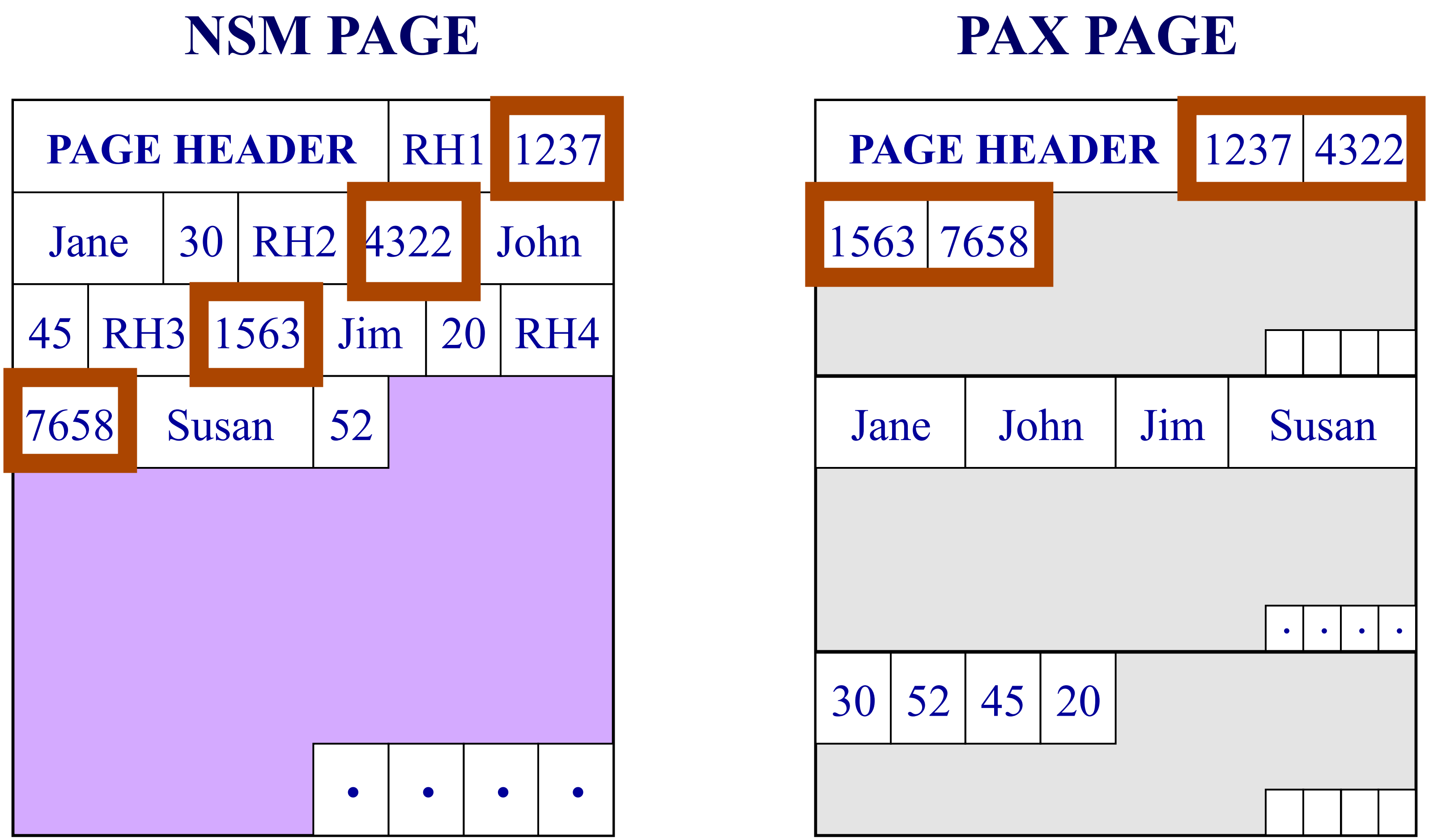

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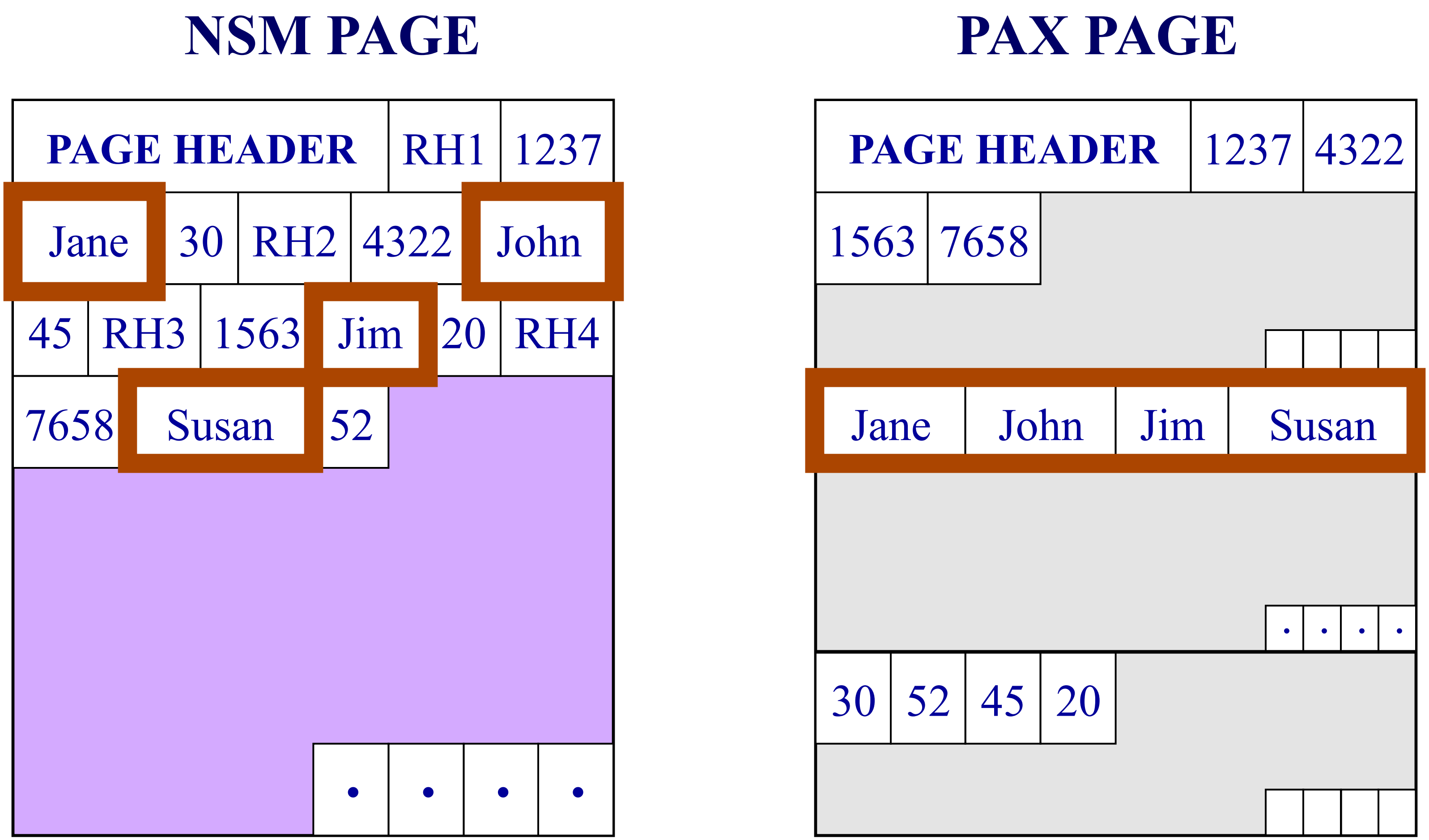

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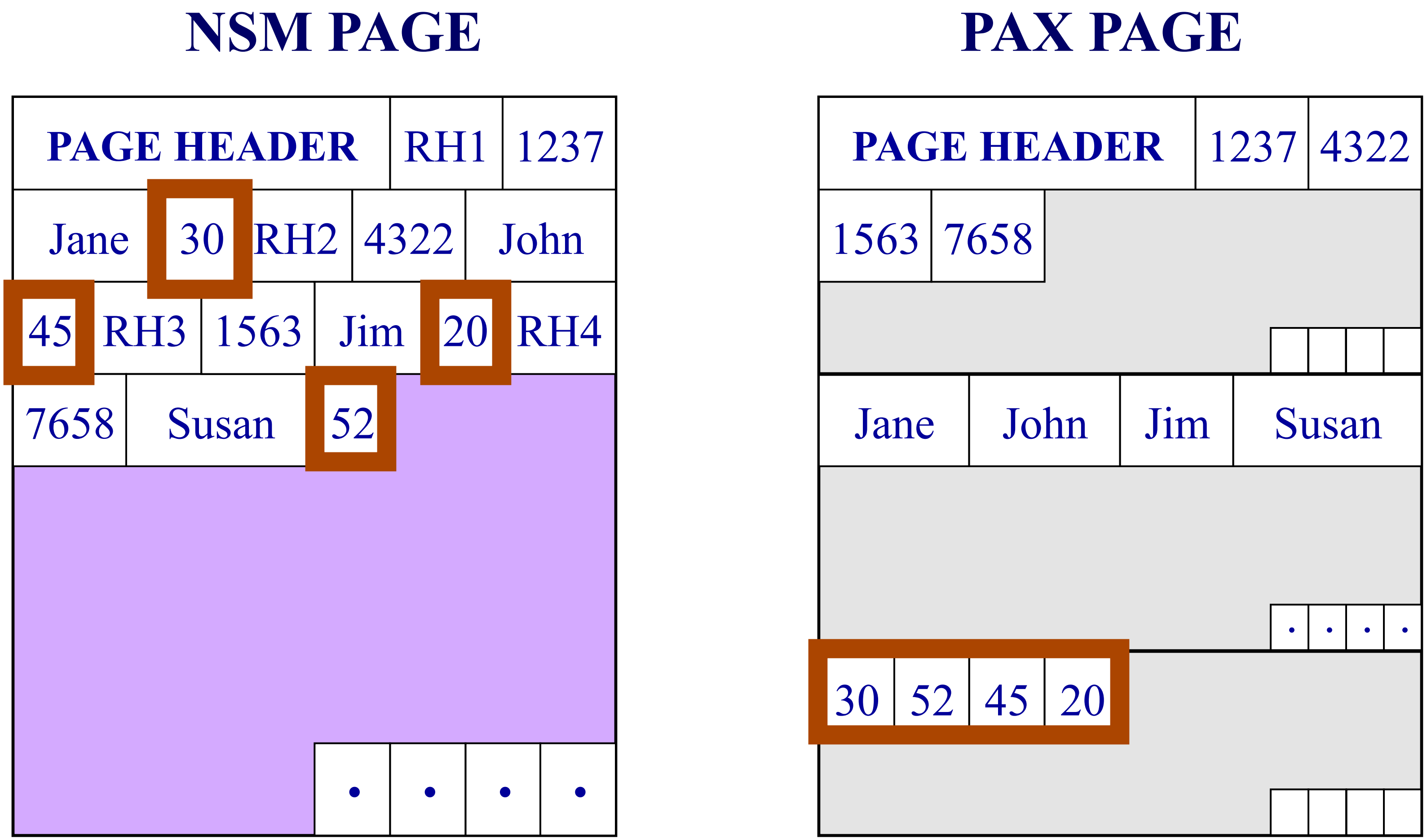

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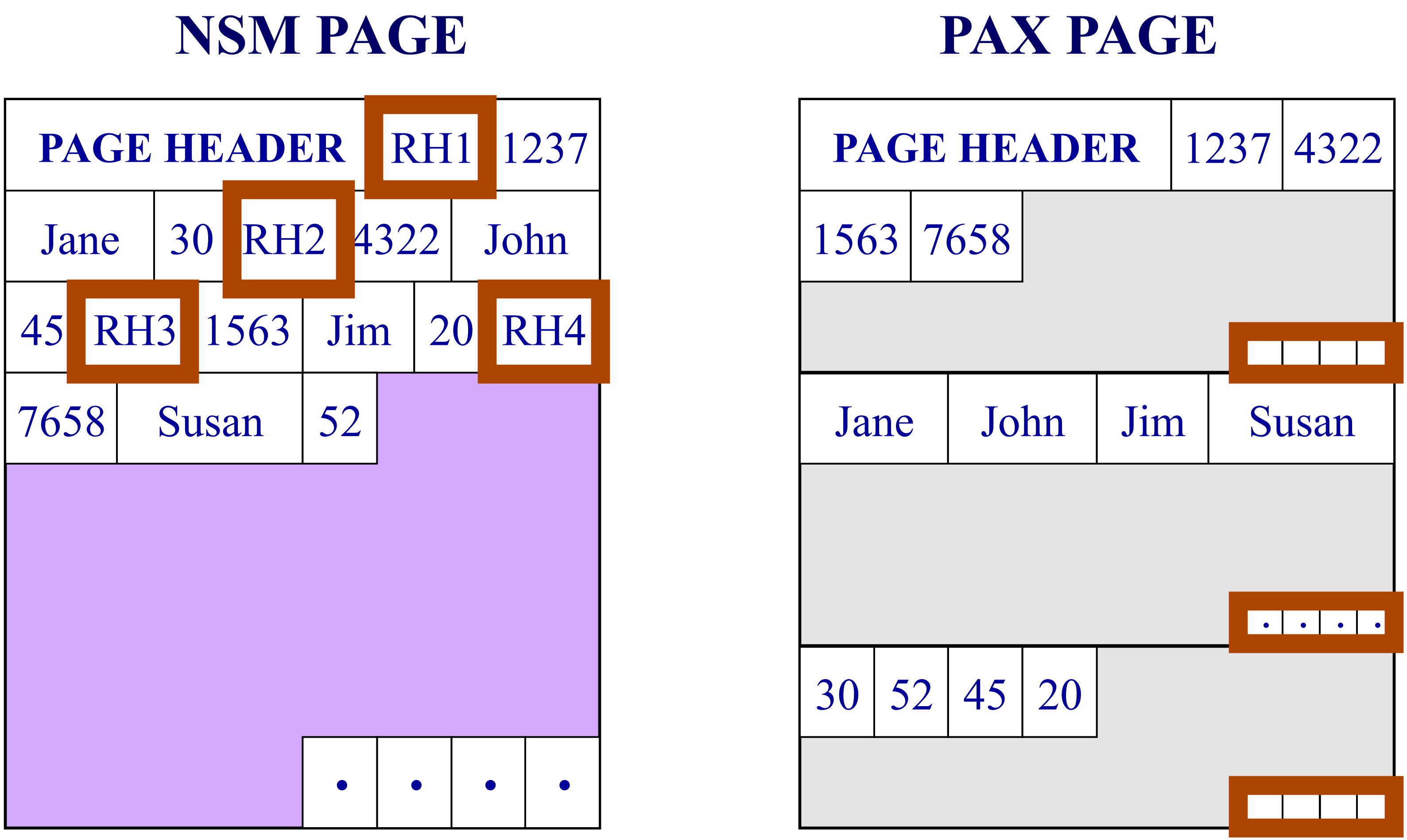

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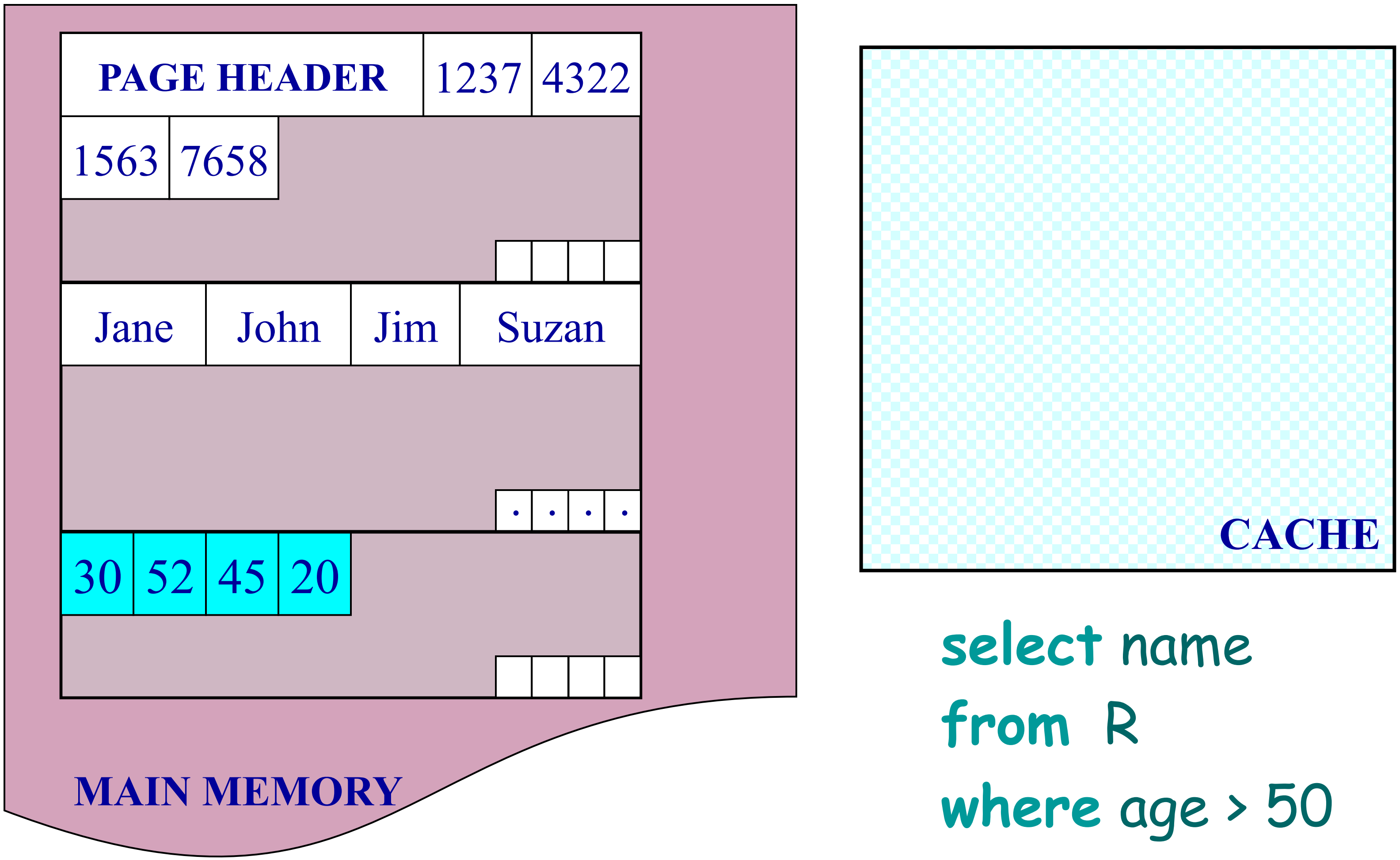

