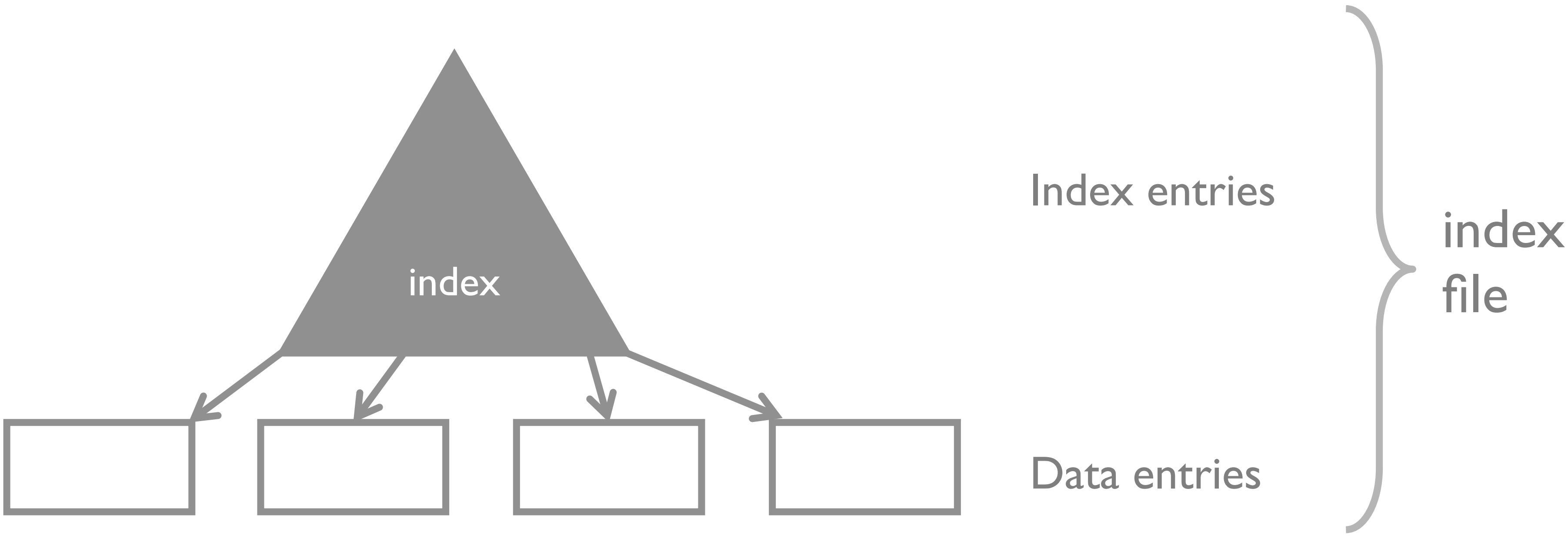
# L20
# Indexing Continued

# High level index structure




What is a data entry?

actual data record

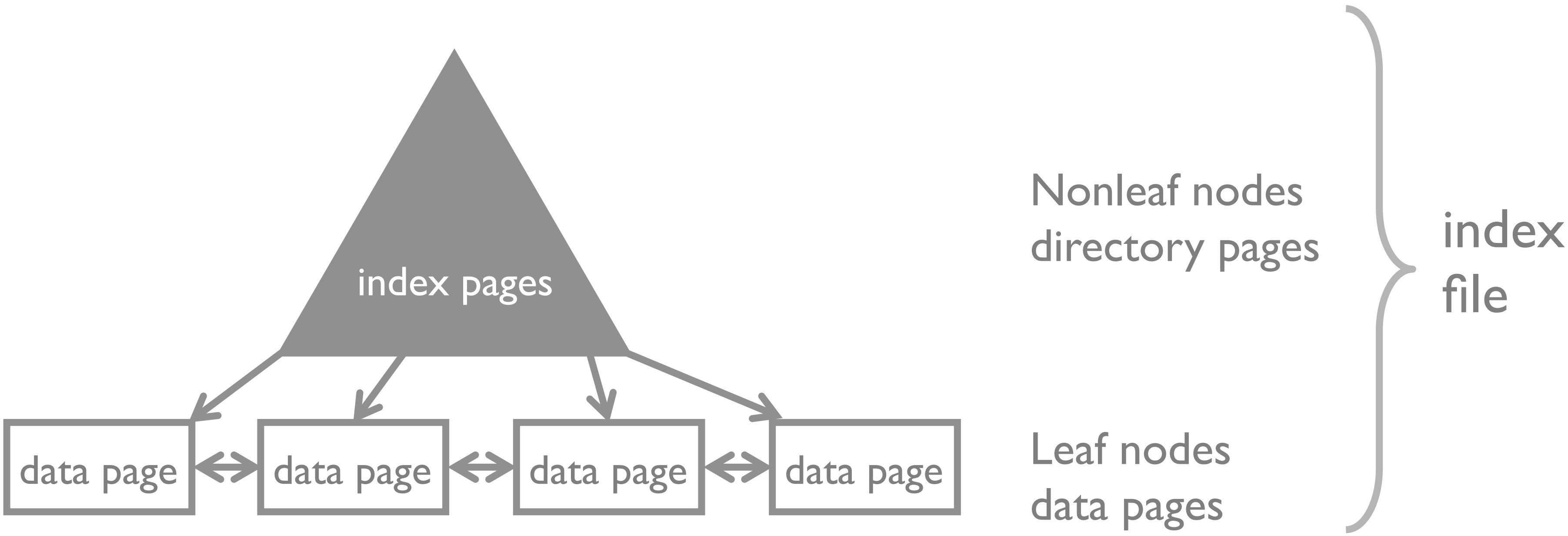
<search key value, rid>

Tradeoffs

directly access tuple.

