Formal Modelling of a Usable Identity Management Solution for Virtual Organisations

Ali N. Haidar, P. V. Coveney
Centre for Computational Science
University College London
London, UK
{Ali.Haidar, P.V.Coveney}@ucl.ac.uk

Ali E. Abdallah
E-Security Center
Department of Informatics
London South Bank University, UK
A.abdallah@lsbu.ac.uk

P. Y. A. Ryan
University of Luxembourg
Luxembourg
peter.ryan@uni.lu

B. Beckles
University of Cambridge Computing Service
Cambridge, UK
mbb10@cam.ac.uk

J. M. Brooke, M. A. S. Jones
University of Manchester
Manchester, UK
{mike.jones,john.brook}@manchester.ac.uk

This paper attempts to accurately model security requirements for computational grid environments with particular focus on authentication. We introduce the Audited Credential Delegation (ACD) architecture as a solution to some of the virtual organisations (VO) identity management usability problems. The approach uses two complementary models: one is state based, described in Z notation, and the other is event-based, expressed in the Process Algebra of Hoare's Communicating Sequential Processes (CSP). The former will be used to capture the state of the VO and to model “back-end” operations on it whereas the latter will be used to model behavior, and in particular, “front-end” interactions and communications. The modelling helps to clearly and precisely understand functional and security requirements and provide a basis for verifying that the system meets its intended requirements.

1 Introduction

The mission of a Virtual Organisation (VO) is to offer a simplified end user access to and use of high performance computing resources shared across a number of different institutions with different administrative security domains. A typical example of a VO is the computational grid, which aims to provide control over distributed resources consisting of enormous computational power (parallel processing machines), data storage (hard disks, memory) and visualisation on high speed networks. Examples of currently operating grids include: the UK National Grid Service (NGS) [10] and US TeraGrid [14].

The sharing of these resources is intended to support academic research and industrial development. A computational grid environment may consist of a mixture of several kinds of organisations including academic, governmental, industrial and commercial institutions (will be referred to as “Sites” in this paper).

One major problem faced by end-users and administrators of VOs is to do with the usability of the security mechanisms usually deployed in these environments [4]. In particular identity management solutions. Many of the existing computational grid environments use Public Key Infrastructure (PKI) and X.509 digital certificates [6] as a corner stone for their security architectures. However, security solutions based on PKI have to be usable to be effective. Some of the common grid identity management encountered include: adding and removing users, acquiring and using digital certificates. End-users, such as scientists who are not security experts, are concerned with the results of the computations they perform on the grid. Many of the existing grid middleware, such as Globus and Unicore [4], require that

Jeremy W. Bryans and John S. Fitzgerald (Eds.):
Formal Aspects of Virtual Organisations 2009 (FAVO2009)
EPTCS 16, 2010, pp. 41–50 doi:10.4204/EPTCS.16.4
© Ali N. Haidar et al. This work is licensed under the Creative Commons Attribution License.
the end-user creates a short lived certificate, known as proxy certificate, prior to running application on
the grid. In addition, many users engage in practices which weakens the security of the grid environment,
such as the sharing of the private key of a single personal certificate because acquiring certificates can be
a lengthy process [1].

We introduce the Audited Credential Delegation (ACD) architecture as a solution to some of the
above problems and we present a formal model of this architecture. The proposed solution carefully
hides the use of digital certificates from end-users and enables them to acquire credentials from their local
site administrators. It also enables the latter to to create/remove user accounts in a more efficient way.
A combination of state-based model, described in Z notation [15], and event-based model, expressed
in the Process Algebra of Hoares Communicating Sequential Processes (CSP) [5] is used to model the
architecture. Z is widely used in industry for modelling complex and large systems. It will be used
to capture the state of the VO components and to model “back-end” operations on it whereas the latter
will be used to model behavior, and in particular, “front-end” interactions and communications. Both
notations have clear and precise semantics. The Z descriptions in this work have been type checked with
ZTC tool. The modelling helps to clearly and precisely understand functional and security requirements
and provide a basis for verifying that the system meets its intended requirements. There are several
formal frameworks that combine state-based and event-based approaches and can also be used to have
a clear and concise model of this architecture, such as Circus in [8] and CSP∥B in [12]. Circus also
combines Z and CSP. In this work we are interested in modelling the VO architecture and the nature of Z
as a pure specification language [15], with a purer mathematical notation is therefore more appropriate
than VDM and B because they are more akin to conventional programming languages, and hence why
refinement into code is easier with these languages.