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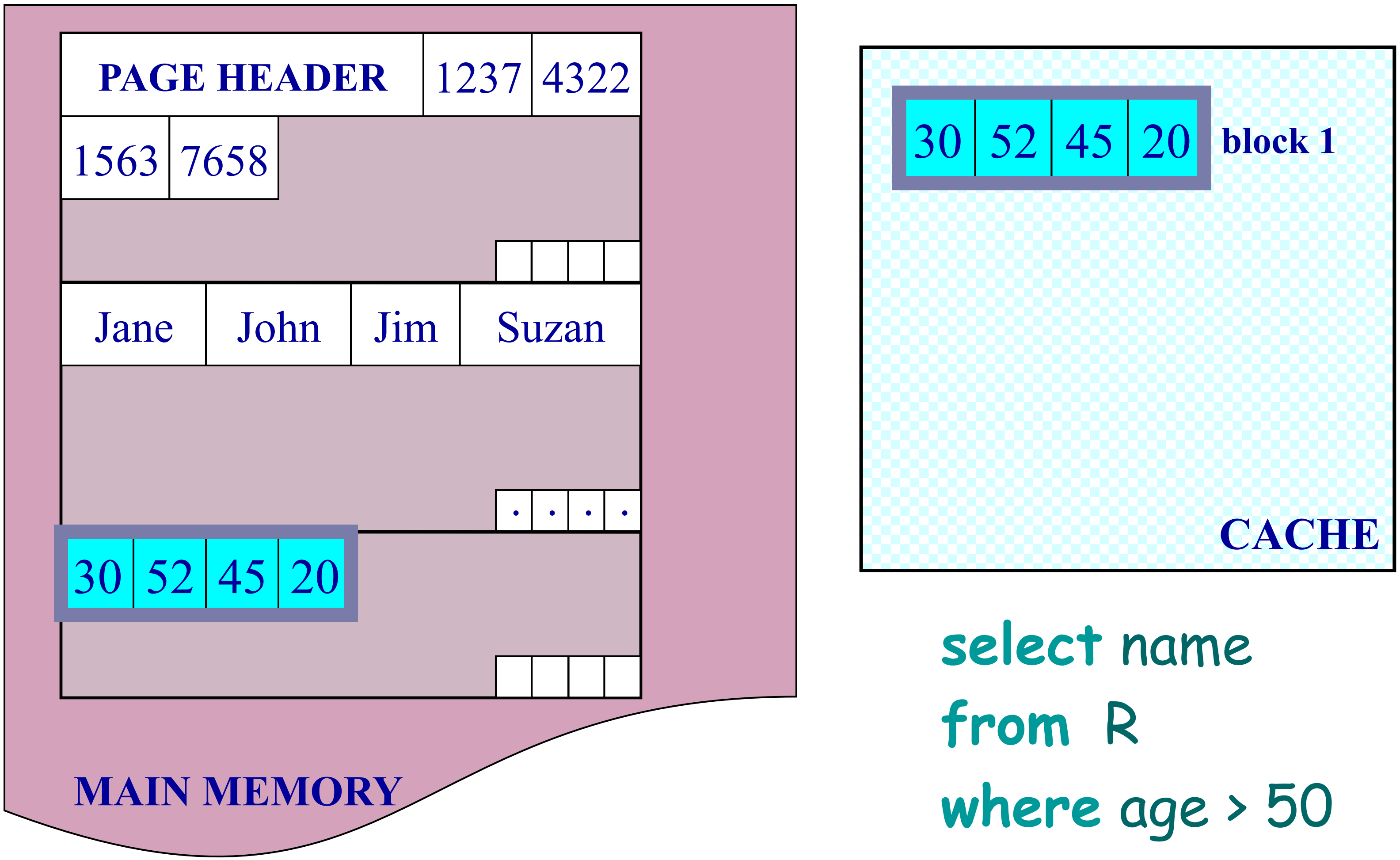
Fewer cache misses, low reconstruction cost

Predicate Evaluation using PAX

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```

Fewer cache misses, low reconstruction cost

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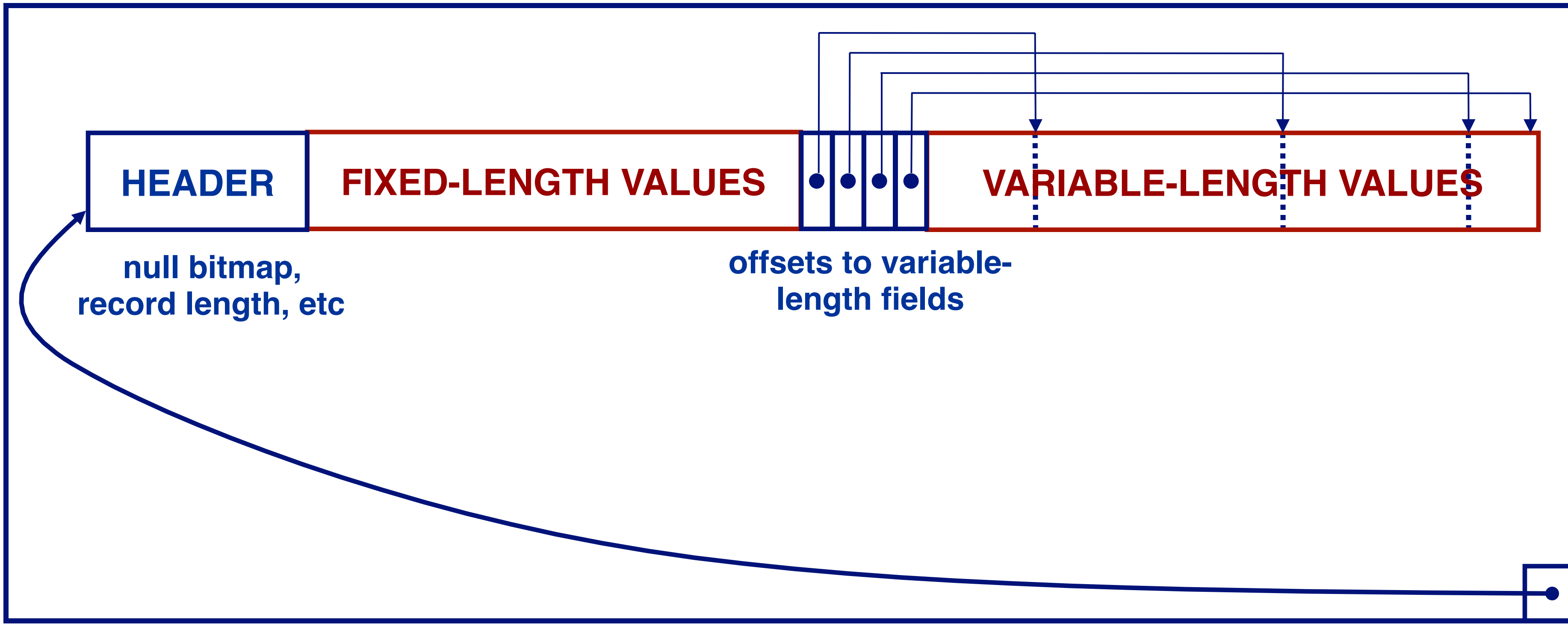
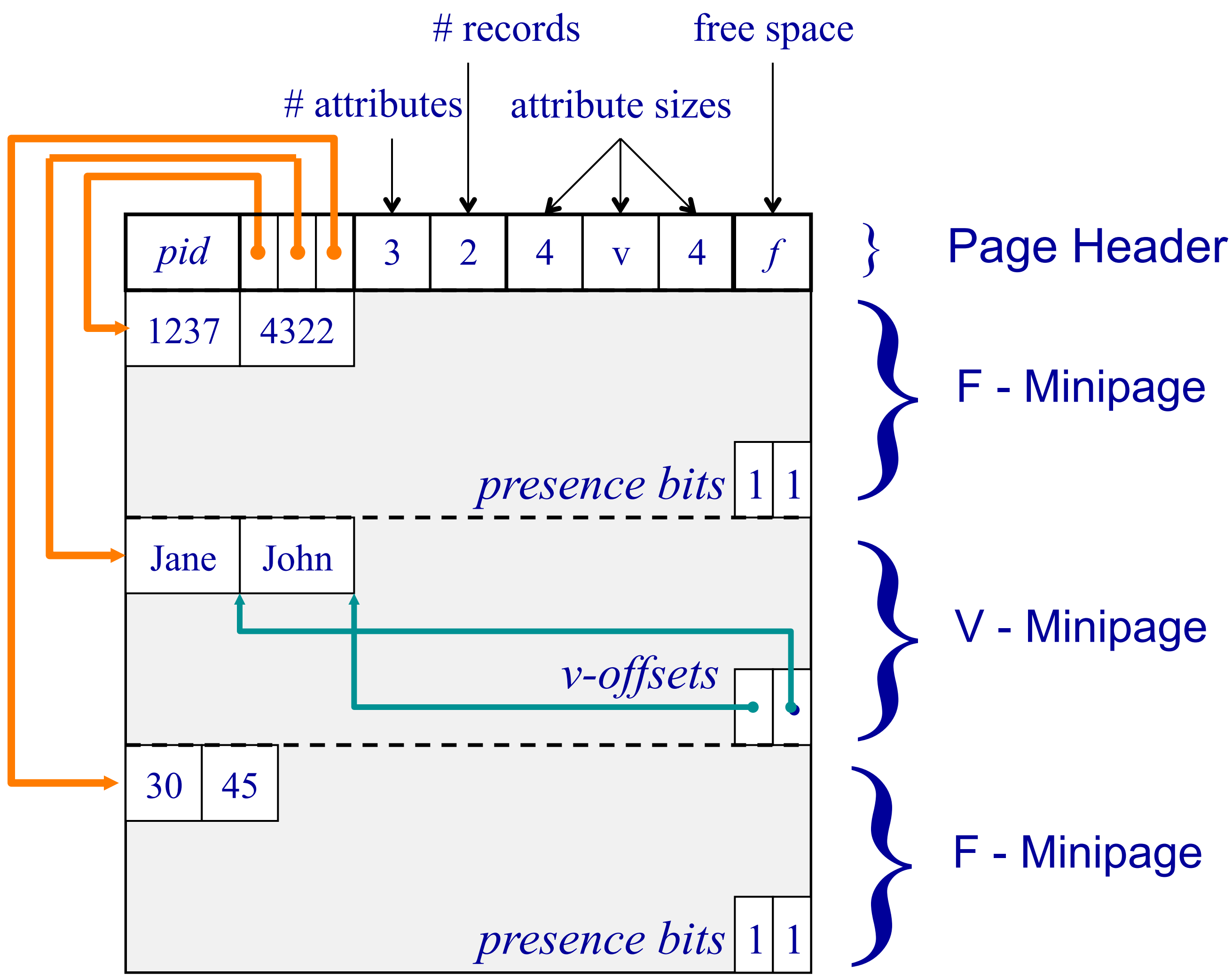
A Real NSM Record



NSM: All fields of record stored together + slots

Ailamaki VLDB'01 http://research.cs.wisc.edu/multifacet/papers/vldb01_pax_talk.ppt

PAX: Detailed Design

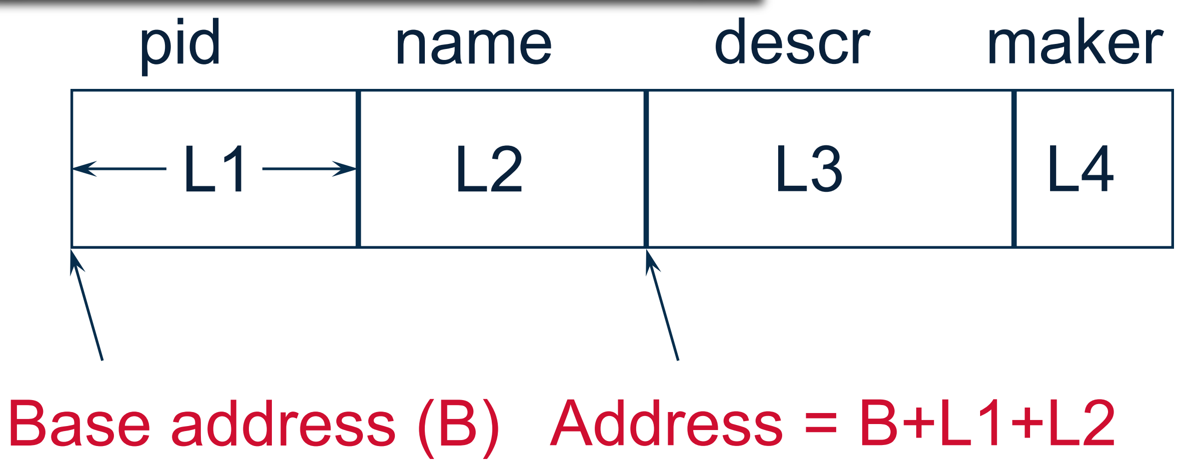


PAX: Group fields + amortizes record headers

Ailamaki VLDB'01 http://research.cs.wisc.edu/multifacet/papers/vldb01_pax_talk.ppt

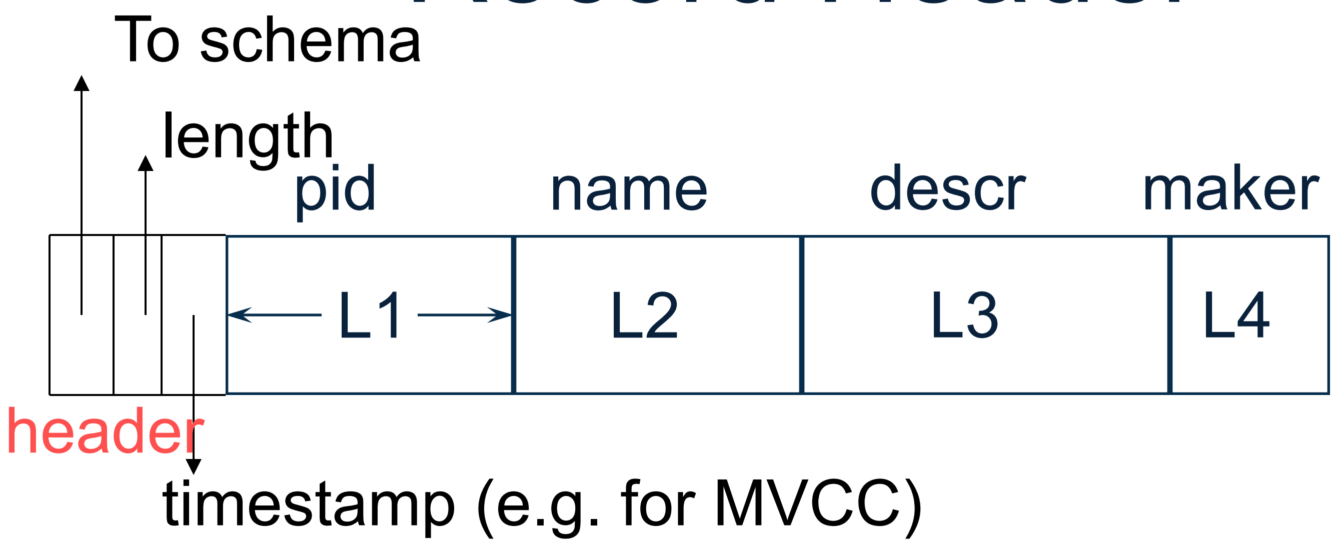
Record Formats: Fixed Length

Product(pid, name, descr, maker)



- Information about field types same for all records in a file; stored in *system catalogs.*
- Finding *i'th* field requires scan of record.
- Note the importance of schema information!

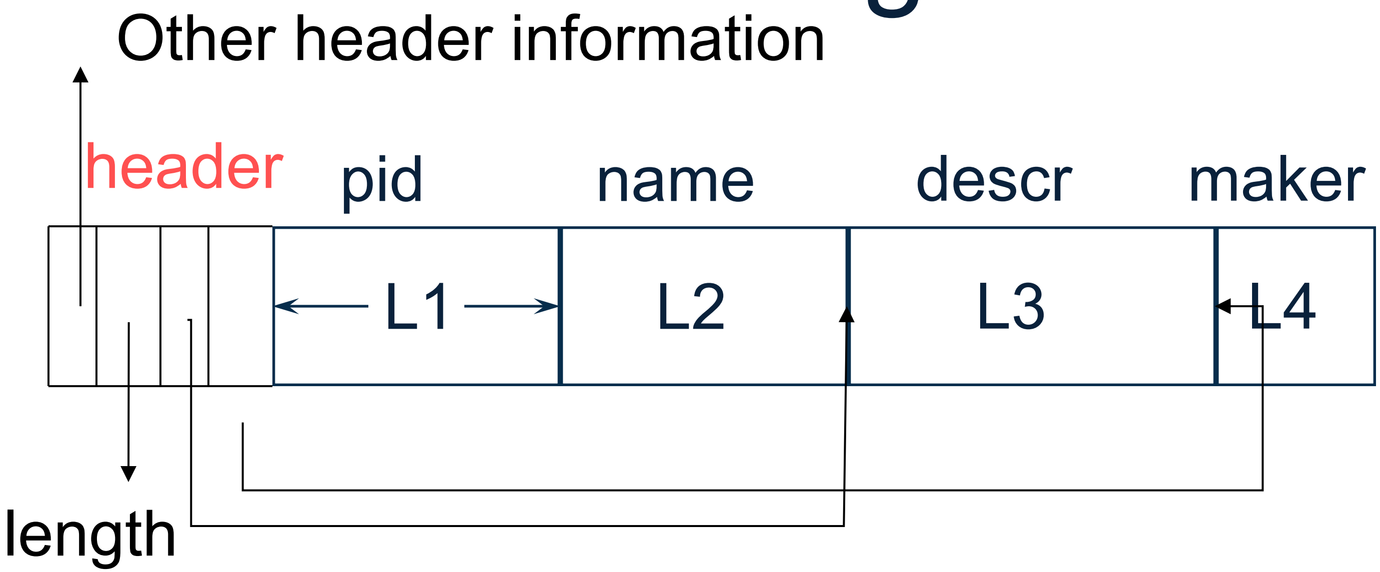
Record Header



Need the header because:

- The schema may change
  for a while new+old may coexist
- Records from different relations may coexist

Variable Length Records



Place the fixed fields first: F1
Then the variable length fields: F2, F3, F4
Null values take 2 bytes only
Sometimes they take 0 bytes (when at the end)

BLOB

- Binary large objects
- Supported by modern database systems
- E.g. images, sounds, etc.
- Storage: attempt to cluster blocks together

CLOB = character large object

- Supports only restricted operations

File Organizations

- Heap (random order) files: Suitable when typical access is a file scan retrieving all records.
- Sorted Files Best if records must be retrieved in some order, or only a `range' of records is needed.
- Indexes Data structures to organize records via trees or hashing.
  - Like sorted files, they speed up searches for a subset of records, based on values in certain ("search key") fields
  - Updates are much faster than in sorted files.

