Testing of Object-Oriented Programs Based on Finite State Machines*

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Abstract

In object-oriented testing literature, a class is considered to be a basic unit of testing. A major characteristic of classes is the interaction between data members and member functions. This interaction is represented as definitions and uses of data members in member functions and can be properly modeled with finite state machines (FSM). In this paper, we discuss how FSMs can be effectively used for class testing. We demonstrate how to specify the behavior of classes using FSMs and present a test case generation technique based on FSMs. In our technique, FSMs are transformed into a flow graph from which we can explicitly identify data flows of the FSM. Then we generate test cases using conventional data flow testing techniques upon the flow graph.

1 Introduction

In object-oriented programs, there is a single entity called an object which represents both data and operations. Objects with similar data and operations can be specified by their common class. A class is a template that declares data members (attributes, properties) and operations (methods, member functions). A class is considered to be a basic unit of testing in object-oriented testing literature. The majority of class testing techniques generate test cases based on either algebraic specifications[5, 8, 10] or model-based specifications[13, 14, 21].

In this paper, we discuss the application of finite state machines (FSM) in class testing. A major characteristic of classes is the interaction between data members and member functions. The behavior of member functions is determined by the values of data

members and in turn, member functions manipulate data members. This interaction is represented as definitions and uses of data members in member functions and can be properly modeled with FSMs; data members represent the allowable states of an object and member functions represent a change of states, i.e., a transition of FSMs. Therefore, FSMs are often used as a specification of classes in most object-oriented analysis and design (OOA/OOD) methods[3, 6, 18, 19]. However, FSMs in OOA/OOD methods are described with English or pseudo-code and lack formal semantics to enable automated generation of test cases. We propose *class state machine* (CSM) for automatic test cases generation. The basic features of CSM are based on FSMs used in Rumbaugh et al.'s method[18]. CSM is a sort of extended FSMs composed of states, transitions, and data members of a class.

In our technique, we specify the behavior of classes in terms of CSM and generate test cases based on data flows in CSM. First, we transform CSM into a flow graph from which we can explicitly identify data flows; definitions and uses of each data member in CSM. Then we apply conventional data flow testing techniques[9, 16] upon the flow graph. This generates test cases which cover associations between definitions and uses of each data member. We can determine whether or not data flows in CSM are correctly implemented in the class's code with these test cases.

This paper is organized as follows: Section 2 discusses class specification based on FSM and formally defines CSM. Section 3 presents our testing technique based on CSM. Section 4 describes related works to class testing and compares our work with them. Conclusion and future works are given in section 5.

2 Class Specification Based on FSMs

Booch[3] discussed the motivation of using FSMs in class specification: An object has state, behavior, and identity. The existence of state within an object

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means that the order in which operations are invoked is important and we can formally characterize the behavior of the object in terms of FSMs.

Rumbaugh et al.[18] specified the behavior of a class in terms of states and events. When an event is received, the next state depends on the current state as well as the event; a change of state caused by an event is called a transition. The properties of states and transitions can be stated as follows:

- A state is an abstraction of the data members of a class. A set of values is grouped together into a state according to properties that affect the gross behavior of the class. Therefore, a state can be associated with the values of data members satisfying certain condition.
- A transition is composed of event, guard, and action. An event is an accident that cause the transition and can be represented as a call to a member function of the class. A guard is a condition that should be satisfied in order for the transition to occur and can refer to any data members in the class. An action is an operation that should be performed when the transition occurs and can refer to or manipulate the values of data members in the class.

For example, we assume that class Door has data members *angle*, *locked* and member functions *open()*, *close()*. If class Door has states, *closed* and *opened*, then each state can be associated with the values of data member *angle* as follows:

closed: *angle* = 0
opened: $0 < \text{angle} \leq 180$

An event which triggers a transition can be represented as a call to a member function. For example, a transition from *closed* to *opened* is triggered when a member function *open()* is called. The guard and action of a transition can be defined in terms of data members. If a transition from state *closed* to *opened* can occur, a guard that the door is not locked should hold. This condition can be expressed in terms of data member *locked* as *locked* = false. Similarly, the action of a transition from state *opened* to *closed* can be expressed by the assignment on data member *angle* as *angle* := 0.

