6.5830 Lecture 4

Database Internals

September 18, 2023

What happens inside?

```
SELECT *
FROM animals
WHERE species = 'Giraffe'
```

id	name	age	species	cageno
2	Mike	12	Giraffe	1

What happens inside?

```
SELECT name, addr, balance
FROM accounts
WHERE userid = ?
```

name	addr	balance
…	…	…

What happens inside?

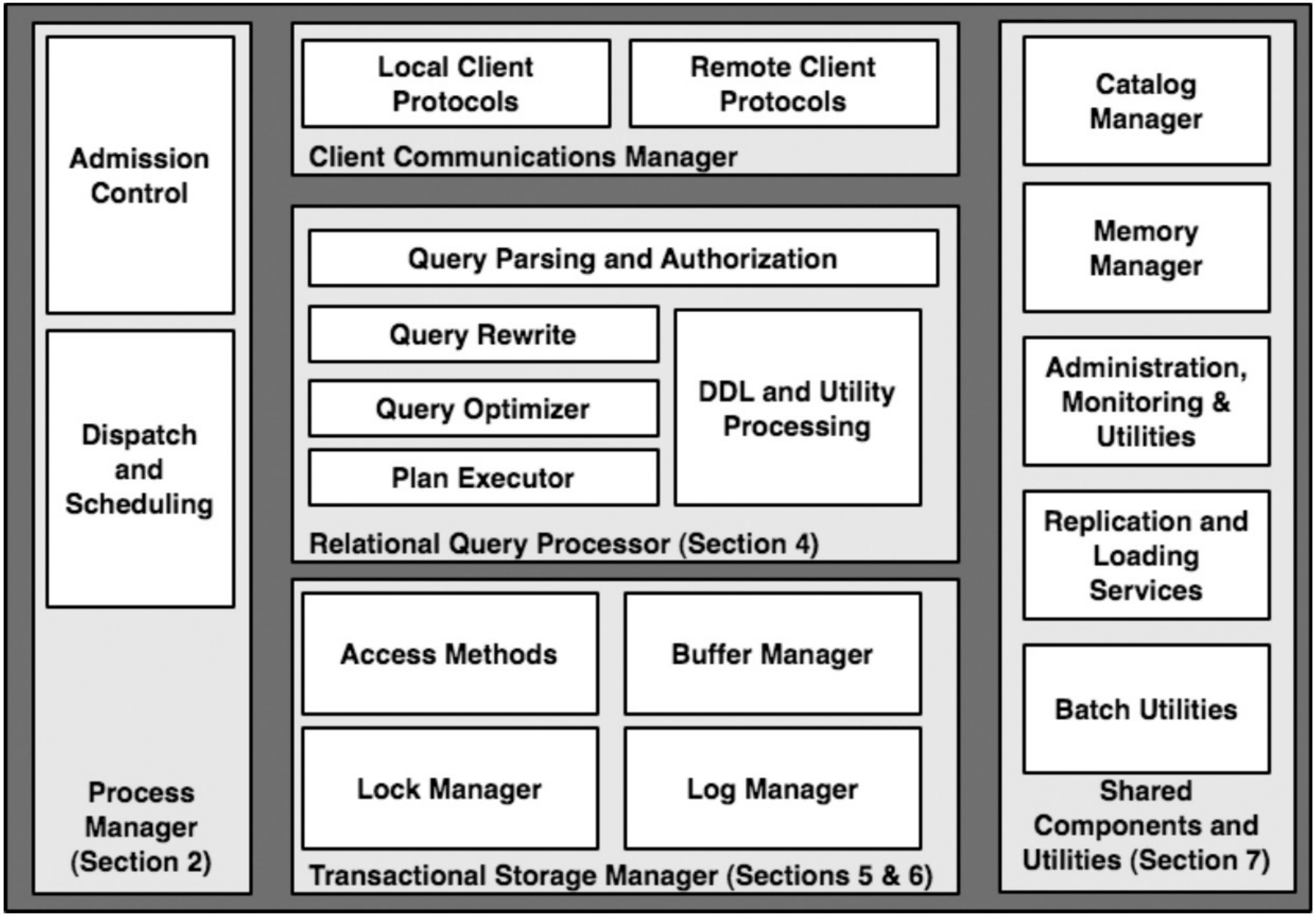
```
SELECT image, imgid
FROM planet_images
WHERE likelyPlanet(image)=TRUE
```

Database systems can support
- interactive queries
- web applications
- large-scale science

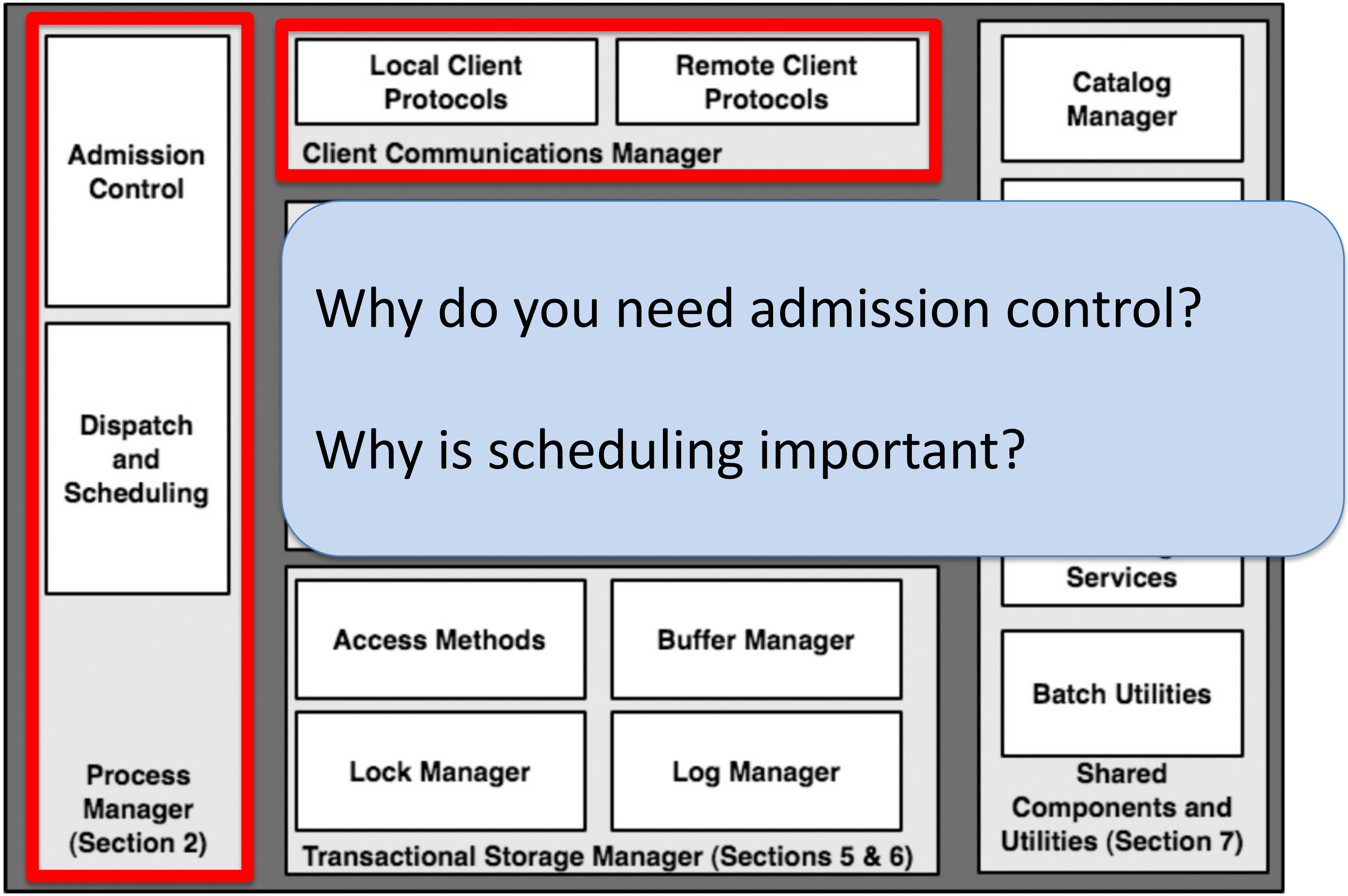
and many other workloads

image	imgid
...	...

What happens inside?



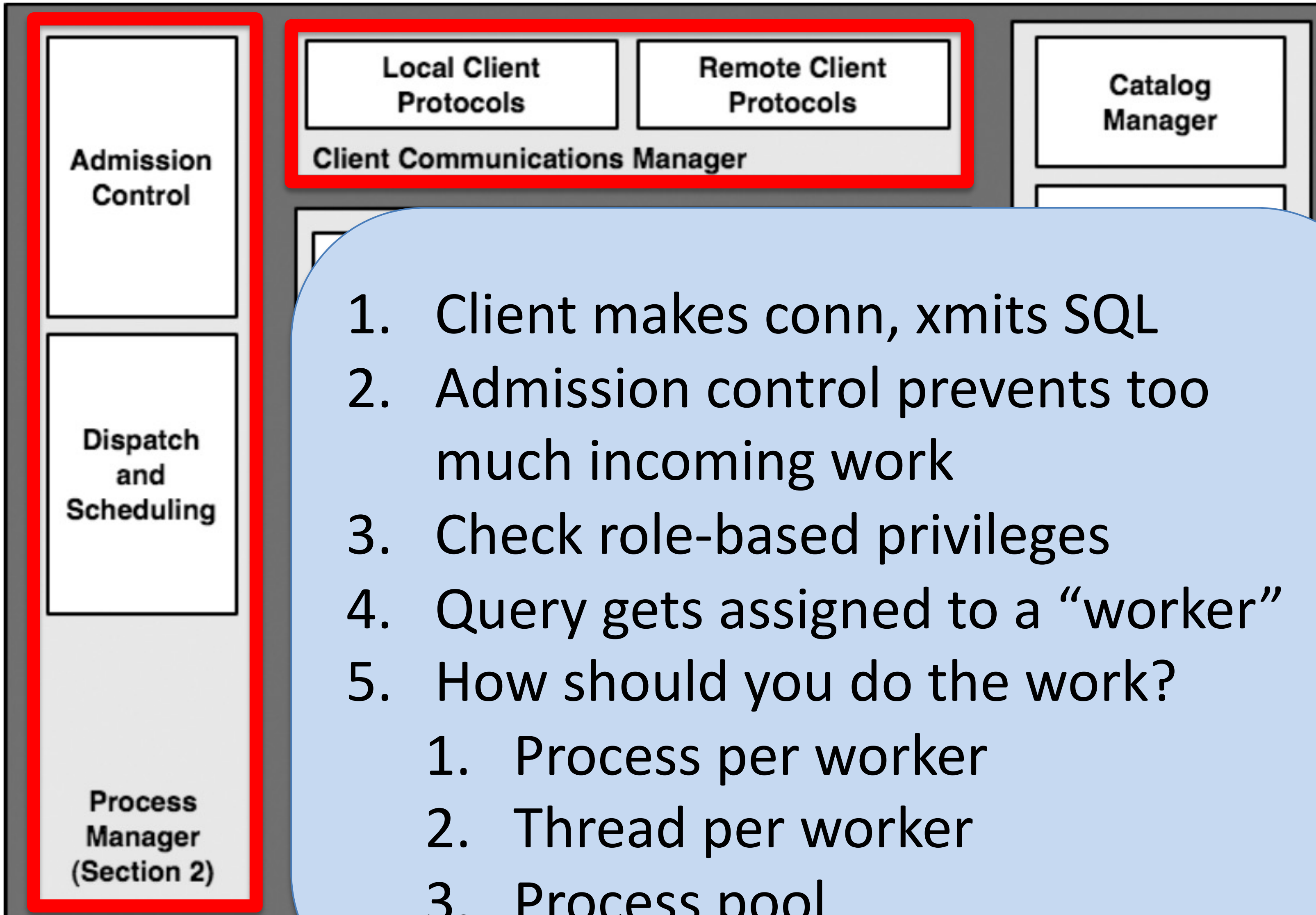
What happens inside?



Why do you need admission control?

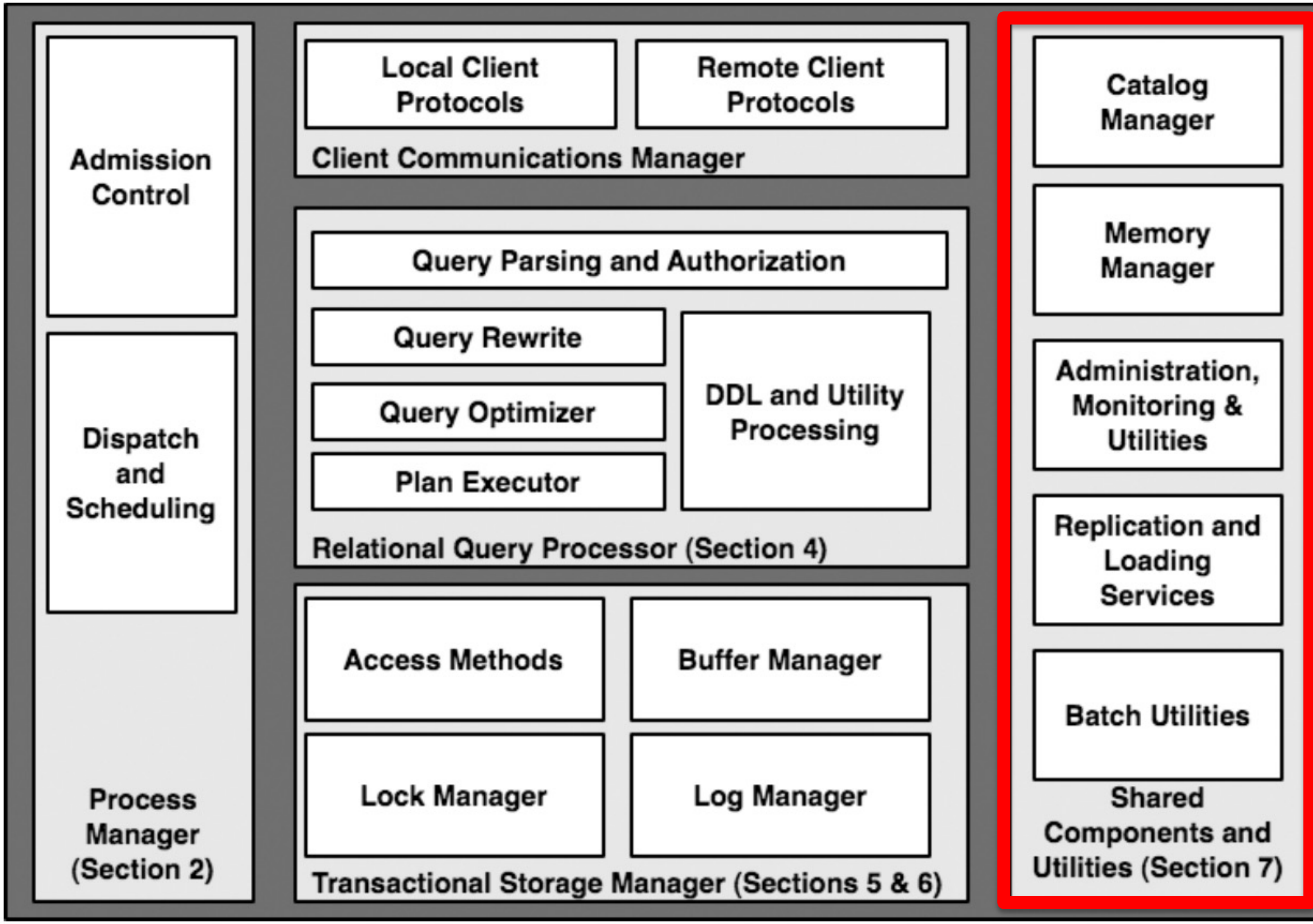
Why is scheduling important?