compact, fixed size entries

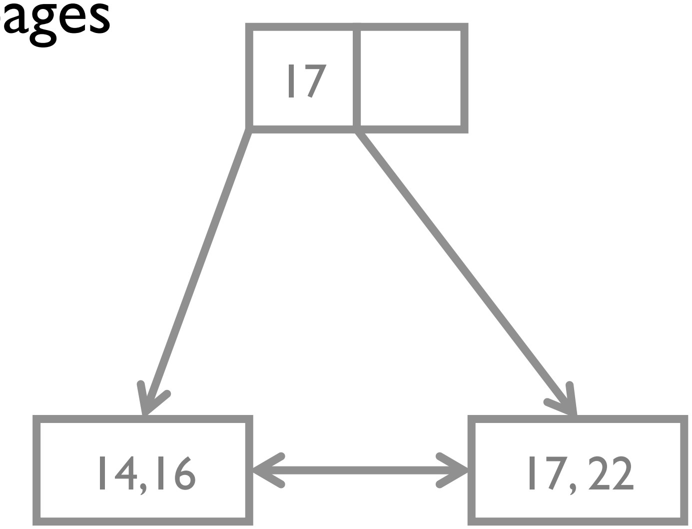
# B+ Tree Index




Node = Page
Equality and range queries
Self balancing
Leaf nodes are connected
Disk optimized

# B+ Tree on (age)

Non-leaf directory pages
m index entries
m+1 pointers

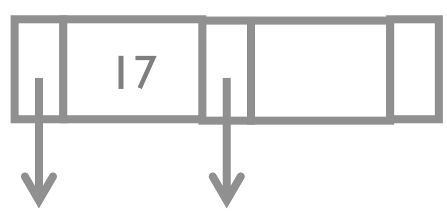



index & data
page contents
are in order

Leaf Data pages
data entries/tuples

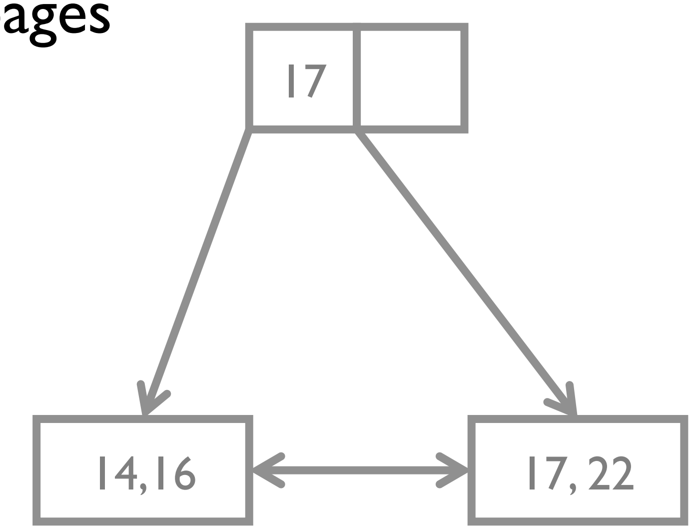
Query: SELECT * WHERE age= 14

directory page



# Index Only Queries: B+ Tree on (age)

**Non-leaf directory pages**
m index entries
m+1 pointers

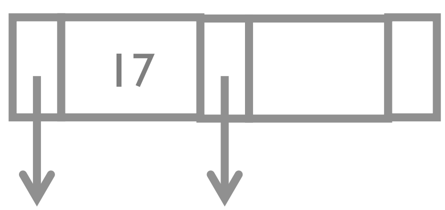



index & data
page contents
are in order

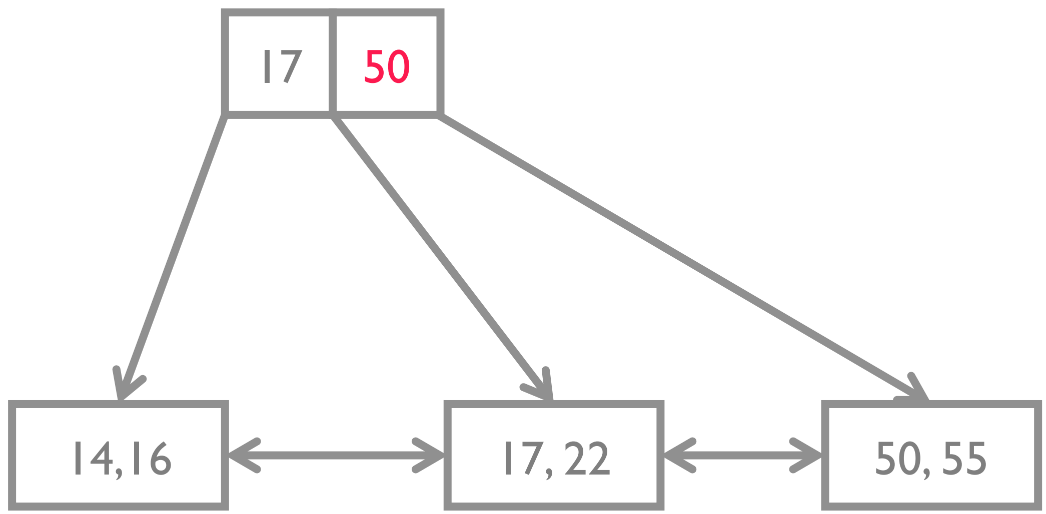
**Leaf Data pages**
data entries/tuples

Query: SELECT age WHERE age = 14
(index only!)

