1. Objektorientierte Implementierung endlicher Automaten

Lösungsideen:

faOf():

Beim Durchdenken des Algorithmus habe ich festgestellt, dass Epsilon-Alternativen in der reguläre Grammatik die Umsetzung erschweren könnten. Deshalb wird zunächst die reguläre Grammatik mit der Methode **newEpsilonFreeGrammarOf** aus dem ersten Übungszettel Epsilon-frei gemacht. Man kann dann die reguläre Grammatik relativ einfach in einen endlichen Automaten umwandeln, indem man jede Alternative einer Regel (z.B. **S -> a B**) in einen Zustandsübergang vom NTSymbol der Regel (**S**) auf den Zustand (NTSymbol an zweiter Stelle in der Alternative **B**) mit dem Band-Symbol (TSymbol an erster Stelle in der Alternative **a**) umwandelt. Alle Alternativen, die nur aus einem TSymbol bestehen, bekommen einen Zustandsübergang auf einen allgemeinen End-Zustand (**END**). Da die reguläre Grammatik Epsilon-frei ist, gibt es höchstens ein Epsilon, welches sich im Satz-Symbol befinden könnte. In diesem Fall wird der Zustand für das Satz-Symbol auch als End-Zustand markiert.

grammarOf():

Es kann ein beliebiger **FA** übergeben werden. Damit ich DFA und NFA bei der Implemtierung des Algorithmus gleich behandeln kann, habe ich die Sichtbarkeit der Methode **virtual StateSet FA::deltaAt(const State &src, TapeSymbol tSy) const = 0;** auf public geändert und immer mit **StateSet**s gearbeitet.

Es werden alle Kombinationen von Zuständen und Band-Symbolen auf die Zustandsüberführungsfunktion angewandt (verschachtelte Schleife). Um nicht zwischen DFA und NFA unterscheiden zu müssen, wurde die Sichtbarkeit von der Methode **deltaOf() der Klasse FA** von **protected** auf **public** geändert und immer mit **StateSet**s gearbeitet. Bei jeder Anwendung der Zustandsüberführungsfunktion ist der **State** (Variable in der Schleife) die Regel der Grammatik. Das Band-Symbol (Variable in der Schleife => TSymbol) und die von **deltaOf()** gelieferten Zustände (NTSymbol) bilden Sequenzen dieser Regel. Falls die **deltaOf()** von gelieferten Zustände keine ausgehenden Zustandsüberführungen mehr haben, dann werden diese in der Grammatik einfach ignoriert und das Band-Symbol hat in der Alternative kein nachfolgendes NTSymbol. Falls der Start-Zustand bereits ein End-Zustand ist, bekommt die Regel dieses Zustandes eine Epsilon-Alternative.