What happens inside?

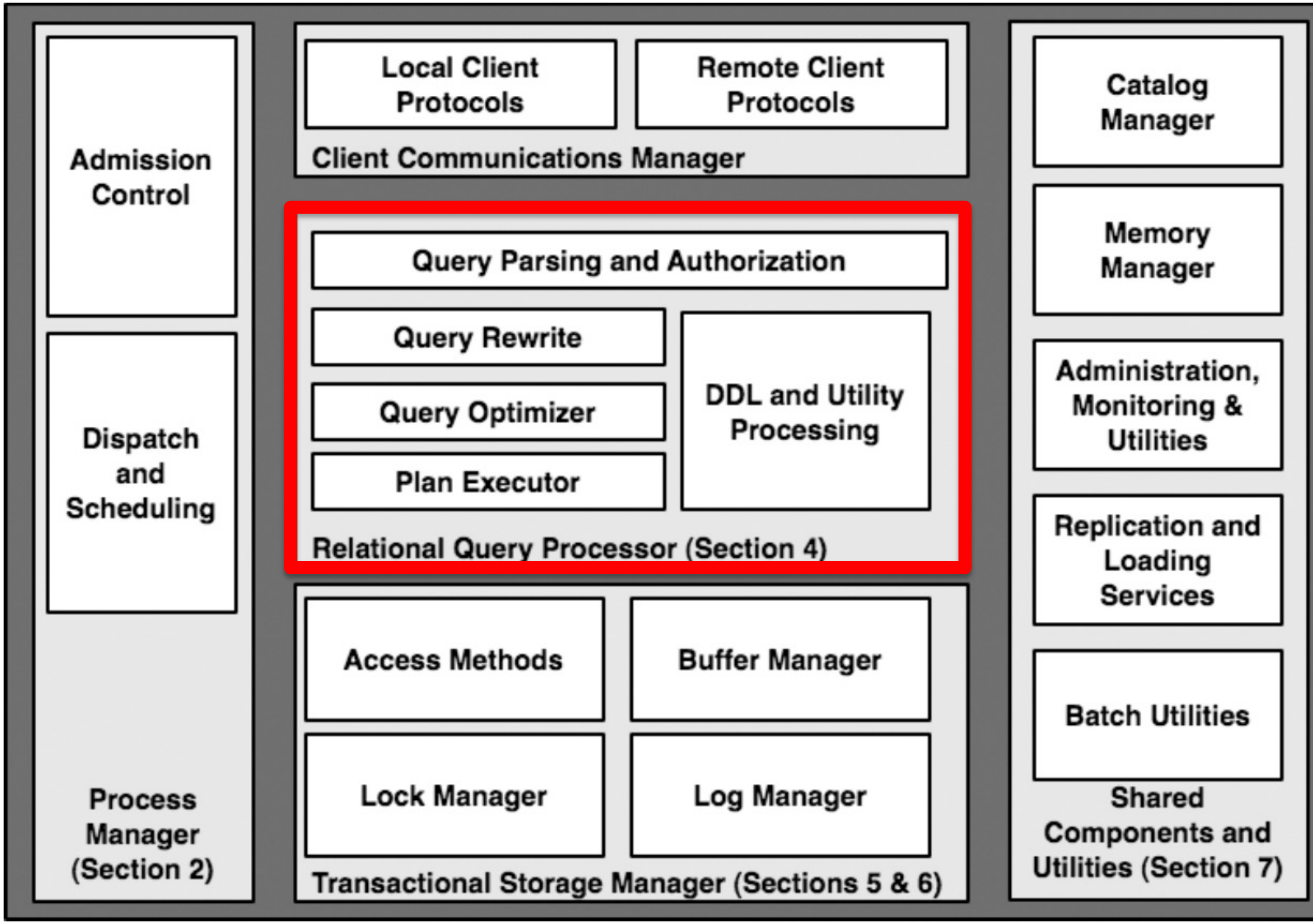


1. Client makes conn, xmits SQL
2. Admission control prevents too much incoming work
3. Check role-based privileges
4. Query gets assigned to a “worker”
5. How should you do the work?
    1. Process per worker
    2. Thread per worker
    3. Process pool

What happens inside?



What happens inside?



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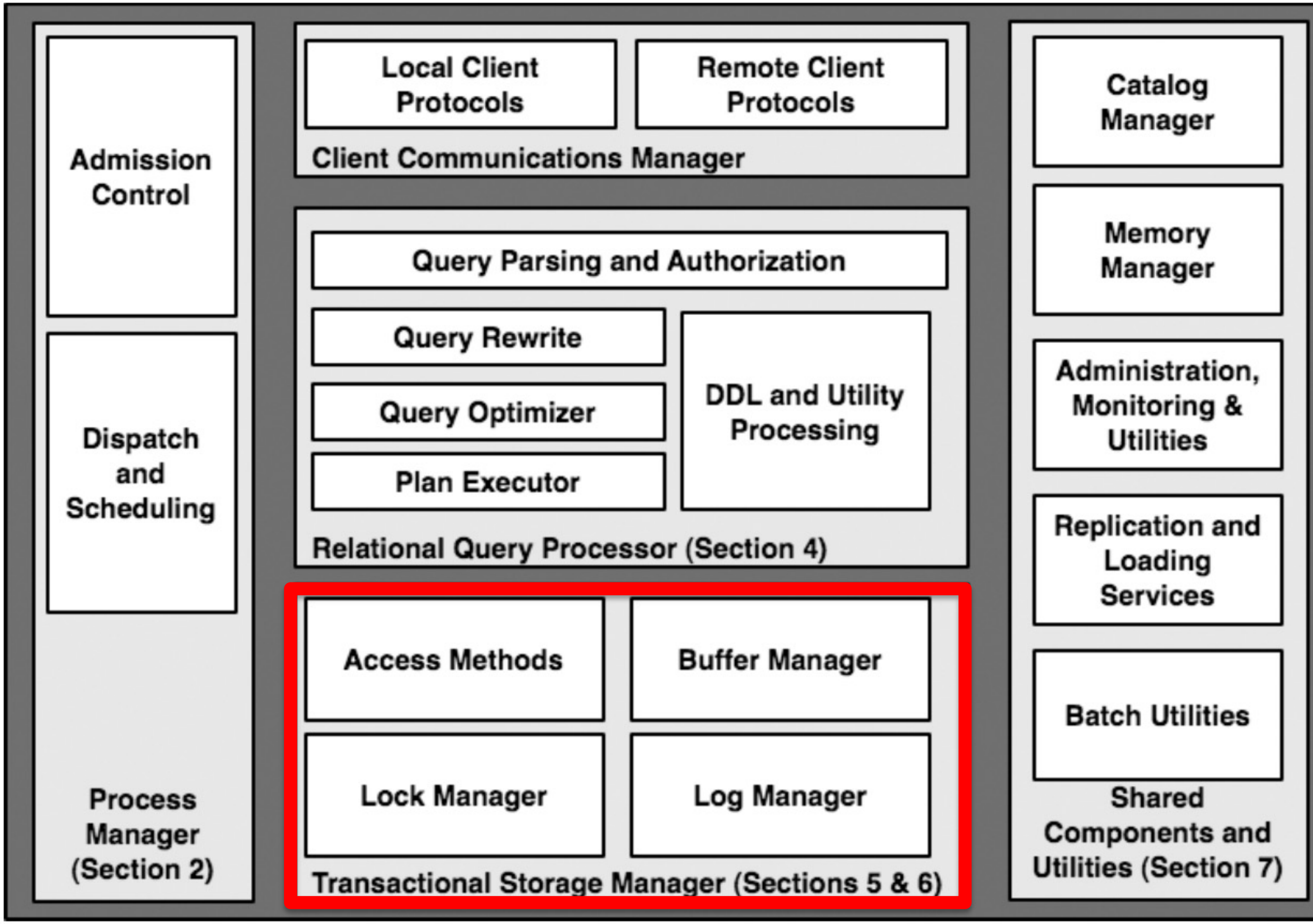

