A Maintainer’s Guide

for the Datatype Module in HDF5 Library

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This document explains the design, architecture, organization, and algorithms of the datatype module in the HDF5 library.

# Introduction

The purpose of this document is to explain the basic design of the datatype module in the HDF5 library – its architecture, organization, and algorithms. For the maintainers of the library, this document should give them enough knowledge to understand, adjust, or fix the library if any problem arises. For the users of the library, the existing documents such as the User’s Guide, the Reference Manual, and the File Format Specification should give them sufficient knowledge to use the library. But if any power user wants to find out how the library is designed, this document can be helpful to some extent. This document is written based on the HDF5 release 1.8.8.

# The Way That the Library Defines Data Types

## Integers

Integers generally have simple bit patterns. Using the twos-complement notation, a signed integer of n bits in size will have a range from -2n-1 to 2n-1 – 1. The high-order bit is the sign bit. There are n-1 data bits. For unsigned integers, the high-order bit becomes a data bit and all n bits are data bits. So an unsigned integer of n bit in size has a range from 0 to 2n–1. An example bit sequence of a 1 byte signed integer is 10010111. The high-order (leftmost) bit is set to 1, meaning the value is negative, -105. If the same bit sequence represents an unsigned integer, the high-order bit becomes a data bit, making the value 151.

In the HDF5 library, each integer data type, predefined or user-defined, has the following properties:

Order The byte order: big or little endian

Sign Signed or unsigned

Size The size of the entire integer data type in bytes

Precision The size of the actual data part of

the integer in bits

Offset The bit offset of the actual data within the data

type

LSB padding The padding bit values on the least significant

side of the data value

MSB padding The padding bit values on the most significant

side of the data value

These properties help the library define or identify each integer type. For example, the following properties define a four-byte little-endian signed integer:

Order little-endian

Sign signed

Size 4 bytes

Precision 32 bits

Offset 0

LSB padding 0

MSB padding 0

**The library provides API functions to query or adjust these properties, such as H5Tset(get)\_size, H5Tset(get)\_order, H5Tset(get)\_precision, H5Tset(get)\_offset, H5Tset(get)\_sign, and H5Tset(get)\_pad. These functions also work for other atomic data types, i.e. floating-point numbers and bitfield types.**

## Floating-Point Numbers

The floating-point number representation is more complicated. A more thorough description of IEEE standard floating-point numbers can be found in the *IEEE Standard 754* document. For IEEE standard floating-point numbers, there are three components for a floating-point number - the sign, the exponent, and the mantissa. The table below shows the layouts of IEEE float and double types.

Table 1. IEEE representation of floating-point numbers

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Type | Sign Bits | Exponent Bits | Mantissa Bits | Bias |
| Float | 1[31] | 8[30-23] | 23[22-00] | 127 |
| Double | 1[63] | 11[62-52] | 52[51-00] | 1023 |

In the table, the numbers are the size of each component. The bit positions are in the square brackets. To calculate the true exponent value, the bias has to be subtracted from the value represented by the bits of exponent. The mantissa represents the precision bits. The leading ‘1’ bit of the mantissa is implied. When the true precision is calculated, this implicit bit will be restored. Consider this bit sequence for float in little-endian order,

byte 3 byte 2 byte 1 byte 0

11000011 11110000 00000000 00000000

The high-order (leftmost) bit is the sign bit. It is set to indicate the number is negative. The eight bits following the sign bit, 10000111 in byte 3 and 2, is the exponent. The value of these eight bits is 135. After subtracting the bias 127, the true exponent is 8. The 23 bits following the exponent, 1110000 00000000 00000000 in bytes 2, 1, 0, is the mantissa. After restoring the implicit leading bit and adding the radix, the mantissa becomes 1.1110000 00000000 00000000. The value of this float number is 1.111 x 28 = 111100000.0 in binary. Adding the sign bit, the value is -480.0 in decimal.

There are a few special values for floating-point numbers,

*Denormalized* – when exponent bits are all 0s but mantissa bits are non-zero. There will be no implicit bit for the mantissa. (Some applications use it for underflow values)

*Zero* – when exponent and mantissa bits are all set to 0s. There can be both +0 and -0, depending on the value of the sign bit.

*Infinity* – when exponent bits are all 1s and mantissa bits are all 0s. There can be both positive and negative infinities, depending on the value of the sign bit.

*NaN*(Not a Number) – when exponent bits are all 1s and mantissa bits are not all 0s. NaN can be either positive or negative, depending on the value the sign bit.

Other predefined or user-defined floating-point types, they should be similar to IEEE standard[[1]](#footnote-1). There should be the sign, exponent, mantissa, and bias information defined. The bits of exponent or mantissa should be contiguous.

Properties of floating-point number datatypes are more complicated than those for integer types. Each floating-point datatype, predefined or user-defined, has the following properties:

Order The byte order: big endian, little

endian, or VAX

Size The size of the entire data type in bytes

Precision The size of the actual data part of the

data type in bits

Offset The bit offset of the start of the actual data within the data type

LSB padding The padding bit value on the least significant

side of the data value

MSB padding The padding bit value on the most significant

side of the data value

Sign The bit offset of the sign bit

Exponent position The bit offset of the start of exponent

bits

Exponent size The number of the exponent bits

Exponent bias The value of the exponent bias

Mantissa position The bit offset of the start of mantissa

bits

Mantissa size The number of the mantissa bits

Norm Flag indicating a normalized floating number

Padding The padding bit value for the unused internal bits

For example, an IEEE standard little-endian single floating-point number is four bytes in size and thirty-two bits in precision. Its sign bit is at the thirty-first bit. The exponent is eight bits long and starts at the twenty-third bits. The mantissa is twenty-three bits long and starts at bit 0. We can use the following diagram to illustrate this floating number:

byte 3 byte 2 byte 1 byte 0

SEEEEEEE EMMMMMMM MMMMMMMM MMMMMMMM

So it has the following properties:

Order little-endian

Size 4 bytes

Precision 32 bits

Offset 0

LSB padding 0

MSB padding 0

Sign 31

Exponent position 23

Exponent size 8

Exponent bias 127

Mantissa position 0

Mantissa size 23

Norm Implied

Padding 0

Besides the API functions listed above in the section on integers for atomic datatypes, the library provides several functions for floating numbers specifically. These functions are H5Tset(get)\_fields, H5Tset(get)\_ebias, H5Tset(get)\_norm, and H5Tset(get)\_inpad.

