Code Generation from Extended Finite State Machines

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Outline

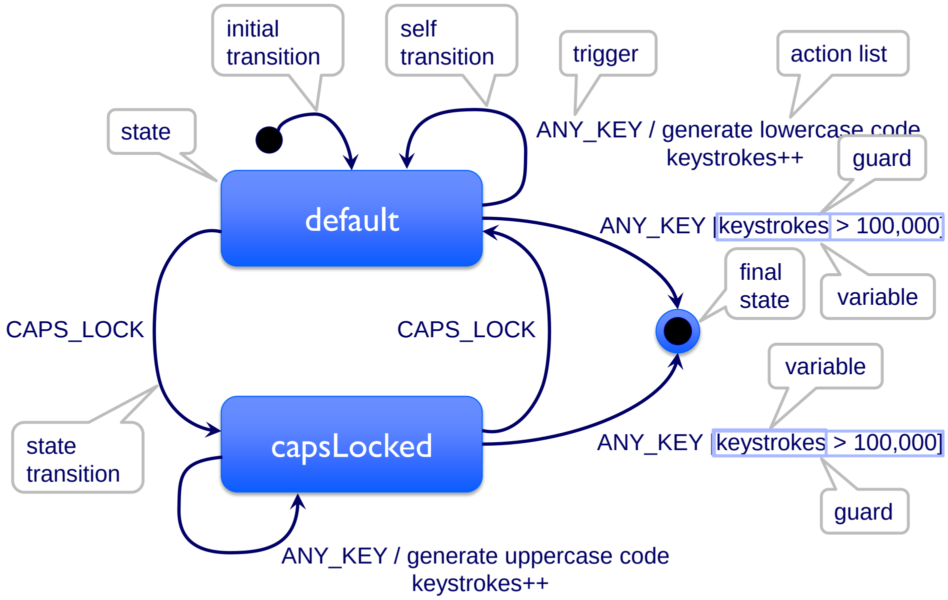
- Definition of Extended Finite State Machines
- General Code Generation Schemes
- Introduction to The EFSM Toolset

EXTENDED FINITE STATE MACHINES

Extended Finite State Machines

- A Keyboard Example
- Formal Definitions
- Variants

EFSM: A Keyboard Example



EFSM: Definitions

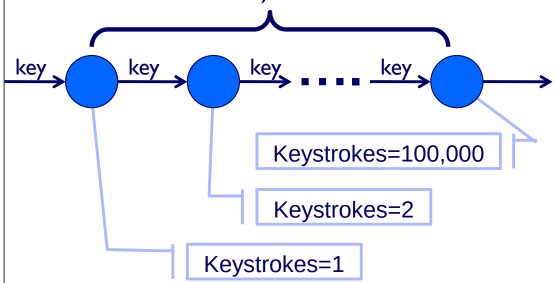
- An EFSM consists of
  - Extended States, Guards, Events, Actions, and Transitions.
- A **state** is a situation or condition of a system during which
  - some (usually implicit) invariant holds,
  - the system performs some activity, or
  - the system waits for some external event.
- An **extended 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

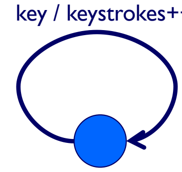
- One state represents one number
- Needs 100,000 states



No concept of variable 'keystrokes', using different states to represent them.

Extended States

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



One state and one variable to represent all.

EFSM: Definitions

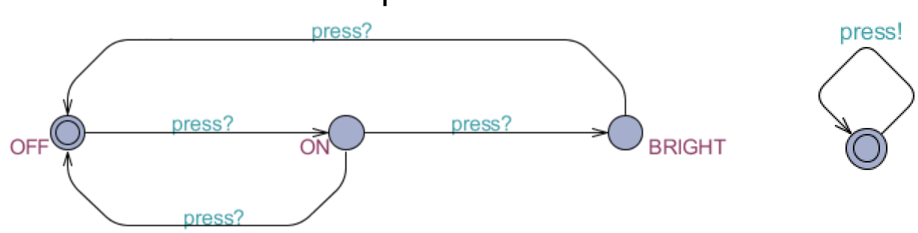
- **Guards** are
  - boolean conditions on extended state variables which enables or disables certain operations (e.g., change of states).
  - evaluated dynamically based on the extended state variable values.
  - immediate consequence of using extended state variables.
- An **event**
  - is an occurrence 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.

