Formalizing Structured File Services
for the Data Storage and Retrieval
Subsystem of the Data Management
System for Spacestation Freedom

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Research Institute for Computing and Information Systems
University of Houston-Clear Lake

FINAL REPORT
The RICIS Concept

The University of Houston-Clear Lake established the Research Institute for Computing and Information Systems (RICIS) in 1986 to encourage the NASA Johnson Space Center (JSC) and local industry to actively support research in the computing and information sciences. As part of this endeavor, UHCL proposed a partnership with JSC to jointly define and manage an integrated program of research in advanced data processing technology needed for JSC's main missions, including administrative, engineering and science responsibilities. JSC agreed and entered into a continuing cooperative agreement with UHCL beginning in May 1986, to jointly plan and execute such research through RICIS. Additionally, under Cooperative Agreement NCC 9-16, computing and educational facilities are shared by the two institutions to conduct the research.

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A major role of RICIS then is to find the best match of sponsors, researchers and research objectives to advance knowledge in the computing and information sciences. RICIS, working jointly with its sponsors, advises on research needs, recommends principals for conducting the research, provides technical and administrative support to coordinate the research and integrates technical results into the goals of UHCL, NASA/JSC and industry.
Formalizing Structured File Services for the Data Storage and Retrieval Subsystem of the Data Management System for Spacestation Freedom
RICIS Preface

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1 Introduction

This report presents a brief example of the use of formal methods techniques in the specification of a software system. The report is part of a larger effort targeted at defining a formal methods pilot project for NASA. This report’s purpose is to present one possible application domain that may be used to demonstrate the effective use of formal methods techniques within the NASA environment. It is not intended to provide a tutorial on either formal methods techniques or the application being addressed. It should, however, provide an indication that the application being considered is suitable for a formal methods by showing how such a task may be started.

The particular system being addressed is the Structured File Services (SFS), which is a part of the Data Storage and Retrieval Subsystem (DSAR), which in turn is part of the Data Management System (DMS) onboard Spacestation Freedom [1]. This is a software system that is currently under development for NASA.
An informal mathematical development is presented in the section 2. Section 3 contains the same development using Penelope [23], an Ada specification and verification system. The complete text of the English version Software Requirements Specification (SRS) is reproduced in Appendix A.

2 An Informal Mathematical Model

In beginning the task of formally describing a computer system, a specifier of the system will initially develop an informal mathematical model. In developing the informal model the specifier will naturally use common intuitive notions from mathematics. Set theory and function theory will be used to describe the behavior of the SFS. Describing the system in terms of its state and how the system may transition from one state to another is also a common technique that we will use. While the use of these techniques will be informal and ad hoc, the next section will use a formal notation for describing the SFS that reflects the developments in this section.

We begin by examining the processing requirements placed on the SFS. These are captured in a series of shalls written in plain english text.

Shall 1 SFS shall (1) create a structured file upon request from the software user.

The first shall introduces several terms. To model these terms, we introduce several definitions.

- The set \( \text{USER} \) is the set of SFS users.
- The set \( \text{SFS\_FILE} \) is the set of all SFS files.
- The set \( \text{FILE\_NAME} \) is the set of SFS file names.

Now a function, \( \text{create\_file} \), can be defined. This function, when supplied a user and a filename, returns a valid SFS file. The domain and range of the function are defined as

- \( \text{create\_file} : \text{USER} \times \text{FILE\_NAME} \rightarrow \text{SFS\_FILE} \).
As additional elements of the SFS model are defined, the behavior of the function create_file may then be defined.

The SFS files are part of the state of the SFS system. As the system executes and user requests are serviced, this state will change. To describe these changes in state, various components, as well as the overall state, are given names. We call the entire state, sfs.state. The SFS files are called sfs_files and are a component of sfs_state. Also the SFS file names are sfs_file_names and are also a component of the state.

