A Formal Model of Use-Cases and Its Application in Generating A Hierarchical Class-Structure

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***Abstract*—Creating an object-oriented design from user requirements, given as a set of use-cases, means deriving a detailed class structure that can support an implementation of those requirements. We introduce here the Augmented Finite-State (AFS) model for a set of use-cases. An AFS model of a single use-case U incorporates the inputs, outputs, and operations for each interaction in U, including the "internal" dataflows among those interactions. The AFS model for a set of use-cases $\mathcal{U}$ combines the AFS models of individual use-cases $U_j \in \mathcal{U}$ to account for common interactions among U_j's and the control-flows among U_j's. After we decompose the combined model into a unique set of disjoint Maximal Linear Segments (MLSs), we derive one class from each MLS and finally create the class-hierarchy based on the next-relationship among the MLSs. One advantage of our approach over those based on the concept-analysis is that the AFS model gives a simple controller for the call-sequences of the class-methods corresponding to each U_j.**

Keywords*–Augmented finite-state model; class hierarchy; object-oriented design; refactoring; use-case model.

I. INTRODUCTION

Software design is an essential part of any software development effort. For an object-oriented software, the design consists of the classes (their attributes, methods, and method-parameters) and the relationships among those classes, which includes the class-hierarchy and other associations. The design gives a global view of the functionalities and structure of the software, and plays a critical role in understanding, implementation, and analysis of the software.

Semi-automated generation of UML-models and class-diagrams from natural language description of requirements are discussed in [1][2]. Automated generation of UML-models are discussed in [3][4]. These works are based on Natural Language Processing, and rely on use-cases defined using a semi-formal syntaxes and semantics. Cockburn [5] argued that there is no formal syntax or semantics for writing use-cases. Roussev [6] uses an informal notion of "balance" of objects involved in a use-case, and assumes the use-cases are given in terms of pre-conditions, post-conditions and invariants on the objects involved in the use-cases. The identification of objects is a key missing step in [6]; also, the notion of "balance" of objects has a basic flaw because "information" do not behave like the physical quantities force, energy, and mass, and we don't have a principle like the "conservation of energy" for "information".

Modeling means choosing a proper abstraction and a suitable representation of it to facilitate its use. Finite-state models and interaction-diagrams are often used in explaining a class-structure design [7]. We use a reverse approach: we first create an Augmented Finite-State (AFS) model of the use-cases (interactions) that describe the requirements and then we build the classes and their relationships from this model. This gives a more systematic and precise (semi-formal) technique compared to the other methods in the literature. A class design involves identification and grouping of operations and their supporting variables (inputs and outputs of the operations, and other intermediate stored data to avoid recomputation) in a way that minimizes the information overload. The AFS model facilitates both of these steps by capturing the essential operational details of the system's functional requirement. The identification of operational details for each use-case plays a key role in our approach. The method presented here can be regarded as a refinement of that in Kundu [8].

Many models are used in software engineering as effective tools. For example, *Finite-state* machines are used by Chow [9] for automated software testing. Our AFS model has some resemblance to *X-machines* [10]. In *X-machines*, a transition between two states is labeled by an operation whereas in AFS the labels are constraints; the dataflow items in AFS model correspond to the concept of "memory" in *X-machines*.

In Section II, we give the detailed formal definition of a use-case, and Section III defines the AFS model of a set of use-cases. Sections IV and V explain our AFS-based approach for generating a class-hierarchy using a simplified set of use-cases for a bank's ATM machine. Section VI provides a brief conclusion.

II. A FORMAL DEFINITION OF USE-CASE

Jacobson [11] defines a use-case as a sequence (chain) of interactions $U = \langle t_1, t_2, \cdots, t_n \rangle$, which provides the user a useful service, i.e., corresponds to a complete high-level functional requirement. If U_1 and U_2 are two use-cases, then clearly U_1U_2 is also a use-case. Henceforth, a use-case U will mean an *elementary* use-case, which cannot be decomposed into a sequence of two or more disjoint smaller use-cases.

A. Interaction t_j

Formally, an interaction $t_j = (in_j, op_j, out_j)$ is a triplet, where $in_j = in(t_j)$ is a set of input data-items, $op_j = op(t_j)$ is an operation, and $out_j = out(t_j)$ is a set of output data-items.

The inputs in_j consist of two disjoint parts: user-inputs in_j^u and other "external" (with respect to U) inputs in_j^e. The term "interaction" means $in_j^u \neq \emptyset$; however, one possible exception to this is that the last interaction t_n in U may have $in_n^u = \emptyset$ (cf. Theorem 1). An operation op_j may have multiple parts and a user may provide different parts of in_j^u at different stages of op_j, with in_j and out_j interleaved. The inputs to op_j may also include zero or more additional "internal" data-items d_i that are generated by previous op_i's, $i < j$ and $t_i \in U$. We refer to such d_i's as *dataflows*. The outputs out_j also consists of two parts: user-outputs out_j^u and external-outputs out_j^e; because parts of out_j^u maybe saved for use in other use-cases and hence included in out_j^e, we may have $out_j^u \cap out_j^e \neq \emptyset$. Clearly, $in_j = in_j^u \cup in_j^e$ and $out_j = out_j^u \cup out_j^e$. Henceforth, we use t_j and op_j interchangeably when no confusion is likely. Figure 1 shows the structure of an interaction t_j. We can regard op_j as a function of in_j and zero or more d_i, $i < j$, i.e., $in(op_j) = \bigcup_{i \leq j} in_i$. In contrast, $in(t_j) = in_j$ and thus t_j is not exactly the same as op_j. The dataflow d_j is not determined by op_j but by $t_k, k > j$ in U; also, d_j need not be a subset of out_j.

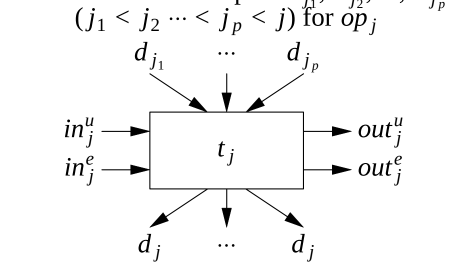

"internal" dataflow inputs $d_{j_1}, d_{j_2}, \cdots, d_{j_p}$
$(j_1 < j_2 \cdots < j_p < j)$ for op_j
d_{j_1}
$\cdots$
d_{j_p}
in_j^u
in_j^e
t_j
out_j^u
out_j^e
d_j
$\cdots$
d_j
d_j generated by op_j to zero or more op_k, $k > j$

Figure 1. Structure of an interaction t_j.

B. Use-Case U

We formally define a use-case as a sequence of interactions $U = \langle t_1, t_2, \cdots, t_n \rangle$ with the properties (1)-(4) below.