The remainder of this paper is organized as follows. Section 2 gives a brief overview of the proposed
VO architecture. Section 3 and 4 present formal state-based models of the authentication components
followed by a CSP description of their pattern of interactions. Section 5 presents our conclusion.

2 Overview of Proposed Architecture

The physical infrastructure of this VO involves a separate administration site and a dedicate gateway
service, which is aimed at hiding digital certificates from end-user environment.

Figure 1: Audited Credential Delegation Architecture
The gateway is responsible for identity management and consists of the following components: (1) Credential repository that stores certificates and their corresponding private keys in order to communicate with the computational grid. It also maintains a list of active proxy certificates, their corresponding private keys and an association between users and proxies. The main role of this component is to enable local site users to authenticate to external sites in the grid. (2) Local Authentication Service (LAS) component that enables authenticating local site users within their organization using a locally provided usable authentication mechanism rather than digital certificates. The LAS can support several types of authentication mechanisms that scientists are used to such as Kerberos [7], Shibboleth [13] or a local password database maintained at the gateway. End-users interact only with this component of the gateway. (3) An authorization component that controls requests issued from local site users to Grid resources.

In this paper the focus is on the local and external authentication components. The gateway will be integrated with the Application Hosting Environment (AHE) [11], which allows scientists to run application codes on grid resources; manage the transfer of files to and from the grid resources; and allow the user to monitor the status of application instances that are run on the grid resources. This way it becomes possible to identify legitimate users and to ensure that only those legitimate users are allowed access to grid resources according to the policy defined on the grid projet. In this model, a scientist can login locally using a username/password pair for the whole session and run applications on the grid via the AHE server in a controlled manner. We are hoping to be able to deploy this solution within AHE for use on TeraGrid, NGS and DEISA within the next 12 months.

3 VO Internal Authentication

The aim of this component is to enable end-user to authenticate locally using a username-password mechanism. To be authenticated, a user must show knowledge of a valid username/password pair that matches an entry in an authentication table, which can be a database or a password file. In this work, a simple database password is considered for simplicity. In future work, Shibboleth and Kerberos can also be used in the architecture. One of the techniques used for implementing this approach is to store the hash of a salted password rather than the password itself in clear text. This way it is possible to know that the user knows the correct password without ever having to store the original password on the authentication server.

Figure 2: Local Database and Credential Repository that store digital Certificates, proxies and users’ credentials
3.1 State-Based Model of the Local Authentication Component

Let UserID and Data be abstract types for denoting the set of all usernames, passwords and encrypted passwords.

\[[ UserID, Data \]

**State:** The state of the local database authentication server comprises: a set of registered users; a partial function pwdDB that associates each userID with one encrypted password; partial function that associates each user with a salt; and a partial function encrypt that is used to encrypt/hash clear text passwords. The invariant ensures that every registered user must have a password and that every user has an associated salt. The model can be described in Z as follows:

\[
\begin{align*}
DB_{LAS} & \quad \text{registered}_\text{users} : \mathbb{P} \text{UserID} \quad \text{pwd} : \text{UserID} \rightarrow \text{Data} \\
& \quad \text{salting} : \text{UserID} \rightarrow \text{Data} \quad \text{encrypt} : \text{Data} \rightarrow \text{Data} \\
& \quad \text{registered}_\text{users} = \text{dom}_\text{pwdDB} \land \text{dom}_\text{pwdDB} = \text{dom}_\text{salting}
\end{align*}
\]

**Authentication Component Operations:** The set of operations considered on this component are shown in Figure 2. We only present the following operations on the DB_{LAS}: Login, ChangePassword and AddCredential because of space limitation. For more details about this model the reader is referred to [3]. The operation Login takes a username and a password as inputs and checks whether the pair matches an entry in the database. The operation is described in the following Z schema:

\[
\begin{align*}
\Sigma_{DB_{LAS}} & \quad \text{username} ? : \text{UserID} \quad \text{pwd} ? : \text{Data} \\
& \quad \text{encrypt}(\text{salting}(\text{username} ?) + \text{pwd} ?) = \text{pwdDB}(\text{username} ?)
\end{align*}
\]

