Conversion and Emulation-aware Dependency Reasoning for Curation Services

Yannis Tzitzikas and Yannis Marketakis and Yannis Kargakis
Institute of Computer Science, FORTH-ICS
Computer Science Department, University of Crete, Greece
{tzitzik|marketak|kargakis}@ics.forth.gr

ABSTRACT

A quite general view of the digital preservation problem and its associated tasks (e.g. intelligibility and task-performability checking, risk detection, identification of missing resources for performing a task) is to approach it from a *dependency management* point of view. In this paper we extend past rule-based approaches for dependency management for modeling also *converters* and *emulators* and we demonstrate how this modeling allows performing the desired reasoning and thus enables offering more advanced digital preservation services. Specifically these services can greatly reduce the human effort required for periodically checking (monitoring) whether a task on a digital object is performable.

1. INTRODUCTION

In digital preservation there is a need for services that help archivists in checking whether the archived digital artifacts remain *intelligible* and *functional*, and in identifying the consequences of probable losses (obsolescence risks). To tackle the aforementioned requirements [14] showed how the needed services can be reduced to *dependency management* services, and how a semantic registry (compatible with OAIS[1]) can be used for offering a plethora of curation services. Subsequently, [15] extended that model with *disjunctive dependencies*. The key notions of these works is the notion of *module*, *dependency* and *profile*. In a nutshell, a *module* can be a software/hardware component or even a knowledge base expressed either formally or informally, explicitly or tacitly, that we want to preserve. A module may require the availability of other modules in order to function, be understood or managed. We can denote such *dependency relationships* as $t > t'$ meaning that module t depends on module t'. A *profile* is the set of modules that are assumed to be known (available or intelligible) by a user (or community of users), and this notion allows controlling the number of dependencies that have to be recorded formally (or packaged in the context of an *encapsulation preservation strategy*). Subsequently, and since there is not any objective method to specify exactly which are the dependencies of a particular digital object, [10] extended the model with *task-based* dependencies where the notion of task is used for determining the dependencies of an object. That work actually introduced an extensible *object-oriented* modeling of dependency graphs expressed in Semantic Web (SW) languages (RDF/S). Based on that model, a number of services have been defined for checking whether a module is *intelligible* by a community (or for computing the corresponding *intelligibility gap*), or for checking the *performability of a task*. These dependency management services were realized over the available SW query languages. For instance, `GapMgr`[2] and `PreScan`[3] [9] are two systems that have been developed based on this model, and have been applied successfully in the context of the EU project CASPAR[4]. Subsequently, [16] introduced a *rule-based* model which also supports task-based dependencies, and (a) simplifies the disjunctive dependencies of [15], and (b) is more expressive and flexible than [10] as it allows expressing the various properties of dependencies (e.g. transitivity, symmetry) straightforwardly. That work actually reduced the problem of dependency management to *Datalog*-based modeling and query answering.

However, the aforementioned works did not capture *converters* and *emulators*. Since conversion (or migration) and emulation are quite important preservation strategies, a dependency management approach should allow modeling explicitly converters and emulators (and analyze them from a dependency point of view, since they have to be preserved too), and exploit them during the offered preservation services. For example, a sequence of conversions can be enough for vanishing an intelligibility gap, or for allowing performing a task. Since there is a plethora of emulation and migration approaches that concern various layers of a computer system (from hardware to software) or various source/target formats (e.g. see [3] for an overview), it is beneficial to use advanced knowledge management techniques for aiding the exploitation of all possibilities that the existing and emerging emulators/converters enable, and assist *preservation planning* (e.g. [1]). This is crucial since the scale and complexity of information assets and systems evolve towards overwhelming the capability of human archivists and curators (either system administrators, programmers and designers).

[1]Open Archival Information System (ISO 14721:2003).

[2]http://athena.ics.forth.gr:9090/Applications/GapManager/
[3]http://www.ics.forth.gr/isl/PreScan
[4]http://www.casparpreserves.eu/

In a nutshell, the main contributions of this paper are: (a) we extend the rule-based approach of [16] for modeling explicitly converters and emulators, (b) we demonstrate how this modeling apart from capturing the preservability of converters and emulators, enables the desired reasoning regarding intelligibility gaps, task performability, risk detection etc, (c) we introduce an algorithm for visualizing the intelligibility gaps and thus assisting their treatment, and (d) shows how the approach can be implemented using recently emerged Semantic Web tools. The rest of this paper is organized as follows. Section 2 discusses the motivation and the context of our work. Section 3 introduces the rule based modeling and Section 4 discusses the corresponding inference services. Section 5 shows how the approach can be implemented using Semantic Web tools. Finally Section 6 summarizes, discusses related issues and identifies issues for further research.

2. CONTEXT AND BACKGROUND

Migration (according to Wikipedia) is a set of organized tasks designed to achieve the periodic transfer of digital materials from one hardware/software configuration to another, or from one generation of computer technology to a subsequent generation. The purpose of migration is to preserve the integrity of digital objects and to retain the ability for clients to retrieve, display, and otherwise use them in the face of constantly changing technology. *Emulation* (according to Wikipedia) combines software and hardware to reproduce in all essential characteristics the performance of another computer of a different design, allowing programs or media designed for a particular environment to operate in a different, usually newer environment. Emulation requires the creation of emulators, programs that translate code and instructions from one computing environment so it can be properly executed in another. Popular examples of emulators include QEMU [2], Dioscuri [17], etc. There is currently a rising interest on emulators for the needs of digital preservation [8]. Just indicatively, [18] overviews the emulation strategies for digital preservation and discusses related issues, and several recent projects have focused on the development of emulators for the needs of digital preservation (e.g. see [17] and [11]).