Index

- A (possibly separate) file, that allows fast access to records in the data file
- The index contains (key, value) pairs:
  - The key = an attribute value
  - The value = one of:
    - pointer to the record *secondary index*
    - or the record itself *primary index*

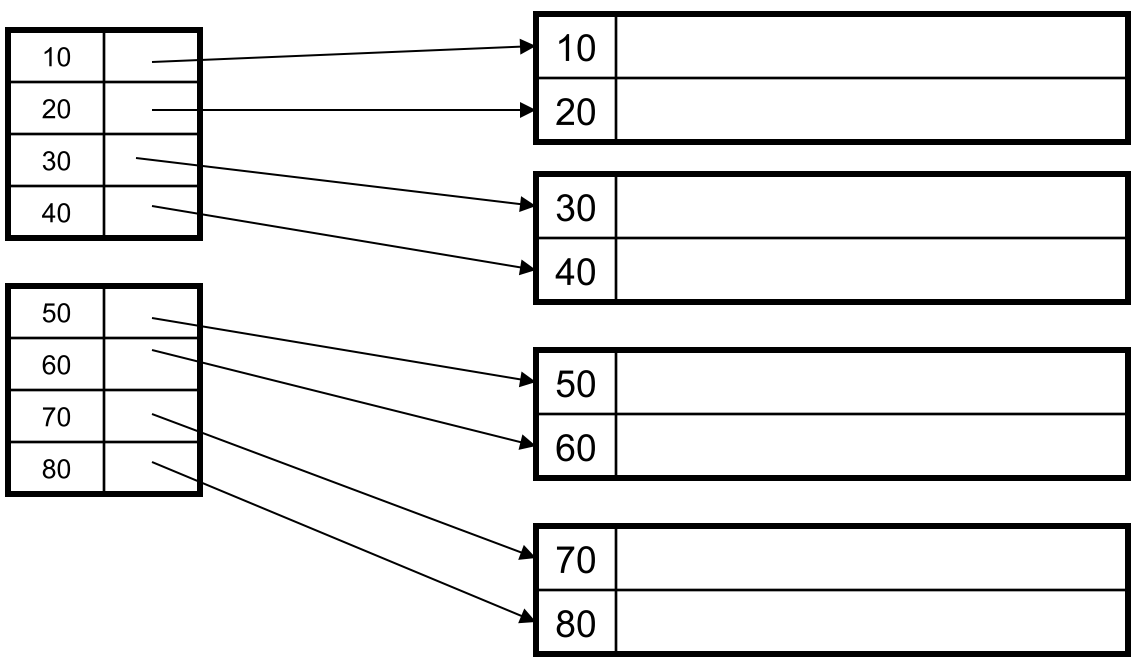
Note: "key" (aka "search key") again means something else

Index Classification

- Clustered/unclustered
  - Clustered = records close in index are close in data
  - Unclustered = records close in index may be far in data
- Primary/secondary
  - Meaning 1:
    - Primary = is over attributes that include the primary key
    - Secondary = otherwise
  - Meaning 2: means the same as clustered/unclustered
- Organization B+ tree or Hash table

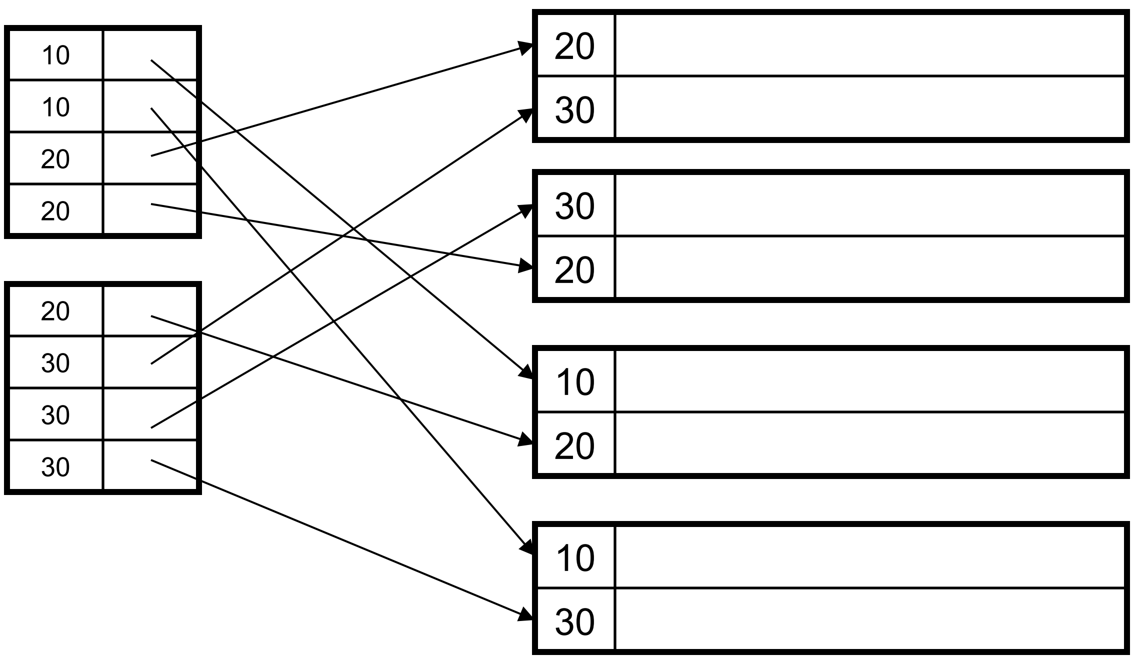
Clustered Index

- File is sorted on the index attribute
- Only one per table

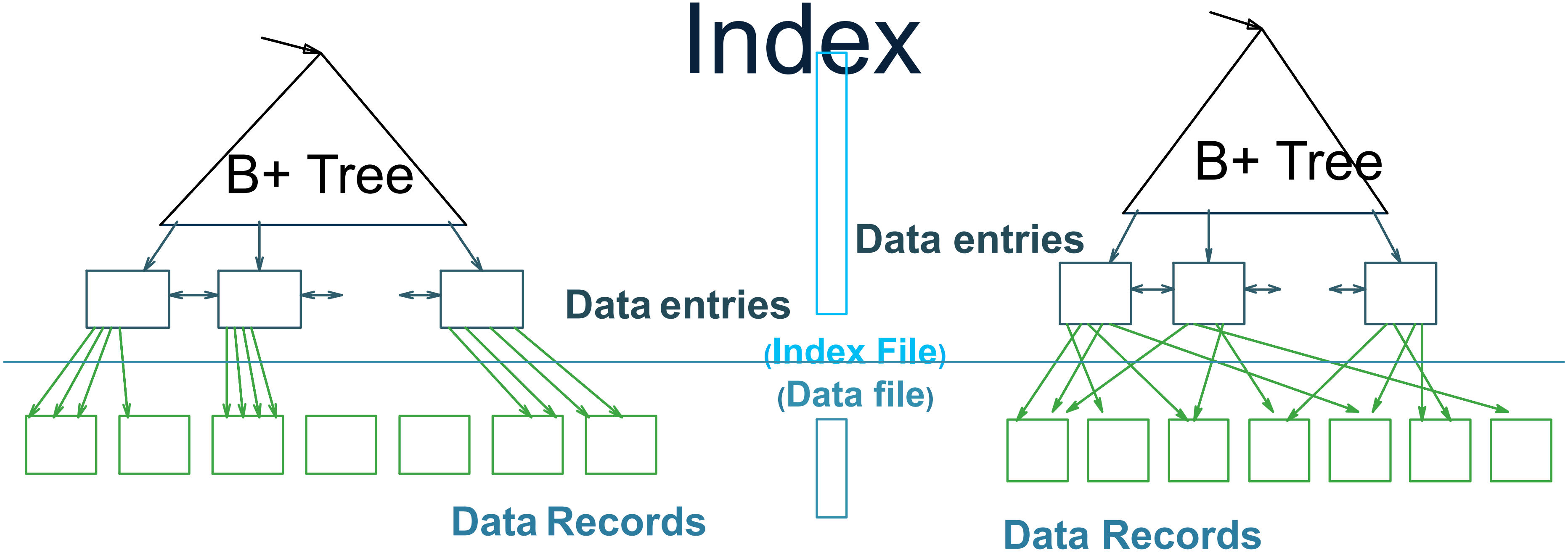


Unclustered Index

- Several per table



Clustered vs. Unclustered Index

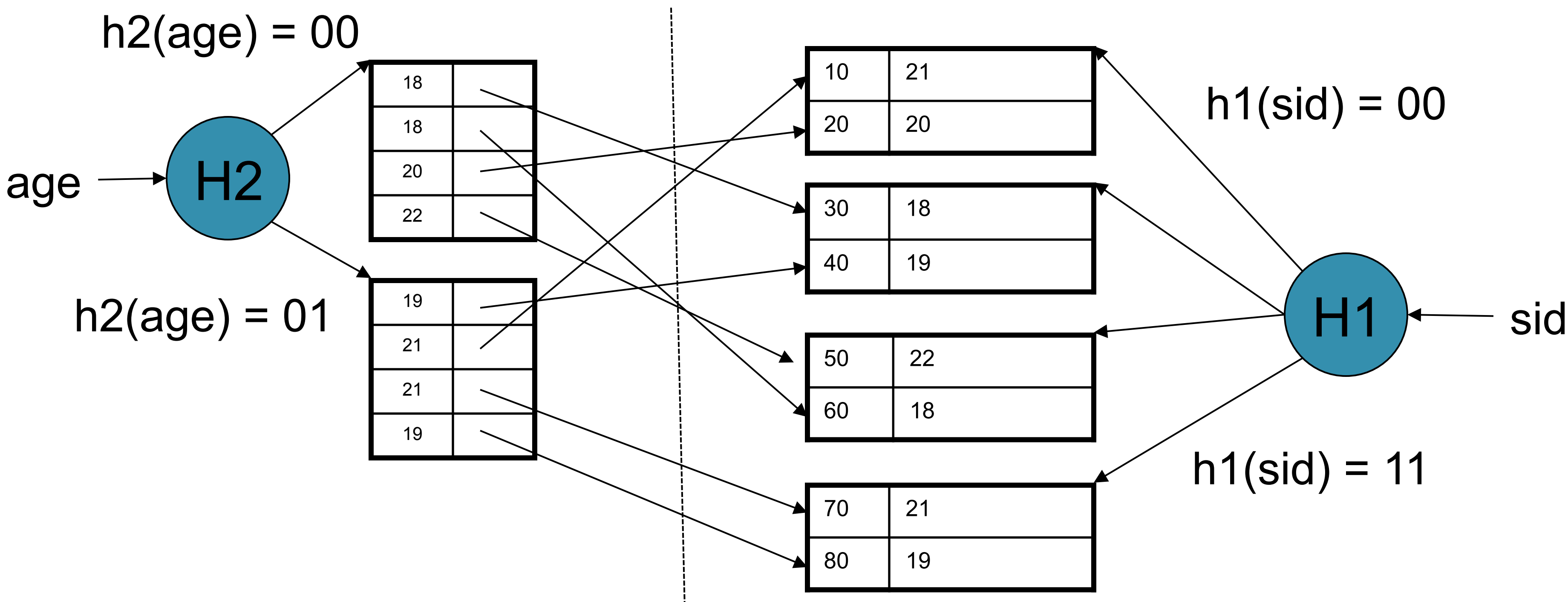


CLUSTERED

UNCLUSTERED

Hash-Based Index

Good for point queries but not range queries



Another example of unclustered/secondary index

Another example of clustered/primary index

Alternatives for Data Entry k* in Index

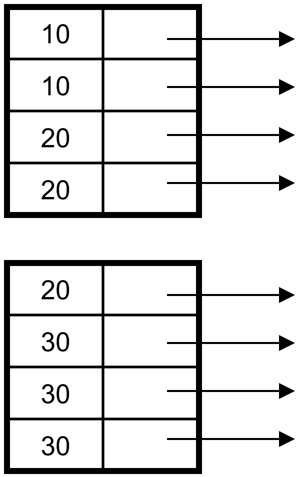
Three alternatives for **k***:

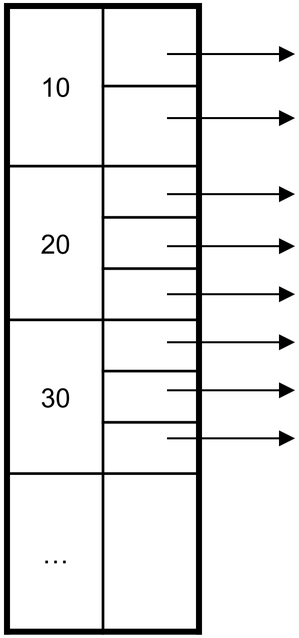
- Data record with key value **k**
- <**k**, **rid** of data record with key = **k**>
- <**k**, list of **rids** of data records with key = **k**>

Alternatives 1, 2, 3

10	ssn	age	…
10	ssn	age	…
20	ssn	age	…
20	ssn	age	…

20	ssn	age	…
30	ssn	age	…
30	ssn	age	…
30	ssn	age	…



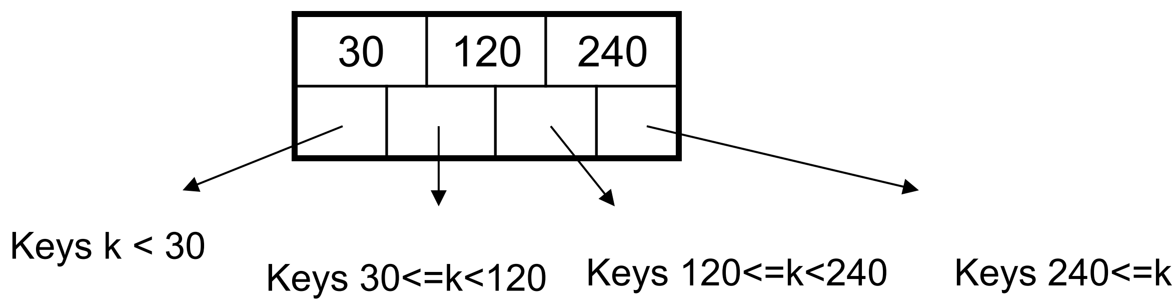


B+ Trees

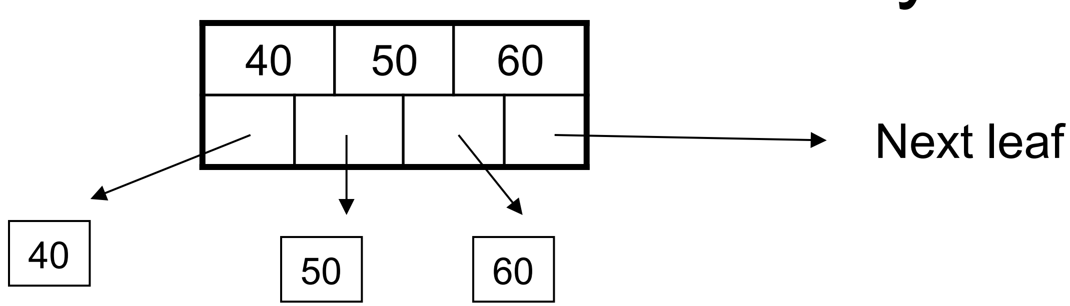
- Search trees
- Idea in B Trees
  - Make 1 node = 1 block
  - Keep tree balanced in height
- Idea in B+ Trees
  - Make leaves into a linked list: facilitates range queries

B+ Trees Basics

- Parameter d = the *degree*
- Each node has >= d and <= 2d keys (except root)



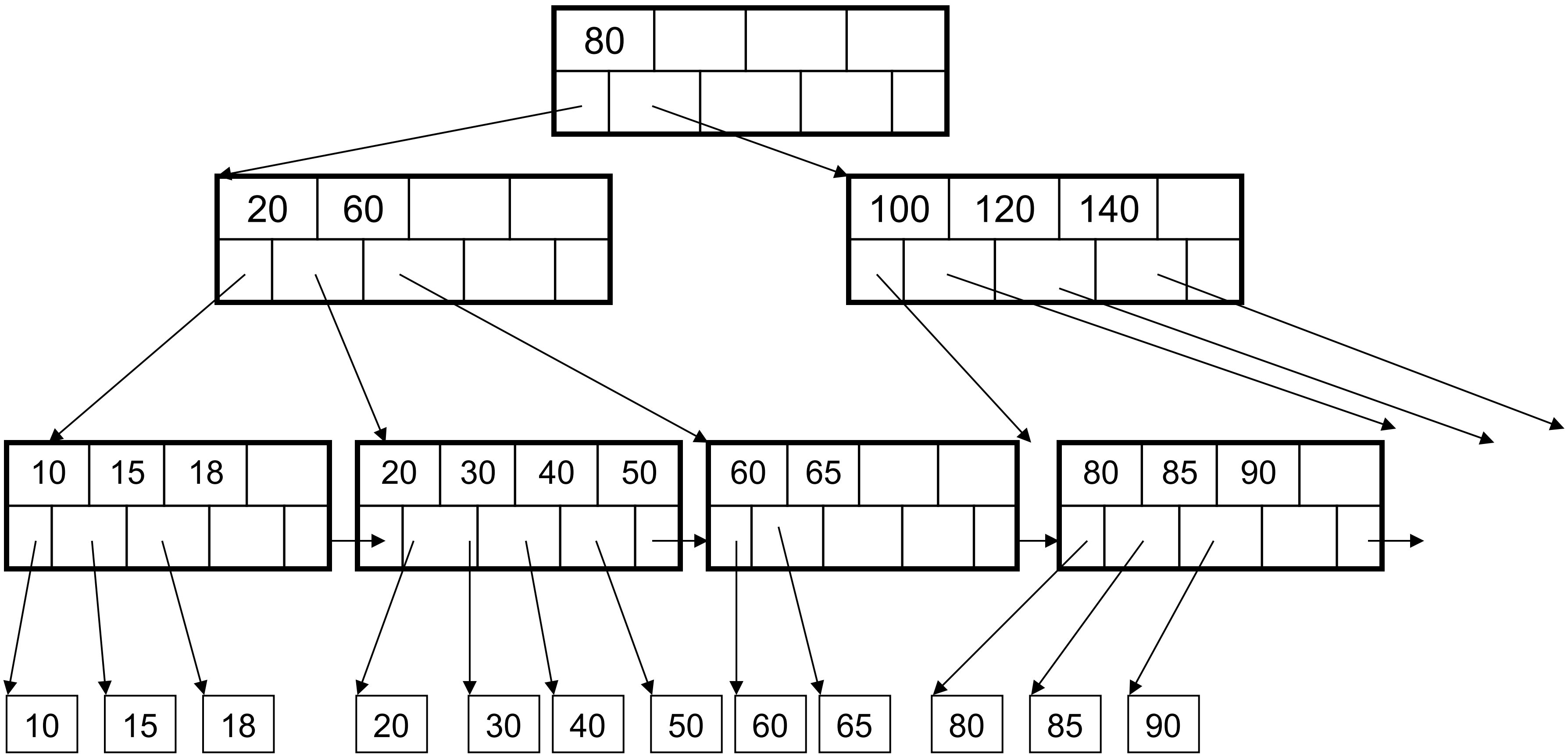
- Each leaf has >=d and <= 2d keys:



