Lecture 5: Memory Management

Administrivia

- Assignment 1 is due on September 7th @ 11:59pm

Poll

https://www.strawpoll.me/20863490

P4. CPP

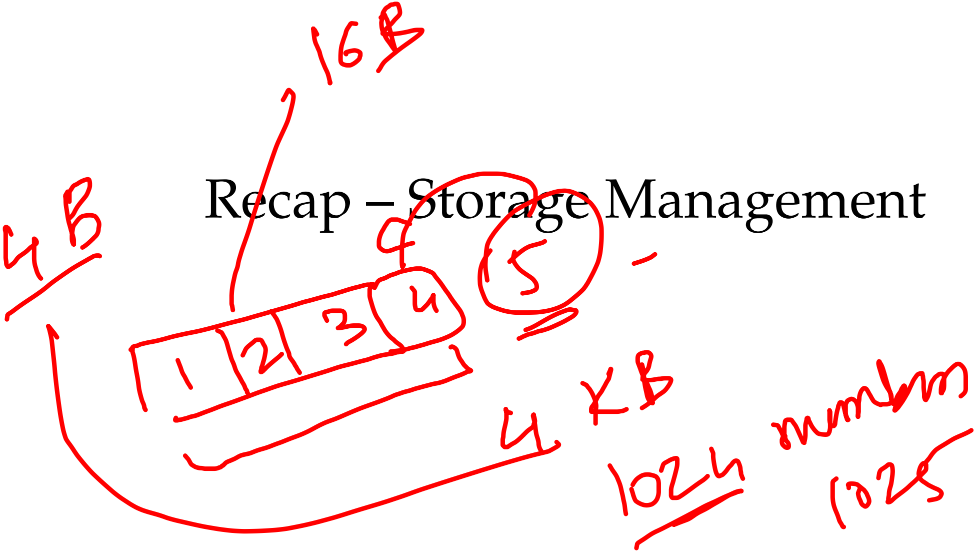
1. Constraint Input Size

1 KB → 1024 B

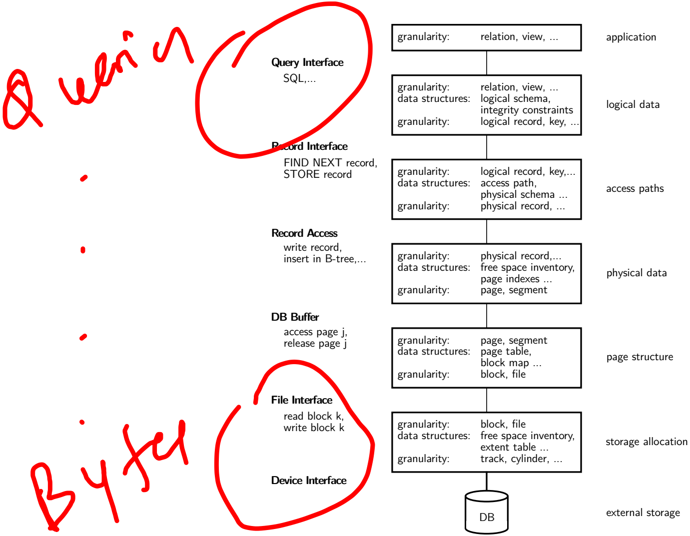
2. CPP Ref

2. Separate files to learn concepts

Recap – Storage Management



Layered Architecture



Query

Bytes

Query Interface
SQL,...

granularity: relation, view, ...

application

granularity: relation, view, ...
data structures: logical schema, integrity constraints
granularity: logical record, key, ...

logical data

Record Interface
FIND NEXT record, STORE record

granularity: logical record, key,...
data structures: access path, physical schema ...
granularity: physical record, ...

access paths

Record Access
write record, insert in B-tree,...

granularity: physical record,...
data structures: free space inventory, page indexes ...
granularity: page, segment

physical data

DB Buffer
access page j, release page j

granularity: page, segment
data structures: page table, block map ...
granularity: block, file

page structure

File Interface
read block k, write block k

granularity: block, file
data structures: free space inventory, extent table ...
granularity: track, cylinder, ...