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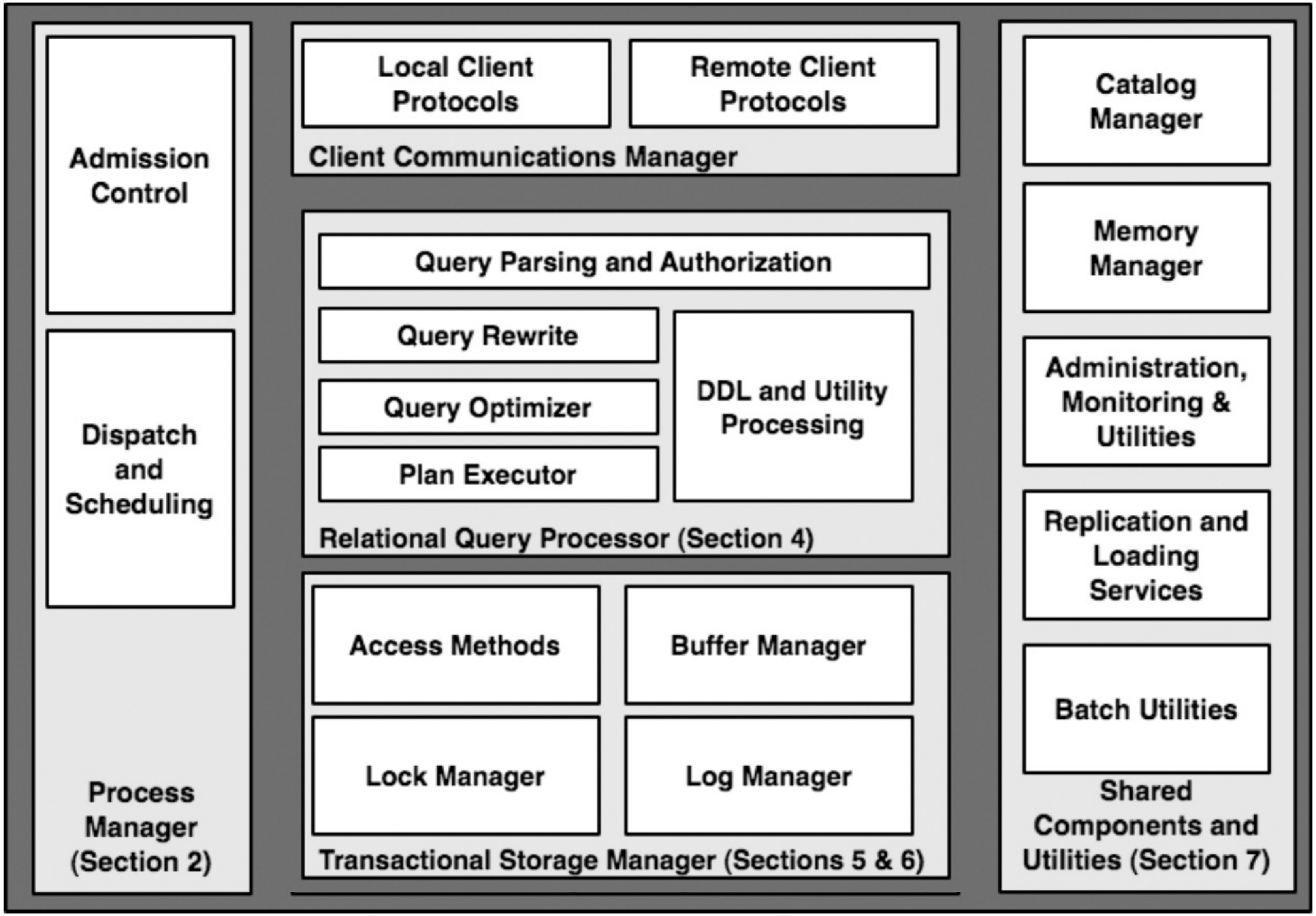
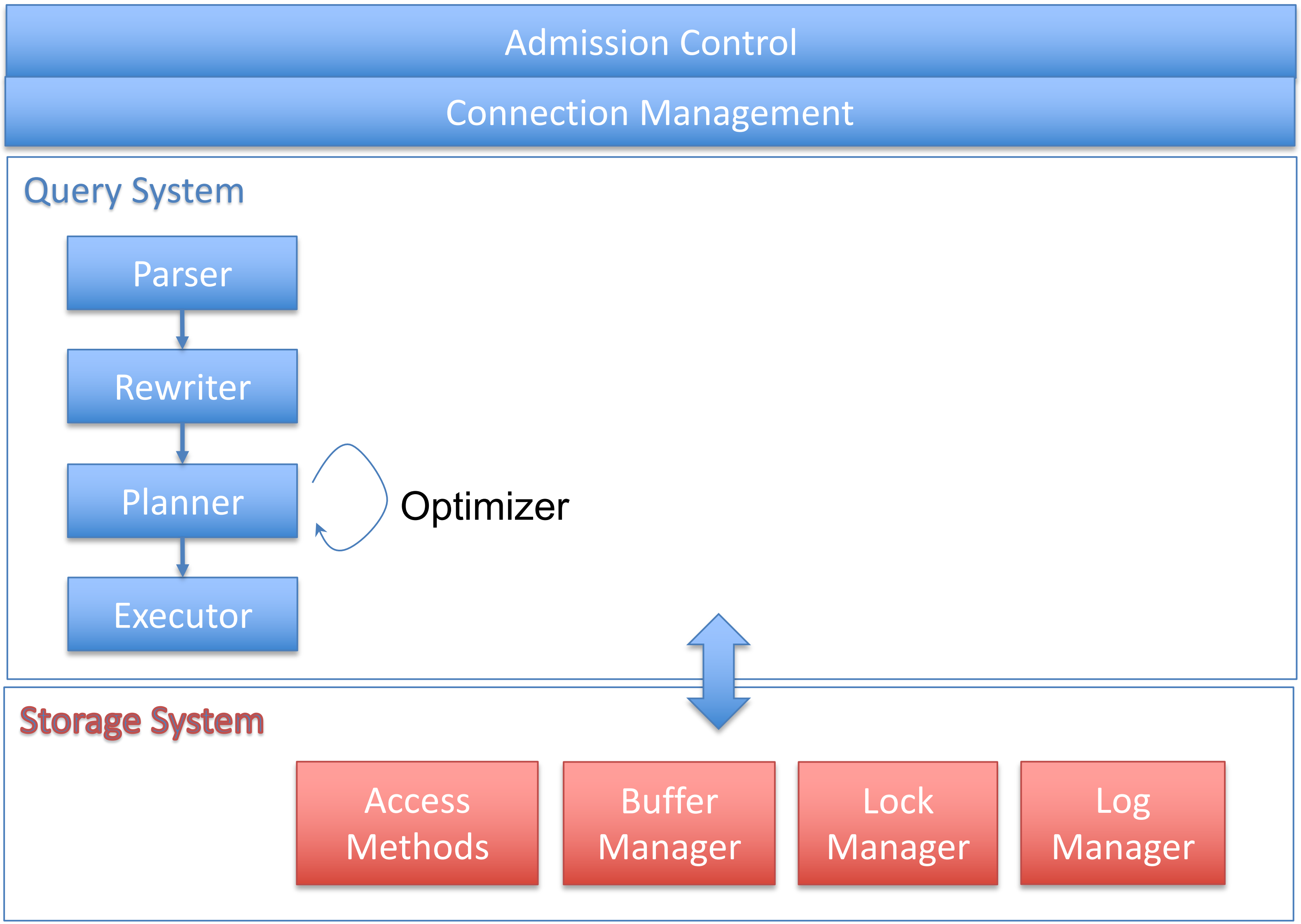
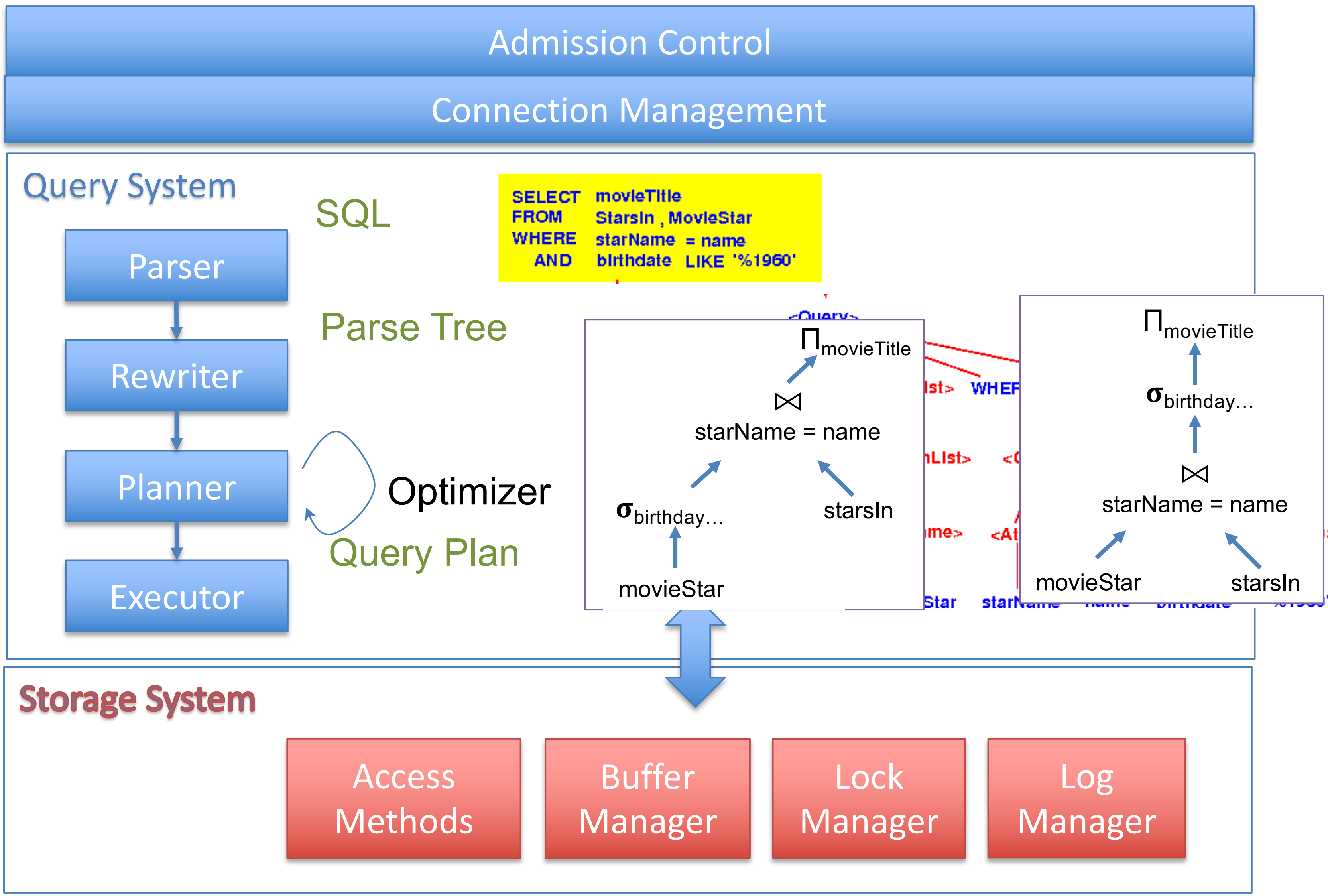


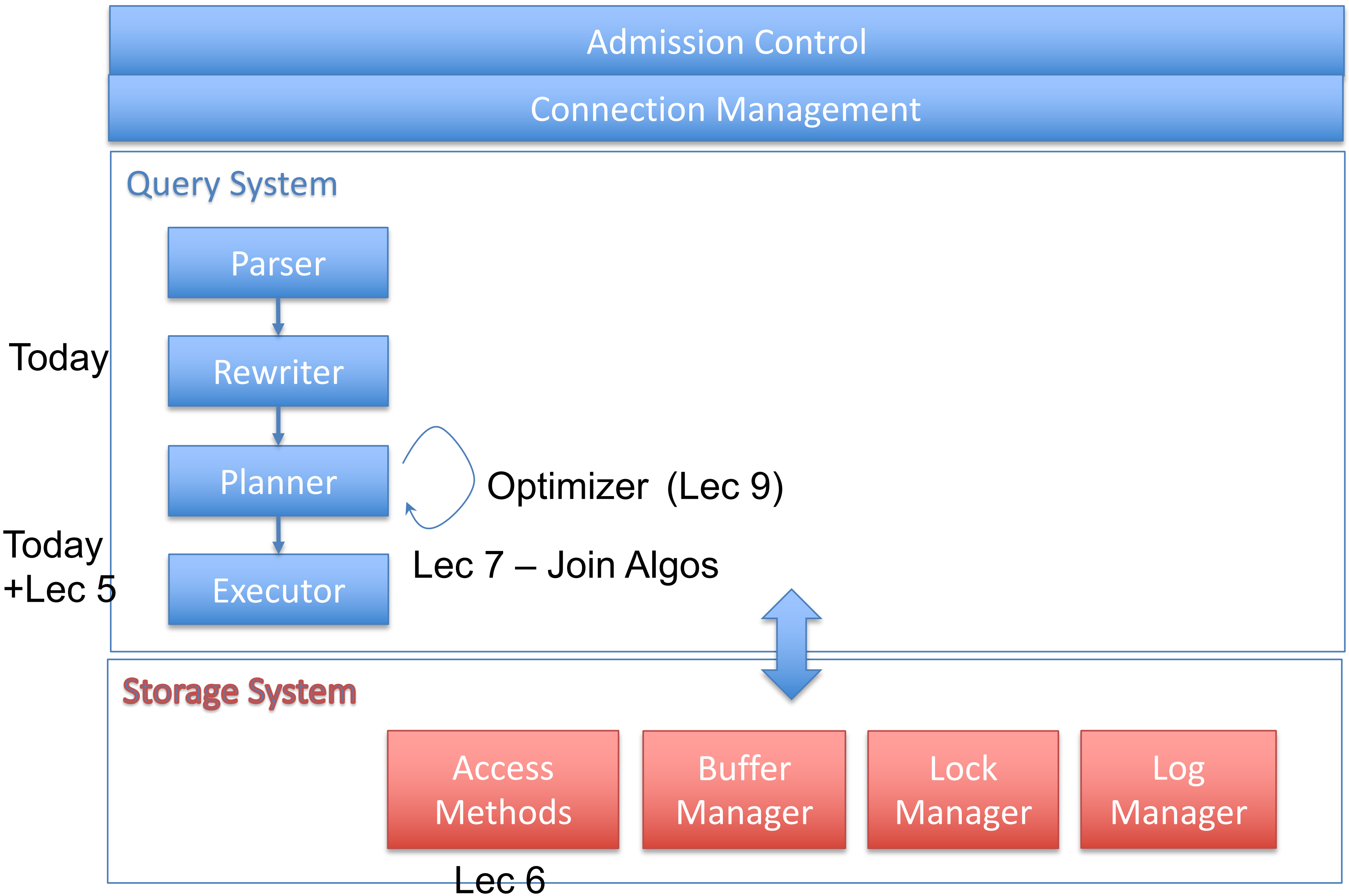
DB Core Components



Flow of a Query



Plan for Next Few Lectures



Query Processing Steps

- Admission Control
- Query Rewriting
- Plan Formulation (SQL → Tree)
- Optimization

Query Processing Steps

- Admission Control
- **Query Rewriting**
- Plan Formulation (SQL → Tree)
- Optimization

Query Rewriting

- View Substitution
- Predicate Transforms
- Subquery Flattening

View Substitution

emp : id, sal, age, dept

```
create view sals as (
   select dept, avg(sal) as sal
   from emp
   group by dept
)
```

```
select sal from sals where dept = 'eecs';
```

```
select sal from (


)where dept = 'eecs';
```

Predicate Transforms

- Remove & simplify expressions, improve
- Constant Simplification

  `WHERE sal > 1000 + 4000` ➔ `WHERE sal > 5000`

- Exploit constraints

  `a.did = 10 and a.did = dept.dno` and *`dept.dno = 10`*

- Remove redundant expressions

  `a.sal > 10k and  sal > 20k`

Predicate Transforms

- Remove & simplify expressions, improve
- Constant Simplification

  `WHERE sal > 1000 + 4000` ➔ `WHERE sal > 5000`

- Exploit constraints

  `a.did = 10 and a.did = dept.dno` and *`dept.dno = 10`*

- Remove redundant expressions

  ~~`a.sal > 10k and`~~ `sal > 20k`

Subquery Flattening

- Many Subqueries Can Be Eliminated

```
select sal from (
        select dept, avg(sal) as sal
        from emp
        group by dept
)where dept = 'eecs';
```

```
select avg(sal)
        from emp
        group by dept
having dept = 'eecs';
```

Can you come up with an example where this is not possible?

Subquery Flattening

- Many Subqueries Can Be Eliminated

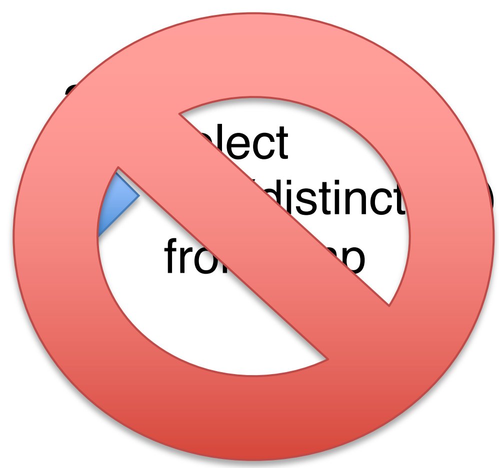
```
select sal from (
      select dept, avg(sal) as sal
      from emp
      group by dept
)where dept = 'eecs';
```

```
select avg(sal)
      from emp
      group by dept
having dept = 'eecs';
```

- Not always possible; consider

```
create view sals as {
      select distinct dept, sal
      from emp
}
select avg(sal) from sals
```

```
select avg(sal) from (
      select distinct dept, sal
      from emp
)
```



Study Break (Tricky)

Flatten this query (*departments where number of machines is more than number of employees*):

```
SELECT dept.name
FROM dept
WHERE dept.num_machines >=
    (SELECT COUNT(emp.*)
     FROM emp
     WHERE dept.name=emp.dept_name)
```

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Original

```
SELECT dept.name FROM dept
WHERE dept.num_machines >= (SELECT COUNT(emp.*) FROM emp
                              WHERE dept.name=emp.dept_name)
```

A

```
SELECT dept.name
FROM dept d, emp e
WHERE d.name=e.dept_name
    and d.num_machines >=
COUNT(e.*)
GROUP BY d.name, d.num_machines
```

B

```
SELECT dept.name
FROM dept d, emp e
WHERE d.name=e.dept_name
GROUP BY d.name
HAVING COUNT(d.num_machines) >= COUNT(e.*)
```

C

```
SELECT dept.name
FROM dept d, emp e
WHERE d.name=e.dept_name
GROUP BY d.name, d.num_machines
HAVING d.num_machines >= COUNT(e.*)
```

D

```
SELECT dept.name
FROM dept d
LEFT OUTER JOIN emp e
    ON (d.name=e.dept_name)
GROUP BY d.name, d.num_machines
HAVING d.num_machines >= COUNT(e.*)
```

“Query rewrite optimization rules in IBM DB2 universal database”

“Rule Engine for Query Transformation in Starburst and IBM DB2 C/S DBMS “

```
SELEC
FROM
WHERE
GROUP BY dept.name,
         dept.num_machines
HAVING dept.num_machines >= COUNT(emp.*)
```

```
SELECT dept.name
FROM dept
LEFT OUTER JOIN emp ON (dept.name=emp.dept_name)
GROUP BY dept.name,
         dept.num_machines
HAVING dept.num_machines >= COUNT(emp.*)
```

Query Processing Steps

- Admission Control
- Query Rewriting
- **Plan Formulation (SQL → Tree)**
- Optimization

Plan Formulation

emp (<u>eno</u>, ename, sal, *dno*)

dept (<u>dno</u>, dname, bldg)

kids (<u>kno</u>, *eno*, kname, bday)

