Code Generation from Extended Finite State Machines

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Outline

• Definition of Extended Finite State Machines

• General Code Generation Schemes

• Introduction to The EFSM Toolset
Extended Finite State Machines

- A Keyboard Example
- Formal Definitions
- Variants
EFSM: A Keyboard Example

EFSM: Definitions

- An EFSM consists of
  - Extended States, Guards, Events, Actions, and Transitions.
- A state is a situation or condition of a system during which
  - some (usually implicit) invariant holds,
  - the system performs some activity, or
  - the system waits for some external event.
- An extended state is a state with “memory”
  - E.g., using 100,000 states to count 100,000 key strokes; or, using one extended state with a variable “count”.
States vs Extended States
Example: Counting Number of Keystrokes (<= 100,000)

States
- One state represents one number
- Needs 100,000 states

Extended States
- One state represents all
- Needs one state with one variable

EFSM: Definitions
- Guards are
  - boolean conditions on extended state variables which enables or disables certain operations (e.g., change of states).
  - evaluated dynamically based on the extended state variable values.
  - immediate consequence of using extended state variables.
- An event
  - is an occurrence in time and space that has significance to the system.
  - may also be parametric which conveys quantitative info.
**EFSM: Definitions**

- **Actions**
  - are performed when an event instance is dispatched.
  - include
    - changing a variable;
    - performing I/O;
    - invoking a function;
    - generating another event instance; or
    - changing to another state (state transition).

- **Transitions**
  - can be triggered by events.
  - can also have a guard.

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**EFSM Variants: An Example**

- **Two Communicating EFSMs**
  - with event channel “press”

- **How to model “pressing twice fast”?**
  - need time variables – timed automata
EFSM: Variants

- **Input/output Variables**
  - can serve as enhanced messages in communicating EFSMs

- **Communicating EFSMs**
  - input/output events are properly defined to convey info
  - EFSMs communicate by sending and receiving events via channels

- **Timed Automata**
  - “clock” variables are added, increasing automatically as
    - clock ticks (discrete) or
    - time elapses (continuous)

- **Hierarchical EFSMs**
  - inside a state, the system behavior is also like an EFSM

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**STATE MACHINE CODING SCHEMES**
State Machine Coding Schemes

- State Machine Interface
- A Running Example
- Coding Schemes
  - Nested Switch Statement
  - State Table
  - Object-oriented State Design Pattern
  - Multiple-threaded Implementation
- Tradeoffs between EFSM Implementations

State Machine Interface

- Three methods
  - init() – take a top-level initial transition
  - dispatch() – dispatch an event to the state machine
  - tran() – take an arbitrary state transition
- Each coding scheme virtually implements these
- To use an EFSM in the main logic of the code
  - create an EFSM instance
  - invoke init() once
  - call dispatch()
    - repetitively in a loop
    - or sporadically based on detected events
  - dispatch() will then call the corresponding trans() function
The C Comment Parser Example

- A comment in the C language: /* comments */

The Nested Switch Statement

- Nest switch statement with
  - a scalar state variable in the first level for states,
  - an event signal in the second level, and
  - transition logic (actions) in the innermost level

- Two alternatives
  - Switch with events first and then states
  - Use one switch that combines both.
The Nested Switch Statement: Example

```cpp
enum Signal {                                  // enumeration for CParser signals
    CHAR_SIG, STAR_SIG, SLASH_SIG
};

enum State {                                    // enumeration for CParser states
    CODE, SLASH, COMMENT, STAR
};

class CParser1 {
    private:
        State myState;                                    // the scalar state-variable
        long myCommentCtr;                                // comment character counter
    /* ... */                                         // other CParser1 attributes
    public:
        void init() { myCommentCtr = 0; tran(CODE); }             // default transition
        void dispatch(unsigned const sig); 
        void tran(State target) { myState = target; }
        long getCommentCtr() const { return myCommentCtr; }
};
```