## 2.3 Predefined Numeric Datatypes

### 2.3.1 Integers

Integer datatypes include all the library’s predefined integers and any user-defined integers. The library’s predefined integer types include standard, Unix-specific, Intel-specific, Alpha-specific, MIPS-specific, ANSI C9x-specific, and native data types. The *HDF5 Predefined Datatypes* section in the *HDF5 Reference Manual* lists all these predefined data types.

### 2.3.2 Floating-Point Numbers

Floating-point datatypes include all the library’s predefined floating numbers and any user-defined floating numbers. The library’s predefined floating-point types include IEEE standard and C native datatypes. The *HDF5 Predefined Datatypes* section in the *HDF5 Reference Manual* lists all these predefined datatypes.

## 2.4 User-Defined Numeric Datatypes

Users can define their own datatypes based on the default datatypes in the library. By adjusting the properties of the existent data types with datatype API functions, users can create new datatypes. These API functions are listed under the *Atomic Datatype Properties* category of *H5T Datatype Interface*. After defining a type’s properties, users can call H5Tcommit to store the datatype in a file.

For example, a user defines a two-byte big-endian unsigned integer. But its precision is only ten bits long. The offset is four bits. The padding is one. We can represent this integer as

Byte 0 byte 1

1111XXXX XXXXXX11

where X stands for the data value and 1 stands for the padding. This integer has the following properties:

Order big-endian

Sign unsigned

Size 2 bytes

Precision 10 bits

Offset 4 bits

LSB padding 1

MSB padding 1

Another example is a user-defined three-byte big-endian floating number. Its precision is eighteen bits. The data value offset is four bits. The other properties are displayed below:

Order big-endian

Size 3 bytes

Precision 18 bits

Offset 4 bits

LSB padding 0

MSB padding 0

Sign 19

Exponent position 13

Exponent size 6

Exponent bias 31

Mantissa position 2

Mantissa size 11

Norm Implied

Padding 0

We can use the following diagram to illustrate this floating number:

byte 0 byte 1 byte 2

0000SEEE EEEMMMMM MMMMMM00

## 2.5 Non-Numeric Datatypes

The datatypes (integers and floating-point numbers) we discussed above describe numeric values. There are non-numerical datatypes in the library as well. Some of them are derived from the numeric datatypes, such as *enum* and *array* types. The library does not have default data types for these non-numeric types. Users must define them. It is necessary to define a few terms that we normally use to describe the kinds of data types in the library. Please see the *Terminology* section in the end of the document for the definitions of these terms.

### 2.5.1 String Datatypes

String types are atomic datatypes. They have the following properties:

Cset ASCII or Unicode character set

Pad space or null padding for extra bytes

### The functions that the library provides to query or adjust these properties are H5Tset(get)\_cset and H5Tset(get)\_strpad.

### 2.5.2 Reference Datatypes

Reference types are another kind of atomic datatypes. A reference datatype only has one property:

Rytpe object or region reference

### The functions for reference datatypes are under the H5R interface, such as H5Rcreate, H5Rdereference, and H5Rget\_obj\_type.

### 2.5.3 Compound Datatypes

A HDF5 compound datatype can contain members of any HDF5 datatype. All the properties for compound datatypes are related to its members, such as:

Nmembs The number of member fields

Sorted How the members are sorted

Packed Whether the members packed together

Members Information about each member (below)

Besides its own properties as a HDF5 datatype, each compound datatype’s member has the following individual properties:

Name The name of this member

Size The size of this data type

Offset The offset from the beginning of the compound

datatype

The functions that the library provides to query or adjust the properties of compound datatypes and their members are: H5Tinsert, H5Tpack, H5Tget\_nmembers, H5Tget\_member\_class, H5Tget\_member\_name, H5Tget\_member\_index, H5Tget\_member\_offset, and H5Tget\_member\_type.

### 2.5.4 Enumeration Datatypes

Enumeration datatypes are currently derived from integers. They have the following properties:

Nmembs number of members

Sorted how the members are sorted

Names member names

Values member values

### The library provides these API functions to create enumeration datatypes or query their properties: H5Tenum\_create, H5Tenum\_insert, H5Tenum\_nameof, H5Tenum\_valueof, H5Tget\_member\_value, H5Tget\_nmembers, H5Tget\_member\_name, and H5Tget\_member\_index.

### 2.5.5 Variable-length Datatypes

The variable-length datatype is a derived datatype. Its base type can be any HDF5 datatype. It has the following properties:

Type string or sequence of other datatype

Cset character type (for VL string)

Pad space or null padding for extra bytes (for

VL string)

### The API functions that the library provides to create and query variable-length datatypes are: H5Tvlen\_create and H5Tis\_variable\_str.

### 2.5.6 Array Datatypes

The array data type is a derived data type. Its base type can be any HDF5 datatype. The array datatype has the following properties:

Nelem total number of elements in the array

Ndims number of dimensions

Dim[ ] sizes of dimensions

### The API functions that the library provides to create or query array datatypes are: H5Tarray\_create, H5Tget\_array\_ndims, and H5Tget\_array\_dims.

### 2.5.7 Opaque Datatypes

The opaque datatype only has one property:

Tag short description string

The library provides these two API functions, H5Tset(get)\_tag, to query or adjust the property of opaque datatypes.

### 2.5.8 Bitfield Datatypes

The bitfield datatypes are based on unsigned integer types. They have the same properties as unsigned integers. Please see section 2.1 for those properties. The major difference is that bitfield is always unsigned. **The library provides API functions to query or adjust these properties, such as H5Tset(get)\_size, H5Tset(get)\_order, H5Tset(get)\_precision, H5Tset(get)\_offset, and H5Tset(get)\_pad.**

### 2.5.9 Time Datatypes

The group has decided to deprecate the time datatype.