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

STATE MACHINE CODING SCHEMES

State Machine Coding Schemes

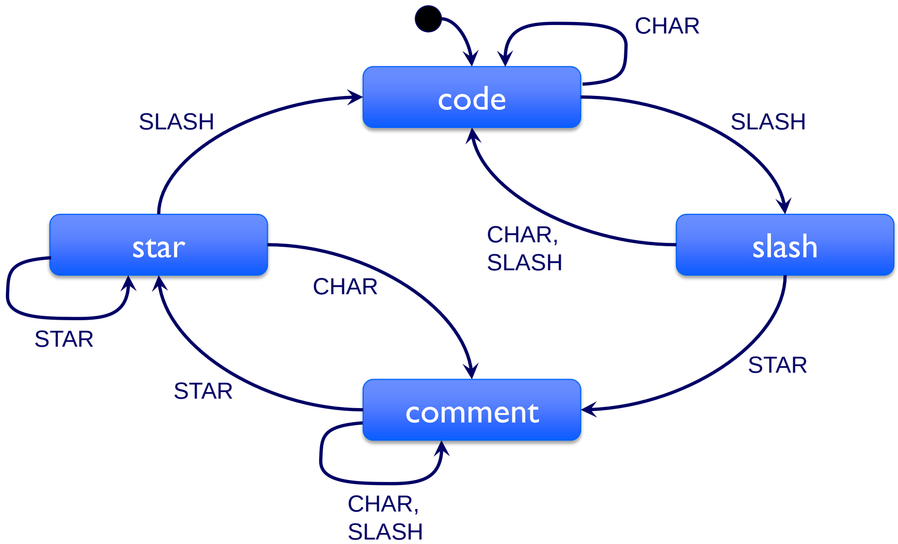
- State Machine Interface
- A Running Example
- Coding Schemes
  - Nested Switch Statement
  - State Table
  - Object-oriented State Design Pattern
  - Multiple-threaded Implementation
- Tradeoffs between EFSM Implementations

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

```
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 transiton
   void dispatch(unsigned const sig);
   void tran(State target) { myState = target; }
   long getCommentCtr() const { return myCommentCtr; }
};
```

state machine interface

The Nested `switch` Statement: Example

first switching the states

then switch signals inside each state

finally the business logic

```
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:
      case SLASH_SIG:
         tran(CODE);
         break;
      }
      break;
   case COMMENT:
      switch (sig) {
      case STAR_SIG:
         tran(STAR);
         break;
      case CHAR_SIG:
      case SLASH_SIG:
         ++myCommentCtr;
         break;
      }
      break;
```

The Nested `switch` Statement: Example

one more time, for state STAR

```
   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

```
trans *t = tableAddress + state * numSignals + sig;
```

Signals →

States ↓

	CHAR_SIG	STAR_SIG	SLASH_SIG
code			doNothing(), slash
slash	doNothing(), code	a2(), comment	doNothing(), code
comment	a1(), comment	doNothing(), star	a1(), comment
star	a2(), comment	a1(), star	a2(), code

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

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

Signals →

States ↓

	CHAR_SIG	STAR_SIG	SLASH_SIG
code			doNothing(), slash
slash	doNothing(), code	a2(), comment	doNothing(), code
comment	a1(), comment	doNothing(), star	a1(), comment
star	a2(), comment	a1(), star	a2(), code

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

State Table: Example

a generic state table class

struct for transitions

struct for transitions

fast dispatching