SELECT ename, count(*)

FROM emp, dept, kids

AND emp.dno=dept.dno

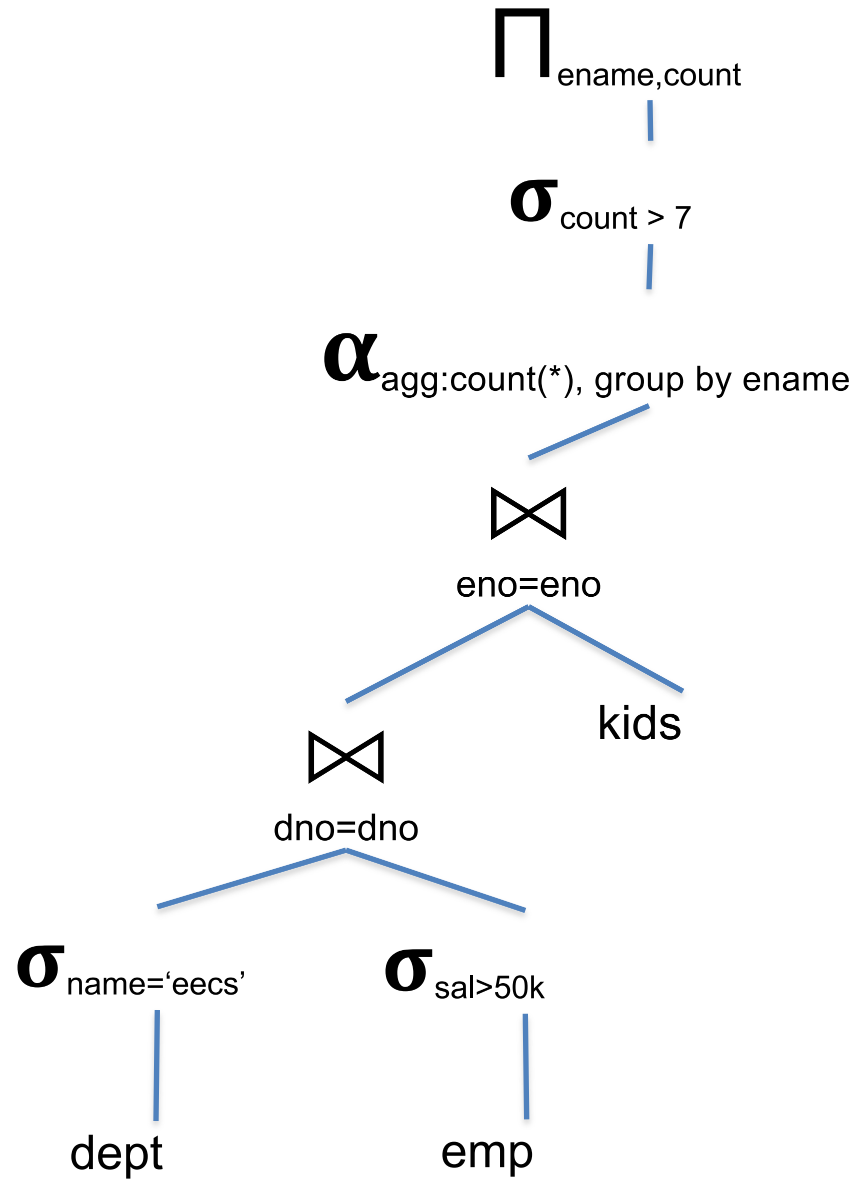
AND kids.eno=emp.eno

AND emp.sal > 50000

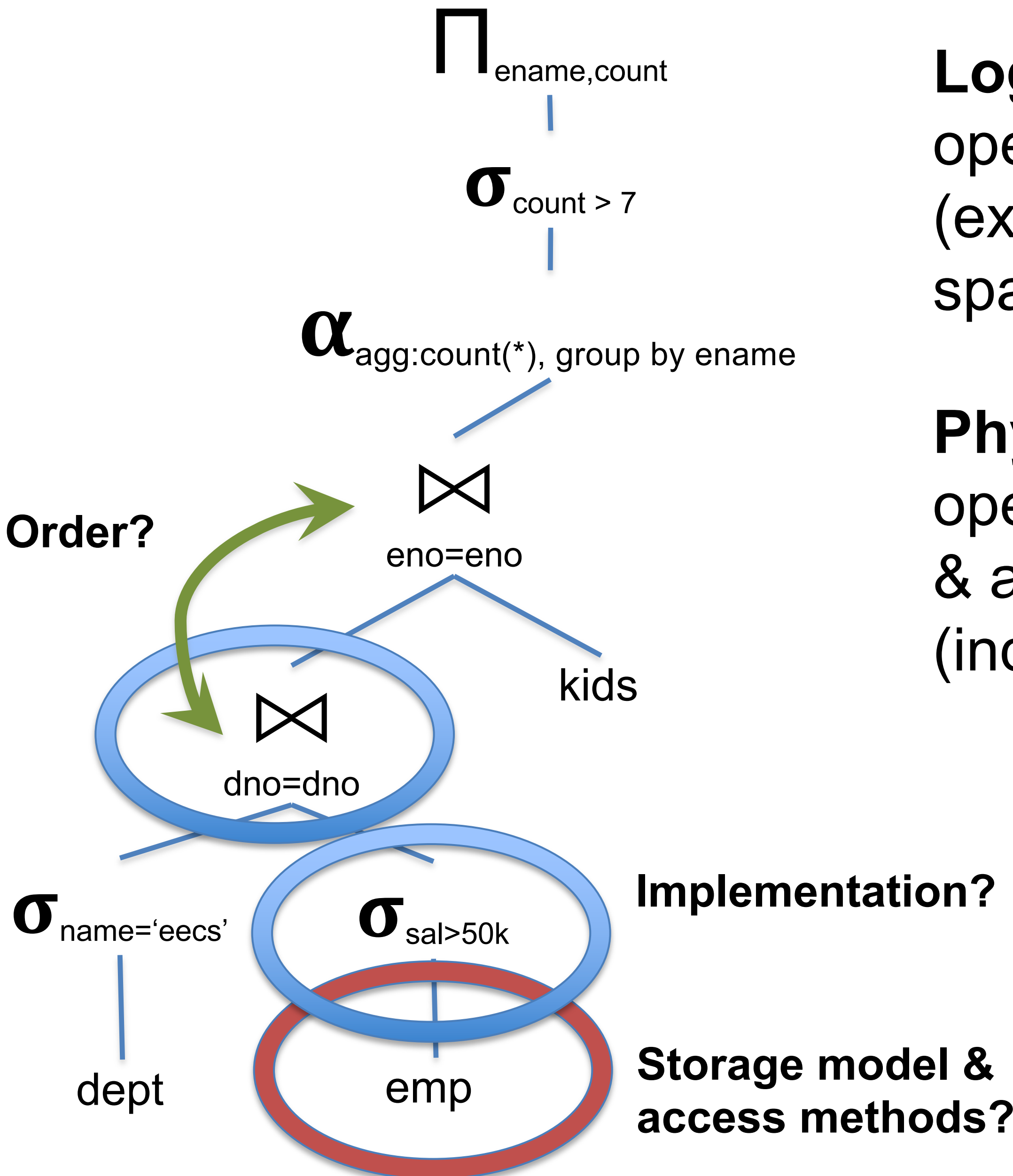
AND dept.name = 'eecs'

GROUP BY ename

HAVING count(*) > 7



Query Optimization



Logical planning: operator ordering (exponential search space)

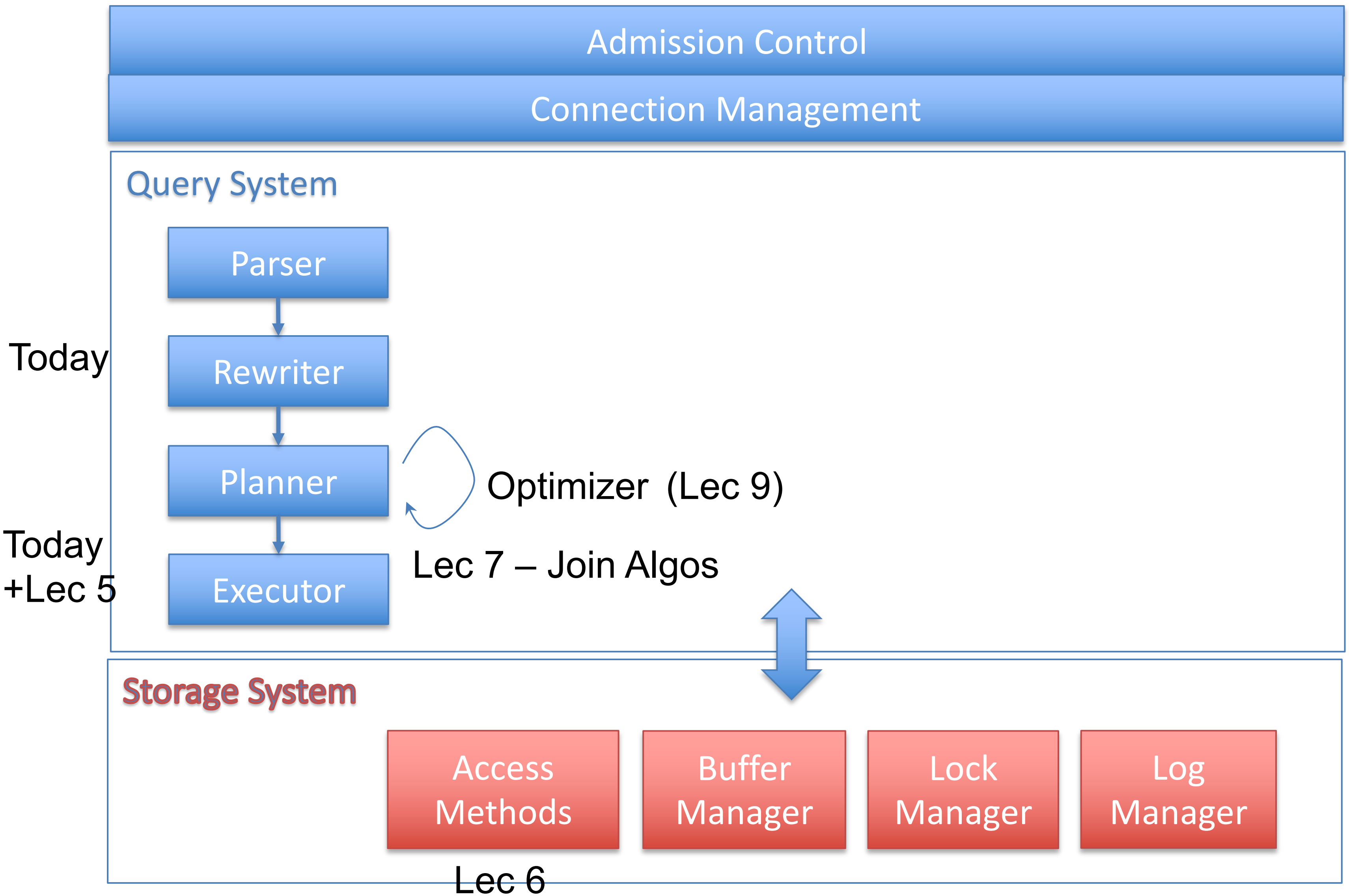
Physical planning: operator implementation & access methods (indexes vs heap files)

Joins and Ordering

- Consider a nested loop join operator of tables Outer and Inner
- for tuple1 in Outer
  for tuple2 in Inner
    if predicate(tuple1, tuple2) then
      emit join(tuple1, tuple2)

- What if Inner is itself a join result?
- Plans might be “left-deep” or “bushy”

Plan for Next Few Lectures



Query Execution

- Executing a query involves chaining together a series of operators that implement the query
- Operator types:

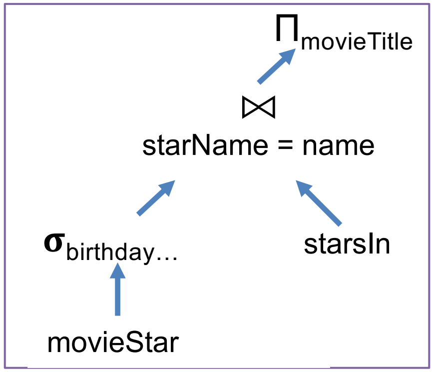
  scan from disk/mem

  filter records

  join records

  aggregate records

→ Requires a model of data representation



Physical Layout

- Arrangement of records on disk / in memory
- Disk / memory are linear, tables are 2D

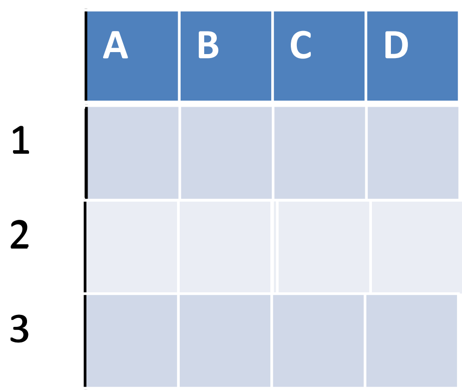
	A	B	C	D
1				
2				
3				

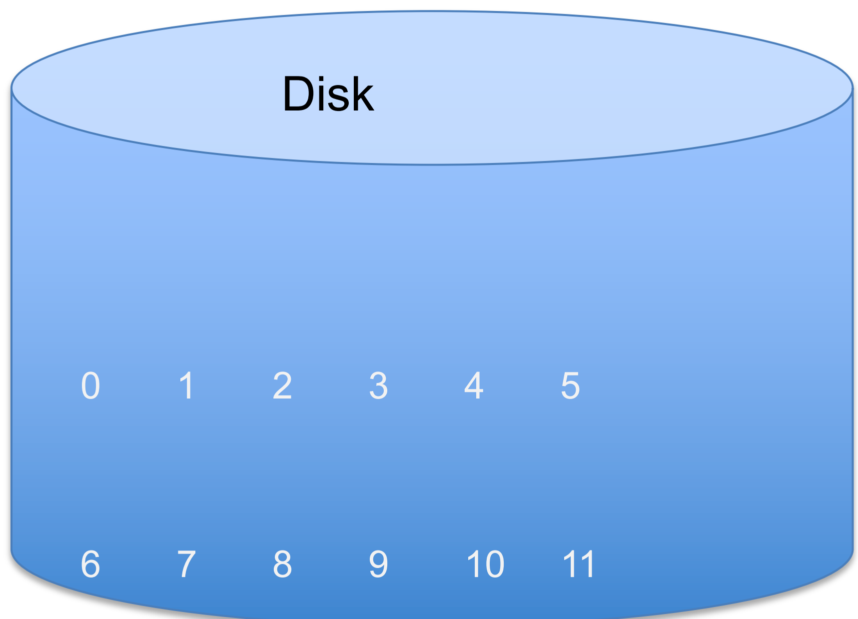
How would you store the table on disk?