B+ Tree Example

d = 2

Find the key 40

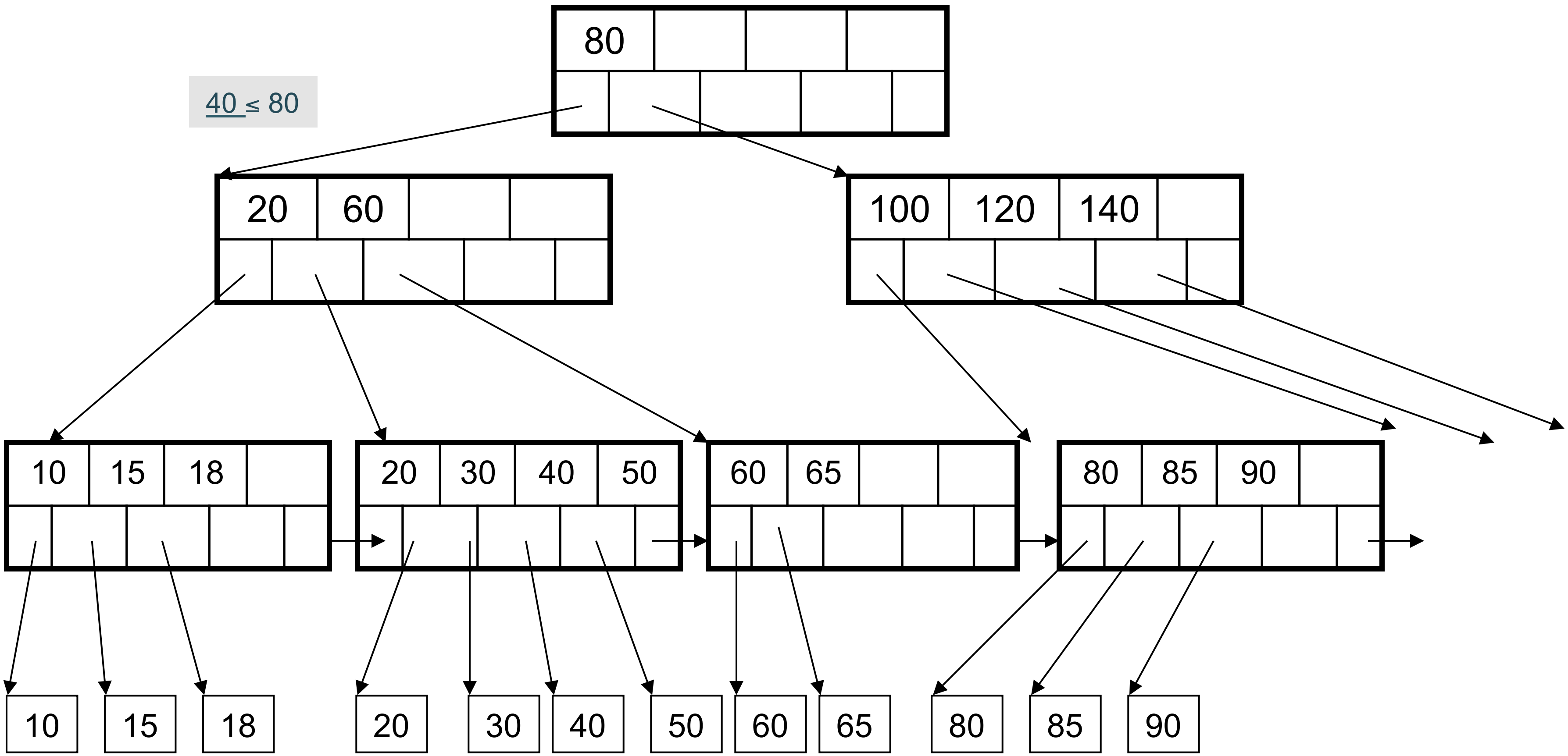


B+ Tree Example

d = 2

Find the key 40

40 ≤ 80



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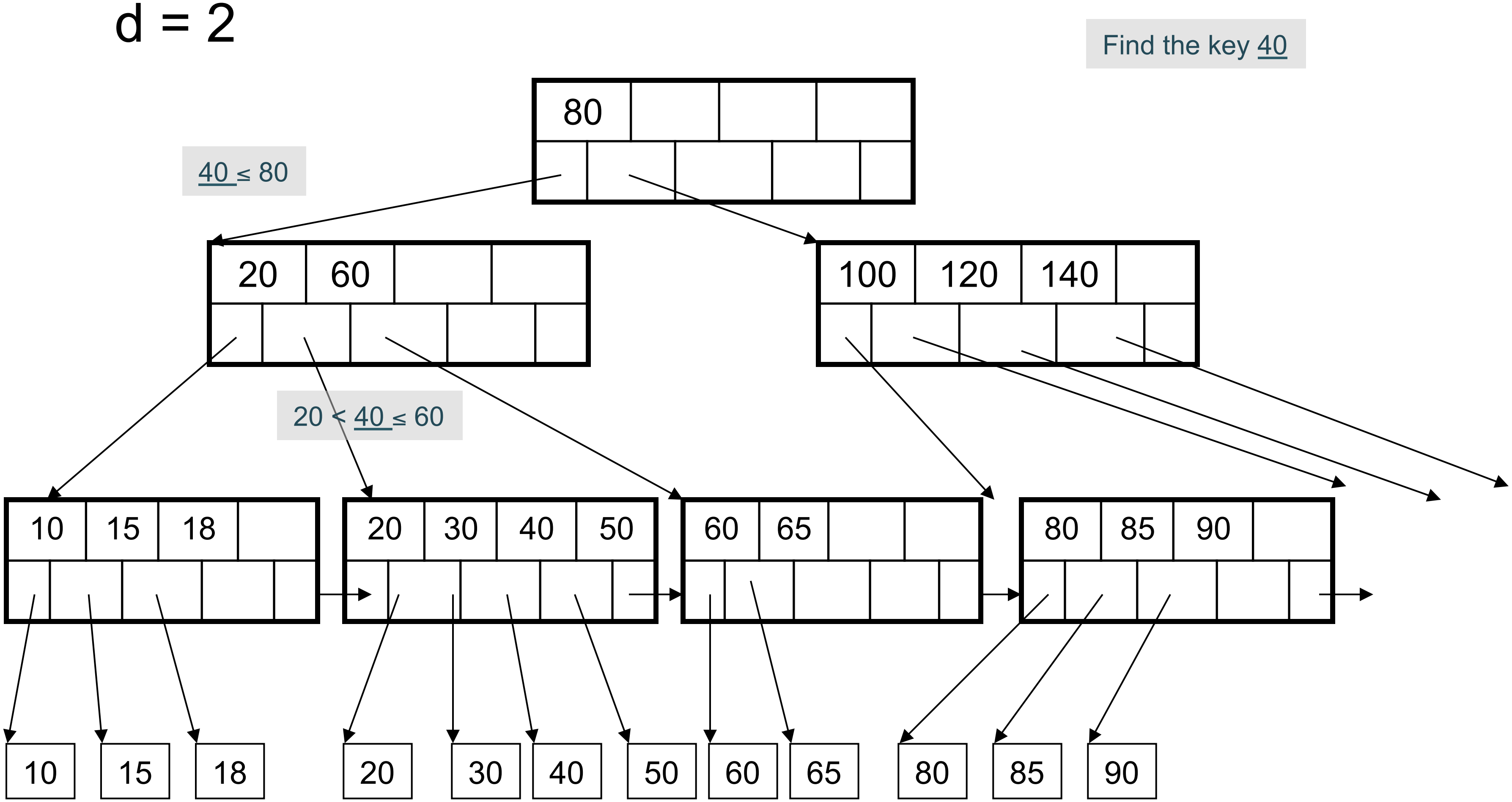

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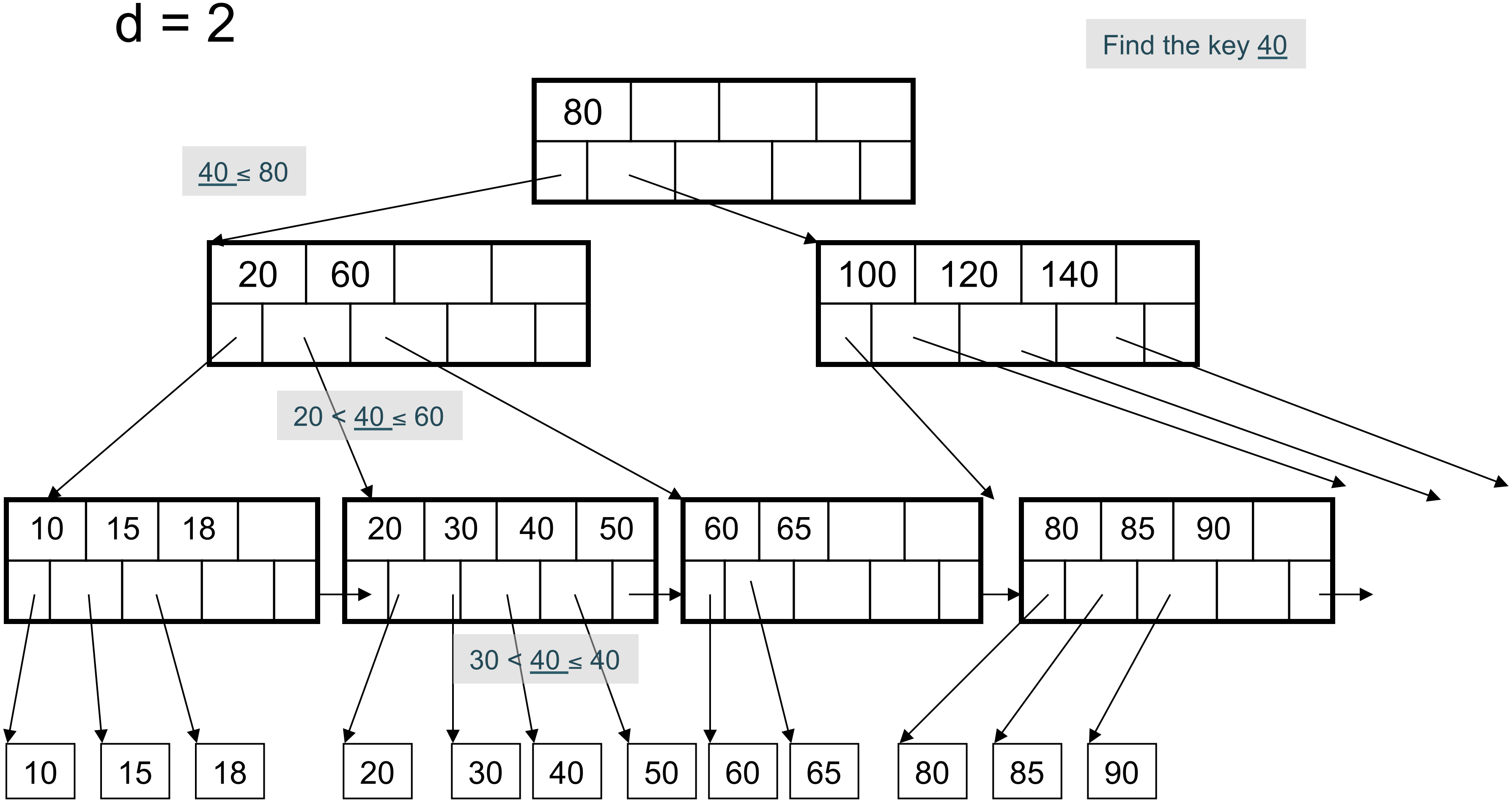


Using a B+ Tree

Index on People(age)

- Exact key values:
  - Start at the root
  - Proceed down, to the leaf

```
SELECT name
FROM People
WHERE age = 25
```

- Range queries:
  - As above
  - Then sequential traversal

```
SELECT name
FROM People
WHERE 20 <= age
  and  age <= 30
```

Which queries can use this index ?

Index on People(name, zipcode)

```
SELECT *
FROM People
WHERE name = ‘Smith’
   and zipcode = 12345
```

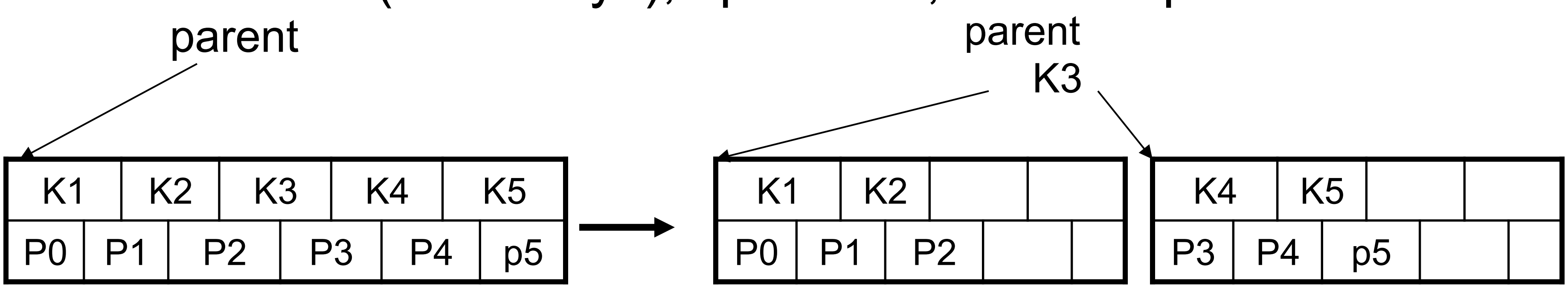
```
SELECT *
FROM People
WHERE name = ‘Smith’
```

```
SELECT *
FROM People
WHERE zipcode = 12345
```

Insertion in a B+ Tree

Insert (K, P)

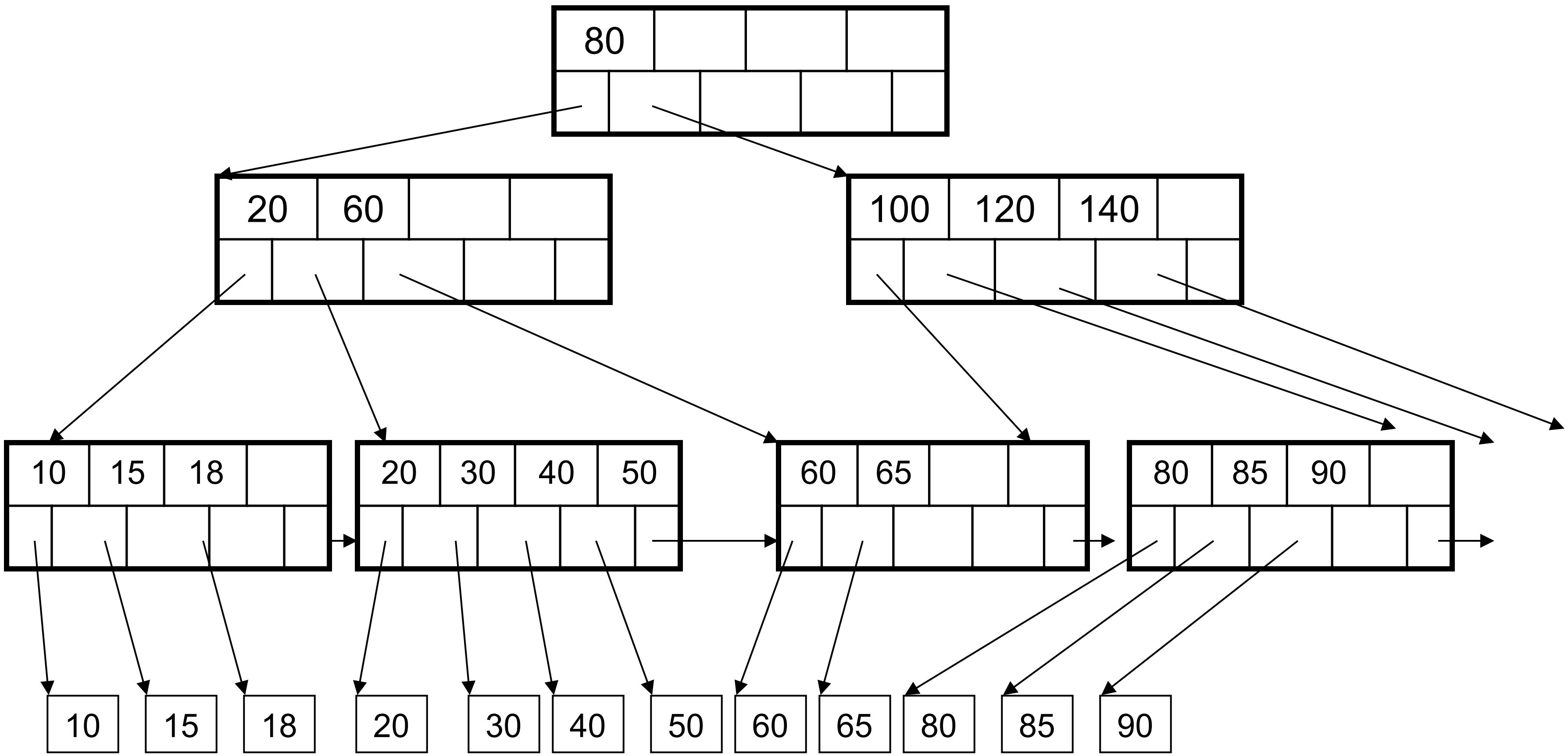
- Find leaf where K belongs, insert
- If no overflow (2d keys or less), halt
- If overflow (2d+1 keys), split node, insert in parent:



- If leaf, keep K3 too in right node
- When root splits, new root has 1 key only

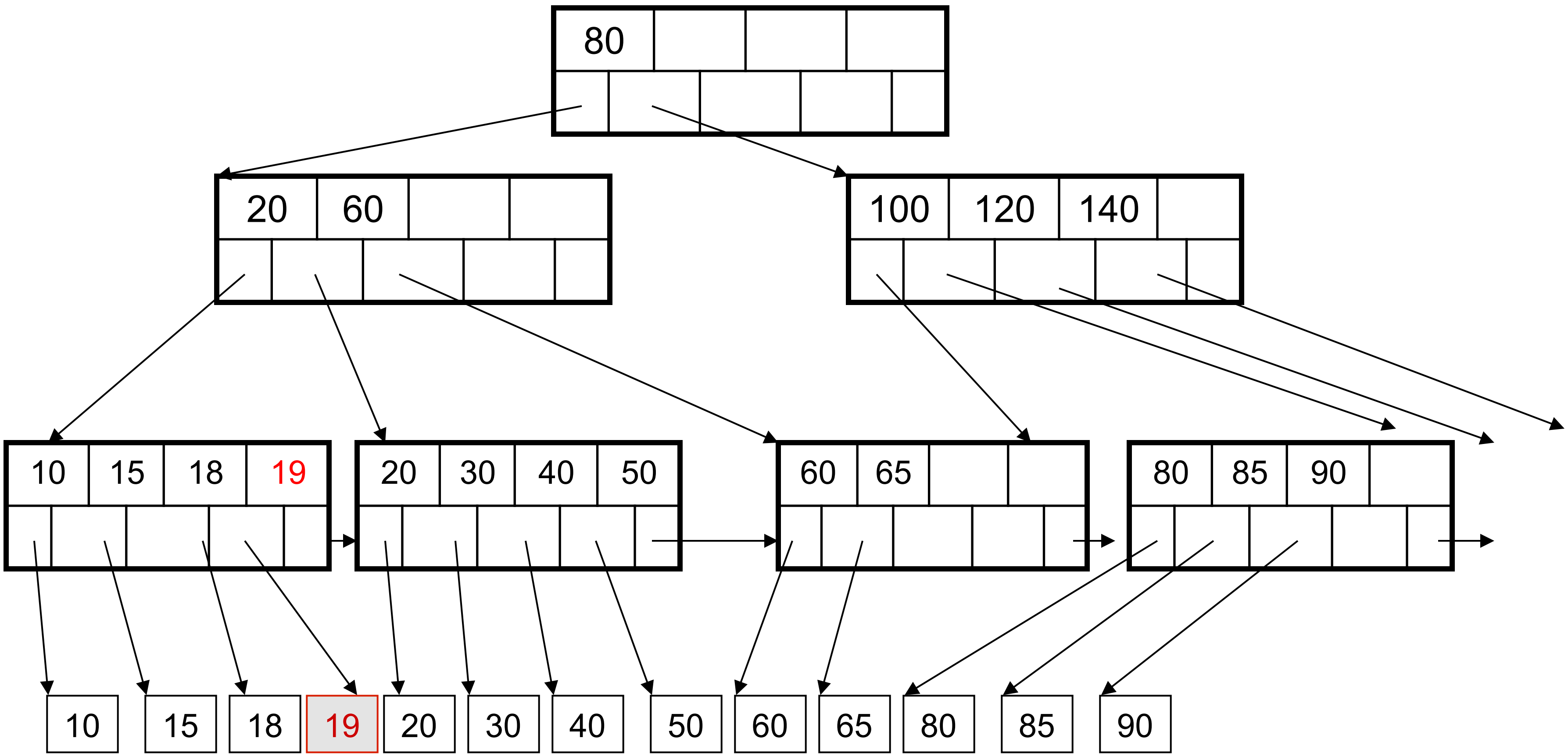
Insertion in a B+ Tree

Insert K=19



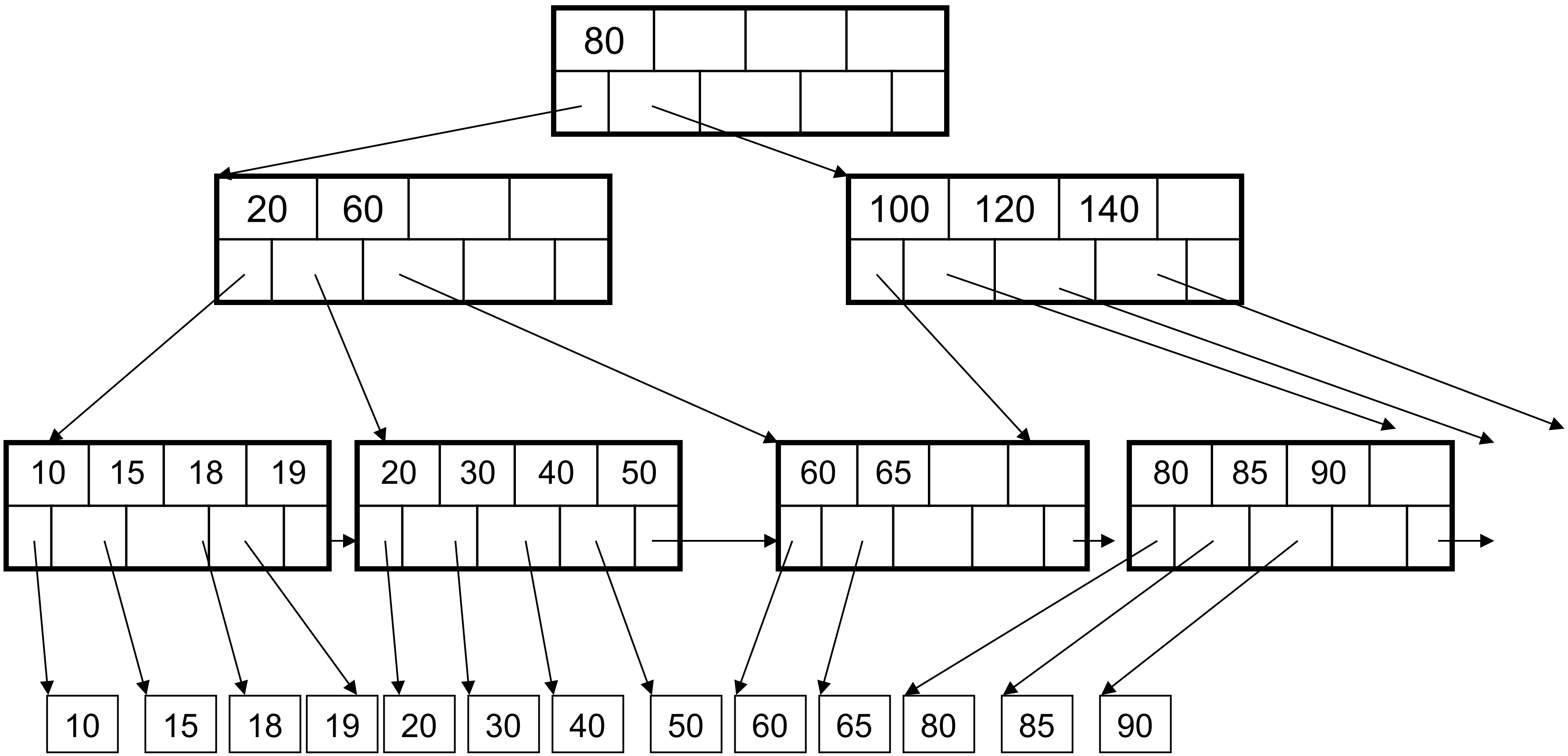
Insertion in a B+ Tree

After insertion



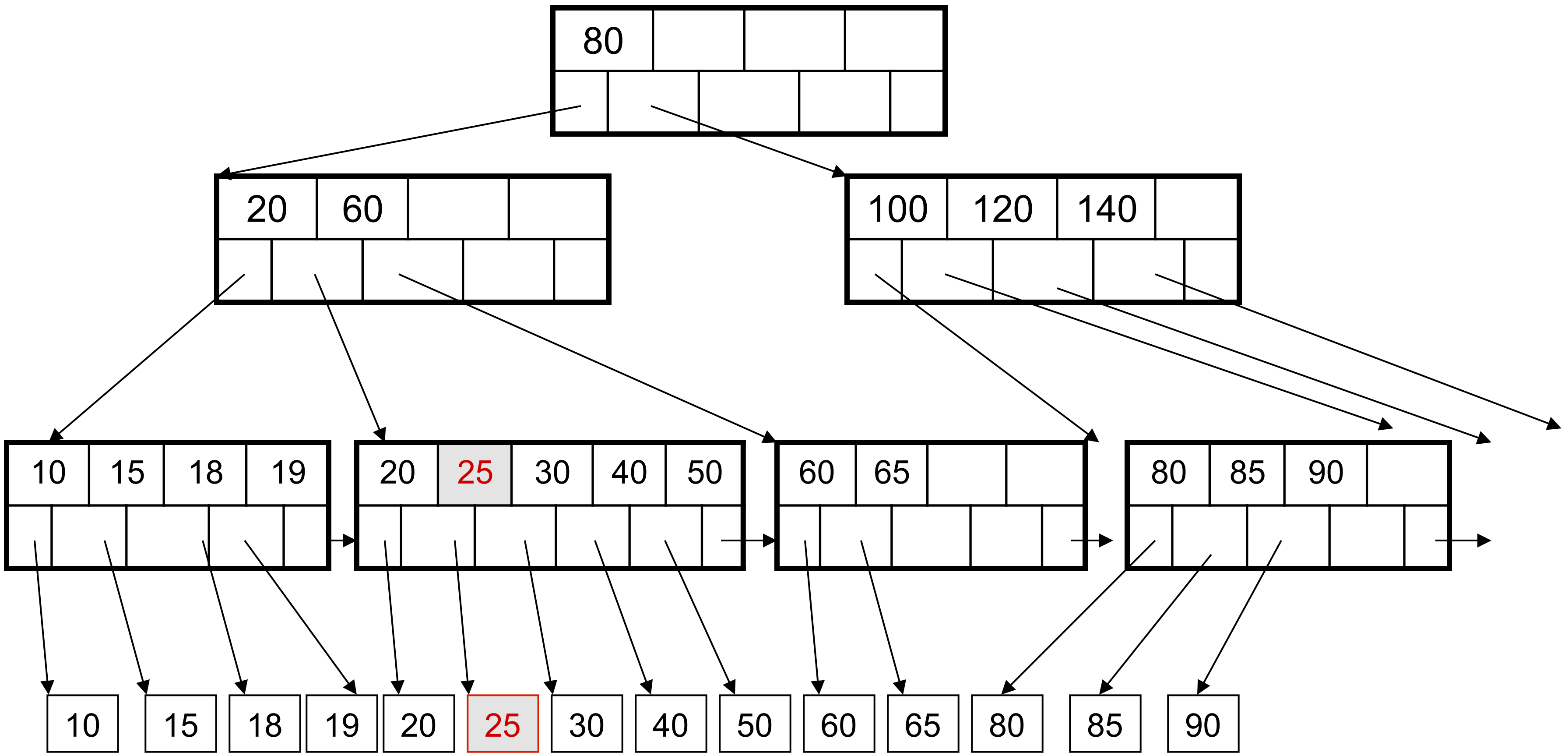
Insertion in a B+ Tree

Now insert 25



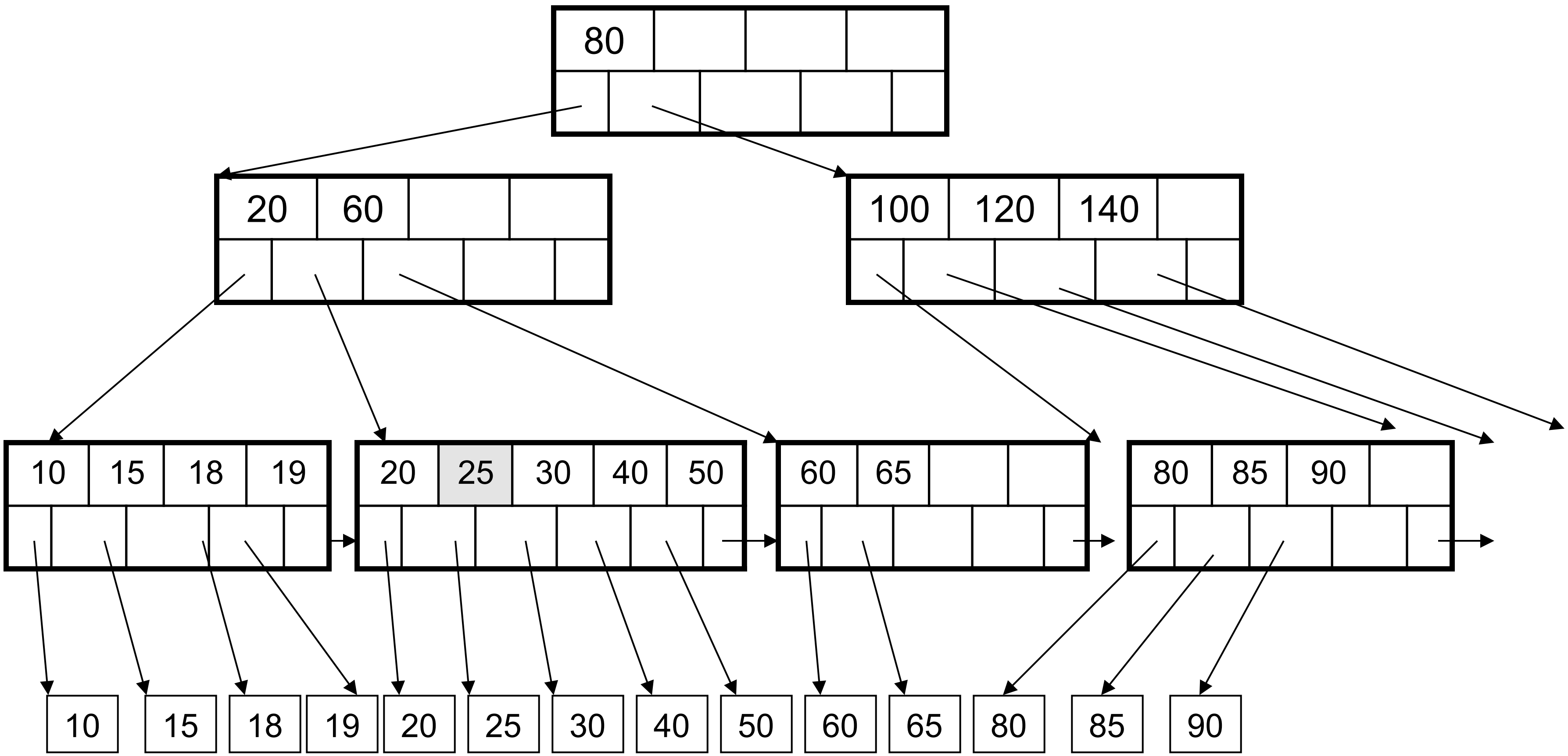
Insertion in a B+ Tree

After insertion



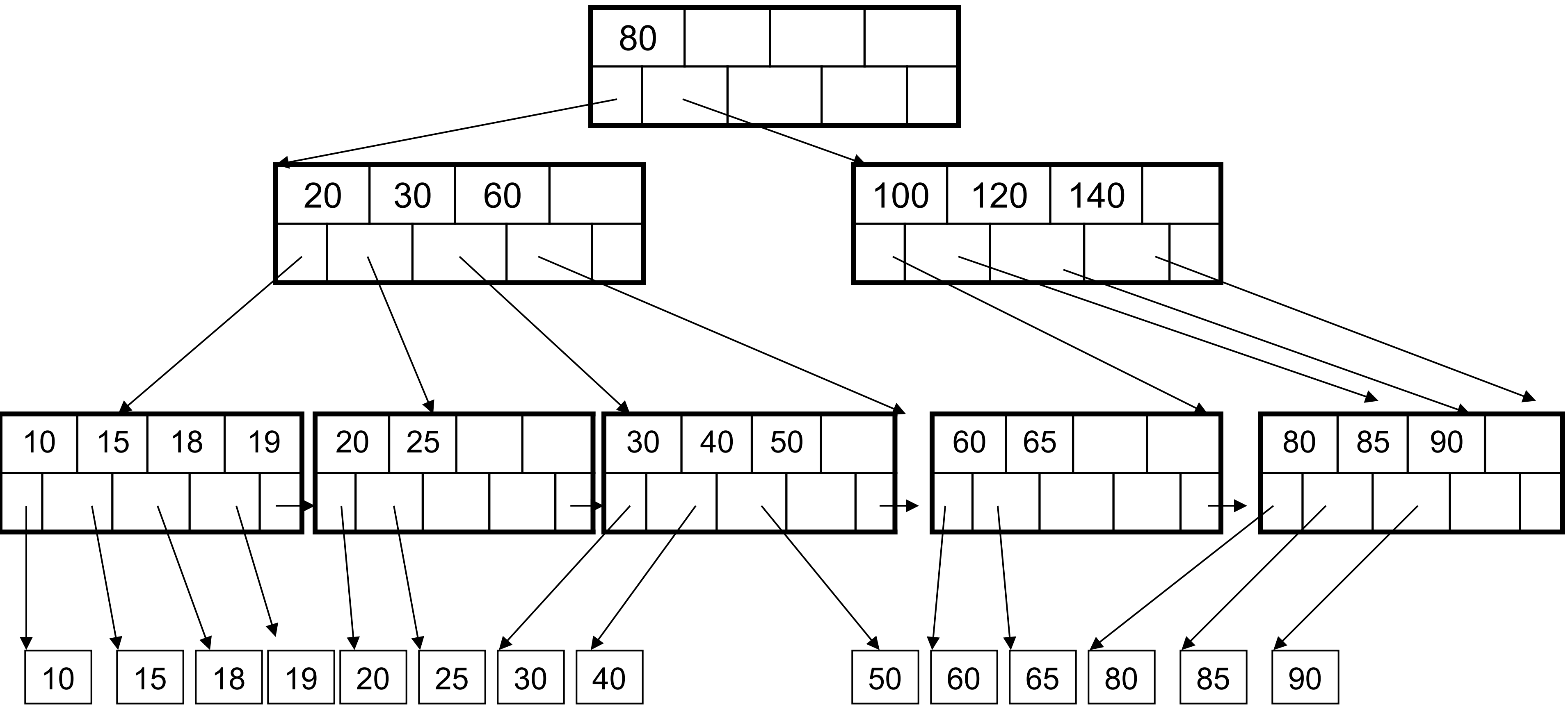
Insertion in a B+ Tree

But now have to split !



