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INFORMATION TECHNOLOGY FOR EUROPEAN ADVANCEMENT

VMAP

Virtual Material Modelling in Manufacturing

STANDARD SPECIFICATIONS

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Current Version is for BETA testing only.

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How to Use This Booklet

The aim of this book is to aid understanding of the VMAP Standard Specifications. If you are new to VMAP, then please read the VMAP General Information. It explains the VMAP Project and provides an overview of the VMAP Use Cases. This book introduces the ongoing VMAP specifications. For the CAE Tool, software and application engineers this book provides ongoing specifications and implementation specifications.

Overview of Booklet Structure

This VMAP information is divided into two complimentary documents: VMAP General Information and VMAP Standard Specification Documentation.

VMAP General Information:

- Chapter 1 introduces and explains the VMAP Standard, the guiding idea and the definition.
- Chapter 2 throws light on State of the Art.
- Chapter 3 provides a brief account of the requirement analysis, which led to the inception of VMAP.
- Chapter 4 introduces the Software Architecture of VMAP and the output technology used by VMAP.
- Chapter 5 describes the Use Cases that were used to demonstrate the usefulness and capacity of the VMAP Standards.

VMAP Standard Specification Documentation:

- Chapter 1 introduces the Software Architecture of VMAP and the output technology used by VMAP.
- Chapter 2 shows how to start using the API.
- Chapter 3 describes the relationship among the C++ structures defined in VMAP Standard I/O Library.
- Chapter 4 gives an account of the VMAP Standard I/O Library or VMAP Standard API.
- Chapter 5 contains information on compiling the VMAP Standard API.
- Chapter 6 provides a possibility to implement your own VMAP I/O Library. This chapter should be used carefully, since the `Nomenclature` and structure used by VMAP is explained in detail. It is essential to follow this `Nomenclature` and structure to get the correct VMAP Standard file.
- Chapter 7 shows the snapshots from the HDF5 Viewer of a standard VMAP .h5 file.

- Chapter 8 further elaborates on the specifications. It describes the standard VMAP Element definitions, which are already part of the factory, and how to define one of your own elements.
- Chapter 9 further elaborates on the specifications with standard VMAP Integration Type definitions and how to define one of your own integration types.
- Chapter 10 provides some basic tutorials on how to use the VMAP Standard API.
- Chapter 11 defines simple test cases which could be used by a developer or an end user.

Target Audience

To be able to use the VMAP Documentation efficiently, prior knowledge of modelling and simulation is required. The user should have hands-on experience of at least one CAE Tool, or at the very least, basic knowledge of Finite Element Analysis. Users and Developers may have different needs so in the table below we have categorised the documentation accordingly.

<table>
<tr><th colspan="2">VMAP Documentation Chapters of Interest</th></tr>
<tr><td colspan="2">CAE Tool End Users to understand the VMAP Standard background, format and testing.</td></tr>
<tr><td>VMAP General Information</td><td>VMAP Standards Document</td></tr>
<tr><td>1
2
3
4
5</td><td>11</td></tr>
<tr><td colspan="2">CAE Tool Developers to understand and implement VMAP Standard API within their own software tool.</td></tr>
<tr><td>VMAP General Information</td><td>VMAP Standards Document</td></tr>
<tr><td>1
4</td><td>2
4
7
8
9
10
11</td></tr>
<tr><td colspan="2">CAE Tool Developers to implement their own VMAP I/O Library instead of using the VMAP Standard I/O Library. These users should check every detail carefully to implement the correct VMAP Standard, especially noting the implementation of element types and integration types.</td></tr>
<tr><td>VMAP General Information</td><td>VMAP Standards Document</td></tr>
<tr><td>1
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</table>

Abbreviations

CAE	Computer Aided Engineering
FEM	Finite Element Methods
FEA	Finite Element Analysis
SWIG	Simplified Wrapper and Interface Generator
API	Application Programming Interface

Contents

Chapter 1

VMAP Software Architecture

This chapter explains the VMAP software architecture (Figure 1.1), briefly going through all the layers. The further chapters then focus on each layer in detail.

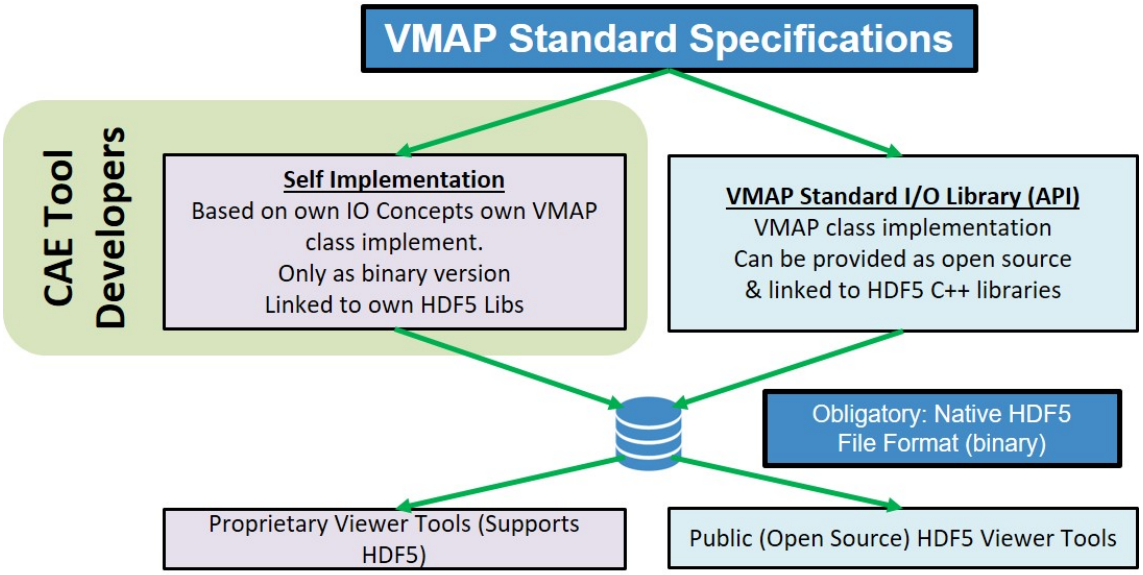


Figure 1.1: VMAP Software Architecture

VMAP Standard Specifications are at the core of the software architecture. VMAP offers two options for every user. The first, is to use the VMAP Standard Specifications via the VMAP Standard I/O Library (API) built in C++. The second option is to implement the user's own VMAP I/O classes using the VMAP Standard Specifications. The only obligation is to use the native HDF5 file format as the output. HDF5 file format is an optimal and apt output option for VMAP because HDF5 Viewer is an open source tool, just like VMAP Standard Specifications are open source. Section 1.3 explains HDF5 Technology in detail.

The VMAP Standard I/O Library or **VMAP Standard API** is explained in detail in

chapters 3 & 4. The option to implement the user's own VMAP I/O Library is explained with schematic diagrams in chapter 6.

1.1 VMAP Interface to CAE Tools

Almost all CAE tools offer API, these API are used by ISVs to build codes. ISV codes written in C++ can be directly linked to the 'VMAP Standard API'. ISV codes written in Python, Java, C# or FORTRAN utilize the 'VMAP Standard API' through a language specific interface. For Python, Java and C# such a language specific interface can be automatically generated using the **Simplified Wrapper and Interface Generator (SWIG)** (Section 1.2). For FORTRAN the language specific interface is possible but must be written manually. Figure 1.2 shows the extended software architecture.

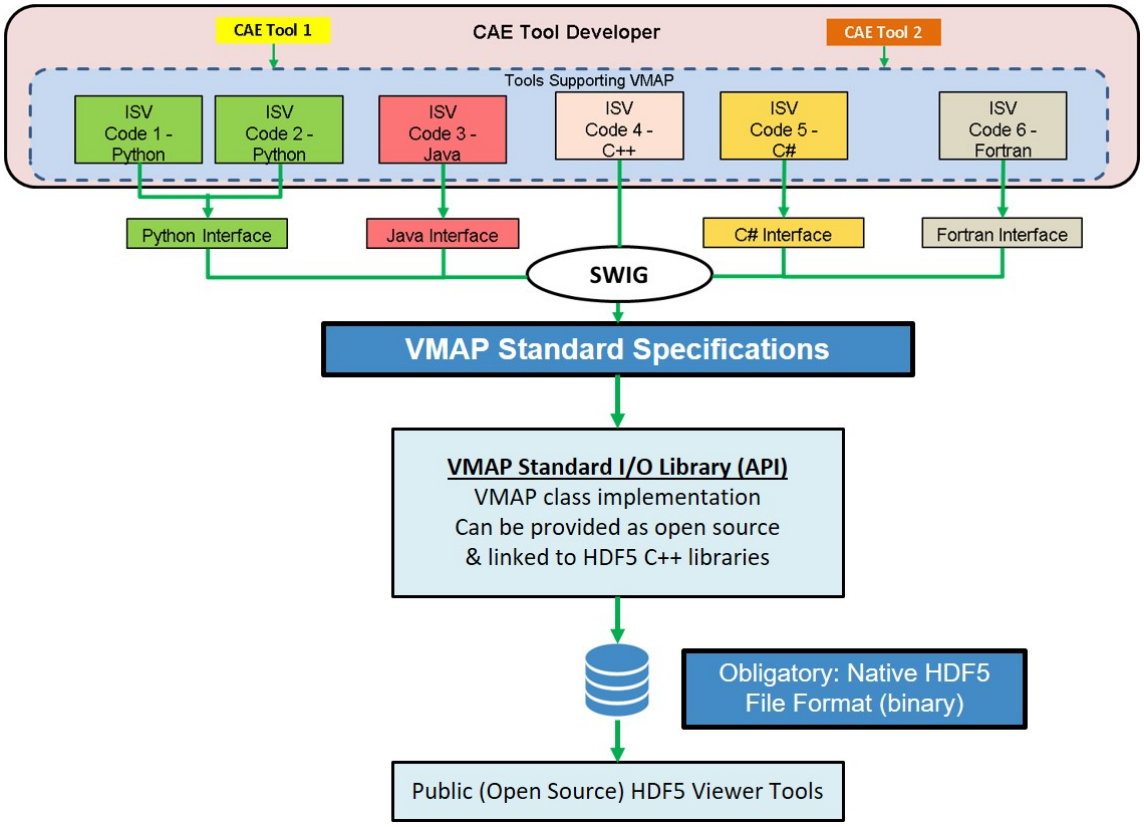


Figure 1.2: Extended VMAP Software Architecture

The VMAP Standard API and its role in a chain CAE simulation process is represented in (Figure 1.3). The image shows two simulations, Blow Moulding simulation carried out using Code A and Cooling simulation carried out using Code B. The cooling simulation requires the output result of the blow moulding simulation. Such a situation arises very often in the industry, where results of one simulation are required to carry out another simulation. Since, there are multiple CAE tools (Codes) available on the market, each time a combination of tools is used a new specific converter needs to be developed. This is

where VMAP Standard comes in; with all CAE tools providing VMAP Standard format as one of the output options, the specific converters become unnecessary. VMAP Standard will facilitate reusability and thus will be time saving. Since VMAP Standard is currently in development phase, the converter is replaced by an external VMAP converter. As the standard is completely formalised, the VMAP Standard API can be directly integrated into the CAE tool.

CAE tools which additionally require a Mapper to map data from Simulation Model A to Simulation Model B, can also have the Mapper integrated with the VMAP Standard API.

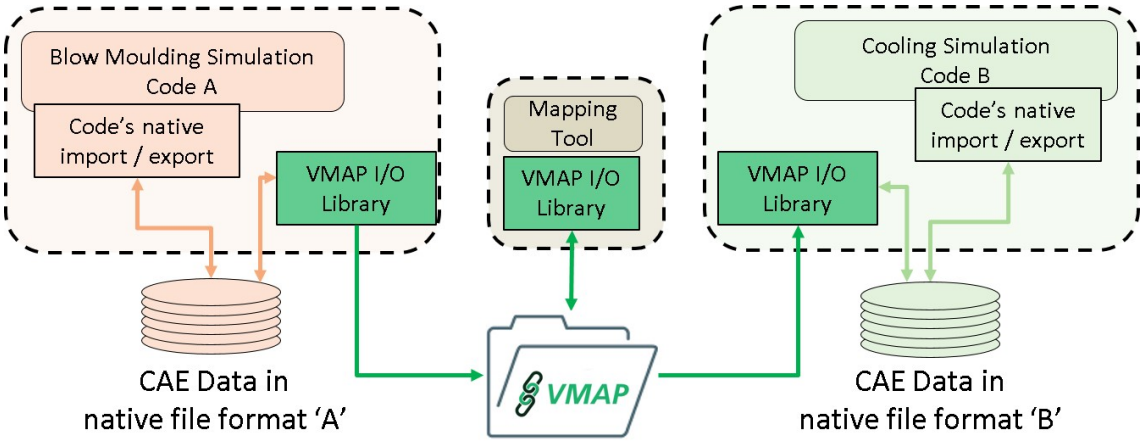


Figure 1.3: VMAP Standard API in CAE chain simulation process

1.2 SWIG

SWIG is a software development tool that connects programs written in C and C++ with a variety of high-level programming languages. SWIG is used with different types of target languages including common scripting languages such as JavaScript, Perl, PHP, Python, Tcl and Ruby. The list of supported languages also includes non-scripting languages such as C#. SWIG is most commonly used to create high-level interpreted or compiled programming environments, user interfaces and as a tool for testing and prototyping C/C++ software. SWIG is typically used to parse C/C++ interfaces and generate the 'glue code' required for the above target languages to call into the C/C++ code [5]

1.3 HDF5 technology

The VMAP interface and transfer file relies on the HDF5 technology. The Hierarchical Data Format (HDF) implements a model for managing and storing data. The model includes an abstract data model, an abstract storage model (the data format) and libraries to implement the abstract model and map the storage model to different storage mechanisms. The HDF5 Library provides a programming interface to a concrete implementation of the abstract models. The library also implements a model of data transfer, an efficient

movement of data from one stored representation to another stored representation. The figure below illustrates the relationships between the models and implementations. This chapter explains these models in detail.

The Hierarchical Data Format version 5 (HDF5), is an open source file format that supports large, complex, heterogeneous data. HDF5 uses a "file directory" like structure that allows you to organize data within the file in many different structured ways, as you might do with files on your computer. The HDF5 format also allows for embedding of metadata making it self-describing.

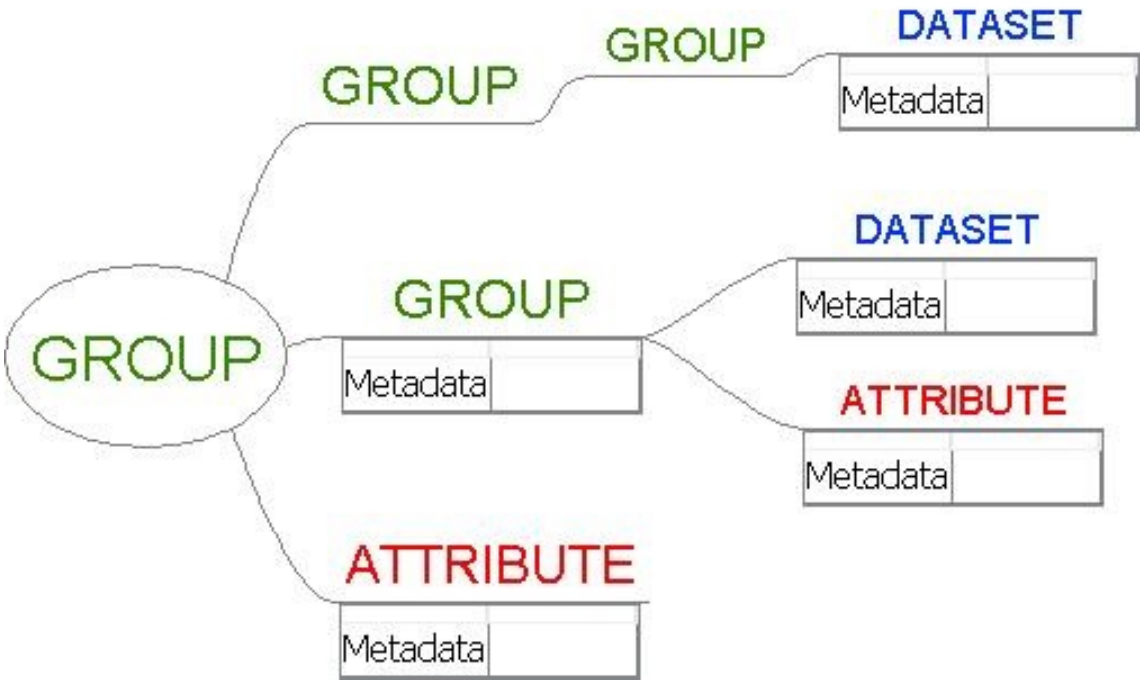


Figure 1.4: HDF5 file format

Chapter 2

VMAP Standard API Build

This chapter outlines the steps to use the VMAP Standard API. The header and source code files provided as VMAP standard are explained in the following section.

2.1 VMAP Header & Source Code Files

2.1.1 VMAPFile.h

This header file contains all the read & write functions of VMAP Standard API. These functions are used to read/write from/to the .h5 file. This file only contains the declaration of these functions.

2.1.2 VMAPFile.cxx

This source code file initializes the .h5 file format and defines all the read & write functions declared in VMAPFile.h header file.

2.1.3 VMAP.h

This header file contains all the arguments read and written by the VMAPFile.h. These arguments are defined using **struct** reference, default **constructor** & **destructor** and **get** & **set** functions to assign values to the attributes of the structure. Only the declarations are part of this file, but no definitions.

2.1.4 VMAP.cxx

This source code file initializes the **constructor** & **destructor** defined in VMAP.h header file. It also defines all the **get** & **set** functions of each **struct** reference defined in VMAP.h header file.

2.1.5 VMAPH5Tools.h

This header file defines and declares certain H5 specific tools, which are used by the VMAP I/O.

2.2 VMAP Standard API Calling Sequence - Creating VMAP .h5 File

A VMAP .h5 file is created using `VMAPFile` class which is defined in **VMAPFile.h**. Figure 2.1 shows a sample initiation code for VMAP API.

```
#include "H5Cpp.h"
#include "VMAP.h"
#include "VMAPFile.h"

int main(int argc, char** argv) {
  using namespace H5;
  using namespace VMAP;

  Initialize();
  VMAPFile vmapFile("/tmp/testfile.h5");
  ...
  ...
  ...
  return 0;
}
```

Figure 2.1: C++ Code to call VMAP API

VMAP Standard API calling sequence is further sub-divided into three categories - writing system data, mesh and state variables to the VMAP .h5 file. All the functions, defined in the following flowcharts, are declared in VMAPFile.h and all the structures are declared in VMAP.h

2.2.1 Writing System Data

The following flowchart (Figure 2.2) shows the calling sequence to write your own VMAP .h5 file with the mandatory system data.

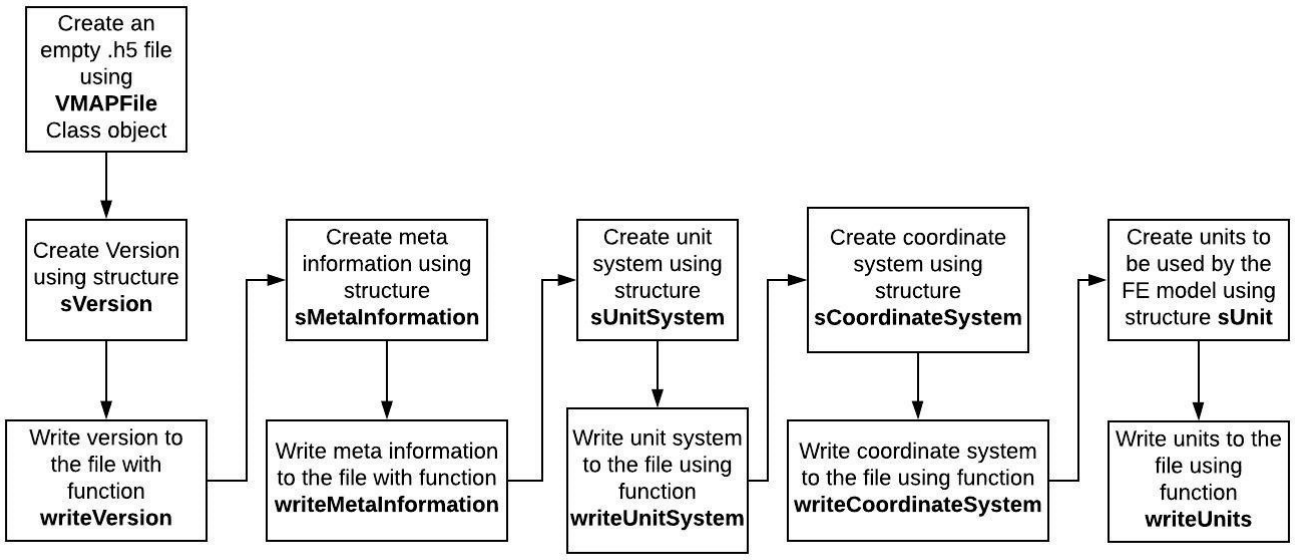


Figure 2.2: Write VMAP .h5 File

2.2.2 Writing an FE Mesh

The following flowchart (Figure 2.3) can be followed to create an FE mesh.

VMAP offers the choice to create an Element Type or use one of the Element Types defined in **VMAPElementTypeFactory.cxx**. The factory offers over 30 different types of 1D, 2D & 3D elements. The specifications of these element types and specification for writing your own element type can be found in Chapter 8. Additionally, VMAP offers the option to create an Integration Type or use one of the Integration Type defined in **VMAPIntegrationTypeFactory.cxx** (Chapter 9)

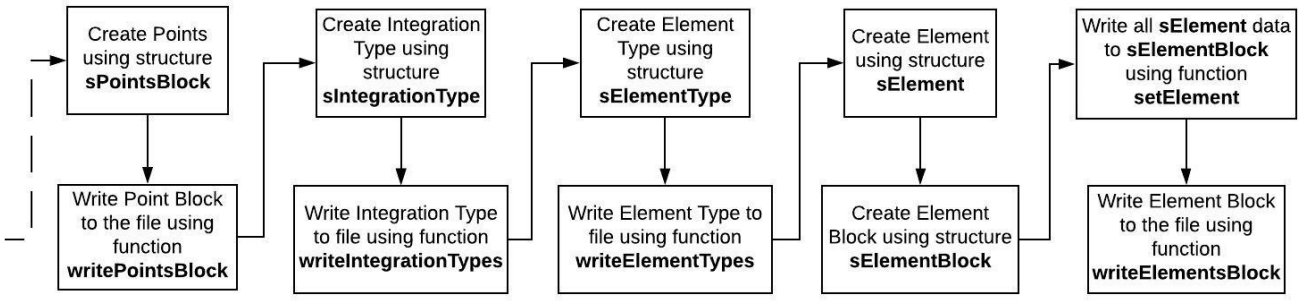


Figure 2.3: Write Mesh to file

In order to define elements and further build element blocks, it is necessary to define the points block, integration types and element types.

2.2.3 Writing State Variables

A State Variable can be defined Globally, or over one/more Point(s), Element(s), Element Face(s), Integration Point(s). The following flowchart shows the structure and function used for creating and writing State Variables.

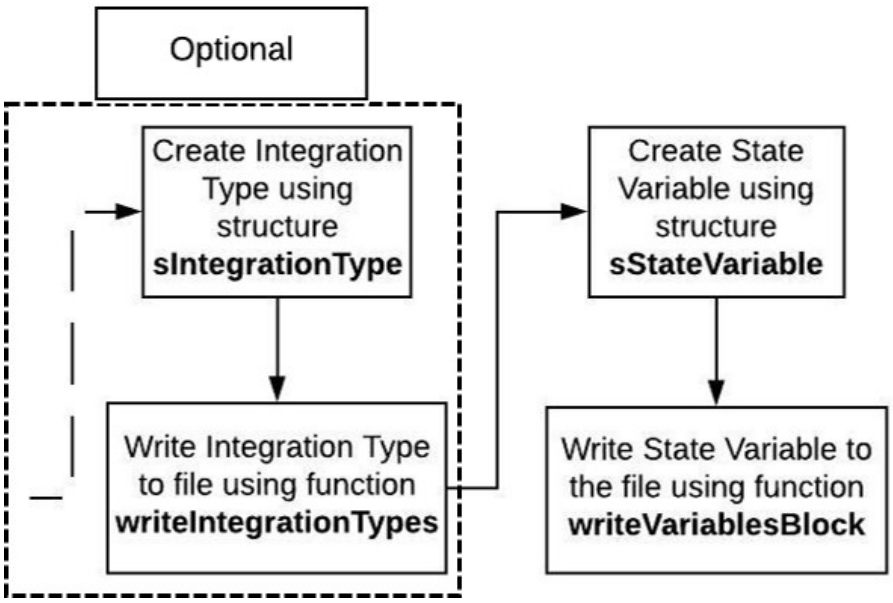


Figure 2.4: Write State Variable

Chapter 3

VMAP Standard API - Data Structure Relationship

This chapter explains the relationship between various structures and classes defined in the VMAP Standard I/O Library. All structures and functions are defined within the namespace `VMAP`.

3.1 Data Structure Dependency

The data structure dependency is explained in the following sections by means of schematic diagrams. The groups can contain several other groups, datasets and attributes. The VMAP API defines the groups, datasets and attributes with the help of structures defined in C++. In the descriptions below, for all attributes and datasets and some groups, the structure name is defined in brackets e.g. (sStructure).

3.1.1 `VMAP` Group

`VMAP` Group in VMAP Standard I/O library contains data from groups - `GEOMETRY`, `MATERIAL`, `VARIABLES` & `SYSTEM` and attribute - `VERSION` (`sVersion`). Figure 3.1 shows a schematic of the `VMAP` group and the data it contains.

3.1.2 `GEOMETRY` Group

The `GEOMETRY` group in VMAP Standard I/O library contains sub-group <`PART-ID`>, within this lies groups `POINTS` (`sPointsBlock`) and `ELEMENTS` (`sElementBlock`). Figure 3.2 shows a schematic of group `GEOMETRY`.

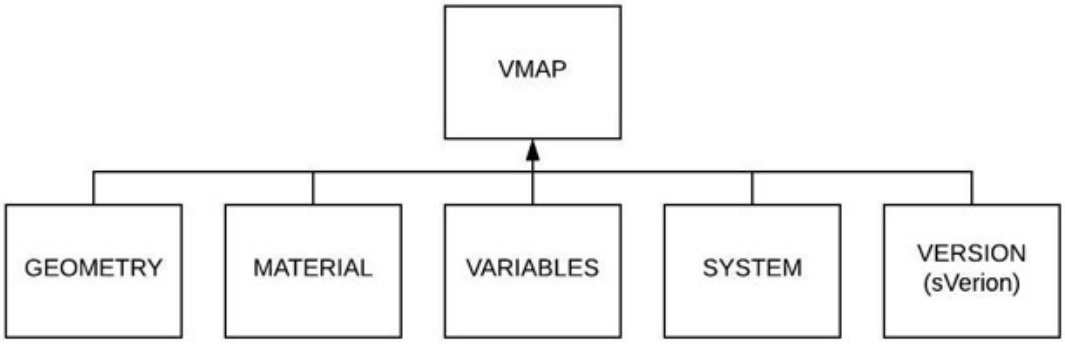


Figure 3.1: VMAP Group Dependency

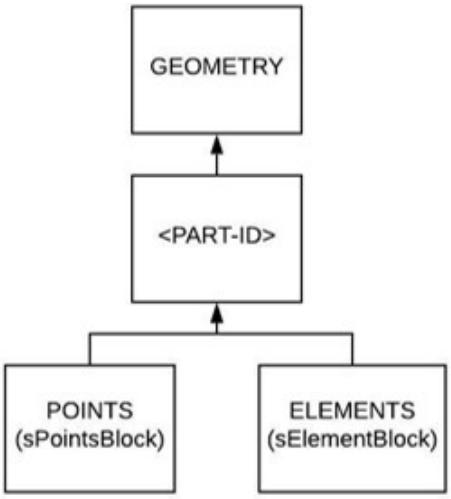


Figure 3.2: GEOMETRY Group Dependency

3.1.3 `VARIABLES` Group

The `VARIABLES` group in VMAP Standard I/O library contains sub-groups `STATE-<n>` and further `<PART-ID>`, within this lies the state variables (`sStateVariable`). Figure 3.3 shows a schematic of group `VARIABLES`.

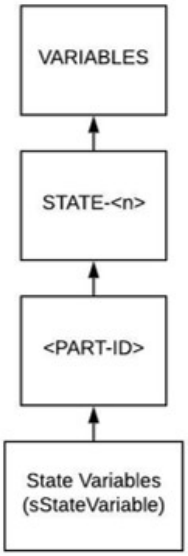


Figure 3.3: VARIABLES Group Dependency

3.1.4 SYSTEM Group

The SYSTEM group in VMAP Standard I/O library contains datasets - METADATA (sMetaInformation), UNITSYSTEM (sUnitSystem), COORDINATESYSTEM (sCoordinateSystem), ELEMENTTYPES (sElementTypes), INTEGRATIONTYPES (sIntegrationTypes) and UNITS (sUnit). Figure 3.4 shows a schematic of group SYSTEM.

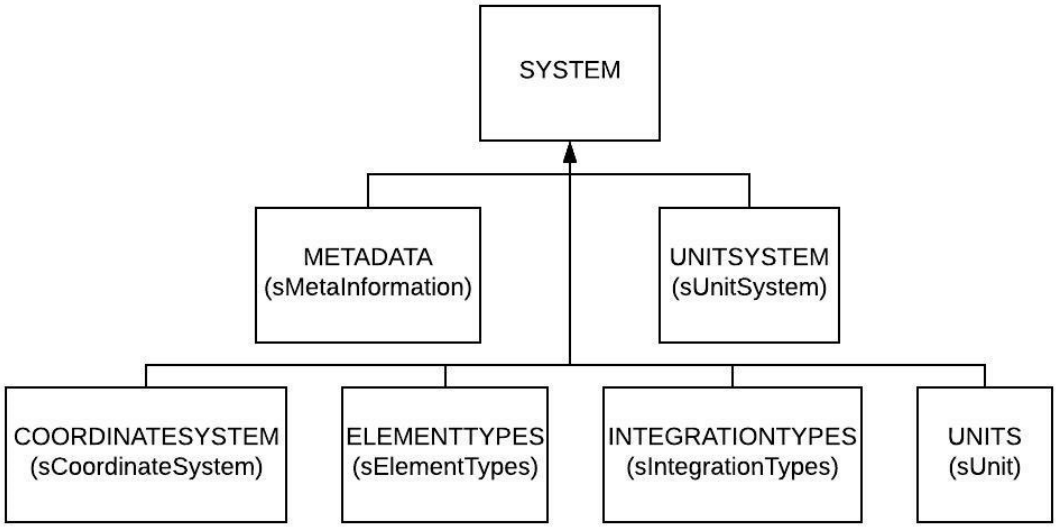


Figure 3.4: SYSTEM Group Dependency

3.1.5 POINTS Group

The POINTS group (sPointsBlock) in VMAP Standard I/O library requires data from the data set COORDINATESYSTEM (sCoordinateSystem). Figure 3.5 shows a schematic of group POINTS.

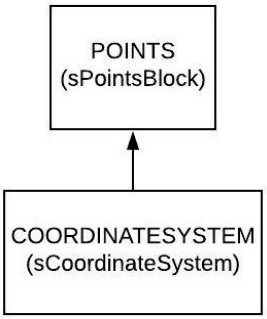


Figure 3.5: POINTS Group Dependency

3.1.6 ELEMENTS Group

The ELEMENTS group (sElementBlock) in VMAP Standard I/O library requires data from data set MYELEMENTS (sElement). Figure 3.6 shows a schematic of group ELEMENTS

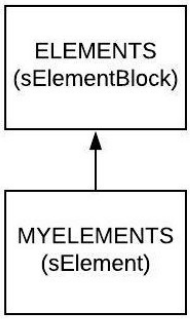


Figure 3.6: ELEMENTS Group Dependency

3.1.7 MYELEMENTS Data Set

The MYELEMENTS data set (sElement) in VMAP Standard I/O library requires data from data sets MATERIALTYPES (sMaterialType), ELEMENTTYPES (sElementType), POINTS ->MYIDENTIFIERS (sPointsBlock), COORDINATESYSTEM (sCoordinateSystem). Figure 3.7 shows a schematic of data set MYELEMENTS.

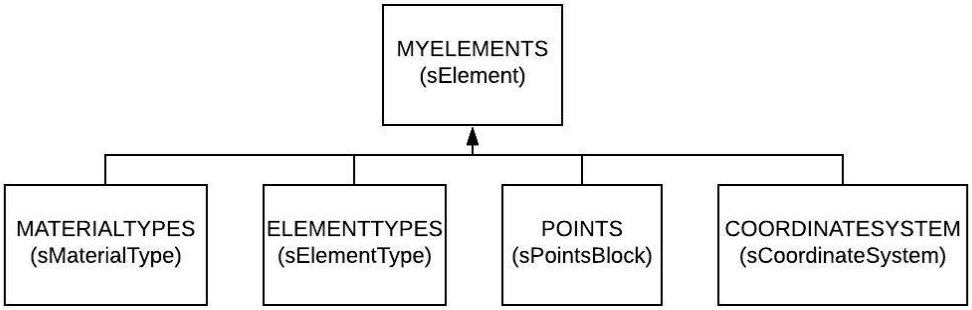


Figure 3.7: MYELEMENTS Data Set Dependency

3.1.8 ELEMENTTYPES Data Set

The ELEMENTTYPES data set (sElementType) in VMAP Standard I/O library requires data from INTEGRATIONTYPES (sIntegrationType) and POINTS (sPointsBlock). Figure 3.8 shows a schematic of data set ELEMENTTYPES.

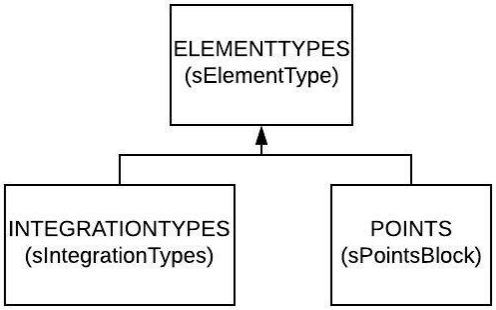


Figure 3.8: ELEMENTTYPES Data Set Dependency

3.1.9 State Variables Group

The State Variables group in VMAP Standard I/O library refers to all the state variables, each state variable (sStateVariable) inherits data from COORDINATESYSTEM (sCoordinateSystem), UNITS (sUnit), and attribute MYLOCATION which could be global, a point, an integration point, an element or an element face. Figure 3.9 shows a schematic of a state variable group.

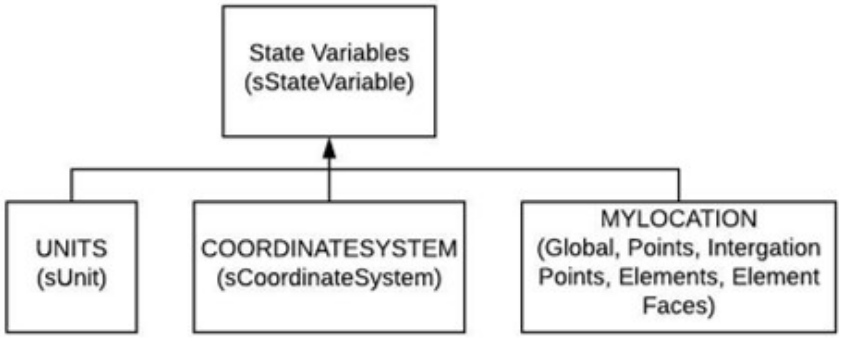


Figure 3.9: State Variable Dependency

Note: Additional Integration Types have to be defined for State Variables, if they do not lie on Integration Points already defined for the Element Type.