storage allocation

Device Interface

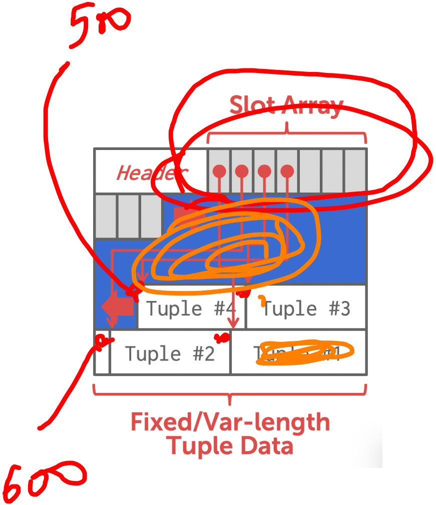
external storage

Database System Architectures

- Disk-Centric Database System
  - The DBMS assumes that the primary storage location of the database is HDD. /SSD
- Memory-Centric Database System
  - The DBMS assumes that the primary storage location of the database is DRAM.

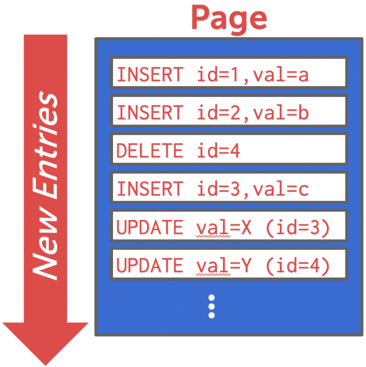
Slotted Pages

- The most common page layout scheme is called slotted pages.
- The **slot array** maps "slots" to the tuples' starting position offsets.
- The header keeps track of:
  - The number of used slots
  - The offset of the starting location of the last slot used.



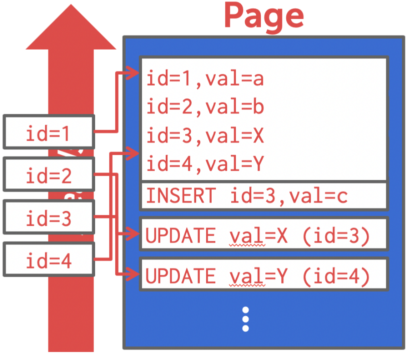
Log-structured File Organization

- Instead of storing tuples in pages, the DBMS only stores log records.
- The system appends log records to the file of how the database was modified:
  - Inserts store the entire tuple.
  - Deletes mark the tuple as deleted.
  - Updates contain the delta of just the attributes that were modified.



Log-structured File Organization

- To read a record, the DBMS scans the log backwards and "recreates" the tuple to find what it needs.
- Build indexes to allow it to jump to locations in the log.
- Periodically compact the log.



Page

id=1,val=a
id=2,val=b
id=3,val=X
id=4,val=Y

INSERT id=3,val=c

UPDATE val=X (id=3)

UPDATE val=Y (id=4)

id=1
id=2
id=3
id=4

Today’s Agenda

- Dynamic Memory Management
- Segments
- System Catalog

Dynamic Memory Management

Virtual Address Space

Each Linux process runs within its own **virtual address space**

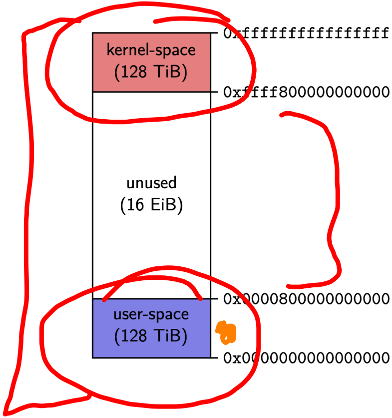
- The kernel pretends that each process has access to a (huge) continuous range of addresses (≈ 256 TiB on x86-64)
- Virtual addresses are mapped to physical addresses by the kernel using page tables and the **memory management unit** (MMU)
- Greatly simplifies memory management code in the kernel and improves security due to memory isolation
- Allows for useful “tricks” such as memory-mapping files

hardware support

Virtual Address Space

The kernel also uses virtual memory

- Part of the address space has to be reserved for kernel memory
- This kernel-space memory is mapped to the same physical address for each process
- Access to this memory is restricted
- Most of the address space is unused
- MMUs on x86-64 platforms only support 48 bit pointers at the moment



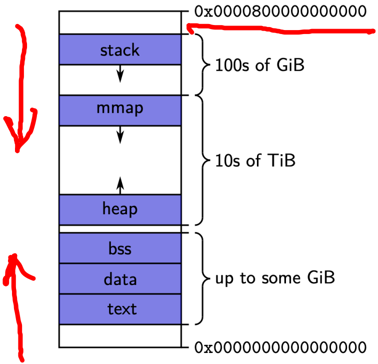
Virtual Address Space

User-space memory is organized in **segments**

- Stack segment
- Memory mapping segment
- Heap segment
- BSS, data and text segments

