DavisBase Nano File Format Guide

Storage Definition Language (SDL)

Version 1.2

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1. Introduction

DavisBase Nano is a relational database management system (DBMS) that implements a small subset of the SQL commands specification. DavisBase is not intended for commercial applications—but instead, for use in an academic setting for use by students to gain an understanding of relational database *internals*. This document assumes that the reader already possesses a basic understanding of (1) basic SQL, (2) relational database theory, and (3) hexadecimal file viewers/editors ("hex editor") such as the built-in Unix command **`hexdump`**.

This File Format Guide describes only the Storage Definition Language (SDL) of DavisBase. It is intended to be a subsection of the overall DavisBase Specification, which also includes a data query language (DQL), data definition language (DDL), data control language (DCL), and data manipulation language (DML). Additionally, an API will be included in a later version that is based on a subset of the JDBC specification.

The DQL

DavisBase SDL file architecture borrows liberally from that of several open-source databases including SQLite, MySQL, and PostgreSQL. In fact, one of the primary goals of DavisBase is to be an educational platform for learning the internals of relational databases. Implementing file structures that mimic those of widely known DBMSs provides insight into the mechanics of relational databases in general.

⚠ We note that DavisBase is not fully ACID[1] compliant! There is neither a system log nor a formal mechanism for rollback or recovery of failed transactions.

2. Database Files

Despite its similarity in name to the real world physical object called a "file", which is typically printed on paper that can be physically touched and held, a computer file is a *virtual* construct. The term "file" can be defined in various ways since it is a logical construct that may be stored in discontiguous subsections or blocks called *pages*, either in volatile memory (RAM, "main memory") or non-volatile memory (hard disk, SSD, CD-ROM, Blu-Ray, "thumb drive", etc.).

A file is represented by a sequence of bytes, even though the sequence may not be stored contiguously in computer memory.

A file may be a virtual construct in volatile storage (i.e. main memory or RAM). It may also be a construct that is physically stored in non-volatile memory like a hard disk, SSD, or thumb drive.

DavisBase SDL uses two types of files: ***table files*** and ***index files***. These are used to store table data and index data, respectively. We note that fully-featured commercial databases utilize additional file types—e.g. view files, script files, macro files, etc. These additional file types are not included in v1.0 of DavisBase Nano.

DavisBase uses a *file-per-table* approach. That is, every table and every index are each stored in a single, separate OS file. Each Table File is strored in an OS file whose name is ***`table_name`*****`.tbl`**, and each Index File is stored in a a file whose name is ***`table_name`*****`.`*****`column_name`*****`.ndx`**.

All DavisBase files are implemented as ***page-based files***. That is, files are subdivided into same-sized logical sections called *pages*. DavisBase supports page sizes of 2^n bytes, where n is an integer in the range 9-15. Therefore, page size is configurable from 512B–32768KB in 2^n byte increments.

[1] https://en.wikipedia.org/wiki/ACID_(computer_science)

All pages of a given file are required to be the same size. All files within the same table space must share the same page size. Once a table space has been initialized, the page size of all of its constituent files is static and constant.

A consequence of this is that the memory footprint of any file must be a multiple of the page size. Files cannot be comprised of partial pages. If data exceeds the capacity of a page, by even one byte, the file must be increased in size by an additional full page.

Most Operating Systems use this same strategy. Most common modern operating systems have a file system that employs a 4k page size (4096 or 2^{12} bytes, exactly). This is the reason that Windows displays two different FIXME

Pages are number usign a zero index convention, like C-style array indexes. That is, the first page in a file is numbered page 0.

Page size is represented in bytes.

All page numbers are 32-bit two's complement integers.

2.1. Offsets

Offsets are the mechanism used to locate specific data or elements within a file.[2] Offsets are expressed as non-negative integers that represent the number of bytes from a given point of reference. There are two kinds of offsets used by DavisBase, ***file offsets*** and ***page offsets***.

File offsets indicate the location of an element expressed as the number of bytes from the beginning of a file. File offsets are most commonly used to identify the location of a page within a file—by multiplying page number time page size. For example, a file with a page size of 512 bytes, page 7 will begin at 3584 (i.e. 7*512) bytes from the beginning of the file.