directory page

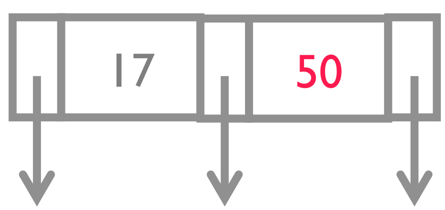


# B+ Tree on (age)

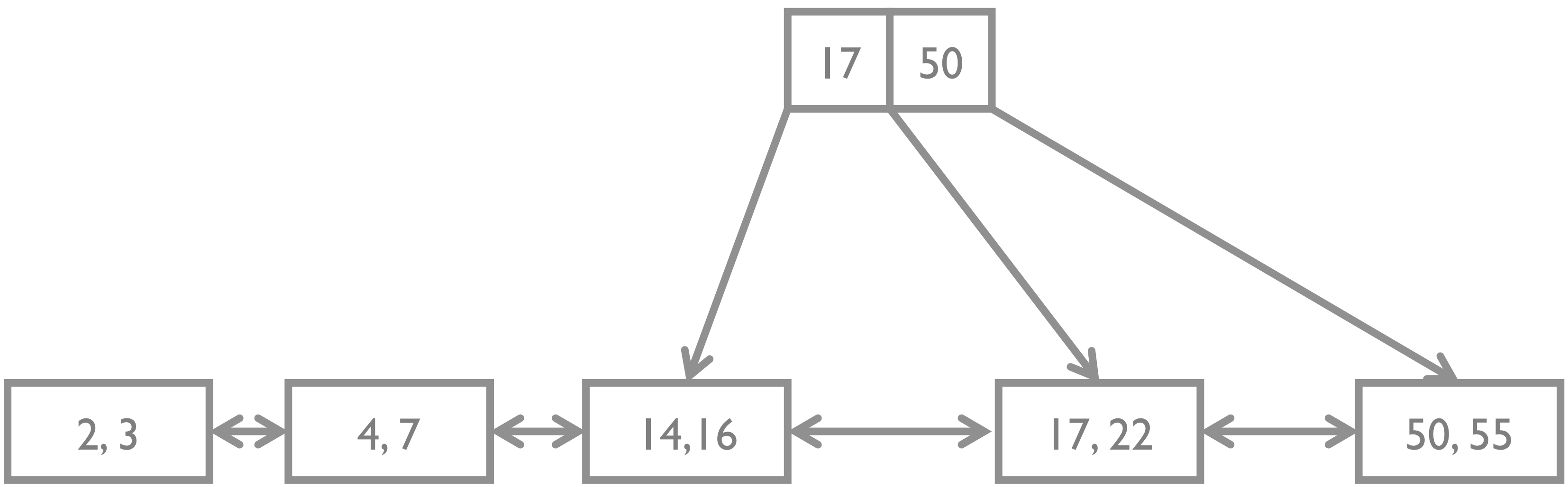



Query: SELECT * WHERE age = 50

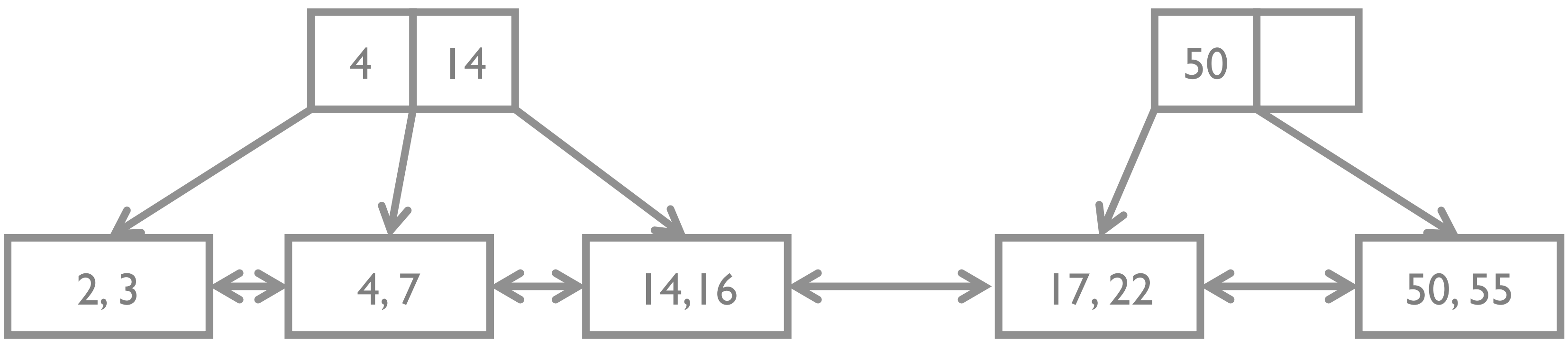
directory page