# Library’s Internal Design for Datatypes

## The Architecture of the Datatype Module

The following diagram (Figure 1) illustrates the basic design of the data type module in the library. The left side of the figure focuses on how the library creates data types and the datatype conversion table. The right side of the figure focuses on the relationship of the conversion table with the IO flow when reading or writing data values. We will explain the detail of the library’s internal design using this diagram.

Predefined (native) datatypes

H5T\_NATIVE\_CHAR H5T\_NATIVE\_INT

H5T\_NATIVE\_FLOAT

:

Conversion

table

H5T.c

Predefined (standard) datatypes

H5T\_STD\_I8BE

H5T\_STD\_U16LE

H5T\_IEEE\_F32BE

H5T\_IEEE\_F64LE

:

User-defined datatypes

H5Tconv.c

H5detect.c

H5Tinit.c

Application

data in

memory

No conversion

H5Dwrite H5Dread

H5T API

functions

H5I\_register

Filter pipeline

Data in file

Application

H5T\_init\_interface

H5T\_path\_find

H5T\_convert

H5Tregister / H5T\_register

Figure 1. Design of datatype module

## Source File That Contains Datatype Properties

Inside the library, all the properties of the datatypes are contained in the structures defined in H5Tpkg.h and used in memory by the library. The diagram below (Figure 2) shows the relationship among these structures. Library developers may want to look at them for information about the datatype properties. (The time datatype is not in this diagram because it has been deprecated) The *HDF5 File Format Specification* describes how an HDF5 file stores the datatype properties.

Figure 2. Relationship among datatypes and their properties

## How H5detect.c Works

When a user builds the HDF5 library with Autotool or CMake build system, the first source file to be built and run is H5detect.c under the library source directory. Running the executable H5detect generates another source file called H5Tinit.c in the user’s build directory. H5detect defines the function H5TN\_init\_interface in H5Tinit.c, which contains all the property information for the library’s predefined native data types (integers and floating numbers) on that system. Then H5Tinit.c is compiled with other source files to build the library. The program H5detect.c detects the properties of all the predefined native data types, such as H5T\_NATIVE\_INT, H5T\_NATIVE\_FLOAT, H5T\_NATIVE\_UINT64, H5T\_NATIVE\_INT\_LEAST64, and H5T\_NATIVE\_INT\_FAST32, etc. Figure 1 shows this relationship.

### Integers

In H5detect.c, the macro DETECT\_I is used to detect the properties of native integers. It has the following signature:

DETECT\_I (TYPE, VAR, INFO)

In the macro’s signature, TYPE is the native type in C such as int or long. VAR is the type name used to construct the identifier of the predefined data type. For example, if VAR is INT, the identifier for int is H5T\_NATIVE\_INT. Please see Part 2.3.1 for the list of some predefined native types. The INFO is a C struct containing properties for both integers and floating numbers. The information for these properties will be printed out into H5Tinit.c. *Appendix A* explains the detail of property detection for integers.

### Floating-Point Numbers

In H5detect.c, the macro DETECT\_F is used to detect the properties of native floating numbers. It has the following signature:

DETECT\_F(TYPE,VAR,INFO)

In the macro’s signature, TYPE is the native type in C such as float or double. VAR is the type name used to construct the identifier of the predefined data type. For example, if VAR is FLOAT, the identifier for float is H5T\_NATIVE\_FLOAT. Please see Section 2.3.2 for the list of some predefined native types. The INFO is a C struct containing properties for both integers and floating numbers. The information of these properties will be printed out into H5Tinit.c. *Appendix B* explains the detail of property detection for floating-point numbers.

### Others

H5detect.c also detects the alignments in structure for several other types and typedefs used in the datatype module, such as pointers, hvl\_t, hobj\_ref\_t, and hdset\_reg\_ref\_t.

### H5Tinit.c

The print\_results routine in H5detect.c prints all the properties of predefined data types of integers and floating numbers into H5Tinit.c. We mentioned earlier that H5Tinit.c is located under the build directory if it is different from the directory of the library’s source code. (Since it is generated during the library build, it should not be modified) After each property is assigned, the data type is registered by calling H5I\_register. An identification value for each predefined datatype is obtained by the library. Please see Figure 1 for this information.

## Other Predefined (Standard) Datatypes

The other predefined (standard) data types are defined in H5T\_init\_interface in H5T.c using some complicated macros. The one that does the major work is H5T\_INIT\_TYPE. The diagram in *Appendix C* shows the organization of those macros. Let us use H5T\_INIT\_TYPE(SINTBE,H5T\_STD\_I32BE\_g,COPY,native\_int,SET,4) as an example to explain they work. From the diagram, we can see that the macro H5T\_INIT\_TYPE registers data types in four steps:

*Step 1.* Gets the data type structure of the base type. The example will call H5T\_INIT\_TYPE\_COPY\_CREATE(native\_int) in this step.

*Step 2.* Adjusts the size and precision for the new type. The example will call

H5T\_INIT\_TYPE\_SET\_SIZE(4) in this step.

*Step 3.* Adjusts other properties for the new type. The example calls

H5T\_INIT\_TYPE\_SINTBE\_CORE, which calls H5T\_INIT\_TYPE\_SINT\_COMMON(H5T\_ORDER\_BE) in turn,

which calls H5T\_INIT\_TYPE\_NUM\_COMMON(H5T\_ORDER\_BE) in turn.

*Step 4.* Registers the new type.

# Data Conversion

## Hard vs. Soft Conversion

Internally, the library has hard and soft conversion functions for data types. A hard conversion is basically a casting done by a compiler. A soft conversion is done by the library’s own conversion function. The library maintains a conversion table (see Figure 1) that contains both hard and soft conversion functions. A hard conversion function is used between a pair of source and destination data types. A soft conversion function is used between a pair of source and destination data type classes. The library’s default conversion between predefined data types is with hard conversions.