2.1 Class State Machine

Definition 2.1 A *class state machine* (CSM) of a class *C* is a tuple $M = (V, F, S, T)$ where

- *V* is a finite set of data members of *C*.
- *F* is a finite set of member functions of *C*.

- *S* is a finite set of states, i.e., $S = \{s \mid s = (def)\}$ where *def* is a predicate on data members in *V*.
- *T* is a finite set of transitions, i.e., $T = \{t \mid t = (source, target, fn, guard, action)\}$ where
 - *source* $\in S$ is a state from which *t* departs.
 - *target* $\in S$ is a state at which *t* arrives.
 - *fn* $\in F$ is a member function which triggers *t*.
 - *guard* is a predicate on data members in *V* and parameters of member functions in *F*.
 - *action* is a set of computations on data members in *V* and parameters of member functions in *F*.

For example, Fig. 1 shows a CSM of class Door.

$V = \{\text{int angle, Boolean locked}\}$
 $F = \{\text{door(), } \sim\text{door(), lock(Boolean l), angle(int a), open(int a), close(), move(int a)}\}$
 $S = \{s_0, \text{closed}, \text{opened}, s_f\}$
 $s_0 = (\text{undefined}),$
 $s_f = (\text{undefined}),$
 $\text{closed} = (\text{angle} = 0),$
 $\text{opened} = (0 < \text{angle} \leq 180)$
 $T = \{t_i \mid 1 \leq i \leq 11\}$
 $t_1 = (s_0, \text{closed}, \text{door()}, \text{true}, \{\text{angle} := 0, \text{locked} := \text{true}\}),$
 $t_2 = (\text{closed}, \text{closed}, \text{angle(a)}, \text{true}, \{a := \text{angle}\}),$
 $t_3 = (\text{closed}, \text{closed}, \text{lock(l)}, \text{true}, \{\text{locked} := l\}),$
 $t_4 = (\text{closed}, \text{opened}, \text{open(a)}, \text{locked} = \text{false} \wedge 0 < a \leq 180, \{\text{angle} := a\}),$
 $t_5 = (\text{closed}, s_f, \sim\text{door()}, \text{true}, \emptyset),$
 $t_6 = (\text{opened}, \text{opened}, \text{angle(a)}, \text{true}, \{a := \text{angle}\}),$
 $t_7 = (\text{opened}, \text{opened}, \text{move(a)}, 0 < a \leq 180, \{\text{angle} := a\}),$
 $t_8 = (\text{opened}, \text{closed}, \text{close()}, \text{true}, \{\text{angle} := 0\}),$
 $t_9 = (\text{opened}, s_f, \sim\text{door()}, \text{true}, \emptyset).$

Figure 1: A class state machine for class Door

A CSM of a class C is composed of two parts: one representing data members and member functions of C ; the other representing states and transitions of C . Class Door is composed of data members: *angle*, *locked* and member functions: *door()* which is a constructor; *~door()* which is a destructor; *lock(l)* which assigns l to *locked*; *angle(a)* which assigns *angle* to a ; *open(a)*, *close()*, *move(a)* which manipulate *angle*.

Class Door has states: s_0 , s_f , *closed*, and *opened*. Each state is composed of *def* which associates a state with a predicate which represents a set of values of data members. For example, *closed.def* is *angle* = 0; this means that when an object is in state *closed*, *angle* = 0 is true. There are special states in CSM, s_0 and s_f :

- s_0 is an initial state representing the period before an object is created, i.e., a constructor of an object is called. $s_0.def$ is undefined because data members have not been created.
- s_f is a final state representing the period after an object is destroyed, i.e., a destructor of an object is called. $s_f.def$ is undefined because data members are killed in s_f .