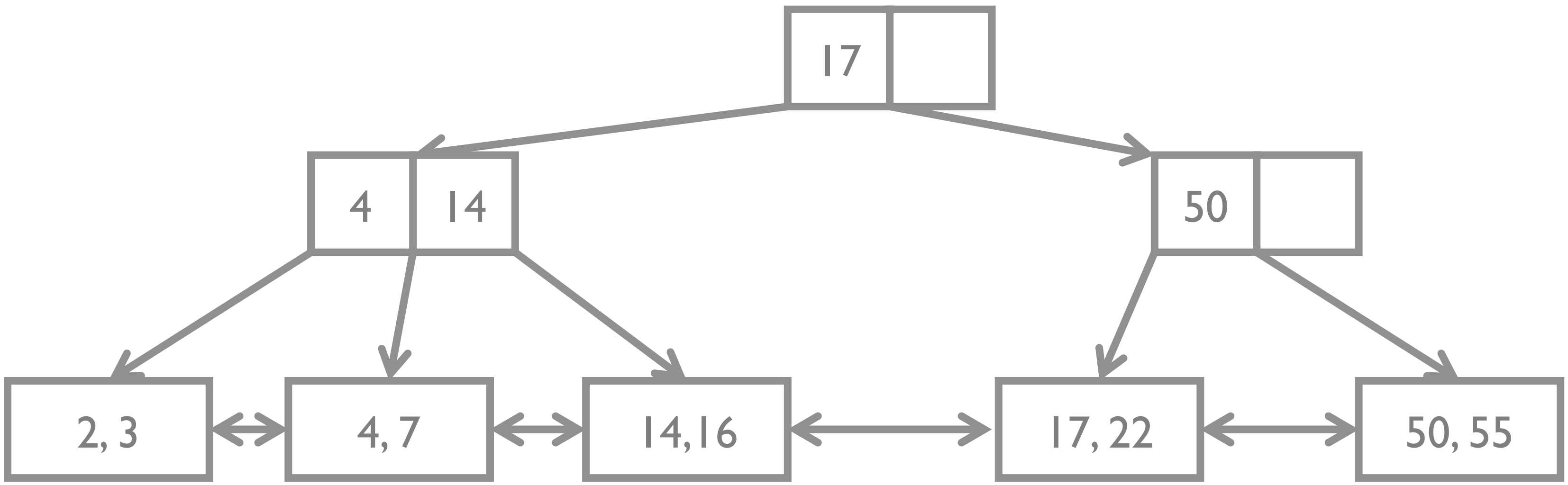
# B+ Tree on (age)



# B+ Tree on (age)

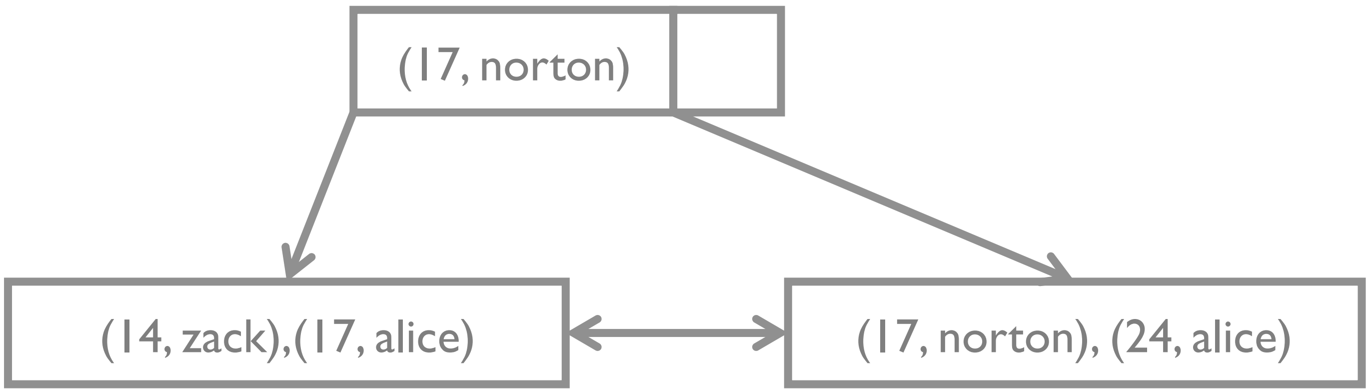


# B+ Tree on (age)




Query: SELECT * WHERE age > 15

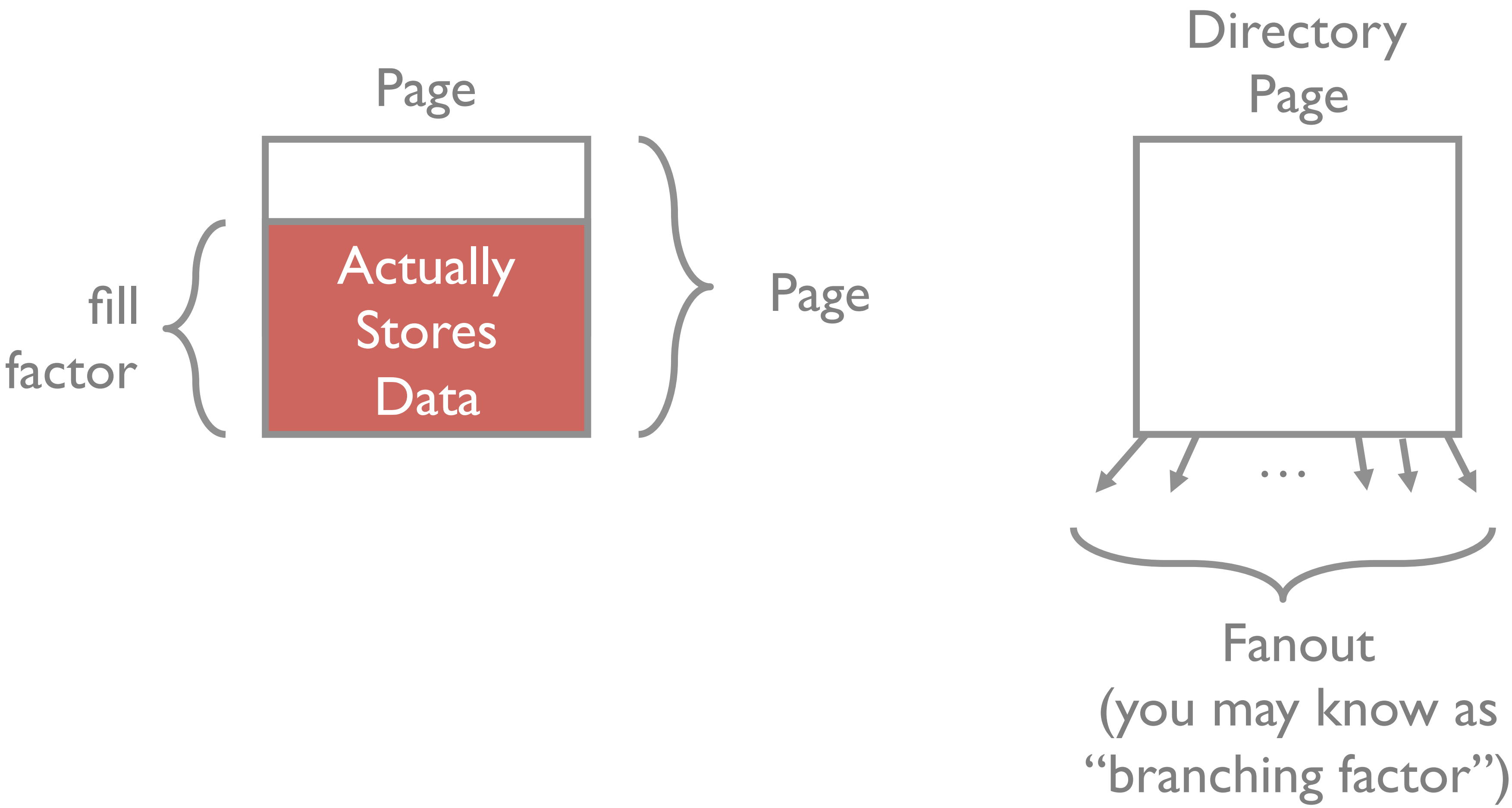
# B+ Tree on (age, name)