## Registering Conversion Functions in the Conversion Table

The library registers its default conversion functions, either hard or soft, into the conversion table in the initialization stage (currently in the function H5T\_init\_interface in H5T.c). It first registers soft conversion functions, which is more general. The hard conversion functions, which are more specific, are registered next. When the library tries to convert data, it always picks a more specific conversion function first. When hard conversion function is not available, it proceeds with the more general soft conversion function. The table below lists all the soft conversion functions in the library.

Table 2. Library’s soft conversion functions

|  |  |  |  |
| --- | --- | --- | --- |
| Source data type | Destination data type | Conversion function | Function type |
| Integer | Integer | H5T\_conv\_i\_i | Soft |
| Integer | Floating number | H5T\_conv\_i\_f | Soft |
| Floating number | Floating number | H5T\_conv\_f\_f | Soft |
| Floating number | Integer | H5T\_conv\_f\_i | Soft |
| Fixed-length string | Fixed-length string | H5T\_conv\_s\_s | Soft |
| Bitfield | Bitfield | H5T\_conv\_b\_b | Soft |
| One byte order | Another byte order | H5T\_conv\_order | Soft |
| Compound | Compound | H5T\_conv\_struct | Soft |
| Enumeration | Enumeration | H5T\_conv\_enum | Soft |
| Variable-length | Variable-length | H5T\_conv\_vlen | Soft |
| Array | Array | H5T\_conv\_array | Soft |

The following table shows some examples of hard conversion functions between floating number types.

Table 3. Examples of hard conversion functions

|  |  |  |  |
| --- | --- | --- | --- |
| Source data type | Destination data type | Conversion function | Function type |
| float | double | H5T\_conv\_float\_double | Hard |
| double | float | H5T\_conv\_double\_float | Hard |
| float | long double | H5T\_conv\_float\_ldouble | Hard |
| double | long double | H5T\_conv\_double\_ldouble | Hard |
| long double | float | H5T\_conv\_ldouble\_float | Hard |
| long double | double | H5T\_conv\_ldouble\_double | Hard |

All conversion functions are defined in H5Tconv.c.

If users want to register their own conversion function, whether a soft or hard function, they can use the API function H5Tregister. This conversion function will replace the library’s default conversion function between the source and destination datatypes specified. Users can also use H5Tunregister to unregister a conversion function.

## The Design of Conversion Functions

Every conversion function, whether it is a hard or soft conversion, follows the steps below:

1. Since the conversion is in-place, the algorithm must determine whether to process the data elements from the beginning of the data buffer (forward) or from the end of the buffer (backward).
2. Convert the data elements one by one. If overflow or underflow happens, call the exception handling function if it is available.

In every conversion function, there are three values for the command passed into the function through a parameter called H5T\_cdata\_t \*cdata. The major value for this command is H5T\_CONV\_CONV. The actual conversion happens under this command. When the library is registering the conversion function into the conversion table, it gives the command H5T\_CONV\_INIT. It verifies the source and destination datatypes and initializes the necessary resources. The H5T\_CONV\_FREE command is for unregistering a conversion function. It releases all the resources that are allocated during the initialization.

### Hard Conversions

The layout of hard conversions is mainly through a sequence of complicated macros defined in H5Tconv.c. The diagram in the *Appendix D* shows the design and flow of the hard conversions. These macros are designed somewhat similar to templates in C++. The “core” part of the macros converts the data elements from the source to the destination. It is glued with the macro of a source-destination pairing (e.g. H5T\_CONV\_sS) in H5T\_CONV macro. The macro of a source-destination pairing is invoked by a hard conversion function. For example, the hard conversion function H5T\_conv\_short\_int invokes the macro H5T\_CONV\_sS.

All the macros of the source-destination pairing have the prefix H5T\_CONV\_ followed by the two letters. These two letters represent the source and destination. The letters “s” or “S” stand for signed integers. The letters “u” and “U” stand for unsigned integers. The letters “f” and “F” stand for floating-point numbers. The letters “x” and “X” stand for both signed and unsigned integers. The uppercase letters indicate that the data value range of the datatype is bigger. The lowercase letters indicate that the data value range is smaller. Thus, the macro H5T\_CONV\_sS converts data from a smaller signed integer type to a bigger signed integer type. Overflow does not happen during the conversion. But the macro H5T\_CONV\_Su converts data from a bigger signed integer type to a smaller unsigned integer type. Overflow can happen.

### Soft Conversions

Since the library does its own conversion in the soft conversion functions, the algorithm can be complicated. The table below lists all the soft conversion functions with brief descriptions of their algorithms.

Table 4. Descriptions of the algorithms for the library’s soft conversion functions