3.1.10 `UNITSYSTEM` Attribute

The `UNITSYSTEM` attribute (`sUnitSystem`) in VMAP Standard I/O library requires data from Base Unit (`sBaseUnit`). Figure 3.10 shows a schematic of attribute `UNITSYSTEM`.

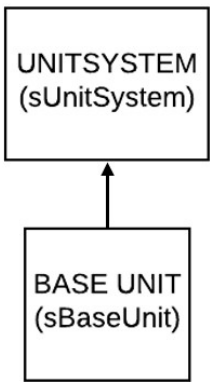


Figure 3.10: UNITSYSTEM Dependency

Chapter 4

VMAP Standard API

4.1 Namespace Documentation

The VMAP namespace is documented in the following section.

4.2 VMAP Namespace Reference

Classes

- struct sVersion
- struct sMetaInformation
- struct sCoordinateSystem
- struct sBaseUnit
- struct sUnitSystem
- struct sUnit
- struct sPointsBlock
- struct sIntegrationType
- struct sElementType
- struct sElement
- struct sElementBlock
- struct sGeometrySet
- struct sStateVariable
- class VMAPElementTypeFactory

  Class to generate file VMAP element types.
- class Exception
- class ErrOutOfRange

- class ErrSpaceMismatch
- class ErrSizeMismatch
- class ErrTypeMismatch
- class ErrUnsupported
- class ErrNotImplemented
- class ErrInvalid
- class VMAPFile

  Class to read / write a VMAP HDF5 file.
- class VMAPIntegrationTypeFactory

  Class to generate file VMAP integration types.

Functions

- template<class tException >
  void VMAP_DECLSPEC Assert (const bool condition)

  General assertion with exception template.
- template<class tException >
  void VMAP_DECLSPEC Assert (const bool condition, const std::string &s)

  General assertion with exception template and string.
- H5::CompType H5VersionType (sizeof(sVersion))
- H5::CompType H5MetaInformationType (sizeof(sMetaInformation))
- H5::CompType H5CoordinateSystemType (sizeof(sCoordinateSystem))
- H5::CompType H5BaseUnitType (sizeof(sBaseUnit))
- H5::CompType H5UnitSystemType (sizeof(sUnitSystem))
- H5::CompType H5UnitType (sizeof(sUnit))
- H5::CompType H5IntegrationTypeType (sizeof(sIntegrationType))
- H5::CompType H5ElementTypeType (sizeof(sElementType))
- H5::CompType H5ElementsType (sizeof(sElement))
- void Initialize ()

  Method to initialize the VMAP HDF5 data classes.
- herr_t collect_subgroup_names (hid_t loc_id, const char ∗name, const H5L_info_t ∗linfo, void ∗opdata)
- static void do_dtype (hid_t)
- static void do_dset (hid_t)
- static void do_link (hid_t, char ∗)
- static void do_attr (hid_t)

- static void do_plist (hid_t)
- static void scan_group (hid_t)
- static void scan_attrs (hid_t)

Variables

- static const int VMAP_VERSION_MAJOR = 0
- static const int VMAP_VERSION_MINOR = 4
- static const int VMAP_VERSION_PATCH = 0
- static H5::VarLenType H5VariableIntType
- static H5::VarLenType H5VariableDoubleType
- static const char * GROUP_VMAP = "/VMAP/"
- static const char * GROUP_SYSTEM = "/VMAP/SYSTEM"
- static const char * GROUP_GEOMETRY = "/VMAP/GEOMETRY"
- static const char * GROUP_VARIABLE = "/VMAP/VARIABLES"
- static const char * ATTRIBUTE_VERSION = "VERSION"
- static const char * ATTRIBUTE_METADATA = "METADATA"
- static const char * ATTRIBUTE_UNITSYSTEM = "UNITSYSTEM"
- static const char * DATASET_UNITS = "UNITS"
- static const char * DATASET_COORDINATESYSTEM = "COORDINATESYSTEM"
- static const char * DATASET_INTEGRATIONTYPES = "INTEGRATIONTYPES"
- static const char * DATASET_ELEMENTTYPES = "ELEMENTTYPES"
- static const char * DATASET_POINTS = "POINTS"
- static const char * DATASET_ELEMENTS = "ELEMENTS"
- static const char * DATASET_GEOMETRYSETS = "GEOMETRYSETS"
- static int INITIALIZATION_FLAG = 0

4.3 File Documentation

All the header and code files are documented in the following sections.

4.4 src/VMAP.cxx File Reference

```
#include "VMAP.h"
#include "H5Cpp.h"
```

Namespaces

- VMAP

4.5 src/VMAP.h File Reference

```
#include <iostream>
#include <string.h>
#include <stdlib.h>
#include <vector>
#include "H5Cpp.h"
#include "VMAPDeclspec.h"
```

Classes

- struct VMAP::sVersion
- struct VMAP::sMetaInformation
- struct VMAP::sCoordinateSystem
- struct VMAP::sBaseUnit
- struct VMAP::sUnitSystem
- struct VMAP::sUnit
- struct VMAP::sPointsBlock
- struct VMAP::sIntegrationType
- struct VMAP::sElementType
- struct VMAP::sElement
- struct VMAP::sElementBlock
- struct VMAP::sGeometrySet
- struct VMAP::sStateVariable

Namespaces

- VMAP

Variables

- static const int VMAP::VMAP_VERSION_MAJOR = 0
- static const int VMAP::VMAP_VERSION_MINOR = 4
- static const int VMAP::VMAP_VERSION_PATCH = 0

4.6 src/VMAPDeclspec.h File Reference

Macros

- #define VMAP_DECLSPEC

4.6.1 Macro Definition Documentation

#define VMAP_DECLSPEC

Definition at line 19 of file VMAPDeclspec.h.

4.7 src/VMAPElementTypeFactory.cxx File Reference

```
#include "VMAPElementTypeFactory.h"
#include <vector>
#include <string>
```

Namespaces

- VMAP

4.8 src/VMAPElementTypeFactory.h File Reference

```
#include "VMAP.h"
```

Classes

- class VMAP::VMAPElementTypeFactory

  Class to generate file VMAP element types.

Namespaces

- VMAP

4.9 src/VMAPException.cxx File Reference

```
#include <iostream>
#include "VMAPException.h"
```

Namespaces

- VMAP

4.10 src/VMAPException.h File Reference

```
#include <string>
#include <iostream>
#include <exception>
#include "VMAPDeclspec.h"
```

Classes

- class VMAP::Exception
- class VMAP::ErrOutOfRange
- class VMAP::ErrSpaceMismatch
- class VMAP::ErrSizeMismatch
- class VMAP::ErrTypeMismatch
- class VMAP::ErrUnsupported
- class VMAP::ErrNotImplemented
- class VMAP::ErrInvalid

Namespaces

- VMAP

Functions

- template<class tException >
  void VMAP_DECLSPEC VMAP::Assert (const bool condition)

  General assertion with exception template.

- template<class tException >
  void VMAP_DECLSPEC VMAP::Assert (const bool condition, const std::string &s)

General assertion with exception template and string.

4.11 src/VMAPFile.cxx File Reference

```
#include "VMAPFile.h"
#include "VMAPH5Tools.h"
#include "VMAPException.h"
#include "hdf5.h"
#include "hdf5_hl.h"
#include <fstream>
#include <sstream>
#include <stdio.h>
#include <stdlib.h>
```

Namespaces

- VMAP

Functions

- H5::CompType VMAP::H5VersionType (sizeof(sVersion))
- H5::CompType VMAP::H5MetaInformationType (sizeof(sMetaInformation))
- H5::CompType VMAP::H5CoordinateSystemType (sizeof(sCoordinateSystem))
- H5::CompType VMAP::H5BaseUnitType (sizeof(sBaseUnit))
- H5::CompType VMAP::H5UnitSystemType (sizeof(sUnitSystem))
- H5::CompType VMAP::H5UnitType (sizeof(sUnit))
- H5::CompType VMAP::H5IntegrationTypeType (sizeof(sIntegrationType))
- H5::CompType VMAP::H5ElementTypeType (sizeof(sElementType))
- H5::CompType VMAP::H5ElementsType (sizeof(sElement))
- void VMAP::Initialize ()

  Method to initialize the VMAP HDF5 data classes.
- herr_t VMAP::collect_subgroup_names (hid_t loc_id, const char ∗name, const H5-L_info_t ∗linfo, void ∗opdata)

Variables

- static H5::VarLenType VMAP::H5VariableIntType
- static H5::VarLenType VMAP::H5VariableDoubleType
- static const char ∗ VMAP::GROUP_VMAP = "/VMAP/"

- static const char * VMAP::GROUP_SYSTEM = "/VMAP/SYSTEM"
- static const char * VMAP::GROUP_GEOMETRY = "/VMAP/GEOMETRY"
- static const char * VMAP::GROUP_VARIABLE = "/VMAP/VARIABLES"
- static const char * VMAP::ATTRIBUTE_VERSION = "VERSION"
- static const char * VMAP::ATTRIBUTE_METADATA = "METADATA"
- static const char * VMAP::ATTRIBUTE_UNITSYSTEM = "UNITSYSTEM"
- static const char * VMAP::DATASET_UNITS = "UNITS"
- static const char * VMAP::DATASET_COORDINATESYSTEM = "COORDINATESYSTEM"
- static const char * VMAP::DATASET_INTEGRATIONTYPES = "INTEGRATIONTYPES"
- static const char * VMAP::DATASET_ELEMENTTYPES = "ELEMENTTYPES"
- static const char * VMAP::DATASET_POINTS = "POINTS"
- static const char * VMAP::DATASET_ELEMENTS = "ELEMENTS"
- static const char * VMAP::DATASET_GEOMETRYSETS = "GEOMETRYSETS"
- static int VMAP::INITIALIZATION_FLAG = 0

4.12 src/VMAPFile.h File Reference

```
#include <iostream>
#include <string.h>
#include <stdlib.h>
#include <vector>
#include "H5Cpp.h"
#include "VMAP.h"
```

Classes

- class VMAP::VMAPFile

  Class to read / write a VMAP HDF5 file.

Namespaces

- VMAP

Functions

- void VMAP::Initialize ()

Method to initialize the VMAP HDF5 data classes.

4.13 src/VMAPH5Tools.h File Reference

```
#include "hdf5.h"
```

Namespaces

- VMAP

Macros

- #define MAX_NAME 1024

Functions

- static void VMAP::do_dtype (hid_t)
- static void VMAP::do_dset (hid_t)
- static void VMAP::do_link (hid_t, char ∗)
- static void VMAP::do_attr (hid_t)
- static void VMAP::do_plist (hid_t)
- static void VMAP::scan_group (hid_t)
- static void VMAP::scan_attrs (hid_t)

4.13.1 Macro Definition Documentation

#define MAX_NAME 1024

Definition at line 17 of file VMAPH5Tools.h.

Referenced by VMAP::do_attr(), VMAP::do_dset(), VMAP::do_link(), VMAP::do_plist(), and VMAP::scan_group().

4.14 src/VMAPIntegrationTypeFactory.cxx File Reference

```
#include "VMAPIntegrationTypeFactory.h"
#include "VMAPException.h"
#include <vector>
#include <math.h>
```

Namespaces

- VMAP

4.15 src/VMAPIntegrationTypeFactory.h File Reference

```
#include "VMAP.h"
```

Classes

- class VMAP::VMAPIntegrationTypeFactory

  Class to generate file VMAP integration types.

Namespaces

- VMAP

Chapter 5

Compiling & Linking The API

This chapter explains how to link CAE tool APIs developed in Python, C#, C++, Java or FORTRAN to the VMAP Standard API.

5.1 Overview

Figure 5.1 shows partial software architecture to remind the users about the SWIG interface explained in chapter 1.

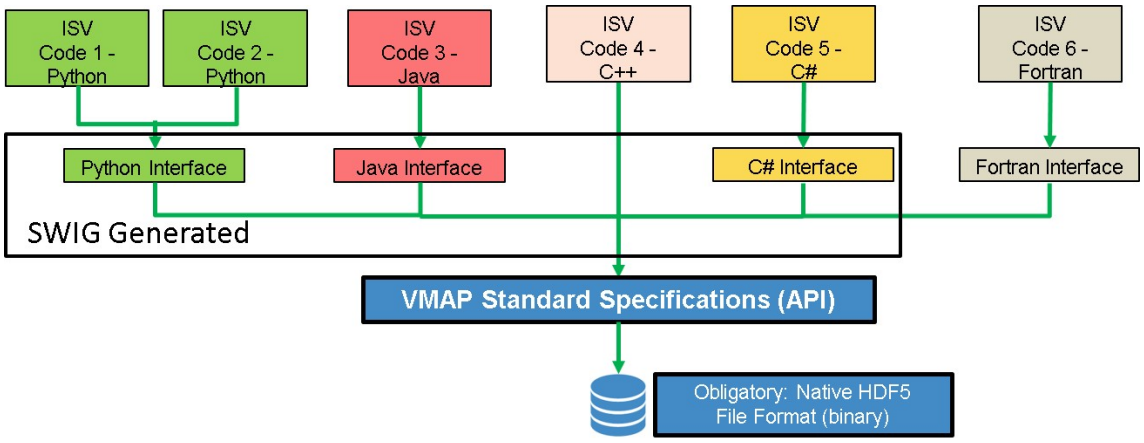


Figure 5.1: SWIG Interface for Linking VMAP Standard API

5.2 Basic Build Requirements for VMAP Standard API

The build requirements for VMAP Standard API are listed below:

1. C++ Compiler
   - Windows: Visual Studio, Intel, Cygwin GCC
   - Linux: GCC, Intel

2. Third party libraries:
    - Native HDF5 library (with C++ API)
        - Available via HDF5
    - Compiled zlib library to utilize compression
3. CMake installation (at least version 3.10.x)
    - CMake

5.3 Additional Requirements for VMAP Standard API

For all code/script formats other than C++, the following is required. #1 is mandatory.

1. SWIG installation (version 2 or higher)
    - SWIG
2. Python installation (for Python Interface)
    - Python
3. Java SDK installation (for Java Interface)
4. C# compiler (for C# Interface)

5.4 Build Using Cmake GUI

1. Open cmake-gui
2. Specify the VMAP source code location
3. Specify the VMAP build location, e.g. in a CMakeFiles sub folder
4. When pressing configure button you have the possibility to select your generator, e.g. Visual Studio 15. See figure 5.2
5. Accept generator with ‘Finish’ selection
6. Cmake will start to create the project file. See figure 5.3
7. You can uncheck the Java, Python and C# interfaces if unwanted and press ’Configure’ again
8. You might get unresolved HDF5 and zlib libraries if cmake is not able to find them
9. Assign them manually per library and ’Configure’ until errors are resolved
10. Finally to select ’Generate’ button to write the project build generator.

Remarks:

- Building Interfaces requires VMAP build as shared library
- Static HDF libraries are not found properly on Windows (to add manually in cmake-gui)

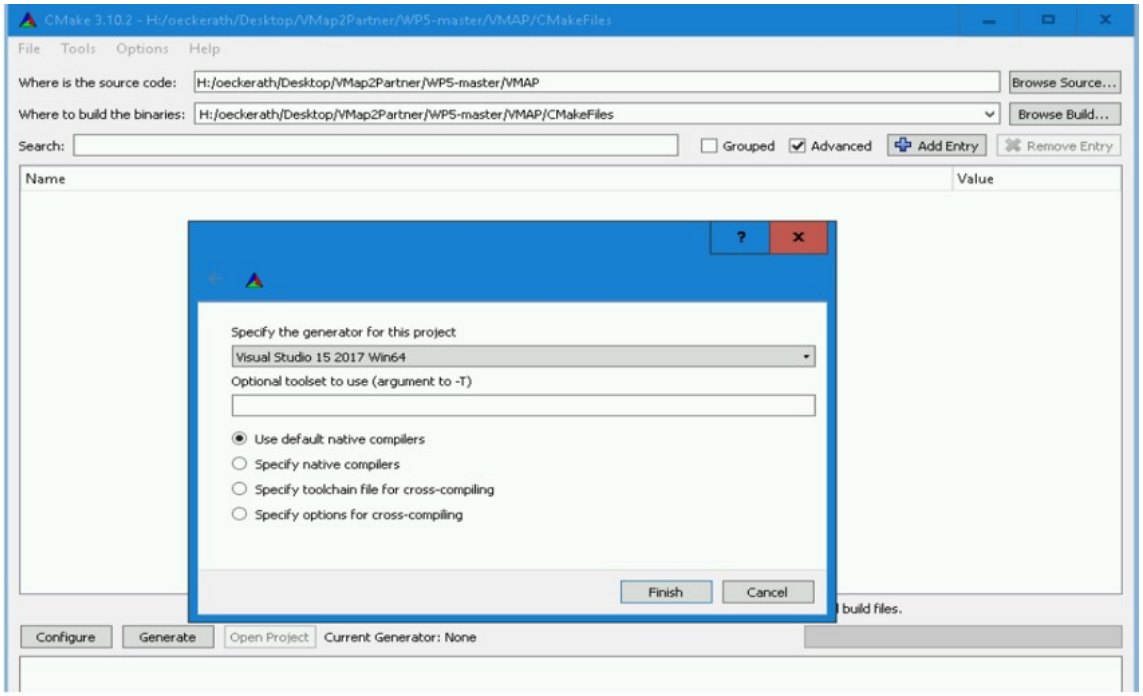


Figure 5.2: Selecting Generator

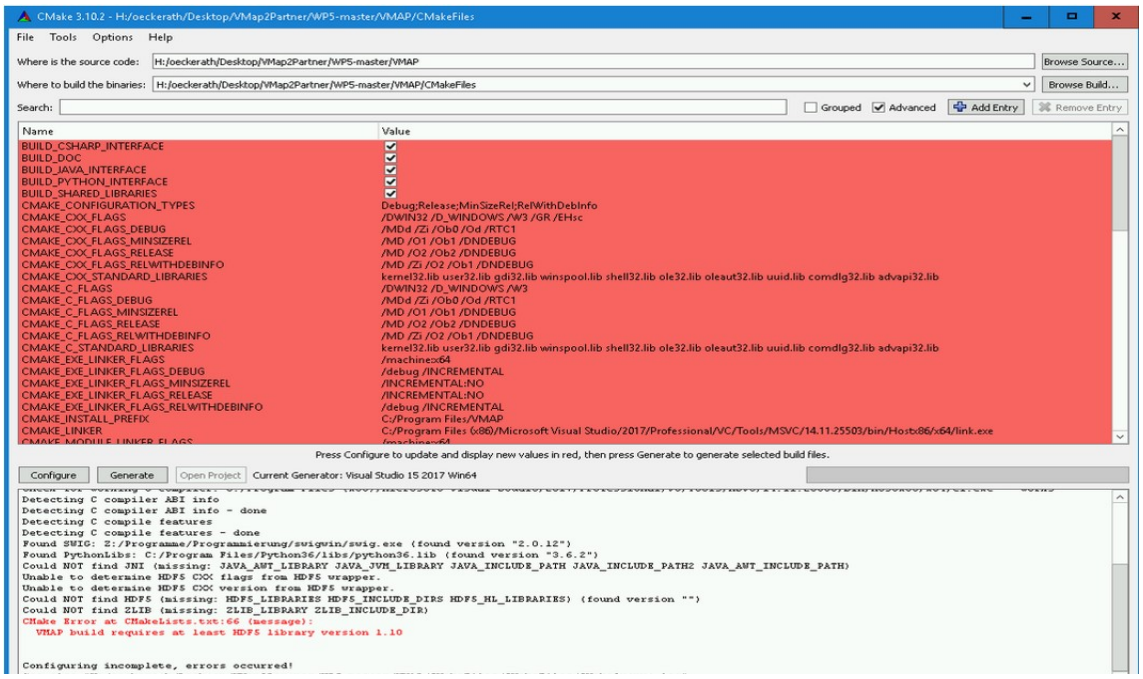


Figure 5.3: Creating Project File

5.5 VMAP Integration

After successfully completing all the previous steps, VMAP integration can be carried out based on the interfaces.

5.5.1 C++ Library

1. Add VMAP 'include' folder to your list of include directories
2. Add libVMAP library to the linker
3. Add HDF5 libraries to the linker
    - libhdf5
    - libhdf5_cpp
    - libhdf5_hl
    - libhdf5_hl_cpp
    - zLib

5.5.2 Python Interface

1. Import module PyVMAP in your Python Code
2. Add libVMAP directory to library path before execution

5.5.3 Java Interface

1. Use System.loadLibrary("JVMAP") in your Java Code
2. Add libJVMAP directory to library path before execution

5.5.4 C# Interface

1. Compile all autogenerated *.cs classes to your application
2. Add libVMAP directory to library path before execution

Chapter 6

Implementation Specifications

This chapter outlines the theory for writing your own VMAP I/O Library which generates a standard VMAP .h5 output file. The aim is to provide users with the flexibility to write their own code without depending on just one standard code. The VMAP .h5 file uses the `same Nomenclature`, for all entities, as described in this chapter. This chapter along with chapter 7 shows the data storage format in a standard VMAP .h5 file. The figures explain the hierarchy of data storage in VMAP format. These figures are colour coded with green, red and blue to differentiate among groups, attributes and data sets respectively. Additionally, the letters 'g', 'a' and 'd' are used as sub-scripts denoting group, attribute and data set respectively; this facilitates a black-and-white print option without losing the differentiation.

6.1 `VMAP` Group

`VMAP` Group has an attribute called `VERSION` and four major groups, which clearly earmark the domains in an FE model. These four groups further consist of groups and data sets along with relevant metadata to comprehensively define an FE model. Tables 6.1 & 6.2 show the `Object Attribute Info` and `General Object Info` of `VMAP` Group, these tables show information as seen in the HDF5 Viewer.

Number of attributes:	1		
Name	Type	Array Size	Value
`VERSION`	Compound {...}	Scalar	{...}

Table 6.1: Object Attribute Info

The hierarchical model (from left to right) in Figure 6.1 shows a schematic of the basic `VMAP` storage structure.

Name:	VMAP
Path:	/
Type:	HDF5 Group
Object Ref:	...

Number of members:	4
Name	Type
GEOMETRY	Group
MATERIAL	Group
VARIABLES	Group
SYSTEM	Group

Table 6.2: General Object Info

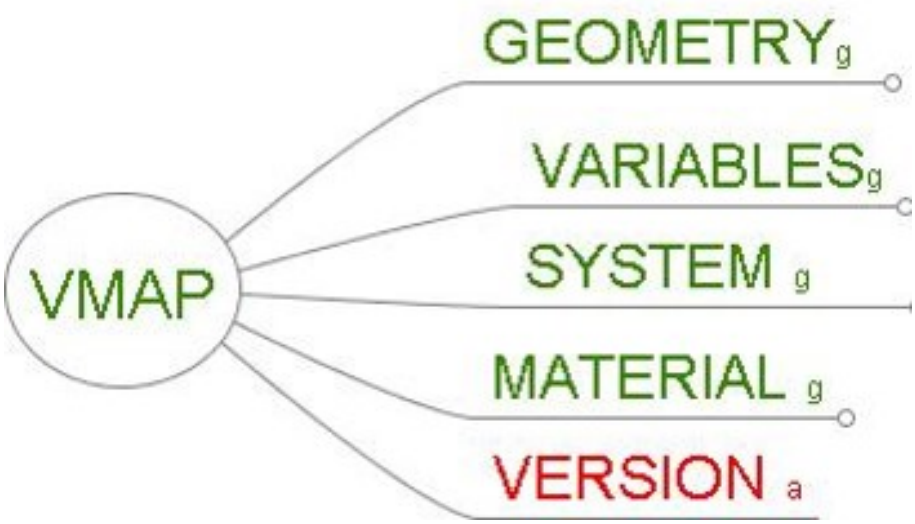


Figure 6.1: VMAP Group

6.1.1 VERSION Attribute

The VERSION attribute defines the VMAP version used by the file. The following metadata is associated with VERSION:

- myMajor: Defines the major version number of VMAP I/O Library.
- myMinor: Defines the minor version number of VMAP I/O Library.
- myPatch: Defines the patch level number of the VMAP I/O Library.

Table 6.3 shows the data types associated with VERSION metadata

Metadata	Data Type
myMajor	Integer
myMinor	Integer
myPatch	Integer

Table 6.3: Data Types of VERSION Metadata

6.2 GEOMETRY Group

GEOMETRY Group stores the geometrical data associated with FE Model, this includes points and elements. Table 6.4 shows only General Object Info for group GEOMETRY. This group has no attribute information. As part of the VMAP Standard, the groups associated with GEOMETRY are all the <Part IDs> or <PROPERTY IDs> of an FE Model. <Part IDs> or <PROPERTY IDs> are used synonymously throughout this document and are synonymous throughout the VMAP domain. The points and elements then belong to the respective <Part IDs> or <PROPERTY IDs>. The groups associated with GEOMETRY are shown in Figure 6.3.

Name:	GEOMETRY
Path:	/VMAP/
Type:	HDF5 Group
Object Ref:	...

Number of members:	n
Name	Type
<PART-ID>	Group

Table 6.4: General Object Info

where n is the number of Parts/Property-Ids in the FE model.

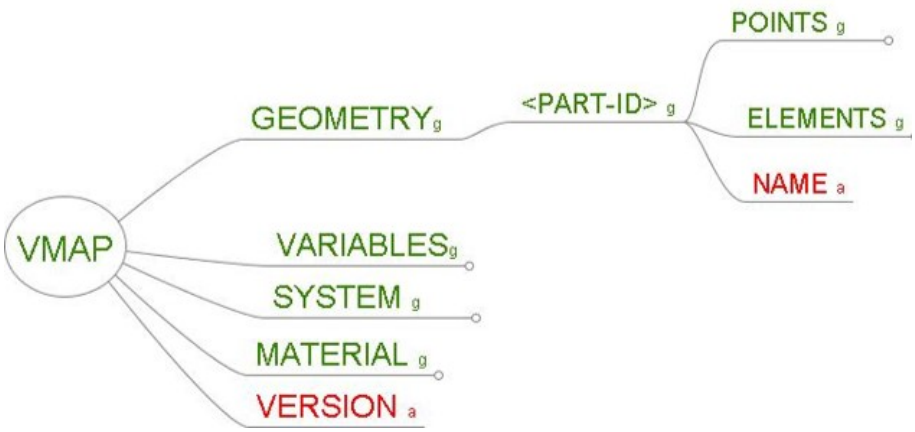


Figure 6.2: GEOMETRY Group

6.3 <PART-ID> Group

<PART-ID> Group stores the points and elements of a particular part/property-id. Tables 6.5 & 6.6 show Object Attribute Info and General Object Info respectively, for group <PART-ID>. The attribute of <PART-ID> is MYNAME. As part of the VMAP Standard, the groups associated with <PART-ID> are POINTS & ELEMENTS.

Number of attributes:	1		
Name	Type	Array Size	Value
MYNAME	String	Scalar	...

Table 6.5: Object Attribute Info

Name:	<PART-ID>
Path:	/VMAP/GEOMETRY
Type:	HDF5 Group
Object Ref:	...

Number of members:	2
Name	Type
POINTS	Group
ELEMENTS	Group

Table 6.6: General Object Info

Note: Within the VMAP Standard Library, there is a create function for generating a group within GEOMETRY group with parameters Part-Id and Part-Name. The basis for this group lies in the fact that, all FE solvers have distinct part numbers and names for every part. Hence, the part number and name are taken directly from the solver file. Additionally, this offers the possibility of duplicate point(s) and/or element(s) numbering among various parts.

6.3.1 MYNAME Attribute

The MYNAME attribute stores the name of the part. The following metadata is associated with MYNAME:

- Value: Defines the name of the part.

Table 6.7 shows the data types associated with MYNAME metadata

Metadata	Data Type
Value	String

Table 6.7: Data Types of MYNAME Metadata

6.4 POINTS Group

POINTS Group stores the points of an FE model, this includes X,Y,Z coordinates and the unique integral identifier for each point. Tables 6.8 & 6.9 show Object Attribute Info and General Object Info respectively, for group POINTS. The two attributes of POINTS group are MYCOORDINATESYSTEM & MYSIZE and two data sets associated with POINTS are MYCOORDINATES & MYIDENTIFIERS, shown in Figure 6.4.

Number of attributes:	2		
Name	Type	Array Size	Value
MYCOORDINATESYSTEM	Integer	Scalar	...
MYSIZE	unsigned Integer	Scalar	...

Table 6.8: Object Attribute Info

Name:	POINTS
Path:	/VMAP/GEOMETRY/<PART-ID>/
Type:	HDF5 Group
Object Ref:	...

Number of members:	2
Name	Type
MYCOORDINATES	Dataset
MYIDENTIFIERS	Dataset

Table 6.9: General Object Info

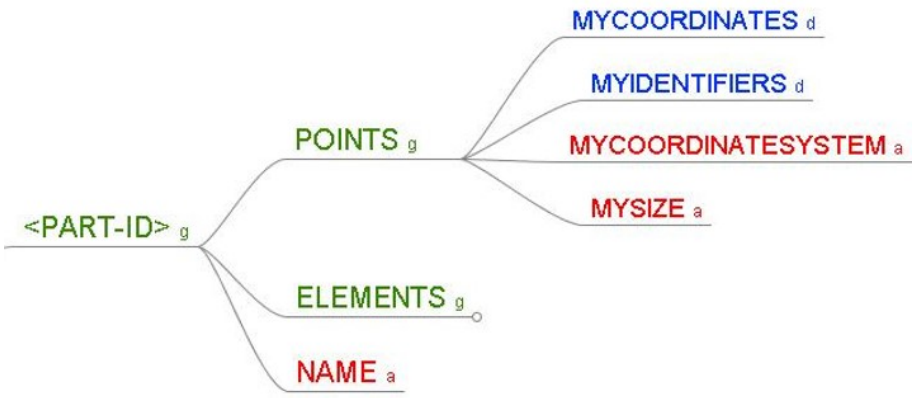


Figure 6.3: POINTS Group

6.4.1 MYCOORDINATESYSTEM Attribute

This attribute contains the coordinate system used by the points.

- Value: Stores the coordinate system reference number. The details of this coordinate system can be found in SYSTEM ->COORDINATESYSTEM, see sub-section 6.10.1 for more details.

Metadata	Data Type
Value	Integer

Table 6.10: Data Types of MYCOORDINATESYSTEM Metadata

6.4.2 MYSIZE Attribute

This attribute contains the number of points of an FE Model.

- Value: Stores the number of points.

Metadata	Data Type
Value	unsigned Integer

Table 6.11: Data Types of MYSIZE Metadata

6.4.3 MYCOORDINATES Data Set

The MYCOORDINATES data set stores the coordinates of the points in the following storage order:

- X: X coordinate of a point.
- Y: Y coordinate of a point.
- Z: Z coordinate of a point.

In the HDF5 Viewer, the columns are by default named 0, 1 and 2 for X,Y and Z respectively.

Metadata	Data Type
X	Float
Y	Float
Z	Float

Table 6.12: Data Types of MYCOORDINATES Metadata

The General Object Info associated with this data set is shown in Table 6.13.

Name:	MYCOORDINATES
Path:	/VMAP/GEOMETRY/<PART-ID>/POINTS/
Type:	HDF5 Dataset
Object Ref:	...

Dataset Dataspace and Datatype	
No. of Dimension(s):	2
Dimension Size(s):	MYSIZE x 3
Max Dimension Size(s):	MYSIZE x 3
Data Type:	64-bit floating point

Table 6.13: General Object Info

6.4.4 MYIDENTIFIERS Data Set

The MYIDENTIFIERS data set stores the integral identifiers to points. In the HDF5 Viewer, the column is named by default as 0 for myvalue (shown below in the table).

Metadata	Data Type
myvalue	Integer

Table 6.14: Data Types of MYIDENTIFIERS Metadata

The `General Object Info` associated with this data set is shown in Table 6.15.

Name:	`MYIDENTIFIERS`
Path:	`/VMAP/GEOMETRY/<PART-ID>/POINTS/`
Type:	HDF5 Dataset
Object Ref:	..

Dataset Dataspace and Datatype	
No. of Dimension(s):	2
Dimension Size(s):	MYSIZE x 1
Max Dimension Size(s):	MYSIZE x 1
Data Type:	32-bit integer

Table 6.15: General Object Info

6.5 `ELEMENTS` Group

`ELEMENTS` Group stores the elements of an FE model, this includes identifier, type, coordinate system, material type, element connectivity. Tables 6.16 & 6.17 show `Object Attribute Info` and `General Object Info` respectively, for group `ELEMENTS`. The attribute associated with `ELEMENTS` is `MYSIZE` and data set is `MYELEMENTS`, shown in Figure 6.4.

Number of attributes:	1		
Name	Type	Array Size	Value
`MYSIZE`	unsigned Integer	Scalar	...

Table 6.16: Object Attribute Info

Name:	`ELEMENTS`
Path:	`/VMAP/GEOMETRY/<PART-ID>/`
Type:	HDF5 Group
Object Ref:	...

Number of members:	1
Name	Type
`MYELEMENTS`	Dataset

Table 6.17: General Object Info

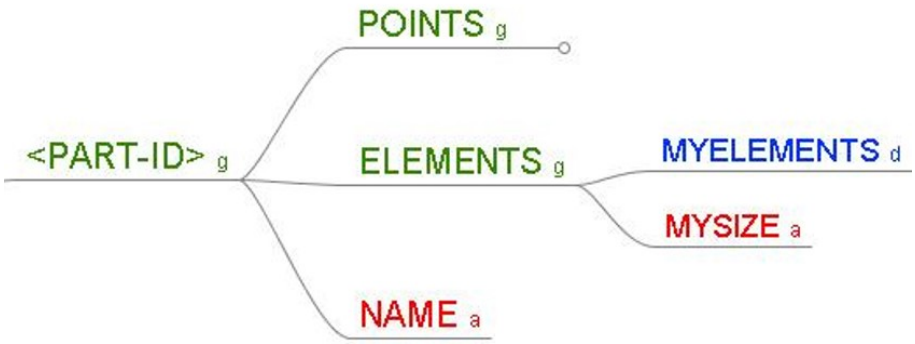


Figure 6.4: ELEMENTS Group

6.5.1 MYSIZE Attribute

This attribute contains the number of elements of an FE Model.

- Value: Stores the number of elements/the size of the data set MYELEMENTS.

Metadata	Data Type
Value	unsigned Integer

Table 6.18: Data Types of MYSIZE Metadata

6.5.2 MYELEMENTS Data Set

The MYELEMENTS data set stores the element details in the following storage order:

- myIdentifier: Integral identifier for each element.
- myElementType: Stores Element Type reference number. For more details about SYSTEM->ELEMENTTYPES see sub-section 6.10.2.
- myCoordinateSystem: Stores the coordinate system reference number. For more details about SYSTEM ->COORDINATESYSTEM, see sub-section 6.10.1.
- myMaterialType: Stores the material type reference number. For more details about MATERIAL ->MATERIALTYPE, see section XX.
- myConnectivity: Stores the point number ordering which forms one element. For details about point number ordering see chapter 8.

This is a compound data set.

Metadata	Data Type
myIdentifier	Integer
myElementType	Integer
myCoordinateSystem	Integer
myMaterialType	Integer
myConnectivity	Integer Array

Table 6.19: Data Types of MYELEMENTS Metadata

The General Object Info associated with this data set is shown in Table 6.20.

Name:	MYELEMENTS
Path:	/VMAP/GEOMETRY/<PART-ID>/ELEMENTS/
Type:	HDF5 Dataset
Object Ref:	...