In brief, and from a dependency perspective, we could say that the *migration* process *changes the dependencies* (e.g. the original digital object depends on an old format, while the migrated digital object now depends on a newer format). Regarding *emulation* we could say that the emulation process does not change the dependencies of digital objects. An emulator essentially makes available the behavior of an old module (actually by emulating its behavior). It follows that the availability of an emulator can "satisfy" the dependencies of some digital objects, but we should note that the emulator itself has its own dependencies that have to be preserved to ensure its performability. The same also holds for converters.

Running Example

James has a laptop where he has installed the `NotePad` text editor, the `javac 1.6` compiler for compiling Java programs and `JRE1.5` for running Java programs (bytecodes). He is learning to program in Java and C++ and to this end, and through `NotePad` he has created two files, `HelloWorld.java` and `HelloWorld.cc`, the first being the source code of a program in java, the second of one in C++. Consider another user, say Helen, who has installed in her laptop the `Vi` editor and `JRE1.5`.
Suppose that we want to preserve these files, i.e. to ensure that in future James and Helen will be able to edit, compile and run these files. In general, to edit a file we need an editor, to compile a program we need a compiler, and to run the bytecodes of a Java program we need a Java Virtual Machine. To ensure preservation we should be able to express the above.
To this end we could use facts and rules. For example, we could state: *A file is editable if it is TextFile and a TextEditor is available*. Since James has two text files (`HelloWorld.java`, `HelloWorld.cc`) and a text editor (`NotePad`), we can conclude that these files are editable by him. By a rule of the form: *If a file is Editable then it is Readable too*, we can also infer that these two files are also readable. We can define more rules in a similar manner to express more task-based dependencies, such as compilability, runability etc. For our running example we could use the following facts and rules:

Facts and Rules	James	Hellen
Facts		
NotePad is a TextEditor	✓	
VI is a TextEditor		✓
HelloWorld.java is a JavaFile	✓	
HelloWorld.cc is a C++File	✓	
javac1.6 is a JavaCompiler	✓	
JRE1.5 is a JVM	✓	✓
gcc is a C++Compiler	✓	
Rules		
A file is Editable if it is a TextFile and a TextEditor is available		
A file is JavaCombilable if it is a JavaFile and a JavaCompiler is available		
A file is C++Combilable if it is a C++File and a C++Compiler is available		
A file is Compilable if it is JavaCompilable or C++Compilable		
A file is a TextFile if it is JavaFile or C++File		
If a file is Editable then it is Readable		

Table 1: Modeling the running examples with Facts and Rules

The last two columns indicate which facts are valid for James and which for Helen. From these we can infer that James is able to compile the file `HelloWorld.java` and that if James sends his TextFiles to Helen then she can only edit them but not compile them since she has no facts about Compilers.

Let us now extend our example with *converters* and *emulators*. Suppose James has also an old source file in Pascal PL, say `game.pas`, and he has found a *converter* from Pascal to C++, say `p2c++`. Further suppose that he has just bought a smart phone running Android OS and he has found an *emulator* of WinOS over Android OS. It should follow that James can run `game.pas` on his mobile phone (by first converting it in C++, then compiling the outcome, and finally by running over the emulator the executable yielded by the compilation). ◇
Regarding curation services, we have identified the following key requirements

Task-Performability Checking. To perform a task we have to perform other subtasks and to fulfil associated requirements for carrying out these tasks. Therefore, we need to be able to decide whether a task can be performed by examining all the necessary subtasks. For example, we might want to ensure that a file is runnable, editable or compilable. This should also exploit the possibilities offered by the availability of converters. For example, the availability of a converter from Pascal to C++, a compiler of C++ over Windows OS and an emulator of Windows OS over Android OS should allow inferring that the particular Pascal file is runnable over Android OS.

Risk Detection. The loss or removal of a software module could also affect the performability of other tasks that depend on it and thus break a chain of task-based dependencies. Therefore, we need to be able to identify which tasks are affected by such removals.

Identification of missing resources to perform a task. When a task cannot be carried out it is desirable to be able to compute the resources that are missing. For example, if Helen wants to compile the file `HelloWorld.cc`, her system cannot perform this task since there is not any C++Compiler. Helen should be informed that she should install a compiler for C++ to perform this task.

Support of Task Hierarchies. It is desirable to be able to define task-type hierarchies for gaining flexibility and reducing the number of rules that have to be defined.

Properties of Dependencies. Some dependencies are *transitive*, some are not. Therefore we should be able to define the properties of each kind of dependency.

Background: Datalog

Datalog is a query and rule language for deductive databases that syntactically is a subset of Prolog. As we will model our approach in Datalog this section provides some background material (the reader who is already familiar with Datalog can skip this section).