First switching the states then switch signals inside each state

```cpp
void CParser1::dispatch(unsigned const sig) {
    switch (myState) {
        case CODE:
            switch (sig) {
                case SLASH_SIG:
                    tran(SLASH); // transition to SLASH
                    break;
            }
            break;
        case SLASH:
            switch (sig) {
                case STAR_SIG:
                    myCommentCtr += 2;
                    tran(COMMENT);
                    break;
                case CHAR_SIG:
                    tran(CODE);
                    break;
            }
            break;
        case COMMENT:
            switch (sig) {
                case STAR_SIG:
                    tran(STAR);
                    break;
                case CHAR_SIG:
                    ++myCommentCtr;
                    tran(SLASH_SIG);
                    break;
                case SLASH_SIG:
                    tran(SLASH);
                    break;
            }
            break;
    }
}
```
The Nested Switch Statement: Example

```java
case STAR:
    switch (sig) {
        case STAR_SIG:
            ++myCommentCtr;                    // count STAR as comment
            break;
        case SLASH_SIG:
            myCommentCtr += 2;                // count STAR-SLASH as comment
            tran(CODE);                       // transition to CODE
            break;
        case CHAR_SIG:
            myCommentCtr += 2;                // count STAR-? as comment
            tran(COMMENT);                    // go back to COMMENT
            break;
    }
    break;
}
```

The Nested Switch Statement

- Nest switch statement with
  - a scalar state variable in the first level for states,
  - an event signal in the second level, and
  - transition logic (actions) in the innermost level

- Advantages
  - Simple and straightforward – just enumeration of stats and triggers
  - Small memory footprint – only a state variable necessary

- Disadvantages
  - Does not promote code reuse
    - all elements of an EFSM must be coded specifically for problem at hand.
  - Manual code is prone to errors
    - when logic becomes complex
  - Difficult to maintain in view of design change
**State Table**

- A table of arrays of transitions for each state
  - function pointers are stored for easy management
  - fast event dispatching
    - store states and signals as integers, then calculate with pointer offsets
    
    ```c
    trans *t = tableAddress + state * numSignals + sig;
    ```

<table>
<thead>
<tr>
<th>Signals</th>
<th>CHAR_SIG</th>
<th>STAR_SIG</th>
<th>SLASH_SIG</th>
</tr>
</thead>
<tbody>
<tr>
<td>code</td>
<td></td>
<td>doNothing(), slash</td>
<td></td>
</tr>
<tr>
<td>slash</td>
<td>doNothing(), code</td>
<td>a2(), comment</td>
<td>doNothing(), code</td>
</tr>
<tr>
<td>comment</td>
<td>a1(), comment</td>
<td>doNothing(), star</td>
<td>a1(), comment</td>
</tr>
<tr>
<td>star</td>
<td>a2(), comment</td>
<td>a1(), star</td>
<td>a2(), code</td>
</tr>
</tbody>
</table>

* a1() and a2() are respective action functions

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**State Table**

- **Advantages**
  - Direct mapping from a tabular representation of an EFSM
  - Fast event dispatching
  - Code reuse of the “generic event dispatching process”

- **Disadvantages**
  - Table maybe large and wasteful

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<td>a2(), comment</td>
<td>a1(), star</td>
<td>a2(), code</td>
</tr>
</tbody>
</table>

* a1() and a2() are respective action functions
class StateTable {
public:
    typedef void (StateTable::*Action)();

    struct Tran {
        Action action;
        unsigned nextState;
    };

    StateTable(Tran const *table, unsigned nStates, unsigned nSignals)
        : myTable(table), myNsignals(nSignals), myNstates(nStates) {
    }

    virtual ~StateTable() {}                          // virtual

    void dispatch(unsigned const sig) {
        register Tran const *t = myTable + myState * myNsignals + sig;
        (this->t->action)();
        myState = t->nextState;
    }

    void doNothing() {} ;

private:
    unsigned myState;
    Tran const *myTable;
    unsigned myNsignals;
    unsigned myNstates;
};

// specific Comment Parser state machine ...
enum Event { CHAR_SIG, STAR_SIG, SLASH_SIG, MAX_SIG };
enum State { CODE, SLASH, COMMENT, STAR, MAX_STATE };
class CParser2 : public StateTable {
public:
    CParser2() :
        StateTable(&myTable[0][0], MAX_STATE, MAX_SIG) {} // CParser2 state machine

    void init() { myCommentCtr = 0; myState = CODE; }  // initial tran
    long getCommentCtr() const { return myCommentCtr; }

private:
    void a1() { myCommentCtr += 1; }  // action method
    void a2() { myCommentCtr += 2; }  // action method

private:
    static StateTable::Tran const *myTable[MAX_STATE][MAX_SIG];
    long myCommentCtr;
};
#include "cparser2.h"

StateTable::Tran const CParser2::myTable[MAX_STATE][MAX_SIG] = {
  {&StateTable::doNothing, CODE },
  {&StateTable::doNothing, CODE },
  {&StateTable::doNothing, SLASH}},