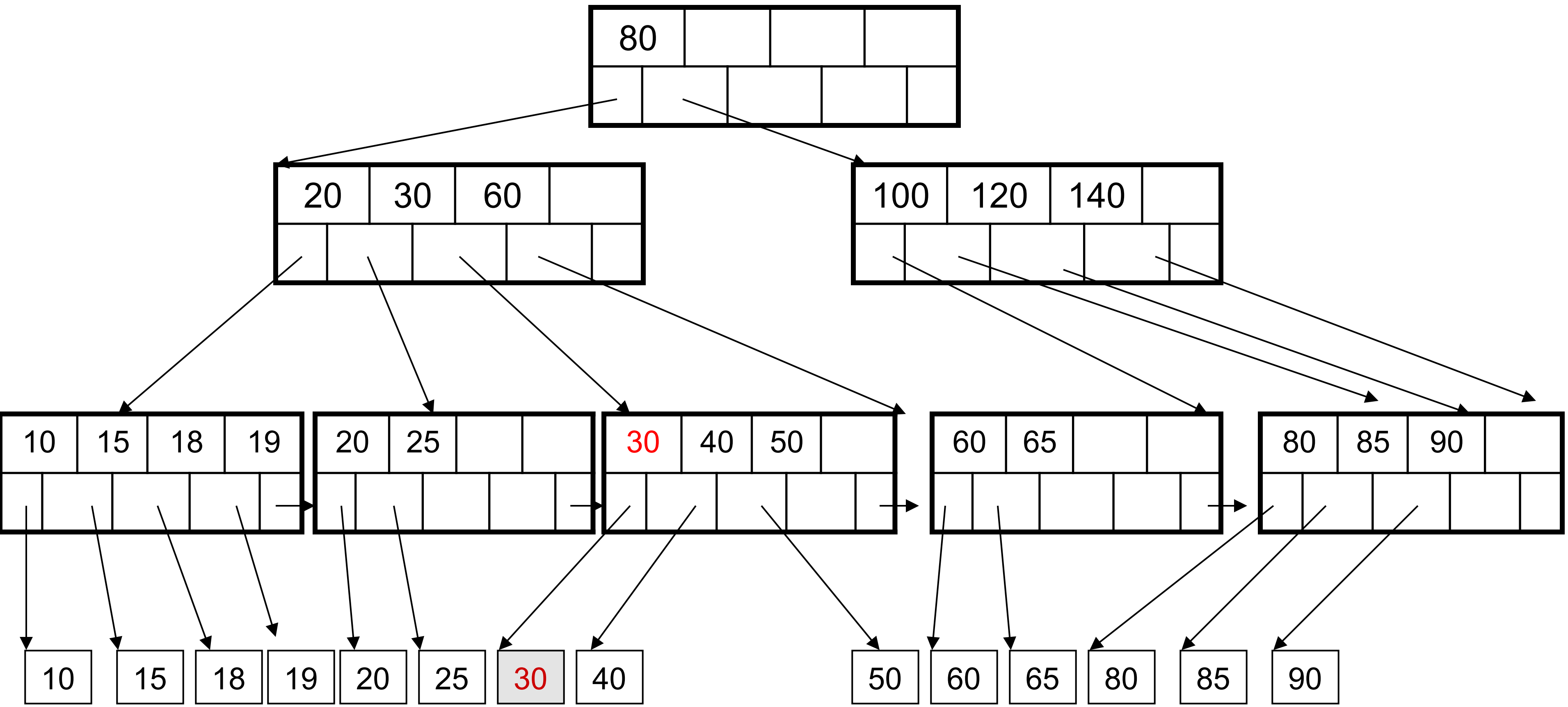
Insertion in a B+ Tree

After the split



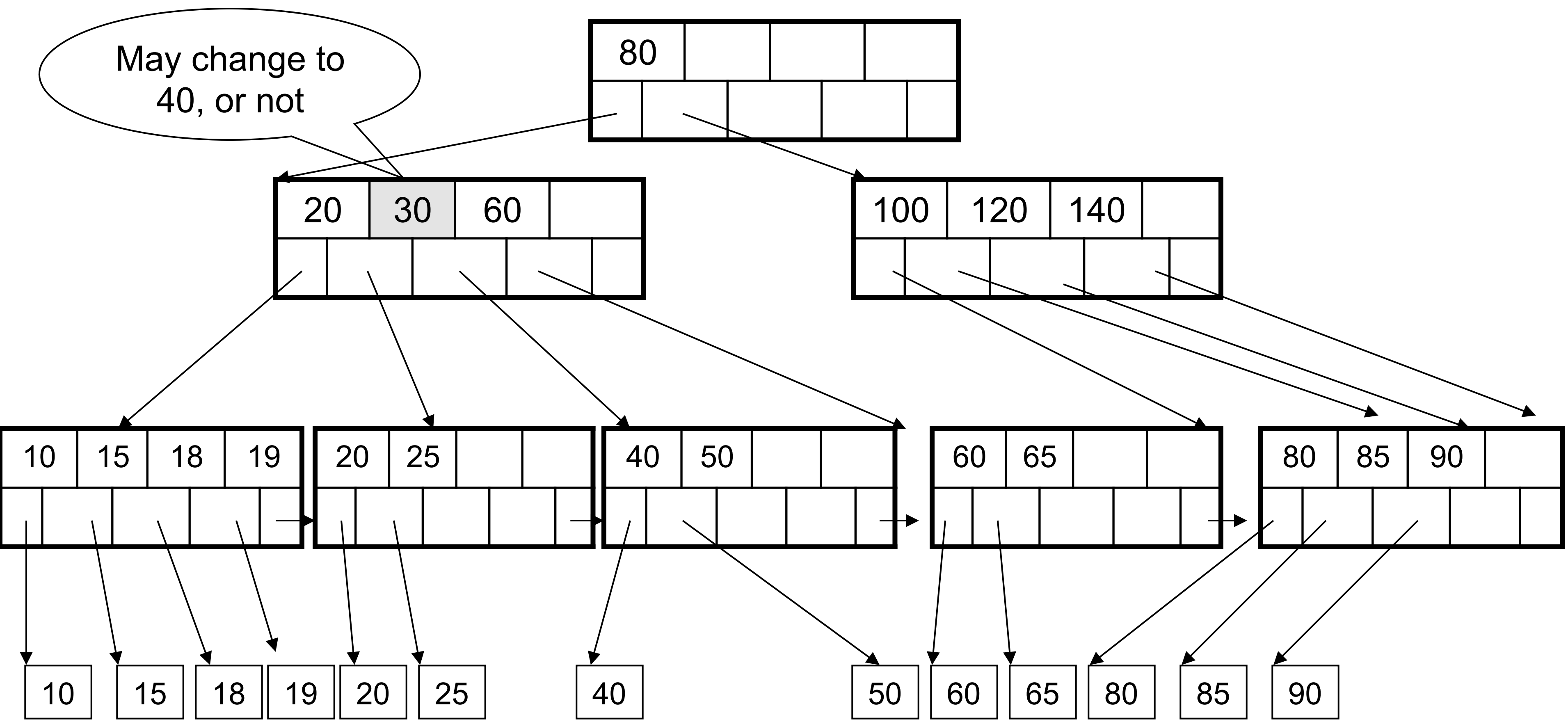
Deletion from a B+ Tree

Delete 30



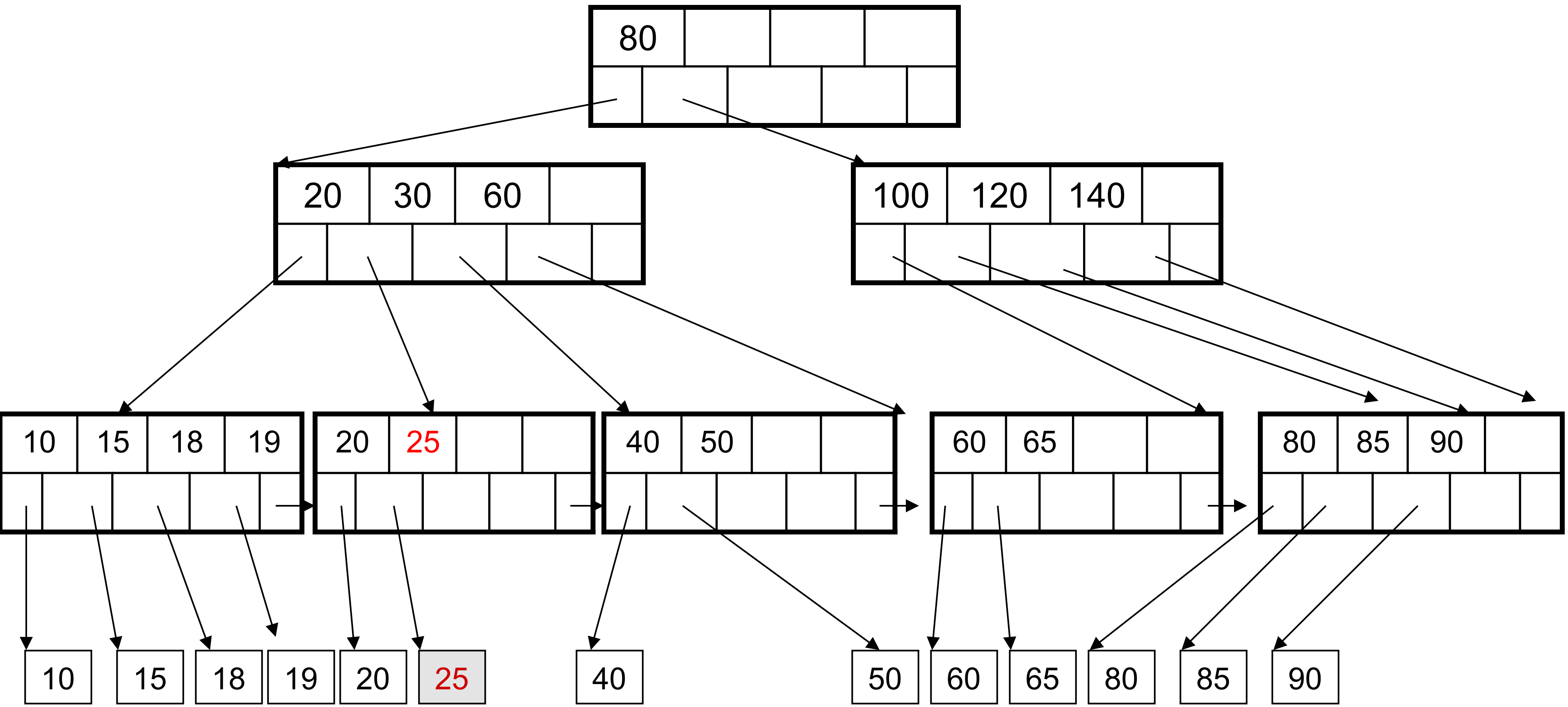
Deletion from a B+ Tree

After deleting 30



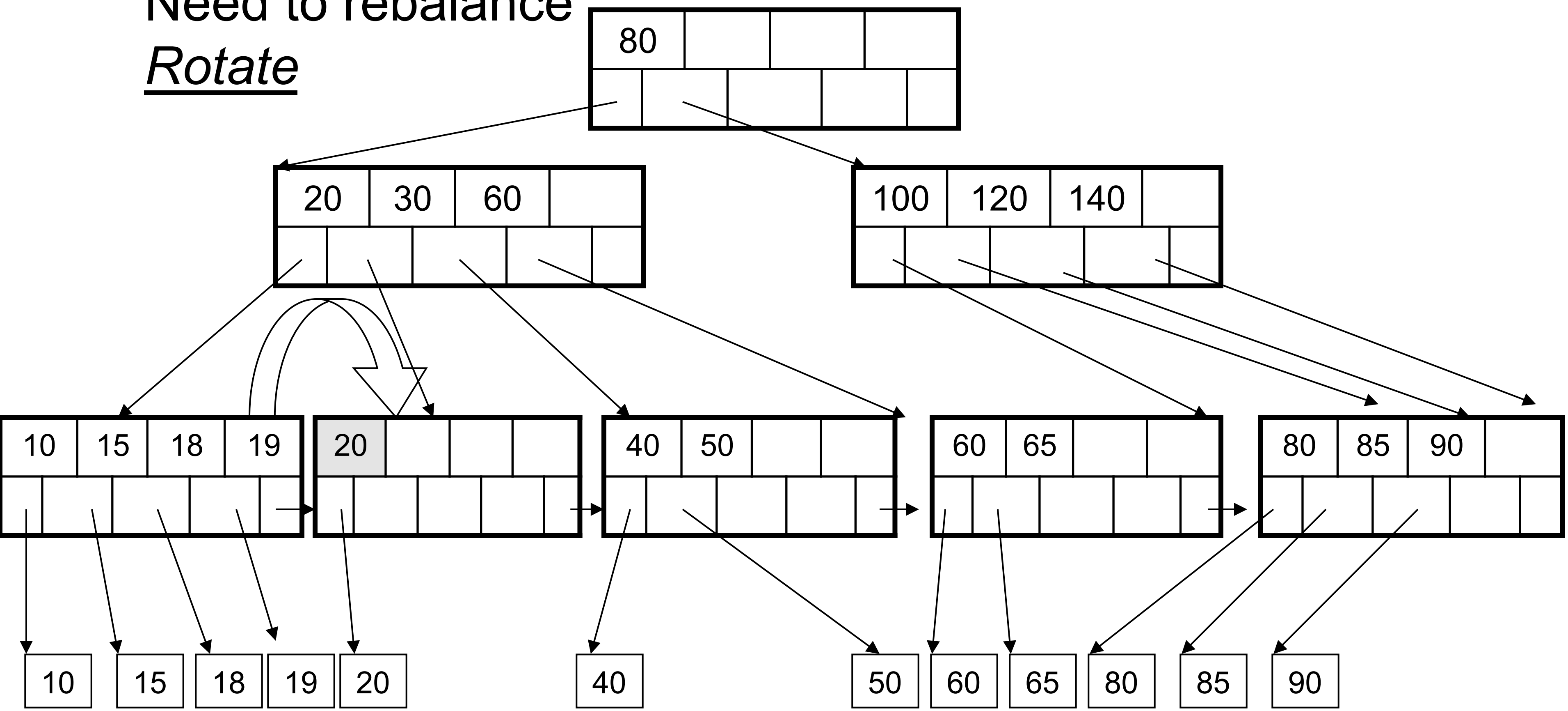
Deletion from a B+ Tree

Now delete 25



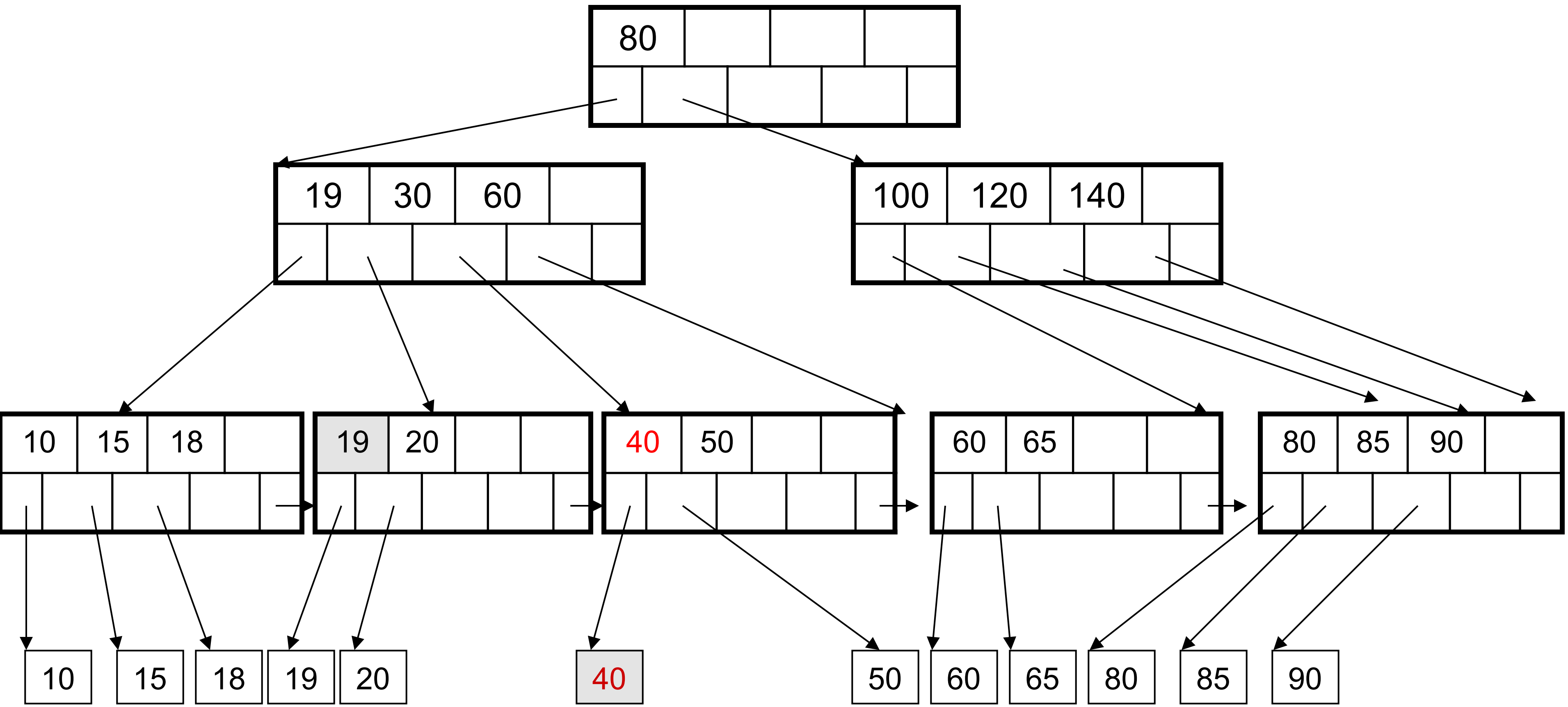
Deletion from a B+ Tree

After deleting 25
Need to rebalance
Rotate



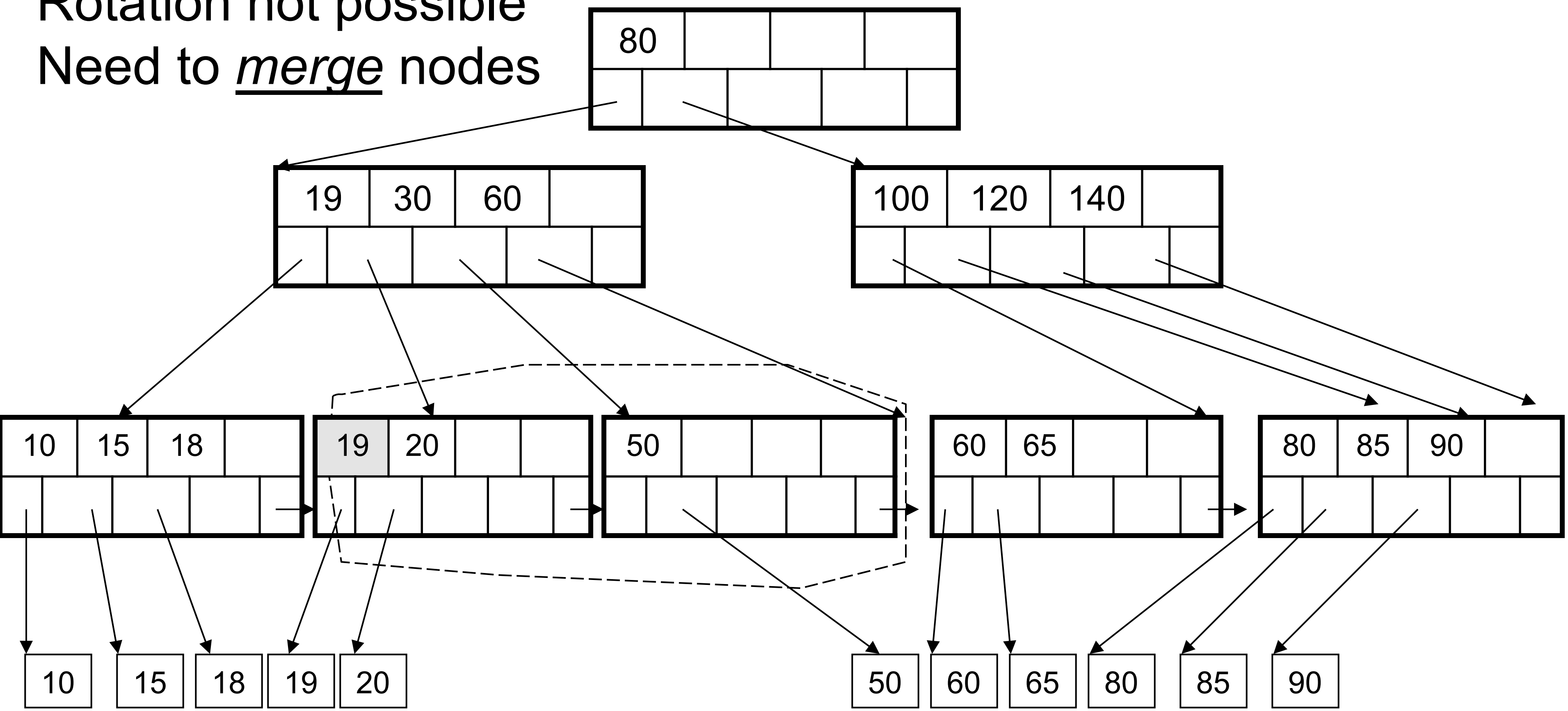
Deletion from a B+ Tree

Now delete 40



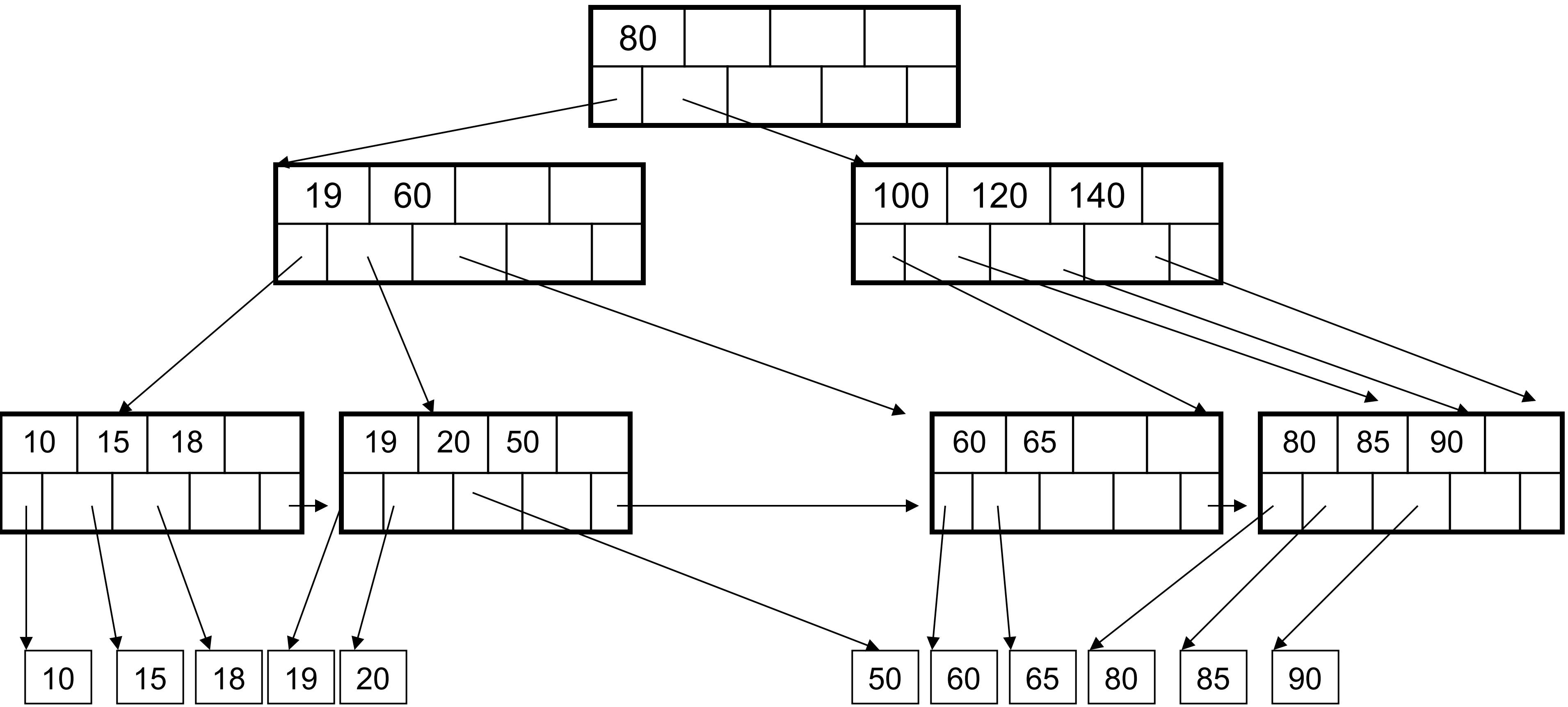
Deletion from a B+ Tree

After deleting 40
Rotation not possible
Need to *merge* nodes



Deletion from a B+ Tree

Final tree



B+ Tree Design

- How large d ?
- Example:
  - Key size = 4 bytes
  - Pointer size = 8 bytes
  - Block size = 4096 byes
- $2d \times 4 + (2d+1) \times 8 <= 4096$
- $d = 170$

B+ Trees in Practice

- Typical order: 100. Typical fill-factor: 67%
  - average fanout = 133
- Typical capacities
  - Height 4: 133^4 = 312,900,700 records
  - Height 3: 133^3 = 2,352,637 records
- Can often hold top levels in buffer pool
  - Level 1 = 1 page = 8 Kbytes
  - Level 2 = 133 pages = 1 Mbyte
  - Level 3 = 17,689 pages = 133 Mbytes

Practical Aspects of B+ Trees

Key compression:

- Each node keeps only the from parent keys
- Jonathan, John, Johnsen, Johnson … →
  - Parent: Jo
  - Child: nathan, hn, hnsen, hnson, …

Practical Aspects of B+ Trees

Bulk insertion

- When a new index is created there are two options:
  - Start from empty tree, insert each key one-by-one
  - Do *bulk insertion* – what does that mean ?