Dataset Dataspace and Datatype	
No. of Dimension(s):	2
Dimension Size(s):	MYSIZE x 1
Max Dimension Size(s):	MYSIZE x 1
Data Type:	Compound

Table 6.20: General Object Info

6.6 VARIABLES Group

VARIABLES Group stores all the variables of an FE model, this includes all input & output state variables. Table 6.21 shows only General Object Info, since this group has no attribute information. The group(s) associated with VARIABLES is/are all the states STATE-<n> of the FE-Model. Figure 6.5 shows the complete hierarchical structure of the VARIABLES Group.

Name:	VARIABLES
Path:	/VMAP/
Type:	HDF5 Group
Object Ref:	...

Number of members:	1
Name	Type
STATE-<n>	Group

Table 6.21: General Object Info

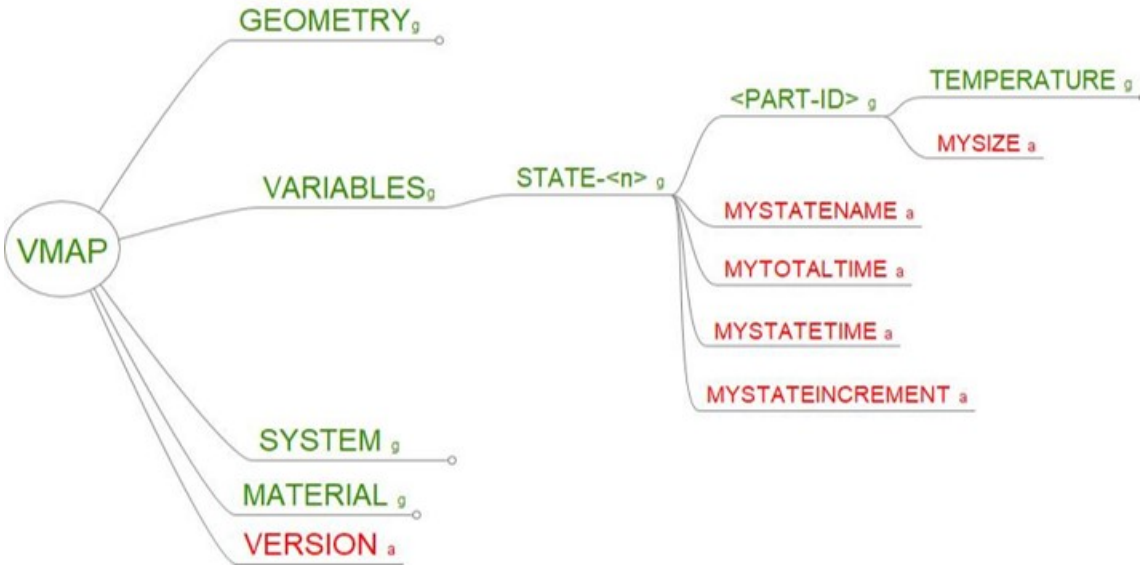


Figure 6.5: VARIABLES Group

6.7 STATE-<n> Group

STATE-<n> Group defines different states of an FE-Model. Here, a **time step**, a **solution step** or a **frame** could be referred as a state. A state is defined as any given time step (e.g. transient simulations), load step (e.g. non-linear simulations) interval or a frame (e.g. different load case), where the FE-model has a certain result set, which may or may not change for the next step or frame. This group contains all the part numbers which have state variables defined for the particular STATE-<n>. Table 6.22 & Table 6.23 show `Object Attribute Info` and `General Object Info` respectively. This group has four **optional** attributes to store the state metadata. The group(s) associated with STATE-<n> is/are all the part-ids <PART-ID> with state variables for this state.

Number of attributes:	4		
Name	Type	Array Size	Value
MYSTATENAME	String	Scalar	...
MYTOTALTIME	Double	Scalar	...
MYSTEPTIME	Double	Scalar	...
MYSTATEINCREMENT	Integer	Scalar	...

Table 6.22: Object Attribute Info

Name:	VARIABLES
Path:	/VMAP/VARIABLES/
Type:	HDF5 Group
Object Ref:	...

Number of members:	n
Name	Type
<PART-ID>	Group

Table 6.23: General Object Info

, where n refers to the number of Parts that have state variables associated with STATE-<n>.

Note: In VMAP, the STATE-0 is defined as the Input state or the initial state of the FE model.

6.7.1 MYSTATENAME Attribute

This attribute contains the name of the state.

- Value: Stores name of the STATE-<n>.

Metadata	Data Type
Value	String

Table 6.24: Data Types of MYSTATENAME Metadata

6.7.2 MYTOTALTIME Attribute

This attribute contains the total time of the analysis.

- Value: Stores total time of the analysis.

Metadata	Data Type
Value	Double

Table 6.25: Data Types of MYTOTALTIME Metadata

6.7.3 MYSTEPTIME Attribute

This attribute contains the time/interval of the state.

- Value: Stores the time/interval of the STATE-<n>.

Metadata	Data Type
Value	Double

Table 6.26: Data Types of MYSTEPTIME Metadata

6.7.4 MYSTATEINCREMENT Attribute

This attribute contains the time increment or state increment of the state.

- Value: Stores the time/state increment of the STATE-<n>.

Metadata	Data Type
Value	Integer

Table 6.27: Data Types of MYSTATEINCREMENT Metadata

6.8 <PART-ID> Group

<PART-ID> Group corresponds to the <PART-ID> Group defined for the GEOMETRY Group. This means that for a given STATE-<n>, a particular <PART-ID> has state variable(s). Table 6.28 & 6.29 show Object Attribute Info and General Object Info respectively, for group <PART-ID>. The groups associated with <PART-ID> are all state variables, where each state variable is defined as one group.

Number of attributes:	1		
Name	Type	Array Size	Value
MYSIZE	Integer	Scalar	...

Table 6.28: Object Attribute Info

Name:	<PART-ID>
Path:	/VMAP/VARIABLES/STATE-<n>/
Type:	HDF5 Group
Object Ref:	...

Number of members:	MYSIZE
Name	Type
TEMPERATURE	Group

Table 6.29: General Object Info

6.8.1 MYSIZE Attribute

This attribute contains the number of state variables of an FE Model.

- Value: Stores the number of state variables.

Metadata	Data Type
Value	unsigned Integer

Table 6.30: Data Types of MYSIZE Metadata

Section 6.9 explains an example as a State Variable group.

6.9 TEMPERATURE Group

TEMPERATURE is used as an example to show how any state varibable can be stored in VMAP. TEMPERATURE Group stores data about the temperature variation over the FE model for a given time stamp. Table 6.31 & 6.32 show Object Attribute Info and General Object Info respectively, for group TEMPERATURE. There are eleven attributes and two data sets associated with TEMPERATURE or with any other state variable. The attributes are shown in table 6.31 and explained in the following sub-sections. The data set associated with this group is MYVALUES & if the state variable is defined over a set then an additional data set MYGEOMETRYIDS. (Figure 6.6)

Number of attributes:	11		
Name	Type	Array Size	Value
MYCOORDINATESYSTEM	Integer	Scalar	...
MYDIMENSION	Integer	Scalar	...
MYENTITY	Integer	Scalar	...
MYIDENTIFIER	Integer	Scalar	...
MYINCREMENTVALUE	Integer	Scalar	...
MYLOCATION	Integer	Scalar	...
MYMULTIPLICITY	Integer	Scalar	...
MYTIMEVALUE	Floating Point	Scalar	...
MYUNIT	Integer	Scalar	...
MYVARIABLEDESCRIPTION	String	Scalar	...
MYVARIABLENAME	String	Scalar	...

Table 6.31: Object Attribute Info

Name:	TEMPERATURE
Path:	/VMAP/RESULT/STATE-<n>/<PART-ID>/
Type:	HDF5 Group
Object Ref:	...

Number of members:	2
Name	Type
MYVALUES	Dataset
MYGEOMETRYIDS*	Dataset

Table 6.32: General Object Info (*optional)

Figure 6.6: TEMPERATURE Group

6.9.1 `MYCOORDINATESYSTEM` Attribute

Refers to the coordinate system used by the state variable. The details of this coordinate system can be found in `SYSTEM ->COORDINATESYSTEM`, see sub-section 6.10.1 for more details.

- Value: Stores the coordinate system reference number.

Metadata	Data Type
Value	Integer

Table 6.33: Data Types of MYCOORDINATESYSTEM Metadata

6.9.2 `MYDIMENSION` Attribute

refers to the dimension of the state variable `TEMPERATURE`.

- Value: Stores the reference number of `MYDIMENSION`.

Metadata	Data Type
Value	Integer

Table 6.34: Data Types of MYDIMENSION Metadata

Table 6.35 shows the available dimensions and their reference numbers in VMAP.

MYDIMENSION	Reference Number	Storage Format in VMAP
INVALID	0	
SCALAR	1	single value
VECTOR	3	v_X, v_Y, v_Z
2nd Order Plain Tensor Symmetric	4	t_XX, t_YY, t_ZZ, t_XY
2nd Order Tensor Symmetric	6	t_XX,t_YY,t_ZZ,t_XY, t_YZ,t_XZ
2nd Order Tensor	9	t_XX,t_YY,t_ZZ,t_XY, t_YZ,t_XZ,t_YX,t_ZY,t_ZX
STIFFNESS MATRIX	36	Voigt notation: t_11, t_22, t_33, ..., t_66, t_12, t_23, ..., t_56, t_13, t_24,..., t_16
4th Order Tensor Symmetric	45	[[t_1111,t_1122,t_1133,..,t_1121], [t_2222,t_2233,...,t_2221] ,..,[t_2121]]
4th Order Tensor	81	[[t_1111,t_1122,t_1133,...,t_1121], [t_2211,...,t_2221] ,..,[t_2111,...,t_2121]]

Table 6.35: MYDIMENSION Enumeration

6.9.3 `MYENTITY` Attribute

Refers to the entity of the state variable `TEMPERATURE`.

- Value: Stores the reference number of `MYENTITY`

Metadata	Data Type
Value	Integer

Table 6.36: Data Types of MYENTITY Metadata

Table 6.37 shows the available entities and their reference numbers in VMAP

MYENTITY	Reference Number
REAL	1
COMPLEX	2
HAMILTONIAN	4

Table 6.37: MYENTITY Enumeration

6.9.4 `MYIDENTIFIER` Attribute

Refers to the unique integral identifier for the state variable `TEMPERATURE`.

- Value: Stores the unique identifier.

Metadata	Data Type
Value	Integer

Table 6.38: Data Types of MYIDENTIFIER Metadata

6.9.5 `MYINCREMENTVALUE` Attribute

Refers to multiple steps over which the state variable is calculated. This attribute is useful when the state variables are not defined over time.

- Value: Stores the step value for the state variable.

Metadata	Data Type
Value	Integer

Table 6.39: Data Types of MYINCREMENTVALUE Metadata

6.9.6 `MYLOCATION` Attribute

Refers to the location where the state variable `TEMPERATURE` is stored.

- Value: Stores the reference number of `MYLOCATION`.

Metadata	Data Type
Value	Integer

Table 6.40: Data Types of MYLOCATION Metadata

Table 6.41 shows the available locations and their reference numbers in VMAP

MYLOCATION	Reference Number
INVALID	0
GLOBAL	1
NODE	2
ELEMENT	3
INTEGRATION POINT	4
ELEMENT FACE	5

Table 6.41: MYLOCATION Enumeration

6.9.7 `MYMULTIPLICITY` Attribute

Refers to the number of columns in the `MYVALUES` data set. The majority of state variables have multiplicity 1.

- Value: Stores the multiplicity of the `MYVALUES` data set.

Metadata	Data Type
Value	Integer

Table 6.42: Data Types of MYMULTIPLICITY Metadata

A majority of the state variables have `MYMULTIPLICITY` 1. Sometimes it might be necessary to group identical data types into one value e.g. in LS-DYNA a point can have more than one value when it belongs to more than one element. A set of mathematically identical data types could then be grouped, using multiplicity.

6.9.8 `MYTIMEVALUE` Attribute

Refers to the time stamp at which the state variable is calculated.

- Value: Stores the time value of the state variable `TEMPERATURE`.

Metadata	Data Type
Value	Floating-Point

Table 6.43: Data Types of MYTIMEVALUE Metadata

For transient analysis and for other time based analyses, each state variable should be stored per `MYTIMEVALUE`.

6.9.9 `MYUNIT` Attribute

Refers to the unit used by the state variable. The details of this unit can be found in `SYSTEM ->UNITS`, see sub-section 6.10.5 for more details.

- Value: Stores the reference number of the unit.

Metadata	Data Type
Value	Integer

Table 6.44: Data Types of MYUNIT Metadata

6.9.10 `MYVARIABLEDESCRIPTION` Attribute

Stores detailed description of the variable.

- Value: Stores detailed description of the variable based on the source analysis tool.

Metadata	Data Type
Value	String

Table 6.45: Data Types of MYVARIABLEDESCRIPTION Metadata

6.9.11 MYVARIABLENAME Attribute

Stores name of the variable.

- Value: Stores name of the variable.

Metadata	Data Type
Value	String

Table 6.46: Data Types of MYVARIABLENAME Metadata

6.9.12 MYVALUES Data Set

The MYVALUES data set stores the state variable values. The number of columns can be determined based on MYDIMENSION and MYMULTIPLICITY. In the HDF5 Viewer, the column is named by default as 0 for myvalue (shown in Table 6.47).

Based on the MYLOCATION, the state variable could be defined per **Point**, **Element**, **Element Face**, **Integration Point** or it could be **Global**. The order of the state variables is based on the order of **Point**, **Element**, **Element Face**.

If the state variable is defined per **Integration Point**, then there is **an additional data set** MYINTEGRATIONTYPES, explained in the next sub-section, which stores the reference number to the SYSTEM ->INTEGRATIONTYPES. The values are in the order in which the integration points are defined in the referred integration type.

Metadata	Data Type
myvalue	Floating-Point Array

Table 6.47: Data Types of MYVALUES Metadata

The General Object Info associated with this data set is shown in Table 6.48.

Name:	MYVALUES
Path:	/VMAP/VARIABLES/STATE-<n>/<PART-ID>/TEMPERATURE/
Type:	HDF5 Dataset
Object Ref:	...

Dataset Dataspace and Datatype	
No. of Dimension(s):	2
Dimension Size(s):	m x 1
Max Dimension Size(s):	m x 1
Data Type:	64-bit floating-point

Table 6.48: General Object Info

m given in Table 6.48 is the length of the MYVALUES array. When,
MYLOCATION = 2 (=POINTS) then m = MYSIZE of POINTS
MYLOCATION = 3 (=Element) then m = MYSIZE of ELEMENTS
MYLOCATION = 4 (=Integration Point) then
m = $\sum$ (ALL ELEMENT INTEGRATION TYPES) (per in-plane, per out-of-plane Integration Point)
MYLOCATION = 5 (=Element Face) then m = SUM of all ELEMENT FACES

6.9.13 MYGEOMETRYIDS Data Set - Optional

This data set is optional and should be used only when a set of the points, elements, intgeration types or elements faces are used. The set is then defined in this data set. MYLOCATION attribute at the state variable level is used to identify the set type (points, elements, intgeration types or elements faces). In the HDF5 Viewer, the column is named by default as 0 for myvalue (shown in Table 6.49).

Metadata	Data Type
myvalue	Integer

Table 6.49: Data Types of MYGEOMETRYIDS Metadata

The General Object Info associated with this data set is shown in Table 6.50.

Name:	MYGEOMETRYIDS
Path:	/VMAP/VARIABLES/STATE-<n>/<PART-ID>/TEMPERATURE/
Type:	HDF5 Dataset
Object Ref:	...

Dataset Dataspace and Datatype	
No. of Dimension(s):	2
Dimension Size(s):	m x 1
Max Dimension Size(s):	m x 1
Data Type:	32-bit Integer

Table 6.50: General Object Info

m = number of values defined in the set.

6.9.14 MYINTEGRATIONTYPES Data Set

This data set exists only when the MYLOCATION attribute defined at the state variable level (e.g. TEMPERATURE) = 4 (=Integration Point). The data set stores the reference number

of the integration type over which the state variable is defined. In the HDF5 Viewer, the column is named by default as `0` for myvalue (shown in Table 6.51).

Metadata	Data Type
myvalue	Floating-Point Array

Table 6.51: Data Types of MYINTEGRATIONTYPES Metadata

The `General Object Info` associated with this data set is shown in Table 6.52.

Name:	`MYINTEGRATIONTYPES`
Path:	`/VMAP/VARIABLES/STATE-<n>/<PART-ID>/TEMPERATURE/`
Type:	HDF5 Dataset
Object Ref:	...

Dataset Dataspace and Datatype	
No. of Dimension(s):	2
Dimension Size(s):	m x 1
Max Dimension Size(s):	m x 1
Data Type:	32-bit Integer

Table 6.52: General Object Info

m = `MYSIZE` of `ELEMENTS` or based on the number of values in `MYGEOMETRYIDS`, if defined.

6.10 SYSTEM Group

`SYSTEM` Group stores the system data related to the FE model. This includes six data sets - `COORDINATESYSTEM`, `ELEMENTTYPES` & `INTEGRATIONTYPES`, `METADATA`, `UNITS` & `UNITSYSTEM`. Table 6.53 shows `General Object Info`, for group `SYSTEM`. Figure 6.7 shows data sets associated with the `SYSTEM` group.

Name:	`SYSTEM`
Path:	`/VMAP/`
Type:	HDF5 Group
Object Ref:	...

Number of members:	6
Name	Type
`COORDINATESYSTEM`	Dataset
`ELEMENTTYPES`	Dataset
`INTEGRATIONTYPES`	Dataset
`METADATA`	Dataset
`UNITS`	Dataset
`UNITSYSTEM`	Dataset

Table 6.53: General Object Info

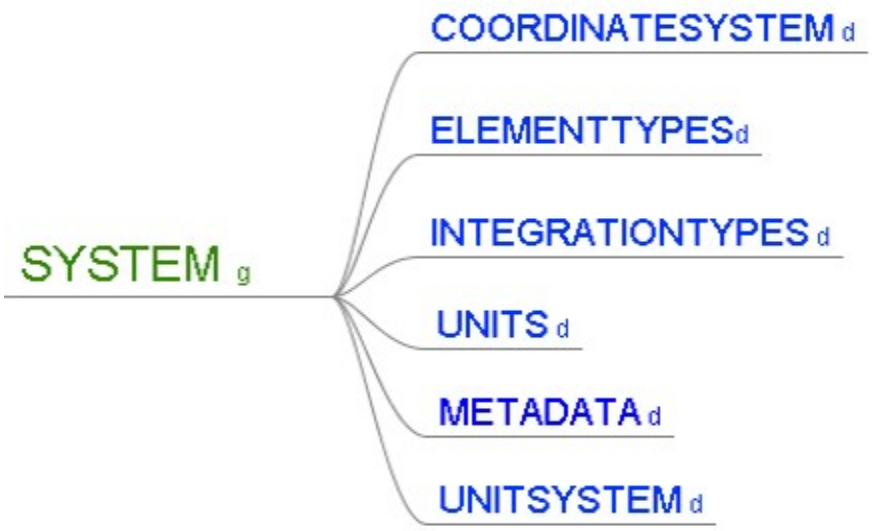


Figure 6.7: SYSTEM Group

6.10.1 `COORDINATESYSTEM` Data Set

The `COORDINATESYSTEM` data set stores the global coordinate system used by the FE Model. All the local coordinate systems are stored as state variables in the `VARIABLES` group. The metadata is stored in the following order:

- `myIdentifier`: Integral identifier for each coordinate system. Best practice involves storing the Global coordinate system with identifier 1.
- `myType`: Stores Coordinate System reference number. For more details about reference number, see Table 6.55.
- `myReferencePoint`: Stores the 3D reference point for system definition, $[0, 0, 0]$ is default.
- `myAxisVector`: Defines up to three vectors describing the coordinate system $[u1, u2, u3, v1, v2, v3, w1, w2, w3]$.

This is a compound data set.

Metadata	Data Type
myIdentifier	Integer
myType	Integer
myReferencePoint	Double Array
myAxisVector	Double Array

Table 6.54: Data Types of COORDINATESYSTEM Metadata

Table 6.55 shows the available coordinate systems and their reference numbers in VMAP.

COORDINATESYSTEM	Reference Number
INVALID	-1
CARTESIAN LEFT HAND	1
CARTESIAN RIGHT HAND	2
NON-ORTHOGONAL	3

Table 6.55: COORDINATESYSTEM Enumeration

The General Object Info associated with this data set is shown in Table 6.56.

Name:	`COORDINATESYSTEM`
Path:	`/VMAP/SYSTEM/`
Type:	HDF5 Dataset
Object Ref:	...

Dataset Dataspace and Datatype	
No. of Dimension(s):	2
Dimension Size(s):	n x 1
Max Dimension Size(s):	n x 1
Data Type:	Compound

Table 6.56: General Object Info

n refers to number of coordinate systems defined for the FE model.

6.10.2 `ELEMENTTYPES` Data Set

The `ELEMENTTYPES` data set stores the various types of elements used by the FE Model. The metadata is stored in the following order:

- `myIdentifier`: Integral identifier for each element type used in the FE Model.
- `myTypeName`: Stores the type of the element. VMAP offers a factory of various element types, which can be directly incorporated in the code. Please refer to chapter 8 for more details.
- `myNumberOfNodes`: Stores the number of nodes of the element type.
- `myDimension`: Stores the dimension of the element.
- `myShapeType` : Stores the reference number of the element from the Element Factory library offered in the VMAP Package.
- `myInterpolationType`: Stores the reference number of the interpolation type used by the element type. Please refer to Table 6.59 for more details on Interpolation types.

- `myIntegrationType`: Stores the reference number of the integration type used by the element type. Please refer to sub-section 6.10.3 for more details on Integration types.
- `myNumberofNormalComponents`: Stores the number of normal components of stress or strain tensor for the element type.
- `myNumberofShearComponents`: Stores the number of shear components of stress or strain tensor for the element type.
- `myConnectivity`: Stores the connectivity of the element.
- `myFaceConnectivity`: Stores the face connectivity of the element.

This is a compound data set.

Metadata	**Data Type**
`myIdentifier`	Integer
`myTypeName`	Character Pointer
`myNumberofNodes`	Integer
`myDimension`	Integer
`myShapeType`	Integer
`myInterpolationType`	Integer
`myIntegrationType`	Integer
`myNumberofNormalComponents`	Integer
`myNumberofShearComponents`	Integer
`myConnectivity`	Integer Array
`myFaceConnectivity`	Integer Array

Table 6.57: Data Types of ELEMENTTYPES Metadata

The General Object Info associated with this data set is shown in Table 6.58.

Name:	`ELEMENTTYPES`
Path:	`/VMAP/SYSTEM/`
Type:	HDF5 Dataset
Object Ref:	...

Dataset Dataspace and Datatype	
No. of Dimension(s):	2
Dimension Size(s):	n x 1
Max Dimension Size(s):	n x 1
Data Type:	Compound

Table 6.58: General Object Info

n refers to number of element types defined for the FE model.

Table 6.59 shows the available interpolation types and their reference numbers in VMAP.

myInterpolationType	Reference Number
CONSTANT	1
LINEAR	2
BILINEAR	3
TRILINEAR	4
QUADRATIC	5
BIQUADRATIC	6
TRIQUADRATIC	7
CUBIC	8
BICUBIC	9
TRICUBIC	10
SPLINE	11

Table 6.59: myInterpolationType Enumeration

6.10.3 `INTEGRATIONTYPES` Data Set

The `INTEGRATIONTYPES` data set stores the various types of integration rules used by the FE Model. The metadata is stored in the following order:

- `myIdentifier`: Integral identifier for each integration type used in the FE Model. This value should be taken directly from the Integration Type library `VMAPIntegrationTypeFactory.cxx`. For user defined integration types, the integral identifier starts from 100000.
- `myTypeName`: Stores the type of the integration rule. VMAP offers a factory of various integration types, which can be directly incorporated in the code. Please refer to chapter 9 for more details.
- `myNumberOfPoints`: Stores the number of points of the integration type.
- `myDimension`: Stores the dimension of abscissa.
- `myOffset`: Stores the shell offset parameter.
- `myAbscissas`: Stores the abscissa of the integration point in local coordinates.
- `myWeights`: Stores the weight of the integration point.
- `mySubTypes`: When a compound integration type is used e.g. Gauss_3 for out-of-plane and Gauss_Triangle_1 for in-plane , then it stores the 2 types together as one single type, $Gauss\_Triangle\_1 \times Gauss\_3$. According to VMAP Standard, the order of compound integration type is,

$$\mathbf{IN-PLANE} \times \mathbf{OUT-OF-PLANE}$$

This is a compound data set.

Metadata	Data Type
myIdentifier	Integer
myTypeName	Character Pointer
myNumberOfPoints	Integer
myDimension	Integer
myOffset	Double
myAbscissas	Double Array
myWeights	Double Array
mySubTypes	Integer Array

Table 6.60: Data Types of INTEGRATIONTYPES Metadata

The General Object Info associated with this data set is shown in Table 6.61.

Name:	INTEGRATIONTYPES
Path:	/VMAP/SYSTEM/
Type:	HDF5 Dataset
Object Ref:	...

Dataset Dataspace and Datatype	
No. of Dimension(s):	2
Dimension Size(s):	n x 1
Max Dimension Size(s):	n x 1
Data Type:	Compound

Table 6.61: General Object Info

n refers to number of integration types defined for the FE model.

6.10.4 METADATA Data Set

The METADATA data set stores all the meta information associated with the FE model. The metadata is stored in the following order:

- myExporterName: Stores the name of the tool generating the VMAP file.
- myFileDate: Stores the date of file generation.
- myFileTime: Stores the time of file generation.
- myDescription: Stores the detailed description of file content.
- myAnalysisType: Stores the analysis type of the exporter.
- myUserId: Stores the name of the user, who generated the VMAP file.

Metadata	Data Type
myExporterName	Character Pointer
myFileDate	Character Pointer
myFileTime	Character Pointer
myDescription	Character Pointer
myAnalysisType	Character Pointer
myUserId	Character Pointer

Table 6.62: Data Types of METADATA Metadata

The General Object Info associated with this data set is shown in Table 6.63.

Name:	METADATA
Path:	/VMAP/SYSTEM/
Type:	HDF5 Dataset
Object Ref:	...

Dataset Dataspace and Datatype	
No. of Dimension(s):	2
Dimension Size(s):	6 x 1
Max Dimension Size(s):	6 x 1
Data Type:	Compound

Table 6.63: General Object Info

6.10.5 UNITS Data Set

The UNITS data set stores the various types of units used by the FE Model. The metadata is stored in the following order:

- myIdentifier: Integral identifier for each unit used in the FE Model.
- myUnitSymbol: Stores the unit symbol.
- myUnitDimension: Stores a combination of 0s and 1s to form a unit based on the SI unit system defined in section 6.10.6. It is an array with length 7.

This is a compound data set.

Metadata	Data Type
myIdentifier	Integer
myUnitSymbol	Character Pointer
myUnitDimension	Integer Array

Table 6.64: Data Types of UNITS Metadata

The General Object Info associated with this data set is shown in Table 6.65.

Name:	UNITS
Path:	/VMAP/SYSTEM/
Type:	HDF5 Dataset
Object Ref:	...

Dataset Dataspace and Datatype	
No. of Dimension(s):	2
Dimension Size(s):	n x 1
Max Dimension Size(s):	n x 1
Data Type:	Compound

Table 6.65: General Object Info

n refers to number of units defined for the FE model.

6.10.6 UNITSYSTEM Data Set

The UNITSYSTEM data set stores the SI unit system. This metadata is stored in the following order:

- myLengthUnit: This defines the standard length unit.
  - myIdentifier: A unique identifier for length unit is 1
  - mySIScale: A scale factor associated with the length unit. Useful to convert the SI system to another user-defined unit system.
  - mySIShift: A shift factor associated with the length unit. Useful to convert the SI system to another user-defined unit system.
  - myUnitSymbol: Unique SI symbol for the length unit 'mm' - millimeter.
  - myUnitQuantity: The name of the unit quantity "LENGTH".
- myMassUnit: This defines the standard mass unit.
  - myIdentifier: A unique identifier for mass unit is 2
  - mySIScale: A scale factor associated with the mass unit. Useful to convert the SI system to another user-defined unit system.
  - mySIShift: A shift factor associated with the mass unit. Useful to convert the SI system to another user-defined unit system.
  - myUnitSymbol: Unique SI symbol for the mass unit 't' - tonne.
  - myUnitQuantity: The name of the unit quantity "MASS".
- myTimeUnit: This defines the standard time unit.

  - myIdentifier: A unique identifier for time unit is 3.
  - mySIScale: A scale factor associated with the time unit. Useful to convert the SI system to another user-defined unit system.
  - mySIShift: A shift factor associated with the time unit. Useful to convert the SI system to another user-defined unit system.
  - myUnitSymbol: Unique SI symbol for the time unit 's' - second.
  - myUnitQuantity: The name is the unit quantity "TIME".
- myCurrentUnit: This defines the standard current unit.
  - myIdentifier: A unique identifier for current unit is 4.
  - mySIScale: A scale factor associated with the current unit. Useful to convert the SI system to another user-defined unit system.
  - mySIShift: A shift factor associated with the current unit. Useful to convert the SI system to another user-defined unit system.
  - myUnitSymbol: Unique SI symbol for the current unit 'A' - Ampere.
  - myUnitQuantity: The name is the unit quantity "ELECTRIC CURRENT".
- myTemperatureUnit: This defines the standard temperature unit.
  - myIdentifier: A unique identifier for temperature unit is 5.
  - mySIScale: A scale factor associated with the temperature unit. Useful to convert the SI system to another user-defined unit system.
  - mySIShift: A shift factor associated with the temperature unit. Useful to convert the SI system to another user-defined unit system.
  - myUnitSymbol: Unique SI symbol for the temperature unit 'K' - Kelvin.
  - myUnitQuantity: The name is the unit quantity "TEMPERATURE".
- myAmountOfSubstanceUnit: This defines the standard amount of substance unit.
  - myIdentifier: A unique identifier for amount of substance unit is 6.
  - mySIScale: A scale factor associated with the amount of substance unit. Useful to convert the SI system to another user-defined unit system.
  - mySIShift: A shift factor associated with the amount of substance unit. Useful to convert the SI system to another user-defined unit system.
  - myUnitSymbol: Unique SI symbol for the amount of substance unit 'mol' - mole.
  - myUnitQuantity: The name is the unit quantity "AMOUNT OF SUBSTANCE".
- myLuminousIntensityUnit: This defines the standard luminous intensity unit.

- `myIdentifier`: A unique identifier for luminous intensity unit is 7.
- `mySIScale`: A scale factor associated with the luminous intensity unit. Useful to convert the SI system to another user-defined unit system.
- `mySIShift`: A shift factor associated with the luminous intensity unit. Useful to convert the SI system to another user-defined unit system.
- `myUnitSymbol`: Unique SI symbol for the luminous intensity unit 'cd' - candela.
- `myUnitQuantity`: The name is the unit quantity "`LUMINOUS INTENSITY`".

This is a compound data set.

Note: The following format is used, when converting the unit system. Conversion factor to SI unit, $SI = \texttt{mySIScale} * value + \texttt{mySIShift}$,
`mySIScale` has a default value of 1 & `mySIShift` has a default value of 0.

Metadata	**Data Type**
`myIdentifier`	Integer
`mySIScale`	Double
`mySIShift`	Double
`myUnitSymbol`	Character Pointer
`myUnitQuantity`	Character Pointer

Table 6.66: Data Types of UNITSYSTEM metadata

The General Object Info associated with this data set is shown in Table 6.67.

Name:	`UNITSYSTEM`
Path:	`/VMAP/SYSTEM/`
Type:	HDF5 Dataset
Object Ref:	...

Dataset Dataspace and Datatype	
No. of Dimension(s):	2
Dimension Size(s):	7 x 1
Max Dimension Size(s):	7 x 1
Data Type:	Compound

Table 6.67: General Object Info

Chapter 7

Storage Format

This chapters shows the VMAP format from HDFView 3.1.0. The HDFView shows the file path at the top. Additionally, there are always two windows for each Group and Dataset 'Object Attribute Info' & 'General Object Info'.