The operation ChangePassword replaces the old password for the specified username with a new password after checking that the username and the old password supplied by a user matches an entry in the database:

\[
\begin{align*}
\Delta_{DB_{LAS}} & \quad \text{username} ? : \text{UserID} \quad \text{pwd} ? : \text{Data} \quad \text{newpwd} ? : \text{Data} \quad \text{newsalt} ? : \text{Data} \\
& \quad \text{encrypt}(\text{salting}(\text{username} ?) + \text{pwd} ?) = \text{pwdDB}(\text{username} ?) \land \\
& \quad \text{pwdDB}' = \text{pwdDB} \oplus \{ \text{username} ? \mapsto \text{encrypt}(\text{newsalt} ? + \text{newpwd} ?) \} \\
& \quad \text{salting}' = \text{salting} \oplus \{ \text{username} ? \mapsto \text{newsalt} ? \}
\end{align*}
\]

The AddCredential operation allows adding a new user to the database.

\[
\begin{align*}
\Delta_{DB_{LAS}} & \quad \text{username} ? : \text{UserID} \quad \text{pwd} ? : \text{Data} \quad \text{salt} ? : \text{Data} \\
& \quad \text{pwdDB}' = \text{pwdDB} \oplus \{ \text{username} ? \mapsto \text{encrypt}(\text{salt} ? + \text{pwd} ?) \} \\
& \quad \text{salting}' = \text{salting} \oplus \{ \text{username} ? \mapsto \text{salt} ? \}
\end{align*}
\]
Let $Report$ be a data type, the values of which are messages indicating whether an operation has been successful or has failed.

$$Report ::= Success \mid Failure$$

**Precondition of each Operation:** The precondition of the operations $Login$ and $ChangePassword$ is that the username and password pair match an entry in the database. The precondition of the operation $AddCredential$ is that the chosen username must not be already in use. The precondition for each operation can be defined in $Z$ as follows:

- $\text{pre Login} \equiv (\text{username}, encrypt(\text{salting(\text{username})} + \text{pwd})) \in pwdDB$
- $\text{pre ChangePassword} \equiv (\text{username}, encrypt(\text{salting(\text{username})} + \text{oldpwd})) \in pwdDB$
- $\text{pre AddCredential} \equiv \text{username} \not\in \text{dom pwdDB}$

**Totalizing:** The totalising technique is used to handle errors resulting from not meeting the above preconditions. An error may arise because the $\text{username}$ doesn’t exist,

| $\exists DB \_ \text{LAS}$ |
|---------------------------|
| $\text{username} : UserID$ |
| $\text{athrep} : Report$ |
| $\text{username} \not\in \text{dom pwdDB} \land \text{athrep} = \text{Failure}$ |

or the combination of username and password is wrong:

| $\exists DB \_ \text{LAS}$ |
|---------------------------|
| $\text{username} : UserID$ |
| $\text{pwd} : Data$ |
| $\text{authenticationdecision} : Report$ |
| $(\text{encrypt(pwd}) = \text{pwdDB} (\text{username})) \land \text{authenticationdecision} = \text{Failure}$ |

A successful operation will result in the same report:

| $\text{Op \_ Success}$ |
|-------------------------|
| $\text{authenticationdecision} : Report$ |
| $\text{authenticationdecision} = \text{Success}$ |

The Authentication component’s operations will then be modeled as follows:

- $Login \equiv (\text{Login0} \land \text{Op \_ Success}) \lor \text{InvalidCredential}$
- $ChangePassword \equiv (\text{ChangePassword0} \land \text{Op \_ Success}) \lor \text{UserIDNotInUse} \lor \text{InvalidCredential}$
- $AddCredential \equiv (\text{AddCredential0} \land \text{Op \_ Success}) \lor \text{UserIDInUse}$

**Initialization:** The initial state of the authentication server component is described as follows:
In this initialization, the hashes of the passwords are generated using MD5 hash [9]. The username/password pairs memorized by the users are: (ali, pwdx), (mark, mrk3000), (joh, wnd1980)

3.2 Modelling the User

The model of a user focuses primarily on the security knowledge that the user must possess and maintain for the purpose of authentication. The abstract state of a user, User, comprises three components: (1) \( u\_names \), set of usernames held by the user (also known as principal); and (2) \( u\_password \), a function that associates each principal with a plain password. The state of a user can be formulated in Z as follows:

\[
\begin{align*}
\text{User} & : \mathbb{P} \text{UserID} & \text{u\_password} & : \text{UserID} \rightarrow \text{Data} \\
\text{dom} \text{u\_password} & = \text{u\_names}
\end{align*}
\]

The invariant states that each username has exactly one password.