The operation of creating a file upon user request will certainly change the state of the SFS. Before defining this change in state, it is worthwhile to note that the SFS, later in the SRS, specifies other user services that may be requested. These correspond to the input DDFS.SFS specified in the SRS as input to the SFS. Let DDFS.SFS = \{create, open, read, write, delete, dir\} be this set of requests. The set DDFS.SFS captures the fact that these various requests exist, but does not indicate how these requests may effect the system.

Now, for some DDFS to SFS request, create ∈ DDFS.SFS, we can specify some change in the sfs.state. That is, for some, user ∈ USER, and file_name ∈ FILE_NAME,

- a new file ∈ SFS.FILE should be created,
- the state component sfs.files should be updated, and
- the state component sfs.files.names should be updated.

Additional, elements of the model must be defined in order to complete the definition of the response to a create ∈ DDFS.SFS request. We continue by examining shall number 2 in the SRS.

**Shall 2** SFS shall (2) establish a dictionary describing the structured file so that it can manage the updating of the file.

It seems clear that an SFS dictionary of some sort should be included as part of the state, call it sfs.dict. This dictionary will provide information about SFS files, so we index it by SFS file names. When looking up the entry for a particular file, by name, we would expect in return an entry for that file which describes various aspects of the file. A function
• \textit{lookup} : \textit{SFS\_DICT} × \textit{FILE\_NAME} → \textit{DICT\_ENTRY}

serves this purpose.

When files change, it may be necessary to modify their dictionary entries. A function \textit{update} is used to update dictionary entries. Given a dictionary and a new entry for a particular file, a new dictionary, appropriately updated will be returned. The domain and range for this function is given as \textit{update} : \textit{SFS\_DICT} × \textit{FILE\_NAME} × \textit{DICT\_ENTRY} → \textit{SFS\_DICT}

The relationship between \textit{lookup} and \textit{update} is that \textit{lookup} will always return the appropriate entry in an updated dictionary. This relationship is formally defined in the next section.

Continuing with the \textit{shalls} from the SRS.

\textbf{Shall 3} \textit{The dictionary shall (3) contain the number of records in the file, the record size, the record structure, the archive threshold (prescribed percentage capacity threshold for archiving the file), an archive/circular indicator (indicating whether the file should be archived or overwritten), and access information (user identification, password, read only access, write access, delete access, archive rights, etc.).}

This \textit{shall} defines various elements of a dictionary entry. The following functions on a dictionary entry are introduced.

• \textit{nrec} : \textit{DICT\_ENTRY} → \mathbb{N}
• \textit{recsize} : \textit{DICT\_ENTRY} → \mathbb{N}
• \textit{recstruct} : \textit{DICT\_ENTRY} → \mathbb{N}
• \textit{archive} : \textit{DICT\_ENTRY} → \mathbb{B}
• \textit{access} : \textit{DICT\_ENTRY} → \textit{ACCESS\_INFO}

where \( \mathbb{N} = \{0, 1, 2, \ldots\} \) and \( \mathbb{B} = \{\text{true}, \text{false}\} \)

An element of the set \textit{ACCESS\_INFO} is a set of access rights granted to users for a particular file. These access rights are defined by the set \textit{ACCESS\_RIGHTS} = \{\text{read, write, delete, execute}\}. So, we may define \textit{ACCESS\_INFO} as the set of all subsets of \textit{ACCESS\_RIGHTS}, or equivalently, \textit{ACCESS\_INFO} = \mathcal{P}(\textit{ACCESS\_RIGHTS}).
To this point, not much more than the naming of various components of the model has taken place. In addition to naming components, we have also indicated some structure and nature of each of the components. As development of the model proceeds this structure would be more fully defined and eventually yield a complete mathematical model of the intended structure of the entire system. The structure would then be suitable for various analysis, refinement and documentation purposes. This short example only serves to give a flavor for a style of development possible.

Given the start of an informal mathematical model, a system designer may decide to record his design formally. The next section addresses the same issues as this section, only in the framework of a formal mathematical notation.