How do the following queries use the index on (age, name)?

```
SELECT age   WHERE age = 14
SELECT *     WHERE age < 18 AND name < 'monica'
SELECT age   WHERE name = 'bobby'
```

# Terminology



# Some numbers (8kb pages)

How many levels?

- fill-factor: ~66%
- ~300 entries per directory page

- height 2: $300^3$ $\sim$ 27 Million entries
- height 3: $300^4$ $\sim$ 8.1 Billion entries

Top levels often in memory

- height 2 only 300 pages ~2.4MB
- height 3 only 90k pages ~750MB

Cool B+Tree viz: https://www.cs.usfca.edu/~galles/visualization/BPlusTree.html

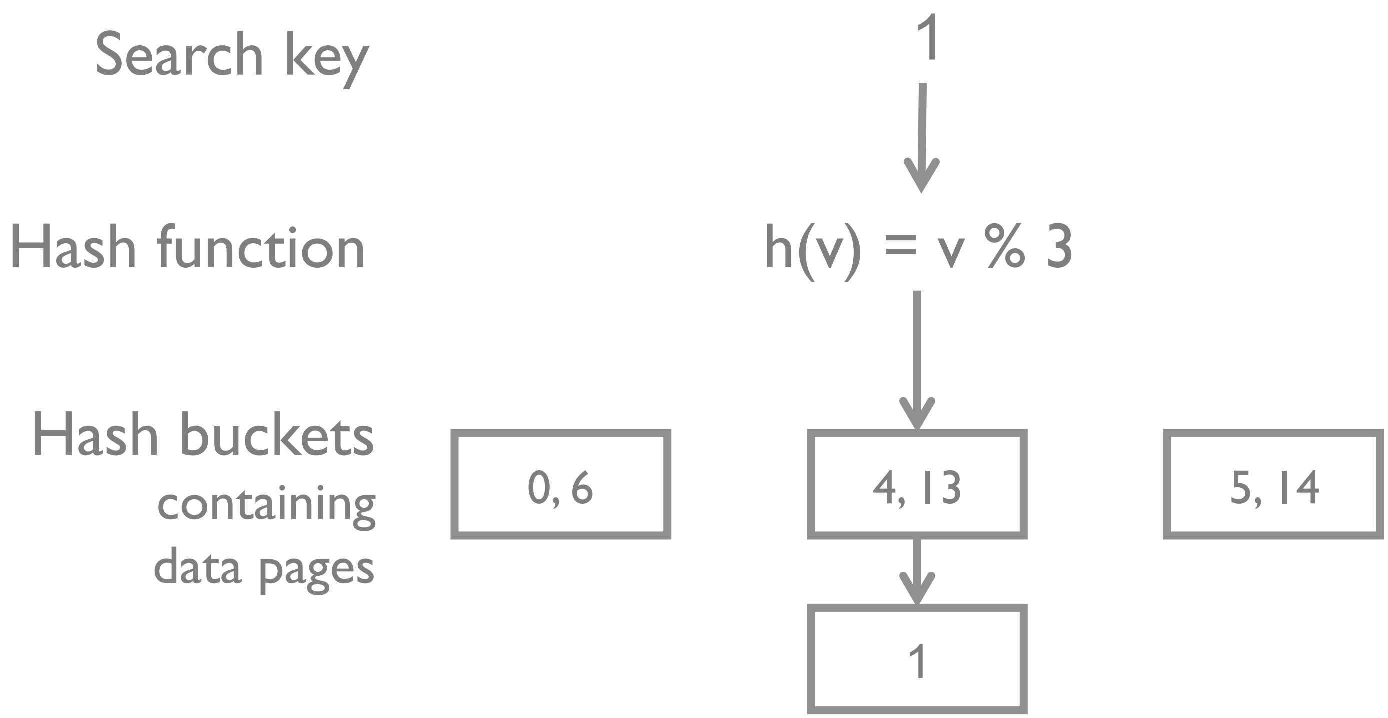
# Hash Index on age

Hash function $h(v) = v \% 3$

Hash buckets containing data pages

| | | |
|---|---|---|
| 0, 6 | 4, 13 | 5, 14 |

# INSERT Hash Index on age

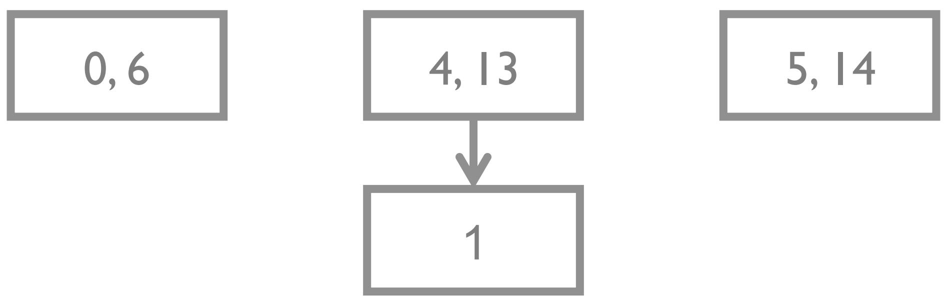


# INSERT Hash Index on age

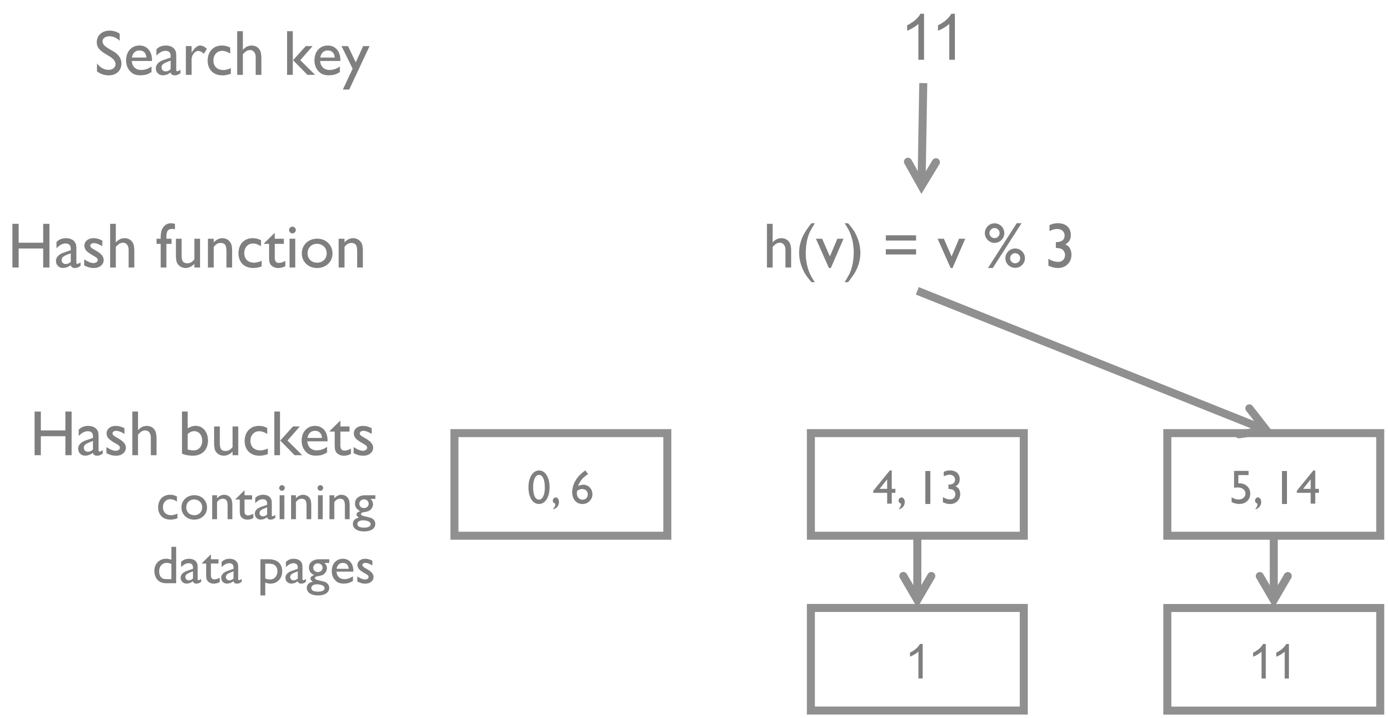
Search key 11

Hash function $h(v) = v \% 3$

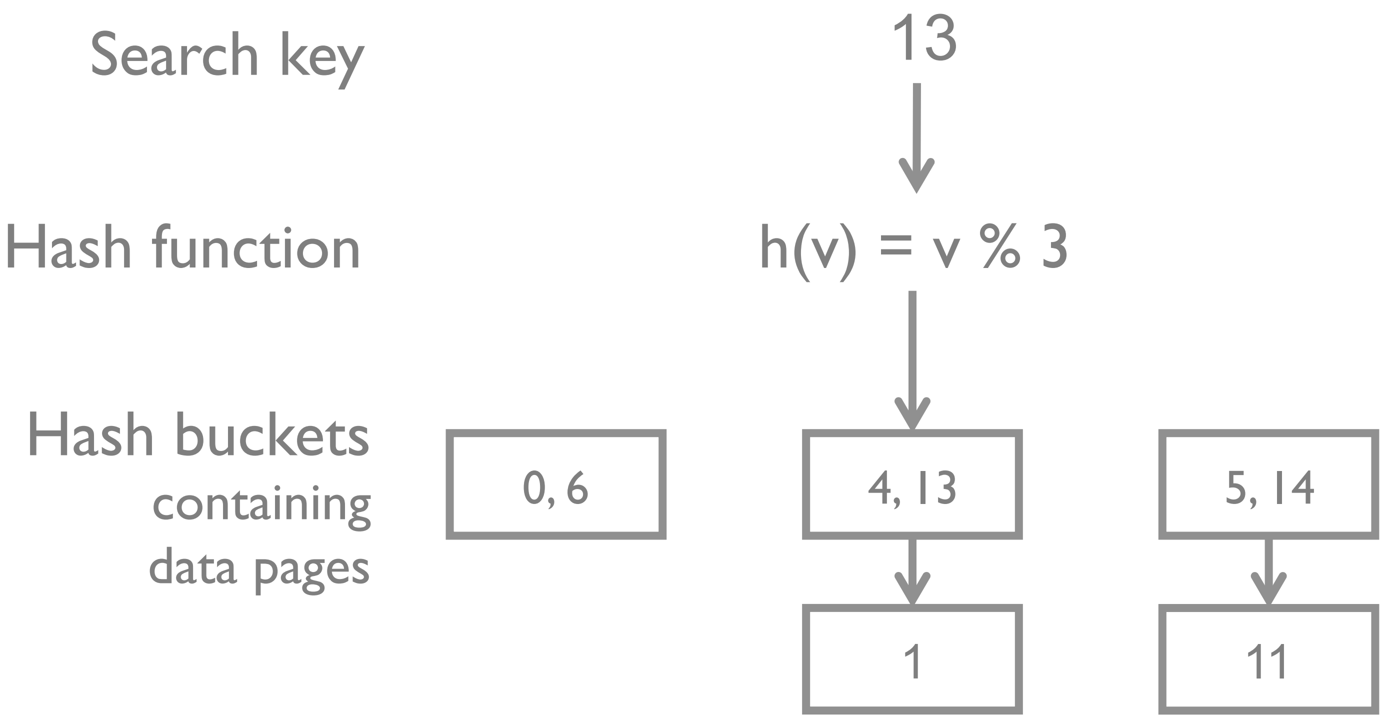
Hash buckets containing data pages



# INSERT Hash Index on age



# SEARCH Hash Index on age




Good for equality selections
Index = data pages + overflow data pages
Hash function h(v) takes as input the *search key*

# Costs

Three file types

- Heap, B+ Tree, Hash

Operations we care about

| | |
|---|---|
| Scan all data | SELECT * FROM R |
| Equality | SELECT * FROM R WHERE x = 1 |
| Range | SELECT * FROM R WHERE 10 < x and x < 50 |
| Insert record | |
| Delete record | |

| | Heap File | Sorted Heap | B+ Tree | Hash |
|---|---|---|---|---|
| Scan everything | | | | |
| Equality | | | | |
| Range | | | | |
| Insert | | | | |
| Delete | | | | |

B # *data* pages

D time to read/write page

M # pages in range query

| | Heap File | Sorted Heap | B+ Tree | Hash |
|---|---|---|---|---|