  {&StateTable::doNothing, CODE },
  {static_cast<StateTable::Action>(&CParser2::a2), COMMENT },
  {&StateTable::doNothing, CODE }},

  {static_cast<StateTable::Action>(&CParser2::a1), COMMENT },
  {&StateTable::doNothing, STAR },
  {static_cast<StateTable::Action>(&CParser2::a2), CODE }}
};

filling out the table statically

State Design Pattern [Gamma+ 95, Douglass 99]

- An abstract state class
  - defines a common interface for handling events
  - each event corresponds to a virtual method
- Concrete states are subclasses of an abstract state class
- A context class delegates all events for processing to the current state object (myState variable)
- State transitions are explicit and are accomplished by reassigning the (myState variable)
- Adding new events corresponds adding it to the abstract state class
- Adding new states is to subclass the abstract state class
(1) A class for abstract states, contains all possible signals as virtual methods.

(2) A state in an EFSM is an object of a subclass of the CParseState. (CodeState, SlashState, etc.)
(3) The parser has exactly one object for each concrete state class (e.g., myCodeState, mySlashState, etc.)…

(4) … as well as a myState variable, which can points to any of them.
(5) State transition is just reassigning myState variable.

(6) Event dispatching relies on C++ virtual function dispatching rules. (If concrete class has the method, use it; otherwise use the virtual methods.) – Fast dispatching.
State Design Pattern: Example

class CParserState {                                // abstract State
public:
    virtual void onCHAR(CParser3 *context, char ch) {}
    virtual void onSTAR(CParser3 *context) {}  
    virtual void onSLASH(CParser3 *context) {}  
};
public:
    virtual void onSLASH(CParser3 *context); 
};
class SlashState : public CParserState {    // concrete State “Slash”
public:
    virtual void onCHAR(CParser3 *context, char ch);
    virtual void onSTAR(CParser3 *context);  
};
class CommentState : public CParserState { //concrete State “Comment”
    ....
};
class StarState : public CParserState {      // concrete State “Star”
    ....
};

class CParser3 {                                     // Context class
friend class CodeState;
friend class SlashState;
friend class CommentState;
friend class StarState;
static CodeState myCodeState;
static SlashState mySlashState;
static CommentState myCommentState;
static StarState myStarState;

CParserState *myState;
long myCommentCtr;
public:
    void init() { myCommentCtr = 0; tran(myCodeState);
    void tran(CParserState *target) { myState = target;
    long getCommentCtr() const { return myCommentCtr;
    void onCHAR(char ch) { myState->onCHAR(this, ch);
    void onSTAR() { myState->onSTAR(this);  
    void onSLASH() { myState->onSLASH(this); }  
};

The same story once more, in code.

(1) A class for abstract states, contains all possible signals as virtual methods.

(2) A state in an EFSM is an object of a subclass of the CParserState. (CodeState, SlashState, etc.)

(3) The parser has exactly one object for each concrete state class (e.g.,  
    myCodeState, mySlashState).
(4) … as well as a myState variable, which can points to
(5) State transition is just
(6) Event dispatching relies on C++ virtual function dispatching rules. (If concrete  
    class has the method, use it;  
    otherwise use the virtual methods.) – Fast dispatching.
State Design Pattern: Example

```cpp
#include "cparser3.h"

CodeState CParser3::myCodeState;
SlashState CParser3::mySlashState;
CommentState CParser3::myCommentState;
StarState CParser3::myStarState;

void CodeState::onSLASH(CParser3 *context) {
  context->tran(&CParser3::mySlashState);
}
void SlashState::onCHAR(CParser3 *context, char ch) {
  context->tran(&CParser3::myCodeState);
}
....
void StarState::onSTAR(CParser3 *context) {
  context->myCommentCtr++;
}
void StarState::onSLASH(CParser3 *context) {
  context->myCommentCtr += 2;
  context->tran(&CParser3::myCodeState);
}
```

The same story once more, in code.

(7) Implementation of individual actions are writing transition functions on need. (Default behavior is doNothing() as in the virtual function.)

State Design Pattern [Gamma+ 95, Douglass 99]

- **Advantages**
  - It localizes state specific behavior in separate (sub)classes.
  - Efficient state transition – reassigning a pointer.
  - Fast event dispatching – using C++ mechanism for function look up.
  - Parameterized events made easy – passing function parameters.
  - No need for enumeration of states or events beforehand.