Segments grow over time

- Stack and memory mapping segments usually grow down (i.e. addresses decrease)
- Heap segment usually grows up (i.e. addresses increase)



Stack Segment

Stack memory is typically used for objects with automatic storage duration

- The compiler can statically decide when allocations and deallocations must happen
- The memory layout is known at compile-time
- Allows for highly optimized code (allocations and deallocations simply increase/decrease a pointer)

Fast, but inflexible memory

- The stack grows and shrinks as functions push and pop local variables
- Stack variables only exist while the function that created them is running
- Array sizes must be known at compile-time
- No dynamic data structures are possible (trees, graphs, *e.t.c.*)

runtime

Stack Segment

All variables are allocated using stack memory

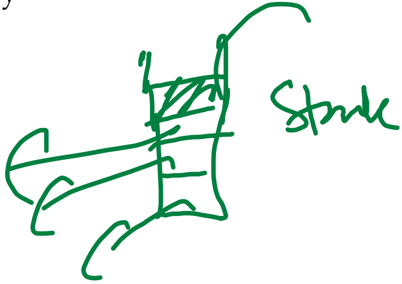
```
include <stdio.h>

double multiplyByTwo (double input) {
  double twice = input * 2.0;
  return twice;
}

int main (int argc, char *argv[]){
  int age = 30;
  double salary = 12345.67;
  double myList[3] = {1.2, 2.3, 3.4};

  printf("double your salary is %.3f\n", multiplyByTwo(salary));

  return 0;
}
```



Heap Segment

The heap is typically used for objects with dynamic storage duration

- The programmer must explicitly manage allocations and deallocations
- Allows for more flexible memory management

glibc

jemalloc

Disadvantages

- Performance impact of heap-based memory allocator
- Memory fragmentation
- Dynamic memory allocation is error-prone
  - Memory leaks
  - Double free (deallocation)
  - Make use of **debugging tools**! (GDB, Valgrind, ASAN)

Heap Segment

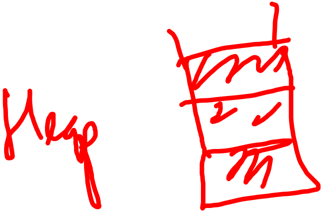
All variables are allocated using heap memory

```
include <stdio.h>
include <stdlib.h>

double *multiplyByTwo (double *input) {
  double *twice = malloc(sizeof(double));
  *twice = *input * 2.0;
  return twice;
}

int main (int argc, char *argv[]) {
  int *age = malloc(sizeof(int)); *age = 30;
  double *salary = malloc(sizeof(double));  *salary = 12345.67;
  double *twiceSalary = multiplyByTwo(salary);
  printf("double your salary is %.3f\n", *twiceSalary);

  free(age);  free(salary);  free(twiceSalary);
  return 0;
}
```



Dynamic Memory Management in C++

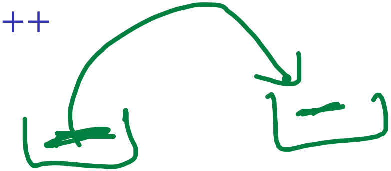
C++ provides several mechanisms for dynamic memory management

- Through `new` and `delete` expressions (discouraged)
- Through the C functions `malloc` and `free` (discouraged)
- Through **smart pointers** and ownership semantics (**preferred**)

Mechanisms give control over the storage duration and possibly lifetime of objects

- Level of control varies by method
- In all cases: manual intervention required

Dynamic Memory Management in C++



Key functions and features

- `std::memcpy` : copies bytes between non-overlapping memory regions
- `std::memmove` : copies bytes between possibly overlapping memory region
- `std::unique_ptr`: assumes unique ownership of another C++ object through a pointer

Dynamic Memory Management in C++

Key functions and features

- copy semantics: Assignment and construction of classes typically employ copy semantics
- move semantics: Move constructors/assignment operators typically "steal" the resource of the argument

```
struct A {
        A(const A& other);
        A(A&& other);
};

int main() {
        A a1;
        A a2(a1);          // calls copy constructor
        A a3(std::move(a1));          // calls move constructor
}
```

a1

a2 = a1

a3 =

Memory Mapping Files

POSIX defines the function `mmap()` in the header `<sys/mman.h>` which can be used to manage the virtual address space of a process.

```
void* mmap(void* addr, size_t length, int prot, int flags, int fd, off_t offset)
```