(1) $in_i^u \cap in_j^u = \emptyset$ for $i \neq j$. A user should not be required to provide the same input more than once in a use-case. If $op_j, j > i$, requires parts of the user-input in_i^u, then op_i may include those parts of in_i^u in the internal dataflow item d_i generated by op_i. However, $out_i^u \cap out_j^u$ may be non-empty because parts of out_i^u might be repeated in out_j^u (e.g., a "confirm operation" prompt to the user for a critical operation like deleting a file). We assume each in_j is as small as possible, i.e., no unnecessary "early" inputs and all of in_j is used in op_j. Likewise, we assume each out_j is as large as possible, i.e., no "late" outputs. For efficient input/output operations involving files and databases, one may want to maximize each chunk of information exchange but for modeling purpose these "early" and "late" viewpoints are more logical.

(2) $in_i^e \cap in_j^e = \emptyset = out_i^e \cap out_j^e$ for $i \neq j$. As before, if $op_j, j > i$, requires parts of in_i^e, then op_i may include those parts of in_i^e in d_i. This is desirable if accessing the external input data-items are computationally expensive. We may also include parts of out_i in d_i to avoid recomputing them in $op_j, j > i$. (A non-empty $out_i^e \cap out_j^e$ would mean parts of out_i^e is overwritten by op_j, $j > i$, based on additional information available at op_j.) Because op_j does not use any in_k or d_k, $k > j$, there is no *cyclic dependency* among op_j's.

(3) $d_i \cap d_j = \emptyset$ for $i \neq j$. Any part of d_i can be made available to each $op_j, j > i$, as needed.

(4) Each (t_j, t_{j+1})-pair has an associated *transition-condition* $c_{j,j+1}$ which needs to be satisfied after op_j is completed in order for op_{j+1} to start; $c_{j,j+1} = true$ means the condition is trivially satisfied. The condition $c_{j,j+1}$ does not depend on in_k, $k > j$, and may depend only on parts of $in(op_j)$. All non-trivial conditions $c_{i,i+1}, i \leq j$, contribute directly or indirectly to the pre-condition for op_{j+1}. We assume for now that $c_{j,j+1}$ is evaluated by op_j.

We write $I_U^u = \bigcup in_j^u$ and $I_U^e = \bigcup in_j^e$, where the unions are taken over all j, and finally $I_U = I_U^u \cup I_U^e$. Similarly, we write $O_U^u = \bigcup out_j^u$, $O_U^e = \bigcup out_j^e$, $O_U = O_U^u \cup O_U^e$, $D_U = \bigcup d_j$, and $C_U = \{c_{j,j+1} : 1 \leq j < n\}$. The entities in I_U, O_U, and D_U are the names of data-items and not any specific values for them. (An instance of a use-case U, with concrete values for the data-items in I_U and hence concrete values for the data-items in $D_U \cup O_U$, is called a scenario.)

If the use-case U' is used after the use-case U and we need to use parts of in_j^u at $t_j \in U$ as parts of $in_{j'}^u$ at $t_{j'} \in U'$, then we can include those parts of in_j^u into out_j^e and those parts of out_j^e can now become a part of $in_{j'}^e$. This avoids having to provide the common parts of in_j^u and $in_{j'}^u$ more than once.

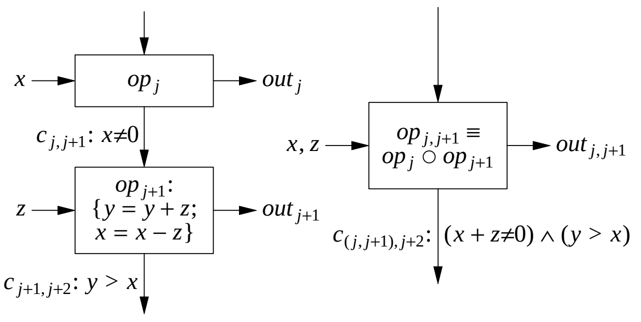
A proper choice of the individual interactions t_j in modeling a use-case U is a non-trivial task. A simpler or smaller t_j can help to reduce errors in determining $in(op_j), out(op_j)$, and $c_{j,j+1}$, but it can also introduce unnecessary details in the design of a class-structure for U. A complex or larger t_j can, on the other hand, prevent sharing interactions between different use-cases. These issues are described next.

C. Merging Interactions

If we merge $t_j, t_{j+1} \in U$ into a single interaction $t_{j,j+1}$, then we have $in_{j,j+1}^u = in_j^u \cup in_{j+1}^u$ and similarly for $in_{j,j+1}^e$, $out_{j,j+1}^u$, and $out_{j,j+1}^e$. In general, $d_{j,j+1} \subseteq d_j \cup d_{j+1}$, with $t_{j,j+1}$ hiding dataflows from t_j to t_{j+1} (making them internal to $op_{j,j+1}$); in the extreme case, we may have $d_{j,j+1} = d_{j+1}$. Also, $op_{j,j+1} = op_j \circ op_{j+1}$, the composition (roughly speaking in view of $c_{j,j+1}$) of op_j and op_{j+1}, in that order. The new interaction sequence $\langle t_1, t_2, \cdots, t_{j-1}, t_{j,j+1}, t_{j+2}, \cdots, t_n \rangle$ has less information about $op_{j,j+1}$ (equivalently, $t_{j,j+1}$) because we know less about which parts of $in_{j,j+1}$ are used by which parts of $op_{j,j+1}$ to produce which parts of $out_{j,j+1}$ and $d_{j,j+1}$. There is, however, no change in I_U^u, I_U^e, O_U^u, and O_U^e.

Except for the loss of some information as noted above, it is safe to merge t_j and t_{j+1} when $c_{j,j+1} = true$. In this case, each use-case U' containing t_j will also contain t_{j+1} and thus we can replace t_j and t_{j+1} by $t_{j,j+1}$ in each U'.

The merging of t_j and t_{j+1} has no impact on the condition from t_{j-1} to $t_{j,j+1}$, i.e., $c_{j-1,(j,j+1)} = c_{j-1,j}$, which will be evaluated by op_{j-1}. However, determining the condition $c_{(j,j+1),j+2}$ from $t_{j,j+1}$ to t_{j+2} might pose a problem as shown below. Consider the situation on the left-side in Figure 2. The part $\bar{c}_{j,j+1}$: "$x + z \neq 0$" in $c_{(j,j+1),j+2} = \bar{c}_{j,j+1} \wedge c_{j+1,j+2}$ shown on the rightside in Figure 2 is the result of "pushing down" the condition $c_{j,j+1}$: "$x \neq 0$" through op_{j+1}, which gives $x_{new} = x_{old} - z$, i.e., $x_{old} = x_{new} + z$, and thus $c_{j,j+1}$: "$x \neq 0$" = "$x_{old} \neq 0$" becomes $\bar{c}_{j,j+1}$: "$x_{new} + z \neq 0$" = "$x + z \neq 0$". But a difficulty arises if we replace "$x = x - z$" in op_{j+1} by "$x = x^2 - z$" because we cannot express now x_{old} in terms of x_{new}. We can, however, add the computation "$x_{old} = x$" at the end of op_j and call it op'_j, let $op_{j,j+1} = op'_j \circ op_{j+1}$ and $c_{(j,j+1),j+2}$: $(x_{old} \neq 0) \wedge (y > x)$. But such tricks do not always suffice as would be the case if "$x = x - z$" in op_{j+1} is replaced by "$x = x - z/x$"; op_{j+1} now needs $x \neq 0$ and thus we cannot afford to do the test "$x_{old} \neq 0$" after $op_{j,j+1}$.



x
op_j
out_j
c_{j,j+1}: x≠0
z
op_{j+1}: {y = y + z; x = x − z}
out_{j+1}
c_{j+1,j+2}: y > x
x, z
op_{j,j+1} ≡ op_j ○ op_{j+1}
out_{j,j+1}
c_{(j,j+1),j+2}: (x + z≠0) ∧ (y > x)

Figure 2. Illustration of a simple case of $c_{(j,j+1),j+2}$.