The basic elements of Datalog are: *variables* (denoted by a capital letter), *constants* (numbers or alphanumeric strings), and *predicates* (alphanumeric strings). A *term* is either a constant or a variable. A constant is called *ground term* and the *Herbrand Universe* of a Datalog program is the set of constants occurring in it. An *atom* $p(t_1, ..., t_n)$ consists of an n-ary predicate symbol p and a list of arguments $(t_1, ..., t_n)$ such that each t_i is a term. A *literal* is an atom $p(t_1, ..., t_n)$ or a negated atom $\neg p(t_1, ..., t_n)$. A *clause* is a finite list of literals, and a *ground clause* is a clause which does not contain any variables. Clauses containing only negative literals are called *negative clauses*, while *positive clauses* are those with only positive literals in it. A *unit clause* is a clause with only one literal. *Horn Clauses* contain at most one positive literal. There are three possible types of Horn clauses, for which additional restrictions apply in Datalog:

- *Facts* are positive unit clauses, which also have to be ground clauses.
- *Rules* are clauses with exactly one positive literal. The positive literal is called the *head*, and the list of negative literals is called the *body* of the rule. In Datalog, rules also must be *safe*, i.e. all variables occuring in the head also must occur in the body of the rule.
- A *goal clause* is a negative clause which represents a query to the Datalog program to be answered.

In Datalog, the set of predicates is partitioned into two disjoint sets, $EPred$ and $IPred$. The elements of $EPred$ denote extensionally defined predicates, i.e. predicates whose extensions are given by the facts of the Datalog programs (i.e. tuples of database tables), while the elements of $IPred$ denote intensionally defined predicates, where the extension is defined by means of the rules of the Datalog program.

In our context, the proposed implementation is described at Section 5.

3. THE RULE-BASED MODEL

In accordance to [16], digital files and profiles (as well as particular software archives or system settings) are represented by facts (i.e. database tuples), while task-based dependencies (and their properties) are represented as Datalog rules. To assist understanding, Figure 1 depicts the basic notions in the form of a rather informal concept map, in the sense that a rule-based approach cannot be illustrated with a graph in a manner both intuitive and precise.

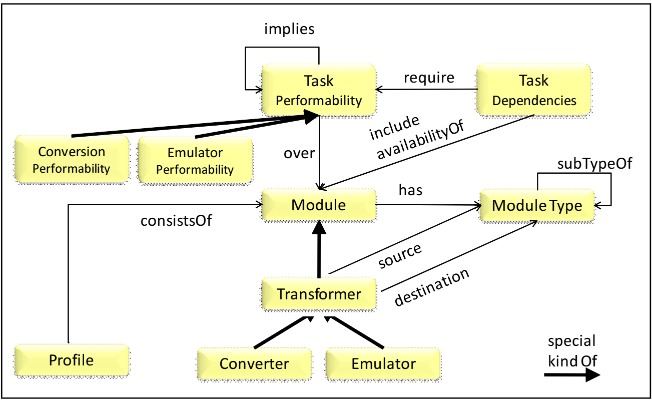


Figure 1: Informal concept map

Digital Files, Type Hierarchies, and Profiles

Digital files and their types are represented as EDB facts using predicates that denote their types, e.g. for the three files of our running example we can have the facts shown in the left column of the following table. Software components are described analogously (e.g. see right column).

Facts	
for digital files	for software components
`JavaFile(HelloWorld.java).`	`TextEditor(vi).`
`C++File(HelloWorld.cc).`	`JVM(jre1.5win)`
`PascalFile(game.pas).`	`JVM(jre1.6linux)`

Each file can be associated with more than one type. In general we could capture several features of the files (apart from types) using predicates (not necessarily unary), e.g. `LastModifDate(HelloWorld.java, 2008-10-18)`.

The types of the digital files can be organized *hierarchically*, and such taxonomies can be represented with rules, e.g. to define that every `JavaFile` is also a `UTF8File` we must add the rule `UTF8File(X) :- JavaFile(X)`.

A *profile* is a set of facts, describing the modules available (or assumed to be known) to a user (or community). For example, the profiles of James and Helen are the ticked facts in the corresponding columns of Table 1.

Task-Dependencies and Task Hierarchies

We will also use (IPred) predicates to model tasks and their dependencies. Specifically, for each real world task we define *two* intensional predicates: one (which is usually unary) to denote the (performability of the) task, and another one (with arity greater than one) for denoting the dependencies of the task. For instance, `Compile(HelloWorld.java)` will denote the compilability of `HelloWorld.java`. Since its compilability depends on the availability of a compiler (specifically a compiler for the Java language), we can express this dependency using a rule of the form: `Compile(X) :- Compilable(X,Y)` where the binary predicate `Compilable(X, Y)` is used for expressing the appropriateness of a `Y` for compiling a `X`. For example, `Compilable(HelloWorld.java, javac 1.6)` expresses that `HelloWorld.java` is compilable by `javac 1.6`. It is beneficial to express such relationships at the class level (not at the level of individuals), specifically over the types (and other properties) of the digital objects and software components, i.e. with rules of the form:

```
Compilable(X,Y) :- JavaFile(X), JavaCompiler(Y).
Compilable(X,Y) :- C++File(X), C++Compiler(Y).
Runable(X,Y)    :- JavaClassFile(X), JVM(Y).
Editable(X,Y) :- JavaFile(X), TextEditor(Y).
```

Relations of higher arity can be employed based on the requirements, e.g.:

```
Run(X) :- Runnable(X,Y,Z)
Runnable(X,Y,Z) :- JavaFile(X), Compilable(X,Y), JVM(Z)
```

We can express *hierarchies of tasks* as we did for file type hierarchies, for enabling deductions of the form: "if we can do task A then certainly we can do task B", e.g. "if we can edit something then certainly we can read it too" expressed as : `Read(X) :- Edit(X)`.