|  |  |
| --- | --- |
| Soft conversion function | Description of algorithm |
| H5T\_conv\_i\_i | First, swap the source data in little-endian order for operation convenience. Then copy the bit sequence of the data from the source to the destination. Finally, swap the data back in the right order. But handle overflow correctly as it can happen in the following situations:   1. If the source and destination are both unsigned integers, when the source size is greater than the destination size. 2. If the source is signed integer and the destination is unsigned integer, when the source value is negative or the most significant bit of the source value is greater than the destination precision. 3. If the source is unsigned and the destination is unsigned integers, when the most significant bit of the source is value is greater than the destination precision. 4. If the source and the destination are both signed, when the source value is negative and is too small for the destination, and when the source value is positive and is too big for the destination. |
| H5T\_conv\_i\_f | 1. First, swap the source data in little-endian order for operation convenience. 2. Find the position of the first bit of the most significant bit in the source and use it to calculate the exponent of the destination. But if the source value is negative, first do some bit operations equivalent to ~(i-1) as the representation of negative values for floating-point number is different from integers. 3. Handle the mantissa part by shifting the bit sequence of the source. If the bit sequence of the source is too long and cannot fit in the mantissa part of the destination, round off the extra bits (precision loss). If the bit sequence of the source is shorter than the mantissa part, left-shift it to fit in from the high order of the bit position. This step is done in a temporary buffer. 4. Copy the exponent and mantissa into the destination. 5. Finally, swap the destination data back in the right order. |
| H5T\_conv\_f\_f | 1. First, swap the source data in little-endian order for operation convenience. 2. Handle special values of the source like +0, -0, +Inf, -Inf, and NaN. 3. Figure out the exponent value of the source and write it to the destination. If the source exponent is too big for the destination, overflow happens. 4. Copy the mantissa from the source to the destination. If the source mantissa is too big for the destination. Round it first. 5. Finally, swap the destination data back in the right order. |
| H5T\_conv\_f\_i | 1. Swap the source data in little-endian order for operation convenience. 2. Handle special values of the source like +0, -0, +Inf, -Inf, and NaN. 3. Read the exponent value from the source and adjust it with the bias. 4. Copy the bit sequence of the mantissa from the source into a temporary buffer. 5. Shift the mantissa by the difference between the exponent value and mantissa size and drop off the fraction part. |
| H5T\_conv\_s\_s | Copy the characters from the source to the destination. Then terminate or pad the destination. |
| H5T\_conv\_b\_b | First, swap the source data in little-endian order for operation convenience. Then copy the bits of the data part from the source to the destination. Then pad the non-data part of the destination. Finally, swap the data back in the right order. |
| H5T\_conv\_order | Since the only difference between the source and destination datatypes, simply swap the bytes with the macro H5\_SWAP\_BYTES. |
| H5T\_conv\_struct | During the H5T\_CONV\_INIT stage, build the mapping from the source members to the destination members by names. Also figure out the conversion path between the datatypes of each pair of matching source and destination members. During the H5T\_CONV\_CONV stage, for each data element,   1. in the first round, iterate through each compound member and convert it if the destination size is smaller than or equal to the source size. But simply copy the member if the destination size is greater than the source size to protect the members after since the conversion is in place. The data is in the conversion buffer now. 2. In the second round, iterate through the compound members backwards and convert the member into the background buffer if the destination size is greater than the source size. But simply copy the member into the background buffer if the destination size is smaller than or equal to the source size since it has been converted in the first round. The data is in the background buffer now.   In the end, copy each data element from the background buffer into the data conversion buffer. There are a few situations that library optimizes its algorithm. |
| H5T\_conv\_enum | During the H5T\_CONV\_INIT stage, build the mapping from the source members to the destination members. In the H5T\_CONV\_CONV stage, put the destination value to which the source maps directly in the destination buffer. |
| H5T\_conv\_vlen | Allocate a temporary buffer for conversion. Read the actual data from the source as it is stored in the global heap on file or a structure in memory. Convert the data from the base type of the source to the one of the destination. Write the data to the destination buffer as the library stores it in the global heap on file or a structure in memory. |
| H5T\_conv\_array | Find the conversion path between the base datatypes of the source and destination datatypes. Convert each array with the conversion path found using H5T\_convert. |

Let us choose a relatively simple soft conversion function H5T\_conv\_array as an example to explain how the library handles conversion. First of all, it follows the basic steps described earlier in this section (4.3). But it has a few extra steps for the Array datatype particularly:

1. Since the conversion is in-place, the algorithm must determine whether to process the data elements from the beginning of the data buffer (forward) or from the end of the buffer (backward). If the source datatype is bigger than the destination datatype, process the data from the beginning to the end. Otherwise, process from the end to the beginning.
2. Find out the conversion path (function) between the base datatypes of the source and destination array datatypes with the function H5T\_path\_find.
3. Convert the elements one by one. First, copy the element from the source to the destination position in the data buffer. Then convert the whole array with the conversion path found in Step b using H5T\_convert. Finally, move to the next element and repeat the same process.

## Converting Data

When a user application tries to read or write data and the source and destination data types are different, or when it tries to call H5Tconvert to convert data, data conversion happens (see Figure 1). The first thing that the library does is to search for the correct conversion function between the source and destination datatypes (This is done through the H5T\_path\_find function in H5T.c). Then it calls H5T\_convert with the conversion path information to convert the data. This process is clearly shown in the definition of the API function H5Tconvert in H5T.c. The same process happens when a program is trying to read or write data.

## The Test dt\_arith.c

## We need to explain the basic method of testing the data conversion in dt\_arith.c. In each test, it initializes a data buffer of the source data type. If the data is integer values, the macro INIT\_INTEGER fills the data buffer with bit sequences like

## 00000001, 00000010, 00000100, 00001000, 00010000, 00100000, 01000000, 10000000,

## 00000000, 00000011, 00000111, 00001111, 00011111, 00111111, 01111111, 11111111,

## 11111111, 11111110, 11111100, 11111000, 11110000, 11100000, 11000000, 10000000

## It tries to cover most of bit sequences and avoid any casting, assignment, and comparison at the same time because it is testing some hard conversion functions that involve these operations.

## If the data is floating-point values, the macro INIT\_FP\_NORM fills the data buffer with values between the minimal and maximal values for that type. Each value is the previous value times a multiplication factor (i.e. value \*= multiplication factor). The macros INIT\_FP\_DENORM and INIT\_FP\_SPECIAL fill the buffer with some special values for testing, too.

# Adding Support for New Predefined Data Types

## New native datatypes

Let us use C99 type \_Bool as an example to walk through the steps for adding new native integer types:

1. Detect the size of the new type in configure.in along with other native datatypes:

AC\_CHECK\_SIZEOF([\_Bool], [1])

Regenerate configure with bin/reconfigure. After the configuration, a new macro called H5\_SIZEOF\_\_BOOL is defined as 1 (one) in H5pubconf.h in the src/ directory under the build directory. If the compiler does not support this datatype, the value of H5\_SIZEOF\_\_BOOL would be 0 (zero).

1. Add the new type for integer detection in src/H5detect.c:

DETECT\_I(\_Bool, BOOL, d\_g[nd\_g]); nd\_g++;

After compiling H5detect.c and running H5detect, the properties of the \_Bool type is generated in H5Tinit.c.