| Scan everything | BD | | | |
| Equality | 0.5BD (avg) | | | |
| Range | BD | | | |
| Insert | 2D | | | |
| Delete | Search + D | | | |

Heap File

equality on a key. How many results?

B # *data* pages

D time to read/write page

M # pages in range query

| | Heap File | Sorted Heap | B+ Tree | Hash |
|---|---|---|---|---|
| Scan everything | BD | BD | | |
| Equality | 0.5BD | $D(\log_2 B)$ | | |
| Range | BD | $D(\log_2 B + M)$ | | |
| Insert | 2D | Search + BD | | |
| Delete | Search + D | Search + BD | | |

Heap File

equality on a key. How many results?

Sorted File

files compacted after deletion

B # *data* pages

D time to read/write page

M # pages in range query

| | Heap File | Sorted Heap | B+ Tree | Hash |
|---|---|---|---|---|
| Scan everything | BD | BD | 1.25BD | |
| Equality | 0.5BD | $D(\log_2 B)$ | $D(\log_{80} 1.25B + 1)$ | |
| Range | BD | $D(\log_2 B + M)$ | $D(\log_{80} 1.25B + M)$ | |
| Insert | 2D | Search + BD | $D(\log_{80} 1.25B + 2)$ | |
| Delete | Search + D | Search + BD | $D(\log_{80} 1.25B + 2)$ | |

Heap File

equality on a key. How many results?

Sorted File

files compacted after deletion

B+ Tree

100 entries/directory page

80% fill factor

B # *data* pages

D time to read/write page

M # pages in range query

| | Heap File | Sorted Heap | B+ Tree | Hash |
|---|---|---|---|---|
| Scan everything | BD | BD | 1.25BD | 1.25BD |
| Equality | 0.5BD | $D(\log_2 B)$ | $D(\log_{80} 1.25B + 1)$ | D |
| Range | BD | $D(\log_2 B + M)$ | $D(\log_{80} 1.25B + M)$ | 1.25BD |
| Insert | 2D | Search + BD | $D(\log_{80} 1.25B + 2)$ | 2D |
| Delete | Search + D | Search + BD | $D(\log_{80} 1.25B + 2)$ | 2D |

Heap File

equality on a key. How many results?

Sorted File

files compacted after deletion

B+ Tree