We can also express *general properties* of task dependencies, like *transitivity*. For example, from `Runnable(a.class, JVM)` and `Runnable(JVM, Windows)` we might want to infer that `Runnable(a.class, Windows)`. Such inferences can be specified by a rule of the form:
`Runable(X,Y) :- Runnable(X,Z), Runnable(Z,Y).`
As another example, `IntelligibleBy(X,Y) :- IntelligibleBy(X,Z), IntelligibleBy(Z,Y)`. This means that if `X` is intelligible by `Z` and `Z` is intelligible by `Y`, then `X` is intelligible by `Y`. This captures the assumptions of the dependency model described in [14] (i.e. the transitivity of dependencies).

Modeling Converters

Conversions are special kinds of tasks and are modeled differently. In brief to model a converter and a corresponding conversion we have to introduce one unary predicate for modeling the converter (as we did for the types of digital files) and one rule for each conversion that is possible with that converter (specifically one for each supported type-to-type conversion).

In our running example, consider the file `game.pas` (which contains source code in Pascal PL), and the converter `p2c++` from Pascal to C++. Recall that James has a compiler for C++. It follows that James can compile `game.pas` since he can first convert it in C++ (using the converter), then compile it and finally run it. To capture the above scenario it is enough to introduce a predicate for modeling the converters from Pascal to C++, say `ConverterPascal2C++`, and adding the following rule:

```
C++File(X) :- PascalFile(X), ConverterPascal2C++(Y).
```

Since the profile of James will contain the facts `PascalFile(game.pas)` and `ConverterPascal2C++(p2c++)`, we will infer `C++File(game.pas)`, and subsequently that this file is compilable and runnable.

Finally we should not forget that a converter is itself a module with its own dependencies, and for performing the intended task the converter has to be runnable. Therefore, we have to update the rule as follows:

```
C++File(X) :- PascalFile(X), ConverterPascal2C++(Y),
              Run(Y).
```

Modeling Emulators

Emulation is again a special kind of task and is modeled differently. Essentially we want to express the following: (i) If we have a module X which is runnable over Y,
(ii) and an emulator E of Y over Z (hosting system=Z, target system=Y,
(iii) and we have Z and E,
(iv) then X is runnable over Z. For example, consider the case where:
`X=a.exe` (a file which is executable in Windows operating system),
`Y=WinOS` (the Windows operating system),
`Z=AndroidOS` (the Android operating system), and
`E=W4A` (i.e. an emulator of WinOS over AndoidOS).

In brief, for each available emulator (between a pair of systems) we can introduce a unary predicate for modeling the emulator (as we did for the types of digital files, as well as for the converters), and writing one rule for the emulation.

For example, suppose we have a file named `a.exe` which is executable over WinOS. For this case we would have written:

```
Run(X)   :- Runnable(X,Y)
Runnable(X,Y) :- WinExecutable(X), WinOS(Y)
```

and the profile of a user that has this file and runs WinOS would contain the facts `WinExecutable(a.exe)` and `WinOS(mycomputer)`, and by putting them together it follows that `Run(a.exe)` holds. Now consider a different user who has the file `a.exe` but runs `AndroidOS`. However suppose that he has the emulator `W4A` (i.e. an emulator of WinOS over AndoidOS). The profile of that user would contain:

```
WinExecutable(a.exe)
AndroidOS(mycomputer)  // instead of WinOS(mycomputer)
EmulatorWinAndroid(W4A)
```

To achieve our goal (i.e. to infer that `a.exe` is `runnable`), we have to add one rule for the emulation. We can follow two approaches. The first is to write a rule that concerns the `runnable` predicate, while the second is to write a rule for classifying the system that is equipped with the emulator to the type of the emulated system:

A. Additional rule for `Runnable`
This relies on adding the following rule:

```
Runnable(X,Y,Z):- WinExecutable(X),
            EmulatorWinAndroid(Y), AndroidOS(Z)
```

Note that since the profile of the user contains the fact `EmulatorWinAndroid(W4A)` the body of the rule is satisfied (for `X=a.exe, Y=W4A, Z=myComputer`), i.e. the rule will yield the desired inferred tuple `Runnable(a.exe,W4A,mycomputer)`.

Note that here we added a rule for the `runnable` which has 3 variables signifying the ternary relationship between executable, emulator and hosting environment.

B. Additional type rule (w.r.t. the emulated Behavior)
An alternative modeling approach is to consider that if a system is equipped with one emulator then it can also operate as the emulated system. In our example this can be expressed by the following rule:

```
WinOS(X):- AndroidOS(X), EmulatorWinAndroid(Y).
```

It follows that if the profile of the user has an emulator of type `EmulatorWinAndroid` (here `W4A`) and `mycomputer` is of type `AndroidOS`, then that rule will infer that `WinOS(mycomputer)`, implying that the file `a.exe` will be inferred to be `runnable` due to the basic rule of `runnable` which is independent of emulators (i.e. due to the rule
`Runnable(X,Y) :- WinExecutable(X), WinOS(Y)`).