1. Declare the variables related to the new type in the top of H5T.c:

hid\_t H5T\_NATIVE\_BOOL\_g = FAIL;

size\_t H5T\_NATIVE\_BOOL\_ALIGN\_g = 0;

size\_t H5T\_NATIVE\_BOOL\_COMP\_ALIGN\_g = 0;

1. Release the variable in H5T\_term\_interface of H5T.c:

H5T\_NATIVE\_BOOL\_g = FAIL;

1. Make the datatype ID public by defining a macro in H5Tpublic.h:

#define H5T\_NATIVE\_BOOL (H5OPEN H5T\_NATIVE\_BOOL\_g)

1. Declare the variables for alignments in H5Tpkg.h:

H5\_DLLVAR size\_t H5T\_NATIVE\_BOOL\_COMP\_ALIGN\_g;

H5\_DLLVAR size\_t H5T\_NATIVE\_BOOL\_ALIGN\_g;

1. Add a printout for the new type in H5\_trace of H5trace.c along with other integer types.
2. Add the prototypes of hard conversion functions for this new datatype in H5Tpkg.h. There should be functions between the new datatype and all other native integer types and all native floating-point number types:

H5T\_\_conv\_schar\_bool, H5T\_\_conv\_uchar\_bool,

H5T\_\_conv\_short\_bool, H5T\_\_conv\_ushort\_bool,

H5T\_\_conv\_int\_bool, H5T\_\_conv\_uint\_bool,

H5T\_\_conv\_long\_bool, H5T\_\_conv\_ulong\_bool,

H5T\_\_conv\_llong\_bool, H5T\_\_conv\_ullong\_bool,

H5T\_\_conv\_float\_bool, H5T\_\_conv\_double\_bool,

H5T\_\_conv\_ldouble\_bool, H5T\_\_conv\_bool\_ldouble,

H5T\_\_conv\_bool\_float, H5T\_\_conv\_bool\_double,

H5T\_\_conv\_bool\_schar, H5T\_\_conv\_bool\_uchar,

H5T\_\_conv\_bool\_short, H5T\_\_conv\_bool\_ushort,

H5T\_\_conv\_bool\_int, H5T\_\_conv\_bool\_uint,

H5T\_\_conv\_bool\_long, H5T\_\_conv\_bool\_ulong,

H5T\_\_conv\_bool\_llong, H5T\_\_conv\_bool\_ullong

1. Add the definitions of the hard conversion functions for this new datatype in H5Tconv.c. There should be definitions for all the functions listed in *Step h*.
2. Add test cases for the new type in the test suite, especially the data conversion test dt\_arith.c.

If the new datatype is a floating-point number, most steps will be similar. The main difference is in Step b. It should use DETECT\_F instead of DETECT\_I.

## New standard datatypes

The predefined standard datatypes are based on similar native datatypes. Let us use 128-bit floating-point datatype as an example to walk through the steps (I did not test these steps because the changes to the source code are not simple):

1. Follow the steps in 5.1, add \_\_float128 as a new native datatypes (\_\_float128 is the quadruple precision type of GNU compiler on i386, x86\_64, and IA64 architecture). We get the ID H5T\_NATIVE\_FLOAT128 for this new native datatype.
2. Define IEEE 128-bit quadruple precision type in H5T.c based on the 128-bit native datatype defined in Step a:

H5T\_INIT\_TYPE(FLOAT128LE,H5T\_IEEE\_F128LE\_g,COPY,native\_float128,SET,16)

1. Follow the definition of the macros for float or double and define new macros for the new type:

H5T\_INIT\_TYPE\_QUADRUPLELE\_CORE and H5T\_INIT\_TYPE\_QUADRUPLELE\_CORE and H5T\_INIT\_TYPE\_QUADRUPLE\_COMMON

Adjust the properties for this type in these macros.

1. Declare the variable related to the new type in the top of H5T.c:

hid\_t H5T\_IEEE\_F128LE\_g = FAIL;

1. Release the variable in H5T\_term\_interface of H5T.c:

H5T\_IEEE\_F128LE\_g = FAIL;

1. Make the datatype ID public by defining a macro in H5Tpublic.h:

#define H5T\_IEEE\_F128LE (H5OPEN H5T\_IEEE\_F128LE\_g)

H5\_DLLVAR hid\_t H5T\_IEEE\_F128LE\_g;

1. Add a printout for the new type in H5\_trace of H5trace.c along with other integer types.
2. Add test cases for the new type in the test suite, especially the data conversion test dt\_arith.c.

# Revision History

|  |  |
| --- | --- |
| *January 20, 2012:* | First draft circulated for comments to Elena, Quincey, Mike M., and Frank. |

*May 15, 2012:* Second draft circulated for comments to Elena, Quincey, Mike M., and Frank.

# Appendix A:

# This appendix explains the detail of property detection for integers in H5detect.c.

#### Byte order

In the definition of the macro DETECT\_I, H5detect first tries to figure out the byte order of the data type (e.g. int) with this algorithm:

int v;

unsigned char \*x;

for(i=sizeof(int), v=0; i>0; --i)

v = (v << 8) + i;

for(i = 0; x = &v; i < sizeof(int); i++) {

j = (\*x++) -1;

d\_g[nd\_g].perm[i] = j;

}

If the machine is little-endian, the first loop fills each byte with sequential numbers

byte 3 byte 2 byte 1 byte 0

4 3 2 1

The second loop fills the perm[] array with the following numbers

perm[0] perm[1] perm[2] perm[3]

0 1 2 3

When the program H5detect prints the results into H5Tinit.c, this sequence of value is considered as little-endian. The reversed order is considered as big-endian.

#### Offset

H5detect.c also uses the permutation perm[] to decide the precision and offset of the native integer types. The function precision() checks whether the beginning or ending of perm[] is -1. If the beginning or ending bytes are value -1, they are padding, assuming the offset is always in whole byte. The precision is the size of the type subtracting the offset.