Code:

```
FA *faOf(const Grammar *g)
{
  bool deleteG = false;
  FABuilder fab{};
  const Grammar* gToUse = g;
  // ensure g is epsilon-free
  if (!g->isEpsilonFree()) {
    deleteG = true;
    gToUse = newEpsilonFreeGrammarOf(g);
  }
```

```
  // set final states
  if (deleteG) { // means that g has S' => is end state
    fab.addFinalState(g->root->name);
  } else {
    // if rule of root already contained epsilon,
    // mark it as end state
    for (auto rootAlternatives : g->rules[g->root]) {
      if (rootAlternatives->size() == 0)
        fab.addFinalState(g->root->name);
    }
  }

  fab.setStartState(g->root->name);
  // generic end state "END" for alternatives without NT
  fab.addFinalState("END");

  for (auto [ntSy, alternatives] : g->rules) {
    for (auto alternative : alternatives) {

      if (alternative->size() > 0) { // ignore eps alternatives
        char ts = alternative->at(0)->name[0];
        if (alternative->size() == 1) {
          // no ntSy in alternative =>
          // ntSy has edge to artificial end state with ts
          fab.addTransition(ntSy->name, ts, "END");
        } else if (alternative->size() == 2) {
          // ntSy has edge to nextState with ts
          string nextState = alternative->at(1)->name;
          fab.addTransition(ntSy->name, ts, nextState);
        }
      }
    }
  }

  // delete generated epsilon-free grammar
  if (deleteG) delete g;

  return fab.buildNFA();
}

Grammar* grammarOf(const FA* fa) {

  SymbolPool sp{};
  GrammarBuilder gb{sp.ntSymbol(fa->s1)};

  // iterate over each state
  for (const State& state : fa->S) {
    // iterate over each tape symbol
    for (const TapeSymbol& ts : fa->V) {
      // get all possible transition destinatons from state using tape symbol
      auto destinations = fa->deltaAt(state, ts);
      for (const State& dest : destinations) {
        // add this transition to grammar as alternative
```

```
        // takes care of states like S' or END
        // if dest does not have any outgoing tape symbols
        // => ignore dest in grammar
        bool hasOutgoing = false;
        for (const TapeSymbol& ts1 : fa->V) {
          if (fa->deltaAt(dest, ts1).size() > 0) {
            hasOutgoing = true;
          }
        }

        if (hasOutgoing) {
          gb.addRule(sp.ntSymbol(state),
            new Sequence({
              sp.tSymbol(string{ts}),
              sp.ntSymbol(dest)}
              )
          );
        } else {
          gb.addRule(sp.ntSymbol(state),
            new Sequence({sp.tSymbol(string{ts})})
          );
        }

        // if dest is an end state, also add alternative without dest
        if (fa->F.contains(dest)) {
          gb.addRule(sp.ntSymbol(state),
            new Sequence(sp.tSymbol(string{ts}))
          );
        }
      }
    }
  }

  // if start state is also end state, add epsilon as alternative
  if (fa->F.contains(fa->s1)) {
    gb.addRule(sp.ntSymbol(fa->s1), new Sequence());
  }

  return gb.buildGrammar();
}
```

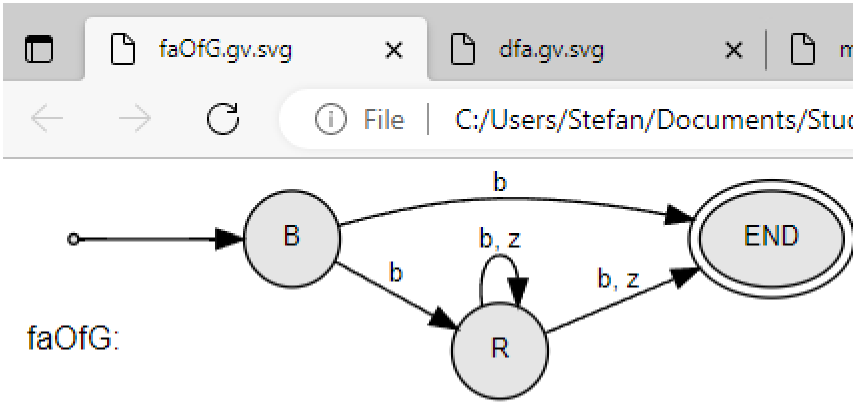
Tests:

```
  cout << "1.a) faOf" << endl;
  cout << "------" << endl;
  cout << endl;

  GrammarBuilder gb{string("G.txt")};

  Grammar* g = gb.buildGrammar();
```

```
    FA* faOfG = faOf(g);
    vizualizeFA("faOfG", faOfG);

    cout << "1.b) grammarOf" << endl;
    cout << "------" << endl;
    cout << endl;

    Grammar* gOfFaOfG = grammarOf(faOfG);
    std::cout << *gOfFaOfG;

    delete g;
    delete faOfG;
    delete gOfFaOfG;
```