7.1 .h5 File View

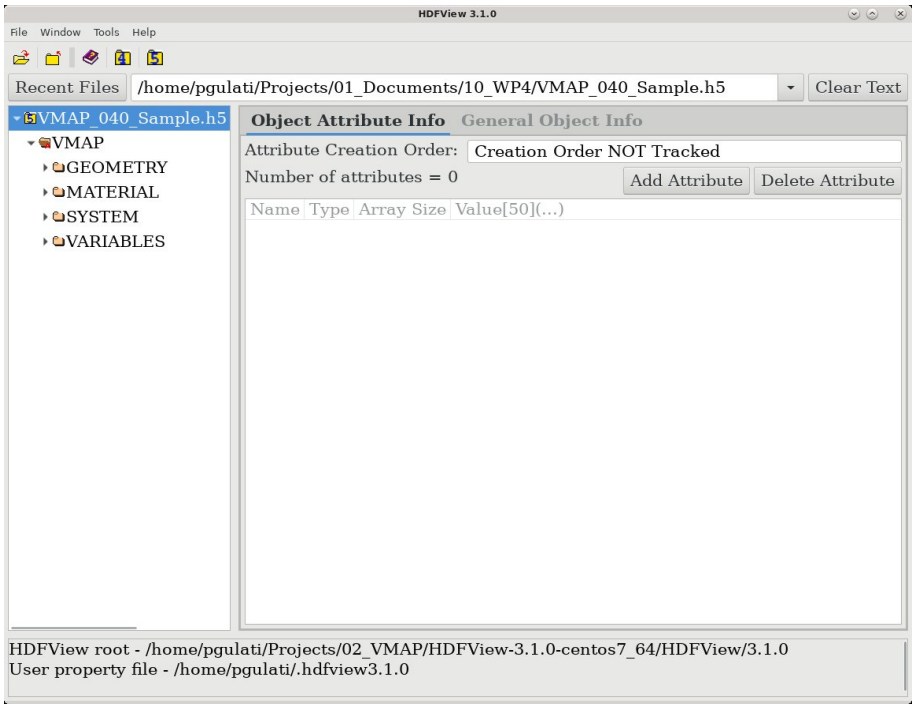


Figure 7.1: .h5 File View - Object Attribute Info

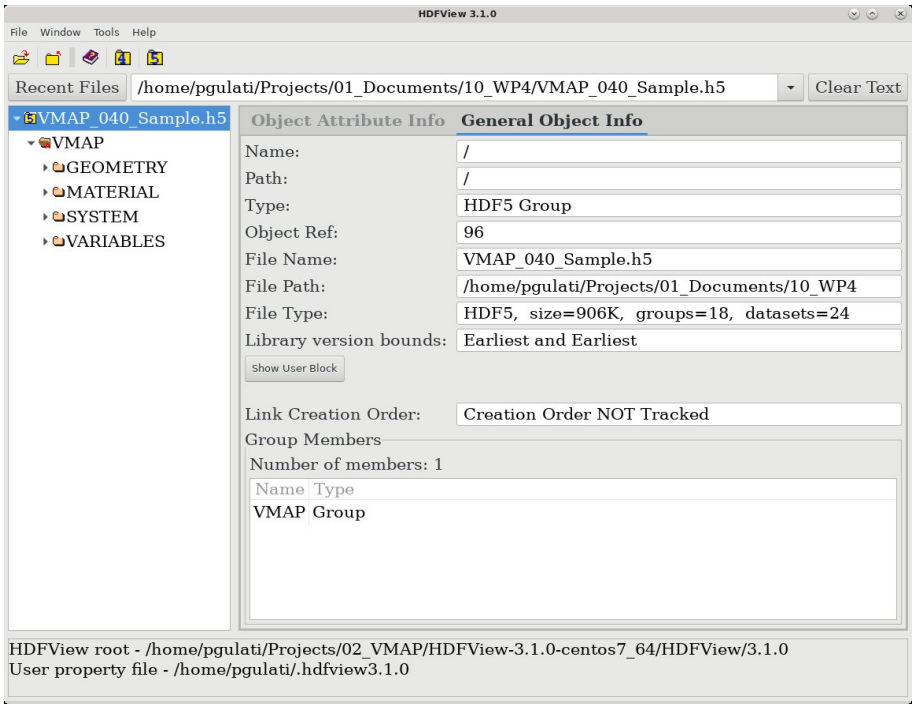


Figure 7.2: .h5 File View - General Object Info

7.2 VMAP Group View

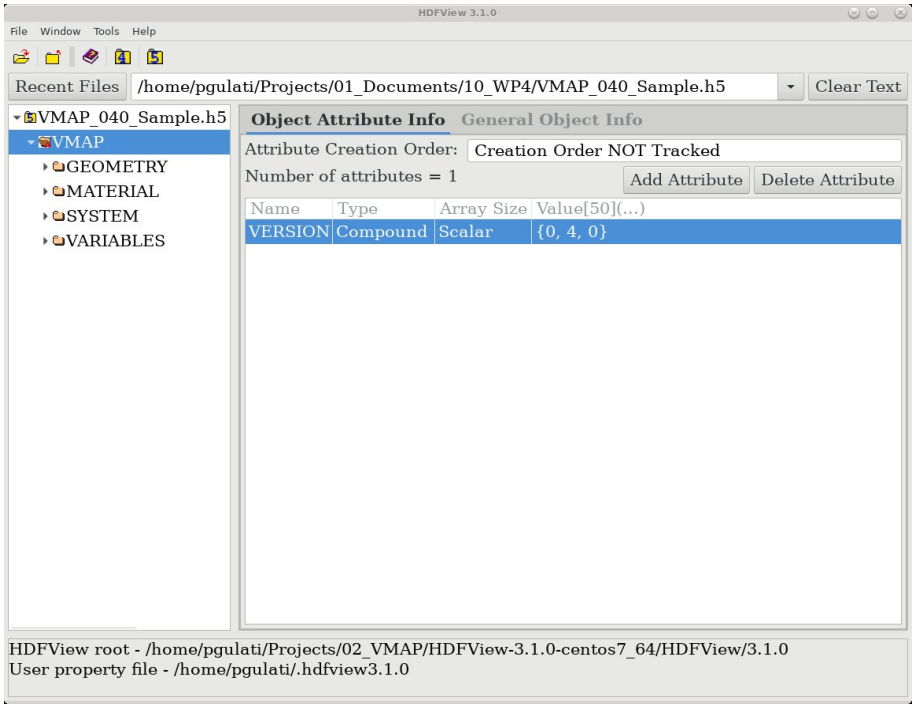


Figure 7.3: VMAP Group View - Object Attribute Info

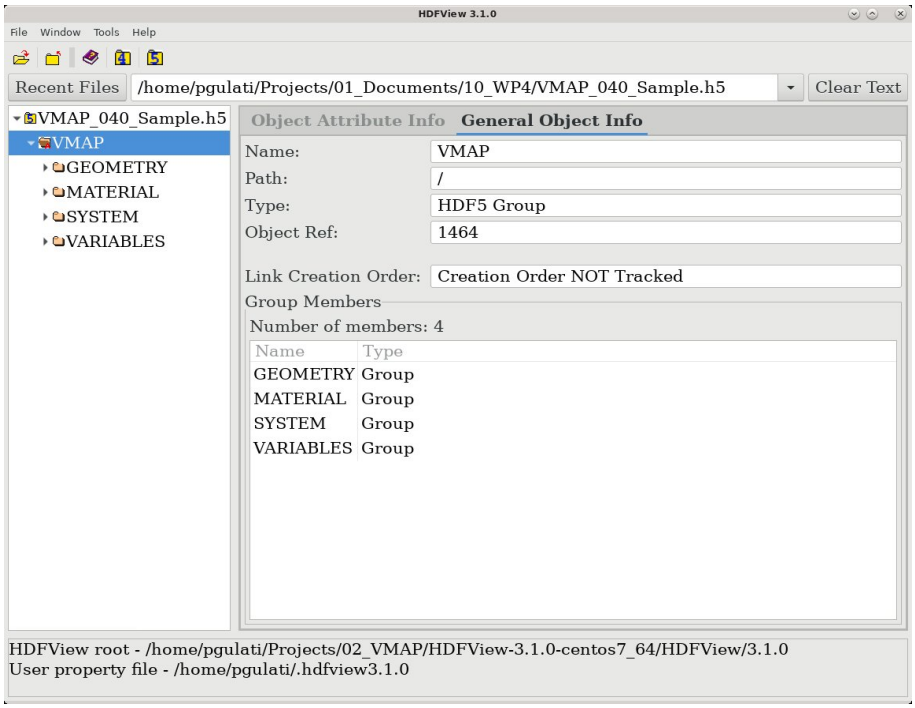


Figure 7.4: VMAP Group View - General Object Info

7.2.1 VERSION Attribute View

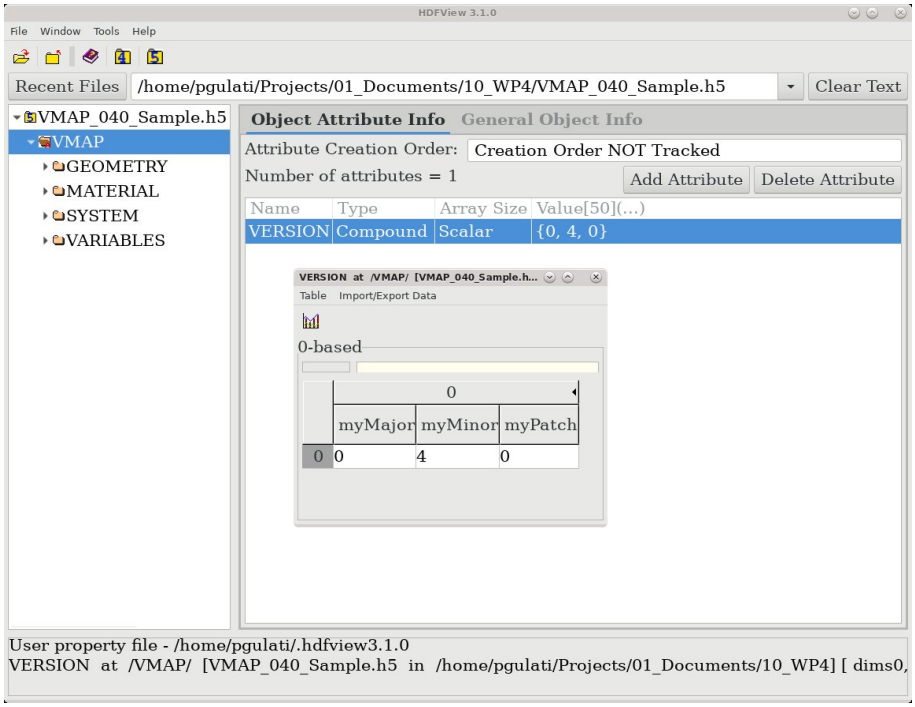


Figure 7.5: VERSION Attribute View - Metadata

7.3 GEOMETRY Group View

GEOMETRY Group has no attributes.

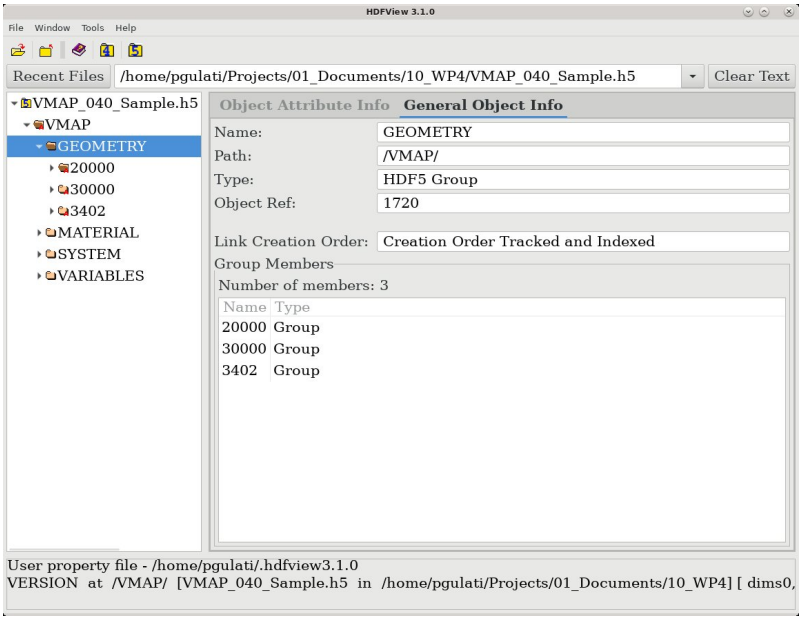


Figure 7.6: GEOMETRY Group View - General Object Info

7.4 <PART-ID> Group View

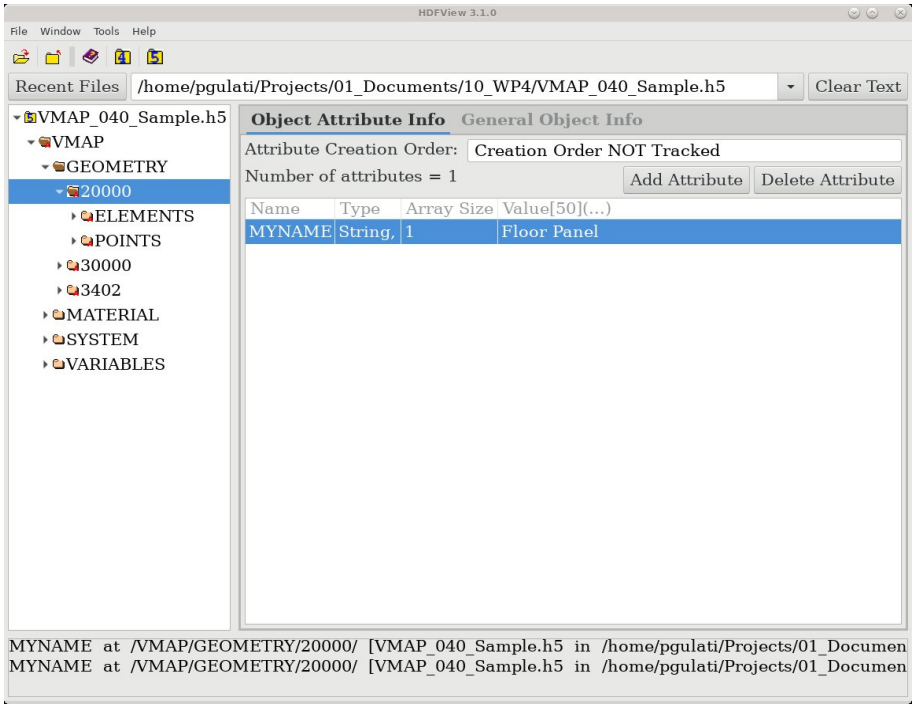


Figure 7.7: <PART-ID> Group View - Object Attribute Info

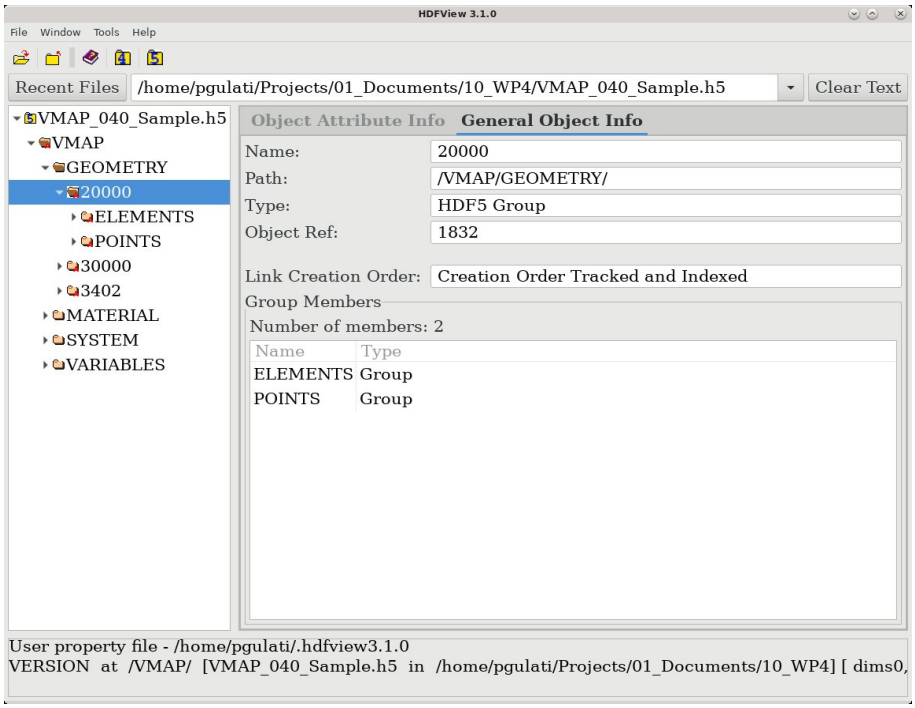


Figure 7.8: <PART-ID> Group View - General Object Info

The attribute MYNAME and its Value is shown in Figure 7.7

7.5 POINTS Group View

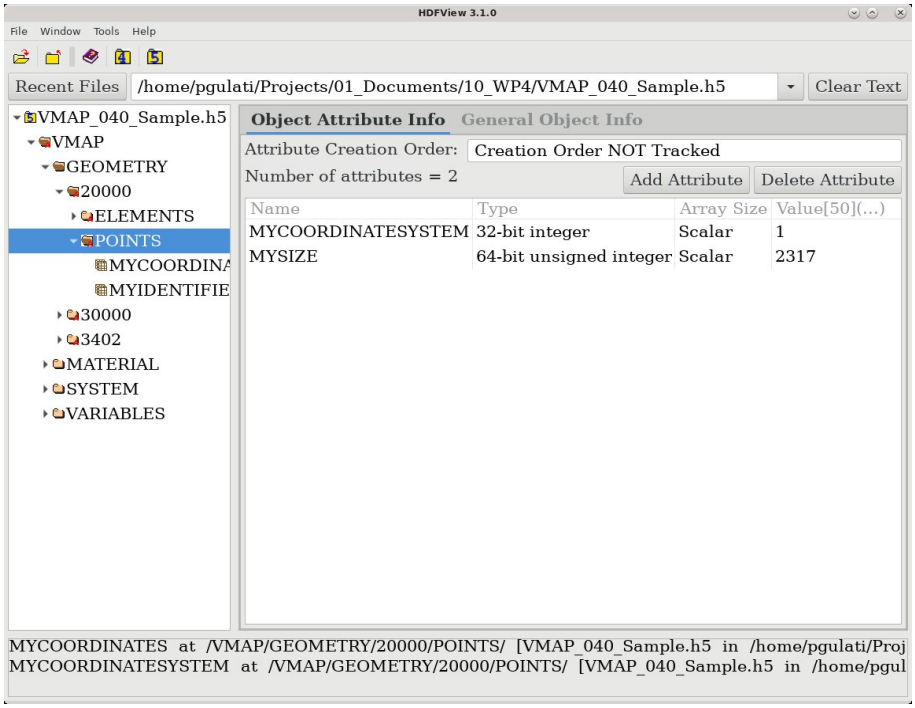


Figure 7.9: POINTS Group View - Object Attribute Info

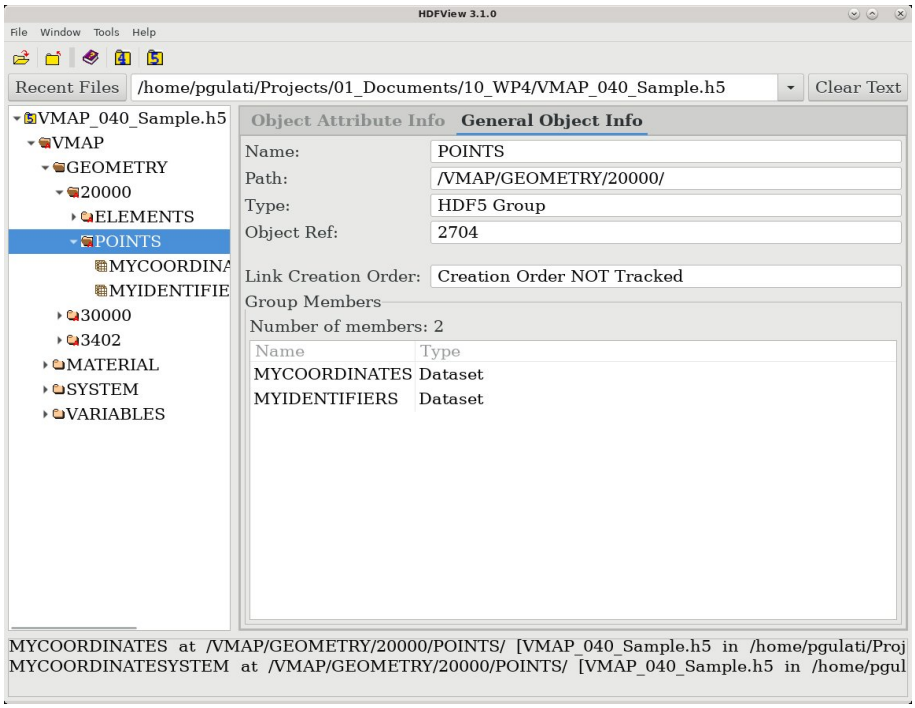


Figure 7.10: POINTS Group View - General Object Info

The attributes MYCOORDINATESYSTEM & MYSIZE are shown in Figure 7.9.

7.5.1 MYCOORDINATES Dataset

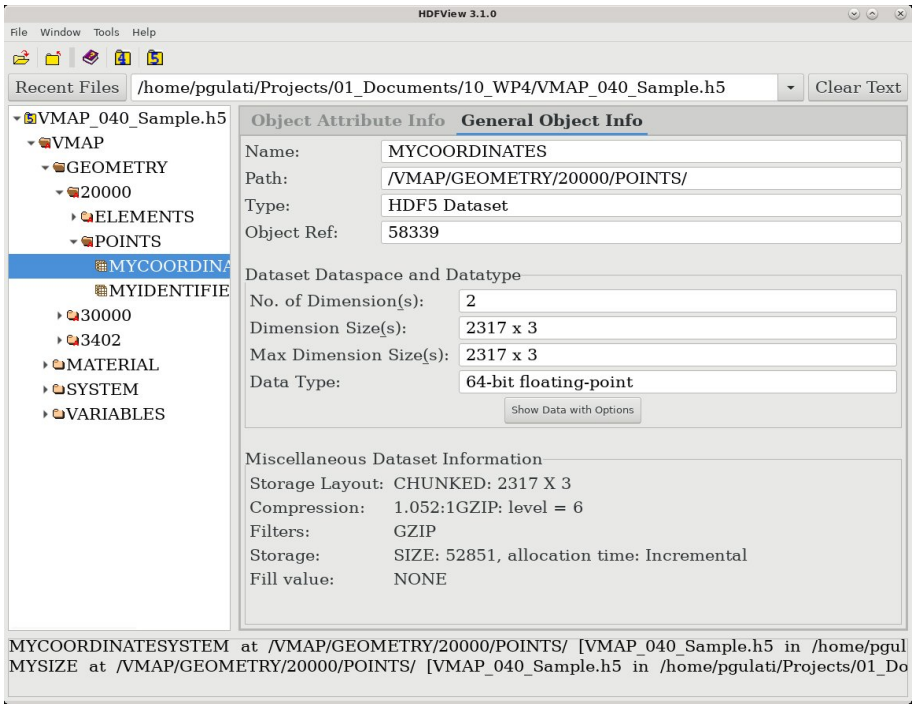


Figure 7.11: MYCOORDINATES Dataset View - General Object Info

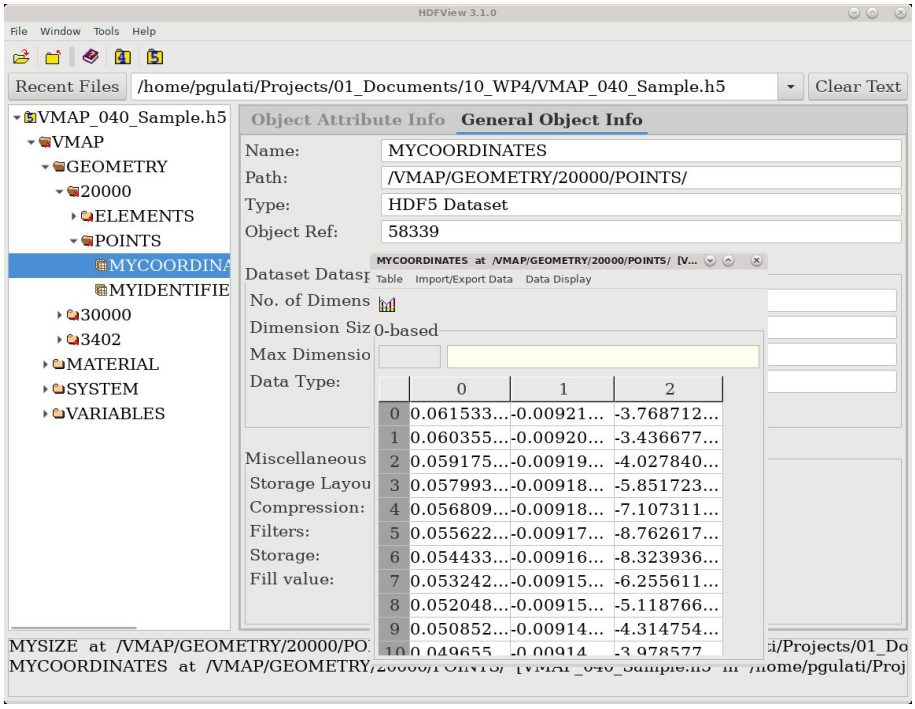


Figure 7.12: MYCOORDINATES Dataset View - Metadata

7.5.2 MYIDENTIFIERS Dataset

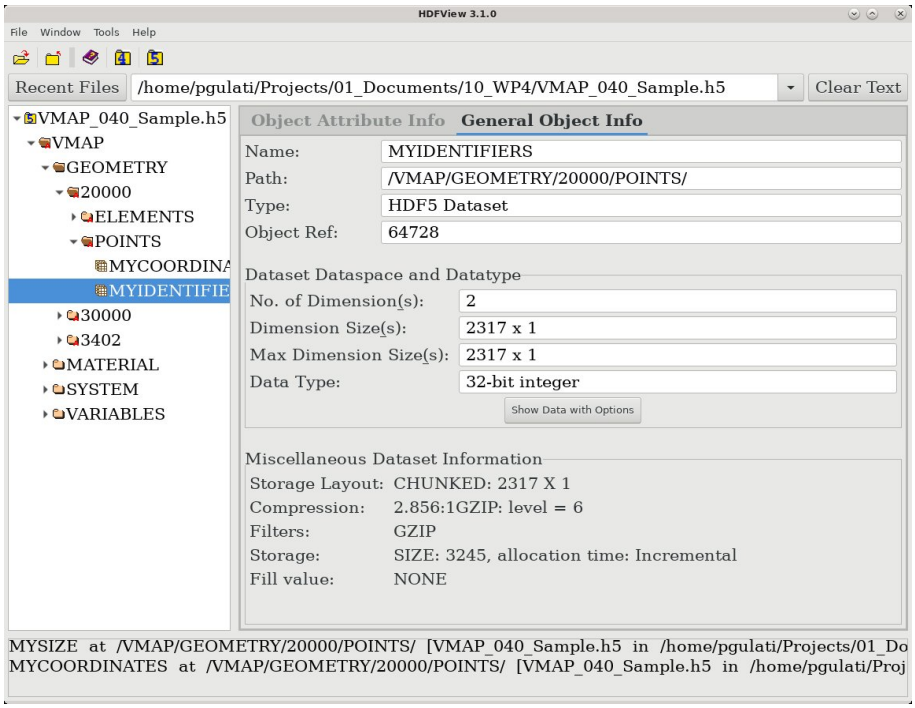


Figure 7.13: MYIDENTIFIERS Dataset View - General Object Info

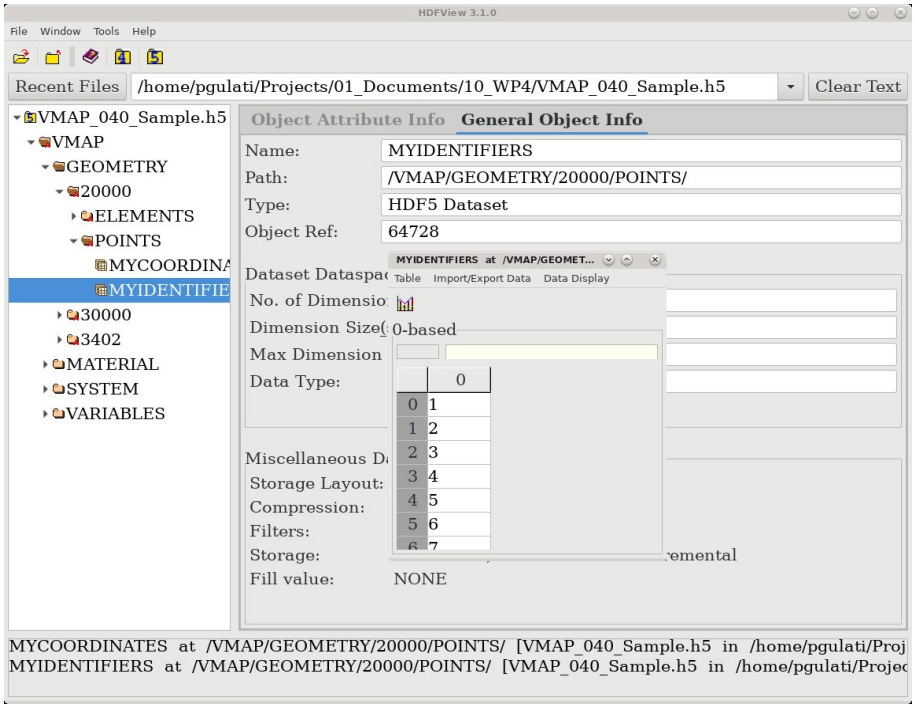


Figure 7.14: MYIDENTIFIERS Dataset View - Metadata

7.6 ELEMENTS Group View

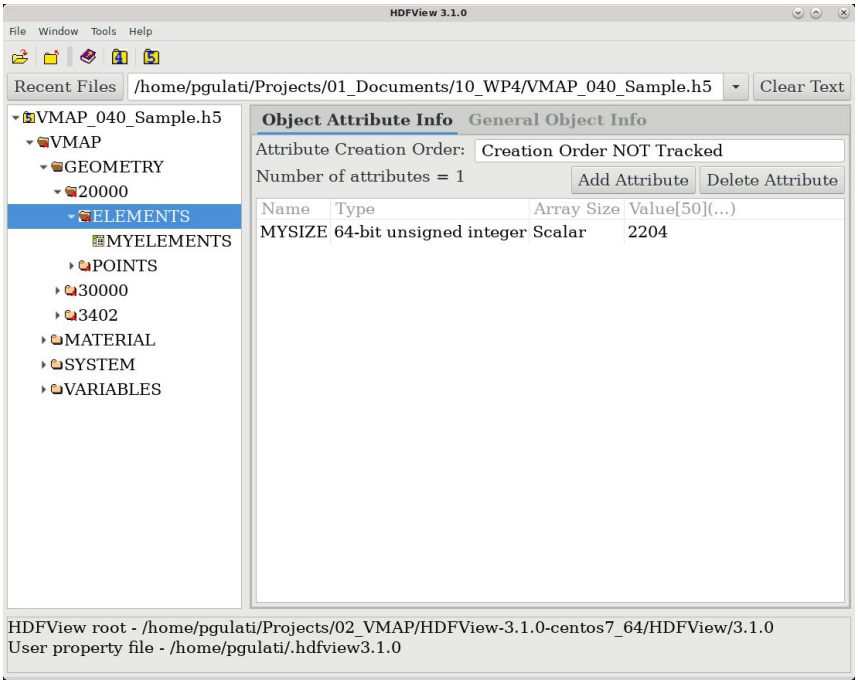


Figure 7.15: ELEMENTS Group View - Object Attribute Info

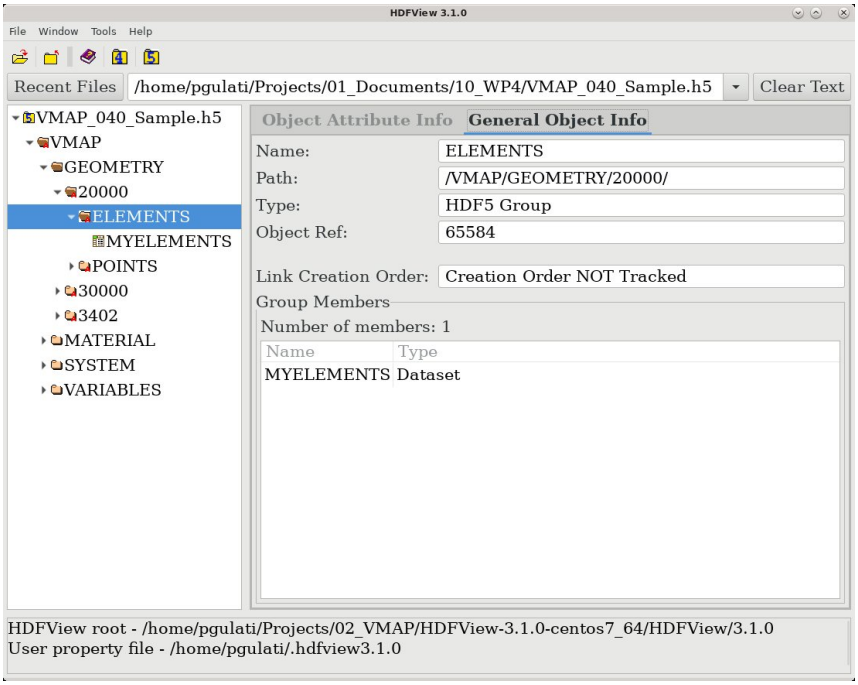


Figure 7.16: ELEMENTS Group View - General Object Info

The attribute MYSIZE is shown in Figure 7.15.

7.6.1 MYELEMENTS Dataset

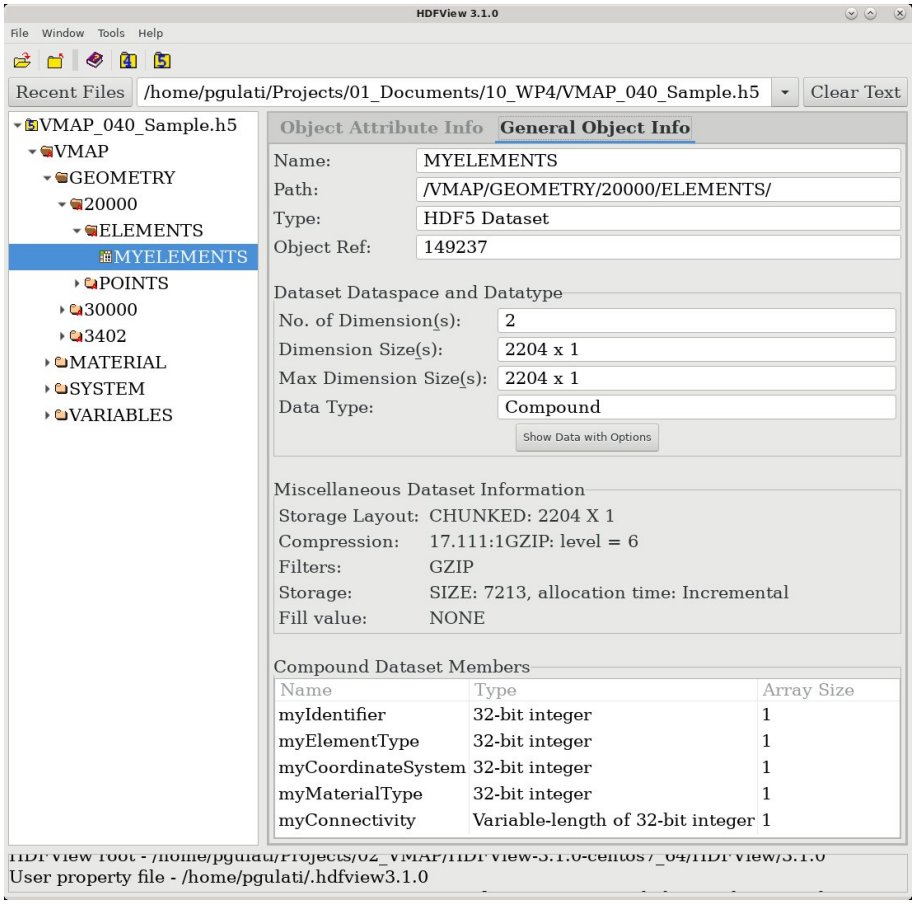
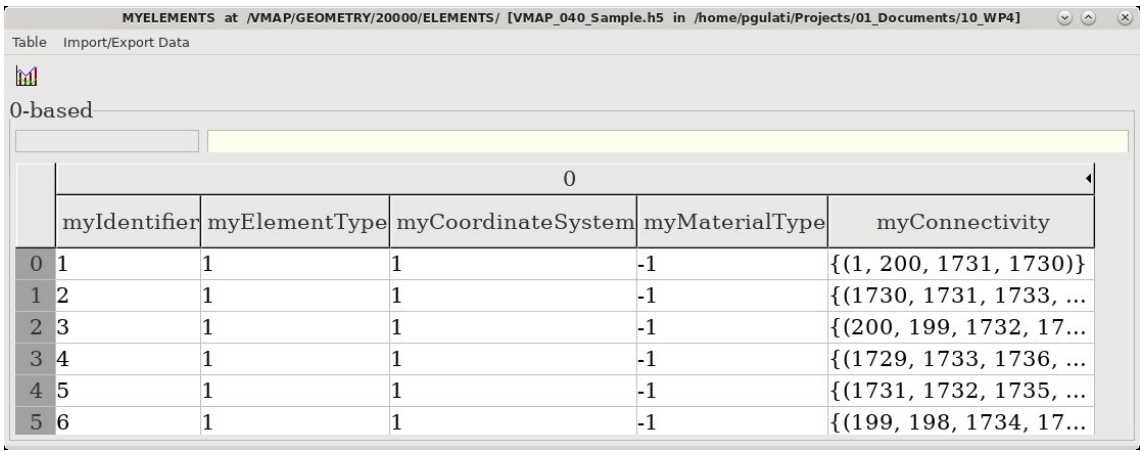


Figure 7.17: MYELEMENTS Dataset View - General Object Info



	0				
	myIdentifier	myElementType	myCoordinateSystem	myMaterialType	myConnectivity
0	1	1	1	-1	{(1, 200, 1731, 1730)}
1	2	1	1	-1	{(1730, 1731, 1733, ...
2	3	1	1	-1	{(200, 199, 1732, 17...
3	4	1	1	-1	{(1729, 1733, 1736, ...
4	5	1	1	-1	{(1731, 1732, 1735, ...
5	6	1	1	-1	{(199, 198, 1734, 17...

Figure 7.18: MYELEMENTS Dataset View - Metadata

7.7 VARIABLES Group View

RESULT Group has no attributes.