- **Disadvantages**
  - Adding states requires creating subclasses.
  - Adding new events requires adding handlers to state interface.
  - In some situations where C++ or Java is not supported (e.g., some embedded systems), mockups of OO design maybe an overkill.
Multiple-threaded Implementation

App. I
- Each EFSM is implemented inside one thread.
- Threads run simultaneously, scheduled in round-robin.
- EFSMs share variables in the process.

Advantage
- Straightforward transformation from model.
- EFSM communication easily implemented with thread messages.

Disadvantage
- In some situations, no ready thread support in specific platform.
- Related analysis (progressiveness if semaphores are used, timing properties, etc) may be difficult.

Approach II
- Event detectors are implemented in threads.
- Transition actions are implemented in functions.
- Location information is stored with a variable.
- When event detector threads detects, calls corresponding functions and switching locations.

Advantage
- Easy adaption to model changes.

Disadvantage
- In some situations, no ready thread support in specific platform.
- Code may be unstructured/unreadable.
**Multiple-threaded Implementation: Example (Approach II)**

```c
void *trans3(void *ptr) {
    int t;
    while(1) {
        sem_wait(&Sense);
        if(current==WAIT_VRP && TRUE) {
            t=getTimer(&v_x);
            printf("Sense:%d\n", t);
            clearTimer(&v_x);
            current=ST_IDLE;
            sem_post(&ST_IDLE);
        }
    }
}
```

- A transition logic is written inside a function
  - Wait for semaphore for triggering signal.
  - If succeeded, check state (WAIT_VRP) and guard (TRUE).
  - Execute updates.
    - Print out timer value (for debugging)
    - Reset timer value
    - Change state

- All threads initialized and run in main

**Optimal EFSM Implementation**

- Does there exist one?
- A trade off based on
  - platform (available libraries? languages to use?)
  - purpose of coding
    - just for implementation or for analysis?
    - what type of analysis? etc.
  - efficiency requirement
  - possibility of model changes
The EFSM Toolset

- Introduction
- The EFSM Language
- Checking for Non-determinism and Totality
- Translations to Other Languages
- Test Generation from EFSMs
- Script Generation
- Code Generation
- Simulation
Introduction to EFSM Toolset

- Targets designers and engineers without specialized training in formal methods
- Uses easily human-readable languages in description
- Features
  - based on communicating EFSMs
  - using communication channels as well as shared variables
  - with input, output, and local variables

The EFSM Language

- Example

```plaintext
SYSTEM LampSystem:
  Channel: press, sync, B;
  EFSM Lamp {
    States: off, low, bright;
   InitialState: off;
    LocalVars:
      bint[0..5] y =0,
      boolean x = false;
    Transition: From off to low when true==true do press ? x , y =0;
    Transition: From low to off when y>=5 do press ? x;
    Transition: From low to bright when y<5 do press ? x;
    Transition: From bright to off when true==true do press ? x;
  }
  EFSM User {
    States: idle;
   InitialState: idle;
    LocalVars:
      boolean x = false;
    Transition: From idle to idle when true==true do press ! x;
  }
```
The EFSM Language: Channels

- **Specification**: Channel: <name>, <type>, <r/w/b>;
  - <type> maybe “sync” or “async”
    - “sync”: one-to-one, blocking synchronization of two EFSMs
    - “async”: one-writer-to-many-readers, non-blocking for writer, non-consuming from the readers, asynchronous
  - <r/w/b> – reader channel, writer channel, or both

- **Communication action**: <channel name> <action> <arg>
  - <action> can be !, ?, !!, ??
    - ! means writing, ? means reading
    - single mark means synchronous; double marks means asynchronous
  - <arg> is a typeless value
Non-determinism and Totality

- Example: A system with a bounded integer \( x \) in \([1..5]\) and
  
  (1) From start to discard if \( x \leq 4 \);
  (2) From start to use if \( x > 3 \);
  (3) From start to redo if \( x = 5 \);

- To check for non-determinism for the “start” state, we need to check
  
  (a) \( (x \leq 4) \land (x > 3) \)
  (b) \( (x \leq 4) \land (x = 5) \)
  (c) \( (x > 3) \land (x = 5) \)

  which are transformed to \( (x_k \text{ means } x = k \text{ is true}) \)
  
  (a) \( (x_1 \lor x_2 \lor x_3 \lor x_4) \land (x_4 \lor x_5) \)
  (b) \( (x_1 \lor x_2 \lor x_3 \lor x_4) \land (x_5) \)
  (c) \( (x_4 \lor x_5) \land (x_5) \)