Both (A and B) approaches require the introduction of a new unary predicate about the corresponding pair of systems, here `EmulatorWinAndroid`. Approach (A) requires introducing a rule for making the predicate `runnable` "emulator-aware", while approach (B) requires a rule for classifying the system to the type of the emulated system. Since emulators are modules that can have their own dependencies, they should be runnable in the hosting system. To require their runnability during an emulation we have to update the above rules as follows (notice that last atom in the bodies of the rules):

```
A': Runnable(X,Y,Z):-      |B': WinOS(X):-
      WinExecutable(X),     |     AndroidOS(X),
      EmulatorWinAndroid(Y),|     EmulatorWinAndroid(Y),
      AndroidOS(Z),         |     Runnable(Y,X)
      Runnable(Y,Z)         |
```

Synopsis To synopsize, methodologically for each real world task we define two intensional predicates: one (which is usually unary) to denote the performability of the task, and another one (which is usually binary) for denoting the dependencies of task (e.g. `Read` and `Readable`). To model a *converter* and a corresponding conversion we have to introduce one unary predicate for modeling the converter (as we did for the types of digital files) and one rule for each conversion that is possible with that converter (specifically one for each supported type-to-type conversion). To model an *emulator* (between a pair of systems) we introduce a unary predicate for modeling the emulator and writing one rule for the emulation. Regarding the latter we can either write a rule that concerns the `runnable` predicate, or write a rule for classifying the system that is equipped with the emulator to the type of the emulated system. Finally, and since converters and emulators are themselves modules, they have their own dependencies, and thus their performability and dependencies (actually their runnability) should be modeled too (as in ordinary tasks).

4. REASONING SERVICES

In general, Datalog query answering and methods of logical inference (i.e. deductive and abductive reasoning) are exploited for enabling the required inference services (performability, risk detection, etc). Here we describe how the reasoning services described at Section 2 can be realized in the proposed framework.

Task-Performability. This service aims at answering if a task can be performed by a user/system. It relies on query answering over the Profiles of the user. E.g. to check if `HelloWorld.cc` is compilable we have to check if `HelloWorld.cc` is in the answer of the query `Compile(X)`. As we described earlier, *converters* and *emulators* will be taken into account, meaning that a positive answer may be based on a complex sequence of conversions and emulations. This is the essential benefit from the proposed modeling. Furthermore, classical *automated planning*, e.g. the STRIPS planning method [6], could be applied for returning one of the possible ways to achieve (perform) a tack. This is useful in case there are several ways to achieve the task.

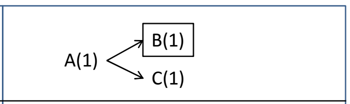
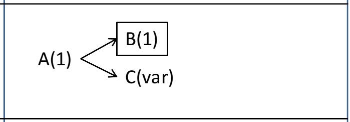
Risk-Detection. Suppose that we want to identify the consequences on *editability* after removing a module, say `NotePad`. To do so: (a) we compute the answer of the query `Edit(X)`, let A be the returned set of elements, (b) we delete `NotePad` from the database and we do the same, let B be the returned set of elements[5], and (c) we compute and return the elements in $A \setminus B$ (they are the ones that will be affected).

Computation of Gaps (Missing Modules). The gap is actually the set of facts that are missing and are needed to perform a task. There can be more than one way to fill a gap due to the disjunctive nature of dependencies since the same predicate can be the head of more than one rules (e.g. the predicate `TextEditor` in the example earlier). One method for informing the curator about the possible ways to fill it is to construct and visualize a *graph* that contains information about only the related facts and rules. We propose a graph which is actually a form of AND-OR graph. The user can specify the desired depth of that graph, or interactively decide to increase the depth gradually. The graph is actually a compact method for presenting the (possibly numerous) ways to fill a gap. The construction of the graph resembles the way *planning algorithms* (in particular backwards search-based planners) operate. The algorithm starts from the goal and shows the corresponding rules for achieving that goal. Those atoms of the rules which have a grounding that belongs to (or can be inferred from) the facts of the profile at hand, are visualized differently (e.g. colored in green, or enclosed in squares) so that the user can discriminate the missing from the available facts. Figure 2 shows some indicative examples. In all cases the goal is a grounded atom, i.e. `A(1)`, however the rules and the recorded facts are different in each case. In case (I) the graph shows that the gap is a grounded atom (i.e. `C(1)`), while in case (II) the graph shows that the gap is a non grounded atom (i.e. `C(var)`). Case (III) demonstrates a case where more than one rules with the same head are involved, and the depth of the graph is greater than one. The graph makes evident that there are two possible ways to fill the gap; according to the first the

[5]In an implementation over Prolog, we could use the *retract* feature to delete a fact from the database.

gap comprises two non grounded atoms (i.e. `D(var)` and `E(var)`), while according to the second it consists of one non grounded atom (i.e. `D(var)`).