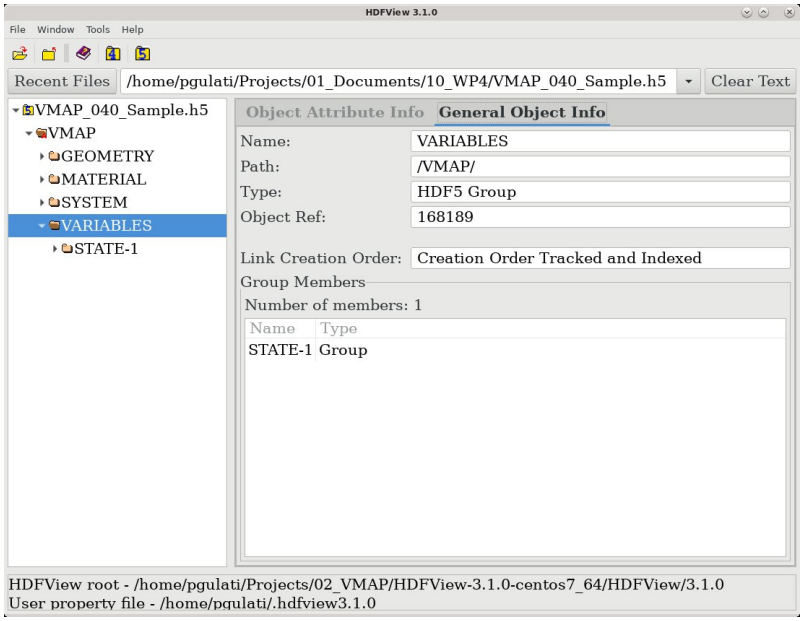


Figure 7.19: RESULT Group View - General Object Info

7.8 STATE-<n> Group View

STATE-<n> Group has no attributes.

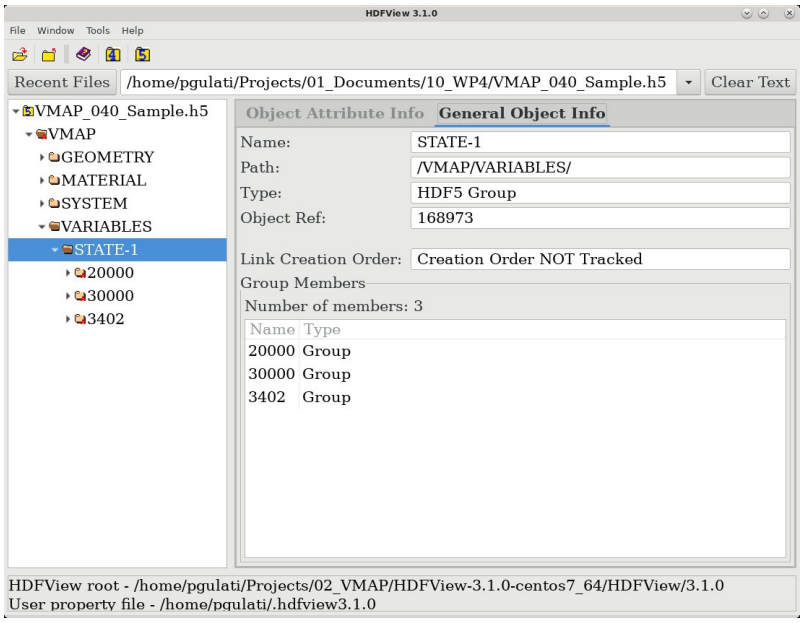


Figure 7.20: STATE-<n> Group View - General Object Info

7.9 <PART-ID> Group View

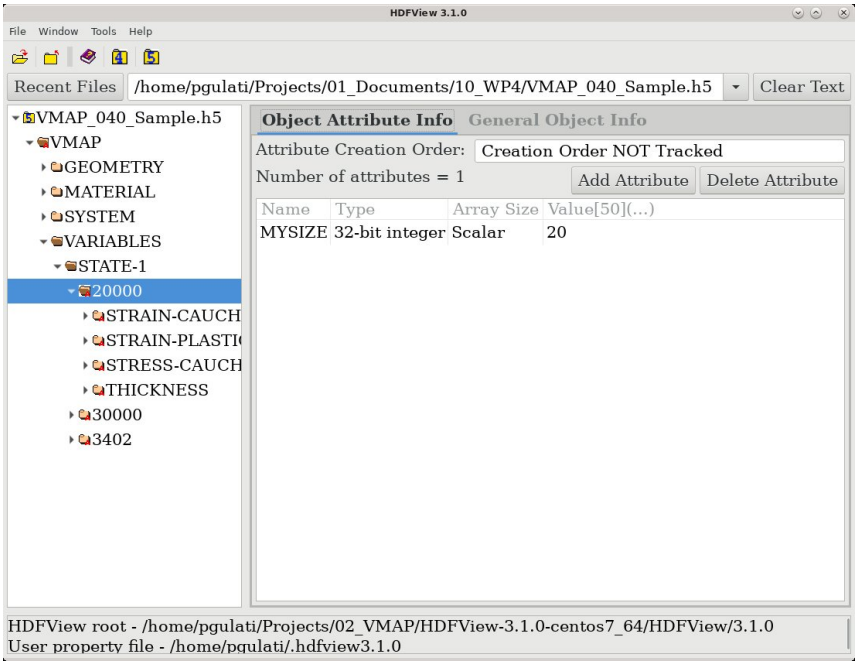


Figure 7.21: <PART-ID> Group View - Object Attribute Info

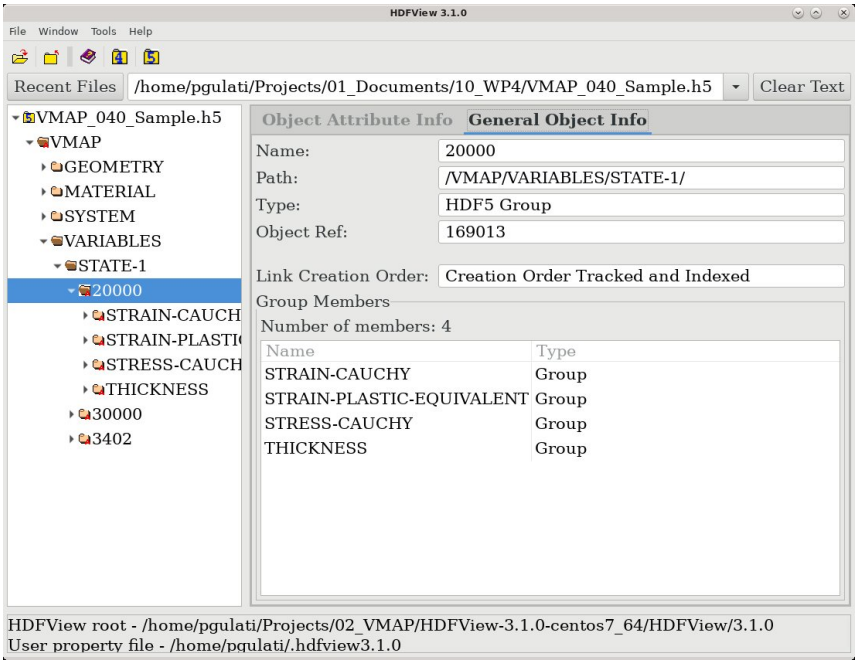


Figure 7.22: <PART-ID> Group View - General Object Info

The attribute MYSIZE is seen in Figure 7.21

7.10 STRAIN-CAUCHY Group View

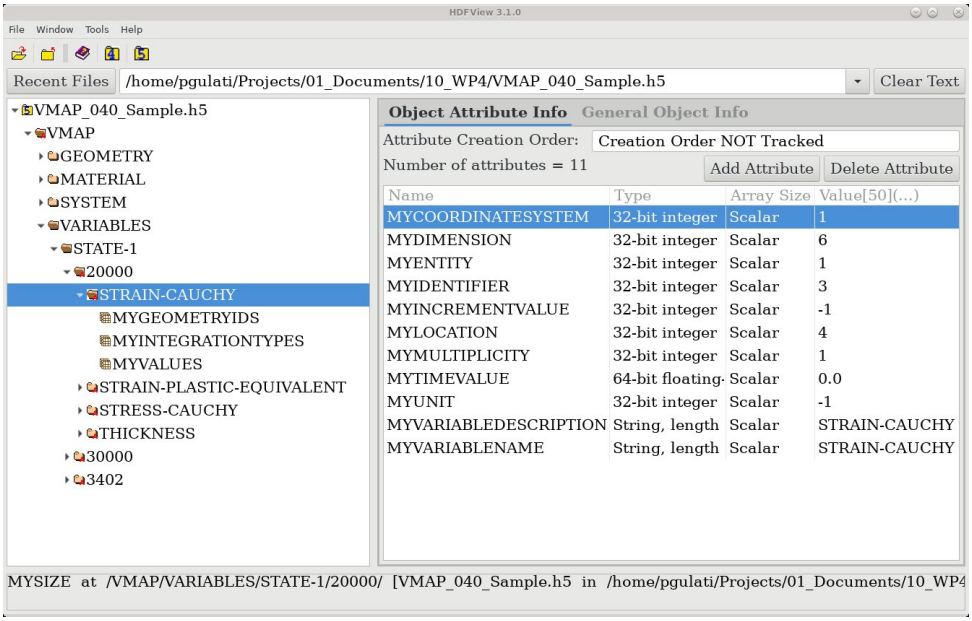


Figure 7.23: STRAIN-CAUCHY Group View - Object Attribute Info

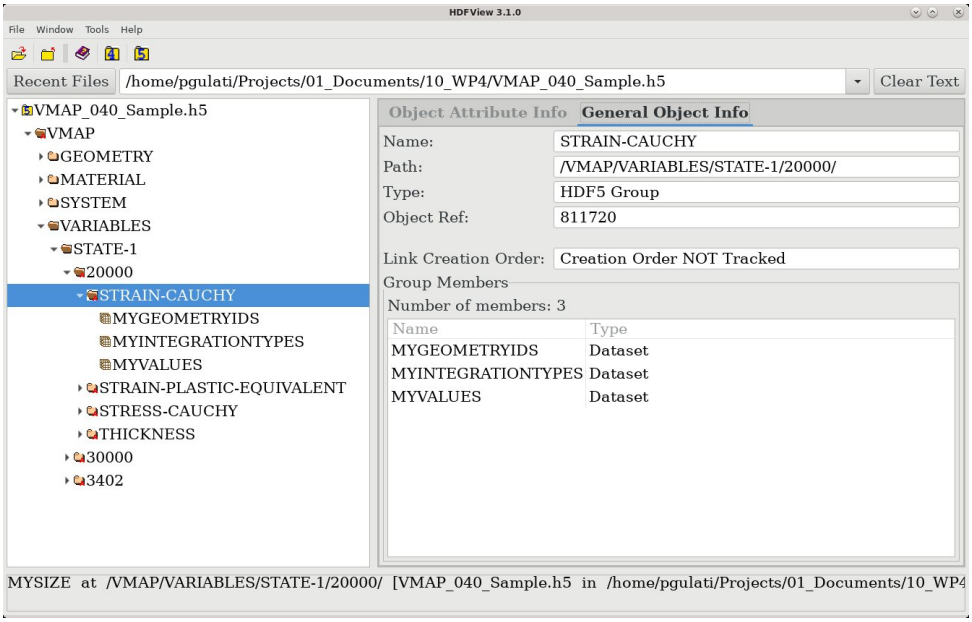


Figure 7.24: STRAIN-CAUCHY Group View - General Object Info

All attribute results can be seen in column Value of figure 7.23.

7.10.1 MYGEOMETRYIDS Dataset

This is an optional dataset.

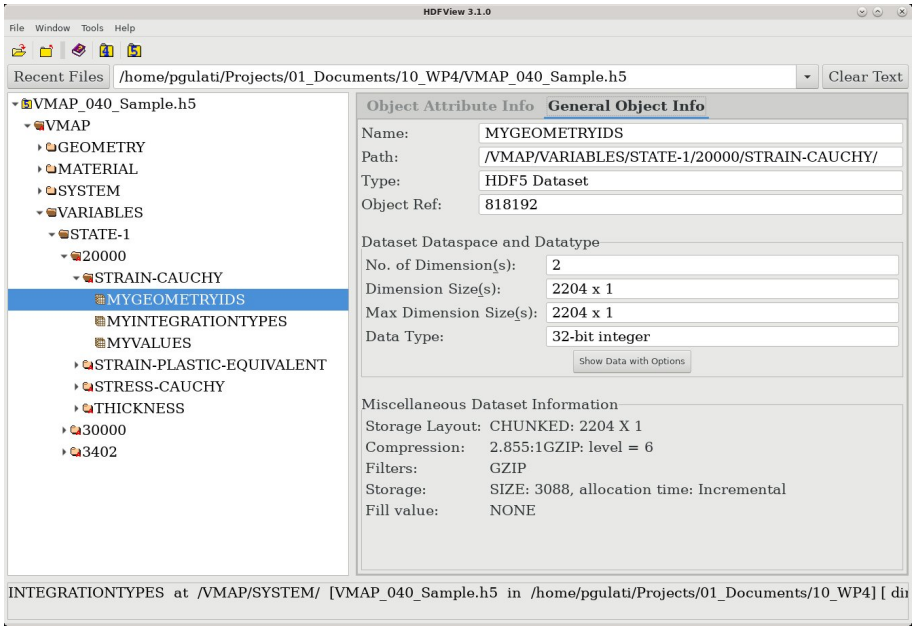


Figure 7.25: MYGEOMETRYIDS Dataset View - General Object Info

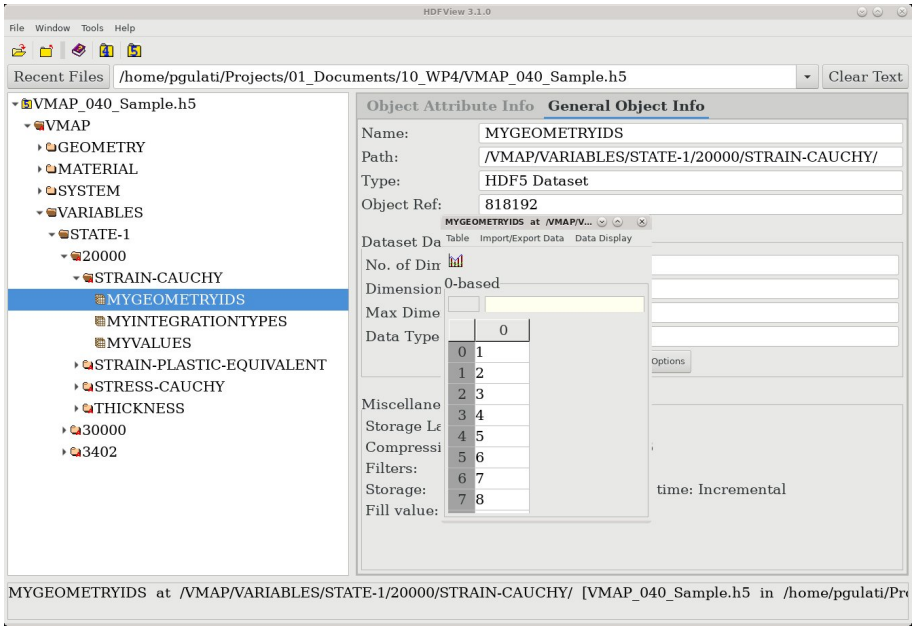


Figure 7.26: MYGEOMETRYIDS Dataset View - Metadata

7.10.2 MYVALUES Dataset

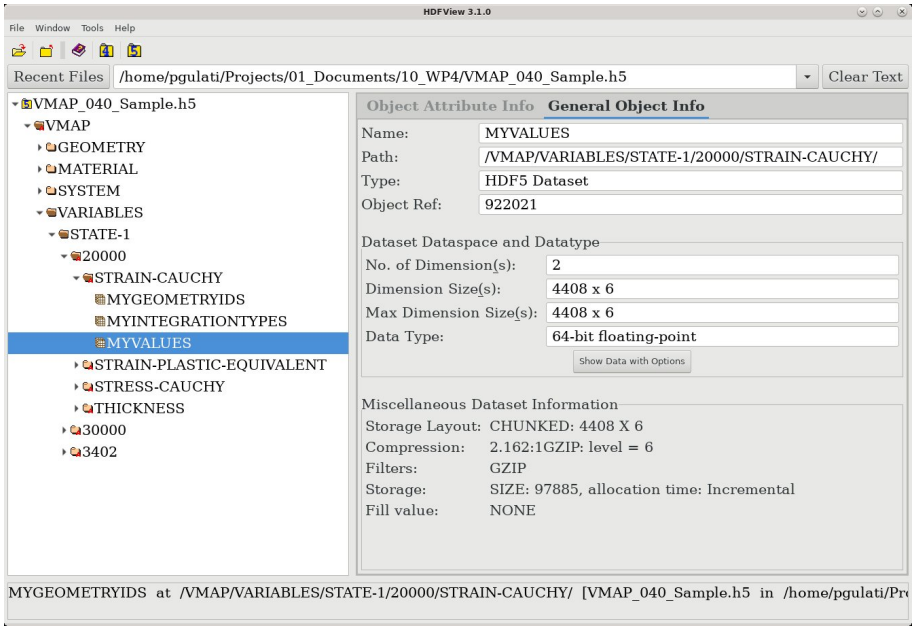


Figure 7.27: MYVALUES Dataset View - General Object Info

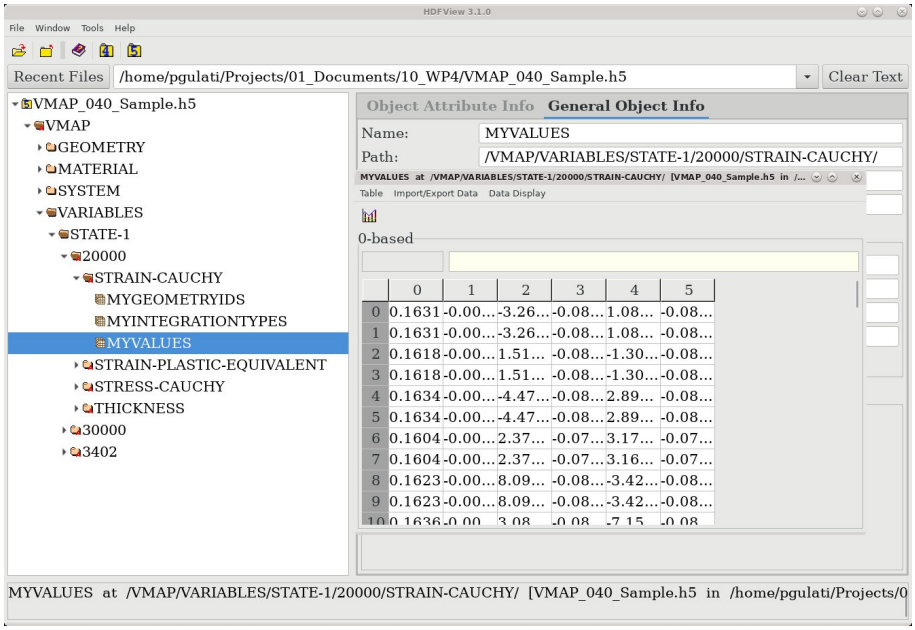


Figure 7.28: MYVALUES Dataset View - Metadata

7.10.3 MYINTEGRATIONTYPES Dataset

This dataset exists only when the MYLOCATION Attribute in Fig. 7.23 is 4.

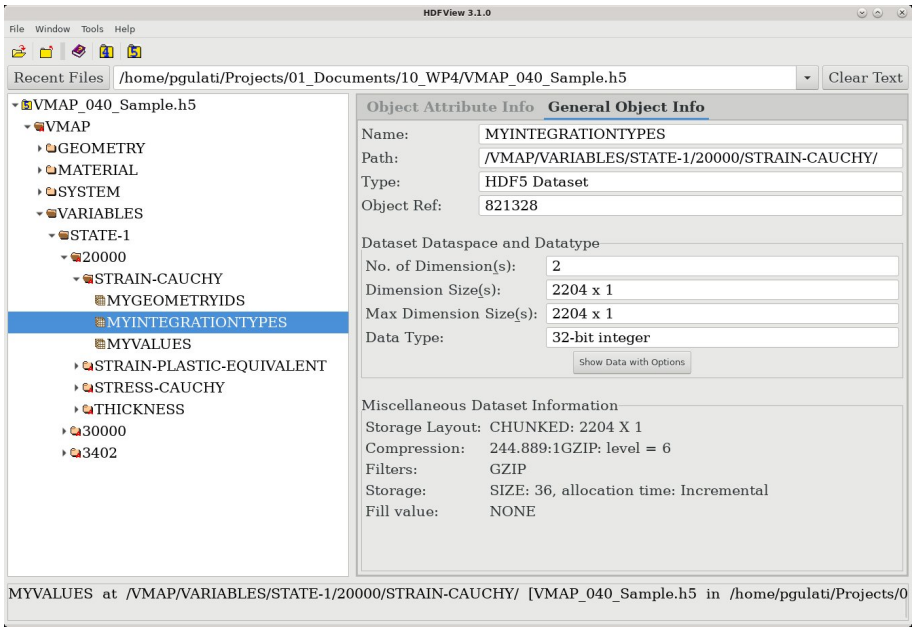


Figure 7.29: MYINTEGRATIONTYPES Dataset View - General Object Info

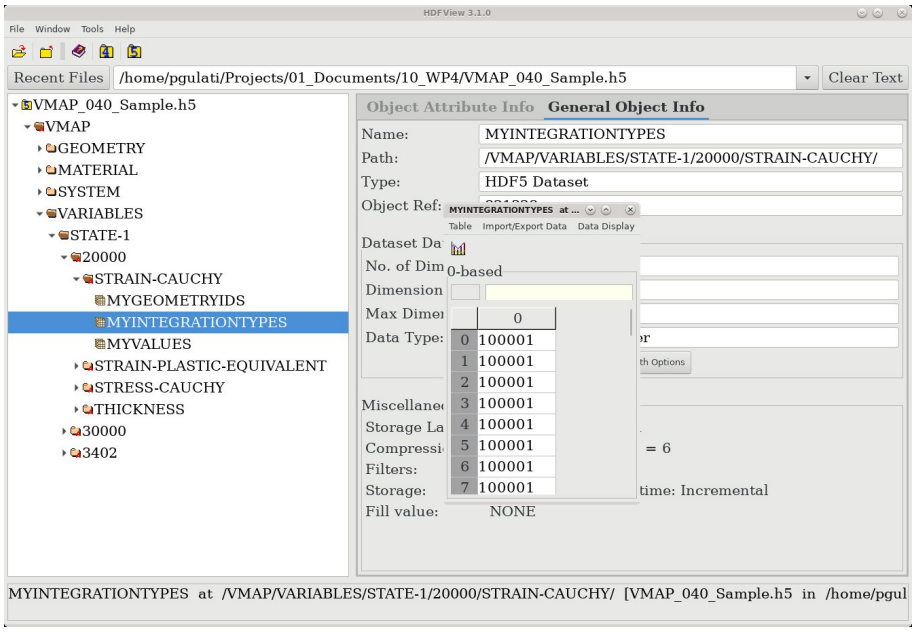


Figure 7.30: MYINTEGRATIONTYPES Dataset View - Metadata

7.11 SYSTEM Group View

SYSTEM Group has no attributes.

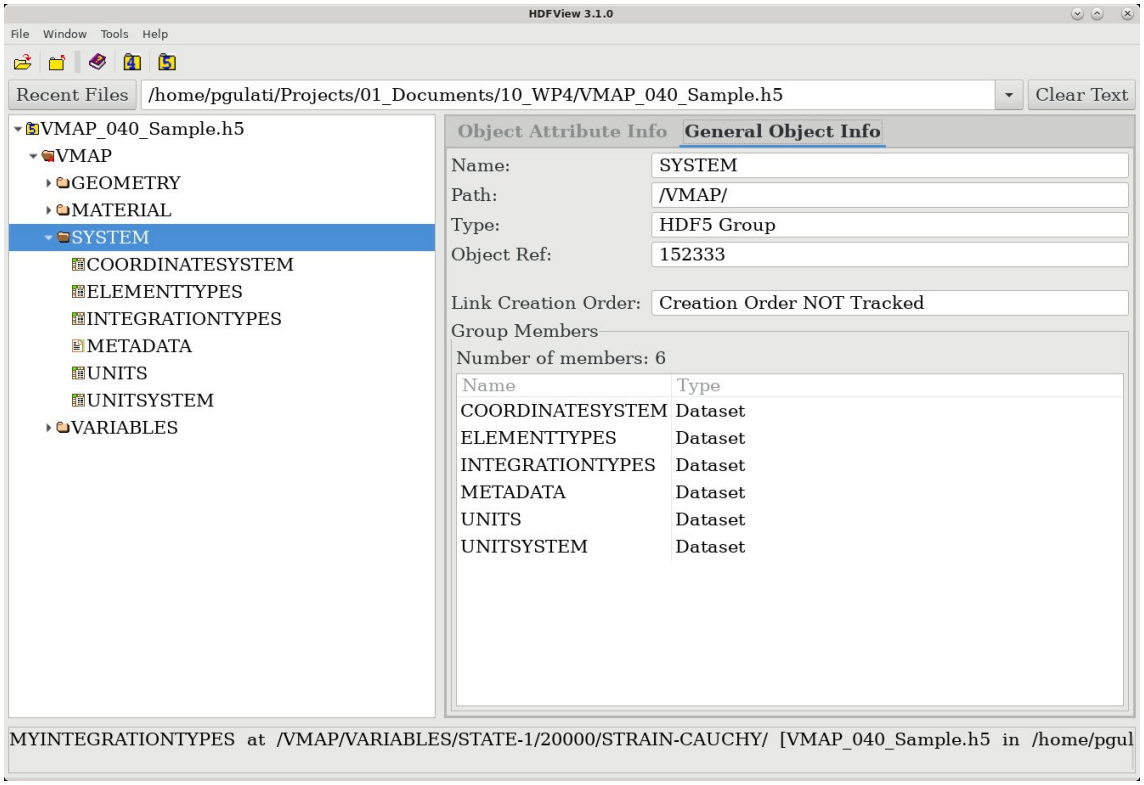


Figure 7.31: SYSTEM Group View - General Object Info

7.11.1 COORDINATESYSTEM Dataset

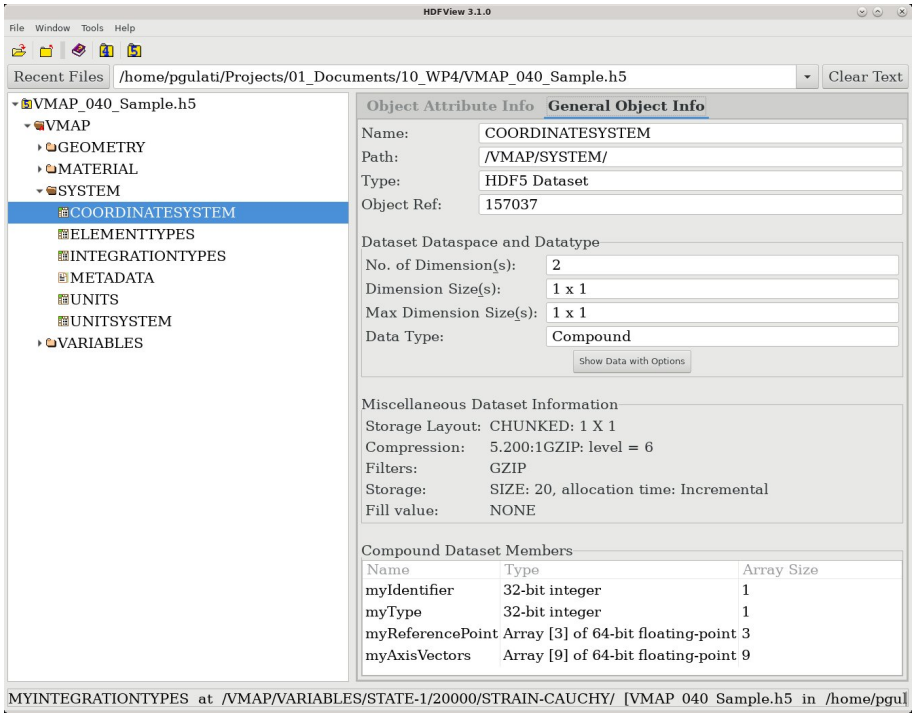


Figure 7.32: COORDINATESYSTEM Dataset View - General Object Info

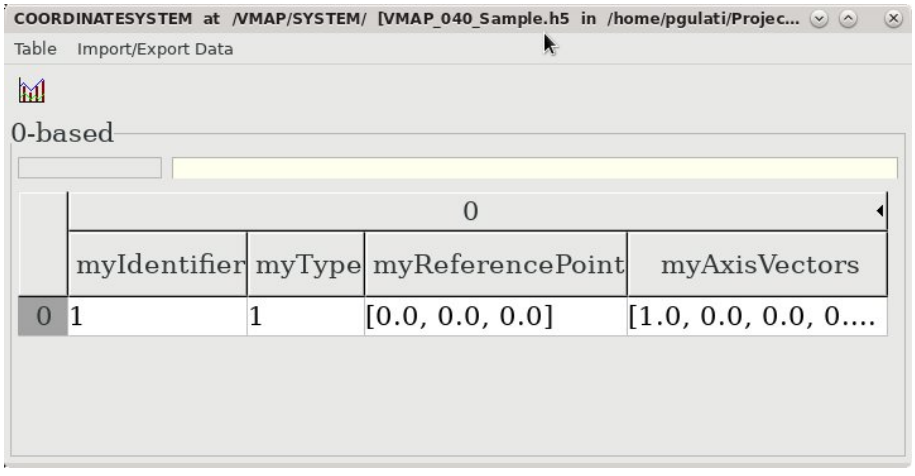


Figure 7.33: COORDINATESYSTEM Dataset View - Metadata

7.11.2 ELEMENTTYPES Dataset

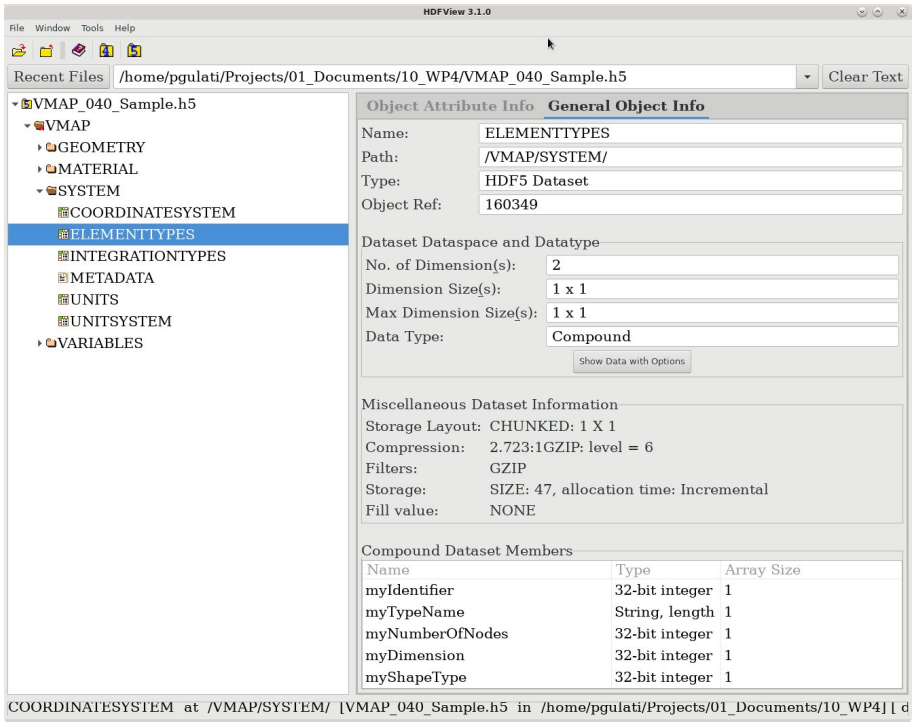


Figure 7.34: ELEMENTTYPES Dataset View - General Object Info

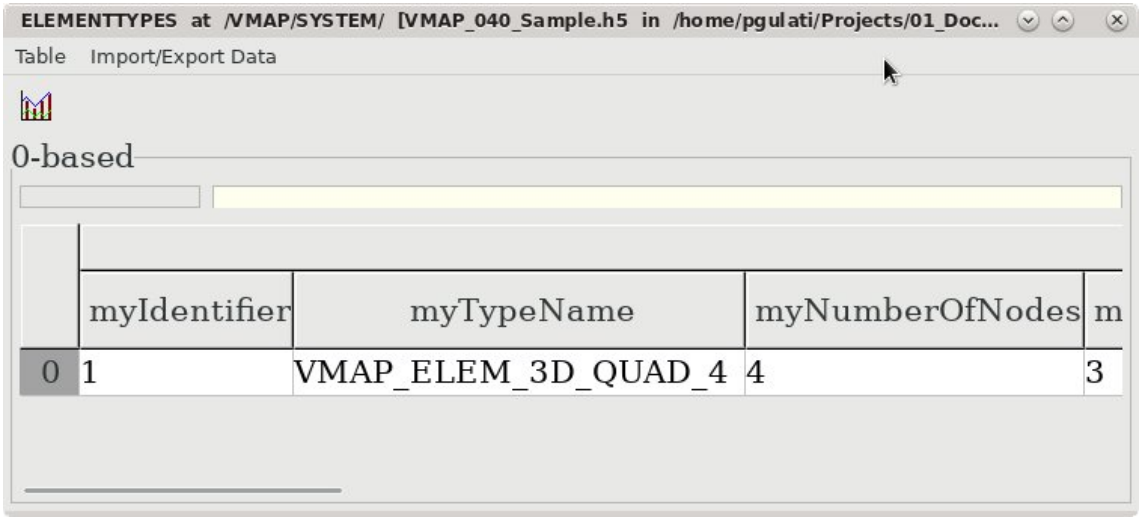


Figure 7.35: ELEMENTTYPES Dataset View - Metadata

7.11.3 INTEGRATIONTYPES Dataset

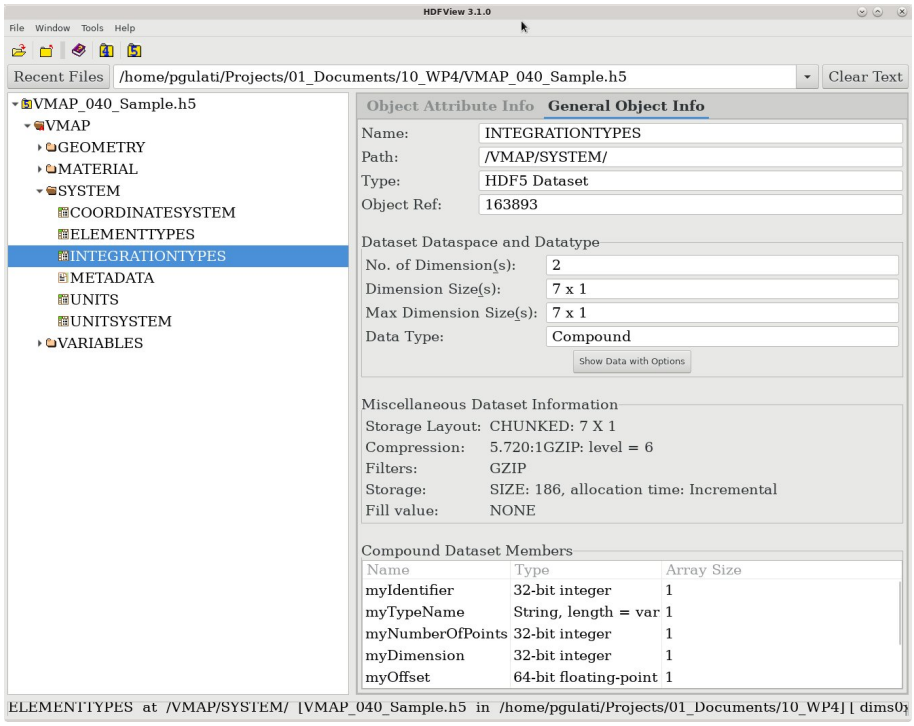


Figure 7.36: INTEGRATIONTYPES Dataset View - General Object Info

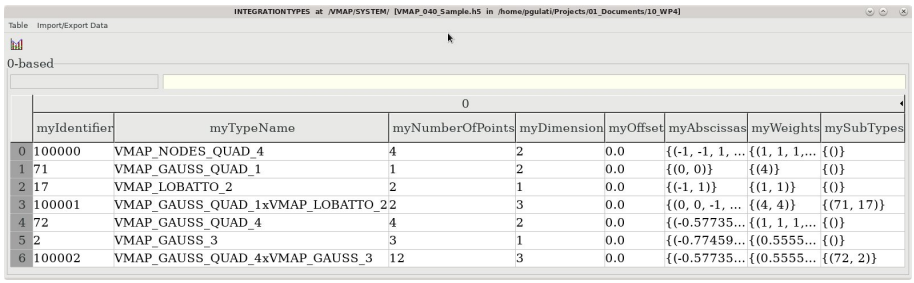


Figure 7.37: INTEGRATIONTYPES Dataset View - Metadata

7.11.4 METADATA Dataset

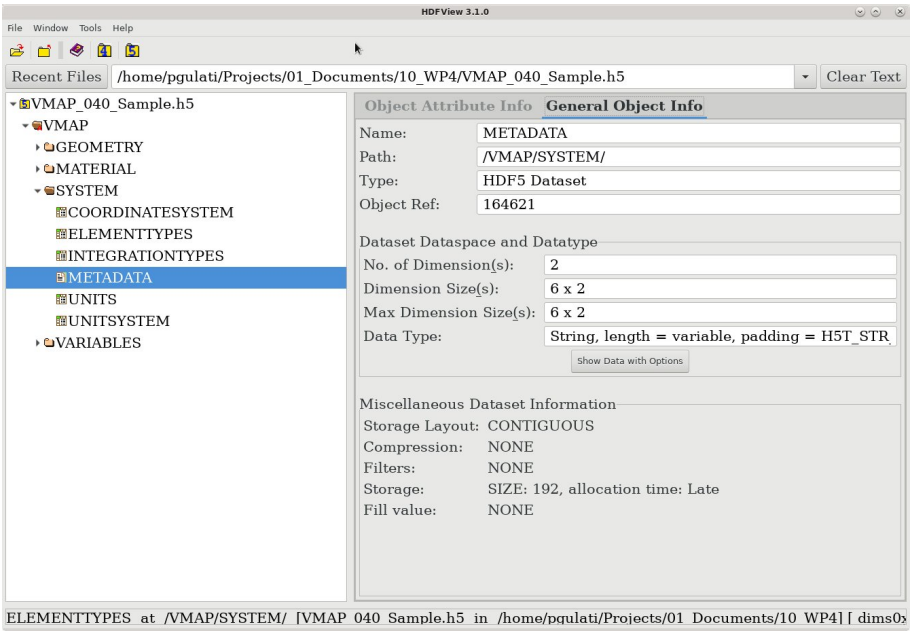
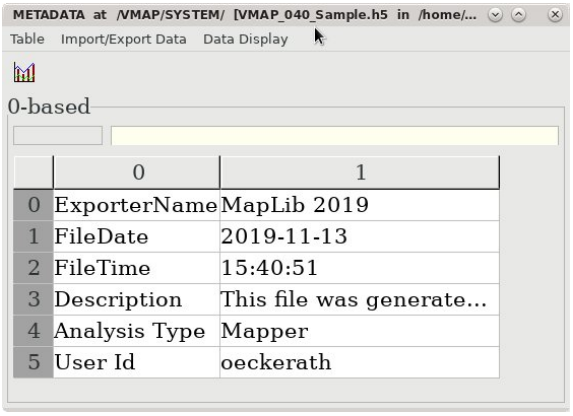