A transition consists of *source*, *target*, *fn*, *guard*, and *action*. If an object is in state *source*, *fn* is called and *guard* is true, then a transition occurs. Hence, the pre-condition of a transition consists of source state and guard. When a transition occurs, *action* is performed and the state is changed into *target*. Hence, the post-condition of a transition consists of target state and action. For example, transition t_4 in Fig. 1 has *closed*, *opened* as a source and target state, respectively. t_4 can occur when an object is in *closed*, member function *open(a)* is called and guard (*locked* = false $\wedge$ $0 < a \leq 180$) is true. When t_4 occurs, *angle* := a is performed and the state is changed into *closed*. Hence, the pre-condition of t_4 is (*angle* = 0) $\wedge$ (*locked* = false $\wedge$ $0 < a \leq 180$). The post-condition of t_4 is ($0 < angle \leq 180$) $\wedge$ (*angle* := a).

2.2 Error transitions in CSM

CSM in Fig. 1 is incompletely specified in the sense that some transitions are unspecified. For example, suppose that *move(a)* is called when an object is in state *closed*. There exists no transition whose source state is *closed* and member function is *move(a)*. For another example, suppose that an object is in *opened* and *move(a)* is called. If $0 < a \leq 180$, transition t_7 occur. However, in the case of $a \leq 0 \vee a < 180$ there exists no possible transition. We interpret these cases as an error transition, i.e., if *move(a)* is called in *closed*, then the state of an object is changed to a state s_e . s_e is an error state representing that an error

has occurred and $s_e.def$ is undefined. In order to formally define error transitions, we adopt the following notation.

Definition 2.2 Let $M = (V, F, S, T)$ be a CSM, $s \in S$ be a state, and $f \in F$ be a member function. $T(s, f)$ is a set of transitions whose source state is s and triggering member function is f , i.e.,

$$T(s, f) = \{t \in T \mid t.source = s \wedge t.fn = f\}.$$

In Fig. 1, $T(closed, move(a))$ is $\emptyset$ and $T(opened, move(a))$ is $\{t_7\}$.

Definition 2.3 Let $M = (V, F, S, T)$ be a CSM, $s \in S$ be a state, and $f \in F$ be a member function.

- If $T(s, f) = \emptyset$, then $(s, s_e, f, true, \emptyset)$ is called an *error transition* of M .
- If $T(s, f) = \{t_i \mid 1 \leq i \leq n\}$ and $t_1.guard \vee t_2.guard \vee \dots \vee t_n.guard \neq true$, then $(s, s_e, f, \neg(t_1.guard \vee t_2.guard \vee \dots \vee t_n.guard), \emptyset)$ is called an *error transition* of M .

For example, in Fig. 1 (*closed*, s_e , *move(a)*, *true*, $\emptyset$) is an error transition because $T(closed, move(a)) = \emptyset$. (*opened*, s_e , *move(a)*, $\neg(0 < a \leq 180)$, $\emptyset$) is also an error transition because $T(opened, move(a))$ is $\{t_7\}$ and $t_7.guard \neq true$. Fig. 2 shows a CSM with error transitions for class Door.

- $t_{10} = (closed, s_e, open(), \neg(0 < a \leq 180), \emptyset)$
- $t_{11} = (closed, s_e, close(), true, \emptyset)$
- $t_{12} = (closed, s_e, move(a), true, \emptyset)$
- $t_{13} = (opened, s_e, lock(l), true, \emptyset)$
- $t_{14} = (opened, s_e, open(a), true, \emptyset)$
- $t_{15} = (opened, s_e, move(a), \neg(0 < a \leq 180), \emptyset)$

Figure 2: A CSM with error transitions for class Door

3 Class Testing Based on FSMs

In this section, we present a class testing technique based on CSM. Briefly our technique consists of the following steps:

1. We transform CSM into a flow graph called *class flow graph* (CFG) from which we can explicitly identify data flows in CSM.
2. We generate test cases from CFG using conventional data flow testing techniques.
 - (a) We identify definitions and uses of each data member in CFG.
 - (b) Based on these definitions and uses, every association between definitions and uses is established.
 - (c) Test cases are generated to cover these associations using data flow testing criteria.

The following subsections describe these steps in detail.