Even if we could define a suitable $c_{(j,j+1),j+2}$, the creation of $t_{j,j+1}$ would prevent sharing just one of t_j and t_{j+1} with another use-case U', and this can be a good reason not to create $t_{j,j+1}$. On the other hand, if we have a use-case $U' = \langle \cdots, t_j, t_{j+1}, t'_{j+2}, \cdots \rangle$ containing both t_j and t_{j+1} but a different t'_{j+2}, with $c'_{j+1,j+2}$ = "$y \leq x$" = $\neg c_{j+1,j+2}$ for the pair (t_{j+1}, t'_{j+2}), then after we create $t_{j,j+1}$ we will have $c'_{(j,j+1),j+2}$ = $(x + z \neq 0) \wedge (y \leq x)$ in U'. Obviously, we cannot merge t_j and t_k, $k > j+1$, and keep U acyclic.

Theorem 1. For a use-case $U = \langle t_1, t_2, \cdots, t_n \rangle$, there is no loss of generality to assume that each $in_j \neq \emptyset$ for $j < n$ if some use-cases U' share $t_i \in U$ exactly upto t_j.

Proof. If $in_j = \emptyset$ and $j < n$, then $c_{j,j+1}$ depends only on $\bigcup_{i<j} in_i$ and thus we can create the shortened use-case $\underline{U}$ by merging t_j into t_{j+1} as follows. We let $c_{j-1,j+1} = c_{j-1,j} \wedge lift(c_{j,j+1})$, where $lift(c_{j,j+1})$ is the result of "lifting up" $c_{j,j+1}$ through op_j, and replace op_{j+1} by $\underline{op}_{j+1} = op_j \circ op_{j+1}$. Note that $c_{j-1,j+1}$ can be evaluated by op_{j-1}. If there is another use-case $U' = \langle \cdots, t_{j-1}, t_j, t'_{j+1}, \cdots \rangle$, which is identical to U upto t_j, then we can likewise create the shortened use-case $\underline{U'}$ by merging t_j into t'_{j+1}, with op'_{j+1} replaced by $\underline{op'}_{j+1} = op_j \circ op'_{j+1}$ and letting $c'_{j-1,j+1} = c_{j-1,j} \wedge lift(c'_{j,j+1})$, where $c'_{j,j+1}$ is the condition for the pair (t_j, t'_{j+1}). Note that $c_{j-1,j+1} \wedge c'_{j-1,j+1} = c_{j-1,j} \wedge lift(c_{j,j+1}) \wedge lift(c'_{j,j+1}) = c_{j-1,j} \wedge lift(c_{j,j+1} \wedge c'_{j,j+1}) = c_{j-1,j} \wedge lift(false) = c_{j-1,j} \wedge false = false$, as desired. The shortened use-cases $\underline{U}$ and $\underline{U'}$ now share only upto t_{j-1}. □

Two remarks are due here. First, merging t_j with t_{j+1} to avoid $in_j \neq \emptyset$ does not cost us in terms of its effect on the class design. The methods for $\underline{op}_{j+1}$ and $\underline{op'}_{j+1}$ in the classes for $\underline{U}$ and $\underline{U'}$ will now have some commonalities because op_j is a part of both $\underline{op}_{j+1}$ and $\underline{op'}_{j+1}$. However, we can refactor the common part, if needed, to a parent class. Second, we do not merge t_j into t_{j-1} in the proof of Theorem 1 because if there is an use-case U'' that is identical to U only upto t_{j-1} then the merging would create an overloaded $t_{j-1,j}$ in terms of outputs and the operation $op_{j-1,j} = op_{j-1} \circ op_j$, and this can cause problems with the condition for $(t_{j-1,j}, t''_j)$-pair for U''. If there is no U'', we could form $t_{j-1,j}$ to eliminate t_j.

D. Decomposing an Interaction

If we can decompose an op_j into a chain of suboperations $\langle op_{j.1}, op_{j.2}, \cdots, op_{j.m} \rangle$, $m \geq 2$, then should we replace t_j in U by the chain of interactions $\langle t_{j.1}, t_{j.2}, \cdots, t_{j.m} \rangle$, where $op_{j.p}$ corresponds to $t_{j.p}$? If we did, then we will have $c_{j-1,(j.1)} = c_{j-1,j}$, $c_{(j.m),j+1} = c_{j,j+1}$, and $c_{j.p,j.(p+1)} = true, 1 \leq p < m$. This implies that it is safe to merge $t_{j.p}$'s and hence the decomposition is unnecessary. Note that because $c_{j.p,j.(p+1)} = true$, there is no use-case U' that includes $t_{j.p}$ but not $t_{j.(p+1)}$.

E. Deleting an Interaction

In general, the deletion of a $t_j \in U$ may not give a valid use-case $\langle t_1, t_2, \cdots, t_{j-1}, t_{j+1}, t_{j+2}, \cdots, t_n \rangle$. For example, if t_k, $k > j$, requires d_j generated by op_j then removal of t_j makes op_k inapplicable; hence t_k needs to be removed. This may, in turn, require other t_m, $m > k$, to be removed and so on. On the other hand, if $k > j$ is the smallest index such that t_k requires d_j then $\langle t_1, t_2, \cdots, t_{j-1}, t_{j+1}, t_{j+2}, \cdots, t_{k-1} \rangle$ may not be a valid use-case because the output of t_{k-1} may involve a prompt to the user to provide an input ($in^u_k \neq \emptyset$). The same argument shows that deletion of t_{k-1} may create a problem, and so on. A similar argument shows that an initial part of a use-case may not be a valid use-case. Likewise, a tail part $\langle t_{k+1}, t_{k+2}, \cdots, t_n \rangle$ of a use-case may not be a valid use-case because the output of t_k may involve a prompt to the user to provide an input and without that prompt t_{k+1} becomes meaningless.