Knowing that you must efficiently support inserts, deletes, and that some records are more often read than others?

Physical Layout

- Arrangement of records on disk / in memory
- Disk / memory are linear, tables are 2D
  - "Row Major" - Row at a time

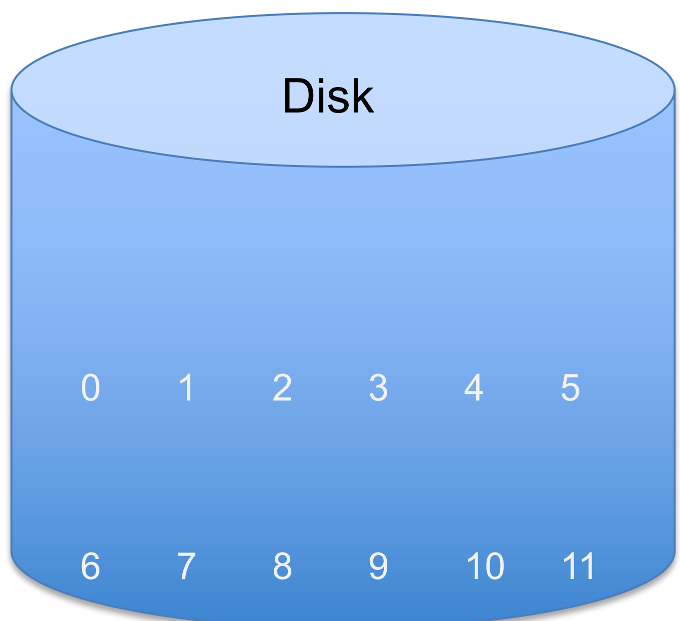




Physical Layout

- Arrangement of records on disk / in memory
- Disk / memory are linear, tables are 2D
  - ”Row Major” - Row at a time
  - “Column Major” Column at a time

A	B	C	D

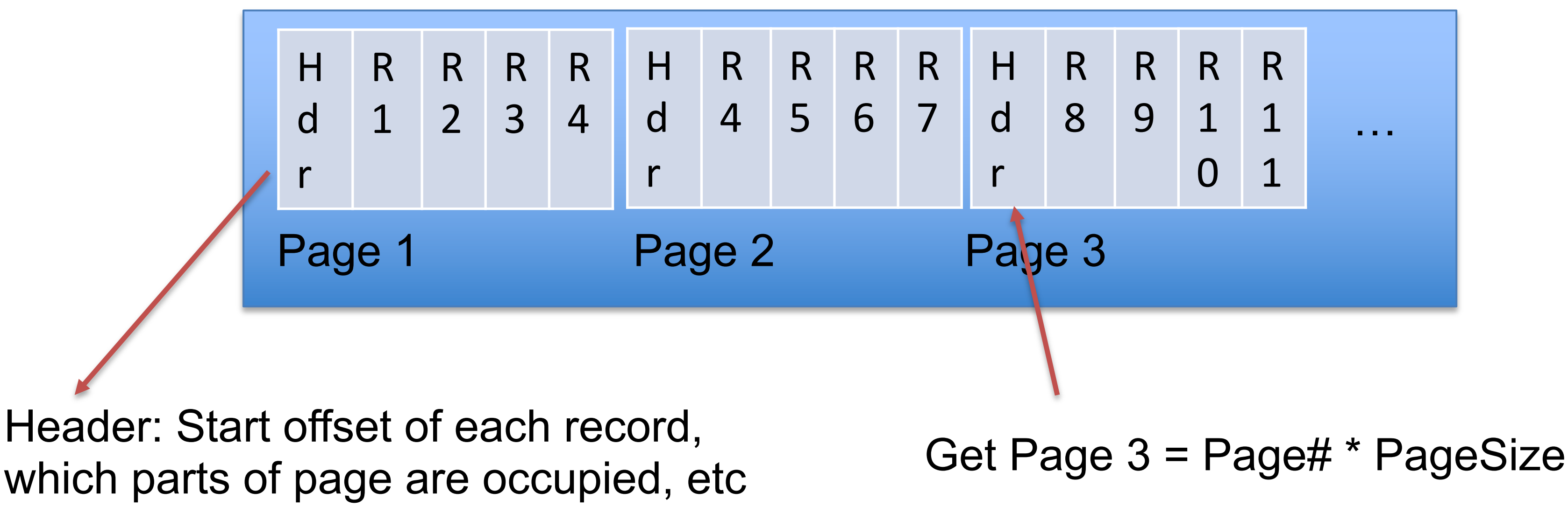


For now, let's assume row-major!

How would you store records on disk?

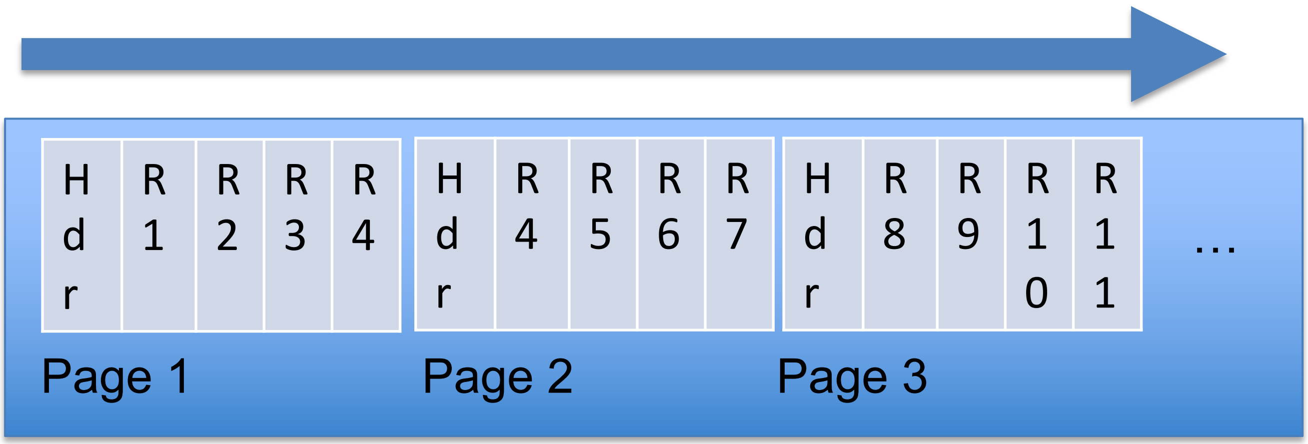
Accessing Data

- Access Method: way to read data from disk
- Heap File: unordered arrangement of records
  - Arranged in pages
  - You read/write/cache data in the granularity of pages.



Heap Scan

- Read Heap File In Stored Order
  - Even with a predicate, read all records



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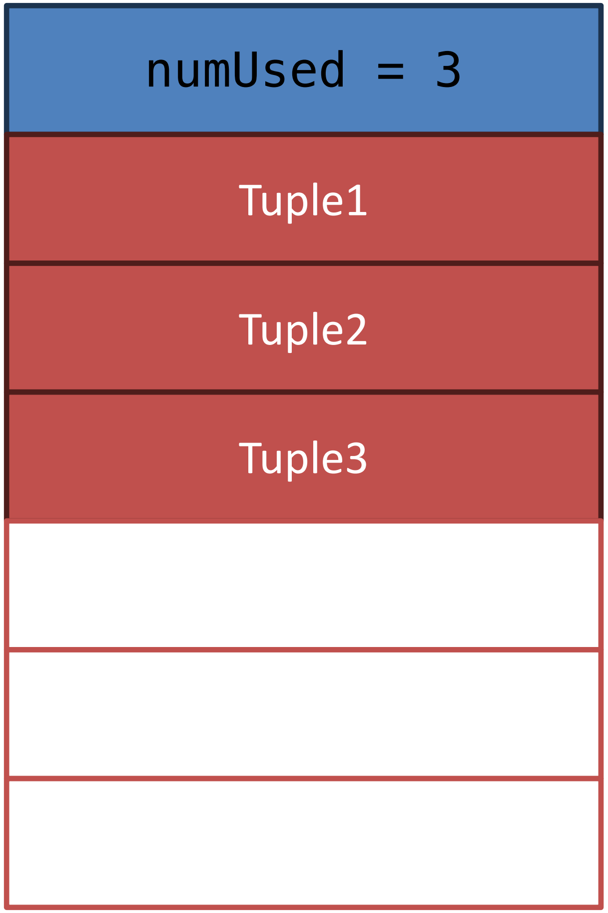
Hardware (e.g., SSDs) and OS (e.g., virtual memory) also use pages. They often are 4KB large.

Why does a database management introduce yet another paging mechanism?

Page designs

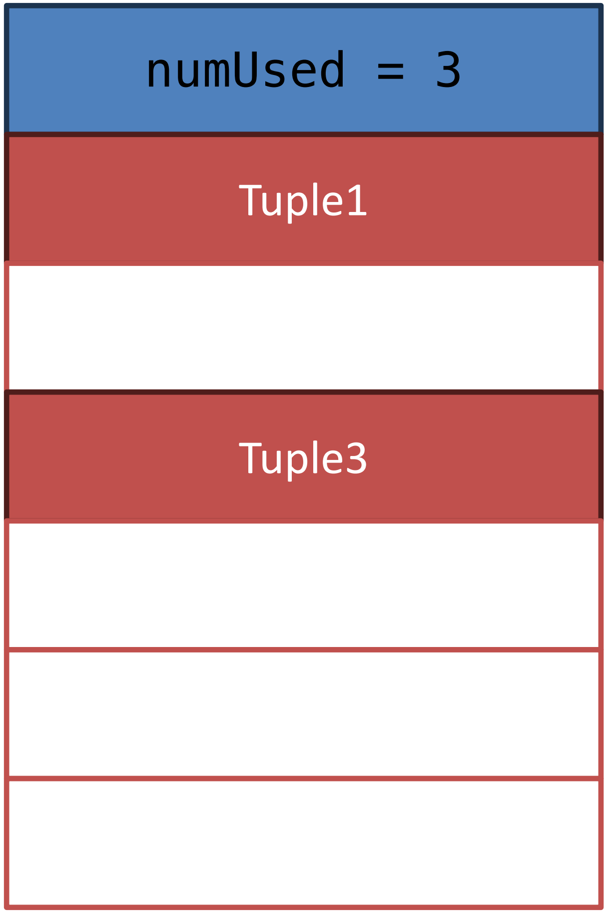
Strawman idea: Keep track of tuples in a page?

Any problems with this design?



Page designs

Strawman idea: Keep track of tuples in a page?

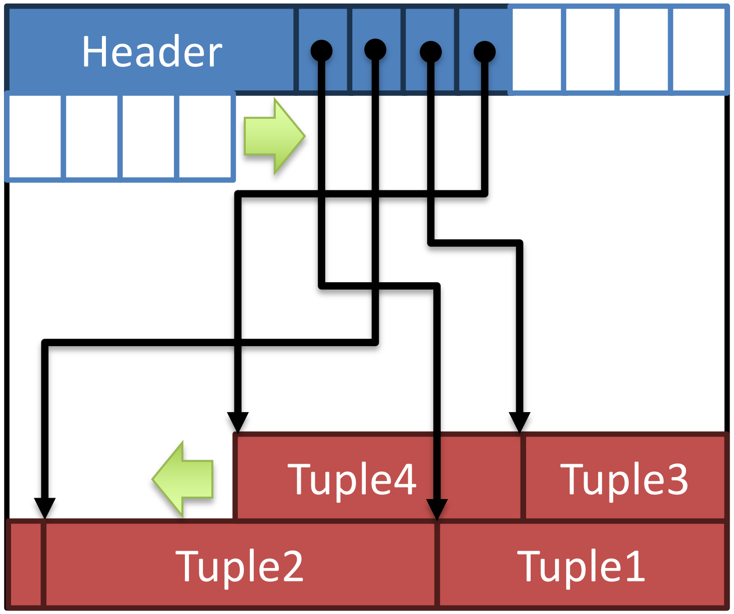


- What happens with deletes?
- What happens with variable length tuples (e.g., variable length strings)?

Slotted pages

Common layout scheme

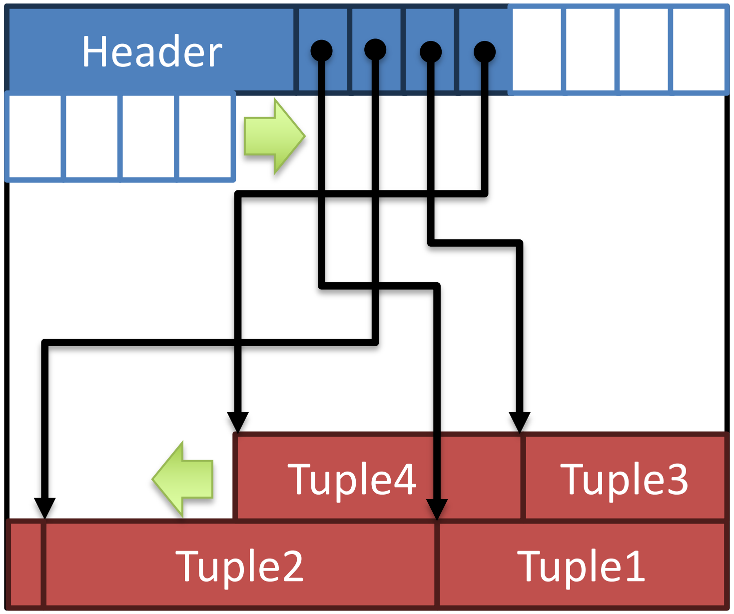
- Slot array maps "slots" to tuples starting postion
- The header keeps track of:
  → The # of used slots
  → The offset of the starting location of the last slot used.



Slotted pages

How would you simplify the layout if tuples have a fixed length?

Do you need to store the slot map?