3.1 Transforming CSM into CFG

A flow graph is a graphical representation of a program's control structure. The nodes of a flow graph are statements of a program and edges indicate possible flow of control between nodes. In our technique, CSM is transformed into CFG. CFG is a flow graph which explicitly represent both the control and data flows of a class. The definition of CFG is as follows:

Definition 3.1 A *class flow graph* (CFG) of a class C is a directed graph $G = (N, E)$ where

- $N = N_s \cup N_g \cup N_t$
 - N_s, N_g , and N_t are a set of s -nodes, g -nodes, and t -nodes, respectively.
- $E = E_{st} \cup E_{sg} \cup E_{gt} \cup E_{ts}$.
 - E_{st} is a set of st -edges; a st -edge is (s, t) , $s \in N_s, t \in N_t$
 - E_{sg} is a set of sg -edges; a sg -edge is (s, g) , $s \in N_s, g \in N_g$
 - E_{gt} is a set of gt -edge; a gt -edge is (g, t) , $g \in N_g, t \in N_t$
 - E_{ts} is a set of ts -edges; a ts -edge is (t, s) , $t \in N_t, s \in N_s$

A node of CFG is s -node, g -node, or t -node which represent state, guard of a transition, and member function in CSM, respectively. Edges of CFG represent possible flow of control between these nodes. We transform CSM into CFG as follows:

Algorithm 3.1 Transformation of CSM to CFG

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input   CSM,  $M = (V, F, S, s_0, s_f, T)$  where
           $S = \{s_1, s_2, \dots, s_n\}$  and  $T = \{t_1, t_2, \dots, t_m\}$ 
output  CFG,  $G = (N, E)$  where
           $N = N_s \cup N_g \cup N_t$  and  $E = E_{sg} \cup E_{st} \cup E_{gt} \cup E_{ts}$ 