100 entries/directory page

80% fill factor

Hash index

no overflow

80% fill factor

B # *data* pages

D time to read/write page

M # pages in range query

# How to pick?

Depends on your queries (workload)

- Which relations?
- Which attributes?
- Which types of predicates (=, <,>)
- *Selectivity*
- Insert/delete/update queries? how many?

# Naïve Algorithm

```
get query workload
group queries by type
for each query type in order of importance
   calculate best cost using current indexes
   if new index IDX will further reduce cost
      create IDX
```

## Why not create every index?

- updates are slower: upkeep costs
- takes up space

# High level guidelines

Check the WHERE clauses

- attributes in WHERE are search/index keys
- equality predicate → hash index
- range predicate → tree index

Multi-attribute search keys supported

- order of attributes matters for range queries
- may enable queries that don't look at data pages (*index-only*)

# Summary

Design depends on economics, access cost ratios

Disk still dominant wrt cost/capacity ratio

Many physical layouts for files

- same APIs, difference performance
- remember physical independence

Indexes

- Structures to speed up read queries
- Multiple indexes possible
- Decision depends on workload

# Things to Know

- How a hard drive works and its major performance characteristics
- The storage hierarchy and rough performance differences between RAM, SSD, Hard drives
- What files, pages, and records are, and how they are different than the UNIX model
- Heap File data structure
- B+ tree and Hash indexes
- Performance characteristics of different file organizations

# L20
# Query Execution & Optimization

# Steps for a New Application

Requirements

what are you going to build?