3.3 Event-Based Model of the Local Authentication Component

We derive the CSP interface of the authentication server from the Z specification. This description has been structured as follows:

- State = DB\_LASInit.
- Operations = \{Login, ChangePassword, ResetPassword, AddCredential, RemoveCredential, Logout\}.
- Preconditions of each operation. For instance, for the login operation:
  \( \text{Login}: (\text{username}\?, \text{encrypt} (\text{salting}(\text{username}\?) + \text{pwd}\?)) \in \text{pwdDB} \)
- Initial WS state = DB\_LASInit, totalizing the operations and adding reports to handle incorrect inputs.

The interface of the authentication server is:

\[\alpha_{DB} = \{\text{Login, LoginRequest, LoginResponse, ChangePassword, ChangePasswordRequest, ChangePasswordResponse, ResetPassword, ResetPasswordRequest, ResetPasswordResponse, AddCredential, AddCredentialRequest, AddCredentialResponse, RemoveCredential, RemoveCredentialRequest, RemoveCredentialResponse, Logout, LogoutRequest, LogoutResponse}\}\]

The behaviour of the authentication server is modelled by the CSP process DB shown below. The description doesn’t consider the pattern of interactions corresponding to the operations \( \text{ResetPassword, RemoveCredential and AddCredential} \), because this depends on the role of the authenticated user. For
example, only an authenticated user holding an administrator role can add/remove other users and reset passwords.

\[
DB(State) = LOGIN(state)
\]

\[
LOGIN(state) = Login \rightarrow LoginRequest?(username?, pwd?) \rightarrow
\]

\[
( LoginResponse!(authenticationdecision! \leadsto Success)
\]

\[
\rightarrow AUTH(u) \leftarrow \text{pre } Login(username?, pwd?) \triangleright
\]

\[
LoginResponse!(authenticationdecision! \leadsto Failure) \rightarrow DB((state))
\]

\[
AUTH(u) = CHGPWD(state) \square LOGOUT(state)
\]

\[
CHGPWD(state) = ChangePassword \rightarrow
\]

\[
ChangePasswordRequest?(username?, oldpwd?, newpwd?) \rightarrow
\]

\[
( ChangePasswordResponse!(athrep! \leadsto Success) \rightarrow
\]

\[
AS(state') \leftarrow \text{pre } ChangePassword(username?, oldpwd?, newpwd?) \triangleright
\]

\[
ChangePasswordResponse!(athrep! \leadsto Failure) \rightarrow AUTH(u)
\]

\[
LOGOUT(state) = Logout \rightarrow LogoutRequest?(username?) \rightarrow
\]

\[
( LogoutResponse!(athrep! \leadsto Failure) \rightarrow AS(state') \leftarrow \text{pre } Logout(username?) \triangleright
\]

\[
 LogoutResponse!(athrep! \leadsto Failure) \rightarrow DB(state)
\]

Figure 3: Client and Database Server models

So for example, a user with a valid username and password, say ali and pwdx respectively, can be authenticated by the server by issuing the following sequence of interactions:

\[
CLIENT1 = DoLogin \rightarrow DoLoginRequest!(username? \leadsto ali, pwd? \leadsto 6f\ldots fb5c)
\rightarrow DoLoginResponse?authenticationdecision! \rightarrow SKIP
\]

where encrypt(pwdx) = 6f8cacf5b994687f7a05619e3324fb5c.

The CSP operator \([+Op+]\) models the interaction between two processes in which the handshake is on the operation \(Op\). Both processes synchronize on the channel \(Op\). The input values flows from the requestor to the provider and the output values flows in the opposite direction. For instance, the result of \(CLIENT1\) sequence of interactions with the authentication server is calculated using a parallel composition of \(CLIENT1\) and \(AS\) processes as follows:

\[
DB(state)[+]Login[+]CLIENT1 = Login \rightarrow
\]

\[
LoginRequest!(username? \leadsto ali, pwd? \leadsto 6f8cacf5b994687f7a05619c3324fb5c)
\]

\[
LoginResponse!(authenticationdecision! \leadsto Success) \rightarrow DB(state')
\]
4 VO External Authentication

The credential repository is used to store digital certificates or proxy certificates for named grid projects and resources and their corresponding private keys to enable communication with the grid. These certificates will be shared by a group of users and will be used to create proxy certificates.