III. Augmented Finite State (AFS) Model

The AFS model of a set of use-cases $\mathcal{U}$, denoted by $AFS(\mathcal{U})$, combines the notions of finite state machines, flowcharts, and Dataflow Diagrams (DFDs, which can be regarded as high-level dataflow-abstractions of flowcharts). As a finite-state machine, each state s_j in $AFS(\mathcal{U})$ corresponds to an interaction t_j in a use-case in $\mathcal{U}$. Each transition (s_j, s_k) corresponds to the next-interaction t_k of t_j in a use-case in $\mathcal{U}$ that contains t_j, and associated with the transition (s_j, s_k) we have the corresponding condition $c_{j,k}$. Clearly, $c_{j,k}$ is independent of the use-case in which t_k is the next interaction after t_j, and it can be likened to a branching-condition in a flowchart. We also have the dataflows d_i between interactions or states. As before, we consider a state $s_j = t_j$ to be synonymous with the operation op_j associated with t_j. If $|\mathcal{U}|$ = 1, then $AFS(\mathcal{U})$ takes the form of a single chain. The condition $c_{j,k}$ associated with transition (s_j, s_k) must be satisfied for the transition to take place. For two transitions (s_j, s_k) and (s_j, s'_k), $s_k \neq s'_k$, the conditions $c_{j,k}$ and $c_{j,k'}$ must be disjoint, i.e., $c_{j,k} \wedge c_{j,k'} = false$. Unlike a flowchart, an $AFS(\mathcal{U})$ by definition does not have a cycle and this prevents cyclic data-dependencies. The usual use-dependencies among data-items in assignments and other computations in a flowchart are replaced in $AFS(\mathcal{U})$ by the higher-level abstractions inputs, outputs, and dataflows associated with a state.

We formally define $AFS(\mathcal{U})$ = (S, s_0, S_{final}, C, D, I^u, I^e, O^u, O^e, $\tau, \delta, \phi^u, \psi^u, \phi^e, \psi^e$), where

1) $S \neq \emptyset$ is a set of states and $s_0 \in S$ is the start-state; each state s_j is reachable from s_0 by a sequence of transitions and has an associated operation op_j.

2) $S_{final} \subseteq S$ is the subset of final (terminal) states, from which there are no transitions.
3) $C = \{c_{i,j}$: conditions associated with transitions $(s_i, s_j)\} = \bigcup C_U$, union over the use-cases $U \in \mathcal{U}$.
4) $D = \{d_i$: the internal dataflow item generated by op_i at $s_i\} = \bigcup D_U$, union over the use-cases $U \in \mathcal{U}$.
5) $I^u = \bigcup I^u_U$, $I^e = \bigcup I^e_U$, $O^u = \bigcup O^u_U$ and $O^e = \bigcup O^e_U$, each union over the use-cases $U \in \mathcal{U}$.
6) $\tau : S \times C \rightarrow S$ is the transition function.
7) $\delta : D \rightarrow S \times \mathcal{P}^+(S)$ is the function representing the dataflows, where $\mathcal{P}^+(S)$ = the set of non-empty subsets of S, $\delta(d_j) = (s_j, S_j) = (\delta_1(d_j), \delta_2(d_j))$ means $S_j = \{s_k$: s_k uses d_j generated at $s_j\}$, and $d_i \neq d_j$ means $s_i = \delta_1(d_i) \neq \delta_1(d_j) = s_j$.
8) $\phi^u : I^u \rightarrow \mathcal{P}^+(S)$ is the user-input function; $\phi^u(u') = \{s_k$: s_k requires user-input $u'\}$.
9) $\phi^e : I^e \rightarrow \mathcal{P}^+(S)$ is the external-input function; $\phi^e(e') = \{s_k$: s_k requires external-input $u'\}$.
10) $\psi^u : O^u \rightarrow \mathcal{P}^+(S)$ is the user-output function.
11) $\psi^e : O^e \rightarrow \mathcal{P}^+(S)$ is the external-output function.
12) For each $s_i \notin S_{final}$, the conditions $c_{i,j}$ are mutually disjoint (i.e., $c_{i,j} \wedge c_{i,k} = false$ for $j \neq k$). We may also assume that $\bigvee c_{i,j} = true$ because otherwise we can add a "graceful" exit-transition to a new final state s'_i with the transition-condition $c_{i,i'} = \neg \bigvee c_{i,j}$.
13) For any $s_i, s_j \in \phi^u(u')$ for an user-input u', neither of s_i and s_j is reachable from the other. Similarly for ϕ^e and ψ^e. (But this is not required for ψ^u.)

In what follows, we consider only the special case where $AFS(\mathcal{U})$ has a tree-structure. Recall that not all paths in a flowchart, even in absence of cycles, may represent a valid execution-path; likewise, if the transitions in $AFS(\mathcal{U})$ form a general acyclic digraph, then we may have paths from the start-state s_0 to a final-state that do not represent a valid use-case and this can severely complicate the derivation of a suitable class-structure from $AFS(\mathcal{U})$. In the case of a tree-structured $AFS(\mathcal{U})$, each path from the start-state s_0 to a final-state represents a valid use-case in $AFS(\mathcal{U})$.

$AFS(\mathcal{U})$ helps us to see the relationships among the use-cases $\mathcal{U}$ in terms of their shared interactions. In particular, it helps us to identify inconsistencies inconsistent order of operations, invalid dataflow dependencies, and missing inputs/outputs for the use-cases $\mathcal{U}$. One must, indeed, resolve all inconsistencies before attempting to create a class-structure from $\mathcal{U}$ for the desired software.

IV. METHODOLOGY

Given the AFS-model of a single use-case U, we use the Class-Creation-Rules below to obtain a class that supports an implementation of U. These rules can be used also, more generally, for any linear chain of interactions. Initially, the class-methods have no parameters and this has the advantage of a simple control mechanism for executing the methods in a class (see Section V-C). We may later use refactoring to introduce new methods (possibly, with parameters) for common or similar parts of the original class-methods, and replace the common parts in the original methods by calls to the new refactored methods with suitable parameter-values.

Class-Creation-Rules for a single use-case U:
1. The variables are the internal dataflows, which may include parts of $I_U \cup O_U$.
2. The class-methods are the operations $op_j \in U$ or parts of them.

If $|\mathcal{U}| > 1$, we can first create one class for each use-case in $\mathcal{U}$ and then refactor common class-variables and methods to create the final class-structure. A better method is to build the class-structure directly from the combined model $AFS(\mathcal{U})$, whose tree-structure directly leads to a tree-structured class-hierarchy, with one class for each maximal linear segment (MLS) of the tree. A linear segment in $AFS(\mathcal{U})$ is a path π in $AFS(\mathcal{U})$, where each state in π other than those at the start and end of π has a single child (next) node.

We remark that the notation $t_j = (in_j, op_j, out_j)$ implies that if $t_j \in U$ is shared and equals $t'_j = (in'_j, op'_j, out'_j) \in U'$, then $in_j = in'_j$, $op_j = op'_j$, and $out_j = out'_j$. However, the dataflow d_j from op_j in U may differ from the dataflow d'_j from op'_j in U'. For a tree-structured $AFS(\mathcal{U})$, with $U, U' \in \mathcal{U}$, $t_j = t'_j$ implies $op_j = op'_j$ can compute $d_j \cup d'_j$, and thus we can replace both d_j in U and d'_j in U' by $d_j \cup d'_j$. Viewed another way, this simply points out that while the classes for U and U' obtained by the Class-Creation-Rules may contain different class variables due to $d_j \neq d'_j$, when we merge those classes to create a class-hierarchy the class containing $op_j = op'_j$ can include the variables for both d_j and d'_j.