```
class StateTable {
public:
   typedef void (StateTable::*
   struct Tran {
      Action action;
      unsigned nextState;
   };
   StateTable(Tran const *table, unsigned nStates, unsigned nSignals)
      : myTable(table), myNsignals(nSignals), myNstates(nS
   virtual ~StateTable() {}                           // vi
   void dispatch(unsigned const sig) {
      register Tran const *t = myTable + myState*myNsignals + sig;
      (this->*(t->action))();
      myState = t->nextState;
   }
   void doNothing() {}
protected:
   unsigned myState;
};
```

```
private:
   Tran const *myTable;
   unsigned myNsignals;
   unsigned myNstates;
```


State Table: Example

table size

constructing customized state table

```
// 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 {                  // CPa
public:
   CParser2() : StateTable(&myTable[0][0], MAX_STATE, MAX_SIG) {}
   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
   long myCommentCtr;                                   character counter
};
```

business logic implemented as private functions of the table

static field holding the state table

State Table: Example

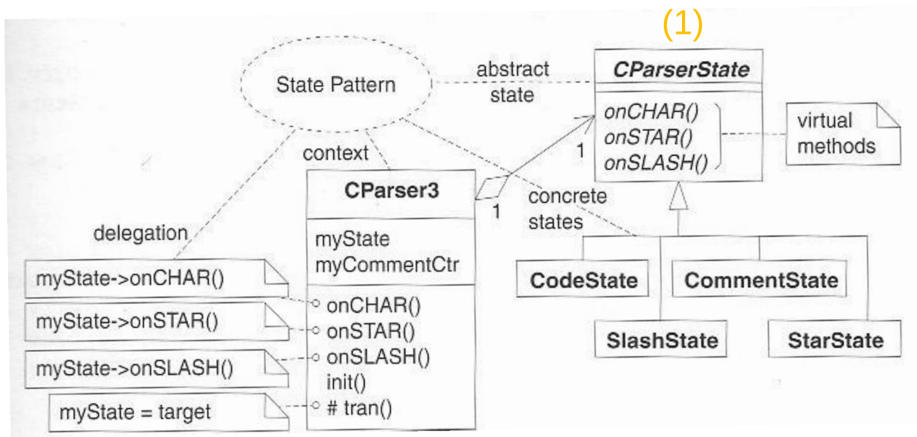
filling out the table statically

```
#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::a1), COMMENT }},

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


State Design Pattern [Gamma+ 95, Douglass 99]

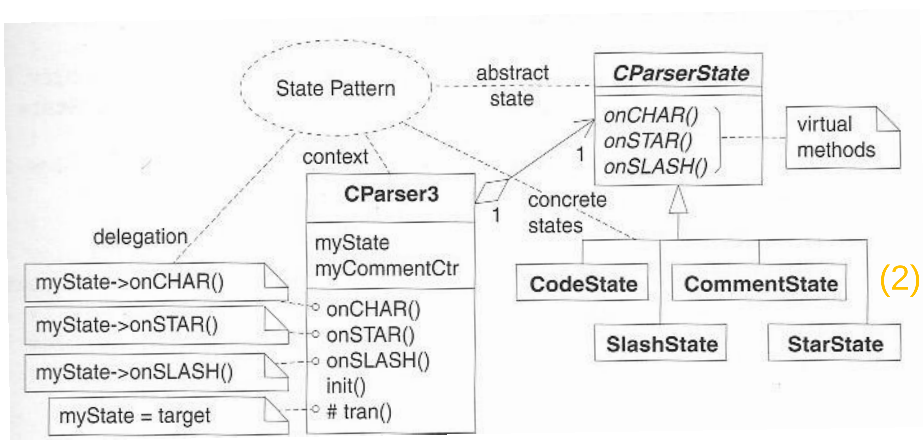
- An abstract state class
  - defines a common interface for handling events
  - each event corresponds to a virtual method
- Concrete states are subclasses of an abstract state class
- A context class delegates all events for processing to the current state object (myState variable)
- State transitions 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

State Design Pattern [Gamma+ 95, Douglass 99]