begin
  /* nodes of CFG */
   $N_s := N_g := N_t := \emptyset$ ;
  for  $i := 1$  to  $n$  do insert  $s_i$  into  $N_s$ ;
  for  $i := 1$  to  $m$  do begin
    if  $t_i.guard \neq \text{true}$  then
      insert  $t_i.guard$  into  $N_g$ ;
    insert  $t_i$  into  $N_t$ ;
  end
  /* edges of CFG */
   $E_{sg} := E_{st} := E_{gt} := E_{ts} := \emptyset$ ;
  for  $i := 1$  to  $m$  do begin
    if  $t_i.guard = \text{true}$  then
      insert  $(t_i.source, t_i)$  into  $E_{st}$ ;
    if  $t_i.guard \neq \text{true}$  then begin
      insert  $(t_i.source, t_i.guard)$  into  $E_{sg}$ ;
      insert  $(t_i.guard, t_i)$  into  $E_{gt}$ ;
    end
    insert  $(t_i, t_i.target)$  into  $E_{ts}$ ;
  end
end

```

The above algorithm accepts a CSM as an input and outputs a CFG. For example, CSM in Fig. 1 is transformed into CFG in Fig. 3 by Algorithm 3.1.

Each state in CSM is represented by the corresponding s -node in CFG. In Fig. 3 there exist s -nodes, which are drawn by ellipses, representing states of CSM in Fig. 1; $s_0, s_f, s_e, \text{closed}$, and opened . The diamond is a g -node; each guard of a transition in CSM which is not true is represented by a g -node. If the guard of a transition is true, there exists no g -node which represent the guard. The rectangle is a t -node; each transition in CSM is represented by a t -node.

Edges of CFG represent possible control flows between s -nodes, g -nodes, and t -nodes. We note that the following characteristics of the edges in CFG:

- In an st -edge (s, t) , s is source state of transition t ; this represents that if an object is in s , transition t will occur. For example, (closed, t_2) in Fig. 3 is an st -edge and represents that t_2 will occur in closed .
- An sg -edge (s, g) is followed by an gt -edge (g, t) . s is the source state of t and g is the guard of t ; this represents that if an object is in s and g is satisfied, then t will occur. For example, edges (closed, g_4) and (g_4, t_4) represent that if an object is in closed and g_4 is satisfied, t_4 will occur.

	angle	lock
def-c-use association	$(t_1, t_2), (t_8, t_2), (t_4, t_6), (t_7, t_6)$	$\emptyset$
def-p-use association	$(t_1, \text{closed}, t_2), (t_1, \text{closed}, t_3), (t_1, \text{closed}, g_4), (t_1, \text{closed}, t_5), (t_1, \text{closed}, g_{10}), (t_1, \text{closed}, t_{11}), (t_1, \text{closed}, t_{12}), (t_4, \text{opened}, t_6), (t_4, \text{opened}, g_7), (t_4, \text{opened}, t_8), (t_4, \text{opened}, t_9), (t_4, \text{opened}, t_{13}), (t_4, \text{opened}, t_{14}), (t_4, \text{opened}, g_{15}), (t_7, \text{opened}, t_6), (t_7, \text{opened}, g_7), (t_7, \text{opened}, t_8), (t_7, \text{opened}, t_9), (t_7, \text{opened}, t_{13}), (t_7, \text{opened}, t_{14}), (t_7, \text{opened}, g_{15}), (t_8, \text{closed}, t_2), (t_8, \text{closed}, t_3), (t_8, \text{closed}, g_4), (t_8, \text{closed}, t_5), (t_8, \text{closed}, g_{10}), (t_8, \text{closed}, t_{11}), (t_8, \text{closed}, t_{12})$	$(t_1, g_4, t_4), (t_4, g_4, t_4)$

Table 2: Def-use associations of class Door

- a) A *def-c-use association* of v is an ordered pair (d, c) where d is a t -node containing a definition of v and c is a t -node containing a c-use of v that can be reached by d .
- b) A *def-p-use association* of v is an ordered pair (d, p) where d is a t -node containing a definition of v and p is an *st*-edge, *sg*-edge or *gt*-edge containing a p-use of v that can be reached by d .
- c) A *def-use association* is either def-c-use association or def-p-use association.

Finally, test cases are generated to cover associations between definitions and uses of each data member using certain data flow testing criteria. A number of coverage criteria such as *all-definition*, *all-use*, and *all-du* path coverage have been studied and compared[9, 16]. All-definition coverage requires that every definition be covered by at least one use. All-uses coverage requires that at least one path from every definition to every use be exercised. All-du path coverage requires that every path from every definition to every use be exercised. For example, Table 3 shows test cases generated by all-def criteria for class Door.

$(s_0, t_1, \text{closed}, t_2, \text{closed}, t_5, s_f),$
 $(s_0, t_1, \text{closed}, g_4, t_4, \text{opened}, t_6, \text{opened}, t_9, s_f),$
 $(s_0, t_1, \text{closed}, g_4, t_4, \text{opened}, g_7, t_7, \text{opened}, t_{13}, s_e),$
 $(s_0, t_1, \text{closed}, g_4, t_4, \text{opened}, t_8, \text{closed}, t_{11}, s_e),$
 $(s_0, t_1, \text{closed}, g_4, t_4, \text{opened}, t_9, s_f),$
 $(s_0, t_1, \text{closed}, t_3, \text{closed}, g_4, t_4, \text{opened}, t_9, s_f)$

Table 3: Test cases generated by all-definition coverage

Each path in Table 3 represents a test case which covers a def-use association. For example, $(s_0, t_1, \text{closed}, t_2, \text{closed}, t_5, s_f)$ is a sequence of member

functions, $(\text{door}(), \text{angle}(a), \sim\text{door}())$ and covers the association of definition of *angle* at t_1 and c-use at t_2 .

4 Related Works