We illustrate below our method by deriving a class-structure for a bank's ATM-system with three high-level functional requirements or use-cases $\mathcal{U} = \{U_1, U_2, U_3\}$, where U_1 = successful withdrawal, U_2 = failed withdrawal due to insufficient funds, and U_3 = balance enquiry. We first derive a class for each U_j using the Create-Class-Rules and then show that the class-structure obtained by refactoring these classes can be obtained directly from $\mathcal{U}$.

A. Informal Description of ATM

A user swipes a debit card in the ATM's card-slot. The ATM reads the debit card and prompts the user to enter the PIN. We assume for simplicity that no invalid ATM card or PIN is used, and there is no cash dispenser malfunction. The ATM validates the PIN and asks the user to choose one of two displayed options "withdrawal" and "balance-enquiry". If the user selects withdrawal-option, the ATM calculates and displays the maximum allowable withdrawal amount based on the available ATM cash and debit-card-account-information. Then, the ATM asks the user to enter the withdrawal amount and it reads that amount. Then, either the ATM displays the updates to debit-card-account-info and dispenses the desired cash, or it displays a transaction-fail-message when withdrawal amount is too large. If the user selects balance-enquiry option, the ATM displays the debit-card-account-balance. In each case, the ATM writes a transaction-log for future audit analysis as part of session-closing operation.

B. Formal Description of Use-Case U_1

We show below the decomposition of U_1 into four interactions t_1-t_4 and also show each op_j in detail, including its lower level operations. This simplifies the identification of inputs in_j, outputs out_j, dataflow items d_j, and the transition conditions $c_{j,j+1}$ for U_1, which are shown in Tables I and

II. The data-item ATMidAndOtherInfo in in_3^e includes ATM-cash-balance among others. The Transaction-Log-Information (TLI) has many parts, including dateTime of transaction, transaction amount, update of Bank-Debit-card-Account-Detail-Info, etc. Different out_j^e includes different parts of TLI.

U_1: Successful withdrawal

- **t_1:** User swipes the debit card in the ATM's card slot and enters PIN when requested. [**op_1:** ATM reads the debit card number, then reads Bank-Debit-Card-PIN Information based on the debit card number, displays ”Enter PIN” message, reads the PIN entered and validates it with Bank-Debit-Card-PIN information, reads Bank-Debit-Card-Account-Detail Information for the debit card number, and writes part-1 (debit card number, PIN, and transaction dateTime) of TLI]
- **t_2:** User sees the displayed transaction options and selects the ”withdrawal” option. [**op_2:** ATM displays the transaction-options ”balance-enquiry” and ”withdrawal”, requests the user to select an option, reads the selected option (= ”withdrawal” for U_1), and writes part-2 (transactionOption = withdrawal) of TLI.]
- **t_3:** User sees the displayed max allowed withdrawal amount and enters the desired withdrawal amount. [**op_3:** ATM calculates and displays the max allowed withdrawal amount based on the ATM-cash-balance (which is part of the external input ATMidAndOtherInfo) and the debit-card-account-detail information (such as the single-transaction-limit, the daily-withdrawal-limit for the card, today's-current-total-withdrawal, and the debit-card-account-balance). Then, ATM requests user to enter the desired-withdrawal-amount, reads it, and writes part-3 (max allowed withdrawal amount) of TLI.]
- **t_4:** User takes the dispensed cash. [**op_4:** ATM updates ATM-cash-balance part of ATMidAndOtherInfo and the Bank-Debit-Card-Account-Detail information (such as today's-total-withdrawal and debit-card-account-balance), displays the updated debit-card-account-balance, displays ”collect-cash” message (which includes the amount withdrawn), dispenses cash for the withdrawal amount, and writes part-4 (updates of ATM-cash-balance, this withdrawal amount, debit-card-account-balance) of TLI.]

TABLE I. Inputs in_j and outputs out_j for U_1

in_1	u: Debit-card number, PIN number e: Bank-Debit-Card-PIN Info, Bank-Debit-Card-Account-Detail Info	out_1	u: "Enter PIN" message e: Part-1 of TLI
		out_2	u: Transaction-options display, "Select Option" message e: Part-2 of TLI
in_2	u: Selected Transaction Option	out_3	u: Max Allowable Withdrawal Amount display, "Enter Desired Withdrawal Amount" message e: Part-3 of TLI
in_3	u: Desired Withdrawal Amount ATM-id-And-Other Info	out_4	u: New BankAccountDetailInfo, "Collect Cash" message e: New BankAccountDetailInfo, New ATMidAndOtherInfo, Part-4 of TLI
in_4	u: Cash Collected		

TABLE II. Conditions $c_{j,j+1}$ and data-items d_j for U_1

$c_{1,2}$	true (no invalid card or PIN)	d_1	Bank-Debit-Card-Account-Detail Info
$c_{2,3}$	"Withdrawal" = Selected Transaction Option	d_2	Selected Transaction Option
$c_{3,4}$	Max Allowable Withdrawal Amount ≥ Desired Withdrawal Amount	d_3	Max Allowable Withdrawal Amount, Withdrawal Amount Desired

In general, the conjunction of $c_{j,j+1}$'s for the interaction-sequence of a use-case U does not give a pre-condition for U because each $c_{j,j+1}$ is stated in terms of values of data-items ”after” the operation op_j. For U_1, $c_{2,3} \wedge c_{3,4}$ does give its pre-condition. We consider d_2 to be an ”implicit” dataflow from op_2 to op_3 because execution of op_3 requires $c_{2,3}$ to be true. Similarly, we consider d_3 to be an implicit dataflow from op_3 to op_4. (The controller to drive the execution of the methods in the class for U_1 will use d_2 and d_3; see Section V-C.) See Figure 3, which shows the finite-state machine model and the dataflow model for U_1. There is no dataflow from t_1 to t_2.

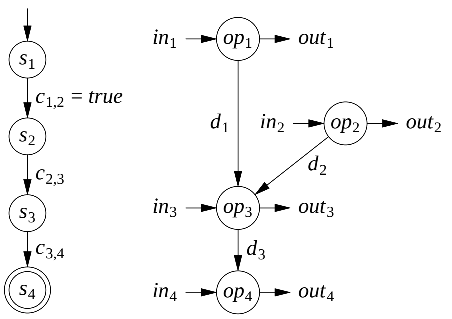
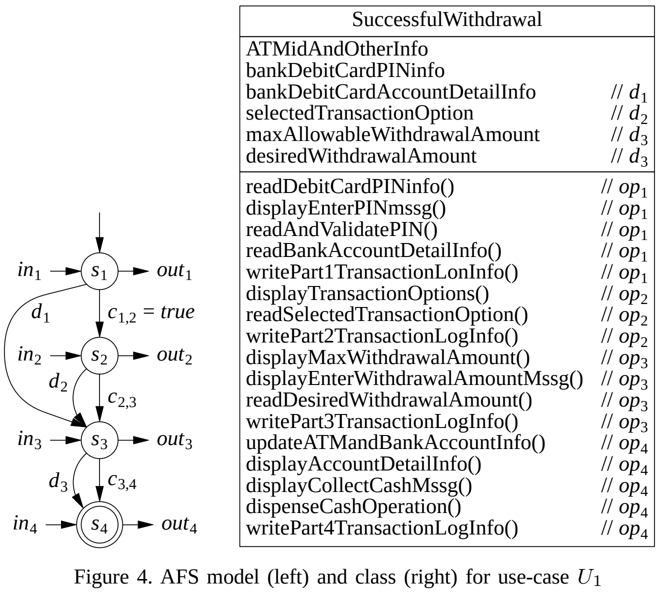