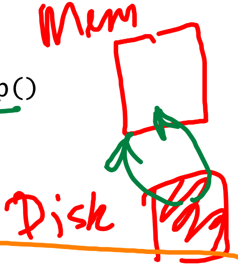
malloc

- Arguments have different meaning depending on flags
- On error, the special value `MAP_FAILED` is returned
- If a pointer is returned successfully, it must be freed with `munmap()`

```
int munmap(void* addr, size_t length)
```

free

- addr must be a value returned from `mmap()`
- length must be the same value passed to `mmap()`
- `munmap()` should be called to follow the **Resource Acquisition Is Initialization** (RAII) principle

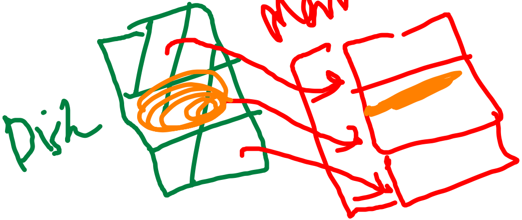


Memory Mapping Files

One use case for `mmap()` is to map the contents of a file into the virtual memory. To map a file, the arguments are used as follows:

```
void* mmap(void* addr, size_t length, int prot, int flags, int fd, off_t offset)
```

- `addr`: hint for the kernel which address to use, should be nullptr
- `length`: length of the returned memory mapping (usually multiple of page size)
- `prot`: determines how the mapped pages may be accessed and is a combination (with bitwise or) of the following flags:
  - `PROT_EXEC`: pages may be executed
  - `PROT_READ`:pages may be read
  - `PROT_WRITE`: pages may be written
  - `PROT_NONE`: pages may not be accessed



Memory Mapping Files

One use case for mmap() is to map the contents of a file into the virtual memory. To map a file, the arguments are used as follows:

```
void* mmap(void* addr, size_t length, int prot, int flags, int fd, off_t offset)
```

- `flags`: should be either `MAP_SHARED` (changes to the mapped memory are written to the file) or `MAP_PRIVATE` (changes are not written to the file)
- `fd`: descriptor of an opened file
- `offset`: Offset into the file where the mapping should start (multiple of page size)

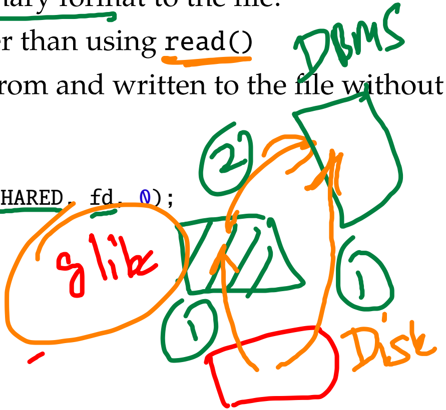
Memory Mapping Files

Example of reading integers from file /tmp/ints:

- Note: This assumes that integers are written in binary format to the file!
- Using `mmap()` to read from large files is often faster than using `read()`
- This is because with `mmap()` data is directly read from and written to the file without copying it to a buffer first

```
int fd = open(``/tmp/ints'', O_RDONLY);
void* mappedFile= mmap(nullptr, 4096, PROT_READ, MAP_SHARED, fd, 0);
int* fileInts= static_cast<int*>(mappedFile);
for (int i = 0; i < 1024; ++i)
        std::cout<< fileInts[i] << std::endl;
munmap(mappedFile, 4096);
close(fd)
```

void* → int*



Using mmap for Memory Allocation

mmap() can also be used to allocate memory by not associating it with a file.