Page offsets indicate the location of an element expressed as the number of bytes from the beginning of a page.

2.2. Table Files

A table file stores the records (i.e. rows) of a given table in a single file.[3]

Table files are implemented as Bplus-trees where each node of the tree is a page of the file. Table Files store all record data for a given table. Table records reside solely in leaf pages of the B+ tree.

Table Files are not required to have any Index Files, i.e. they may have zero-to-many indexes. However, every Index File must have <u>*exactly one*</u> Table File that it indexes.

Each record in a Table File has an automatically generated unique identifier that is used by DavisBase for internal housekeeping. This is like a hidden extra column that is included in every table. Various databases use different names for this unique identfier: **`rowid`** , **`row_id`**, and **`uid`** are all common. DavisBase uses the name **`rowid`**. Each **`rowid`** is automatically generated based on the following strategy —The first record inserted into a given table is numbered "1", then each subsequen **`rowid`** increases monotonically in integer increments with no gaps. If a record is deleted, its **`rowid`** is never reused. Each

[2] Offsets are the mechanism used by almost *all* relational databases to locate elements within a file.

[3] In the relational model, the "tuples of a relation".

rowid is represented by a 4-byte two's complement integer. Therefore, no table may contain more than 2^{31}–1 (2147483647) total unique records over the lifetime of a table.

If a table schema is created without an explicit PRIMARY KEY, users may insert records that contain duplicate values for all user-defined columns. This would seem to violate relational theory which requres that all tuples (records) be unique. However, every record is still unique since each contains a unique value for this hidden **rowid**. Most relational databases use this strategy of a hidden unique identifier for internal housekeeping.

When a table file is created with a **CREATE TABLE** command it does not have any associated index files by default. However, if a column has been explicitly designated as a **PRIMARY KEY**, then an index file shall be automatically created that indexes this column, and that **PRIMARY KEY** column shall additionally be automatically designated to be **UNIQUE**.

All other columns, whether unique or not, shall not have an index implicitly created. Except for a **PRIMARY KEY** index, all other indexes must be created via an explicit **CREATE INDEX** command. All indexes may have at most a single column. including the **PRIMARY KEY**. Thus, neither composite indexes nor composite keys are supported.

2.2.1. Row IDs

Each record in a table file is uniquely identified by an internally assigned key called the *Row ID*. The Row ID is a column (field or attribute) that is created automatically when a table is created with the column name **rowid**.

The **rowid** column *does not display* when a query is executed that references the **SELECT *** column wildcard. Only user defined columns will display. However, a user may explicity add **rowid** to the list of attributes in the **SELECT** clause to force it to display. For example,

```
SELECT *, rowid FROM table_name;
```

Rowid is an integer. It is automatically generated. It is always monotonically increasing. By nature **rowid** is unique. If a record is deleted, its **rowid** is never re-purposed.

2.3. Index Files

Index files provide efficient access paths to records within table files. All DavisBase indexes provide access paths to records based only on *single columns*. Multi-column indexes are not supported by DavisBase.

Index Files are implemented as B-tree files where each node a B-tree is a page of the file. Index Files store indexing information that provide an access path to a related Table File.

There is a single index entry in an index file for each distinct value in an indexed table column. However, a single index entry may have one to many **`rowid`** numbers depending on how many records in its associated table share the same column value.

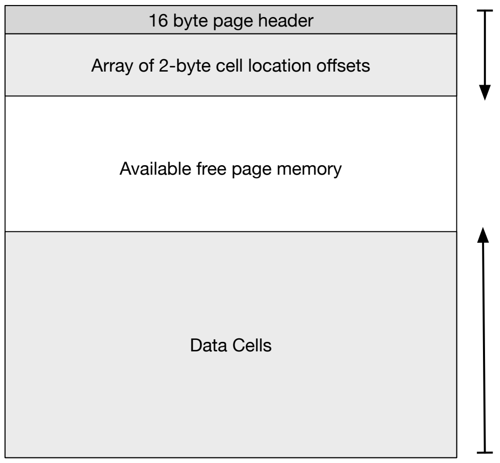
2.4. Database Catalog

The database catalog (i.e. meta-data) for DavisBase is stored in specially designated tables. These are also referred to as **system tables**.[4] The Table Files associated with these are structured exactly the same as Table Files generated with user-defined tables.