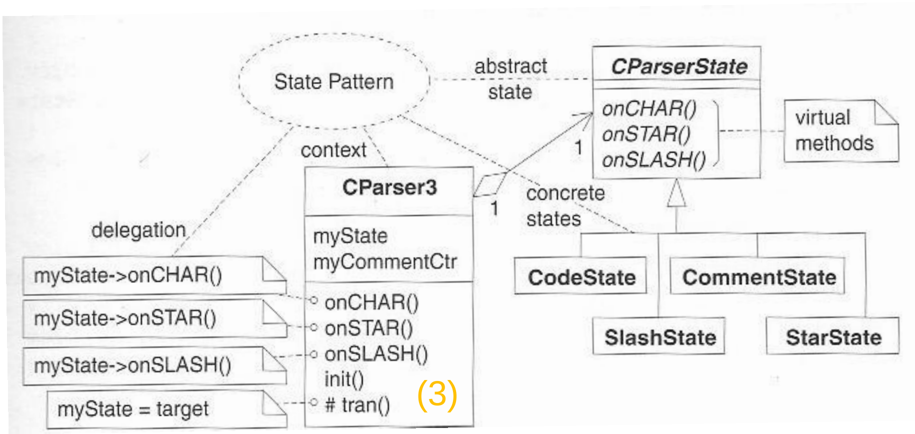
(1) A class for abstract states, contains all possible signals as virtual methods.

State Design Pattern [Gamma+ 95, Douglass 99]



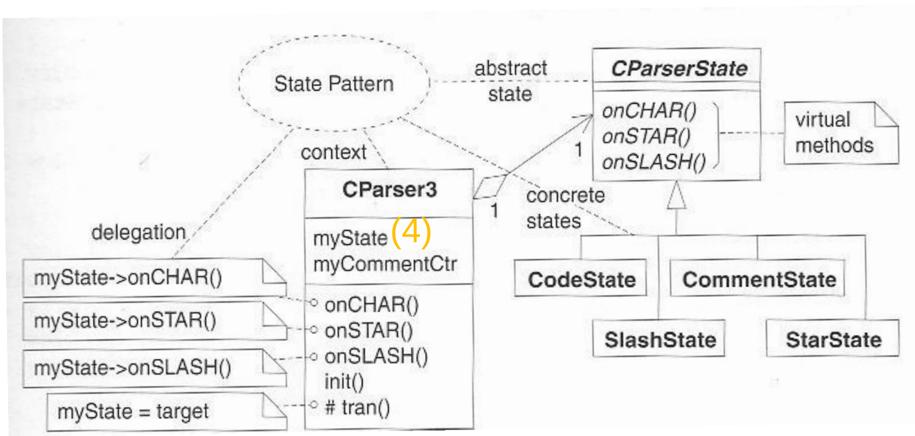
(2) A state in an EFSM is an object of a subclass of the CParserState. (CodeState, SlashState, etc.)

State Design Pattern [Gamma+ 95, Douglass 99]



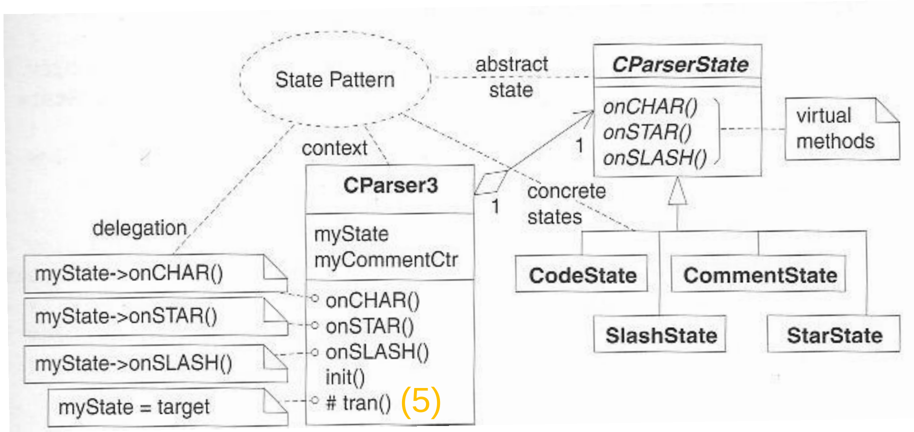
(3) The parser has exactly one object for each concrete state class (e.g., myCodeState, mySlashState, etc.)…