- flags must be `MAP_PRIVATE | MAP_ANONYMOUS`
- fd must be -1; offset must be 0
- Used by `malloc()` internally
- Should be used manually only to allocate large regions of memory (*e.g.*, several MBs)

Example of allocating 100 MiB of memory:

```
void* mem = mmap(nullptr, 100 * (1ull << 20),
                                 PROT_READ | PROT_WRITE,
                                 MAP_PRIVATE | MAP_ANONYMOUS,
                                 -1, 0);

// [...]
munmap(mem, 100 * (1ull << 20));
```

Tuple Layout

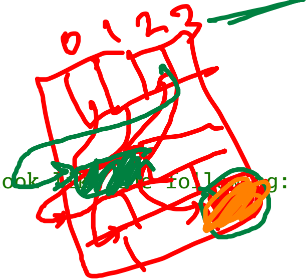
1 Byte

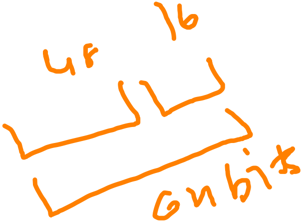
(5, 2)
(10, 3)

- A tuple is essentially a sequence of bytes.
- The DBMS needs a way to keep track of individual tuples.
- Each tuple is assigned a unique record identifier: `TID`.

```
std::vector<char> tuple_data;

struct TID {
  explicit TID(uint64_t raw_value);
  TID(uint64_t page, uint16_t slot);
  /// The TID could, for instance, look like the following:
  /// - 48 bit page id
  /// - 16 bit slot id
  uint64_t value;
};
```



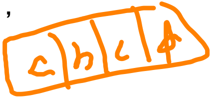


Tuple Schema

- It's the job of the DBMS to interpret those bytes into attribute types and values.

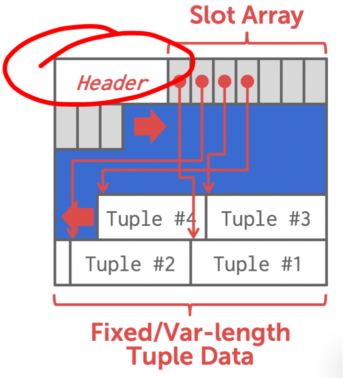
```
std::vector<schema::Table> tables{
  schema::Table(
      "customer",
      {
          schema::Column("c_custkey", schema::Type::Integer()),
          schema::Column("c_name", schema::Type::Varchar(25)),
          schema::Column("c_address", schema::Type::Varchar(40)),
          schema::Column("c_acctbal", schema::Type::Numeric(12, 2)),
      }
};

auto schema = std::make_unique<schema::Schema>(std::move(tables));
```



Page Layout

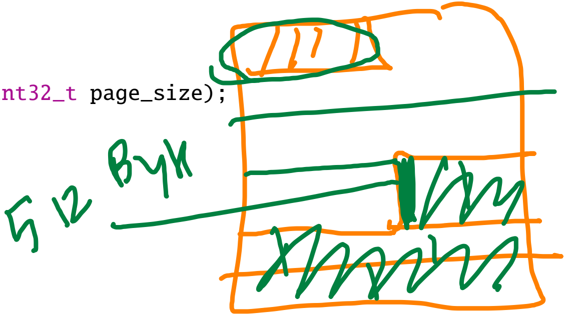
- The most common page layout scheme is called slotted pages.
- The **slot array** maps "slots" to the tuples' starting position offsets.
- The header keeps track of:
    - The number of used slots
    - The offset of the starting location of the last slot used.



Page Layout

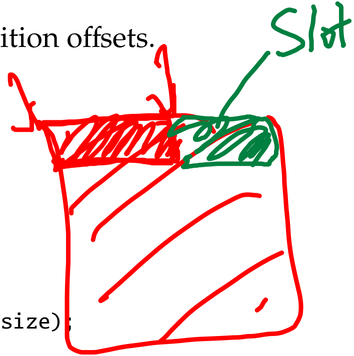
- The header keeps track of:
  - The number of used slots
  - The offset of the starting location of the last slot used.

```
struct SlottedPage {
  struct Header {
    // Constructor
    explicit Header(char *_buffer_frame, uint32_t page_size);
    /// overall page id
    uint64_t overall_page_id;
    /// location of the page in memory
    char *buffer_frame;
    /// Number of currently used slots
    uint16_t slot_count;
    /// Lower end of the data
    uint32_t data_start;
  };
};
```



Page Layout

- The **slot array** maps "slots" to the tuples' starting position offsets.



```
struct SlottedPage {
  ...
  struct Slot {
    Slot() = default;
    /// The slot value
    uint64_t value;
  };
  /// Constructor.
  explicit SlottedPage(char *buffer_frame, uint32_t page_size);
  /// Slot helper functions
  TID addSlot(uint32_t size);
  void setSlot(uint16_t slotId, uint64_t value);
  Slot getSlot(uint16_t slotId);
};
/// Slot array
auto *slots = reinterpret_cast<Slot *>(header.buffer_frame + sizeof(header));
```

Poll

https://www.strawpoll.me/20858648

Segments

Segments

While page granularity is fine for I/O, it is somewhat unwieldy

- most data structures within a DBMS span multiple pages
- convenient to treat these as one entity: **segment**
- relations, indexes, free space inventory (FSI), *e.t.c.*
- each logical DBMS structure is managed as a segment

Conceptually similar to file (but supports **non-linear ordering** of data).