[4] The term "system tables" distinguishes them from "user tables", those createMySQL groups these system tables together in what it calls the INFORMATION_SCHEMA.

3. Page Formats

All pages use the basic format of a fixed size header of 16-bytes followed immediately by an array of 2-byte integers that indicate the location of cells within the page (i.e. page offsets). Cells contained in the cell area are written from highest-to-lowest page address upward.


16 byte page header
Array of 2-byte cell location offsets
Available free page memory
Data Cells

3.1. Page Header Format

Page headers are located at the top—page offset zero (0)—of each page within a file. A page header is 16 bytes size. Not all bytes within the header are currently used. By convention, unused bytes are initialized to byte value zero (0x00), however the value is irrelevant since they are never referenced.

Page Offset	Element Size	Description
0x00	1	The one-byte flag at page offset 0x00 indicates the type of b-tree page. • A value of 2 (0x02) means the page is an ***index*** b-tree ***interior*** page. • A value of 5 (0x05) means the page is an ***table*** b-tree ***interior*** page. • A value of 10 (0x0a) means the page is an ***index*** b-tree ***leaf*** page. • A value of 13 (0x0d) means the page is a ***table*** b-tree ***leaf*** page. Any other value for the b-tree page type is an error. These are the same page type values used by SQLite.
0x01	1	Unused
0x02	2	The two-byte integer at offset 2 designates the number of cells on the page. The value of this two-byte integer is the number of cell offsets in the array that begin at location 0x10
0x04	2	The two-byte integer at offset 4 designates the page offset for the start of the cell content area. A zero value for this integer is interpreted as 65536.
0x06	2	The two-byte integer at page offset 0x06 indicates the root page of the file. All pages in the file will have the same value for this two bytes.
0x08	2	The two-byte integer page pointer at page offset 0x08 has a different role depending on the b-tree page type: • For a Table or Index ***interior page*** - value is the page number of rightmost child • For a Table or Index ***leaf page*** - value is the page number of sibling to the right
0x0A	2	The two-byte integer page pointer at offset 0x0A references the page's parent. If this is a root page, then it has no parent and the special value 0xFFFF is used.
0x0C	4	Unused

0x10	2 x *cells on page*	An array of 2-byte integers that indicate the page offset location of each data cell. The array size is 2*n*, where *n* is the number of cells on the page. The array is maintained in key-sorted order.

Table 1 - Page Header Format

The number of cells on any type of page is represented by a 2-byte two's complement integer. Therefore, no page may contain more than 2^{15}–1 (32767) cells.

Page numbers for both types of file are represented by a 4-byte two's complement integer. Therefore, no file may contain more than 2^{31}–1 (2147483647) pages.

3.2. Cell Formats

The **cell** is the basic unit of content for all types of pages. The cell content area of each page is located at the high offset values, i.e. cell content grows from the end of each page upwards.

The array of cell locations immediately following the page header is an array whose *order is maintained to be sorted according to criteria within the cells*, depending upon file type. Table file cells are maintained in rowid sorted order.

File Type	Page Type	Cell Header			Cell Body
		4-byte int	2-byte int	4-byte int	N-byte array
		Left Child Page#	Bytes of Cell Payload	Rowid	Payload
Table	Leaf		✔	✔	✔
	Interior	✔		✔	
Index	Leaf		✔		✔
	Interior	✔	✔		✔

Figure 1: Cell Formats

Note that only interior pages have child pointers, since leaf pages don't have childeren.

The following two tables indicate the contents of the cell body (i.e. the "payload") of record cells and index cells, respectively.

Record Header		**Record Body**
Number of Columns	**List of Column Data Types**	**List of Column Data Values**
1-byte INT	**Array of 1-byte INTs**	***N*-bytes**

Figure 2: Record Format (i.e. Cell Body of Table Leaf Cell)

Index Header			**Index Body**
Number of rowids associated with index value	**Index Data Type**	**Index Value**	**List of rowids associated with index value**
1-byte INT	**1-byte INT**	***N*-bytes**	**Number of rowids x 4-bytes**

Figure 3: Index Format (i.e. Cell Body of All Index Cells)

3.3. Data Types

All data types represented by DavisBase by a 1-byte integer that designates their type. Notice that TEXT (i.e. string) data types are represented by at *set* of 1-byte values. Each particular length of string is represented as its own unique data type. For example, a five character is string is data type 0x11 (i.e. 0x0C + 0x05) and a 43 (0x2B) character string is data type 0x37 (i.e. 0x0C + 0x2B).