State Design Pattern [Gamma+ 95, Douglass 99]



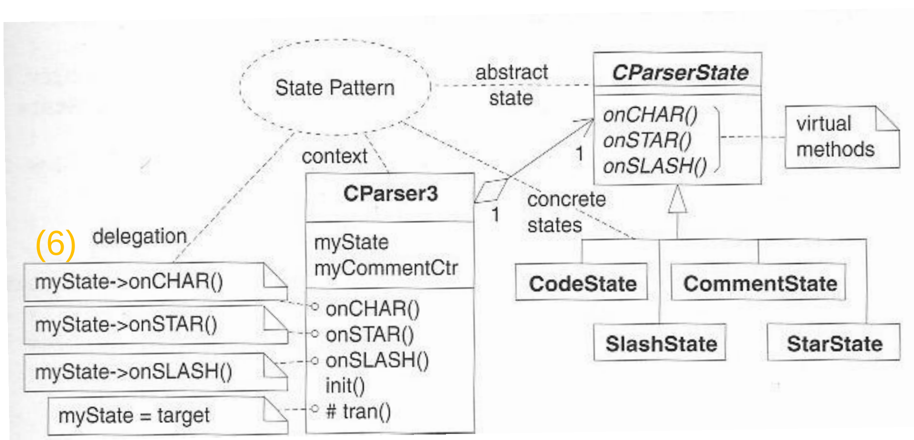
(4) … as well as a myState variable, which can points to any of them.

State Design Pattern [Gamma+ 95, Douglass 99]



(5) State transition is just reassigning myState variable.

State Design Pattern [Gamma+ 95, Douglass 99]



(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

The same story once more, in code.

```
class CParserState {                                  // abstract State
public:
    virtual void onCHAR(CParser3 *context, char ch)  {}
    virtual void onSTAR(CParser3 *context) {}
    virtual void onSLASH(CParser3 *context) {}
};
class CodeState : public CParserState {
public:
    virtual void onSLASH(CParser3 *conte
};
class SlashState : public CParserState
public:
    virtual void onCHAR(CParser3 *context, char ch);
    virtual void onSTAR(CParser3 *context);
};
class CommentState : public CParserState
    ....
};
class StarState : public CParserState {
    ....
};
```

(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.)

State Design Pattern: Example

The same story once more, in code.

```
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(&myCodeS
   void tran(CParserState *target) { myState = t
   long getCommentCtr() const { return myComment
   void onCHAR(char ch) { myState->onCHAR(this,
   void onSTAR() { myState->onSTAR(this);  }
   void onSLASH() { myState->onSLASH(this); }
};
```

(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

The same story once more, in code.

```
#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);
}
```

(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

- Approach 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.

Multiple-threaded Implementation

- 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)

```
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);
        }
    }
}
int main(int argc, char *argv[]) {
    pthread_t thread1, thread2,thread3;
    // ... initilization code ...
    pthread_create( &thread1, NULL, trans1, NULL);
    pthread_create( &thread2, NULL, trans2, NULL);
    pthread_create( &thread3, NULL, trans3, NULL);
    pthread_join( thread1, NULL);
    return 0;
}
```