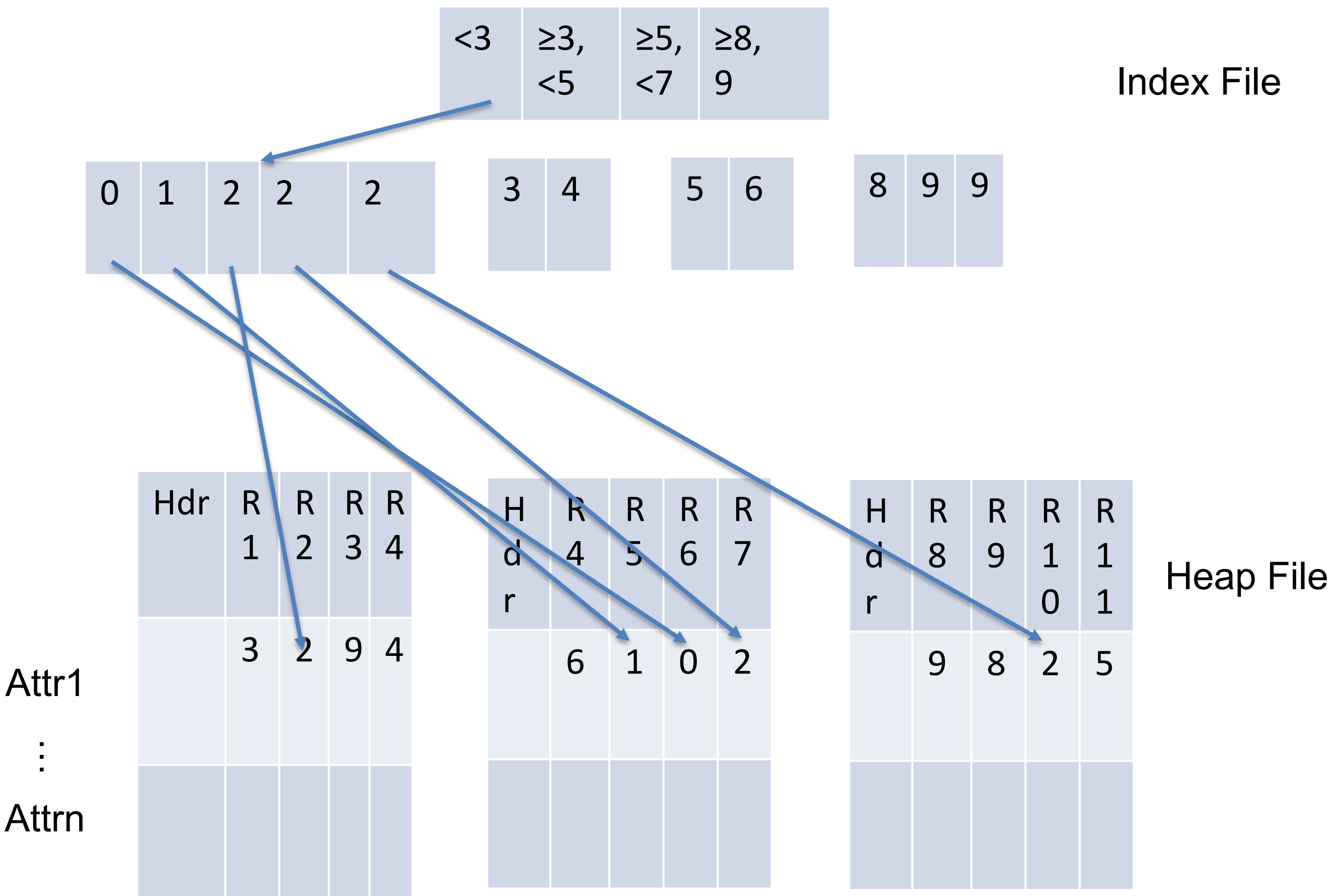
Index

- Index maps from a value or range of values of some attribute to records with that value or values
- Several types of indexes, including trees (most commonly B+Trees) and hash indexes

API:
Lookup(value) → records
Lookup(v1 .. vn) → records

Value is an attribute of the table, called the "key" of the index

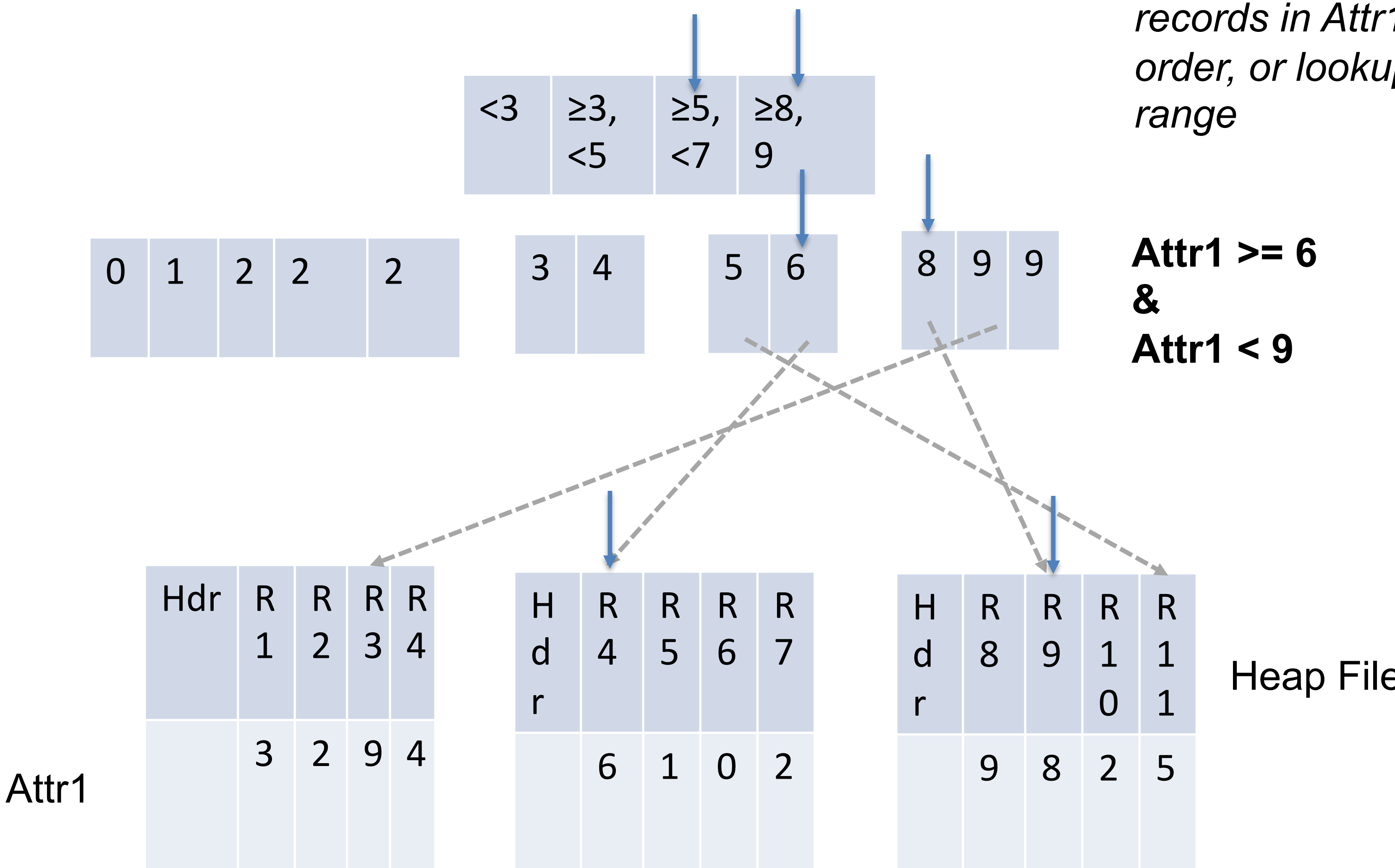
Tree Index



<3
≥3, <5
≥5, <7
≥8, 9
Index File
0 1 2 2 2
3 4
5 6
8 9 9
Hdr R1 R2 R3 R4
3 2 9 4
Hdr R4 R5 R6 R7
6 1 0 2
Hdr R8 R9 R10 R11
9 8 2 5
Heap File
Attr1
⋮
Attrn

Index Scan

Traverse the records in Attr1 order, or lookup a range

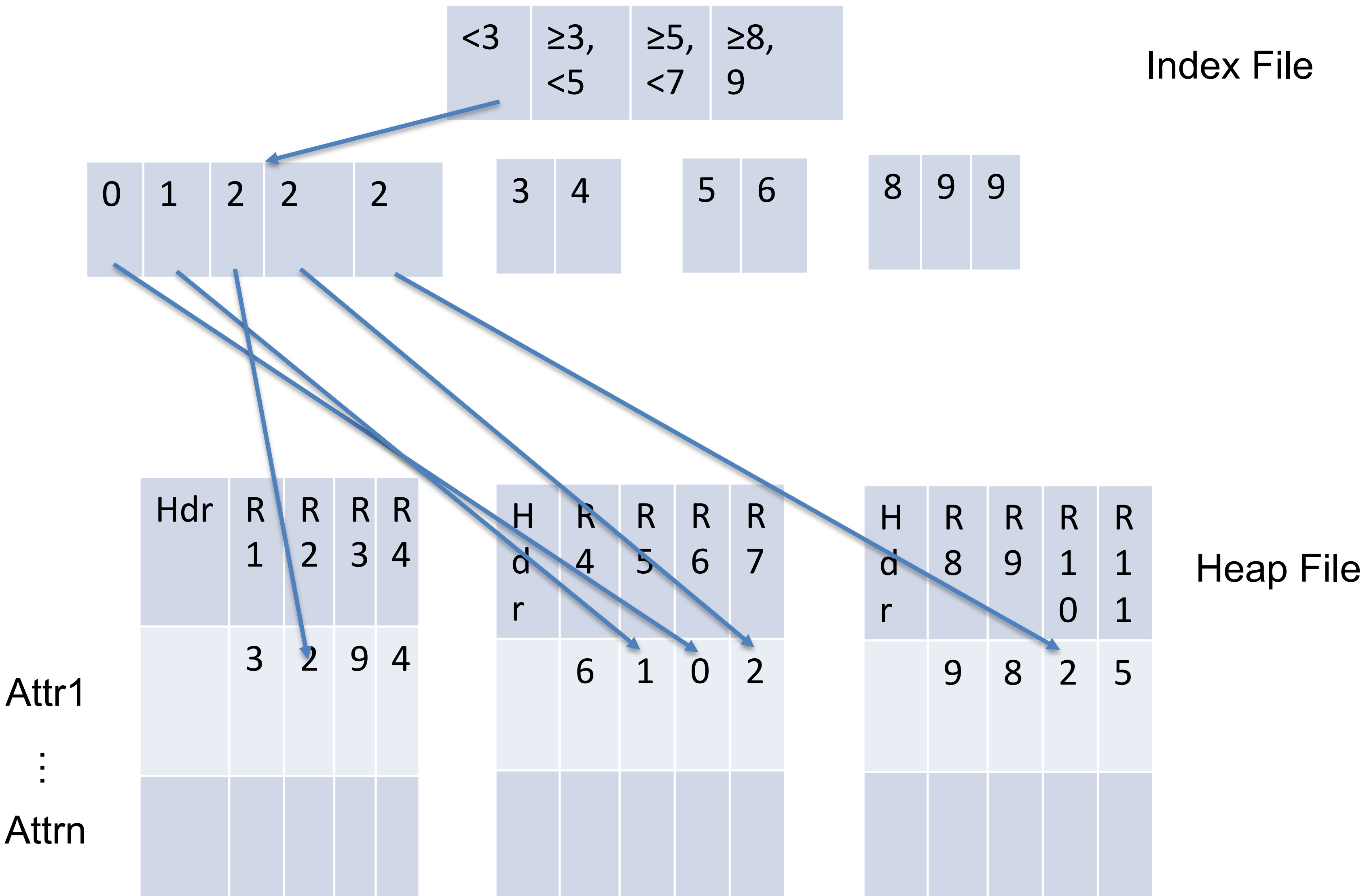


Attr1 >= 6
&
Attr1 < 9

Note random vs sequential access!

