A Pragmatic Approach for Transforming Coloured Petri Net Models into Code
- A Case Study of the IETF WebSocket Protocol*

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Concurrent Systems

- The vast majority of IT systems today can be characterised as concurrent software systems:
  - Structured as a collection of concurrently executing software components and applications.
  - Operation relies inherently on communication, synchronisation, and resource sharing.

Internet and Web-based applications, protocols
Multi-core platforms and multi-threaded software
Embedded systems and networked control systems
Concurrent Systems

- The engineering of concurrent systems is **challenging due to their complex behaviour:**
  - Concurrently executing and independently scheduled software components.
  - Non-deterministic and asynchronous behaviour (e.g., timeouts, message loss, external events, ...).
  - Almost impossible for software developers to have a complete understanding of the system behaviour.
  - Reproducing errors is often difficult.

- **Techniques to support the engineering of reliable concurrent systems** are important.
Coloured Petri Nets (CPNs)

- Graphical modelling language for the engineering of concurrent systems.
- Combines Petri Nets and a programming language:
  - Petri Nets
    - graphical notation
    - concurrency
    - communication
    - synchronisation
    - resource sharing
  - Programming language
    - data types
    - data manipulation
    - compact modelling
    - parameterisable models

- Supported by CPN Tools [www.cpntools.org]
Application of CPNs

- CPNs have been widely used for modelling and validation of communication protocols:
  - Application Layer Protocols: IOTP, SIP, WAP, ...
  - Transport Layer Protocols: TCP, DCCP, SCTP, ...
  - Routing Layer Protocols: DYMO, AODV, ERDP, ...

- It would be desirable to use CPN models more directly for implementation of protocol software.

- Limited work on automatic code generation.

- This talk:
  - A newly developed approach to structure-based code generation from CPN models.
  - Application to the IETF WebSocket Protocol.
Automated Code Generation

- It is difficult (in general) to recognize programming language constructs in CPNs:

  ![Diagram]

- Conclusion: some additional syntactical constraints and/or annotations are required.
Main Requirements

1. **Platform independence:**
   - Enable code generation for multiple languages / platforms.

2. **Integratebility of the generated code:**
   - **Upwards integration:** the generated code must expose an explicit interface for service invocation.
   - **Downwards integration:** ability for the generated code to invoke and rely on underlying libraries.

3. **Model checking and property verification:**
   - Code generation capability should not introduce complexity problems for the verification of the CPN models.

4. **Readability of the generated code:**
   - Enable code review of the automatically generated code.
   - Enable performance enhancements (if required).

5. **Scalability:**
   - Applicable to industrial-sized communication protocols.
The IETF WebSocket Protocol

- Provides a bi-directional and message-oriented service on top of the HTTP protocol:

Three main phases: connection establishment, data transfer, and connection close.
Overview of Approach

- **Modelling structure** requiring the CPN model to be organised into three levels:
  1. **Protocol system level** specifying the protocol principals and the communication channels between them.
  2. **Principal level** reflecting the life-cycle and services provided by each principal in the protocol system.
  3. **Service level** specifying the behaviour of the services provided by each principal.

- Annotate the CPN model elements with **code generation pragmatics** to direct code generation.

- A **template-based** model-to-text transformation for generating the protocol software.
Code Generation Pragmatics

- **Syntactical annotations** *(name and attributes)* that can be associated with CPN model elements:
  - Structural pragmatics designating principals and services.
  - Control-flow pragmatics identifying control-flow elements and control-flow constructs.
  - Operation pragmatics identifying data manipulation.