3 Developing a Formal Mathematical Model

The previous section developed a model of the SFS using a relatively informal style of mathematical presentation based on commonly understood mathematical notions of set and function theory. This section addresses essentially the same portions of the specification but uses a formal mathematical notation. The notation used is taken from the Penelope Ada specification and verification system developed at Odyssey Research Associates [23]. It is a system based on the Larch style of specification and is similar in its mathematical style to systems such as EHDM, LSL, PVS. That is, its specifications are algebraic in nature. Penelope has the additional ability to directly address issues of Ada code specification and verification. The details of Penelope are not presented here and the specification is presented simply as a demonstration of the feasibility of applying mechanical means to the specification and verification of systems such as the DSAR SFS.

In the following treatment a basic style of algebraic specification is used to capture the meaning of statements in the SRS. English text provides an informal description of each component of the specification. In the following treatment the Larch construct called a trait is used to encapsulate a particular theory. That is, a set of related facts which form a logical structure and from which further facts may be deduced. The algebraic form of specification in Larch uses sorts and operators to define logical theories. Sorts and collections of objects. Operators define functions from sorts into sorts.
In the previous section, sets were used to describe various aspects of the model. The notion of a set needs to be formally defined by introducing operators and sorts which capture the usual behavior of sets. In this case, `empty`, and `member` are alternate notations for the usual notions `{}` and `∈`, respectively.

```plaintext
trait Set is
  introduces
  empty: -> Set;
  insert: Element, Set -> Set;
  member: Element, Set -> Bool;
< ... additional set operations omitted ...>
  asserts
  Set generated by empty, insert
  Set partitioned by member
  axioms: forall [e:Element, e1:Element, s:Set]
  not_member_empty: (not member(e, empty()));
  member_insert: (member(e, insert(e1, s))=
    ((e=e1) or member(e, s)));
< ... axiomatization of additional set operations omitted ...>
  end axioms;
```

Additional set manipulations constructs such as set union and intersection may be similarly defined. Basic mathematical notions such as sets, sequences, lists, and stacks, would normally be provided in a collection of theories gathered in a library and available for use by the specifier. This theory of sets is developed in a generalized form and later used (and reused) in several specialized forms.

The following trait defines a general theory of dictionaries that will be used subsequently. A dictionary is some object to which the operations `update` and `lookup` may be applied and in which update and lookup have the appropriate relation to each other. In addition, the operation `defined` may be used to check the definedness of a particular index.

```plaintext
trait Dictionary is
  introduces
```
empty: -> Dict;
update: Index, Ent, Dict -> Dict;
lookup: Index, Dict -> Ent;
defined: Index, Dict -> Bool;
asserts
Dict generated by empty, update
Dict partitioned by lookup
axioms: forall [il, i2:Index, e1, e2:Ent, d1, d2:Dict]
not_defined: (not defined(il, empty()));
defined: (defined(i2, update(il, e1, d1))=
((il=i2) or
 defined(i2, d1));
lookup: (lookup(i2, update(il, e1, d1))
 =
 (if (il=i2) then e1 else lookup(i2, d1)));
end axioms;
lemmas: forall [il, i2:Index, e1, e2:Ent, d1, d2:Dict]
lookup_same: (lookup(i1, update(i1, e1, d1))=e1);
proof:
! BY synthesis of FORALL
! BY synthesis of FORALL
! BY synthesis of FORALL
! BY lookup in trait Dictionary
! substituting for left
! BY synthesis of TRUE
end lemmas;

While this theory is developed in general in terms of Index, Entry, Dict, etc. The use of the theory will be in terms of file names and SFS files, as in Section 2. In fact, it may eventually be reused in various specialized forms.

The trait Dictionary not only introduces some new concepts related to dictionaries but also contains the proof of a property lookup_same which says that after updating a dictionary entry, looking it up will return the correct entry. Proofs of properties that follow from basic definitions can be considered a form of design verification.

The SRS specifies various items as input to the SFS. One of these is a DDFS to SFS message or data item. The DDFS_SFS trait defines the possi-
ble DDFS to SFS operations, `create, open, read, write, dir`. The behavior of these operations is not yet defined.

```plaintext
--| trait DDFS_SFS is
--| introduces
--| sort DDFS_SFS is enumeration (create, open, read, write, dir)
```

The enumeration construct defines a particular sort and its individual elements much as in section 2 we used the set notation, \( DDFS_{SFS} \equiv \{create, open, read, write, delete, dir\} \) to define \( DDFS_{SFS} \).