Practical Aspects of B+ Trees

Concurrency control

- The root of the tree is a “hot spot”
  - Leads to lock contention during insert/ delete
- Solution: do proactive split during insert, or proactive merge during delete
  - Insert/delete now require only one traversal, from the root to a leaf
  - Use the “tree locking” protocol

Summary on B+ Trees

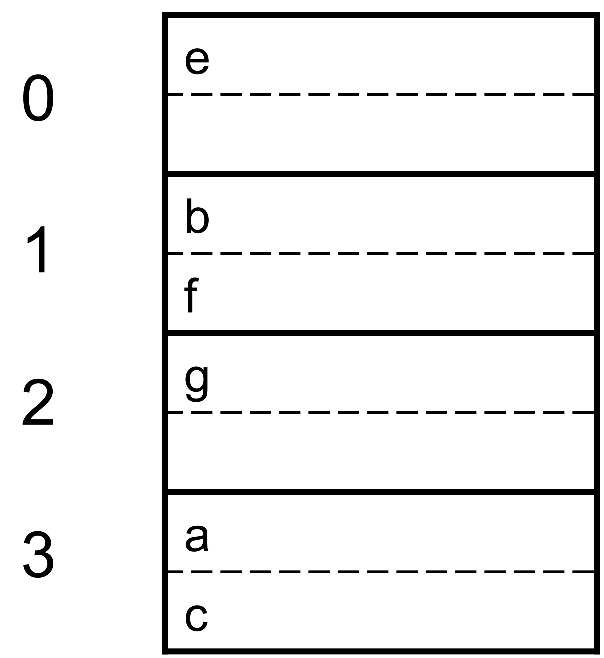
- Default index structure on most DBMS
- Very effective at answering ‘point’ queries:
  productName = ‘gizmo’
- Effective for range queries:
  50 < price AND price < 100
- Less effective for multirange:
  50 < price < 100 AND 2 < quant < 20

Hash Tables

- Secondary storage hash tables are much like main memory ones
- Recall basics:
  - There are n *buckets*
  - A hash function f(k) maps a key k to {0, 1, …, n-1}
  - Store in bucket f(k) a pointer to record with key k
- Secondary storage: bucket = block, use overflow blocks when needed

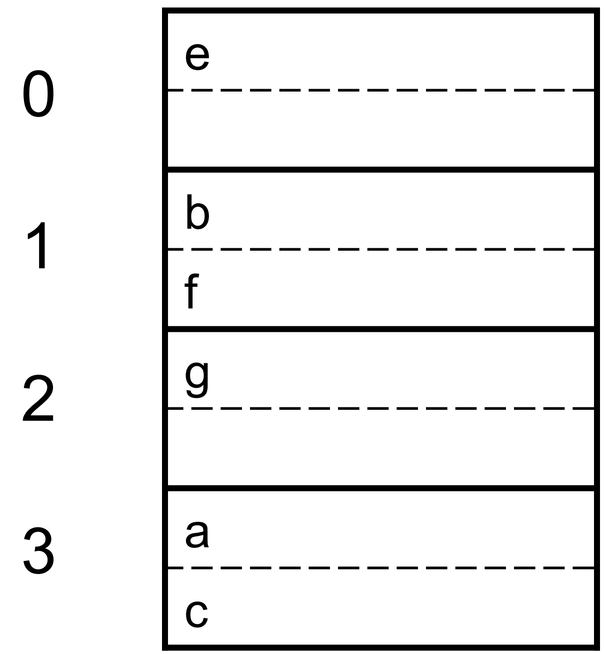
Hash Table Example

- Assume 1 bucket (block) stores 2 keys + pointers
- h(e)=0
- h(b)=h(f)=1
- h(g)=2
- h(a)=h(c)=3



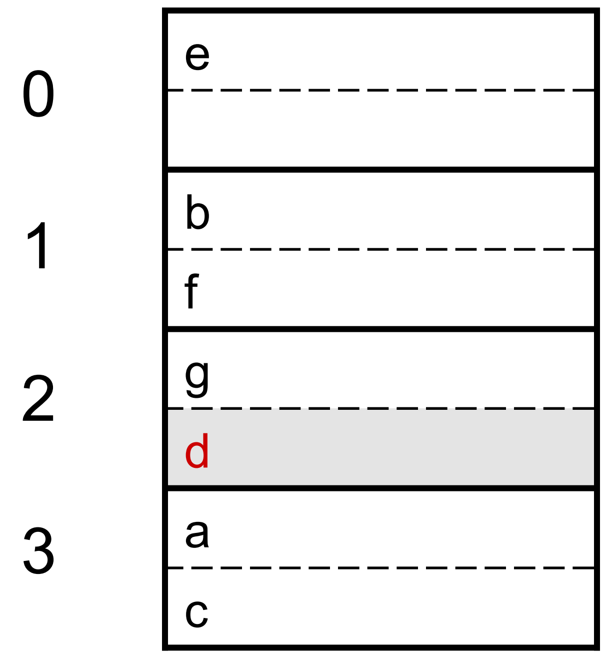
Searching in a Hash Table

- Search for a:
- Compute h(a)=3
- Read bucket 3
- 1 disk access



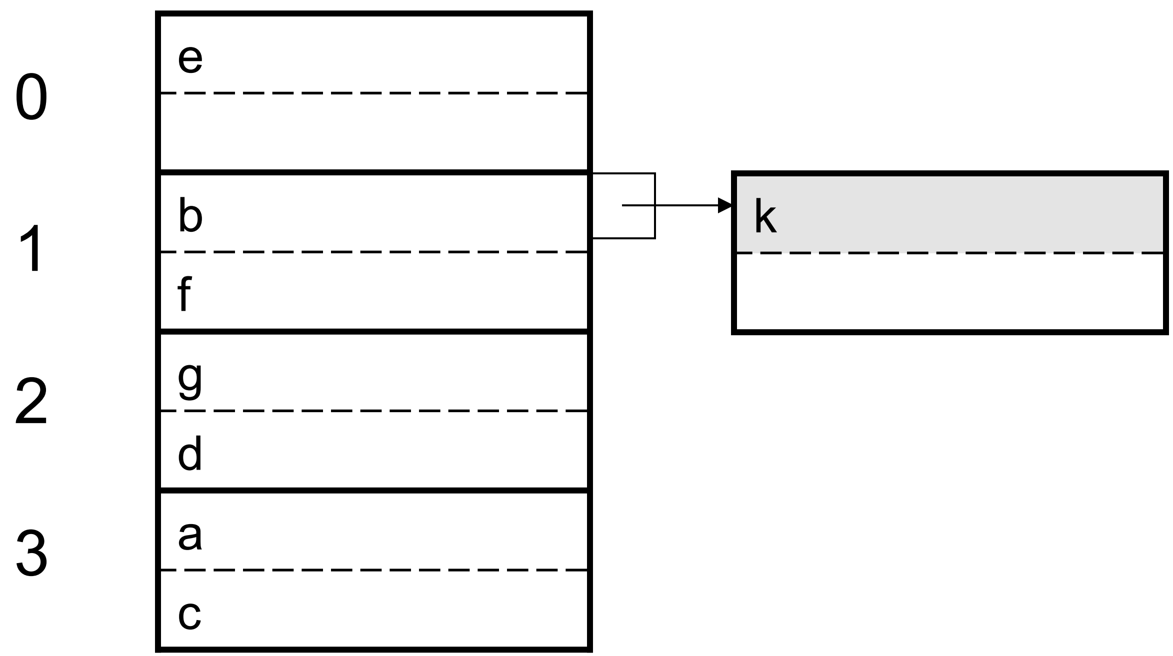
Insertion in Hash Table

- Place in right bucket, if space
- E.g. h(d)=2



Insertion in Hash Table

- Create overflow block, if no space
- E.g. h(k)=1



- More over-flow blocks may be needed

Hash Table Performance

- Excellent, if no overflow blocks
- Degrades considerably when number of keys exceeds the number of buckets (I.e. many overflow blocks).

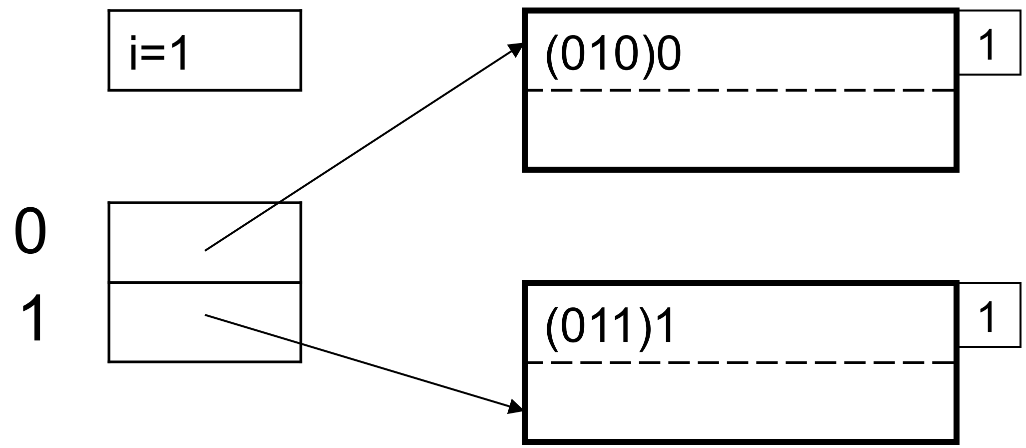
Extensible Hash Table

- Allows has table to grow, to avoid performance degradation
- Assume a hash function h that returns numbers in $\{0, \ldots, 2^k - 1\}$
- Start with $n = 2^i \ll 2^k$, only look at i least significant bits

Extensible Hash Table

- E.g. $i=1$, $n=2^i=2$, $k=4$

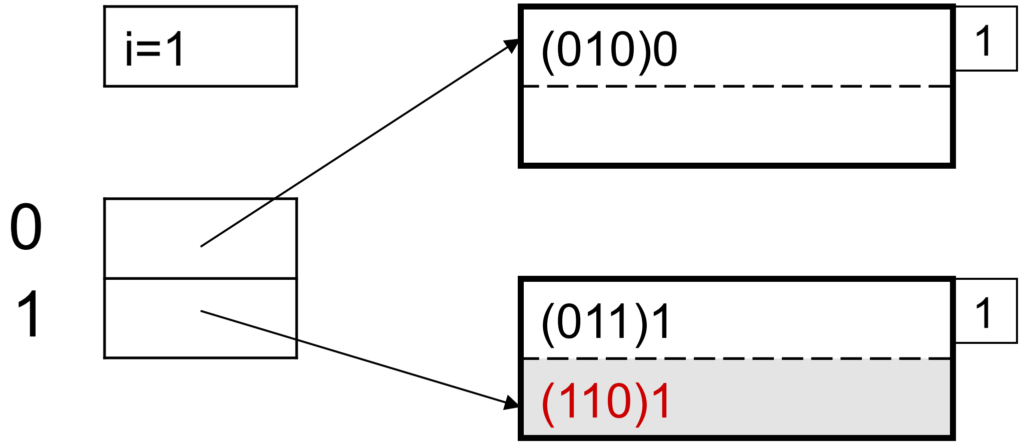
- Keys:
  - 4 (=0100)
  - 7 (=0111)



- Note: we only look at the last bit (0 or 1)

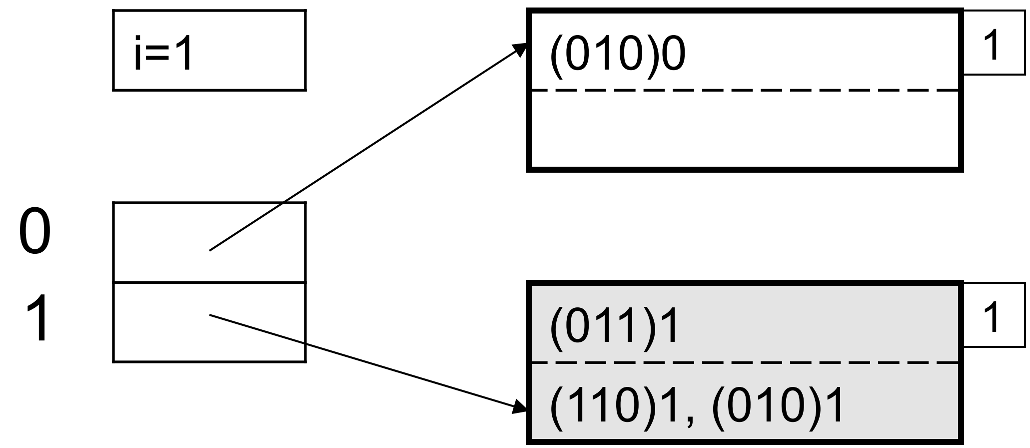
Insertion in Extensible Hash Table

- Insert 13 (=1101)



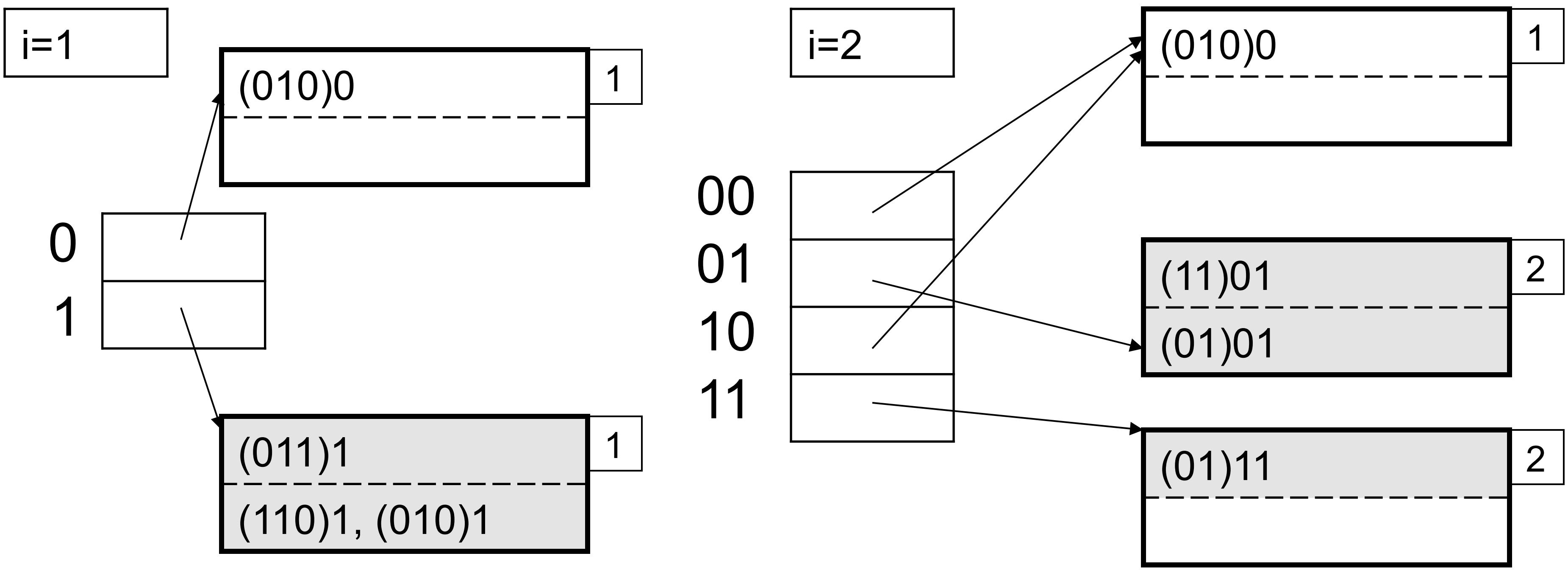
Insertion in Extensible Hash Table

- Now insert 0101



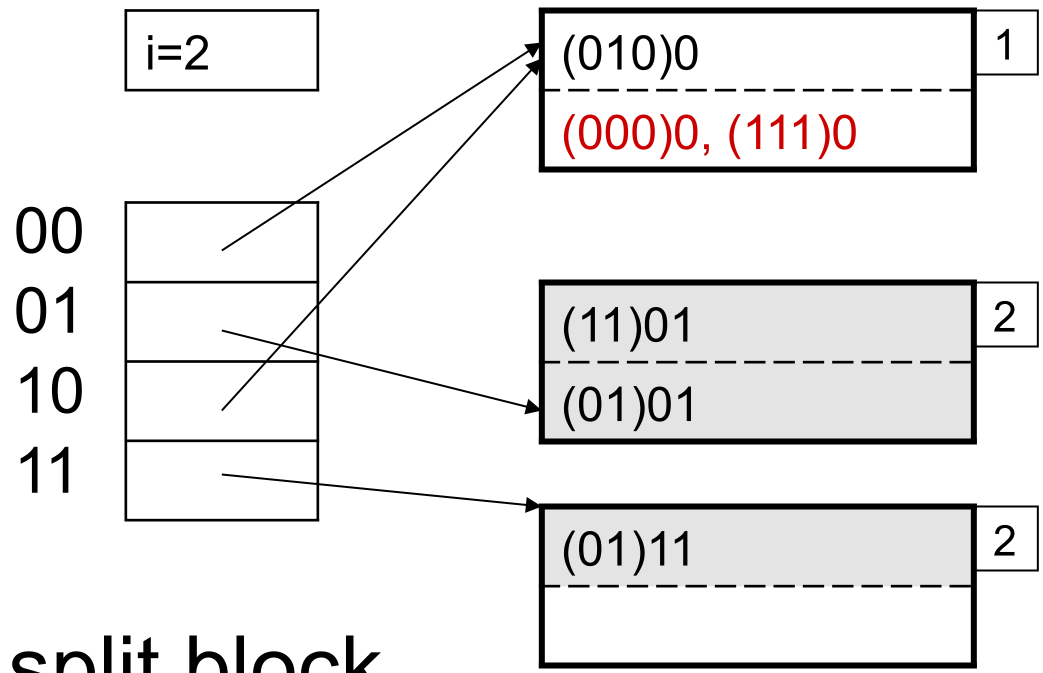
- Need to extend table, split blocks
- i becomes 2

Insertion in Extensible Hash Table



Insertion in Extensible Hash Table

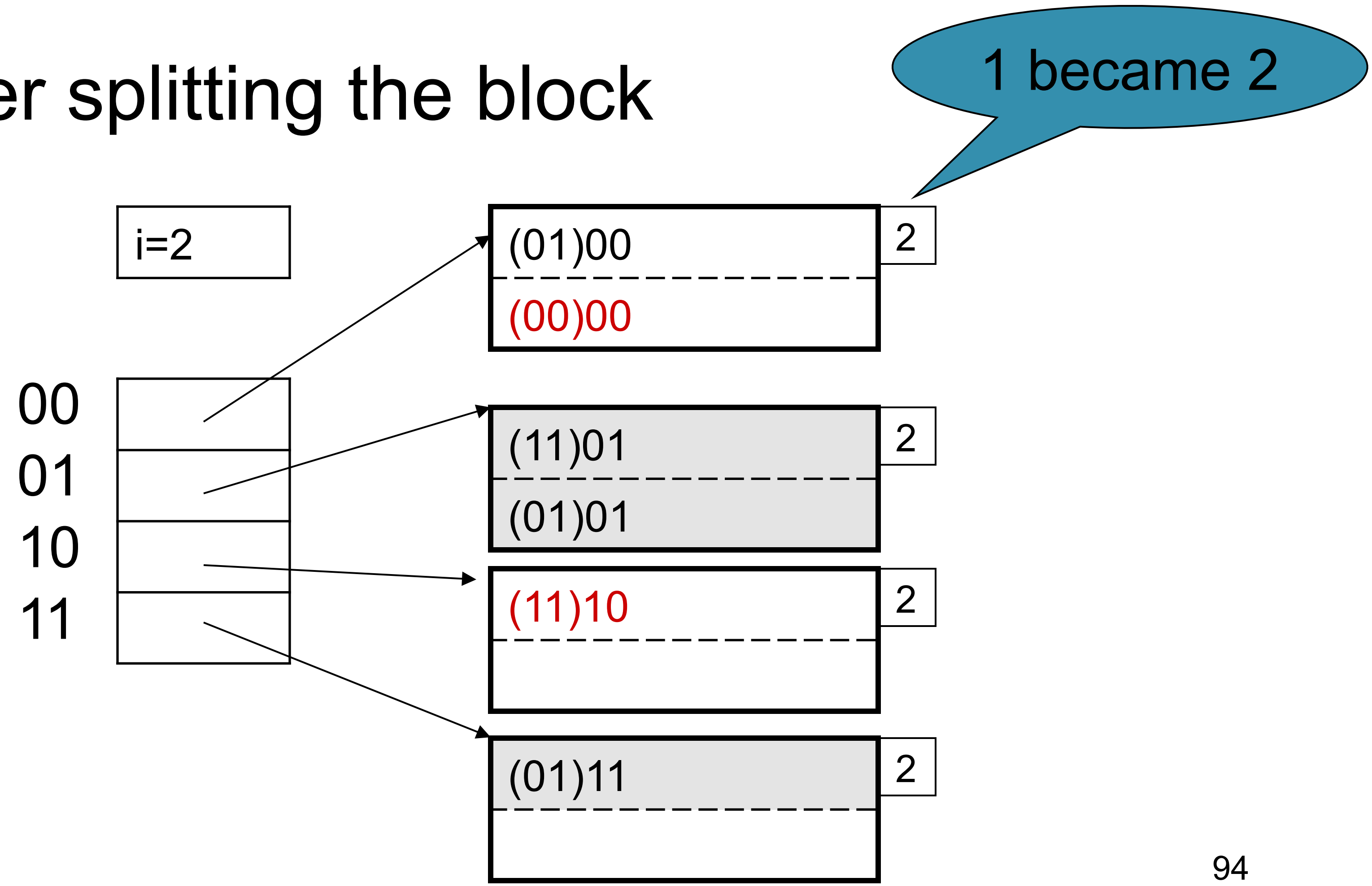
- Now insert 0000, 1110



- Need to split block

Insertion in Extensible Hash Table

- After splitting the block



Extensible Hash Table

- How many buckets (blocks) do we need to touch after an insertion ?