In general, FSM models of software abound in the testing literature[2]. Since Chow proposed testing techniques based on FSMs[7], many FSM-based testing techniques have been proposed especially in protocol conformance testing[4]. However, class testing based on FSMs is a relatively new concept. Recently, FSM-based class testing techniques have been proposed[15, 20] Turner and Robson[20] proposed a general testing procedure based on FSMs. Their technique determines input states and output states for each member function from the design of the class. However, this technique does not consider automatic test cases generation from FSMs. Kung et al.[15] proposed a class testing technique based on object state model (OSD) which is similar to statecharts[11]. They extract OSD from source code and generate test cases by constructing a spanning tree from OSD. Therefore, their technique mainly considers control flows in FSMs when generating test cases. In contrast, our technique generates test cases based on data flows in FSMs.

In object-oriented testing literature, a class is considered to be a basic unit of testing and several techniques have been proposed for class testing. Most of them is a specification-based technique using either algebraic specifications[5, 8, 10] or model-based specifications[13, 14, 21]. An algebraic specification consists of signatures which define the syntactic properties and axioms which define the properties of member functions. A model-based specification specifies the pre-condition and post-condition of each member functions using well-defined mathematical models such as sets or sequences.

In [5, 8, 10] test cases are generated as sequences

of member functions based on the axioms in algebraic specifications. However, in algebraic specifications member functions are treated as a mathematical mapping without side-effects. Therefore, data flows between data members and member functions cannot be explicitly represented in these techniques. On the other hand, in [13, 14, 21] test cases are generated based on the pre-condition and post-condition of each member function. Though member functions are tested whether or not they use and define data members correctly, data flows between member functions are not considered in these testing techniques.

There exist some techniques that adapt conventional flow graph-based testing techniques for class testing [12, 17, 21]. Zweben et al. [21] associated a flow graph with a class using model-based specifications. A node in the flow graph represents a member function. An edge between node *A* and *B* means that it is permissible to invoke *A* followed by *B*. Determining of whether or not an edge exists is based on the model-based specification of a class.

Figure 4: Zweben et al.'s flow graph for class Stack

For example, Fig. 4 shows a flow graph of class Stack constructed by Zweben et al.'s method. There exists no edge from *new* to *pop*, because *new* cannot be followed by *pop*. However, there exist infeasible paths such as (*new*, *push*, *pop*, *pop*) because states of a class are not considered when constructing the flow graph. In contrast, we transform FSMs into a flow graph and states of a class are considered in our flow graph. Therefore, all infeasible paths can be identified as a path containing an error transition.

Parrish et al. [17] extended Zweben et al.'s work so that a flow graph can be generated with or without specifications. A node of their flow graph is a member function and there exists an edge for every pair of nodes. Then a specification, if it exists, must be used to find infeasible paths. However, in the absence of specification, every sequence of member functions is assumed feasible.

Harrold and Rothermel [12] proposed data flow testing techniques for classes. They identify three levels

of class testing: (i) intra-method testing which tests member functions individually, (ii) inter-method testing which tests a member function together with other member functions that it calls and, (iii) intra-class testing which tests the interactions of member functions when they are called in various sequences. To support each data flow in the three levels, they construct a flow graph which represents every possible sequences of member functions from the class's code. Then they generate test cases using inter-procedural data flow testing techniques.

The works in [12, 17] are code-based, i.e., a flow graph is constructed from the class's code without specifications and every sequence of member functions is assumed feasible. In contrast, our technique is specification-based, i.e., we specify the behavior of classes using FSMs and a flow graph is constructed from FSMs. There exist infeasible sequences of member functions in our flow graph; these sequences are determined by FSMs. Therefore, the works in [12, 17] and our work are complementary each other.

5 Conclusion

In this paper, we have proposed a testing technique for classes in object-oriented programs. Our technique is a specification-based testing using FSMs. By using FSMs as a specification of classes, we can properly model the interactions between data members and member functions. In order to test the behavior of classes effectively, we have generated test cases by transforming FSMs into a flow graph and applying data flow testing techniques upon the flow graph. We have used flow graphs instead of directly generating test cases from FSMs, hence we can adapt conventional data flow testing techniques for class testing.

Our work presented in this paper does not consider inter-class relationships. In general, there are three types of relationships between classes: association, aggregation and inheritance [18]. In several OOA/OOD methods such as [6, 18] these relationships are specified with extended FSMs similar to statecharts [11]. We are investigating testing techniques of inter-class relationships based on statecharts-like specifications.

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