- 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

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

Channels and channel actions

- Example

```
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

- Definitions
  - An EFSM is non-determinism if there exists some state with two or more outgoing transitions which maybe enabled at the same time.
  - An EFSM is total (or complete) if at any state S, there is at least one outgoing edge enabled.
- Checking Non-determinism and Totality
  - The EFSM Toolset utilizes the satisfiability checker zChaff
    - systematically transform logic formula over guards to DIMACS (zChaff accepted format)
    - feed into zChaff and interpret the result

Non-determinism and Totality

- Example: A system with a bounded integer x in [1..5] and
  (1) `From start to discard if x<=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) $(x<=4) \wedge (x>3)$
  (b) $(x<=4) \wedge (x==5)$
  (c) $(x>3) \wedge (x==5)$

  which are transformed to (xk means x==k is true)
  (a) $(x1 \vee x2 \vee x3 \vee x4) \wedge (x4 \vee x5)$
  (b) $(x1 \vee x2 \vee x3 \vee x4) \wedge (x5)$
  (c) $(x4 \vee x5) \wedge (x5)$
- (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

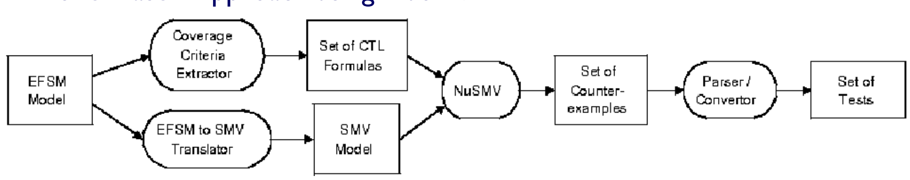
- Table – CSV format most Spreadsheet programs can open
- Text – Human readable text file
- Dotty – Input format of the "dot" program for drawing
- Promela – The Spin model checker input language
  - systems with only synchronous channels are supported now
  - setting channel buffer size to 0 in Promela
- 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 take 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

Test Generation from EFSMs

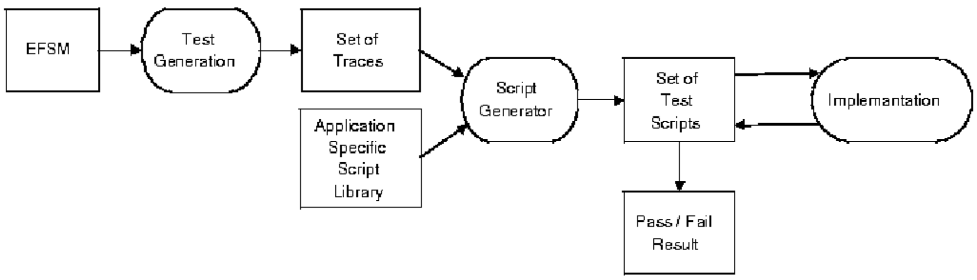
- Model Based Approach using NuSMV



- 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

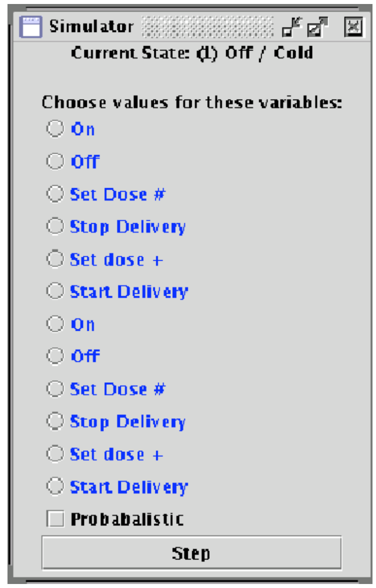
```
while (transition_taken) {
    transition_taken=0;
    if ((currentState==1)&&(current < getNumBots())) {
        PRE_TRANSITION_HOOK;
        current=current+1;
        currentState=2;
        transition_taken=1;
        //printf("rolling:From:incrementTo:check
        //Guard:current <=numBotsAction:current=current+1\n");
        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

```
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

- Miro Samek, *Practical Statecharts in C/C++*, CMPBooks, 2002
  - Source code available online
  - http://www.state-machine.com/psicc/
- David Arney, *EFSM Toolbox Manual*, University of Pennsylvania, 2009

Thank you!