Note that data types 0x00 and 0x0C are the *NULL* value and *empty string*, respectively. Neither would require any bytes in the record body.

Date Type Code	Data Type Name	C	Description
0x00	NULL	0	Data type is a NULL (requires no bytes in the record body)
0x01	TINYINT	1	Data type is an 8-bit twos-complement integer.
0x02	SMALLINT	2	Data type is a big-endian 16-bit twos-complement integer.
0x03	INT	4	Data type is a big-endian 32-bit twos-complement integer.
0x04	BIGINT, LONG	8	Data type is a big-endian 64-bit twos-complement integer.
0x05	FLOAT	4	Data type is a big-endian IEEE 754-2008 32-bit floating point number.
0x06	DOUBLE	8	Data type is a big-endian IEEE 754-2008 64-bit floating point number.
0x08	YEAR	1	Data type is an 8-bit twos-complement integer. Both positive and negative numbers are supported in the range -128 to 127. This indicates a year with respect to the epoch year 2000.
0x09	TIME	4	Data type is a big-endian 32-bit twos-complement integer. Indicates time of day in milliseconds since midnight, i.e. “millis”. Note that only values of 0-86400000 (0x00-0x05265c00) are valid.
0x0A	DATETIME	8	Data type is a big-endian unsigned LONG integer that represents the specified number of milliseconds since the standard base time known as "the epoch”. It should display as a formatted string string: YYYY-MM-DD_hh:mm:ss, e.g. `2016-03-23_13:52:23`.
0x0B	DATE	8	A datetime whose time component is 00:00:00, but does not display.
0x0C + *n*	TEXT	0+	Value is data type of “ASCII string of length *n* ”. C-style string null terminators are not used or needed. A value of 0x0C is the empty string and would have no bytes in the record body.

Table 2 - Data Types and Their Implementation

Note that only strings of size 0-115 ASCII characters are supported. Any value 0x0C or above represents an ASCII string data type. Each length string 0-115 has its own unique data type. For example, 0x41 data type is a string of length 53 characters.

4. Database Catalog (meta-data)

The DavisBase Catalog consists of two tables containing meta-data about each of the user table. You may optionally choose to include meta-data about the two catalog files in the catalog itself. These two tables (and their assocated implmentation files) have the following table schema, as if they had been created via the normal **CREATE** command.

```
CREATE davisbase_tables (
   rowid INT,
   table_name TEXT,
   record_count INT,   -- optional field, may help your implementation
   avg_length SMALLINT -- optional field, may help your implementation
   root_page SMALLINT  -- optional field, may help your implementation
);
```

```
CREATE davisbase_columns (
   rowid            INT,
   table_name       TEXT, -- optionally table_rowid INT
   column_name      TEXT,
   data_type        TEXT,
   ordinal_position TINYINT,
   is_nullable      TEXT
);
```

If you choose to include these two tables in the catalog itself, their content would intially be:

```
SELECT * FROM davisbase_tables;

rowid   table_name
--------------------------
1       davisbase_tables
2       davisbase_columns
```

```
SELECT * FROM davisbase_columns;

rowid   table_name        column_name     data_type  ordinal_position is_nullable
---------------------------------------------------------------------------------
1       davisbase_tables  rowid            INT        1                NO
2       davisbase_tables  table_name       TEXT       2                NO
3       davisbase_columns rowid            INT        1                NO
4       davisbase_columns table_name       TEXT       2                NO
5       davisbase_columns column_name      TEXT       3                NO
6       davisbase_columns data_type        TEXT       4                NO
7       davisbase_columns ordinal_position TINYINT    5                NO
8       davisbase_columns is_nullable      TEXT       6                NO
9       davisbase_columns column_key       TEXT       7                YES
```