4.1 State-Based Model of the External Authentication Component

The model assumes the existence of the following types:

\[ [\text{UserID}, \text{Subject}, \text{Data}, \text{Key}, \text{serialNb}, \text{CipherAlgName}, \text{CertAuthorityName}] \]

The state of the certificate repository comprises: a set of certificates; a set of project and resources names; a partial function \( \text{key association} \) that associates each \( \text{Certificate} \) with its corresponding private key; a partial function \( \text{cert association} \) that is used to associate each project with a digital certificate; a list of issued proxies certificates created using the digital certificates, the proxies secret keys, association between each proxy and the user who generated it.

\[
\begin{align*}
\text{CredentialRepository} & : \text{P} \text{Certificate} \\
\text{certificates} & : \text{P} \text{Certificate} \\
\text{proxyCertificates} & : \text{P} \text{Certificate} \\
\text{projectsNames} & : \text{P} \text{Name} \\
\text{resourcesNames} & : \text{P} \text{Name} \\
\text{key association} & : \text{SerialNb} \rightarrow \text{Key} \\
\text{cert association} & : \text{Name} \rightarrow \text{SerialNb} \\
\text{issuedproxies} & : \text{SerialNb} \rightarrow \text{SerialNb} \\
\text{proxyIssuer} & : \text{SerialNb} \rightarrow \text{SerialNb} \\
\text{proxySecretKey} & : \text{SerialNb} \rightarrow \text{Key} \\
\text{userProxy} & : \text{SerialNb} \rightarrow \text{UserID}
\end{align*}
\]

\[ \forall c : \text{Certificate} \cdot c \in \text{certificates} \land c.\text{serial} \in \text{dom} \text{key association} \land \]
\[ \text{ran} \text{cert association} \subseteq \text{dom} \text{key association} \land \]
\[ \text{dom} \text{cert association} \subseteq \text{projectsNames} \land \]
\[ \text{dom} \text{cert association} \subseteq \text{resourcesNames} \land \]
\[ \forall c : \text{Certificate} \cdot c \in \text{proxyCertificates} \land c.\text{serial} \in \text{dom} \text{proxySecretKey} \land \]
\[ \text{dom} \text{proxySecretKey} = \text{dom} \text{proxyIssuer} = \text{dom} \text{userProxy} \]

Where \( \text{proxyCertificates} \) is the set of all active proxies; \( \text{issuedproxies} \), a function that relates a serial number to a proxy certificate; \( \text{proxyIssuer} \), a function that relates the proxy certificate with its issuer (signer) identified by a public certificate; \( \text{userProxy} \), a function that associates a user in a site with the proxy certificate in a unique way; \( \text{proxySecretKey} \), a function that associates each proxy with its corresponding private key. More details on modelling PKI component in Z and CSP are presented in [2]. 

The same
approach as in the previous section can be applied to model operations. For instance, the administrative operation on the CredentialRepository, AddCertificate, takes a certificate, its corresponding private key, and the project with which it can be used as inputs. The precondition for this operation to succeed states that the cert? should not already be in the list of certificates. The operation is captured in Z as follows:

\[
\text{AddCertificate0} \quad D\text{CredentialRepository} \\
\text{cert? : Certificate} \quad \text{secretkey? : Key} \quad \text{project? : Name} \\
\text{response! : Report} \\
\text{cert! . publicKey validPKIKeyPair secretKey?} \land \\
\text{cert?} \notin \text{certificates} \land \text{certificates'} = \text{certificates} \cup \{\text{cert?}\} \land \\
\text{key_association'} = \text{key_association} \cup \{(\text{cert?}.\text{serial}, \text{secretkey?})\} \land \\
\text{cert_association'} = \text{cert_association} \oplus \{\text{project?} \mapsto \text{cert?}.\text{serial}\}
\]

The operation RemoveCertificate takes a certificate as an argument and removes it with its corresponding secret key from the credential repository. The precondition states that the cert? must exists in the certificates set.

\[
\text{RemoveCertificate0} \quad D\text{CredentialRepository} \\
\text{cert? : Certificate} \\
\text{cert?} \in \text{certificates} \land \text{certificates'} = \text{certificates} \setminus \{\text{cert?}\} \land \\
\text{key_association'} = \{\text{cert?}.\text{serial}\} \triangleleft \text{key_association} \land \\
\text{cert_association'} = \text{cert_association} \triangleright \{\text{cert?}.\text{serial}\}
\]