Testfall 1

```
G(B):
B -> b | b R
R -> b | z | b R | z R
```



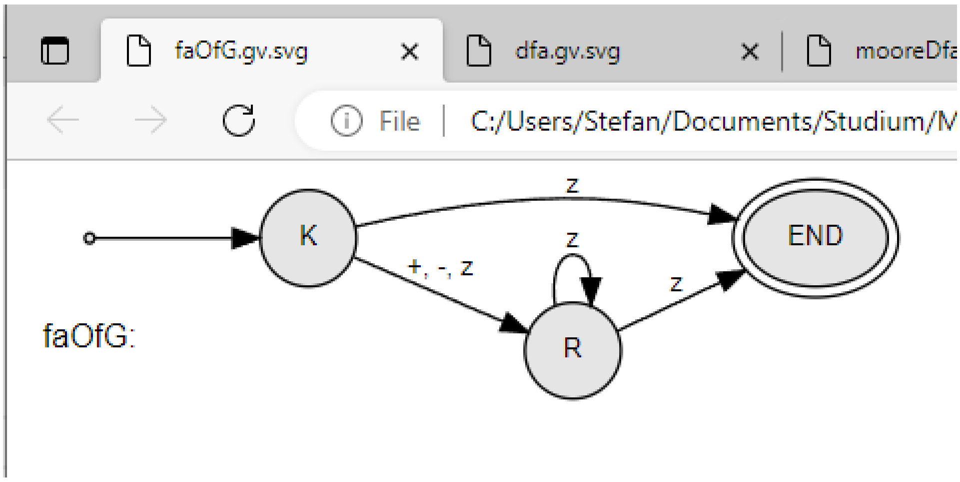
PROBLEMS OUTPUT DEBUG CONSOLE TERMINAL

```
START: Main

1. DFA
------

1.a) faOf
------

writing    faOfG to faOfG.gv ...
rendering  faOfG.gv to faOfG.gv.svg ...
displaying faOfG.gv.svg ...

1.b) grammarOf
------


G(B):
B -> b | b R
R -> b | b R | z | z R
---
VNt = { B, R }, deletable: {  }
VT  = { b, z }
```

gOfFaOfG und Eingabe-Grammatik sind wieder gleich.

Testfall 2

```
G(K):
K -> z | z R | + R | - R
R -> z | z R
```



PROBLEMS OUTPUT DEBUG CONSOLE TERMINAL

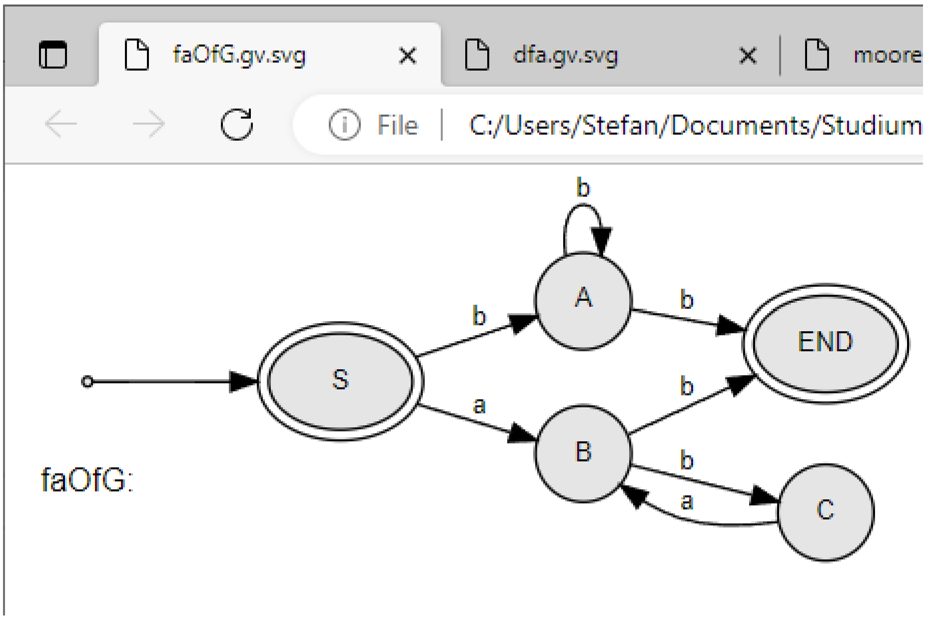
```
1.a) faOf
------

writing   faOfG to faOfG.gv ...
rendering faOfG.gv to faOfG.gv.svg ...
displaying faOfG.gv.svg ...

1.b) grammarOf
------



G(K):
K -> + R | - R | z | z R
R -> z | z R
---
VNt = { K, R }, deletable: {  }
VT  = { +, -, z }

2.a) DFA
------
```

gOfFaOfG und Eingabe-Grammatik sind wieder gleich.