#### Alignment restriction

H5detect.c also tries to detect the alignment restriction of a data type. Alignment restrictions are described in this manner: “Some computers allow data objects to reside in storage at any address regardless of the data’s type. Others impose alignment restrictions on certain data types, requiring that objects of those types occupy only certain addresses. It is not unusual for a byte-addressed computer, for example, to require that 32-bit integers be located on addresses that are a multiple of four. In this case, we say that the ‘alignment modulus’ of those integers is four.”[[2]](#footnote-2)

The macro ALIGNMENT(TYPE,INFO) in H5detect.c detects the information of alignment restriction for integers and floating numbers. Again, TYPE is the native type in C such as int or long. The INFO is a C struct containing properties for both integer and floating numbers. The basic algorithm can be expressed in the following semi-pseudo code:

align\_value[]={1,2,4,8,16};

char \*buf;

TYPE value2, type\_value = 1;

if (setjmp(jmp\_buf)) align\_num++;

if(little\_endian)

/\* Copy the type\_value to the point of the buffer where

\* the assumed alignment is added \*/

memcpy(buf+align\_value[align\_num], &type\_value, sizeof(int));

else /\* big-endian \*/

/\* Skipped \*/

/\* Cast the value in the buffer to another variable \*/

value2 = \*(TYPE\*)(buf+align\_value[align\_num];

if(type\_value != value2)

/\* Alignment isn’t found. Go back to setjmp.

\* Increment alignment value and try again. \*/

longjmp(jmp\_buf, 1);

/\* We have found the alignment \*/

INFO.align = align\_value[align\_num];

In the algorithm, the code between setjmp and longjmp is equivalent to a loop. setjmp saves the current environment into jmp\_buf. jmp\_buf is used by longjmp to restore the program state. (Just imagine that longjmp makes the program jump back to the point where setjmp saves the environment)

#### Field alignment within structures

The alignment of a type when used as a C structure member refers to the value expressed in COMP\_ALIGN in the following pseudo code:

struct {

char c;

TYPE x;

} s;

COMP\_ALIGN = (char\*)(&(s.x)) – (char\*)(&s);

This piece of code is actually the definition of the macro COMP\_ALIGNMENT(TYPE,COMP\_ALIGN) in the H5detect.c program. A C structure normally has it own alignment restriction, which means that it must terminate on the same alignment boundary on which it starts. If it starts on an even byte boundary, it must also end on an even byte boundary. If the first member of the structure is a one-byte character, the space between this character and next member is the alignment of the next member type as a structure member. For example, if the TYPE in the code above is int and the storage of the structure is as below:

x

(space)

c

Bytes 1 3 4

Then the alignment of int as a structure member on this system is 4 bytes.

# Appendix B:

This appendix explains the detail of property detection for floating-point numbers in H5detect.c.

#### Byte order

In the definition of the macro DETECT\_F, the byte order of a floating-point type (e.g. float) is determined by this algorithm:

int i, j, k, first\_mbyte = -1, last\_mbyte = -1;

float value1, value2, value3;

unsigned char buf1[sizeof(float)], buf3[sizeof(float)];

int perm[32];

for(i = 0, value1 = 0.0, value2 = 1.0; i < (int)sizeof(float); i++) {

value3 = value1;

value1 += value2;

value2 /= 256.0;

memcpy(buf1, (const void \*)&value1, sizeof(float));

memcpy(buf3, (const void \*)&value3, sizeof(float));

/\* Found out the first different byte \*/

j = byte\_cmp(sizeof(float), &buf3, &buf1);

/\* Record the first different byte in permutation \*/

if(j >= 0) {

if(0 == i || perm[i - 1] != j) {

perm[i] = j;

last\_mbyte = i;

if(first\_mbyte < 0)

first\_mbyte = i;

}

}

}

In this code, we only want to find out the byte order of the mantissa part of the data type, assuming the exponent part has the same byte order as the mantissa. The byte\_cmp function simply finds the first different byte between two buffers. If no difference found, it returns -1. We can use the little-endian 4-byte float as the example to explain how the algorithm works. The following diagram shows the properties of the example data type:

Byte 3 byte 2 byte 1 byte 0

SEEEEEEEE

MMMMMMMM

MMMMMMMM

EMMMMMMM

During iteration 1:

i = 0 value1 = 1.0 value2 = 1/256 = 1/28 value3 = 0.0

buf1[ ]= {0x00, 0x00, 0x80, 0x3f} or in binary format:

buf1[3] buf1[2] buf1[1] buf1[0]

00111111 10000000 00000000 00000000

buf3[ ] = {0x00, 0x00, 0x00, 0x00} or in binary format:

buf3[3] buf3[2] buf3[1] buf3[0]

00000000 00000000 00000000 00000000

j = 2 perm[0] = 2 last\_mbyte = 2 first\_mbyte = -1

During iteration 2:

i = 1 value1 = 1.0 + 1/28 value2 = 1/216 value3 = 1.0

buf1[ ] = {0x00, 0x80, 0x80, 0x3f} or in binary format:

buf1[3] buf1[2] buf1[1] buf1[0]

00111111 10000000 10000000 00000000

buf3[ ] = {0x00, 0x00, 0x80, 0x3f} or in binary format:

buf3[3] buf3[2] buf3[1] buf3[0]

00111111 10000000 00000000 00000000

j = 1 perm[1] = 1 last\_mbyte = 2 first\_mbyte = 1

During iteration 3:

i = 2 value1 = 1.0 + 1/28 + 1/216 value2 = 1/224 value3 = 1.0 + 1/28

buf1[ ] = {0x80, 0x80, 0x80, 0x3f} or in binary format:

buf1[3] buf1[2] buf1[1] buf1[0]

00111111 10000000 10000000 10000000

buf3[ ] = {0x00, 0x80, 0x80, 0x3f} or in binary format:

buf3[3] buf3[2] buf3[1] buf3[0]

00111111 10000000 10000000 00000000

j = 0 perm[2] = 0 last\_mbyte = 2 first\_mbyte = 0

During iteration 4:

i = 3 value1 = 1.0 + 1/28 + 1/216 + 1/224 value2 = 1/232 value3 = 1.0 + 1/28  + 1/216

buf1[ ] = {0x80, 0x80, 0x80, 0x3f} or in binary format:

buf1[3] buf1[2] buf1[1] buf1[0]

00111111 10000000 10000000 10000000

buf3[ ] = {0x80, 0x80, 0x80, 0x3f} or in binary format:

buf3[3] buf3[2] buf3[1] buf3[0]

00111111 10000000 10000000 10000000

j = -1 perm[3] = -1 last\_mbyte = 2 first\_mbyte = 0

After the loop, the permutation array has the values perm[ ] = {2, 1, 0}. Then DETECT\_F calls the function fix\_order to adjust the permutation to the byte order of little-endian. The permutation becomes perm[ ] = {0, 1, 2}, which is the same as the mantissa part of the diagram above. This byte order detection code handles little-endian, big-endian, and VAX orders.