Figure 7.38: METADATA Dataset View - General Object Info



	0	1
0	ExporterName	MapLib 2019
1	FileDate	2019-11-13
2	FileTime	15:40:51
3	Description	This file was generate...
4	Analysis Type	Mapper
5	User Id	oeckerath

Figure 7.39: METADATA Dataset View - Metadata

7.11.5 UNITS Dataset

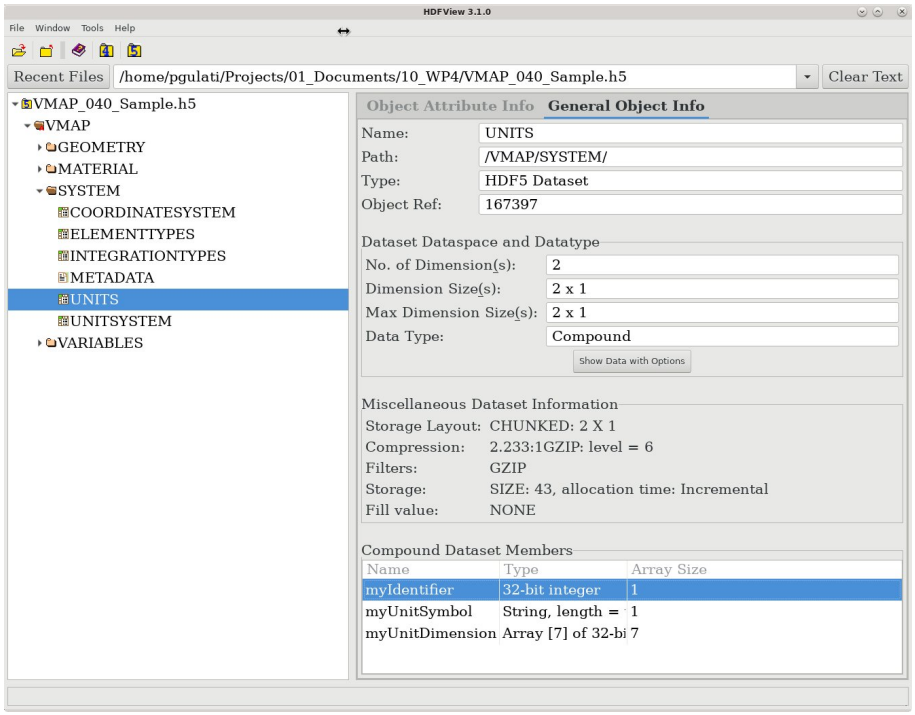


Figure 7.40: UNITS Dataset View - General Object Info

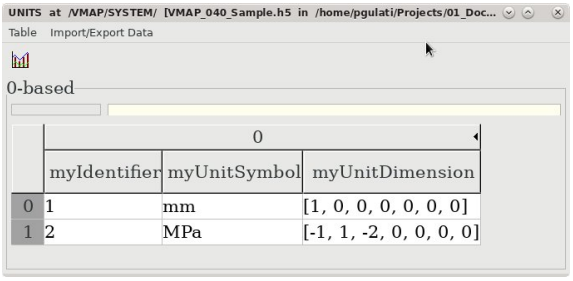


Figure 7.41: UNITS Dataset View - Metadata

7.11.6 UNITSYSTEM Dataset

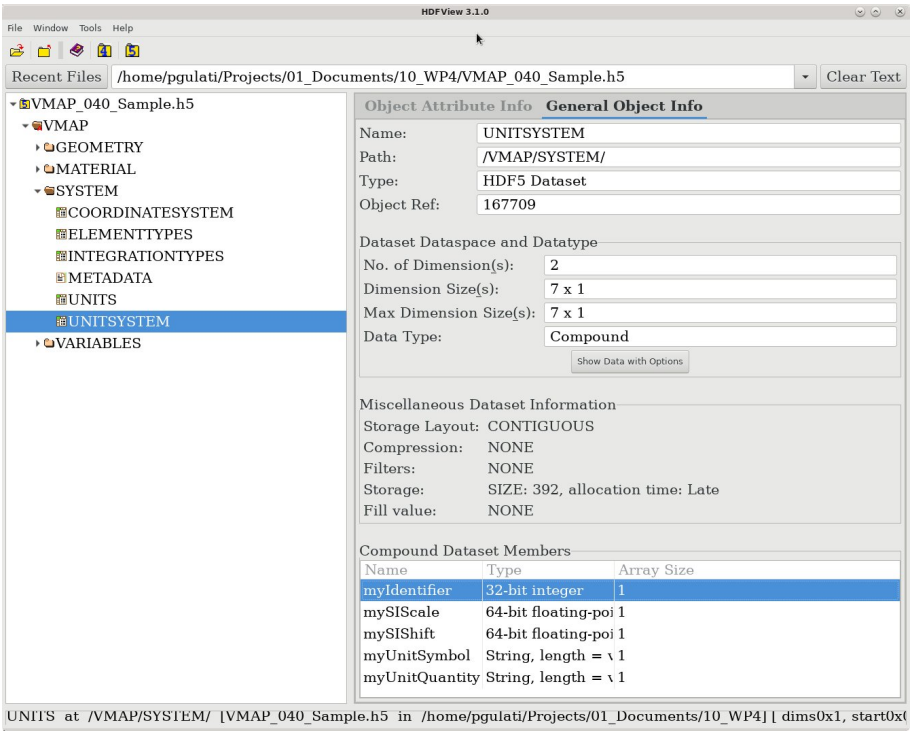
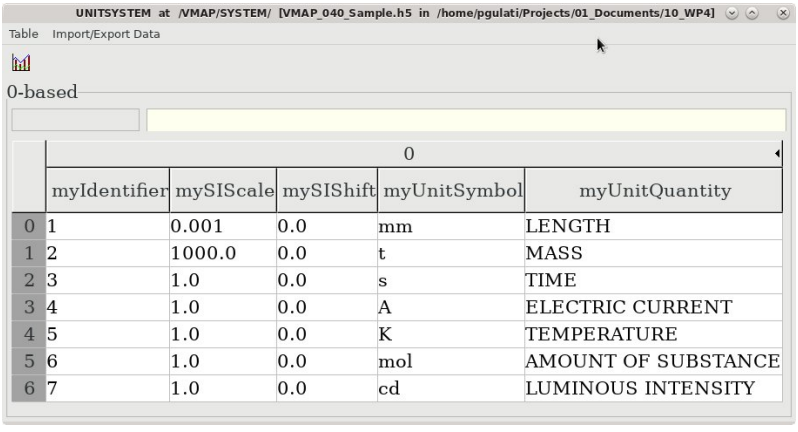


Figure 7.42: UNITSYSTEM Dataset View - General Object Info



	0				
	myIdentifier	mySIScale	mySIShift	myUnitSymbol	myUnitQuantity
0	1	0.001	0.0	mm	LENGTH
1	2	1000.0	0.0	t	MASS
2	3	1.0	0.0	s	TIME
3	4	1.0	0.0	A	ELECTRIC CURRENT
4	5	1.0	0.0	K	TEMPERATURE
5	6	1.0	0.0	mol	AMOUNT OF SUBSTANCE
6	7	1.0	0.0	cd	LUMINOUS INTENSITY

Figure 7.43: UNITSYSTEM Attribute View - Metadata

Chapter 8

Element Definition Specifications

VMAP Element factory contains 31 different 1D, 2D and 3D element definitions. These are some of the basic elements which are largely used in the CAE Domain. This chapter provides the specifications of these elements. Additionally, it outlines a standard method to define your own elements, which follows the same specifications as VMAP Elements. All elements defined in the VMAP Element Library, `VMAPElementTypeFactory.cxx`, belong to domain VMAP e.g. VMAP_ELEM_3D_QUAD_4.

8.1 USER_DEFINED

Using an example to demonstrate, a user-defined element is explained. First step is to define the correct point order, in VMAP the point numbering is defined using the right-hand rule with counter-clockwise direction and the vector pointing out-of-plane for 2D elements. For 3D elements, right-hand rule is used with the counter-clockwise direction and the vector pointing inwards (inside the volume). See figure 8.1.

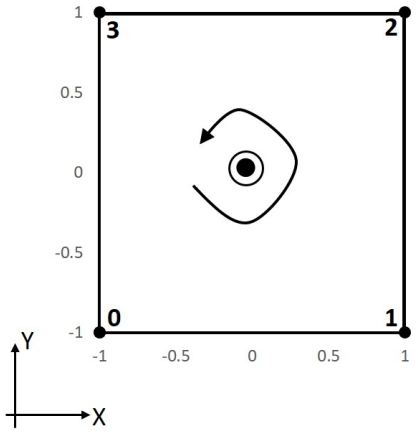


Figure 8.1: Point Ordering for a QUAD Element

Once the correct point numbering is in place, the following method is used by VMAP to define an element. See Figure 8.2

```
case sElementType::QUAD_4: {
    vmapType.setNumberOfNodes(4);

    std::vector<int> connectivity(4);
    connectivity[0] = 0;
    connectivity[1] = 1;
    connectivity[2] = 2;
    connectivity[3] = 3;
    vmapType.setConnectivity(connectivity);

    // Shell like element with two faces
    if(elemDimension == sElementType::ELEM_3D) {
        std::vector<int> faceconnectivity(2*4+2+1);
        faceconnectivity[0] = 2; ①
        // face 1
        faceconnectivity[1] = 4; ②
        faceconnectivity[2] = 0; ③
        faceconnectivity[3] = 1;
        faceconnectivity[4] = 2;
        faceconnectivity[5] = 3;
        // face 2
        faceconnectivity[6] = 4; ②
        faceconnectivity[7] = 0; ③
        faceconnectivity[8] = 3;
        faceconnectivity[9] = 2;
        faceconnectivity[10] = 1;
        vmapType.setFaceConnectivity(faceconnectivity);
    }
```

A switch case with the Element Type

Setting up the connectivity with the correct point ordering.

Length of faceconnectivity vector = No. of Faces x Points per Face + No. of Faces + 1

1. A 3D Quad has 2 faces.
2. Each Face has 4 Points.
3. The order in which the Points are connected

Figure 8.2: C++ Code for QUAD 3D Element Definition

8.2 POINT

POINT is a point element. Such an element can be used to define MASS (STATE VARIABLE). There will be no `connectivity` or `faceconnectivity` vector defined for this element; only parameter `myNumberOfNodes` set via function call `setNumberOfNodes`.

8.3 LINE_2

A line element with 2 Points can be used to define a BEAM, BAR etc. Figure 8.3 shows the LINE_2 element with points 0 and 1.

Figure 8.3: LINE_2 Element

8.4 LINE_3

LINE_3 is a line element with 2 corner points and 1 middle point. Figure 8.4 shows the LINE_3 element with points 0, 1 and 2.

Figure 8.4: LINE_3 Element

8.5 LINE_4

LINE_4 is a line element with 2 corner points and 2 middle points. Figure 8.5 shows the LINE_4 element with points 0, 1, 2 and 3.

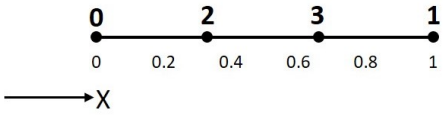
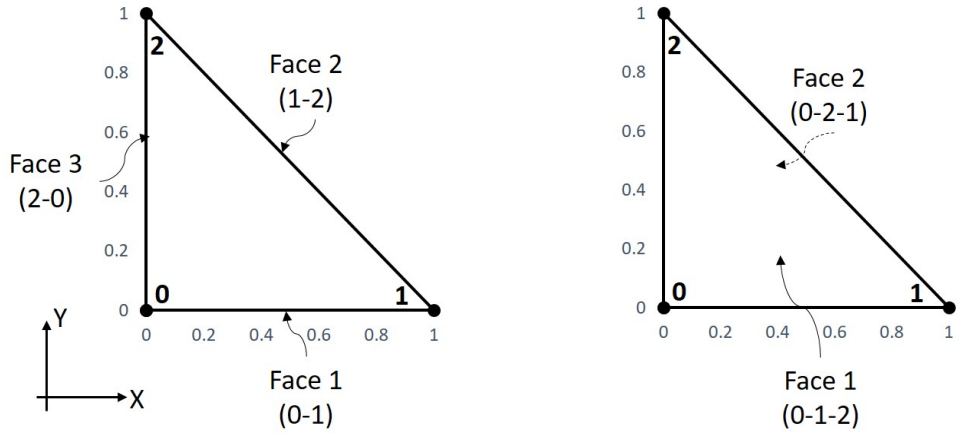


Figure 8.5: LINE_4 Element

8.6 TRIANGLE_3

TRIANGLE_3 element is a triangle with 3 points. This triangle could be used as a 2D element with 3 faces (3 lines) or as a 3D element with 2 faces. Figures 8.6 shows 2D and 3D TRIANGLE_3 elements.



(a) 2D Element

(b) 3D Element

Figure 8.6: TRIANGLE_3

8.7 TRIANGLE_4

TRIANGLE_4 2D has the same parameterization as shown for TRIANGLE_3 2D. The 3D element has an additional center point. The faces are given below.
Face 1: 0-1-2-3
Face 2: 0-2-1-3
Figures 8.7 shows TRIANGLE_4 element.

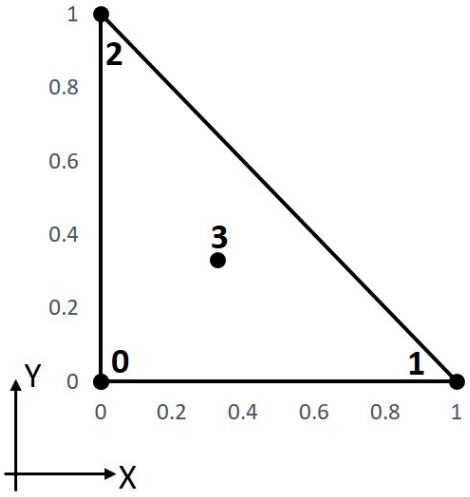
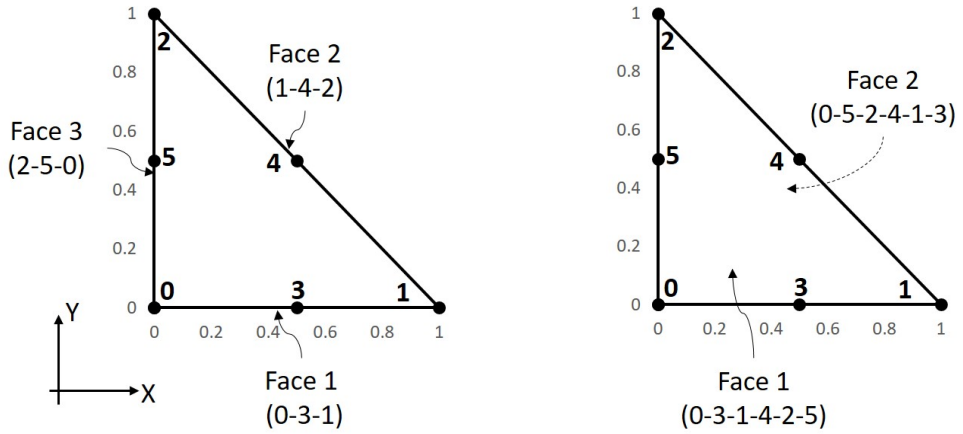


Figure 8.7: TRIANGLE_4 Element

8.8 TRIANGLE_6

TRIANGLE_6 element is a triangle with 3 corner points and 3 middle points - one for each face (line). This triangle could be used as a 2D element with 3 faces (3 lines) or as a 3D element with 2 faces. Figures 8.8 shows 2D and 3D TRIANGLE_6 elements.

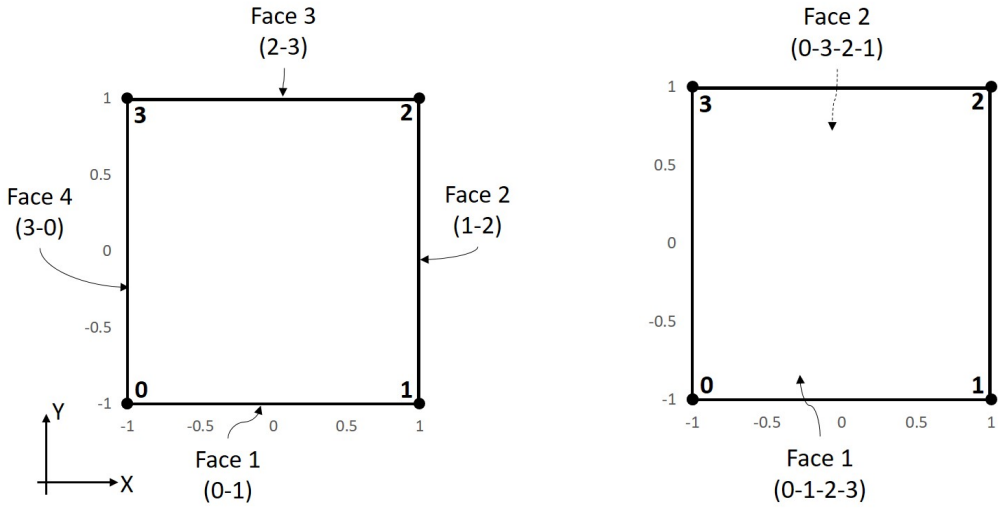


(a) 2D Element (b) 3D Element

Figure 8.8: TRIANGLE_6

8.9 QUAD_4

QUAD_4 is a quadrilateral with 4 points. The quadrilateral could be used as a 2D element with 4 faces (4 lines) or a 3D element with 2 faces. Figures 8.9 shows 2D and 3D QUAD_4 elements.

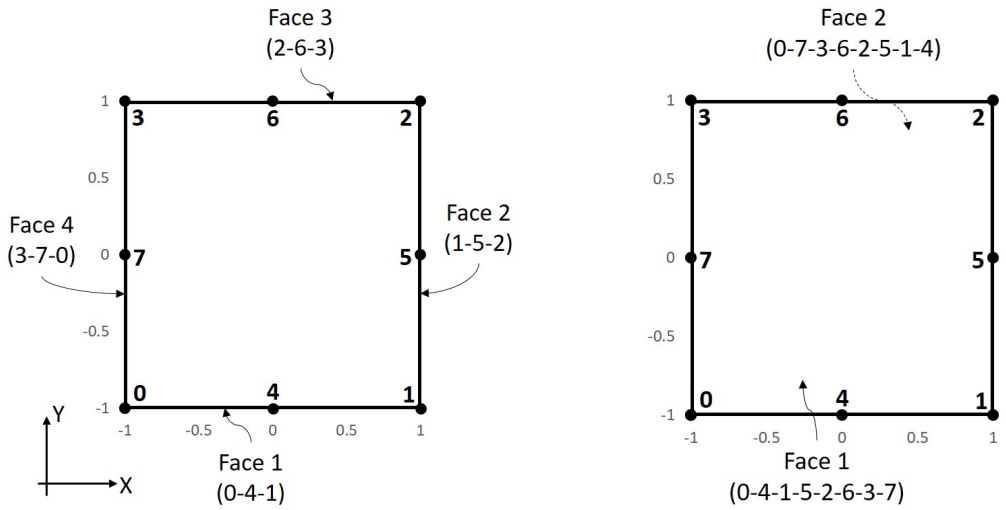


(a) 2D Element (b) 3D Element

Figure 8.9: QUAD_4

8.10 QUAD_8

QUAD_8 is a quadrilateral with 4 corner points and 4 middle points - one for each face (line). The quadrilateral could be used as a 2D element with 4 faces (4 lines) or a 3D element with 2 faces. Figures 8.10 shows 2D and 3D QUAD_8 elements.



(a) 2D Element

(b) 3D Element

Figure 8.10: QUAD_8

8.11 QUAD_9

QUAD_9 2D has the same parameterization as shown for QUAD_8 2D. The 3D element has an additional center point. The faces are given below.
Face 1: 0-4-1-5-2-6-3-7-8
Face 2: 0-7-3-6-2-5-1-4-8
Figures 8.11 shows QUAD_9 element.

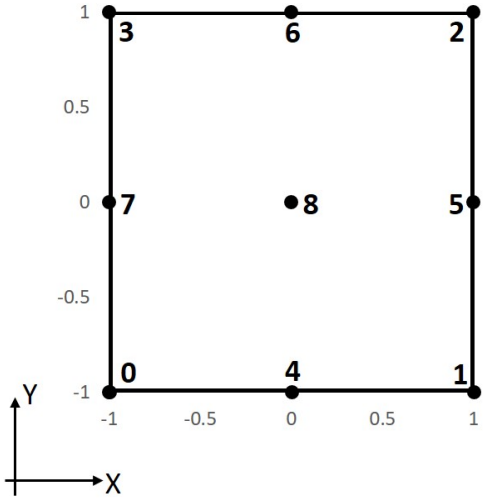


Figure 8.11: QUAD_9 Element

8.12 TETRAHEDRON_4

TETRAHEDRON_4 is a tetrahedral element with 4 points. Figure 8.12 shows a TETRAHEDRON_4 element.

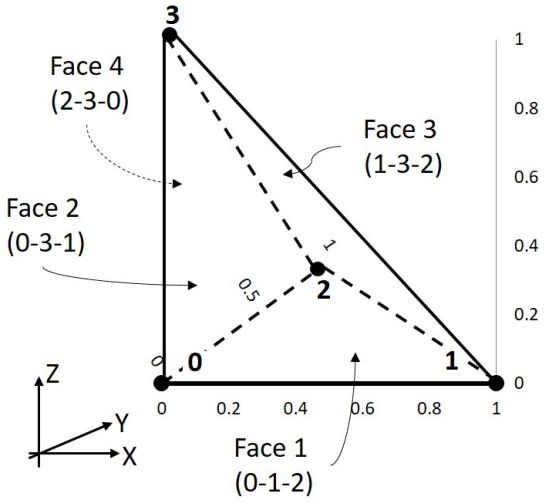


Figure 8.12: TETRAHEDRON_4 Element

8.13 TETRAHEDRON_5

TETRAHEDRON_5 has the same parameterization as TETRAHEDRON_4, with an additional center point. Figure 8.13 shows a TETRAHEDRON_5 element.

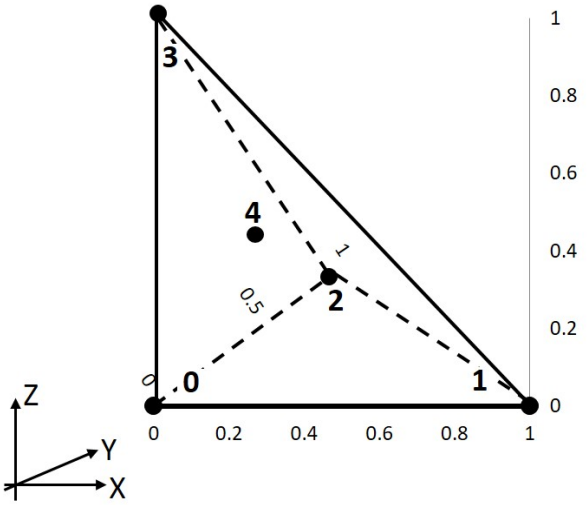


Figure 8.13: TETRAHEDRON_4 Element

8.14 TETRAHEDRON_10

TETRAHEDRON_10 is a tetrahedral element with 4 corner points and 6 middle points - one for each face (line). Figure 8.14 shows a TETRAHEDRON_10 element.

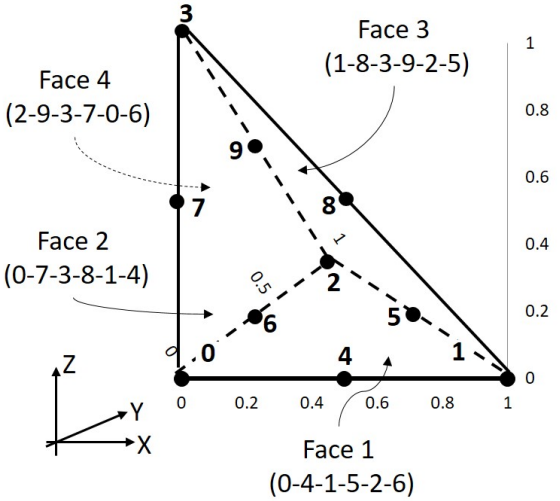


Figure 8.14: TETRAHEDRON_10 Element

8.15 TETRAHEDRON_11

TETRAHEDRON_11 has the same parameterization as TETRAHEDRON_10, with an additional center point. Figure 8.15 shows a TETRAHEDRON_11 element.

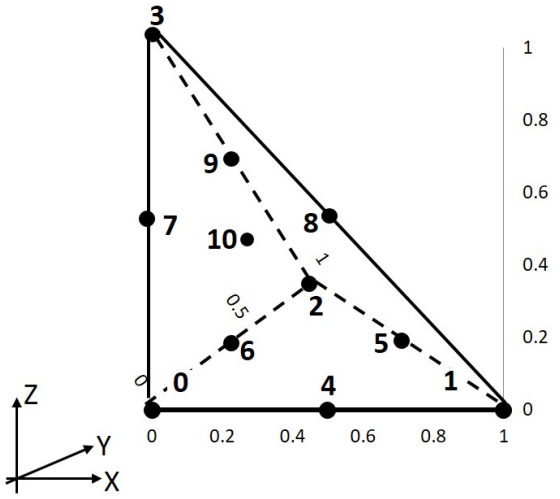


Figure 8.15: TETRAHEDRON_11 Element

8.16 PYRAMID_5

PYRAMID_5 is a pyramid element with 5 points. Figure 8.16 shows a PYRAMID_5 element.

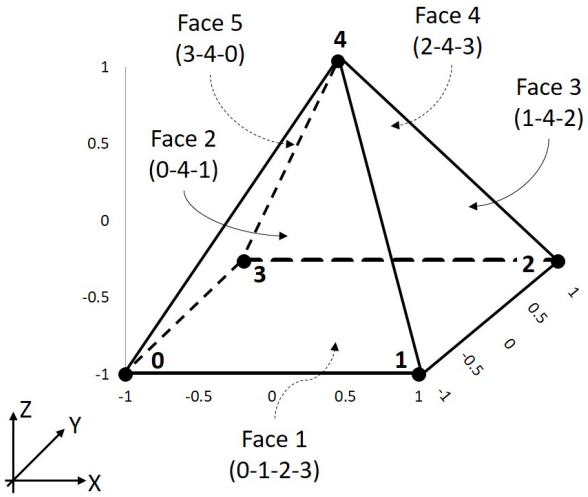


Figure 8.16: PYRAMID_5 Element

8.17 PYRAMID_6

PYRAMID_6 has the same parameterization as PYRAMID_5, with an additional center point. Figure 8.17 shows a PYRAMID_6 element.

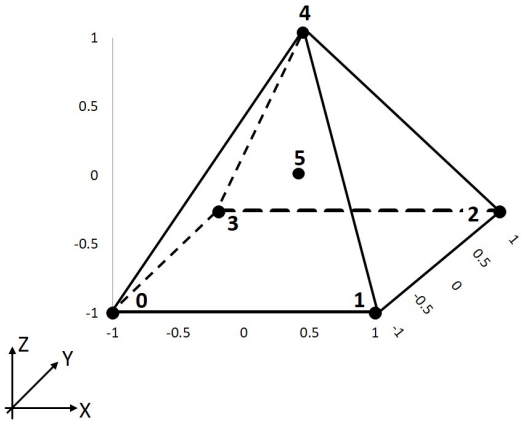


Figure 8.17: PYRAMID_6 Element

8.18 PYRAMID_13

PYRAMID_13 is a pyramid element with 5 corner points, additionally 8 middle points - one on each face (line). Figure 8.18 shows a PYRAMID_13 element.

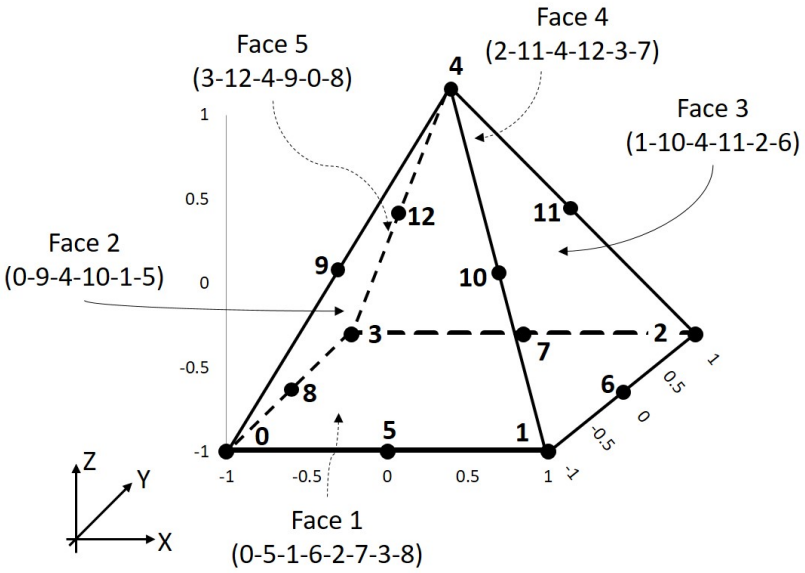


Figure 8.18: PYRAMID_13 Element

8.19 WEDGE_6

WEDGE_6 is a prism element with 6 points. Figure 8.19 shows a WEDGE_6 element.

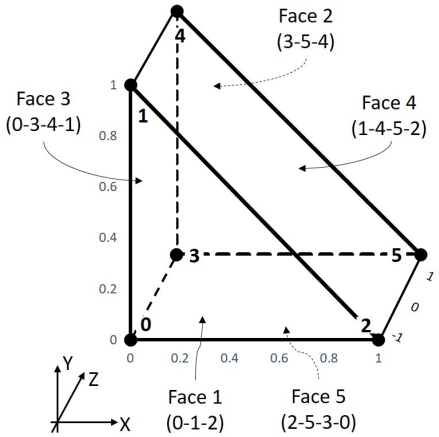


Figure 8.19: WEDGE_6 Element

8.20 WEDGE_15

WEDGE_15 is a prism element with 6 corner points and 9 middle points - one for each face (line). Figure 8.20 shows a WEDGE_15 element.

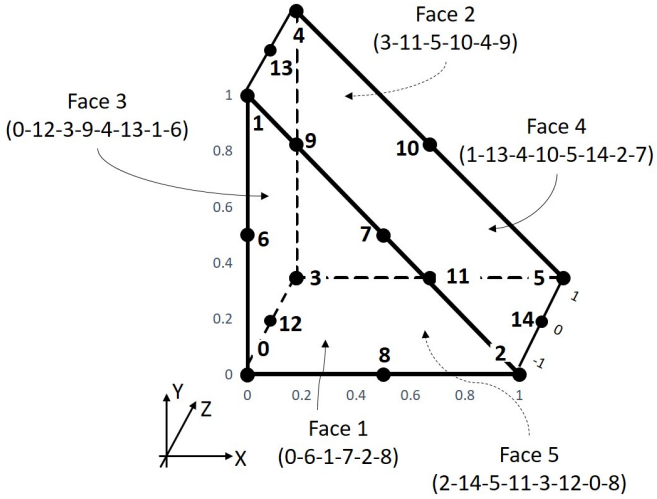


Figure 8.20: WEDGE_15 Element

8.21 HEXAHEDRON_8

HEXAHEDRON_8 is a brick element with 8 points. Figure 8.21 shows a HEXAHEDRON_8 element.

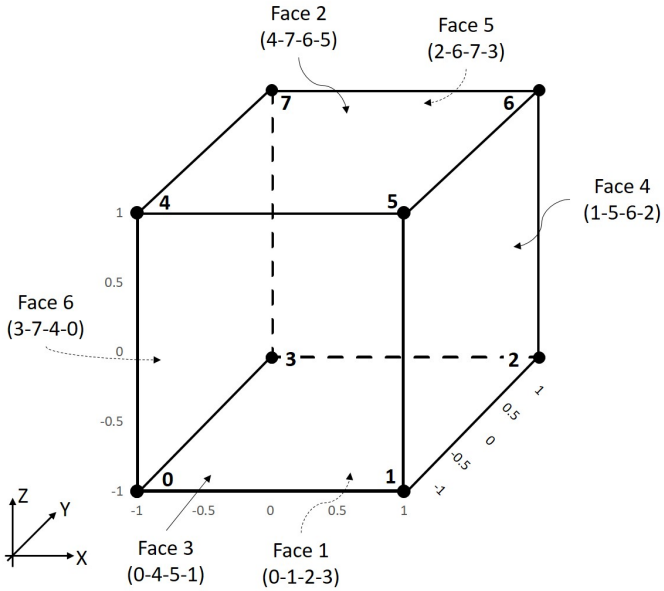


Figure 8.21: HEXAHEDRON_8 Element

8.22 HEXAHEDRON_9

HEXAHEDRON_9 has the same parameterization as HEXAHEDRON_8, with an additional center point. Figure 8.22 shows a HEXAHEDRON_9 element.