Testfall 3 - Grammatik mit Epsilon (vom Übungszettel 2 geklaut)

Anmerkung: Die Grammatik ist bereits Epsilon-Frei. Bei dem Test geht es nur darum, zu sehen, ob der Zustand für das Satz-Symbol (Start-Zustand) auch als End-Zustand markiert wird.

```
G(S):
S -> b A | a B | eps
A -> b A | b
B -> b C | b
C -> a B
```



PROBLEMS OUTPUT DEBUG CONSOLE TERMINAL

```
1. DFA
------

1.a) faOf
------

writing   faOfG to faOfG.gv ...
rendering faOfG.gv to faOfG.gv.svg ...
displaying faOfG.gv.svg ...

1.b) grammarOf
------


G(S):
S -> eps | a B | b A
B -> b | b C
A -> b | b A
C -> a B
---
VNt = { A, B, C, S }, deletable: { S }
VT  = { a, b }

2.a) DFA
```

gOfFaOfG und Eingabe-Grammatik sind wieder gleich, Start-Zustand auch als End-Zustand markiert.

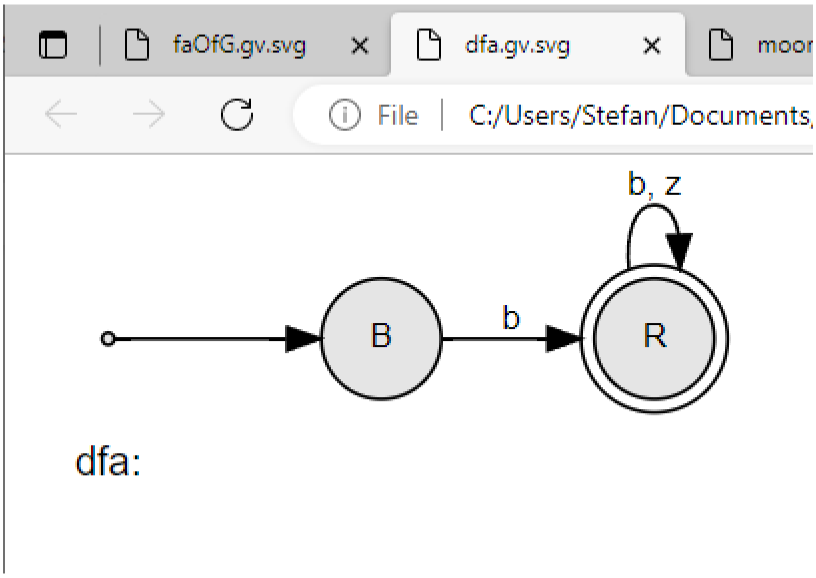
2. DFA, Erkennung und Mealy- oder Moore-Automat

a)

Code:

```
cout << "2.a) DFA" << endl;
cout << "------" << endl;
cout << endl;
```

```
    fab = new FABuilder();
    fab->setStartState("B").
      addFinalState("R").
      addTransition("B", 'b', "R").
      addTransition("R", 'b', "R").
      addTransition("R", 'z', "R");

    dfa = fab->buildDFA();
    vizualizeFA("dfa", dfa);

    cout << "dfa->accepts(\"bzb\") = " << boolalpha << dfa->accepts("bzb") << endl;
    cout << "dfa->accepts(\"bbbbzbzz\") = " << boolalpha << dfa->accepts("bbbbzbzz")
  << endl;
    cout << "dfa->accepts(\"zbb\")   = " << boolalpha << dfa->accepts("z")  << endl;
    cout << endl;

    delete fab;
```



PROBLEMS OUTPUT DEBUG CONSOLE TERMINAL

```
VT  = { b, z }

2.a) DFA
------

writing    dfa to dfa.gv ...
rendering  dfa.gv to dfa.gv.svg ...
displaying dfa.gv.svg ...

dfa->accepts("bzb")       = true
dfa->accepts("bbbbzbzz") = true
dfa->accepts("zbb")       = false
```

Tests:

b)

Eigentlich benötigt der MooreDFA nur eine Map, in der definiert ist, bei welchem State durch welches Symbol ausgegeben wird. Diese Map muss dann beim Erkennen des Band-Inhaltes verwendet werden (hier geben wir den Wert für den State einfach auf der Konsole aus).