In response to the DDFS to SFS operation a message from the SFS to the DDFS is required. The trait \( SFS_{DDFS} \) specifies some messages from the SFS to the DDFS in response to the DDFS to SFS operations. Again, the enumeration construct is used to define the elements of the sort \( SFS_{DDFS} \).

```plaintext
--| trait SFS_{DDFS} is
--| introduces
--| sort SFS_{DDFS} is enumeration (create_ok, create_error, ...)
```

Access rights to files are granted to users of the SFS. These access rights, `read`, `write`, and `delete`, are defined in the next trait.

```plaintext
--| trait AccessRights is
--| introduces
--| sort AccessRight is enumeration (read, write, delete)
```

Various information, beyond simply access rights, must be maintained for files in the system. The trait \( AccessInfo \) defines what this information is and how it can be manipulated. The trait \( AccessInfo \) makes use of previously defined traits for Sets and AccessRights.

```plaintext
--| trait AccessInfo is
--| includes (AccessRights)
--| includes (Set)(AccessRight for Element,
UserAccessRights for Set)
--| includes (Set)(UserAccessInfo for Element,
AccessInfo for Set)
--| introduces
--| sort UserAccessInfo is tuple (User, Password, UserAccessRights)
```
The trait AccessInfo shows how previously defined concepts can now be effectively used to build up more complex theories. In this case, the trait AccessRights is included in its original form. Because we would also like to manipulate sets of AccessRights, we include the trait Set, renaming the general sort Element with the specific sort AccessRights. Similarly, for UserAccessInfo, the trait Set is included. The tuple construct defines the sort UserAccessInfo to be a triple, the first element taken from the sort User, the second from the sort Password, and the last from the sort UserAccessRights.

The SFS Dictionary is a specialization of the general theory of dictionaries defined in the trait Dictionary. It is specialized to the case where entries are file information and the indexes are file names. Additionally, other file information operators are defined which describe the types of file information being retained in the dictionary.

trait SFS_DICTIONARY is
  includes (Dictionary)(Filename for Index,
      FileInfo for Ent,
      SFS_Dict for Dict)
  includes (AccessInfo)
  introduces
      rec_count: FileInfo -> Int;
      rec_size: FileInfo -> Int;
      rec_structure: FileInfo -> RecStruc;
      arch_thresh: FileInfo -> Int;
      arch_circ: FileInfo -> Bool;
      access_info: FileInfo -> AccessInfo;

The SFS state information can now be defined by a trait, SFS_STATE. The components of the SFS_State defined in this trait are SFS_Dict and SFS_Files. There is a distinguished state called sfs_initial_state about which the axiom sfs_initial_state.dict states that “the initial state contains an empty dictionary”. In such a way, information about the desired initial state of the system and any other states in the system may be recorded. For example, the intent of the predicate sfs_valid_state is to specify which states in the system are valid.

trait SFS_STATE is
-- includes (SFS_DICTIONARY)
-- introduces
-- sort SFS_State is tuple (SFS_Dict, SFS_Files);
-- sfs_initial_state: -> SFS_State;
-- sfs_valid_state: SFS_State -> Bool;
-- axioms:
-- sfs_initial_state_dict: (sfs_dict(sfs_initial_state()) =
empty());
<... definition of sfs_valid_state omitted ...>
-- end axioms;

The SFS state information and the messages to and from SFS and DFSS
can now be incorporated into the trait SFS which will define the processing
requirements for SFS. The function \textit{sfs\_operation} when axiomatized will
define how a particular user can operate on a particular file with a particular
operation in a given state of the system. The result is the new state of
the system. The function \textit{sfs\_result} defines the resultant message when the
operation is attempted.