- **Template binding descriptors** associating the pragmatics and code generation templates:
  - Bridges the gap between the platform independent CPN simulation model and the target platform considered.
  - Code can be generated for different platforms (Groovy, Clojure, Java, Python) by changing the template binding descriptors.
WebSocket: Protocol System

- The complete CPN model consists of 19 modules, 136 places, and 84 transitions:

- The <<principal>> pragmatic is used on substitution transitions to designate principals.
- The <<channel>> pragmatic is used to designate channels connecting the principals.
Client: Principal Level

- Makes explicit the services provided and their allowed order of invocation (API life-cycle):

  - **<<service>>** specifies services that can be invoked externally.
  - **<<internal>>** specifies services that are invoked internally in the principal.
  - **<<LCV>>** specifies life-cycle for services.
  - **<<state>>** specifies state variables of the principal.
**Client: MessageBroker Service**

- Internal service started when the client is in the OPEN state.

Service entry point `<<internal>>`

Service-local state is specified using `<<state>>`

Control-flow locations is made explicit using `<<ID>>` pragmatic on places.

Service exit point `<<return>>`
WebSocket Verification

- **State space exploration** prior to code generation used to model check basic connection properties:

  **P0** From the initial state it is possible to reach states in which the WebSocket connection has been opened.

  **P1** All terminal states correspond to states in which the WebSocket connection has been properly closed.

  **P2** From any reachable state, it is always possible to reach a state in which the WebSocket connection has been properly closed.

<table>
<thead>
<tr>
<th>ClientM</th>
<th>ServerM</th>
<th>#Nodes</th>
<th>#Arcs</th>
<th>Time (secs)</th>
<th>#Terminal states</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>-</td>
<td>2,747</td>
<td>9,544</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>-</td>
<td>+</td>
<td>2,867</td>
<td>9,956</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>+</td>
<td>+</td>
<td>39,189</td>
<td>177,238</td>
<td>246</td>
<td>4</td>
</tr>
</tbody>
</table>
Automated Code Generation

- Template-based code generation consisting of three main steps:

Step 1: Computing Derived Pragmatics

Step 2: Abstract Template Tree (ATT) Construction

Step 3: Pragmatics binding and emitting code

```python
1 def getMessage():
2     // vars: __TOKEN__, message
3     def __TOKEN__
4     def message
5     // getMessage
6     if(inBuffer != null && inBuffer.size() > 0){
7         message = inBuffer.remove(0)
8         byte[] bArr = new byte[message.payload.size()]
9         for(int i = 0; i < bArr.length; i++){
10            bArr[i] = message.payload.get(i)
11     }
12     if(message.opCode == 1){
13         message = new String(bArr)
14     else if(message.opCode == 2) {
15         message = bArr
16     }
17     else
18         message = null
19     return message
20 }
```
PetriCode [ www.petricode.org ]

- Command-line tool reading pragmatic-annotated CPN models created with CPN Tools:
  - Pragmatic module: parses CPN models and computes derived pragmatics.
  - ATT construction module: performs block decomposition and constructs the ATT.
  - Code generation module: binds templates to pragmatics and generates source code via ATT traversal.

- Implemented in Groovy and uses the Groovy template engine for code generation.
Step 1: Derived Pragmatics

- Derived pragmatics computed for control-flow constructs and for data (state) manipulation.

A DSL is used for specifying pragmatic descriptors.

**principal** (origin: explicit, constraints:
- [levels: protocol, connectedTypes:
  - SubstitutionTransition])

**endloop** (origin: derived, deviationRules:
- [new PNPATTERN(pragmatics: [Id],
  - minOutEdges: 2,
  - backLinks: 1]),
  - constraints:
    - [levels: service, connectedTypes: Place])
Step 2: Abstract Template Tree

- An intermediate syntax tree representation of the pragmatic-annotated CPN model:

A DSL for template bindings and linkage to the target platform.

```
<%import static org.k1s.petriCode.generation.CodeGenerator.removePrags%>

class ${name} {
<% if(binding.variables.containsKey('lcvs')){
    for(lcv in lcvs){
        %>def ${removePrags(lcv.name.text)} ${lcv.initialMarking.asString() == '(' ? '=' : ''}<%
    }
<% } %>
<% if(binding.variables.containsKey('fields')){
    for(field in fields){
        %>def ${removePrags(field.name.text)}<%
    }
<% } %>
<% yield %>
```