5 Conclusion

In this paper, we have presented a formal model of a VO architecture that combines PKI and username-password mechanisms in order to provide a usable security solution for VO end-users. The model uses a combination of state-based and event-based approach. The consistency of Z model is checked with the ZTC tool. The formalism has clarified the purpose of the VO, the explicit assumptions about sites, users, CAs and third parties. The observation of the states enables to easily know the current capabilities of the user, site and the VO. For instance, it becomes clear from the model of the user that he/she will have to maintain only one identity to authenticate to the gateway. Also, it makes it possible to find a user responsible for performing a task on the grid. This allows local sites and the entity running the gateway to monitor who access resources for auditing and billing purposes. Most importantly, we have linked the CSP model with the Z specification in a systematic way. We derive the CSP interface of the VO from the Z state, operations, precondition on each operation and initial state.

Acknowledgment: This work is supported by EPSRC through the User-Friendly Security for Grid Environments project (EP/D051754/1), RealityGrid platform (EPSRC EP/C536452/1), EU FP6 ViroLab (EU FP6 027446).
References

[1] A. E. Abdallah and Ali N. Haidar. Usability Evaluation of Identity Management Schemes in Three Virtual Organisation Architectures. **Int'l Journal of Information Assurance and Security, Special Issue on Information Assurance and Data Security**, 4(6):560–570, July 2009.

[2] Ali N. Haidar and Ali E. Abdallah. Formal Modelling of PKI Based Authentication. *To appear in: Electronic Notes in Theoretical Computer Science (ENTCS)*, 2008.

[3] Ali Nasrat Haidar and Ali E. Abdallah. Weaving Authentication and Authorization Requirements into the Functional Model of a System Using Z Promotion. In **ISOLA’08: Proceedings of the Third International Symposium on Leveraging Applications of Formal Methods, Verification and Validation**, volume 17 of **Communications in Computer and Information Science**, pages 831–846. Springer, 2008.

[4] P.Y.A. Ryan A.E. Abdallah S.M. Pickles J.M. Brooke B. Beckles, P.V. Coveney and M. McKeown. A user-friendly approach to computational grid security. In **UK e-Science All Hands Meeting 2006**, 2006.

[5] C. A. R. Hoare. *Communicating Sequential Processes*. Prentice Hall, 1985.

[6] S. Chokhani. *Computer Security Hand book*, chapter Public Key Infrastructures and Certificate Authorities. Wiley, fourth edition, 2002.

[7] D. Gollmann. *Computer Security*. Wiley, second edition, 2005.

[8] M V M Oliveira and A L C Cavalcanti and J C P Woodcock. Refining Industrial Scale Systems in Circus. In I.R. East, J. Martin, P.H. Welch, D. Duce, and M. Green, editors, **Communicating Process Architectures 2004**, volume 62 of **Concurrent Systems Engineering Series**, pages 281–309. IOS Press, September 2004.

[9] Menezes, A. and van Oorschot, P. and Vanstone, S. *Handbook of Applied Cryptography*. CRC Press, 1997.

[10] National Grid Service (NGS). [http://www.ngs.ac.uk.]

[11] P.V. Coveney, R.S. Saksena, S.J. Zasada, M. McKeown and S. Pickles. The application hosting environment: Lightweight middleware for grid-based computational science. **Computer Physics Communications**, 176(6):406–418, 2007.

[12] S. Schneider and H. Treharne and N. Evans. Chunks: Component verification in CSP parallel B. In Judi Romijn, Graeme Smith, and Jaco van de Pol, editors, **IFM**, volume 3771 of **Lecture Notes in Computer Science**. Springer, 2005.

[13] R.O. Sinnott, M. Bayer, A. Stell, and J. Koetsier. Grid infrastructures for secure access to and use of bioinformatics data: experiences from the bridges project. In **The First International Conference on Availability, Reliability and Security. (ARES 2006)**. IEEE Computer Society, 2006.

[14] TeraGrid project. [http://www.teragrid.org.]

[15] Woodcock, J. and Davies, J. *Using Z Specification, Refinement, and Proof*. C.A.R Hoare series editor. Prentice Hall International, 1996.