Figure 3. FSM (left) and DFD (right) for the use-case U_1



```
SuccessfulWithdrawal
ATMidAndOtherInfo
bankDebitCardPINinfo
bankDebitCardAccountDetailInfo          // d1
selectedTransactionOption               // d2
maxAllowableWithdrawalAmount            // d3
desiredWithdrawalAmount                 // d3
readDebitCardPINinfo()                  // op1
displayEnterPINmssg()                   // op1
readAndValidatePIN()                    // op1
readBankAccountDetailInfo()             // op1
writePart1TransactionLonInfo()          // op1
displayTransactionOptions()             // op2
readSelectedTransactionOption()         // op2
writePart2TransactionLogInfo()          // op2
displayMaxWithdrawalAmount()            // op3
displayEnterWithdrawalAmountMssg()      // op3
readDesiredWithdrawalAmount()           // op3
writePart3TransactionLogInfo()          // op3
updateATMandBankAccountInfo()           // op4
displayAccountDetailInfo()              // op4
displayCollectCashMssg()                // op4
dispenseCashOperation()                 // op4
writePart4TransactionLogInfo()          // op4
```

Figure 4. AFS model (left) and class (right) for use-case U_1

C. AFS Model of U_1

Figure 4 shows $AFS(U_1)$, obtained by combining the DFD and the FSM shown in Figure 3. It also shows the SuccessfulWithdrawal-class obtained from $AFS(U_1)$ based on Tables I and II and the Class-Creation-Rules, and it is suitable for implementing U_1. The detailed analysis of each t_j identified several low level functions (methods) for the associated op_j, and we have labeled each of those low-level functions as "//op_j" in SuccessfulWithdrawal-class. One could merge the functions with the same label "//op_j" into a single function, and call it op_j. If we let each merged function op_j have parameters corresponding to the dataflows to it and let each op_j call op_{j+1}, then we can eliminate all the class variables except d_1; even d_1 can be eliminated if we use a parameter in op_2 and pass d_1 for it when called by op_1. But we keep the class variables as shown to simplify the design of a single general purpose controller for any sets of use-cases.)

D. Merging and Decomposing Interactions in U_1

We can merge interactions t_1 and t_2 or, equivalently, states s_1 and s_2 in Figure 4 into a single state because $c_{1,2} = true$. This will not adversely affect handling U_2 and U_3 because both t_1 and t_2 are common to U_2 and U_3. We do not merge s_2 and s_3 because that would prevent sharing s_2 (and its associated operations, inputs, and outputs) between U_1 and the use-cases U_2 and U_3. On the other hand, we do not decompose a $t_j, 1 \leq j \leq 4$, into several $t_{j.k}$'s corresponding to the methods in Figure 4 having the label "//op_j" because that does not give us a better sharing of $t_{j,k}$'s among the use-cases $\mathcal{U} = \{U_1, U_2, U_3\}$, and thus does not help in the design of a class-structure for $\mathcal{U}$.

E. Classes and Formal Description of Use-Cases U_2 and U_3

Shown below are the decompositions of the use-cases U_2 and U_3 into their component interactions. The use-case U_2 shares its first three interations with U_1 and U_3 shares its first two interactions with U_1. Note that $t_{10} \in U_3$ is the same as $t_2 \in U_1$, even though the value of data-item $in^u_{10} = in^u_2$ is different in U_1 and U_3; that difference is reflected in $c_{2,3} \neq c_{10,11}$. The condition $c_{7,8} = \neg c_{3,4}$ gives $c_{7,8} \wedge c_{7,8} = false$ and $c_{3,4} \vee c_{7,8} = true$. The pre-condition for U_2 is $c_{2,3} \wedge c_{3,8}$ and that for U_3 is $c_{2,11}$.

U_2: Failed withdrawal due to insufficient funds

t_{j+4}: Same as t_j in U_1 for $1 \leq j \leq 3$.

t_8: User sees "insufficient funds" message. [**op_8:** ATM displays insufficient funds message for the desired withdrawal amount, and writes part-5 ("failed withdrawal", withdrawalAmount = 0) of TLI.]

U_3: Balance enquiry

t_9: Same as t_1 in U_1.

t_{10}: Same as t_2 in U_1 except that the user selects the "balance-enquiry" option.

t_{11}: User sees account balance information. [**op_{11}:** ATM displays the account balance and writes part-6 ("balance enquiry") of TLI.]

Table III gives the inputs and outputs for the interactions t_8, t_{10} and t_{11} in the use-cases U_2 and U_3. Table IV gives the conditions for these new interactions.

TABLE III. Inputs and outputs for U_2 and U_3 that are different from U_1

in_8	∅ (empty)	out_8	u: "Insufficient Funds" message e: Part-5 of TLI
in_{10} = in_2	u: Selected Transaction Option	out_{10} = out_2	∅ (empty)
in_{11}	∅ (empty)	out_{11}	u: Account Balance e: Part-6 of TLI

TABLE IV. Conditions $c_{j,k}$ for U_2 and U_3 that are different from U_1

$c_{7,8} = c_{3,8} = \neg c_{3,4}$	Max Allowable Withdrawal Amount < Withdrawal Amount Desired
$c_{9,10} = c_{1,2}$	true (no invalid Card)
$c_{10,11} = c_{2,11}$	"Balance Enquiry" = Selected Transaction Option

F. AFS Models for U_2 and U_3

We do not show the FSM and DFD for U_2 and U_3, but their AFS models and the corresponding classes are shown in Figures 5 and 6. As in the case of U_1, we could merge the functions (methods) with the same label "//op_j" in Figures 5 and 6 into a single function and call it op_j.

G. Merging of States for U_2 and U_3

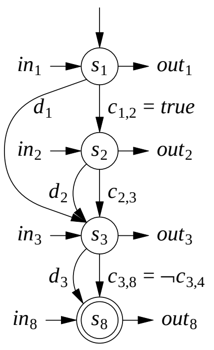
We do not merge s_2 with s_3 or s_{11} because $c_{2,3}$ and $c_{2,11}$ are disjoint; likewise, we do not merge s_3 with s_4 or s_8.

V. CLASS STRUCTURE AND IMPLEMENTATION

The classes in Figures 4-6 together allow us to implement the ATM described in section IV-A. We get the class-hierarchy shown in Figure 8 when we eliminate the duplicate attributes and methods in these classes using refactoring and combine the classes into a hierarchy. We can also directly get the same class-hierarchy, without creating the classes in Figures 4-6, from the combined AFS model for U_1-U_3 shown in Figure 7.