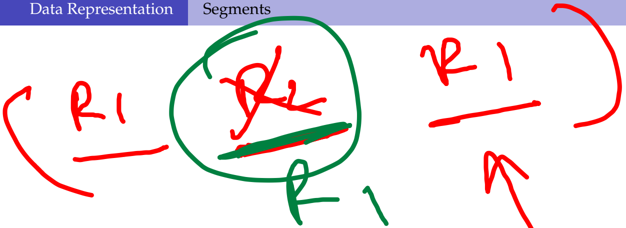
Segments

A segment offers a virtual address space within the DBMS

- can allocate and release new pages
- can iterate over all pages
- can drop the whole segment
- offers a non-linear address space

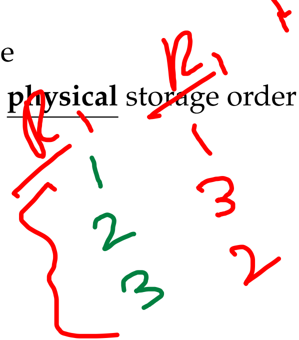
Greatly simplifies the logic of higher layers.

Segments

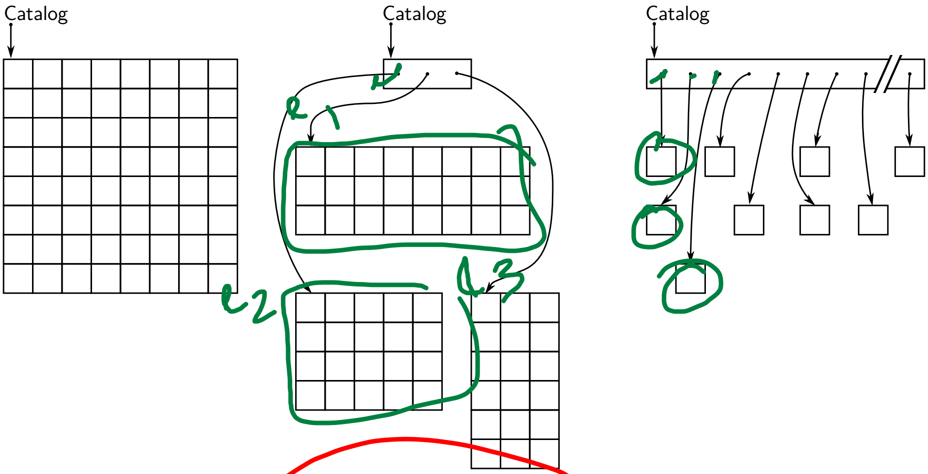


Example: pages from R1 | pages from R2 | pages from R1

- Dropping relation R2 ⟶ hole in the segment
- New pages from R1 may be inserted into the hole
- **Logical** insertion order of R1 does not match the **physical** storage order in segment
- Need `ORDER BY` to guarantee logical ordering



Disk Block Mapping



static file-mapping

dynamic extent-mapping

dynamic block-mapping

Disk Block Mapping

All approaches have pros and cons:

- ❶ static file-mapping
  - very simple, low overhead
  - resizing is difficult
- ❷ dynamic block-mapping
  - maximum flexibility
  - administrative overhead, additional indirection
- ❸ dynamic extent-mapping
  - can handle growth
  - slight overhead

In most cases extent-based mapping is preferable.

Disk Block Mapping

The units of database space allocation are **disk blocks, extents, and segments**.

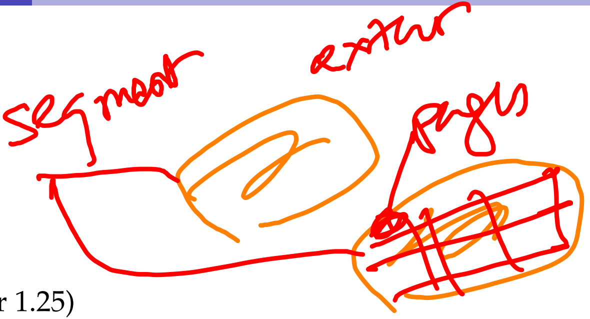
- A disk block is the smallest unit of data used by a database.
- An extent is a logical unit of database storage space allocation made up of a number of **contiguous** disk blocks.
- One or more extents in turn make up a segment.
- When the existing space in a segment is completely used, the DBMS allocates a new extent for the segment.