Protocol System

Client <<principal>>

messageBroker <<internal>>

Server <<principal>>

<<internal>>

<<return>>

<<sequence>>

<<atomic>> <<loop>> <<atomic>>

<<startloop>> <<endloop>>
Step 3: Emitting Code

- Traversal of the ATT, invocation of code generation templates, and code stitching:

```java
class ${name} {
  if (binding.variables.containsKey('lcvs')) {
    for (lcv in lcvs) {
      def removePrags(lcv.name.text) = lcv.initialMarking.asString() == '()' ? 'true' : ''
    }
  }
  if (binding.variables.containsKey('fields')) {
    for (field in fields) {
      def removePrags(field.name.text)
    }
  }
  yield
}
```

```java
def getMessage()
    /*vars: [__TOKEN__, message]*/
    def __TOKEN__
def message
    //getMessage
    if (inBuffer != null && inBuffer.size() > 0) {
        message = inBuffer.remove(0)
        byte[] bArr = new byte[message.payload.size()]
        for (int i = 0; i < bArr.length; i++) {
            bArr[i] = message.payload.get(i)
        }
        if (message.opCode == 1) {
            message = new String(bArr)
        } else if (message.opCode == 2) {
            message = bArr
        } else {
            message = null
        }
    return message
}
def SendPingPong(ping) {
    def ClientClose() {
        def getMessage()
    }
    }
```
Chat Application

- WebSocket tutorial example provided with the Java EE 7 GlassFish Application Server:

  Chat Server [CPN WebSocket model]

  Web-based Chat Client [WebSocket Browser]

  Chat Client [CPN WebSocket model]
Autobahn Testsuite [autobahn.ws/testsuite/]

- Test-suite used by several industrial WebSocket implementation projects (Google Chrome, Apache Tomcat,..).
- Errors encountered with the generated code:
  - One protocol logical error related to the handling of fragmented messages (CPN model change).
  - Several local errors in the code-generation templates were encountered (template change).

<table>
<thead>
<tr>
<th>Tests</th>
<th>Server Passed</th>
<th>Client Passed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Framing (text and binary messages)</td>
<td>16/16</td>
<td>16/16</td>
</tr>
<tr>
<td>2. Pings/Pongs</td>
<td>11/11</td>
<td>11/11</td>
</tr>
<tr>
<td>3. Reserved bits</td>
<td>7/7</td>
<td>7/7</td>
</tr>
<tr>
<td>4. Opcodes</td>
<td>10/10</td>
<td>10/10</td>
</tr>
<tr>
<td>5. Fragmentation</td>
<td>20/20</td>
<td>20/20</td>
</tr>
<tr>
<td>6. UTF-8 handling</td>
<td>137/141</td>
<td>137/141</td>
</tr>
<tr>
<td>7. Close handling</td>
<td>38/38</td>
<td>38/38</td>
</tr>
<tr>
<td>9. Limits/Performance</td>
<td>54/54</td>
<td>48/54</td>
</tr>
<tr>
<td>10. Auto-Fragmentation</td>
<td>1/1</td>
<td>1/1</td>
</tr>
</tbody>
</table>

http://t.k1s.org/wsreport/
Conclusions

- An approach enabling CPN models to be used for code generation of protocol software:
  - Pragmatic annotations and enforcing modelling structure.
  - Binding of pragmatics to code generation templates.
- Implemented in the PetriCode tool to allow for practical applications and initial evaluation.
- Scalability of the approach has been evaluated via application to the IETF WebSocket Protocol:
  - State space-based verification was feasible for verifying basic connection properties prior to code generation.
  - The implementation was tested for interoperability against a comprehensive benchmark test-suite with promising results.
  - A proof-of-concept on the scalability and feasibility of the approach for the implementation of real protocols.
Thank you for your attention!