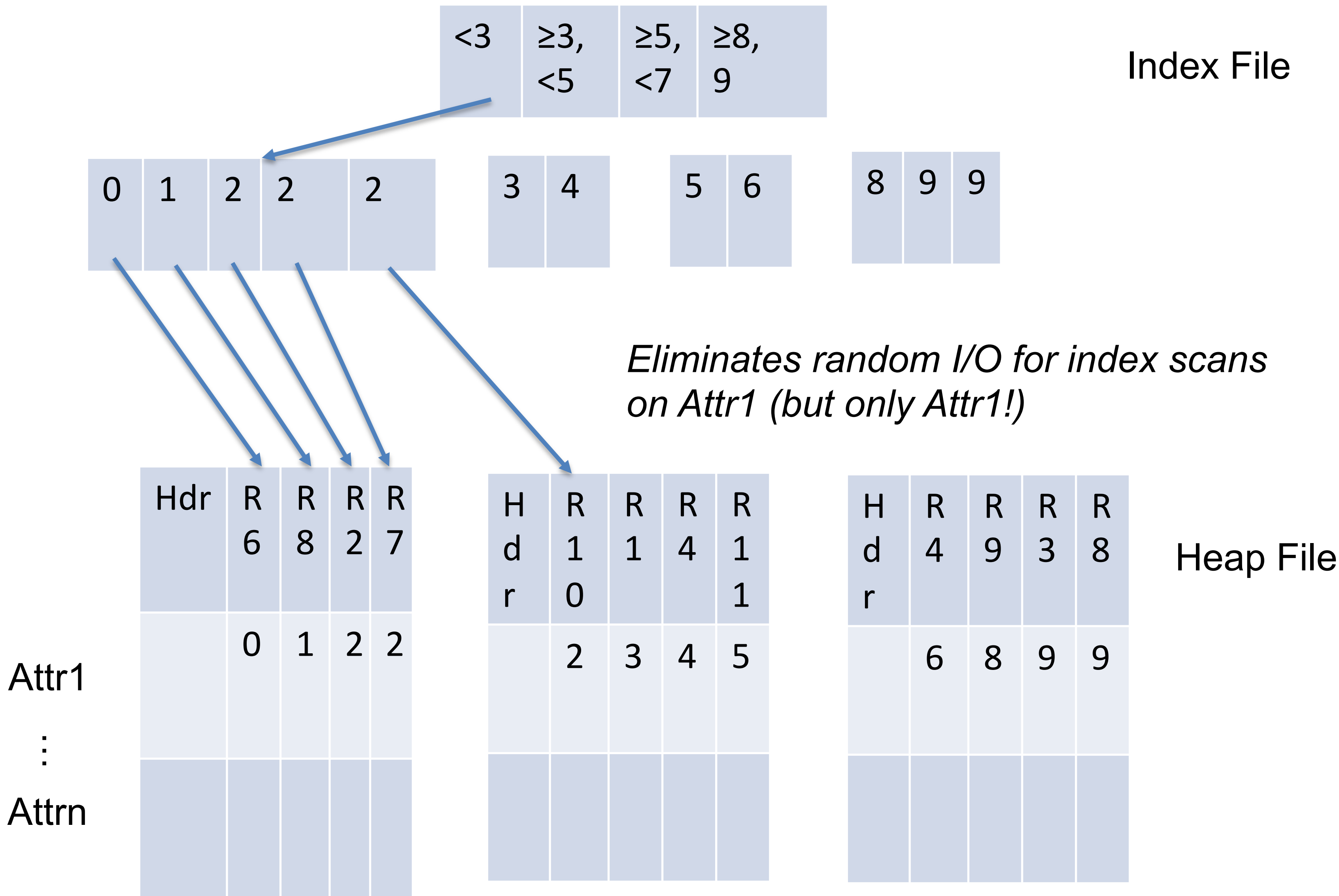
Clustered Index

- Order pages on disk in index order



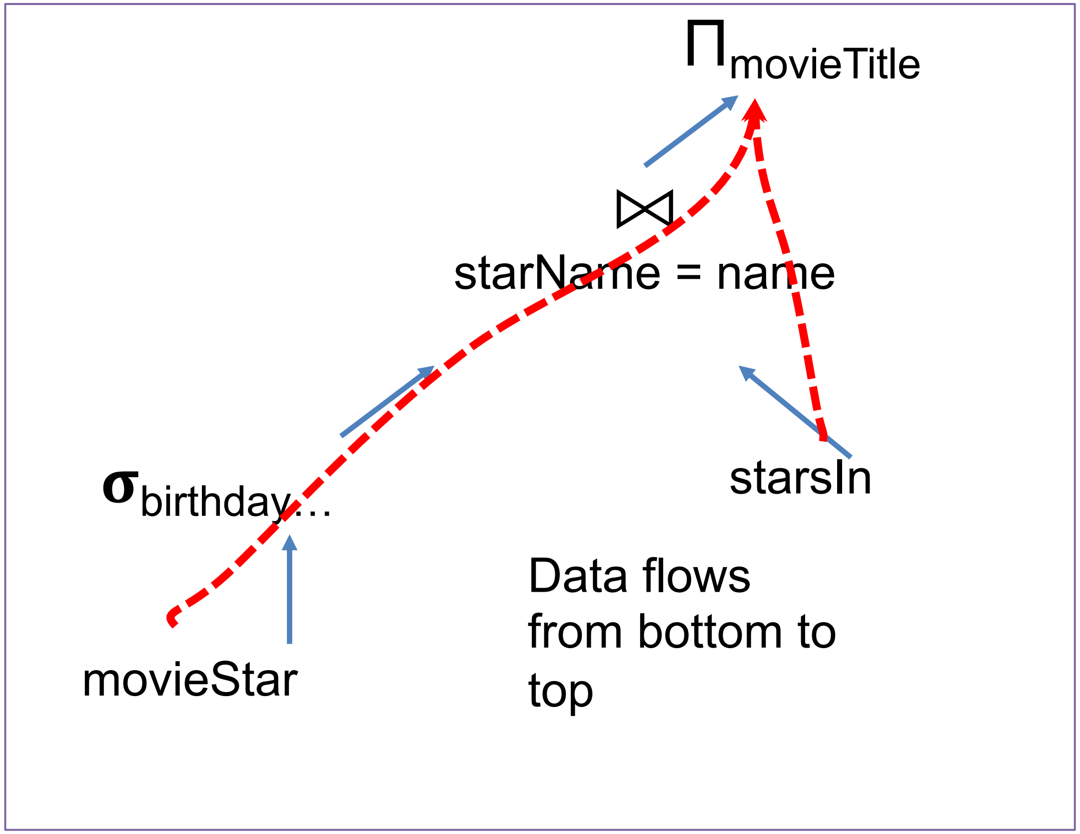
Clustered Index

- Order pages on disk in index order



Let’s take a short break

Connecting Operators: Iterator Model



Each operator implements a simple iterator interface:

open(params)
getNext() → record
close()

Any iterator can compose with any other iterator

it1 = Scan.open("movieStar", …)
it2 = Filter.open(it1, bday=x, …)
it3 = Scan.open("starsIn", …)
it4 = Join.open(it2, it3,
starName=name)
it5 = Proj.open(it4, movieTitle)

Iterator Model

it1 = Scan.open("movieStar", …)
it2 = Filter.open(it1, bday=x, …)
it3 = Scan.open("starsIn", …)
it4 = Join.open(it2, it3,
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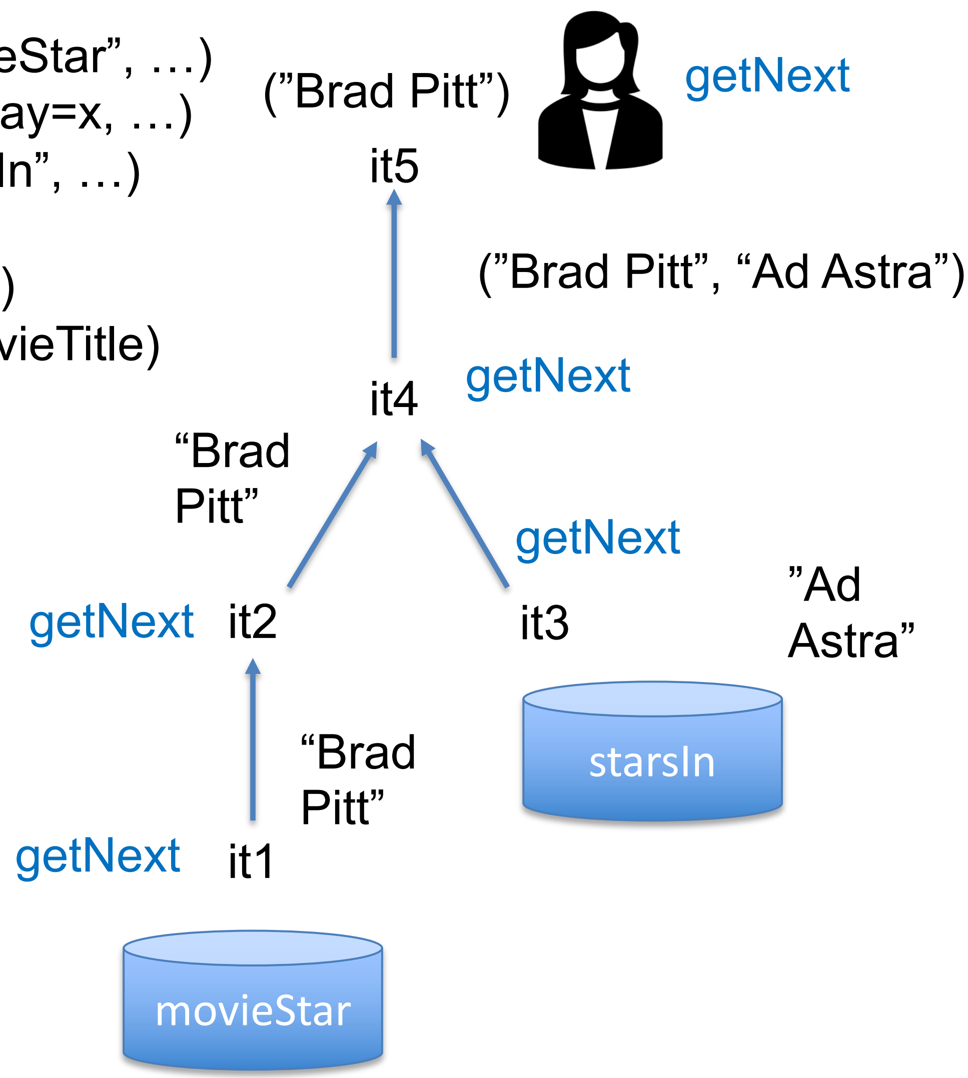


Lab1: What is GoDB?

A basic database system implemented in Go

- A simple storage layer, based on Heap Files (Lab 1)
- A buffer pool for caching pages and implementation page-level locking for transactions (Labs 1-3)
- A set of operators (Labs 1 & 2): Scan, Filter, Join, Aggregate, Order By, Project ...
- A SQL parser (Lab 2), which we implement for you
- Simple transactions (Lab 3)
- Previous years we included recovery, B+Trees, and query optimization, but have reduced the labs because this is our first year in Go.
  - Students in 6.5831 may implement one of these for their final project

What is GoDB Missing?

- Focus is on a simple architecture rather than a complete or high-performance implementation
- Only supports fixed length records with strings and ints
- Only supports sequential scan access methods
- No NULLs
- Uses a simple iterator method, so not super efficient

GoDB Storage Layout

- Each table is stored in one file on disk, called a *heap file*
  - Heap files are an unordered collections of records
  - Only way to access records from a heap file is to scan from beginning to end: “Sequential scan” via an iterator
- Each heap file consists of a number of fixed size heap pages
- Each heap page contains a number of fixed size tuples

- Methods in heap_file.go are used to access the contents of the heap file

Tuples and Tuple Descriptors

- In a given heap file, each tuple has the same layout
- Layout is specified by a TupleDesc object, which specifies the field names and types in the tuple

```go
// FieldType is the type of a field in a tuple, e.g., its name, table, and [godb.DBType].
// TableQualifier may or may not be an empty string, depending on whether the table
// was specified in the query
type FieldType struct {
	Fname string
	TableQualifier string
	Ftype DBType
}

// TupleDesc is "type" of the tuple, e.g., the field names and types
type TupleDesc struct {
	Fields []FieldType
}
```

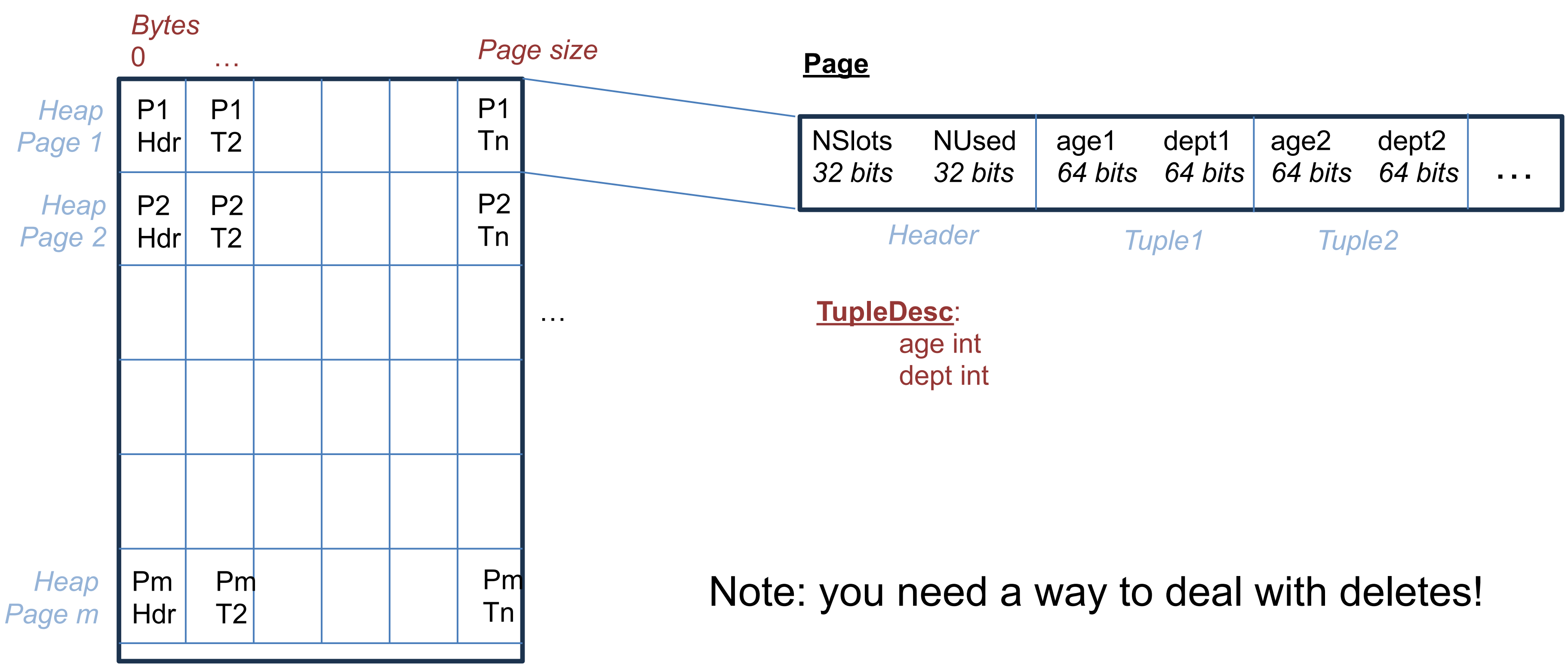
Tuples and Tuple Descriptors (cont.)

- Tuple objects contain the values of each record in Fields
- Field is an interface, implemented by IntField and StringField
- All ints are 64 bits; all string are StringLength characters, padded with zeros

```go
// Tuple represents the contents of a tuple read from a database
// It includes the tuple descriptor, and the value of the fields
type Tuple struct {
     Desc TupleDesc
     Fields []DBValue
     Rid recordID //used to track the page and position this page was read from
}
```

Storage Layout Diagram

HeapFile (table1)



TupleDesc:
age int
dept int

Note: you need a way to deal with deletes!