A recursive algorithm for producing such graphs is given (in pseudocode) at Figure 3. The algorithm takes as input a *goal* (an atom grounded or not), a *depth* (a positive integer ≥ 1) and a *prevNode* (the previous node, it is used only for the recursive calls). Initially, the algorithm is called with the goal of the user (which is a grounded atom) plus the desired depth, and an empty (null) prevNode. The algorithm constructs and returns the corresponding tree graph (like those of Figure 2), whose layout can be derived by adopting one of the several hierarchical graph drawing algorithms.

(I)	g: A(1) facts: {B(1)} R: A(X):-B(X), C(X)	
(II)	g: A(1) facts: {B(1)} R: A(X):-B(X), C(Y)	

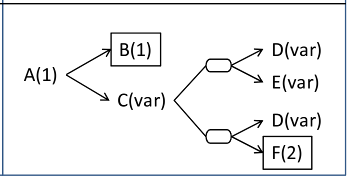
(III)	g: A(1)
	facts: {B(1),F(2)}
	R: A(X):-B(X), C(Y)
	C(X):- D(X), E(Y)
	C(X):- D(X), F(Y)
		 A(1)
		B(1)
		C(var)
		D(var)
		E(var)
		D(var)
		F(2)

Figure 2: Three examples of gap graphs

Figure 4 shows a small example of a graph of depth equal to 2 where conversion is involved. The graph corresponds to a case where a file `a.pas` is not compilable. The graph makes evident that to turn `a.pas` compilable either a *PascalCompiler* is required or a *runnable Pascal2Java converter*. Note that if we had a greater depth, then the expansion of `Pascal2Java(var1)` and `Run(var)`, would not necessarily use the same grounding for var1 and var2, although that would be desired. This and other ways to "inject reasoning" in the graph construction is a subject for further research.

Note that the algorithm returns always a tree and it does not do any arbitrary grounding; it is only the original grounded atom (i.e. the original goal) that is propagated based on the rules. Of course if there are rules whose body contain grounded atoms, the latter appear as such in the graph. The algorithm also does not expand a ground atom if inferred.

Complexity. If $|R|$ denotes the number of rules, d the depth, and Q denotes the cost to check whether a fact exists or is inferred (i.e. the cost of query answering), then the time complexity of the algorithm is in $\mathcal{O}(d * Q * |R|)$. Since $|R|$ is usually low, d is an input parameter which again cannot be very big, we can say that the complexity is low.

5. IMPLEMENTATION

There are several possible implementation approaches. Below we describe one Semantic Web-based implementation using RDF/S and *OpenLink Virtuoso* which is a general purpose RDF triple store with extensive SPARQL and RDF support [5]. Its internal storage method is relational, i.e. RDF triples are stored in tables in the form of quads (g, s, p, o) where g represents the graph, s the subject, p the predicate and o the object. We decided to use this system be-

```
Algorithm GapGraph (goal:Atom, depth:Integer, prevNode:Node):Node
If (prevNode=null) then
    gNode = Create node(goal)
else
    gNode = prevNode
hrs = all rules having the predicate of the goal as head
If (|hrs| = 0) then { // the goal predicate is not head in any rule
    headNode = gNode
    return headNode
}
For each hr in hrs
    If (|hrs| > 1) then { // there are > 1 rules having the same head
        ORnode = create node(ORnode)
        create link(gNode→ORnode)
        headNode = ORnode
    } else
        headNode = gNode
    If (IsGrounded(goal)) then { // e.g. consider the goal A(1)
        Ground the corresponding variable in all atoms of the
        body of the rule hr that contain that variable
    }
    Let BodyAtoms be the resulting set of body atoms
    // if the previous step did not ground anything,
    // then BodyAtoms contains the original body atoms

    for each atom in BodyAtoms {
        atomNode = Create node(atom)
        Create link(headNode → atomNode)
        If ((IsGrounded(atom)) and
        (exists in the fact set (or it can be inferred)) then
            Square(atomNode)
    }
    If (depth > 1) then
        For each atom in BodyAtoms
            If (Square(atomNode)=False) then {
            //atomNode corresponds to atom
                newNode = GapGraph(atom, depth − 1, atomNode)
                Create link(atomNode → newNode)
            }
        }
}
Return headNode
```

Figure 3: The algorithm that produces gap graphs

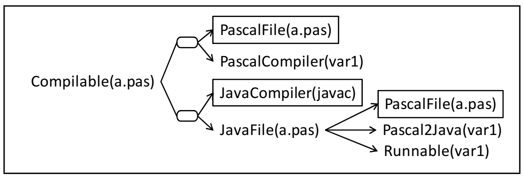


Figure 4: A visualization of a gap graph that involves a converter

cause of its inference capabilities, namely *backward chaining* reasoning, meaning that it does not materialize all inferred facts, but computes them at query level. Its reasoner covers the related entailment rules of `rdfs:subClassOf` and `rdfs:subPropertyOf`, while *user defined custom inference rules* can be expressed using *rule sets*. Practically this means that transitive relations (i.e. *subClassof*, *subPropertyOf*, etc.) are not physically stored in the knowledge base, but they are added to the result set at query answering. *Transitivity* is also supported in two different ways. Given a RDF schema and a rule associated with that schema, the predicates `rdfs:subClassOf` and `rdfs:subPropertyOf` are recognized and the inferred triples are derived when needed. In case of another predicate, the option for transitivity has to be declared in the query.