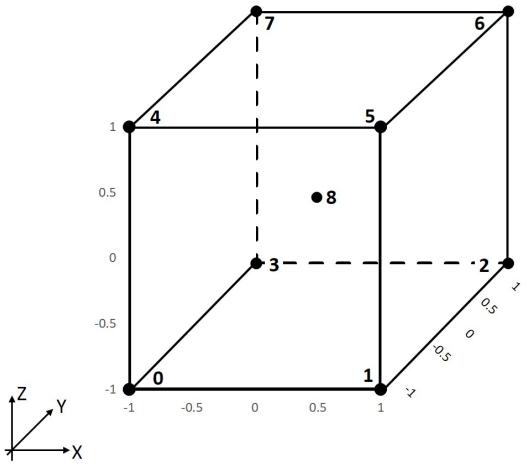


Figure 8.22: HEXAHEDRON_9 Element

8.23 HEXAHEDRON_20

HEXAHEDRON_20 is a brick element with 8 corner points and 12 middle points - one on each face (line) . Figure 8.23 shows a HEXAHEDRON_20 element.

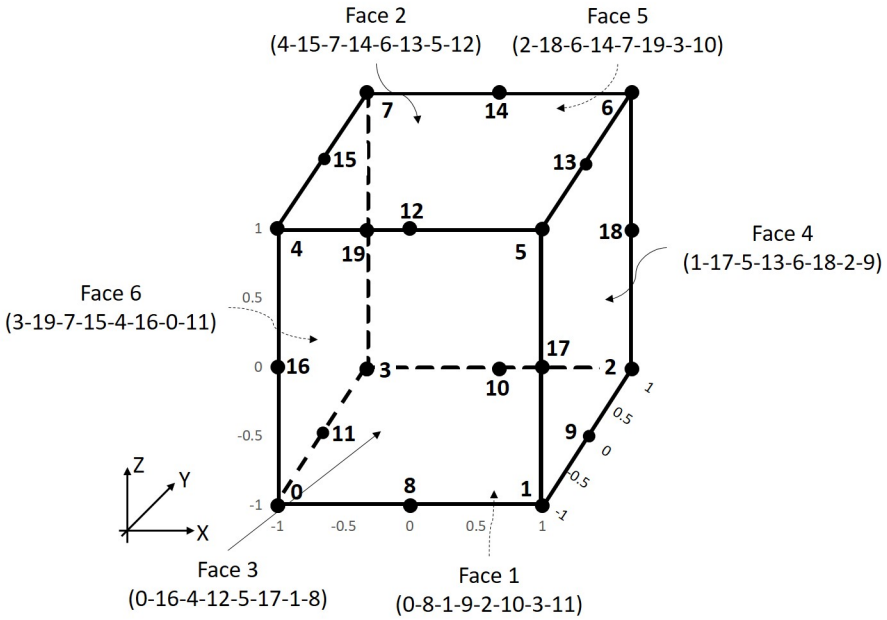


Figure 8.23: HEXAHEDRON_20 Element

8.24 HEXAHEDRON_21

HEXAHEDRON_21 has the same parameterization as HEXAHEDRON_20, with an additional middle point. Figure 8.24 shows a HEXAHEDRON_21 element.

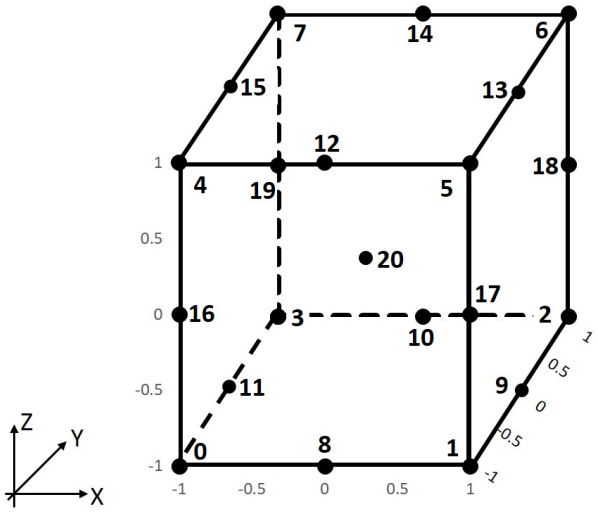


Figure 8.24: HEXAHEDRON_21 Element

8.25 HEXAHEDRON_27

HEXAHEDRON_27 is a brick element with 8 corner points, 12 middle points - one on each face (line), 6 middle points - one on each face and one center point. The faces are listed below.
Face 1: 0-8-1-9-2-10-3-11-21
Face 2: 4-15-7-14-6-13-5-12-22
Face 3: 0-16-4-12-5-17-1-8-23
Face 4: 1-17-5-13-6-18-2-9-24
Face 5: 2-18-6-14-7-19-3-10-25
Face 6: 3-19-7-15-4-16-0-11-26
Figure 8.25 shows a HEXAHEDRON_27 element.

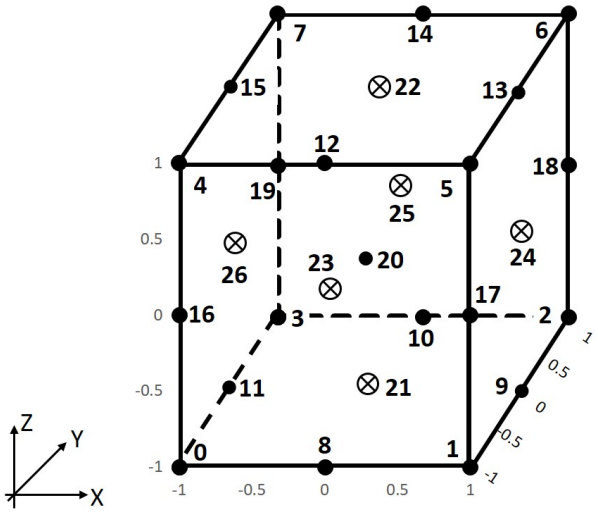


Figure 8.25: HEXAHEDRON_27 Element

8.26 POLYGON

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8.27 POLYHEDRON

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Chapter 9

Integration Type Definition Specifications

This chapter contains all the integration types provided by the `VMAPIntegrationTypeFactory.cxx` file, including user-defined integration type. Additionally, it covers information about **Combined** integration types and **Composite** Integration Types. All integration types defined in VMAP Integration Types Library, belong to the domain VMAP e.g. VMAP_GAUSS_4. All Gauss quadrature rules are over interval $[-1, 1]$. For all 1-Dimensional integration types, the integration point numbering is from the lowest to the highest abscissa value.

9.1 USER_DEFINED

A user-defined integration rule is explained, an example is provided to illustrate. The numbering for combined user defined type starts from 100000. See figure 9.1.

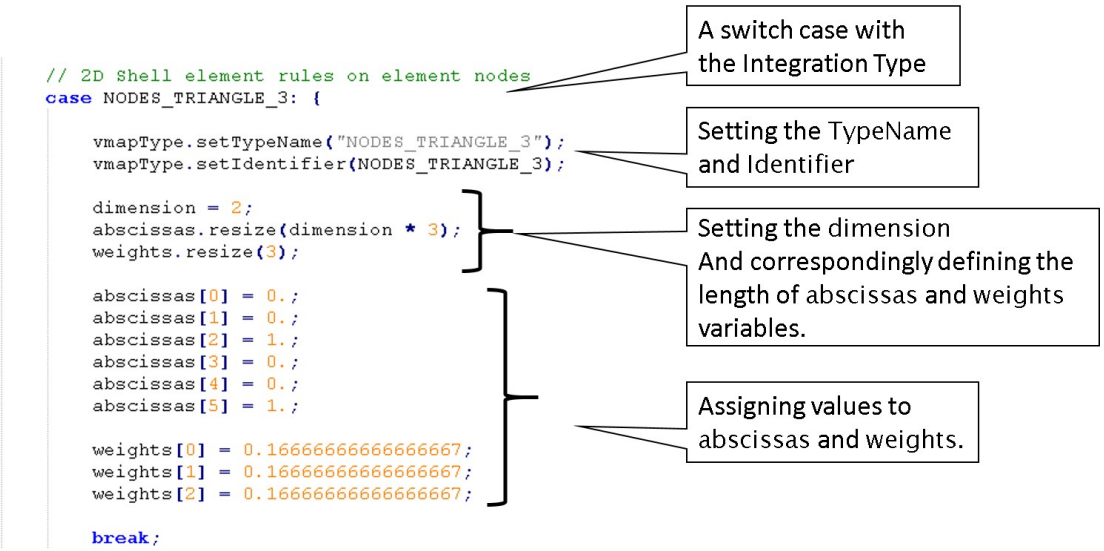

Figure 9.1: C++ Code for NODE_TRIANGLE_3 Integration Rule Definition

9.2 GAUSS_1

Number of Points - n	Weight - w_i	Abscissa - x_i
1	2.000000	0.000000

Table 9.1: GAUSS_1

9.3 GAUSS_2

Number of Points - n	Weight - w_i	Abscissa - x_i
2	1	$\pm$0.5773502691896257

Table 9.2: GAUSS_2

9.4 GAUSS_3

Number of Points - n	Weight - w_i	Abscissa - x_i
3	0.888888	0.000000
	0.555555	$\pm$0.7745966692414834

Table 9.3: GAUSS_3

9.5 GAUSS_4

Number of Points - n	Weight - w_i	Abscissa - x_i
4	0.6521451548625461	$\pm$0.3399810435848563
	0.3478548451374538	$\pm$0.8611363115940526

Table 9.4: GAUSS_4

9.6 GAUSS_5

Number of Points - n	Weight - w_i	Abscissa - x_i
5	0.568889	0.000000
	0.4786286704993665	$\pm$0.5384693101056831
	0.2369268850561891	$\pm$0.9061798459386640

Table 9.5: GAUSS_5

9.7 GAUSS_6

Number of Points - n	Weight - w_i	Abscissa - x_i
6	0.3607615730481386	$\pm$0.6612093864662645
	0.4679139345726910	$\pm$0.2386191860831969
	0.1713244923791704	$\pm$0.9324695142031521

Table 9.6: GAUSS_6

9.8 GAUSS_7

Number of Points - n	Weight - w_i	Abscissa - x_i
7	0.4179591836734694	0.000000
	0.3818300505051189	$\pm$0.4058451513773972
	0.2797053914892766	$\pm$0.7415311855993945
	0.1294849661688697	$\pm$0.9491079123427585

Table 9.7: GAUSS_7

9.9 GAUSS_8

Number of Points - n	Weight - w_i	Abscissa - x_i
8	0.3626837833783620	$\pm$0.1834346424956498
	0.3137066458778873	$\pm$0.5255324099163290
	0.2223810344533745	$\pm$0.7966664774136267
	0.1012285362903763	$\pm$0.9602898564975363

Table 9.8: GAUSS_8

9.10 GAUSS_9

Number of Points - n	Weight - w_i	Abscissa - x_i
9	0.3302393550012598	0.000000
	0.1806481606948574	$\pm$0.8360311073266358
	0.0812743883615744	$\pm$0.9681602395076261
	0.3123470770400029	$\pm$0.3242534234038089
	0.2606106964029354	$\pm$0.6133714327005904

Table 9.9: GAUSS_9

9.11 GAUSS_10

Number of Points - n	Weight - w_i	Abscissa - x_i
10	0.2955242247147529	$\pm$0.1488743389816312
	0.2692667193099963	$\pm$0.4333953941292472
	0.2190863625159820	$\pm$0.6794095682990244
	0.1494513491505806	$\pm$0.8650633666889845
	0.0666713443086881	$\pm$0.9739065285171717

Table 9.10: GAUSS_10

9.12 GAUSS_11

Number of Points - n	Weight - w_i	Abscissa - x_i
11	0.2729250867779006	0.000000
	0.2628045445102467	$\pm$0.2695431559523450
	0.2331937645919905	$\pm$0.5190961292068118
	0.1862902109277343	$\pm$0.7301520055740494
	0.1255803694649046	$\pm$0.8870625997680953
	0.0556685671161737	$\pm$0.9782286581460570

Table 9.11: GAUSS_11

9.13 GAUSS_12

Number of Points - n	Weight - w_i	Abscissa - x_i
12	0.2491470458134028	$\pm$0.1252334085114689
	0.2334925365383548	$\pm$0.3678314989981802
	0.2031674267230659	$\pm$0.5873179542866175
	0.1600783285433462	$\pm$0.7699026741943047
	0.1069393259953184	$\pm$0.9041172563704749
	0.0471753363865118	$\pm$0.9815606342467192

Table 9.12: GAUSS_12

9.14 GAUSS_13

Number of Points - n	Weight - w_i	Abscissa - x_i
13	0.2325515532308739	0.000000
	0.2262831802628972	$\pm$0.2304583159551348
	0.2078160475368885	$\pm$0.4484927510364469
	0.1781459807619457	$\pm$0.6423493394403402
	0.1388735102197872	$\pm$0.8015780907333099
	0.0921214998377285	$\pm$0.9175983992229779
	0.0404840047653159	$\pm$0.9841830547185881

Table 9.13: GAUSS_13

9.15 GAUSS_14

Number of Points - n	Weight - w_i	Abscissa - x_i
14	0.2152638534631578	$\pm$0.1080549487073437
	0.2051984637212956	$\pm$0.3191123689278897
	0.1855383974779378	$\pm$0.5152486363581541
	0.1572031671581935	$\pm$0.6872929048116855
	0.1215185706879032	$\pm$0.8272013150697650
	0.0801580871597602	$\pm$0.9284348836635735
	0.0351194603317519	$\pm$0.9862838086968123

Table 9.14: GAUSS_14

9.16 GAUSS_15

Number of Points - n	Weight - w_i	Abscissa - x_i
15	0.2025782419255613	0.000000
	0.1984314853271116	$\pm$0.2011940939974345
	0.1861610000155622	$\pm$0.3941513470775634
	0.1662692058169939	$\pm$0.5709721726085388
	0.1395706779261543	$\pm$0.7244177313601701
	0.1071592204671719	$\pm$0.8482065834104272
	0.0703660474881081	$\pm$0.9372733924007060
	0.0307532419961173	$\pm$0.9879925180204854

Table 9.15: GAUSS_15

9.17 GAUSS_16

Number of Points - n	Weight - w_i	Abscissa - x_i
16	0.1894506104550685	$\pm$0.0950125098376374
	0.1826034150449236	$\pm$0.2816035507792589
	0.1691565193950025	$\pm$0.4580167776572274
	0.1495959888165767	$\pm$0.6178762444026438
	0.1246289712555339	$\pm$0.7554044083550030
	0.0951585116824928	$\pm$0.8656312023878318
	0.0622535239386479	$\pm$0.9445750230732326
	0.0271524594117541	$\pm$0.9894009349916499

Table 9.16: GAUSS_16

9.18 LOBATTO_1

This integration type is same as GAUSS_1. See table 9.1

9.19 LOBATTO_2

Number of Points - n	Weight - w_i	Abscissa - x_i
2	1.000000	$\pm$1.000000

Table 9.17: LOBATTO_2

9.20 LOBATTO_3

Number of Points - n	Weight - w_i	Abscissa - x_i
3	1.333333	0.000000
	0.333333	$\pm$1.000000

Table 9.18: LOBATTO_3

9.21 LOBATTO_4

Number of Points - n	Weight - w_i	Abscissa - x_i
4	0.833333	$\pm$0.4472135954
	0.166667	$\pm$1.000000

Table 9.19: LOBATTO_4

9.22 LOBATTO_5

Number of Points - n	Weight - w_i	Abscissa - x_i
5	0.711111	0.000000
	0.544444	$\pm$0.6546536707
	0.100000	$\pm$1.000000

Table 9.20: LOBATTO_5

9.23 LOBATTO_6

Number of Points - n	Weight - w_i	Abscissa - x_i
6	0.5548583770	$\pm$0.2852315164
	0.3784749562	$\pm$0.7650553239
	0.066667	$\pm$1.000000

Table 9.21: LOBATTO_6

9.24 LOBATTO_7

Number of Points - n	Weight - w_i	Abscissa - x_i
7	0.4876190476	0.000000
	0.4317453812	$\pm$0.4688487934
	0.2768260473	$\pm$0.8302238962
	0.0476190476	$\pm$1.000000

Table 9.22: LOBATTO_7

9.25 LOBATTO_8

Number of Points - n	Weight - w_i	Abscissa - x_i
8	0.4124587946	$\pm$0.2092992179
	0.3411226924	$\pm$0.5917001814
	0.2107042271	$\pm$0.8717401485
	0.0357142857	$\pm$1.000000

Table 9.23: LOBATTO_8

9.26 LOBATTO_9

Number of Points - n	Weight - w_i	Abscissa - x_i
9	0.3715192743	0.000000
	0.3464285109	$\pm$0.3631174638
	0.2745387125	$\pm$0.6771862795
	0.1654953615	$\pm$0.8997579954
	0.0277777778	$\pm$1.000000

Table 9.24: LOBATTO_9

9.27 LOBATTO_10

Number of Points - n	Weight - w_i	Abscissa - x_i
10	0.3275397611	$\pm$0.1652789576
	0.2920426836	$\pm$0.4779249498
	0.2248893420	$\pm$0.7387738651
	0.1333059908	$\pm$0.9195339081
	0.022222	$\pm$1.000000

Table 9.25: LOBATTO_10

9.28 LOBATTO_11

Number of Points - n	Weight - w_i	Abscissa - x_i
11	0.3002175954	0.000000
	0.2868791247	$\pm$0.2957581355
	0.2480481042	$\pm$0.5652353269
	0.1871698817	$\pm$0.7844834736
	0.1096122732	$\pm$0.9340014304
	0.0181818	$\pm$1.000000

Table 9.26: LOBATTO_11

9.29 LOBATTO_12

Number of Points - n	Weight - w_i	Abscissa - x_i
12	0.271405241	$\pm$0.136552933
	0.251275603	$\pm$0.399530941
	0.212508418	$\pm$0.632876153
	0.157974705	$\pm$0.819279322
	0.09168452	$\pm$0.944899272
	0.015151515	$\pm$1.000000

Table 9.27: LOBATTO_12

9.30 LOBATTO_13

Number of Points - n	Weight - w_i	Abscissa - x_i
13	0.25193085	0.000000
	0.244015790	$\pm$0.24928693
	0.220767793	$\pm$0.48290982
	0.183646865	$\pm$0.68618847
	0.134981926	$\pm$0.84634756
	0.077801687	$\pm$0.95330984
	0.012820512	$\pm$1.000000

Table 9.28: LOBATTO_13

9.31 LOBATTO_14

Number of Points - n	Weight - w_i	Abscissa - x_i
14	0.2316128	$\pm$0.11633187
	0.219126253	$\pm$0.34272401
	0.194826149	$\pm$0.55063940
	0.160021852	$\pm$0.72886859
	0.116586656	$\pm$0.86780105
	0.066837284	$\pm$0.95993505
	0.010989011	$\pm$1.000000

Table 9.29: LOBATTO_14

9.32 LOBATTO_15

Number of Points - n	Weight - w_i	Abscissa - x_i
15	0.2170481	0.000000
	0.211973586	$\pm$0.21535395
	0.196987236	$\pm$0.42063805
	0.172789647	$\pm$0.60625321
	0.140511699	$\pm$0.76351969
	0.101660070	$\pm$0.88508204
	0.058029893	$\pm$0.96524593
	0.009523809	$\pm$1.000000

Table 9.30: LOBATTO_15

9.33 LOBATTO_16

Number of Points - n	Weight - w_i	Abscissa - x_i
16	0.2019583	$\pm$0.10132627
	0.193690024	$\pm$0.29983047
	0.177491913	$\pm$0.48605942
	0.154026981	$\pm$0.65238870
	0.124255382	$\pm$0.79200829
	0.089393697	$\pm$0.89920053
	0.050850361	$\pm$0.96956805
	0.008333333	$\pm$1.000000

Table 9.31: LOBATTO_16

9.34 SIMPSON_1

This integration type is same as GAUSS_1. See table 9.1

9.35 SIMPSON_3

Number of Points - n	Weight - w_i	Abscissa - x_i
3	1.333333	0.000000
	0.333333	$\pm$1.000000

Table 9.32: SIMPSON_3

9.36 SIMPSON_5

Number of Points - n	Weight - w_i	Abscissa - x_i
5	0.333333	0.000000
	0.666667	$\pm$0.500000
	0.166667	$\pm$1.000000

Table 9.33: SIMPSON_5

9.37 SIMPSON_7

Number of Points - n	Weight - w_i	Abscissa - x_i
7	0.444444	0.000000
	0.222222	$\pm$0.333337
	0.444444	$\pm$0.666667
	0.111111	$\pm$1.000000

Table 9.34: SIMPSON_7

9.38 SIMPSON_9

Number of Points - n	Weight - w_i	Abscissa - x_i
9	0.166667	0.00
	0.333333	$\pm$0.25
	0.166667	$\pm$0.50
	0.333333	$\pm$0.75
	0.083333	$\pm$1.00

Table 9.35: SIMPSON_9

9.39 SIMPSON_11

Number of Points - n	Weight - w_i	Abscissa - x_i
11	0.266667	0.00
	0.133333	$\pm$0.20
	0.266667	$\pm$0.40
	0.133333	$\pm$0.60
	0.266667	$\pm$0.80
	0.066667	$\pm$1.00

Table 9.36: SIMPSON_11

9.40 SIMPSON_13

Number of Points - n	Weight - w_i	Abscissa - x_i
13	0.111111	0.00
	0.222222	$\pm$0.166667
	0.111111	$\pm$0.333333
	0.222222	$\pm$0.50
	0.111111	$\pm$0.666667
	0.222222	$\pm$0.833333
	0.055555	$\pm$1.00

Table 9.37: SIMPSON_13

9.41 SIMPSON_15

Number of Points - n	Weight - w_i	Abscissa - x_i
15	0.190476	0.00
	0.095238	$\pm$0.142857
	0.190476	$\pm$0.285714
	0.095238	$\pm$0.428571
	0.190476	$\pm$0.571428
	0.095238	$\pm$0.714285
	0.190476	$\pm$0.857142
	0.047619	$\pm$1.00

Table 9.38: SIMPSON_15

9.42 TRAPEZOIDAL_1

This integration type is same as GAUSS_1. See table 9.1

9.43 TRAPEZOIDAL_2

Number of Points - n	Weight - w_i	Abscissa - x_i
2	1.0	$\pm$1.0

Table 9.39: TRAPEZOIDAL_2

9.44 TRAPEZOIDAL_3

Number of Points - n	Weight - w_i	Abscissa - x_i
3	1.0	0.0
	0.5	$\pm$1.0

Table 9.40: TRAPEZOIDAL_3

9.45 TRAPEZOIDAL_4

Number of Points - n	Weight - w_i	Abscissa - x_i
4	0.666667	$\pm$0.333333
	0.333333	$\pm$1.0

Table 9.41: TRAPEZOIDAL_4

9.46 TRAPEZOIDAL_5

Number of Points - n	Weight - w_i	Abscissa - x_i
5	0.5	0.0
	0.5	$\pm$0.5
	0.25	$\pm$1.0

Table 9.42: TRAPEZOIDAL_5

9.47 TRAPEZOIDAL_6

Number of Points - n	Weight - w_i	Abscissa - x_i
6	0.4	$\pm$0.199999
	0.4	$\pm$0.6
	0.2	$\pm$1.0

Table 9.43: TRAPEZOIDAL_6

9.48 TRAPEZOIDAL_7

Number of Points - n	Weight - w_i	Abscissa - x_i
7	0.333333	0.0
	0.333333	$\pm$0.333333
	0.333333	$\pm$0.666667
	0.166667	$\pm$1.0

Table 9.44: TRAPEZOIDAL_7

9.49 TRAPEZOIDAL_8

Number of Points - n	Weight - w_i	Abscissa - x_i
8	0.285714	$\pm$0.142857
	0.285714	$\pm$0.428571
	0.285714	$\pm$0.714285
	0.142857	$\pm$1.0

Table 9.45: TRAPEZOIDAL_8

9.50 TRAPEZOIDAL_9

Number of Points - n	Weight - w_i	Abscissa - x_i
9	0.25	0.0
	0.25	$\pm$0.25
	0.25	$\pm$0.50
	0.25	$\pm$0.75
	0.125	$\pm$1.0

Table 9.46: TRAPEZOIDAL_9

9.51 TRAPEZOIDAL_10

Number of Points - n	Weight - w_i	Abscissa - x_i
10	0.222222	$\pm$0.111111
	0.222222	$\pm$0.333333
	0.222222	$\pm$0.555556
	0.222222	$\pm$0.777778
	0.111111	$\pm$1.0

Table 9.47: TRAPEZOIDAL_10

9.52 TRAPEZOIDAL_11

Number of Points - n	Weight - w_i	Abscissa - x_i
11	0.25	0.0
	0.2	$\pm$0.20
	0.2	$\pm$0.40
	0.2	$\pm$0.60
	0.2	$\pm$0.80
	0.1	$\pm$1.0

Table 9.48: TRAPEZOIDAL_11

9.53 TRAPEZOIDAL_12

Number of Points - n	Weight - w_i	Abscissa - x_i
12	0.181818	$\pm$0.09090909
	0.181818	$\pm$0.272727273
	0.181818	$\pm$0.454545455
	0.181818	$\pm$0.636363636
	0.181818	$\pm$0.818181818
	0.090909	$\pm$1.0

Table 9.49: TRAPEZOIDAL_12

9.54 TRAPEZOIDAL_13

Number of Points - n	Weight - w_i	Abscissa - x_i
13	0.166667	0.0
	0.166667	$\pm$0.16666667
	0.166667	$\pm$0.33333333
	0.166667	$\pm$0.5
	0.166667	$\pm$0.66666667
	0.166667	$\pm$0.83333333
	0.083333	$\pm$1.0

Table 9.50: TRAPEZOIDAL_13

9.55 TRAPEZOIDAL_14

Number of Points - n	Weight - w_i	Abscissa - x_i
14	0.153846	± 0.076923
	0.153846	± 0.230769
	0.153846	± 0.384615
	0.153846	± 0.538461
	0.153846	± 0.692307
	0.153846	± 0.846153
	0.076923	± 1.0

Table 9.51: TRAPEZOIDAL_14

9.56 TRAPEZOIDAL_15

Number of Points - n	Weight - w_i	Abscissa - x_i
15	0.14285714285714285	0.0
	0.14285714285714285	± 0.142857
	0.14285714285714285	± 0.285714
	0.14285714285714285	± 0.428571
	0.14285714285714285	± 0.571428
	0.14285714285714285	± 0.714285
	0.14285714285714285	± 0.857142
	0.07142857142857142	± 1.0

Table 9.52: TRAPEZOIDAL_15

9.57 GAUSS_TRIANGLE_1

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i
1	0.5	0.333333	0.333333

Table 9.53: GAUSS_TRIANGLE_1

9.58 GAUSS_TRIANGLE_3

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i
3	0.333333	0.166667	0.166667
	0.333333	0.666667	0.166667
	0.333333	0.166667	0.666667

Table 9.54: GAUSS_TRIANGLE_3

9.59 GAUSS_TRIANGLE_4

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i
4	0.520833	0.2	0.2
	0.520833	0.2	0.6
	0.520833	0.6	0.2
	-0.5625	0.333333	0.333333

Table 9.55: GAUSS_TRIANGLE_4

9.60 GAUSS_TRIANGLE_6

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i
6	0.109951743655322	0.091576213509771	0.091576213509771
	0.109951743655322	0.816847572980459	0.091576213509771
	0.109951743655322	0.091576213509771	0.816847572980459
	0.223381589678011	0.445948490915965	0.108103018168070
	0.223381589678011	0.445948490915965	0.445948490915965
	0.223381589678011	0.108103018168070	0.445948490915965

Table 9.56: GAUSS_TRIANGLE_6

9.61 GAUSS_QUAD_1

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i
1	4.0	0.0	0.0

Table 9.57: GAUSS_QUAD_1

9.62 GAUSS_QUAD_4

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i
4	1.0	-0.5773502691896257	-0.5773502691896257
	1.0	0.5773502691896257	-0.5773502691896257
	1.0	-0.5773502691896257	0.5773502691896257
	1.0	0.5773502691896257	0.5773502691896257

Table 9.58: GAUSS_QUAD_4

9.63 GAUSS_QUAD_9

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i
9	0.308641976	-0.7745966692414834	-0.7745966692414834
	0.493827161	0.0	-0.7745966692414834
	0.308641976	0.7745966692414834	-0.7745966692414834
	0.493827161	-0.7745966692414834	0.0
	0.790123457	0.0	0.0
	0.493827161	0.7745966692414834	0.0
	0.308641976	-0.7745966692414834	0.7745966692414834
	0.493827161	0.0	0.7745966692414834
	0.308641976	0.7745966692414834	0.7745966692414834

Table 9.59: GAUSS_QUAD_9

9.64 NODES_TRIANGLE_3

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i
3	0.166667	0.000000	0.000000
	0.166667	1.000000	0.000000
	0.166667	0.000000	1.000000

Table 9.60: NODES_TRIANGLE_3

9.65 NODES_TRIANGLE_6

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i
6	0.000000	0.000000	0.000000
	0.000000	1.000000	0.000000
	0.000000	0.000000	1.000000
	0.166667	0.500000	0.000000
	0.166667	0.500000	0.500000
	0.166667	0.000000	0.500000

Table 9.61: NODES_TRIANGLE_6

9.66 NODES_QUAD_4

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i
4	1.000000	-1.000000	-1.000000
	1.000000	1.000000	-1.000000
	1.000000	1.000000	1.000000
	1.000000	-1.000000	1.000000

Table 9.62: NODES_QUAD_4

9.67 NODES_QUAD_8

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i
8	-0.333333	-1.000000	-1.000000
	-0.333333	1.000000	-1.000000
	-0.333333	1.000000	1.000000
	-0.333333	-1.000000	1.000000
	1.333333	0.000000	-1.000000
	1.333333	1.000000	0.000000
	1.333333	0.000000	1.000000
	1.333333	-1.000000	0.000000

Table 9.63: NODES_QUAD_8

9.68 NODES_QUAD_9

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i
9	0.111111	-1.000000	-1.000000
	0.111111	1.000000	-1.000000
	0.111111	1.000000	1.000000
	0.111111	-1.000000	1.000000
	0.444444	0.000000	-1.000000
	0.444444	1.000000	0.000000
	0.444444	0.000000	1.000000
	0.444444	-1.000000	0.000000
	1.777778	0.000000	0.000000

Table 9.64: NODES_QUAD_9

9.69 GAUSS_LAYERED_HEXAHEDRON_4

to be defined.....

9.70 GAUSS_TETRAHEDRON_1

Please refer to Figure 8.12 for node locations.

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i	Abscissa - z_i
1	0.166667	0.250000	0.250000	0.250000

Table 9.65: GAUSS_TETRAHEDRON_1

9.71 GAUSS_TETRAHEDRON_4

Please refer to Figure 8.12 for node locations.

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i	Abscissa - z_i
4	0.0416667	0.1381966	0.1381966	0.1381966
	0.0416667	0.5854102	0.1381966	0.1381966
	0.0416667	0.1381966	0.5854102	0.1381966
	0.0416667	0.1381966	0.1381966	0.5854102

Table 9.66: GAUSS_TETRAHEDRON_4

9.72 GAUSS_TETRAHEDRON_8

Please refer to Figure 8.12 for node locations.

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i	Abscissa - z_i
8	0.020833	0.131445	0.166666	0.211325
	0.020833	0.490562	0.166666	0.211325
	0.020833	0.035221	0.622008	0.211325
	0.020833	0.131446	0.622008	0.211325
	0.020833	0.035221	0.044658	0.788675
	0.020833	0.131446	0.044658	0.788675
	0.020833	0.009437	0.166667	0.788675
	0.020833	0.035221	0.166667	0.788675

Table 9.67: GAUSS_TETRAHEDRON_8

9.73 GAUSS_TETRAHEDRON_11

Please refer to Figure 8.12 for node locations.

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i	Abscissa - z_i
11	-0.013156	0.250000	0.250000	0.250000
	0.007622	0.071429	0.071429	0.071429
	0.007622	0.785714	0.071429	0.071429
	0.007622	0.071429	0.785714	0.071429
	0.007622	0.071429	0.071429	0.785714
	0.024889	0.100596	0.399404	0.100596
	0.024889	0.399404	0.399404	0.100596
	0.024889	0.399404	0.100596	0.100596
	0.024889	0.100596	0.100596	0.399404
	0.024889	0.399404	0.100596	0.399404
	0.024889	0.100596	0.399404	0.399404

Table 9.68: GAUSS_TETRAHEDRON_11

9.74 GAUSS_TETRAHEDRON_15

Please refer to Figure 8.12 for node locations.

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i	Abscissa - z_i
15	0.019753	0.250000	0.250000	0.250000
	0.011989	0.091971	0.091971	0.091971
	0.011989	0.724087	0.091971	0.091971
	0.011989	0.091971	0.724087	0.091971
	0.011989	0.091971	0.091971	0.724087
	0.011511	0.319794	0.319794	0.319794
	0.011511	0.040619	0.319794	0.319794
	0.011511	0.319794	0.040619	0.319794
	0.011511	0.319794	0.319794	0.040619
	0.008818	0.056351	0.056351	0.443649
	0.008818	0.443649	0.056351	0.056351
	0.008818	0.443649	0.443649	0.056351
	0.008818	0.056351	0.443649	0.443649
	0.008818	0.056351	0.443649	0.056351
	0.008818	0.443649	0.056351	0.443649

Table 9.69: GAUSS_TETRAHEDRON_15

9.75 GAUSS_PYRAMID_1

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i	Abscissa - z_i
1	1.33	0.0	0.0	0.25

Table 9.70: GAUSS_PYRAMID_1

9.76 GAUSS_PYRAMID_5

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i	Abscissa - z_i
5	0.28	∓ 0.487950036474	-0.487950036474	0.165484574527
	0.28	± 0.487950036474	0.487950036474	0.165484574527
	0.213333	0.0	0.0	0.693705983732

Table 9.71: GAUSS_PYRAMID_5

9.77 GAUSS_PYRAMID_9

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i	Abscissa - z_i
9	0.183429925248	-0.526421704396	∓ 0.526421704396	0.087476609247
	0.140354060819	-0.335885351395	∓ 0.335885351395	0.420881747524
	0.140354060819	0.335885351395	± 0.335885351395	0.420881747524
	0.183429925248	0.526421704396	± 0.526421704396	0.087476609247
	0.038197389067	0.0	0.0	0.860272730596

Table 9.72: GAUSS_PYRAMID_9

9.78 GAUSS_WEDGE_1

Please refer to Figure 8.19 for node locations.

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i	Abscissa - z_i
1	1.000000	0.333333	0.333333	0.000000

Table 9.73: GAUSS_WEDGE_1

9.79 GAUSS_WEDGE_2

Please refer to Figure 8.19 for node locations.

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i	Abscissa - z_i
2	0.500000	0.333333	0.333333	∓ 0.577350

Table 9.74: GAUSS_WEDGE_2

9.80 GAUSS_WEDGE_6

Please refer to Figure 8.19 for node locations.