-- trait SFS is
-- includes (SFS\_STATE)
-- includes (SFS\_DDFS)
-- includes (DDFS\_SFS)(Operation for DDFS\_SFS)
-- introduces
-- sfs\_operation: User, Filename, Operation,
SFS\_State -> SFS\_State;
-- sfs\_result: User, Filename, Operation,
SFS\_State -> SFS\_DDFS;
<... axioms for operations omitted ...>

Using the mathematical model developed so far, which culminated in the
trait SFS, a specification of an Ada package can be written. This specification
begins to define the actual Ada constructs, types, objects and functions which
will eventually realize the SFS.

-- with trait SFS ;
package SFS is
The Ada package SFS has associated with it a state, SFS, which given the annotation above, is based on the sort \textit{SFS\textunderscore State} in the sort SFS. The behavior of function and procedure in the package SFS will be partially defined in terms of their effect on this state.

The types introduced are \textit{private} to the package being defined. That is, their actual implementation is not important to the user of the package. However, we note that they are \textit{based on} elements of the mathematical description of the SFS in sort SFS. From this, it is possible to deduce aspects of their behavior.

The single function \texttt{sfs\_create\_file} is also specified in terms of the mathematical objects in the specification. Paraphrased, the specification reads something like: "The function \texttt{sfs\_create\_file} modifies the state of package SFS. On entry to the function the state of SFS must be valid and on exit the new state of SFS must be valid. The new value of the state is defined by the \texttt{sfs\_operation} function when the desired operation is \texttt{create} and the \texttt{user} is returned the value of the \texttt{sfs\_result} function."
This package specification may now serve two purposes.

1. It provides a clear description of the desired program in a manner which is independent of the actual code design of the software. That is, it is based solely on the mathematical description of the design. A designer and developer of the actual code may refer to the mathematical description of the objects being coded whenever a question arises as to the specification's intent.

2. Developed code may be verified against the mathematical description of the code to provide a greater assurance in the correctness of the developed code.

4 Conclusions and Recommendations

This example is meant to show a possible style of specification which may be applied to the SFS software component. The formal specification would provide clear, unambiguous specifications which would be suitable for various kinds of analysis, both mechanical and human.

The presentation was necessarily short and incomplete. Its intention was to provide an insight into the appropriateness of formal methods techniques, as well as the suitability of the DMS DSAR function as a target application.

A formalization of the DSAR requirements appears to be feasible and would result in a clear specification of its functionality. The application of formal methods techniques to this software system does not seem to be a high risk endeavor. Therefore it would seem a likely choice for a pilot project in formal methods at NASA.

The main areas that the formalization would address include:

- Input, output, and state data format specifications,
- Functional description of user interfaces to the DSAR,
- Interaction of functional components of the DSAR.

The most difficult issues to be addressed in a formalization of the requirements should not be overlooked.
There are concurrency and multiprocessing requirements placed on the software. An appropriate technique for mathematically describing concurrency must be selected or developed.

The interface to operating system services must be formalized. This would entail formalizing at least a portion of the Ada/OS runtime environment.

Finally, it should be made clear what the intention of the formalization effort is:

- To provide a clear, concise specification of the system that can be used by system designers in further developing the system, and to serve as a reference point when ambiguities or conflicts arise in the system design and implementation.

- To provide a formal model of the system from which properties of the system may be formally verified. In this case, what those properties are still needs to be determined.

- To provide a basis for the formal design and verification of the actual implementation of the system. This would entail code verification in an effort to increase assurance in the final software product.

For each of these goals, a formal treatment of the software requirements for DSAR will yield a software system with a higher degree of assurance in its correctness.
A Software Requirements Specification

The following software requirements specification is taken from the Data Management System (DMS) Data Storage and Retrieval (DSAR) Software Requirements Specification (SRS). It is the section that addresses processing requirements for the Structured File Services (SFS) component of the DSAR. It is presented here unedited and in its entirety.