#### Implied mantissa bit

Next, DETECT\_F tries to figure out whether the mantissa has an implied bit in the function called imp\_bit. Some floating-point formats discard the most significant bit of the mantissa after normalizing since it will always be one except for the special value 0.0. In DETECT\_F, it calls imp\_bit in this way:

\_v1 = 0.5;

\_v2 = 1.0;

INFO.imp = imp\_bit (sizeof(TYPE), INFO.perm, &\_v1, &\_v2);

imp\_bit is defined as below:

int imp\_bit(int n, int \*perm, void \*\_a, void \*\_b)

{

unsigned char \*a = \_a;

unsigned char \*b = \_b;

int changed, byte\_index, bit\_index;

int msmb; /\*most significant mantissa bit \*/

/\*

\* Look for the least significant bit that has changed between

\* A and B. This is the least significant bit of the exponent.

\*/

changed = bit\_cmp(n, perm, a, b);

/\*

\* The bit to the right (less significant) of the changed bit should

\* be the most significant bit of the mantissa. If it is non-zero

\* then the format does not remove the leading `1' of the mantissa.

\*/

msmb = changed - 1;

byte\_index = msmb / 8;

bit\_index = msmb % 8;

return (a[perm[major]] >> minor) & 0x01 ? 0 : 1;

}

The function bit\_cmp (explained later) compares two bit vectors and returns the index for the first bit that differs between the two vectors. For example, if float is four-bytes little-endian with the most significant mantissa bit implied, the bit sequence for the value of 0.5 represented by \*a in imp\_bit is:

a[3] a[2] a[1] a[0]

00011111 00000000 00000000 00000000

The bit sequence for the value of 1.0 represented by \*b in imp\_bit is:

b[3] b[2] b[1] b[0]

00011111 10000000 00000000 00000000

The value of changed return from bit\_cmp is 23. The value of the most significant mantissa bit (msmb) is 22. The value of the byte index where the msmb falls into is 2. The value of the bit index where the msmb falls into the byte is 6. The final step for the returned value is

perm[2] = 2

a[2] = 0x00

(a[2] >> 6) & 0x01 = 0

return 1

which is interpreted as implied in print\_results.

#### Sign bit

To figure out the location of the sign bit is relatively simple:

\_v1 = 1.0;

\_v2 = -1.0;

INFO.sign = bit\_cmp (sizeof(TYPE), INFO.perm, &\_v1, &\_v2);

Now we can explain how bit\_cmp works:

int bit\_cmp(int nbytes, int \*perm, void \*\_a, void \*\_b)

{

int i, j;

unsigned char \*a = (unsigned char \*) \_a;

unsigned char \*b = (unsigned char \*) \_b;

unsigned char aa, bb;

for (i = 0; i < nbytes; i++) {

/\* Find out where the different byte is \*/

if ((aa = a[perm[i]]) != (bb = b[perm[i]])) {

/\* Find out where the different least-significant bit

\* by right-shifting the variables 1-bit at a time.

\*/

for (j = 0; j < 8; j++, aa >>= 1, bb >>= 1) {

/\* If the least-significant bit is different,

\* return the bit index. \*/

if ((aa & 1) != (bb & 1))

return i \* 8 + j;

}

}

}

return -1;

}

#### Size of mantissa

DETECT\_F checks the difference between the values of 1.0 and 1.5 to find out the size of mantissa. The values of 1.0 and 1.5 differ at the first bit of mantissa if the machine has implied mantissa bit, or at the second bit if the machine implies the first mantissa bit. The starting bit of mantissa is assumed to be the first bit of the data type, i.e. bit 0.

#### Exponent

DETECT\_F assumes the exponent is located in bits between the sign bit and the mantissa.

#### Bias

When a floating number has the value 1.0, the value of its exponent is its bias. After normalization, the value 1.0 is represented by 1.0 x 20. Whatever the value of the exponent has is the bias for the floating number type.

#### Precision, alignment, and alignment in structure

Finding the precision, alignment restriction, and alignment of floating-point types in structures follows the same procedures as described in *Appendix A* for integer types.

# Appendix C:

Please click on this [link](Dtype%20register%20diagram.docx) to see the oversized diagram.

# Appendix D

Please click on this [link](conv%20diagram.docx) to see the oversized diagram.

# Terminology

|  |  |
| --- | --- |
| **numerical data type** | The HDF5 datatype that deals with number, including integer and floating-point number. |
| **non-numerical data type**  **atomic data type**  **derived data type** | The HDF5 datatype other than numerical datatype.  The HDF5 data type that is not composed of other datatypes, including integer, floating-point number, string, and reference type.  The HDF5 data type that is composed of other datatypes, including compound, enumeration, array, variable-length, and opaque type. |
|  |  |

# References

1. The HDF Group. “HDF5 Documentation,” <http://www.hdfgroup.org/HDF5/doc/doc-info.html>.
2. Data Conversion of Arithmetic Datatypes.
3. Hollasch, Steve. 2003. IEEE Standard 754 Floating Point Numbers.
4. Harbison and Steele, C: A Reference Manual

1. The floating-point numbers for VAX are different from IEEE standard. Their byte order is a mixture of little-endian and big-endian. But that is the only difference from IEEE standard. So we will not discuss it in detail here. [↑](#footnote-ref-1)
2. Harbison and Steele, C: A Reference Manual, 6.1.3 Alignment Restrictions. [↑](#footnote-ref-2)