Conceptual Database Design

pen-and-pencil description

Logical Design

formal database schema

Schema Refinement:

fix potential problems, normalization

Physical Database Design

optimize for speed/storage

Optimization

App/Security Design

prevent security problems

# Recall

Relational algebra

equivalence: multiple stmts for same query

some statements (much) faster than others

Which is faster?

a. $\sigma_{v=1}(R \times T)$

b. $\sigma_{v=1}(R) \times T$

$|R| = |T| = 10$ pages. 100? 1M?

# unique values in R = 1. 100? 1M? ← selectivity!

# Overview of Query Optimization

SQL → query plan

How plans are executed

Some implementations of operators

Cost estimation of a plan

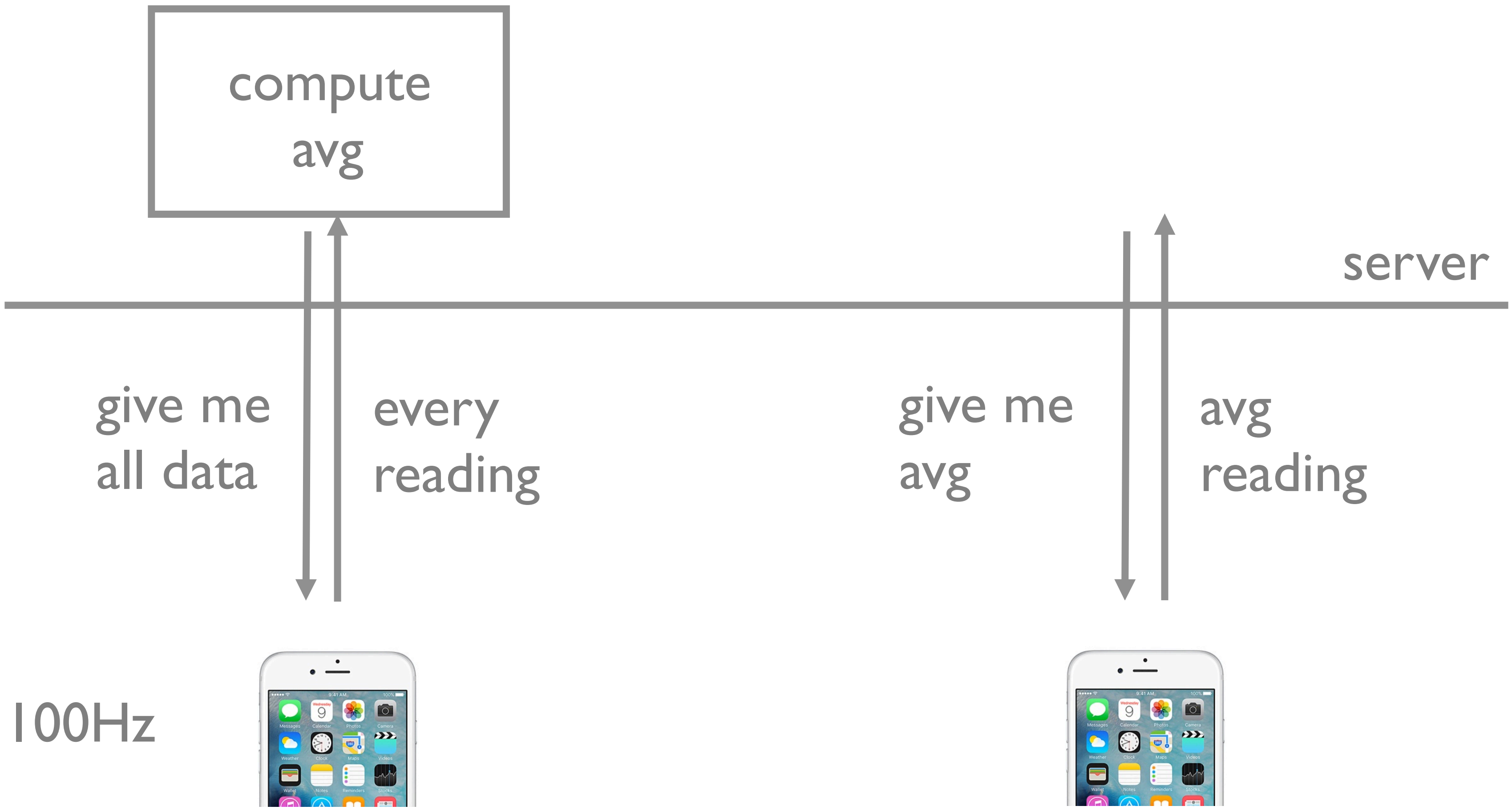
- Selectivity

System R dynamic programming

All ideas from System R's "Selinger Optimizer" 1979

# iPhones as a database

“avg acceleration over the past hour”



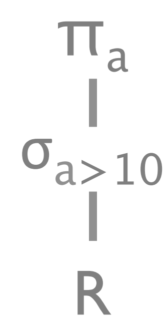
# SQL → Query Plan

SELECT a FROM R

$\pi_a(R)$


SELECT a FROM R
WHERE a > 10

$\pi_a(\sigma_{a>10}(R))$




SELECT a
FROM R JOIN S
ON R.b = S.b

$\pi_a(\bowtie_b(R,S))$