Buffer Pool

- Buffer pool is an in-memory cache of pages
- Allows GoDB to control how much memory is used and support tables larger than memory
- For transactions, will be responsible for implementing page-level locking and two-phase commit (not until lab 3)

- All iterators and operators should use the buffer pool GetPage method to access pages from heap files
- Only the heap file readPage method directly reads data from disk

Iterators

- Each database operator (filter, project, join, etc) implements an *Iterator*

```
type Operator interface {
    Descriptor() *TupleDesc
    Iterator(tid TransactionID) (func() (*Tuple, error), error)
}
```

- Iterator() returns a function that iterates through the operator’s records
- Most operators take a child operator as a part of their constructor

```
func NewIntFilter(constExpr Expr,
    op BoolOp, field Expr, child Operator) (*Filter[int64], error) { … }
```

- Heap file Iterator iterates through pages on disk; other operators iterate through their child tuples
  - E.g., filter iterates through child tuples, applied the filter to them, and returns satisfying tuples

Iterator Implementation

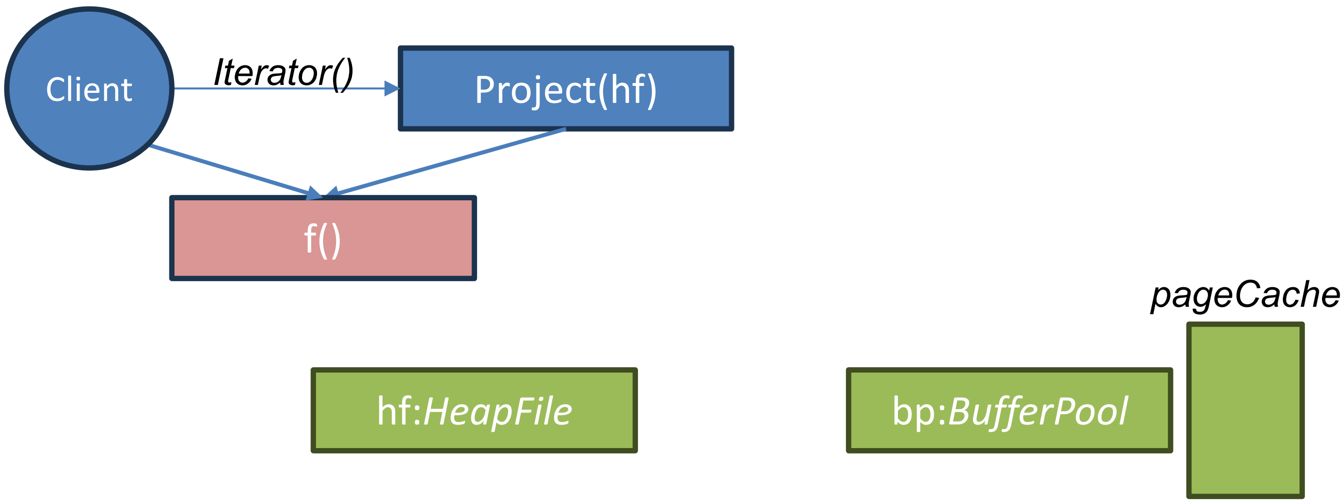
- Returns a function that when called returns the next tuple
- Needs to keep state of where it was in its child

```
func (f *Filter[T]) Iterator(tid TransactionID) (func() (*Tuple, error), error) {

    childIter, _ := f.child.Iterator(tid) //childIter is current iterator state
    …
    return func() (*Tuple, error) {
        for {
            // get child tuple from childIter
            // get tuple fields (e.g., using EvalExpr)
            // apply predicate
            // if matches, return tuple
            // else go onto next tuple
        }, _
    }
```

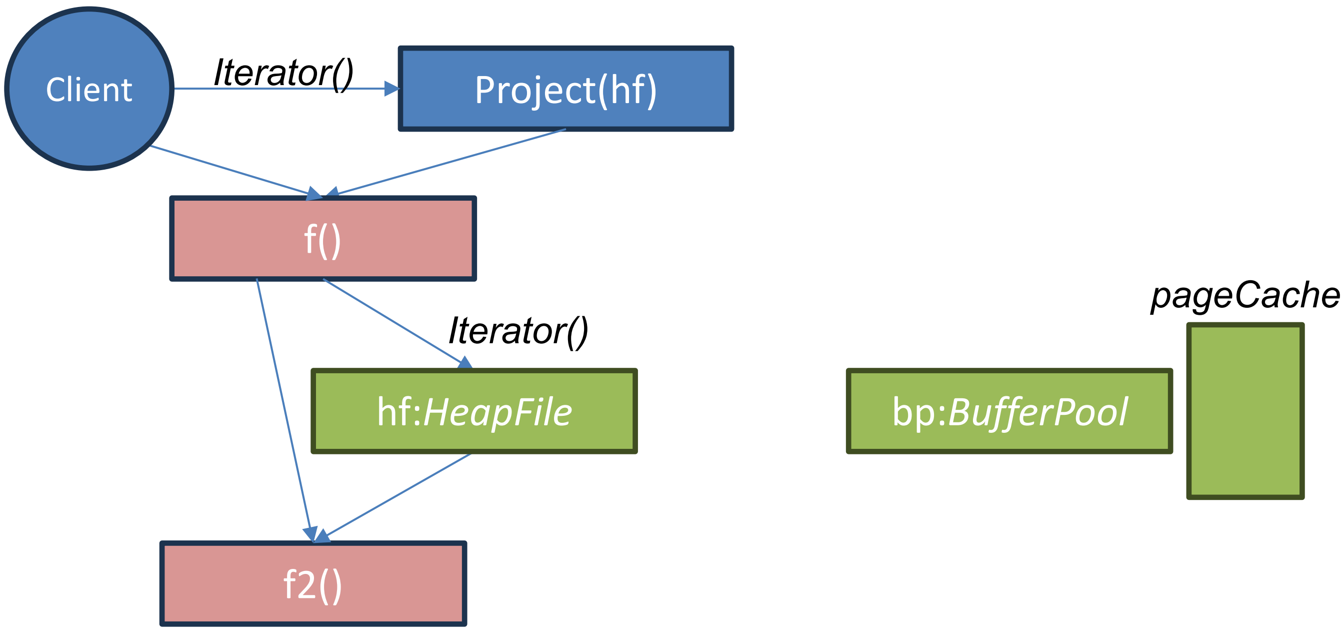

Client
pageCache
hf:HeapFile
bp:BufferPool

Example



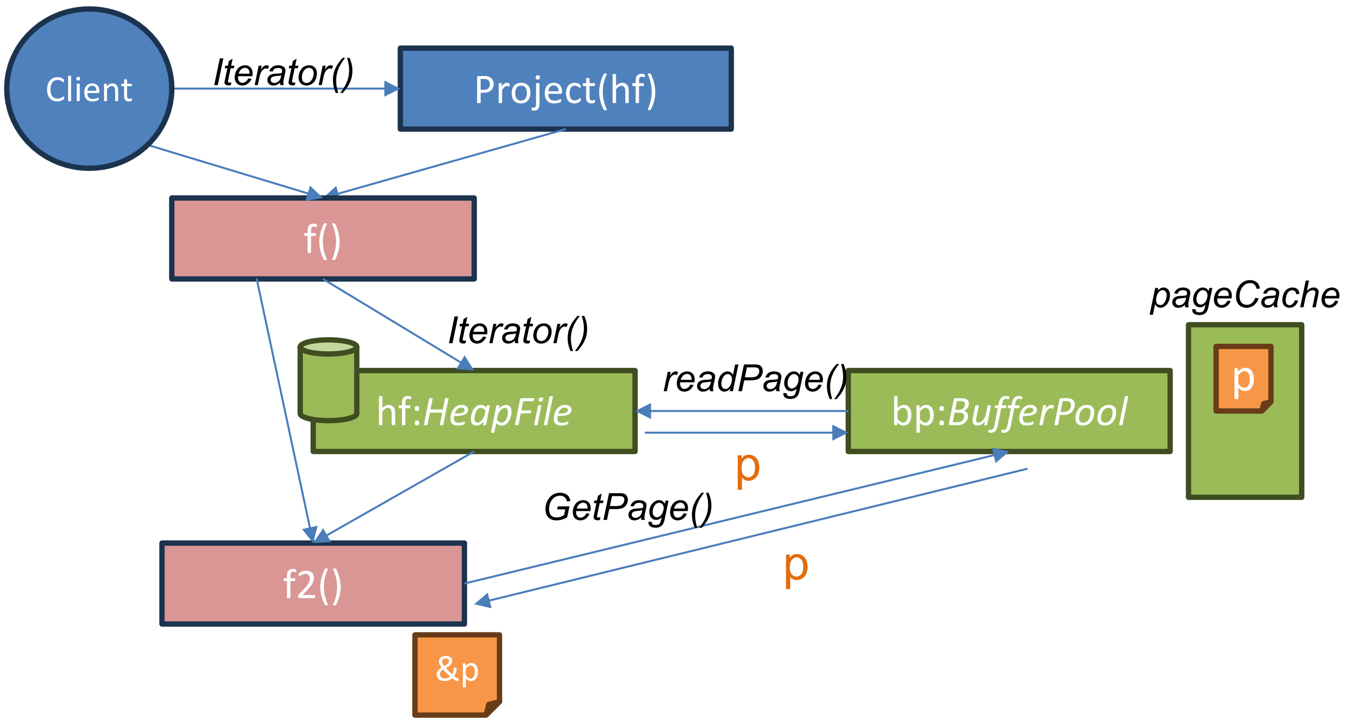
Client
Iterator()
Project(hf)
f()
pageCache
hf:*HeapFile*
bp:*BufferPool*

Example



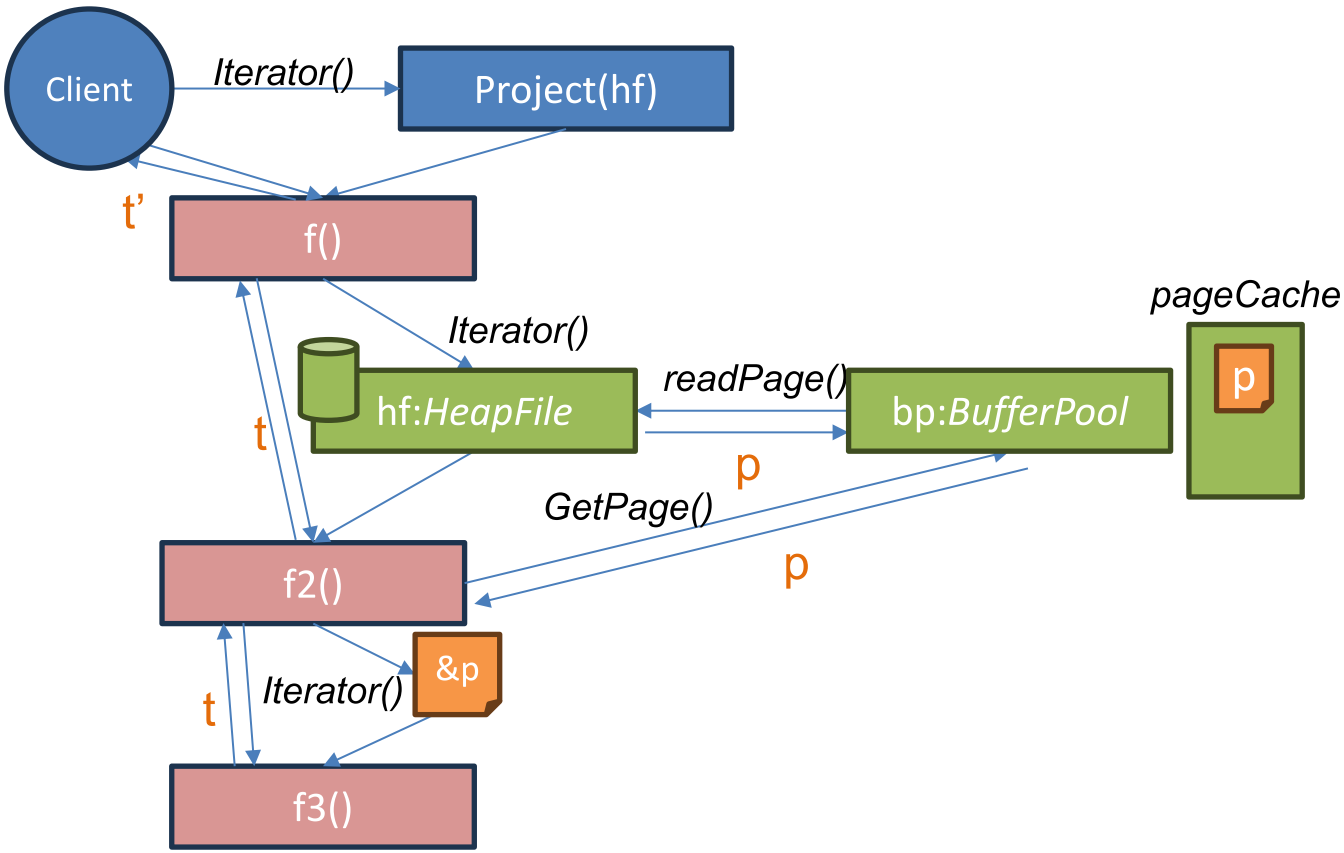
Client
Iterator()
Project(hf)
f()
Iterator()
hf:*HeapFile*
f2()
pageCache
bp:*BufferPool*

Example



Client
Iterator()
Project(hf)
f()
Iterator()
pageCache
readPage()
hf:HeapFile
bp:BufferPool
p
p
GetPage()
p
f2()
&p

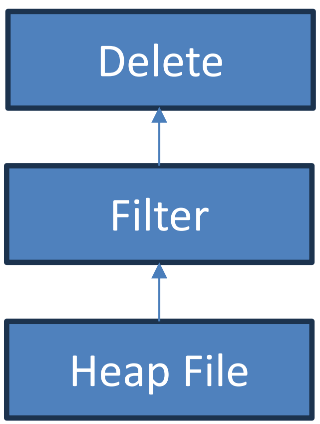
Example



Client
Iterator()
Project(hf)
t'
f()
Iterator()
pageCache
p
readPage()
hf:HeapFile
bp:BufferPool
t
p
GetPage()
p
f2()
&p
Iterator()
t
f3()

Deleting Records and Rids

- Consider a query like:
  DELETE FROM x WHERE f > 10
  This is translated into a plan like



Q: How does the delete operator know which records to delete?

A: Each record from the HeapFile is annotated with a *record id* that is used to identify the position of the record in the heap file to be deleted

Deleting Records and Rids

```
// Remove the provided tuple from the HeapFile. This method should use the
// [Tuple.Rid] field of t to determine which tuple to remove.
// This method is only called with tuples that are read from storage via the
// [Iterator] method, so you can so you can supply the value of the Rid
// for tuples as they are read via [Iterator]. Note that Rid is an empty interface,
// so you can supply any object you wish. You will likely want to identify the
// heap page and slot within the page that the tuple came from.
func (f *HeapFile) deleteTuple(t *Tuple, tid TransactionID) error {
```

- deleteTuple will be called by the delete operator
- Using the t.Rid object, you can clear out the position in the heap file containing the record
- Your heapfile implementation supplies the Rid in the iterator, and so you can identify this position however you like
- A standard Rid implementation is a page number and a slot within the page
  - Recall that all pages have the same number of slots

```go
func computeFieldSum(fileName string, td TupleDesc, sumField string
) (int, error) {

    //Create buffer pool
    bp := NewBufferPool(10)

    hf, err := NewHeapFile("myfile.dat", &td, bp)
    …
    err = hf.LoadFromCSV(CSVfile, true, ",", false)

    //find the column
    fieldNo, err := findFieldInTd(FieldType{sumField, "", IntType}, &td)

    //Start a transaction -> we will do the implementation in another lab
    tid := NewTID()
    bp.BeginTransaction(tid)
    iter, err := hf.Iterator(tid)

    //Iterate through the tuples and sum them up.
    sum := 0
    for {
        tup, err := iter()
        f := tup.Fields[fieldNo].(IntField)
        sum += int(f.Value)
    }

    bp.CommitTransaction() //commit transaction
    return sum, nil //return the value
}
```

Have Fun!

- Start early
- Let us know what you find confusing on Piazza!