For our case, we have to "translate" our facts and rules to quads of the form (g, s, p, o) which are actually RDF triples contained in a graph g. The support of different graphs is very useful for the cases of profiles; we can use a different graph for each profile. We will start by showing how facts can be "translated" to RDF quads and later we will show how inference rules can be expressed using ASK and CONSTRUCT or INSERT SPARQL queries. Note that if we use INSERT instead of CONSTRUCT then the new inferred triples will be stored in the triple store (materialization of inferred triples). Hereafter we will use only CONSTRUCT. For better readability of the SPARQL statements below we omit namespace declarations.

Modules: Module types are modeled using RDF classes while the actual modules are instances of these classes. Module type hierarchies can be defined using the `rdfs:subclassof` relationship. For example the fact `JavaFile('HelloWorld.java')` and the rule for defining the module type hierarchy `TextFile(X) :- JavaFile(X)` will be expressed using the following quads:

```
g, <JavaFile>, rdf:type, rdfs:Class
g, <TextFile>, rdf:type, rdfs:Class
g, <JavaFile>, rdfs:subclassof, <TextFile>
g, <HelloWorld.java>, rdf:type, <JavaFile>
```

Profiles: We exploit the availability of graphs to model different profiles, e.g. we can model the profiles of James and Helen (including only some indicative modules), as follows:

```
<jGrph>, <NotePad>, rdf:type, <TextEditor>
<jGrph>, <HelloWorld.java>, rdf:type, <JavaFile>
<jGrph>, <javac_1_6>, rdf:type, <JavaCompiler>
<hGrph>, <VI>, rdf:type, <TextEditor>
<hGrph>, <jre_1_5>, rdf:type, <JavaVirtualMachine>
```

Dependencies: The rules regarding the performability of tasks and their dependencies are transformed to appropriate SPARQL CONSTRUCT statements which produce the required inferred triples. For example, the rule about the compilability of Java files
(`Compilable(X,Y) :- JavaFile(X),JavaCompiler(Y)`) is expressed as:

```
CONSTRUCT{?x <compilable> ?y}
WHERE{?x rdf:type <JavaFile>.
      ?y rdf:type <JavaCompiler>}
```

To capture the compilability of other kinds of source files (i.e. C++, pascal etc.) we extend the previous statement using the UNION keyword (this is in accordance with the Datalog-based rules; multiple rules with the same head have union semantics). For example the case of Java and C++ is captured by:

```
CONSTRUCT{?x <compilable> ?y}
WHERE{
      {?x rdf:type <JavaFile>.
       ?y rdf:type <JavaCompiler>}
      UNION
      {?x rdf:type <C++File>.
       ?y rdf:type <C++Compiler>}
}
```

Finally the unary predicate for the performability of task, here `Compile`, is expressed as:

```
CONSTRUCT{?x  rdf:type  <Compile>}
WHERE{ {?x <compilable> ?y} }
```

Converters: The rules regarding conversion are modeled analogously, e.g. for the case of a converter from Pascal to C++ we produce:

```
CONSTRUCT{?x rdf:type <C++File>}
WHERE{?x rdf:type <PascalFile>.
      ?y rdf:type <ConverterPascal2C++>.
      ?y rdf:type <Run>}
```

Note the last condition refers is an inferred type triple (Run). If there are more than one converters that change modules to a specific module type then the construct statement is extended using several WHERE clauses separated by UNIONs, as shown previously.

Emulators: Consider the scenario described in section 3, i.e. a user wanting to run `a.exe` upon his Android operating system. The approach B (which does not require expressing any predicate with three variables), can be expressed by:

```
CONSTRUCT{?x rdf:type <WindowsOS>}
WHERE{?x rdf:type <AndroidOS>.
      ?y rdf:type <EmulatorWin4Android>.
      ?y <runnable> ?x}
```

Services: To realize the reasoning services (e.g. task performability, risk detection, etc), we rely on SPARQL queries. For example to answer if the file `HelloWorld.java` can be compiled we can send the INSERT query about the compilability of the files (as shown previously) and then perform the following ASK query on the entailed triples:

```
ASK{<HelloWorld.java> <compilable> ?y}
```

If this query returns true then there is at least one appropriate module for compiling the file.

The risk-detection service requires SELECT and DELETE SPARQL queries (as discussed at section 4). For example to find those modules whose *editability* will be affected if we remove the module `Notepad`, we have to perform

```
SELECT ?x
WHERE {?x rdf:type  <Edit>}

DELETE <Notepad> rdf:type <TextEditor>
```

From the select query we get a set A containing all modules which are editable. Then we remove the triple about

Notepad and perform again the select query, getting a new set B. The set difference $A \setminus B$ will reveal the modules that will be affected. If empty this means that there will be no risk in deleting the Notepad.

Based on the above approach we have implemented a prototype system. Its repository containing the facts and rules of the examples of this paper, and behaving as specified by the theory is accessible through a SPARQL endpoint `http://139.91.183.78:8890/sparql`.

6. CONCLUDING REMARKS

In this paper we have extended past rule-based approaches for dependency management for capturing *converters* and *emulators*, and we have demonstrated that the proposed modeling enables the desired reasoning regarding task performability, which in turn can greatly reduce the human effort required for periodically checking or monitoring whether a task on an archived digital object is performable.