- (a), (c) are satisfied, which means there are non-determinisms between
  
  - the first and the second transitions, and
  - the second and the third transitions

Translations to Other Languages

- Table – CSV format most Spreadsheet programs can open
- Text – Human readable text file
- Dotty – Input format of the “dot” program for drawing
- Promela – The Spin model checker input language
  - systems with only synchronous channels are supported now
  - setting channel buffer size to 0 in Promela
- Uppaal – The Uppaal model checker XML format
  - systems with only synchronous channels are supported now
  - value passing must take place through shared variables
- SMV format – the NuSMV model checker
  - currently supports systems without communication channels
  - shared variables are supported
  - can utilize the verification results from NuSMV for test case generation
Test Generation from EFSMs

- **Test Generation**
  - create a set of traces through the EFSM
  - for testing an implementation of the system
  - coverage criteria
    - state coverage – go through each state at least once
    - transition coverage – ensures that every transition is taken once
    - definition-use coverage – makes a trace from every definition of a variable to each of its subsequent uses

- **Output of Test Generation**
  - a sequence of assignments of variable values
  - necessary to lead the EFSM to take particular paths

**Model Based Approach using NuSMV**

- **Direct Test Generation Algorithm**
  - DFS algorithm to discover set of paths covering all states
  - It keeps track of constraints and assignments along the path.
  - A transition can be added to the path if compatible with other constraints.
  - The algorithm starts with initial state and a set of constraints corresponding to the initial assignments of variables.
  - If a transition can be added (compatible), add it and make a recursive call.
  - Can keep a snapshot of visited states to guarantee termination.
  - Need to use a satisfiability checker.
**Script Generation**

- **Script Generation**
  - takes a set of traces (from test generation)
  - makes a set of scripts
  - which can be run on an implementation

- **Approach**

**Code Generation**

- **Allows mapping state machine variables to arbitrary input/output functions**
  - input function is called each time the variable is read
    - condition like `x==2` will be translated to `readX()==2`
  - output function is called each time the variable is written
    - assignment like `x:=y-2` will become `writeX(y-2)`

- **C**
  - limited to single EFSM model without communication channels
  - repeatedly executing a series of if-else statements like
    - `if (state==X and condition==c) { doSomething(); ... }`

- **Java**
  - supports multiple communicating machines, utilizing JCSP library
  - each EFSM is run inside a thread, and they are all run in parallel
  - scheduled round-robin
**Example: Generated Code Snippet in C**

```c
while (transition_taken) {
    transition_taken=0;
    if (((currentState==1) && (current < getNumBots()))) {
        PRE_TRANSITION_HOOK;
        current= current+1;
        currentState=2;
        transition_taken=1;
        // printf("rolling:From:incrementTo:check
        // Guard:current <=numBotsAction:current=current+1\n");
        POST_TRANSITION_HOOK;
    }
    ....
    if (((currentState==2) && (getSwitch()==1))) {
        PRE_TRANSITION_HOOK;
        setAllAngles(1);
        currentState=1;
        transition_taken=1;
        // printf("rolling:From:checkTo:increment
        // Guard:switchValue == trueAction:setAngles=true \n");
        POST_TRANSITION_HOOK;
    }
}
```

**Example: Generated Code Snippet in Java**

```java
import jcsp.lang.*;
public class gaitThread implements CSProcess {
    private final String name="gaitThread"; ....
    public gaitThread() {}
    public void run() {
        final Skip skip= new Skip(); ....
        while (true) {
            switch (alt.priSelect()) {
                case 0:
                    if (((currentState.equals("footArming")) & (TwoSecondDelay == true))) {
                        currentState="spineArming";
                        System.out.println("gait: From: footArming
                        To:spineArming
                        Guard:TwoSecondDelay== true
                        Action:spine=-20");
                    }
                    if (((currentState.equals("spineArming")) & (TwoSecondDelay == true))) {
                    }
           !}
    }
}
```
Simulation with the EFSM Toolset

- Simulator generates Java code which walks through the EFSM model.
- At each step, it asks the user for input variable values, if any.
- Example screen on the right.
  - Either choose variables to set value and “Step”, or
  - Auto with “Probabilistic”.
- Simulator reports error message if no transitions available.

References

  - Source code available online
- David Arney, *EFSM Toolbox Manual*, University of Pennsylvania, 2009
Thank you!