- How many entries in the hash table do we need to touch after an insertion ?

Performance Extensible Hash Table

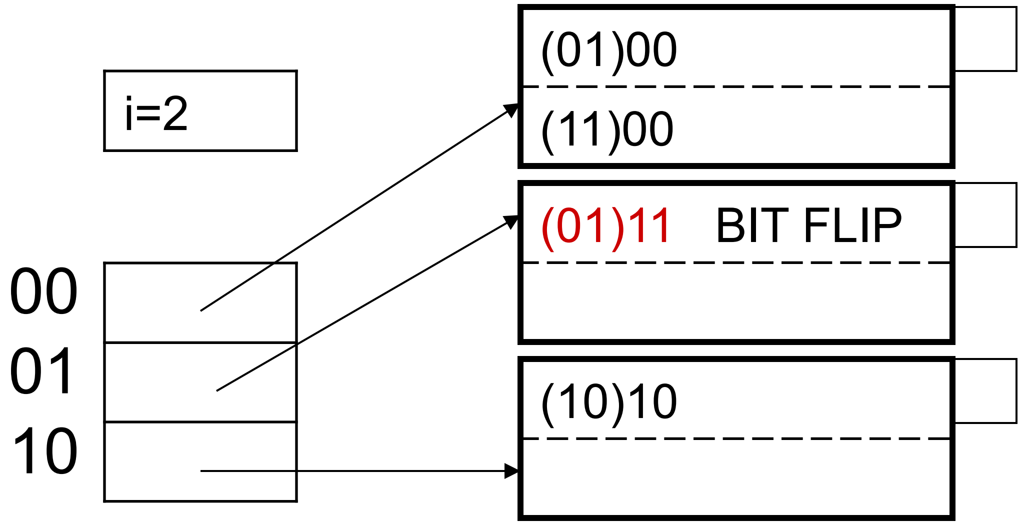
- No overflow blocks: access always one read
- BUT:
  - Extensions can be costly and disruptive
  - After an extension table may no longer fit in memory

Linear Hash Table

- Idea: extend only one entry at a time
- Problem: n= no longer a power of 2
- Let i be such that $2^i <= n < 2^{i+1}$
- After computing h(k), use last i bits:
  - If last i bits represent a number > n, change msb from 1 to 0 (get a number <= n)

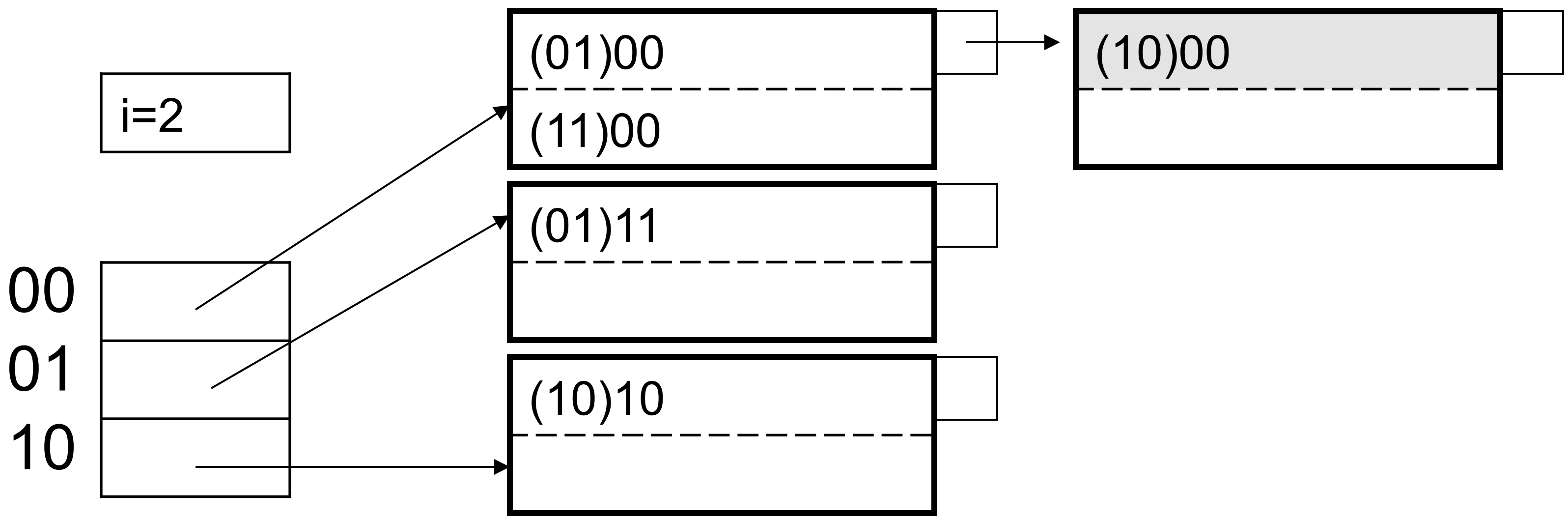
Linear Hash Table Example

- n=3



Linear Hash Table Example

- Insert 1000: overflow blocks…

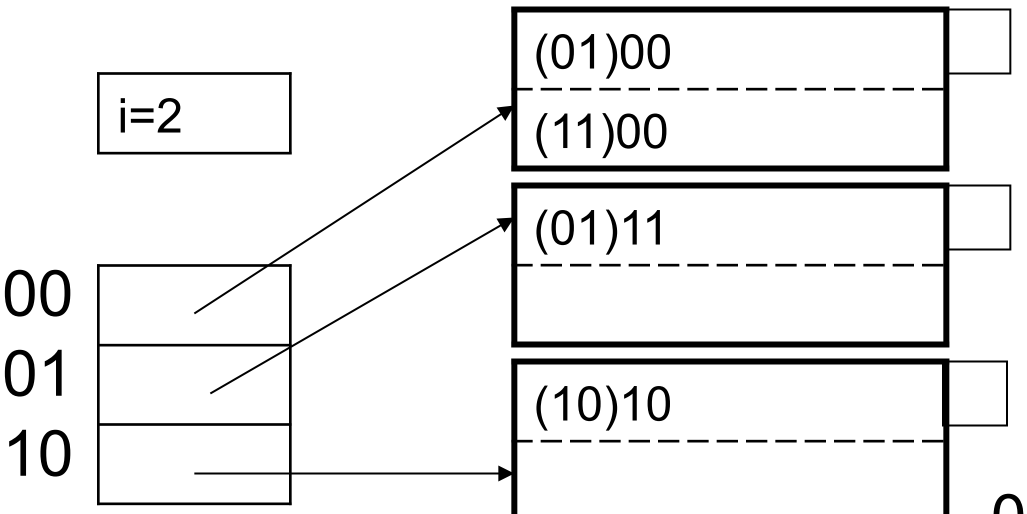


Linear Hash Tables

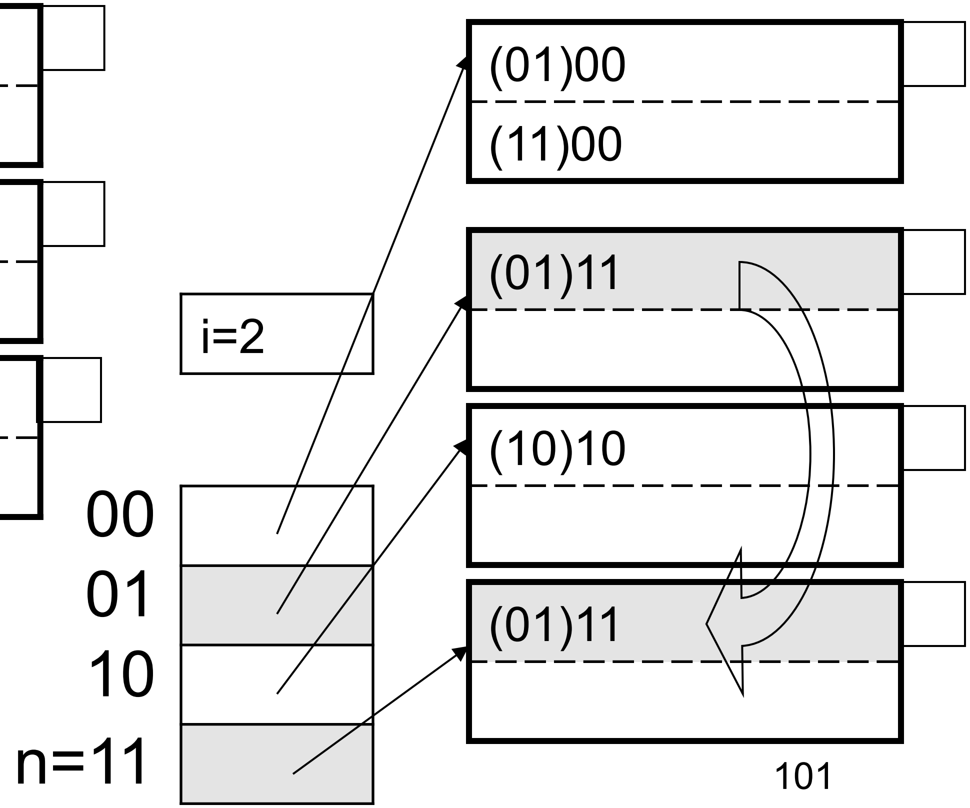
- Extension: independent on overflow blocks
- Extend n:=n+1 when average number of records per block exceeds (say) 80%

Linear Hash Table Extension

- From n=3 to n=4

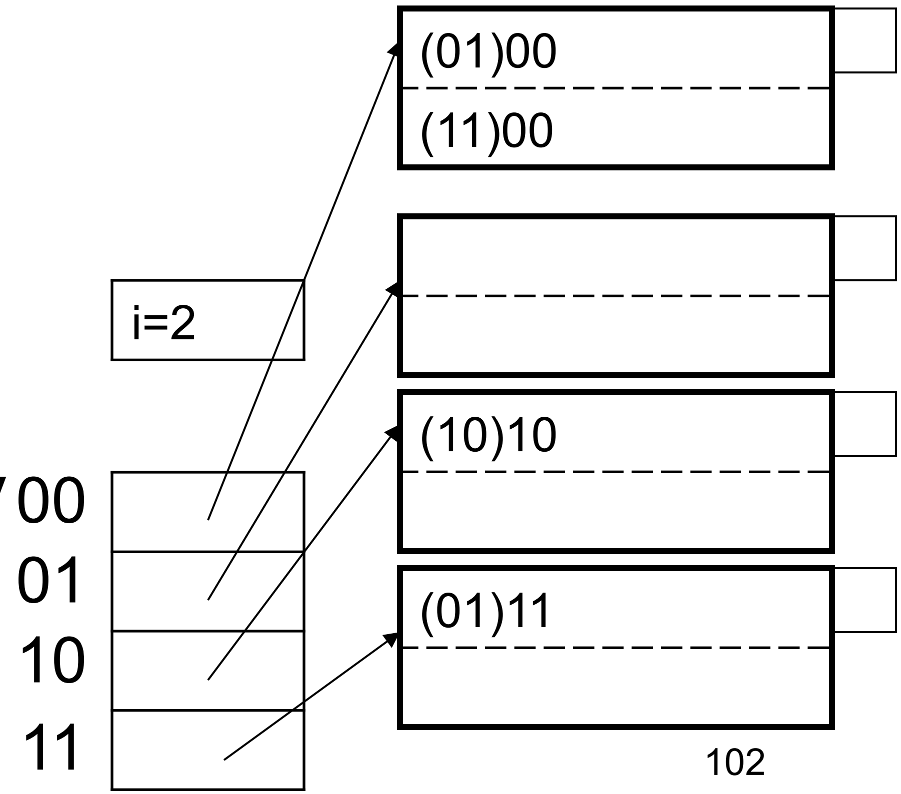


- Only need to touch one block (which one ?)



Linear Hash Table Extension

- From n=3 to n=4 finished
- Extension from n=4 to n=5 (new bit)
- Need to touch every single block (why ?)



Indexes in Postgres

```
CREATE TABLE   V(M int,   N varchar(20),    P int);
```

```
CREATE INDEX V1_N ON V(N)
```

```
CREATE INDEX V2 ON V(P, M)
```

```
CREATE INDEX VVV ON V(M, N)
```

```
CLUSTER V USING V2
```

Makes V2 clustered

Index Selection Problem 1

```
V(M, N, P);
```

Your workload is this

100000 queries:

```
SELECT *
FROM V
WHERE N=?
```

100 queries:

```
SELECT *
FROM V
WHERE P=?
```

Which indexes should we create?

Index Selection Problem 1

```
V(M, N, P);
```

Your workload is this

100000 queries:

```
SELECT *
FROM V
WHERE N=?
```

100 queries:

```
SELECT *
FROM V
WHERE P=?
```

A: V(N) and V(P) (hash tables or B-trees)

Index Selection Problem 2

```
V(M, N, P);
```

Your workload is this

100000 queries:

```
SELECT *
FROM V
WHERE N>? and N<?
```

100 queries:

```
SELECT *
FROM V
WHERE P=?
```

100000 queries:

```
INSERT INTO V
VALUES (?, ?, ?)
```

Which indexes should we create?

Index Selection Problem 2

V(M, N, P);

Your workload is this

100000 queries:

```
SELECT *
FROM V
WHERE N>? and N<?
```

100 queries:

```
SELECT *
FROM V
WHERE P=?
```

100000 queries:

```
INSERT INTO V
VALUES (?, ?, ?)
```

A: definitely V(N) (must B-tree); unsure about V(P)

Index Selection Problem 3

```
V(M, N, P);
```

Your workload is this

100000 queries:

```
SELECT *
FROM V
WHERE N=?
```

1000000 queries:

```
SELECT *
FROM V
WHERE N=? and P>?
```

100000 queries:

```
INSERT INTO V
VALUES (?, ?, ?)
```

Which indexes should we create?

Index Selection Problem 3

```
V(M, N, P);
```

Your workload is this

100000 queries:

```
SELECT *
FROM V
WHERE N=?
```

1000000 queries:

```
SELECT *
FROM V
WHERE N=? and P>?
```

100000 queries:

```
INSERT INTO V
VALUES (?, ?, ?)
```

A: V(N, P)

Index Selection Problem 4

V(M, N, P);

Your workload is this

1000 queries:

```
SELECT *
FROM V
WHERE N>? and N<?
```

100000 queries:

```
SELECT *
FROM V
WHERE P>? and P<?
```

Which indexes should we create?

Index Selection Problem 4

V(M, N, P);

Your workload is this

1000 queries:

```
SELECT *
FROM V
WHERE N>? and N<?
```

100000 queries:

```
SELECT *
FROM V
WHERE P>? and P<?
```

A: V(N) secondary, V(P) primary index

The Index Selection Problem

- SQL Server
  - Automatically, thanks to *AutoAdmin* project
  - Much acclaimed successful research project from mid 90's, similar ideas adopted by the other major vendors
- PostgreSQL
  - You will do it manually, part of homework 5
  - But tuning wizards also exist

Index Selection: Multi-attribute Keys

Consider creating a multi-attribute key on K1, K2, … if

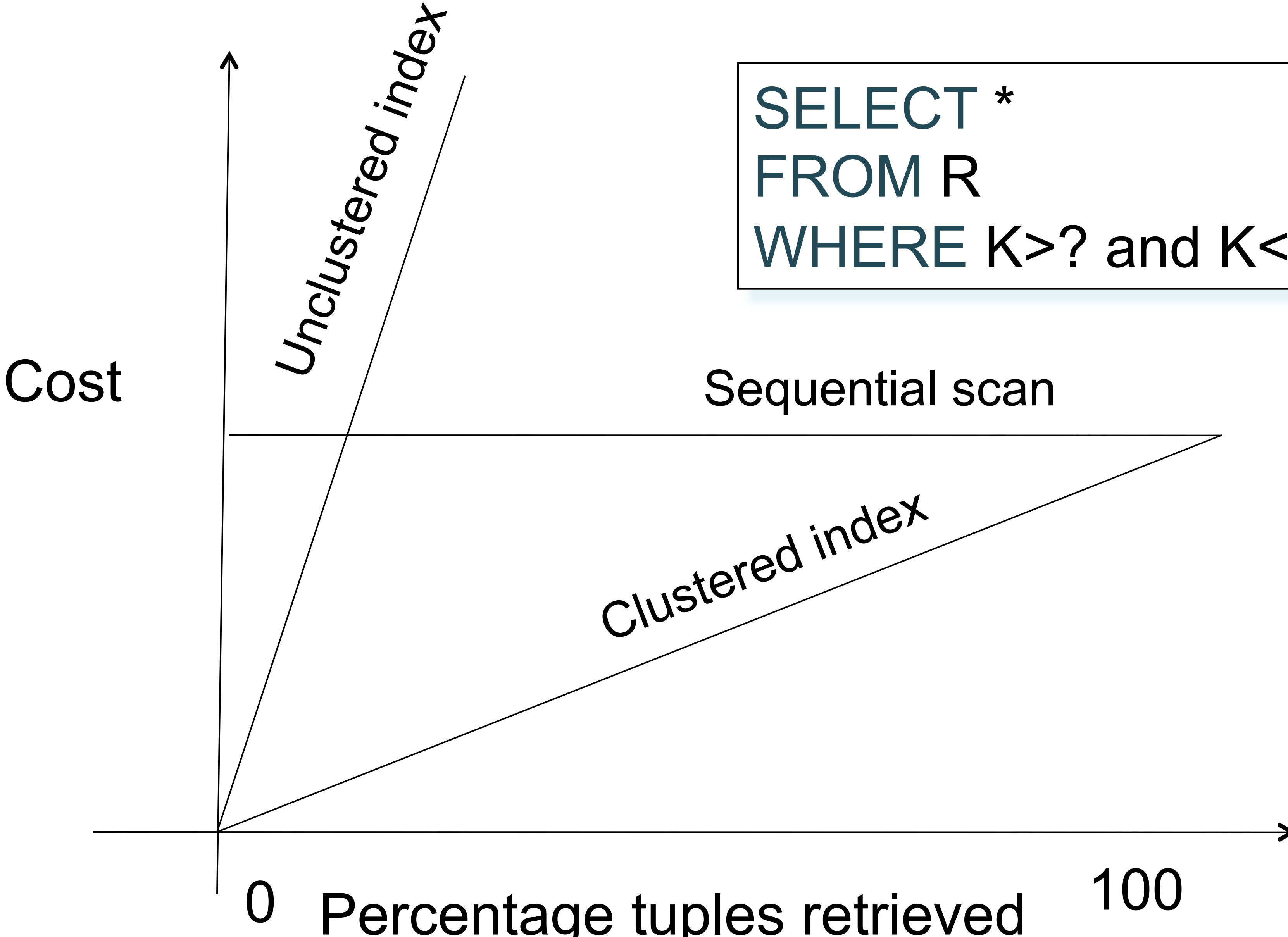
- WHERE clause has matches on K1, K2, …
  - But also consider separate indexes
- SELECT clause contains only K1, K2, ..
  - A *covering index* is one that can be used exclusively to answer a query, e.g. index

```
SELECT K2 FROM R WHERE K1=55
```

To Cluster or Not

- Range queries benefit mostly from clustering
- Covering indexes do *not* need to be clustered: they work equally well unclustered

```
SELECT *
FROM R
WHERE K>? and K<?
```



Hash Table v.s. B+ tree

- Rule 1: always use a B+ tree ☺

- Rule 2: use a Hash table on K when:
  - There is a very important selection query on equality (WHERE K=?), and no range queries
  - You know that the optimizer uses a nested loop join where K is the join attribute of the inner relation (you will understand that in a few lectures)

Balance Queries v.s. Updates

- Indexes speed up queries
  - SELECT FROM WHERE
- But they usually slow down updates:
  - INSERT, DELECTE, UPDATE
  - However some updates benefit from indexes

```
UPDATE R
   SET A = 7
   WHERE K=55
```

Tools for Index Selection

- SQL Server 2000 Index Tuning Wizard
- DB2 Index Advisor

- How they work:
  – They walk through a large number of configurations, compute their costs, and choose the configuration with minimum cost