A.1 4.1.2.1.1 INPUTS

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>DDFS-SFS</td>
<td>The distributed structured file request from a DMS service user, or a directory list request</td>
<td>DDFS</td>
</tr>
<tr>
<td>DFTSS-SFS</td>
<td>Response from an archive request</td>
<td>DFTSS</td>
</tr>
<tr>
<td>ST.FILE-SFS</td>
<td>Input Structured File</td>
<td>ST.FILE</td>
</tr>
</tbody>
</table>

A.2 4.1.2.1.2 PROCESSING

SFS shall (1) create a structured file upon request from the software user. SFS shall (2) establish a dictionary describing the structured file so that it can manage the updating of the file. The dictionary shall (3) contain the number of records in the file, the record size, the record structure, the archive threshold (prescribed percentage capacity threshold for archiving the file), an archive/circular indicator (indicating whether the file should be archived or overwritten), and access information (user identification, password, read only access, write access, delete access, archive rights, etc.). SFS shall (4) inform the requestor that the file has been created.

The SFS shall (5) accept write requests for the structured file. If the file size has exceeded the threshold, SFS shall (6) automatically request that the file be transferred to the archive via the DMS File Transfer Service or begin overwriting the file file depending on the archive/circular indicator. If a file is to be archived, the SFS shall (7) ensure that no structured file processing interferes with archiving the file. Then, SFS shall (8) write the data to a 2KB buffer in main memory. When the buffer is full, SFS shall (9)
write the contents to the mass storage device (MSD). SFS shall (10) notify the requestor of the actions taken.

SFS shall (11) accept requests to open, close, read, or delete a structured file, or provide a directory list. A directory list is a file containing the list of files and the attributes of files contained in a designated directory. SFS shall (12) provide access to structured files via a key to be: record number, time, date, date and time, or a range of dates and/or times. SFS shall (14) permit access to individual field(s) within a record. SFS shall (15) provide for on-demand read requests. SFS shall (16) provide a locking mechanism to protect the integrity of the data. If a read or write request for a locked file is received, SFS shall (17) not honor the request and shall (18) inform the requestor that the file is locked.

SFS shall allow multiple concurrent access to centralized structured files. SFS shall (20) provide for distributed access to structured file services from SDPs and MPACs on core and payload networks. The interface to SFS shall (21) be such that the requestor need not know where the structured files are located or the detail of the mechanisms used to perform the structured file services.

For all of the requests described above, SFS shall (22) determine if the requestor has authorization to access the structured file in the manner requested. If access is not authorized, the SFS shall (23) deny access and inform the requestor of that fact. SFS shall (24) maintain a log of denied accesses and report denied access to predesignated MPAC.

SFS shall (25) accept requests for structured file services from the distributed interface for DMS service users. When the service is complete SFS shall (26) transmit the requested information or status to the requestor. If the service cannot be performed, SFS shall (27) transmit the reasons to the requestor.

SFS shall (28) honor requests for structured file services based on input priority level of the requests. SFS shall (29) provide for concurrent use of the files.

SFS shall (30) maintain a Structured File Dictionary containing a record of all structured files using information provided when a structured file is created.

SFS shall (31) use the file services of the OS/Ada RTE CSCI for interfacing to the MSD. SFS shall (32) SFS shall provide for a number of retries for reads and writes when I/O errors are encountered. The number of retries
will be provided in the detailed design.

SFS shall (33) transmit to SM a service usage notification for logging of SFS activities. SFS shall (24) maintain a log of all errors resulting from structured file requests in an SFS Error Log. SFS shall (35) make the information in the error log available to SM on demand or periodically.

A.3 4.1.2.1.2 OUTPUTS

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Destination</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFS-DDFS</td>
<td>The response from a structured file request or a file containing a directory list request</td>
<td>DDFS</td>
</tr>
<tr>
<td>SFS-DFTSS</td>
<td>Request to transfer a structured file to the archive</td>
<td>DFTSS</td>
</tr>
<tr>
<td>SFS-ST.FILE</td>
<td>Structured File Output</td>
<td>ST.FILE</td>
</tr>
<tr>
<td>SFS-NHSDM</td>
<td>Health and Status, activity data, error log.</td>
<td>SM NHSDM</td>
</tr>
</tbody>
</table>
References