Disk Block Mapping

A segment is a set of extents that contains all the data for a specific logical storage structure within a tablespace.

- For each table, the DBMS allocates one or more extents to form that table's data segment
- For each index, the DBMS allocates one or more extents to form its index segment.

Disk Block Mapping



Dynamic extent-mapping:

- grows by adding a new extent
- should grow exponentially (*e.g.*, factor 1.25)
- exponential growth bounds the number of extents
- reduces both complexity and space consumption
- and helps with sequential I/O! Why?

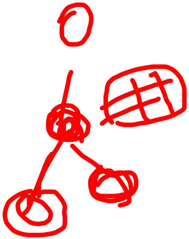
1 MB 1.25 MB 1.25^2 MB . . . . 1.25^{10}

Segment Types

Segments can be classified into types

- public vs. private (*e.g.*, list of segments) // visibility to the user
- permanent (*e.g.*, relation) vs. temporary (*e.g.*, intermediate output of a relational operator in the query plan)
- automatic vs. manual
- with recovery vs. without recovery

Differ in complexity and required effort.



Private Segments

Most DBMS will need at least two private segments:

- segment inventory
  - keeps track of all disk blocks allocated to segments
  - keeps **extent lists** or **page tables** or ...
- **free space inventory** (FSI)
  - keeps track of free pages
  - maintains **bitmaps** or free extents or ...

Public Segments

Public segments built upon these low-level private segments.

Common high-level segments:

- schema
- relations
- temporary segments (created and discarded on demand)
- ...

Slotted Page Segment

Slotted Page Segment

```
class SPSegment : public buzzdb::Segment {
 public:
  /// Constructor
  SPSegment(uint16_t segment_id, BufferManager &buffer_manager,
            SchemaSegment &schema, FSISegment &fsi);
  /// Allocate a new record.
  TID allocate(uint32_t record_size);
  /// Read the data of the record into a buffer.
  uint32_t read(TID tid, std::byte *record, uint32_t capacity) const;
  /// Write a record.
  uint32_t write(TID tid, std::byte *record, uint32_t record_size);
  /// Resize a record.
  void resize(TID tid, uint32_t new_size);
  /// Removes the record from the slotted page
  void erase(TID tid);
};
```

Slotted Page Segment

Slotted Page Segment

```
class SPSegment : public buzzdb::Segment {
 ...
 protected:
  /// Schema segment
  SchemaSegment &schema;
  /// Free space inventory
  FSISegment &fsi;
};
```

Poll

https://www.strawpoll.me/20858678

System Catalog

System Catalog

- A DBMS stores **meta-data** about databases in its internal catalog.
  - List of tables, columns, indexes, views
  - List of users, permissions
  - Internal statistics (*e.g.*, disk reads, storage space allocation)
- Almost every DBMS stores their catalog as a **private database**.
  - Wrap object abstraction around tuples.
  - Specialized code for "bootstrapping" catalog tables. Why?

System Catalog

SQL-92

- You can query the DBMS's `INFORMATION_SCHEMA` database to get info.
  - ANSI standard set of read-only views that provide info about all of the tables, views, columns, and procedures in a database
  - DBMSs also have non-standard shortcuts to retrieve this information.

Accessing Table Schema

SQL Fiddle: Link

- **Task:** List all the tables in the database.

```
--- SQL 92
SELECT *  FROM INFORMATION_SCHEMA.TABLES
        WHERE table_schema = 'public';

--- PostgreSQL
\d
--- MySQL
SHOW TABLES;
--- SQLite
.tables;
```

Accessing Table Schema

- **Task:** List all the columns in the `students` table.

```
--- SQL 92
SELECT *  FROM INFORMATION_SCHEMA.COLUMNS
        WHERE table_name = 'students';
--- PostgreSQL
\d student
--- MySQL
DESCRIBE student;
--- SQLite
.schema student;
```

Conclusion

- The units of database space allocation are disk blocks, extents, and segments
- A DBMS stores meta-data about databases in its internal catalog

References I