A. Combining AFS Models

We use the following notion of *equivalent* states to combine two AFS models $M = AFS(\mathcal{U})$ and $M' = AFS(\mathcal{U}')$ for the sets of use-cases $\mathcal{U}$ and $\mathcal{U}'$. Two states $s_j \in M$ and $s'_j \in M'$ are equivalent if all computations along the path $\pi(s_j)$ from the start-state of M upto s_j are identical to those along the path $\pi'(s'_j)$ from the start-state of M' upto s'_j in terms of the

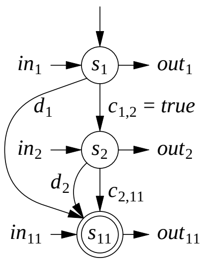


InsufficientFund	
ATMidAndOtherInfo	
bankDebitCardPINinfo	
bankDebitCardAccountDetailInfo	// d_1
selectedTransactionOption	// d_2
maxAllowableWithdrawalAmount	// d_3
desiredWithdrawalAmount	// d_3
readDebitCardPINinfo()	// op_1
displayEnterPINmssg()	// op_1
readAndValidatePIN()	// op_1
readBankAccountDetailInfo()	// op_1
writePart1TransactionLogInfo()	// op_1
displayTransactionOptions()	// op_2
readSelectedTransactionOption()	// op_2
writePart2TransactionLogInfo()	// op_2
displayMaxWithdrawalAmount()	// op_3
displayEnterWithdrawalAmountMssg()	// op_3
readDesiredWithdrawalAmount()	// op_3
writePart3TransactionLogInfo()	// op_3
displayInsufficientFundsMssg()	// op_8
writePart5TransactionLogInfo()	// op_8

Figure 5. AFS model and class for use-case U_2

order of computations and the underlying constraints. To be precise, s_j and s'_j are equivalent if

1) For $k < j$, s_k is equivalent to s'_k.
2) The dataflows to s_j and s'_j are identical in terms of the data-sources and the data-items.
3) The operations at s_j and s'_j are the same: $op_j = op'_j$, including the inputs $in^u_j = in'^u_j$ and $in^e_j = in'^e_j$ and the outputs $out^u_j = out'^u_j$ and $out^e_j = out'^e_j$.
4) The dataflows from s_j and s'_j are the same ($d_j = d'_j$).
5) The condition $c_{j-1,j}$ in M is the same as $c'_{j-1,j}$ in M', i.e., $c_{j-1,j} = c'_{j-1,j}$.



BalanceEnquiry	
ATMidAndOtherInfo	
bankDebitCardPINInfo	
bankAccountDetailInfo	// d_1
selectedTransactionOption	// d_2
readDebitCardPINinfo()	// op_1
displayEnterPINmssg()	// op_1
readAndValidatePIN()	// op_1
readBankAccountDetailInfo()	// op_1
writePart1TransactionLogInfo()	// op_1
displayTransactionOptions()	// op_2
readSelectedTransactionOption()	// op_2
writePart2TransactionLogInfo()	// op_2
displayAccountBalance()	// op_{11}
writePart6TransactionLogInfo()	// op_{11}

Figure 6. AFS model and class for use-case U_3

The conditions (1)-(3) and (5) above imply we can assume $d_j = d'_j$, i.e., condition (4) holds without loss of generality. This can be seen as follows. Because $op_j = op'_j$ can compute each of d_j and d'_j, it can compute $d_j \cup d'_j$ and thus we can replace each of d_j and d'_j by $d_j \cup d'_j$. The equivalence of s_j and s'_j depends only on the states on the paths $\pi(s_j)$ and $\pi'(s'_j)$, the inputs, outputs, and dataflows to and from those states, and the transition-conditions along $\pi(s_j)$ and $\pi'(s'_j)$. Note that the above definition of equivalence differs in many ways from that in finite-state automata theory, where the state-equivalence depends on what can happen in future from those states; in particular, the final states play a critical role. In our definition, the final-states have no special role.

B. Combining AFS models

Suppose U and U' are two (elementary) use-cases with one or more equivalent states. (We can always imagine a dummy start-state for a use-case, which just displays "starting..." and having no dataflow from this state. This will make the start-state of all use-cases equivalent.) We can merge the pairs of equivalent-states, one in each of $AFS(U)$ and $AFS(U')$, and the result is an AFS model having a tree-structure with two terminal nodes (final states). We can repeat the process for a set of use-cases $\mathcal{U}$, merging a state in $AFS(U_j)$ with its equivalent-state (if any) the result of merging $AFS(U_i), 1 \leq i < j$. The final AFS model $AFS(\mathcal{U})$ does not depend on the order in which we merge $AFS(U_i)$'s. Figure 7 shows the merged AFS model obtained from those in Figures 4-6.

The path $\pi = \langle s_1, s_2 \rangle$ in Figure 7 gives the class ATM-Transaction in Figure 8. The other classes in Figure 8 are obtained from the single-state paths $\langle s_3 \rangle$, $\langle s_4 \rangle$, $\langle s_8 \rangle$, and $\langle s_{11} \rangle$. The next-relationship between the paths $\langle s_1, s_2 \rangle$ and $\langle s_3 \rangle$ makes Withdrawal-class a subclass of ATMTransaction-class in Figure 8, and likewise for the other subclass-relationships. We obtain the same class structure in Figure 8 if we start with the classes in Figures 4-6 and apply refactoring [7].

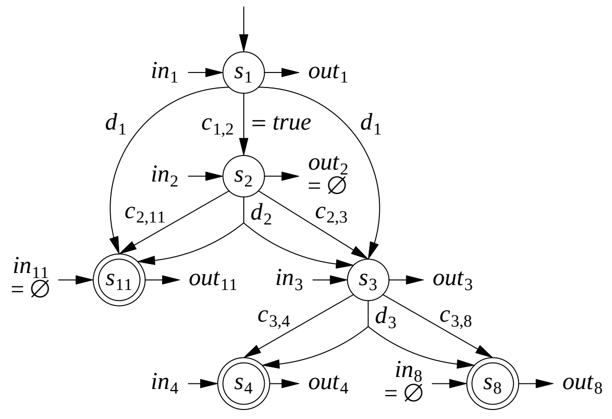
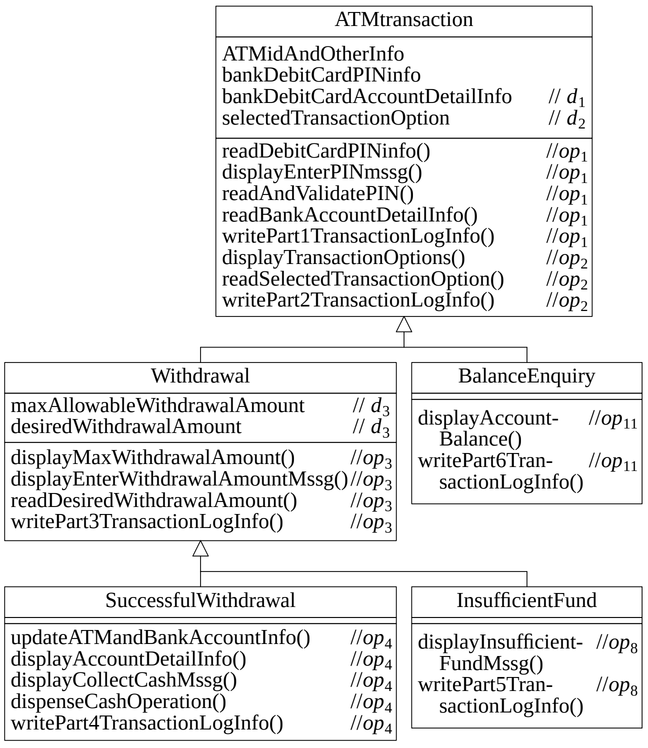


Figure 7. Combined AFS model for U_1-U_3.