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i	Abscissa - z_i
6	0.166667	0.166667	0.166667	-0.577334
	0.166667	0.666667	0.166667	-0.577334
	0.166667	0.166667	0.666667	-0.577334
	0.166667	0.166667	0.166667	0.577334
	0.166667	0.666667	0.166667	0.577334
	0.166667	0.166667	0.666667	0.577334

Table 9.75: GAUSS_WEDGE_6

9.81 GAUSS_WEDGE_8

Please refer to Figure 8.19 for node locations.

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i	Abscissa - z_i
8	0.125	0.166667	0.211325	-0.57735
	0.125	0.622008	0.211325	-0.57735
	0.125	0.044658	0.788675	-0.57735
	0.125	0.166667	0.788675	-0.57735
	0.125	0.166667	0.211325	0.57735
	0.125	0.622008	0.211325	0.57735
	0.125	0.044658	0.788675	0.57735
	0.125	0.166667	0.788675	0.57735

Table 9.76: GAUSS_WEDGE_8

9.82 GAUSS_WEDGE_9

Please refer to Figure 8.19 for node locations.

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i	Abscissa - z_i
9	0.092593	0.166667	0.166667	−0.774597
	0.092593	0.666667	0.166667	−0.774597
	0.092593	0.166667	0.666667	−0.774597
	0.148148	0.166667	0.166667	0.0
	0.148148	0.666667	0.166667	0.0
	0.148148	0.166667	0.666667	0.0
	0.092593	0.166667	0.166667	0.774597
	0.092593	0.666667	0.166667	0.774597
	0.092593	0.166667	0.666667	0.774597

Table 9.77: GAUSS_WEDGE_9

9.83 GAUSS_WEDGE_18

Please refer to figure 8.19 for node locations.

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i	Abscissa - z_i
18	0.030542	0.091576	0.091576	−0.774597
	0.030542	0.816848	0.091576	−0.774597
	0.030542	0.091576	0.816848	−0.774597
	0.062050	0.445948	0.108103	−0.774597
	0.062050	0.445948	0.445948	−0.774597
	0.062050	0.108103	0.445948	−0.774597
	0.048867	0.091576	0.091576	0.0
	0.048867	0.816848	0.091576	0.0
	0.048867	0.091576	0.816848	0.0
	0.099281	0.445948	0.108103	0.0
	0.099281	0.445948	0.445948	0.0
	0.099281	0.108103	0.445948	0.0
	0.030542	0.091576	0.091576	0.774597
	0.030542	0.816848	0.091576	0.774597
	0.030542	0.091576	0.816848	0.774597
	0.062050	0.445948	0.108103	0.774597
	0.062050	0.445948	0.445948	0.774597
	0.062050	0.108103	0.445948	0.774597

Table 9.78: GAUSS_WEDGE_18

9.84 GAUSS_HEXAHEDRON_1

Please refer to figure 8.21 for node locations.

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i	Abscissa - z_i
1	8.0	0.0	0.0	0.0

Table 9.79: GAUSS_HEXAHEDRON_1

9.85 GAUSS_HEXAHEDRON_8

Please refer to figure 8.21 for node locations.

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i	Abscissa - z_i
8	1.0	-0.57735026918962	-0.57735026918962	-0.57735026918962
	1.0	0.57735026918962	-0.57735026918962	-0.57735026918962
	1.0	-0.57735026918962	0.57735026918962	-0.57735026918962
	1.0	0.57735026918962	0.57735026918962	-0.57735026918962
	1.0	-0.57735026918962	-0.57735026918962	0.57735026918962
	1.0	0.57735026918962	-0.57735026918962	0.57735026918962
	1.0	-0.57735026918962	0.57735026918962	0.57735026918962
	1.0	0.57735026918962	0.57735026918962	0.57735026918962

Table 9.80: GAUSS_HEXAHEDRON_8

9.86 GAUSS_HEXAHEDRON_27

Please refer to figure 8.21 for node locations.

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i	Abscissa - z_i
27	0.17146776	-0.77459666924148	-0.77459666924148	-0.77459666924148
	0.27434842	0.0	-0.77459666924148	-0.77459666924148
	0.17146776	0.77459666924148	-0.77459666924148	-0.77459666924148
	0.27434842	-0.77459666924148	0.0	-0.77459666924148
	0.43895748	0.0	0.0	-0.77459666924148
	0.27434842	0.77459666924148	0.0	-0.77459666924148
	0.17146776	-0.77459666924148	0.77459666924148	-0.77459666924148
	0.27434842	0.0	0.77459666924148	-0.77459666924148
	0.17146776	0.77459666924148	0.77459666924148	-0.77459666924148
	0.27434842	-0.77459666924148	-0.77459666924148	0.0
	0.43895748	0.0	-0.77459666924148	0.0
	0.27434842	0.77459666924148	-0.77459666924148	0.0
	0.43895748	-0.77459666924148	0.0	0.0
	0.70233196	0.0	0.0	0.0
	0.43895748	0.77459666924148	0.0	0.0
	0.27434842	-0.77459666924148	0.77459666924148	0.0
	0.43895748	0.0	0.77459666924148	0.0
	0.27434842	0.77459666924148	0.77459666924148	0.0
	0.17146776	-0.77459666924148	-0.77459666924148	0.77459666924148
	0.27434842	0.0	-0.77459666924148	0.77459666924148
	0.17146776	0.77459666924148	-0.77459666924148	0.77459666924148
	0.27434842	-0.77459666924148	0.0	0.77459666924148
	0.43895748	0.0	0.0	0.77459666924148
	0.27434842	0.77459666924148	0.0	0.77459666924148
	0.17146776	-0.77459666924148	0.77459666924148	0.77459666924148
	0.27434842	0.0	0.77459666924148	0.77459666924148
	0.17146776	0.77459666924148	0.77459666924148	0.77459666924148

Table 9.81: GAUSS_HEXAHEDRON_8

9.87 NODES_TETRAHEDRON_4

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i	Abscissa - z_i
4	0.041666	0.0	0.0	0.0
	0.041666	1.0	0.0	0.0
	0.041666	0.0	1.0	0.0
	0.041666	0.0	0.0	1.0

Table 9.82: NODES_TETRAHEDRON_4

9.88 NODES_TETRAHEDRON_10

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i	Abscissa - z_i
10	-0.008333	0.0	0.0	0.0
	-0.008333	1.0	0.0	0.0
	-0.008333	0.0	1.0	0.0
	-0.008333	0.0	0.0	1.0
	0.033333	0.5	0.0	0.0
	0.033333	0.5	0.5	0.0
	0.033333	0.0	0.5	0.0
	0.033333	0.0	0.0	0.5
	0.033333	0.5	0.0	0.5
	0.033333	0.0	0.5	0.5

Table 9.83: NODES_TETRAHEDRON_10

9.89 NODES_WEDGE_6

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i	Abscissa - z_i
6	0.166667	0.0	0.0	-1.0
	0.166667	1.0	0.0	-1.0
	0.166667	0.0	1.0	-1.0
	0.166667	0.0	0.0	1.0
	0.166667	1.0	0.0	1.0
	0.166667	0.0	1.0	1.0

Table 9.84: NODES_WEDGE_6

9.90 NODES_WEDGE_15

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i	Abscissa - z_i
15	-0.111111	0.0	0.0	-1.0
	-0.111111	1.0	0.0	-1.0
	-0.111111	0.0	1.0	-1.0
	-0.111111	0.0	0.0	1.0
	-0.111111	1.0	0.0	1.0
	-0.111111	0.0	1.0	1.0
	0.166667	0.5	0.0	-1.0
	0.166667	0.5	0.5	-1.0
	0.166667	0.0	0.5	-1.0
	0.166667	0.5	0.0	1.0
	0.166667	0.5	0.5	1.0
	0.166667	0.0	0.5	1.0
	0.222222	0.0	0.0	0.0
	0.222222	1.0	0.0	0.0
	0.222222	0.0	1.0	0.0

Table 9.85: NODES_WEDGE_15

9.91 NODES_PYRAMID_5

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i	Abscissa - z_i
5	0.250000	∓ 1.0	-1.0	0.0
	0.250000	± 1.0	1.0	0.0
	0.333333	0.0	0.0	1.0

Table 9.86: NODES_PYRAMID_5

9.92 NODES_HEXAHEDRON_8

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i	Abscissa - z_i
8	1.0	∓ 1.0	-1.0	-1.0
	1.0	± 1.0	1.0	-1.0
	1.0	∓ 1.0	-1.0	1.0
	1.0	± 1.0	1.0	1.0

Table 9.87: NODES_HEXAHEDRON_8

9.93 NODES_HEXAHEDRON_20

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i	Abscissa - z_i
20	-1.0	∓ 1.0	-1.0	-1.0
	-1.0	± 1.0	1.0	-1.0
	-1.0	∓ 1.0	-1.0	1.0
	-1.0	± 1.0	1.0	1.0
	1.333333	0.0	-1.0	-1.0
	1.333333	1.0	0.0	-1.0
	1.333333	0.0	1.0	-1.0
	1.333333	-1.0	0.0	-1.0
	1.333333	0.0	-1.0	1.0
	1.333333	1.0	0.0	1.0
	1.333333	0.0	1.0	1.0
	1.333333	-1.0	0.0	1.0
	1.333333	∓ 1.0	-1.0	0.0
	1.333333	± 1.0	1.0	0.0

Table 9.88: NODES_HEXAHEDRON_20

9.94 NODES_HEXAHEDRON_27

Number of Points - n	Weight - w_i	Abscissa - x_i	Abscissa - y_i	Abscissa - z_i
27	0.037037	∓ 1.0	-1.0	-1.0
	0.037037	± 1.0	1.0	-1.0
	0.037037	∓ 1.0	-1.0	1.0
	0.037037	± 1.0	1.0	1.0
	0.148148	0.0	-1.0	-1.0
	0.148148	1.0	0.0	-1.0
	0.148148	0.0	1.0	-1.0
	0.148148	-1.0	0.0	-1.0
	0.148148	0.0	-1.0	1.0
	0.148148	1.0	0.0	1.0
	0.148148	0.0	1.0	1.0
	0.148148	-1.0	0.0	1.0
	0.148148	∓ 1.0	-1.0	0.0
	0.148148	± 1.0	1.0	0.0
	2.370370	0.0	0.0	0.0
	0.592592	0.0	0.0	∓ 1.0
	0.592592	0.0	-1.0	0.0
	0.592592	1.0	0.0	0.0
	0.592592	0.0	1.0	0.0
	0.592592	-1.0	0.0	0.0

Table 9.89: NODES_HEXAHEDRON_27

9.95 Combined Integration Types

A Combined Integration Type is used for 3D shell elements, where 2D Integration Type is used for In-Plane & 1D Integration Type is used for Out-of-Plane. The definition is as follows:

$$\mathbf{IN-PLANE} \times \mathbf{OUT-OF-PLANE}$$

The numbering for combined type starts from 100000.

9.96 Composite Integration Types

A Composite Integration type can be built using the function `createVMAPComposite-IntegrationType`. It requires the following parameters:

- Number of Composite Layers
- list of integration rule per layer
- list of thicknesses per layer

Chapter 10

Tutorials

This chapter provides tutorials for VMAP I/O Lib in C++.

10.1 Creating or Opening a VMAP .h5 File

VMAPFile::openFile(const std::string & path, int mode)

Function that creates or opens a file based on the mode supplied. The three available modes are:

- **CREATEORREPLACE = 0**, creates new file or overwrite existing. This is the default mode.
- **OPENREADWRITE = 1**, opens existing file with read/write access.
- **OPENREADONLY = 2**, opens existing file with read only access.

10.1.1 Parameters:

- `path` - Local path to file location.
- `mode` - eFileOpenMode to access the file.

10.1.2 Returns:

On success,

with mode CREATEORREPLACE:
A VMAP .h5 file, with four groups, VMAP Group, and three sub-groups within VMAP - GEOMETRY, MATERIAL, VARIABLE & SYSTEM. In addition, the VERSION attribute is created to the VMAP Group and initialized with the current version of VMAP Standard I/O Library being used.

with mode OPENREADWRITE:

Opens the given file in read and write mode. In addition, provides details of the VMAP version of the file and throws an error if the major, minor or patch version is older than the VMAP Standard I/O Library version.

with mode OPENREADONLY:

Opens the given file in read only mode. In addition, provides details of the VMAP version of the file and throws an error if the major, minor or patch version is older than the VMAP Standard I/O Library version.

On failure, doesn't open any file and provides information about possible errors.

The snippet below shows how to use the VMAPFile module to open or create VMAP .h5 file.

10.2 closing a VMAP .h5 File

VMAPFile::closeFile()

Function tries to close a VMAP file.

10.2.1 Returns:

On success,

closes the file.

On failure,

throws an exception.

10.3 Create a Group in VMAP File

VMAPFile::createGroup(const std::string & groupName)

Function that creates a group in the VMAP file.

10.3.1 Parameters:

- `groupName` - Name of the HDF Group to create.

10.3.2 Returns:

On success,

creates the group with the given group name.

On failure,

checks if the Group name already exists then opens that group in the VMAP file.

10.4 Get Sub-Groups from VMAP File

std::vector<std::string> VMAPFile::getSubGroups(const std::string & groupName)

Collects all the sub-groups for the given `groupName`

10.4.1 Parameters:

- `groupName` - Name of the HDF Group to get sub-groups from.

10.4.2 Returns:

On success,

get the list of sub groups.

On failure,

catches failures caused by H5 operations.

10.5 Check if a Group exists in VMAP File

bool VMAPFile::existsGroup(const std::string & groupName)

Check is a group exists in a given `groupName`.

10.5.1 Parameters:

- `groupName` - Name of the HDF Group to check in.

10.5.2 Returns:

On success,

returns `True` if the group exists.

On failure,

catches failures caused by H5 operations.

10.6 Write the Version to VMAP File

VMAPFile::writeVersion(const sVersion & version)

Function that creates VERSION attribute in group '/VMAP/' and sets the value of VERSION parameters. This function is run automatically, when a new file is created. This function is called in the VMAPFile::openFile, which is called by the constructor VMAPFile (10.1).

10.6.1 Parameters:

- `version` - Data structure containing the sVersion.

10.6.2 Returns:

On success,

sets the version of VMAP Standard I/O Library to the VERSION attribute in '/VMAP/' group.

On failure,

prints error.

10.7 Read the Version of VMAP File

VMAPFile::readVersion(sVersion & version)

Function that reads VERSION attribute from group '/VMAP/' and stores content in sVersion. This function is run automatically when an existing file is opened. This function is called in the VMAPFile::openFile, which is called by the constructor VMAPFile (10.1).

10.7.1 Parameters:

- `version` - Data structure read from VMAP file.

10.7.2 Returns:

On success,

returns the version stored in VERSION attribute from '/VMAP/' group.

On failure,

prints error.

10.8 Write the Meta Information to VMAP File

VMAPFile::writeMetaInformation(const sMetaInformation & metaInfo)

Function that creates METADATA dataset in group '/VMAP/SYSTEM/' and sets the values in the METADATA dataset.

10.8.1 Parameters:

- `metaInfo` - Data structure containing the sMetaInformation.

10.8.2 Returns:

On success,

> sets the meta information from the original file to the METADATA dataset in '/VMAP/SYSTEM/' group.

On failure,

> prints error.

more tutorials to be defined.....

Chapter 11

Simple Test Cases

11.1 Break Forming of a Metal Bracket

This test case shows interoperability between Abaqus $\longleftrightarrow$ LS-DYNA using VMAP Standard Specifications.

11.1.1 General Description of the test case "Break Forming of a Metal Bracket"

A flat sheet is formed into an angled bracket by punching it through a hole in a table using a cylindrical punch. After the punch has reached its maximum stroke, the elastic spring-back is computed. The material is elastic-plastic with work hardening.

The analysis consists of two stages. The first stage, in which the punch drives the sheet down into the hole, is a large strain quasi-static contact analysis. The second stage, in which the spring-back is computed, is a large strain quasi-static analysis. In both stages, the sheet is subject to gravity. Plane strain conditions are assumed. Furthermore, plane strain conditions are assumed and the additive decomposition of the incremental strain tensor into an elastic and plastic part is used in the plasticity calculation.

Model description

The model is depicted below in figure 11.1 . It consists of three bodies: a sheet, a punch and a table with a hole. The dimensions of the sheet are:

length : $1.8''$
thickness : $0.1''$

The material properties are given by:

Young's modulus $E = 30 \times 10^6 Psi$
Poisson's ratio $\upsilon = 0.3$
Yield stress $\sigma_y = 5 \times 10^4 (1 + \overline{\epsilon_{\mathrm{p}}}^{0.6}) Psi$

Mass density $\rho = 7.36 \times 10^{-4}(lbf \cdot s^2)/in^4$

Here, $\overline{\epsilon_p}$ is the total equivalent plastic strain. The radius of the punch is $0.1''$ and the size of the hole in the table is $0.6''$. Both the punch and the table are assumed much stiffer than the sheet, such that they can be modelled as rigid (contact) bodies.

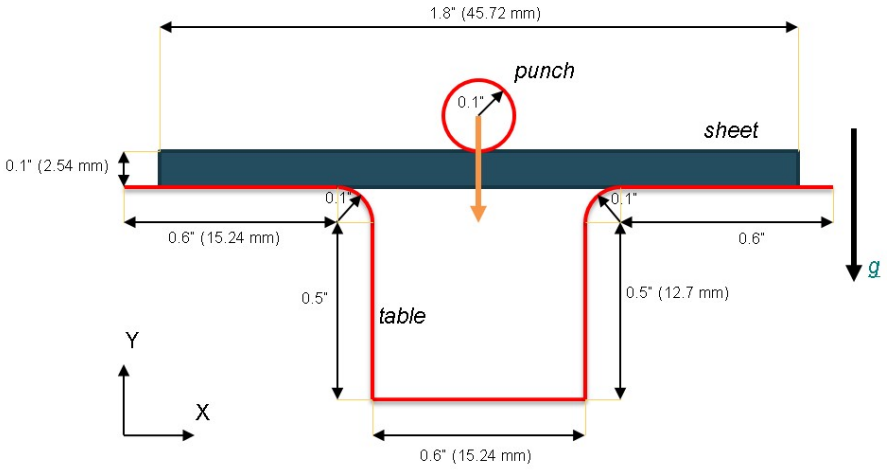

Figure 11.1: Model setup overview

Model Set-up for Step-1: Application of Force

Step-1 is carried out using Abaqus 2016 The sheet is modeled by $1.8'' \times 0.1''$ fully integrated bilinear plane strain elements.

In the first stage of the analysis, the punch drives the sheet down into the hole (i.e. in the negative Y-direction), to a total stroke of $0.3''$ and at a constant pace $(0.6''/s)$. Frictionless contact conditions are defined between the sheet and the punch and between the sheet and the table. The sheet is subjected to gravitational forces acting in the negative Y-direction. The acceleration due to gravity is given by $386.1in/s^2$ The displacements of the nodes in the center of the sheet, right above the center of the hole are suppressed in the horizontal direction (X-direction).

Constraints

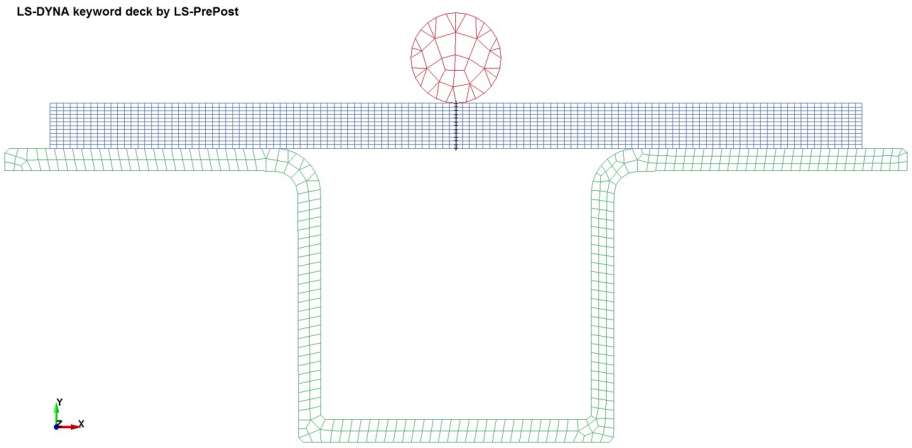

Figure 11.2: Forming simulation constraints. x-translation of the middle nodes are constrained.

Model Set-up for Step-2: Break forming

Step-2 is carried out using LS-DYNA r11.1 In the second stage, the contact conditions and the boundary condition on the center nodes are removed and are replaced by two boundary conditions that suppress the rigid body modes: at two nodes at the center of the sheet, the displacements in X-direction are suppressed and at one of these nodes, the displacement in Y-direction is suppressed as well. In addition, the sheet is subject to gravitation acting in the negative Y-direction. Other than that, no other loads or boundary conditions are applied to the sheet in this stage.

Constraints

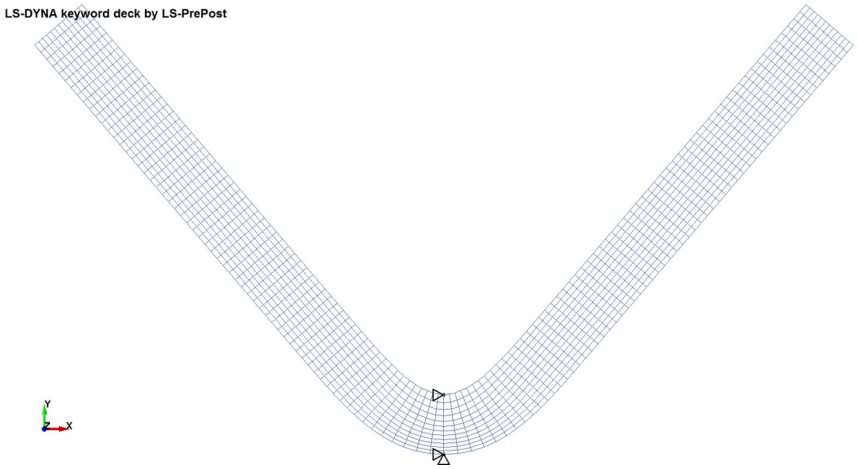

Figure 11.3: Spring-back analysis boundary conditions

Variables Transferred from Step-1 to Step-2

The following data must be transferred at a minimum from the first stage to the second stage in order to compute the spring-back in the latter:

- Nodal coordinates;
- Nodal displacements;
- Element connectivity;
- The four non-zero components of the stress tensor ($\sigma_{xx}, \sigma_{yy}, \sigma_{zz}, \sigma_{xy}$) at the integration points of the elements;
- The total equivalent plastic strain ($\overline{\epsilon_{\mathrm{p}}}$) at the integration points of the elements;

The following quantities are not required for a successful calculation of the spring-back, but may optionally be transferred for post-processing purposes in the second stage:

- Material model dependent history variables.

11.1.2 Software Implementation

Methodology

The two stages are solved in two separate runs. At the end of the first stage, the data listed in Sec. 11.1.1 is saved into a VMAP file, which is then imported into the second stage to define the initial state for the spring-back analysis. For any given solver, the VMAP implementation can be validated by comparing the results of the multi-stage analysis with those of a run in which the two stages are solved in a single analysis.

Software Tool

Step-1 - Abaqus Standard

Step-2 - LS-DYNA and LSPP were used (LS-DYNA is the Finite Element solver, LS-PrePost (LSPP) is the associated pre and post processor).

11.1.3 Results

Simulation Results

Step-1: Result of forming simulation

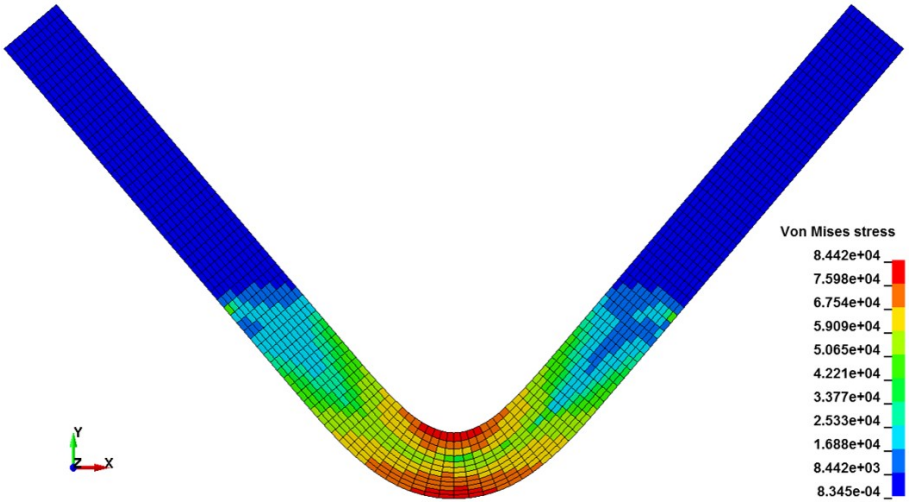

Figure 11.4: Abaqus solver von Mises stress

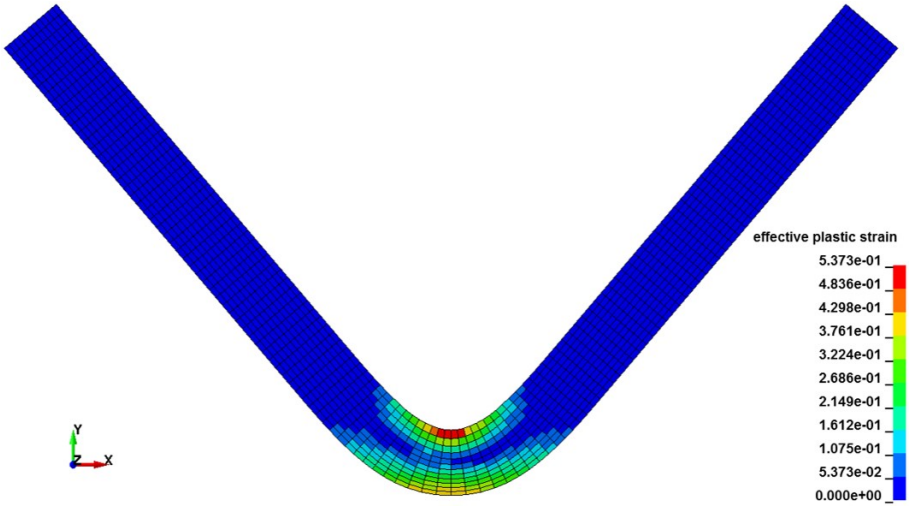

Figure 11.5: Abaqus solver effective plastic strain

Step-2: Spring-back simulation in LS-DYNA after reading Abaqus results in VMAP format

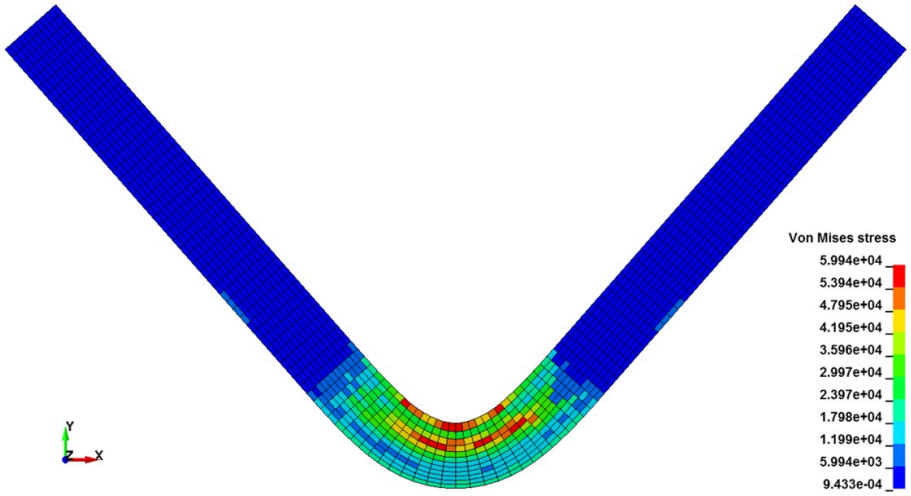

Figure 11.6: LS-DYNA solver spring-back simulation using Abaqus wrapper VMAP file – von Mises stress

Relevant images with referencing

The residual von Mises stress distribution at the end of the second stage after the spring-back is shown in Figure 11.6

Figure 11.7: To measure the spring-back, the displacement in X-direction of the node in the top-left corner of the sheet is plotted as a function of time in the figure below. The red curve shows the displacement of the node after Step-2, when Step-1 is carried out using LS-DYNA as well, while the green curve shows the displacement after Step-2 when Step-1 is carried out using Abaqus. The effect of the spring-back on the displacement of this node is apparent and amounts to $-0.0114''$.

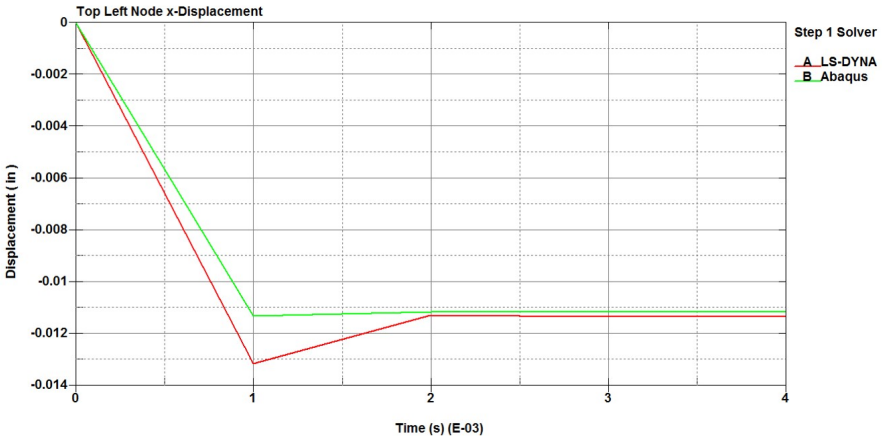

Figure 11.7: Comparison of top left node x-displacement during spring-back simulation

Related analytical results / Reliable experimental results

There are no analytical or experimental results available for this test case.

Evaluation and Validation

Splitting the analysis in two parts and evaluating the second part using the Model Section of the first part gives the same results as when running the analysis as a single model.

Abaqus
In Abaqus the analysis is performed in one step or in two steps. For a two-step run where LS-DYNA is used for Step-1, read the initial stresses and initial plastic strains from the VMAP file and prescribe them as initial conditions in the analysis using SIGINI and HARDINI. The solution obtained via single run in Abaqus can be used as a reference solution for the VMAP implementation in Abaqus.
Comparison of top left node x-displacement using Abaqus as a reference solver.

Simulation Steps	Solver	Result (% error)
Single Step	Abaqus	-0.011311 in
UsingAbaqus for Step-1, changing solvers for Step-2.		
Step-2	Abaqus	-0.0113148 in (0.03%)
Step-2	LS-DYNA	-0.011097 in (1.89%)

LS-DYNA

Comparison of top left node x-displacement using LS-DYNA as a reference solver.

Simulation Steps	Solver	Result (% error)
Single Step	LS-DYNA	-0.0113 in
Using LS-DYNA for Step-1, changing solvers for Step-2.		
Step-2	LS-DYNA	-0.0113 in (0)
Step-2	Abaqus	-0.0112 inch (1.55%)

VMAP Result File

The image below shows a sample VMAP file used to transfer data from Abaqus to LS-DYNA

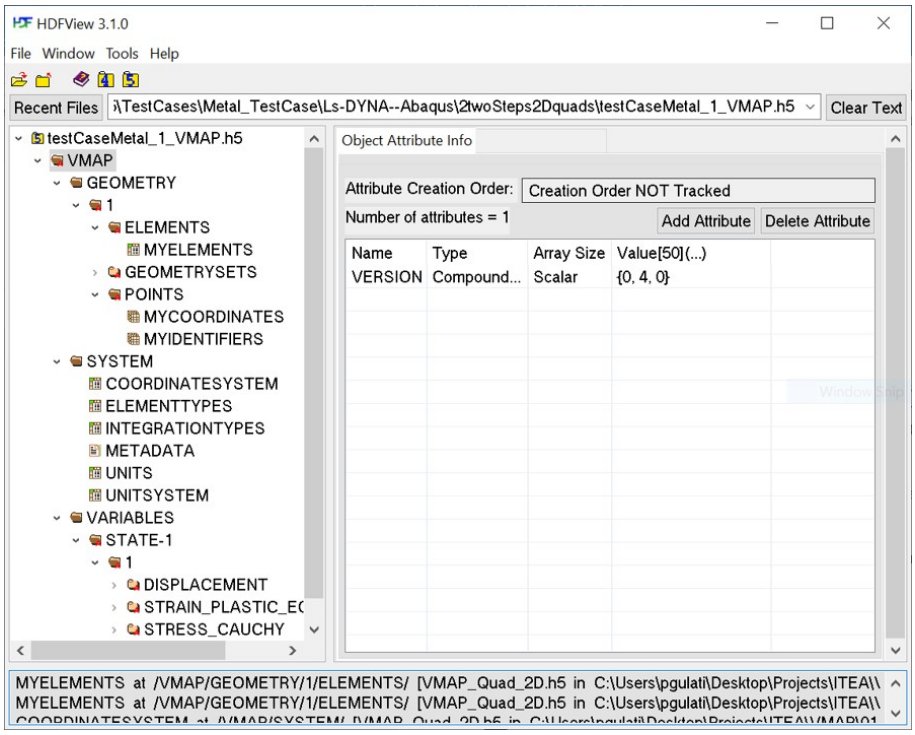

Figure 11.8: VMAP file generated from Abaqus ODB

11.1.4 Extension of the test case “Break Forming of a Metal Bracket”

Mesh Based Extensions

A few mesh based extension of this test case are also available for Abaqus.

- A mixed Quad & Tria- element mesh.
- 3D Hexahedron mesh
- 3D Quadratic Tetrahedral mesh

more simple test cases to be defined.....

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[5] SWIG - Simplified Wrapper and Interface Generator
http://www.swig.org/

Appendix A

Project Funding

The project is organised via the ITEA programme and funded by national regional agencies and companies over the period from October 2017 to September 2020. The total budget is about 16M€ for the 30 project partners from Austria, Belgium, Canada, Germany (including NAFEMS), Netherlands and Switzerland.

ITEA is the EUREKA Cluster programme supporting innovative, industry-driven, pre-competitive R& D projects in the area of Software-intensive Systems & Services (SiSS). ITEA stimulates projects in an open community of large industry, SMEs, universities, research institutes and user organisations.

As ITEA is a EUREKA Cluster, the community is founded in Europe based on the EUREKA principles and is open to participants worldwide.

The **Austrian part** of the joint project is funded by the Austrian Research Promotion Agency (FFG) (number: Projekt 864080 – EUREKA ITEA 3 2017 VMAP Moulding).

The **Belgian part** of the joint project is funded by the companies partaking.

The **Canadian part** of the joint project is funded by the Scientific Research and Development Tax Credit Program (SR& ED)

The **German part** of the joint project is funded by the German Federal Ministry of Education and Research (BMBF) with 3.5 million euros via the ITEA 3 cluster of the European research initiative EUREKA. (number: DLR-Projektträger, Softwaresysteme und Wissenstechnologien – Funding Sign 01|S17025 A – K).

The **Netherlands part** of the joint project is funded by the Netherlands Enterprise Agency

The **Swiss part** of the joint project is funded by the companies partaking.

Project Key Data

ACRONYM and full-length title

16010	VMAP
Program Call	ITEA 3 Call 3
Full-length Title	A new interface Standard for Integrated Virtual Material Modelling in Manufacturing Industry
Roadmap Challenge	Smart Industry

Project duration & size

Size	Effort: 119.62 PY Costs: 14.9M€
Time frame	Start: 2019-09-01 End: 2020-09-30 (37 months)

Coordinator

Germany	Fraunhofer SCAI
Type	Research Institute
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Consortium

Austria	4a engineering GmbH, Wittmann Battenfeld GmbH
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