We should clarify that we do not focus on modeling, logging or reasoning over *composite tasks* in general (as for example it is done in [4]). We focus on the requirements for ensuring the performability of simple (even atomic) tasks, since this is more aligned with the objectives of long term digital preservation. Neither we focus on modeling or logging the particular workflows or derivation chains of the digital artifacts, e.g. using *provenance* models like OPM or CRM Dig [13]. We focus only the dependencies for carrying out the desired tasks. Obviously this view is less space consuming, e.g. in our running example we do not have to record the particular compiler that was used for the derivation of an executable (and its compilation time), we just care to have at our disposal an appropriate compiler for future use. However, if a detailed model of the process is available, then the dependency model can be considered as a read-only view of that model.

As regards applicability, note that some tasks and their dependencies can be extracted automatically as it has been demonstrated in [9, 7]. As regards available datasets, [12] describes the P2 registry, which uses Semantic Web technologies to combine the content of the *PRONOM Technical Registry*, represented as RDF, with additional facts from DBpedia, currently containing about 44,000 RDF statements about file formats and preservation tools.

In the near future we plan to further elaborate on gap visualization methods, while issues for future research include composite objects (e.g. software components, systems), update requirements, and quality-aware reasoning for enabling quality-aware preservation planning.

Acknowledgements
Work done in the context of NoE *APARSEN* (Alliance Permanent Access to the Records of Science in Europe, FP7, Proj. No 269977), and *SCIDIP-ES* (SCIence Data Infrastructure for Preservation - Earth Science, FP7).

7. REFERENCES

[1] C. Becker and A. Rauber. Decision criteria in digital preservation: What to measure and how. *JASIST*, 62(6):1009–1028, 2011.

[2] F. Bellard. QEMU, a fast and portable dynamic translator. In *Procs of the USENIX Annual Technical Conference, FREENIX Track*, pages 41–46, 2005.

[3] David Giaretta (Editor). *Advanced Digital Preservation.* Springer, 2010.

[4] D. Elenius, D. Martin, R. Ford, and G. Denker. Reasoning about Resources and Hierarchical Tasks Using OWL and SWRL. In *Procs of the 8th International Semantic Web Conference (ISWC'2009)*, 2009.

[5] O. Erling and I. Mikhailov. RDF Support in the Virtuoso DBMS. In *Procs of 1st Conference on Social Semantic Web*, 2007.

[6] R.E. Fikes and N.J. Nilsson. Strips: A new approach to the application of theorem proving to problem solving. *Artificial intelligence*, 2(3-4):189–208, 1972.

[7] A.N. Jackson. Using automated dependency analysis to generate representation information. In *Procs of the 8th International Conference on Preservation of Digital Objects (iPres'2011)*, 2011.

[8] B. Lohman, B. Kiers, D. Michel, and van der J. Hoeven. Emulation as a Business Solution: the Emulation Framework. In *Procs of the 8th International Conference on Preservation of Digital Objects (iPres'2011)*, 2011.

[9] Y. Marketakis, M. Tzanakis, and Y. Tzitzikas. PreScan: Towards Automating the Preservation of Digital Objects. In *Procs of the International Conference on Management of Emergent Digital Ecosystems MEDES'2009*, Lyon, France, October, 2009.

[10] Y. Marketakis and Y. Tzitzikas. Dependency Management for Digital Preservation using Semantic Web technologies. *International Journal on Digital Libraries*, 10(4), 2009.

[11] K. Rechert, D. von Suchodoletz, and R. Welte. Emulation based services in digital preservation. In *Procs of the 10th annual joint conference on Digital libraries*, pages 365–368. ACM, 2010.

[12] D. Tarrant, S. Hitchcock, and L. Carr. Where the Semantic Web and Web 2.0 meet format risk management: P2 registry. In *In Procs of the 6th Intern. Conf. on Preservation of Digital Objects (iPres 2009)*, 2009.

[13] M. Theodoridou, Y. Tzitzikas, M. Doerr, Y. Marketakis, and V. Melessanakis. Modeling and Querying Provenance by Extending CIDOC CRM. *J. Distributed and Parallel Databases (Special Issue: Provenance in Scientific Databases)*, 2010.

[14] Y. Tzitzikas. "Dependency Management for the Preservation of Digital Information". In *Procs of the 18th Intern. Conf. on Database and Expert Systems Applications, DEXA'2007*, Regensburg, Germany, September 2007.

[15] Y. Tzitzikas and G. Flouris. "Mind the (Intelligibily) Gap". In *Procs of the 11th European Conference on Research and Advanced Technology for Digital Libraries, ECDL'07*, Budapest, Hungary, September 2007. Springer-Verlag.

[16] Y. Tzitzikas, Y. Marketakis, and G. Antoniou. Task-based Dependency Management for the Preservation of Digital Objects using Rules. In *Procs of 6th Hellenic Conf. on Artificial Intelligence, SETN-2010*, Athens, Greece, 2010.

[17] J. Van der Hoeven, B. Lohman, and R. Verdegem. Emulation for digital preservation in practice: The results. *International Journal of Digital Curation*, 2(2), 2008.

[18] D. von Suchodoletz, K. Rechert, J. van der Hoeven, and J. Schroder. Seven steps for reliable emulation strategies–solved problems and open issues. In *7th Intern. Conf. on Preservation of Digital Objects (iPRES2010)*, pages 19–24, 2010.