ATMtransaction	
ATMidAndOtherInfo	
bankDebitCardPINinfo	
bankDebitCardAccountDetailInfo	// d_1
selectedTransactionOption	// d_2
readDebitCardPINinfo()	//op_1
displayEnterPINmssg()	//op_1
readAndValidatePIN()	//op_1
readBankAccountDetailInfo()	//op_1
writePart1TransactionLogInfo()	//op_1
displayTransactionOptions()	//op_2
readSelectedTransactionOption()	//op_2
writePart2TransactionLogInfo()	//op_2

Withdrawal	
maxAllowableWithdrawalAmount	// d_3
desiredWithdrawalAmount	// d_3
displayMaxWithdrawalAmount()	//op_3
displayEnterWithdrawalAmountMssg()	//op_3
readDesiredWithdrawalAmount()	//op_3
writePart3TransactionLogInfo()	//op_3

BalanceEnquiry	
displayAccount-Balance()	//op_{11}
writePart6Tran-sactionLogInfo()	//op_{11}

SuccessfulWithdrawal	
updateATMandBankAccountInfo()	//op_4
displayAccountDetailInfo()	//op_4
displayCollectCashMssg()	//op_4
dispenseCashOperation()	//op_4
writePart4TransactionLogInfo()	//op_4

InsufficientFund	
displayInsufficient-FundMssg()	//op_8
writePart5Tran-sactionLogInfo()	//op_8

Figure 8. Class-hierarchy from the AFS model in Figure 7

It is worth pointing out that if we apply the concept analysis technique [12] to the attributes (variables) and methods of the classes in Figures 4-6, based on the use-relationship between those variables and methods, then we would arrive basically at the same final class structure in Figure 8, except that each of the classes ATMtransaction and Withdrawal will become a chain of simpler classes (involving a partitioning of variables and methods in those classes). We will then simply merge those chains to form the classes ATMtransaction and Withdrawal as given in Figure 8. Note that a major part of building $AFS(\mathcal{U})$ involves, via the details of the interactions in the use-case $\mathcal{U}$, the identification of all class variables and methods, and their use-relationships, and the latter are the inputs to concept analysis. The only part of $AFS(\mathcal{U})$ which does not explicitly appear in the class-structure and is not used in concept analysis is the transition-conditions; they play, however, a critical role in the correctness of the tree-structure of $AFS(\mathcal{U})$, its unique decomposition into maximal linear segments (like $\langle s_1, s_2\rangle$), and in developing the controller (see Section V-C) to drive the execution of the methods in the class-structure. In this sense, our approach based on the AFS model is superior to the concept analysis method. After all, there is not much value in a class-structure design unless we clearly understand how to control the calls to its methods.

C. Implementation

Figure 9 shows the *execution* dependencies among the methods for the AFS model in Figure 7. Here, f_j represents the group of methods corresponding to op_j (see Figure 8) for state s_j. A link (f_i, f_j) implies the execution of f_j follows that of f_i, partly because d_i generated by f_i is required by f_j for its computations or d_i is needed in determining whether f_j can execute or not. It is not surprising that the links (f_i, f_j) in Figure 9 parallel the links (s_i, s_j) in Figure 7.

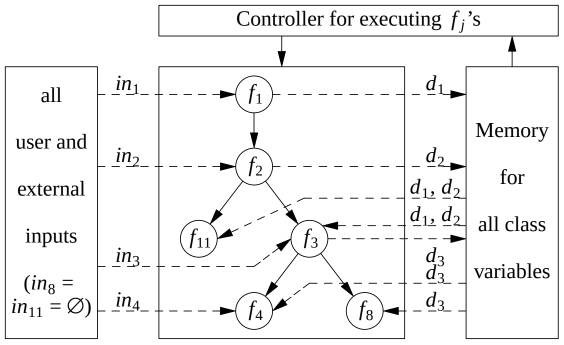


Figure 9. The execution dependency among methods f_j corresponding to op_j in Figure 8; d_j's are the dataflows.

There are many ways [13] to implement the dependencies in Figure 9. The simplest and the best solution is a central controller that works as follows. It first calls the root function f_1, and following the execution of an f_j it tests the disjoint conditions $c_{j,k}$ for the "child" functions f_k of f_j and calls f_k if $c_{j,k}$ is true. Another approach is to start with the root function f_1 as before but let each f_j evaluate the conditions $c_{j,k}$ and call f_k, if $c_{j,k}$ is true, as its last step, Here, changes in $\mathcal{U}$ may require small modifications to several f_j's, depending on how many classes are affected. In the first approach, the modifications to the central controller can be completely automated. As a third alternative, we can introduce parameters to f_j's and let each f_j store d_j as a local variable in it and use it as one of the parameters in the call to an f_k. For Figure 9. this means f_1 executes first and ends with a call to f_2, with d_1 as the parameter. Next, f_2 ends with a call to f_3 or f_{11}, with d_1 and d_2 as parameters. Likewise, f_3 ends with a call to f_4 with $d_1, d_2, \text{and}, d_3$ as parameters, etc. This approach requires fewer class-variables, but changes in requirements may cause many changes in the definition and selection of the parameters. This approach clearly gives a poor quality software.

VI. Conclusion

We have presented here a systematic, semi-formal method to obtain a hierarchical class-structure, including the attributes and methods for each class in the hierarchy, for an object-oriented design of a software from its requirements given in the form of a set of use-cases. We use two formal models: (1) a detailed model of a use-case in terms of its interactions (operations), which includes the user and external inputs/outputs of each operation and the dataflows to/from it, and (2) an Augmented Finite State (AFS) model for a set of use-cases, which captures shared operations among the use-cases, the points-of-divergence between use-cases and the related control-flow conditions. The AFS model can help to identify missing use-cases, missing interactions in the use-cases, and the potential need to decompose some interactions into simpler ones. If the AFS model has a tree structure, then this directly gives a hierarchical class-structure suitable for an object oriented implementation of the requirements. This means, in principle, one could start from, say, a C-program P and reverse engineer it to obtain an AFS model for it, and if the AFS model has a tree structure then create a hierarchical class-structure from that AFS model, and finally obtain an object-oriented program P' with the same functionality as P.

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