Code:

```
// MooreDFA.h:                                                     SWE, 2022
// -----
// Objects of class MooreDFA represent deterministic finite automata.
//======================================================================

#ifndef MooreDFA_h
#define MooreDFA_h

#include "ObjectCounter.h"
#include "TapeStuff.h"
#include "StateStuff.h"
#include "DFA.h"


class FABuilder;

class MooreDFA: public DFA
 /*OC+*/ , private ObjectCounter<MooreDFA> /*+OC*/ {

  friend class FABuilder;
```

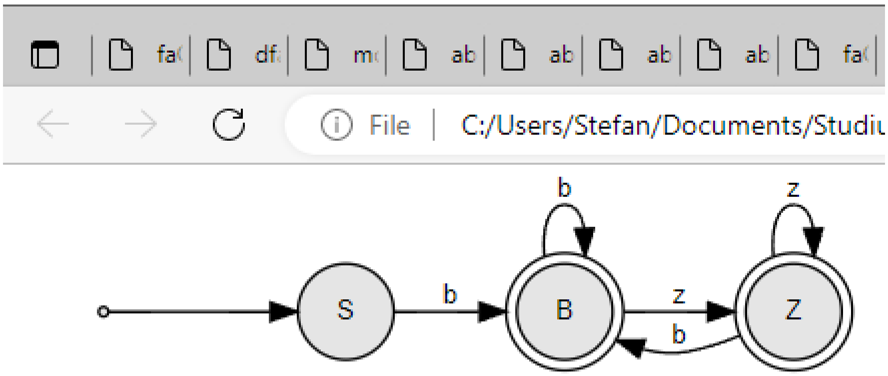
```
  private:
    typedef DFA Base;

  protected: // allows derived classes, e.g., for Mealy and or Moore
    // constructor called by FABuilder::build... methods and derived classes
    MooreDFA(const StateSet &S,  const TapeSymbolSet &V,
        const State    &s1, const StateSet      &F,
        const DDelta   &delta,
        const std::map<State, char> &mooreLambda);

  public:
    const std::map<State, char> mooreLambda;
    MooreDFA(const MooreDFA  &mooredfa) = default;
    MooreDFA(      MooreDFA &&mooredfa) = default;

    virtual ~MooreDFA() = default;
    virtual bool accepts(const Tape &tape) const;

}; // DFA

#endif

// end of MooreDFA.h
//======================================================================

// MooreDFA.cpp:                                                SWE, 2022
// -------
// Objects of class MooreDFA represent deterministic finite automata.
//======================================================================

#include <cmath>
#include <cstring>

#include <iostream>
#include <fstream>
#include <map>
#include <sstream>

using namespace std;

#include "TapeStuff.h"
#include "StateStuff.h"
#include "MbMatrix.h"
#include "FABuilder.h"
#include "MooreDFA.h"

// --- implementation of class MooreDFA ---

MooreDFA::MooreDFA(const StateSet &S,  const TapeSymbolSet &V,
         const State    &s1, const StateSet      &F,
         const DDelta   &delta,
         const std::map<State, char> &mooreLambda)
: DFA(S, V, s1, F, delta), mooreLambda(mooreLambda) {
} // MooreDFA::MooreDFA
```

```
bool MooreDFA::accepts(const Tape &tape) const {
  int        i   = 0;       // index of first symbol
  TapeSymbol tSy = tape[i]; // fetch first tape symbol
  State      s   = s1;      // start state
  cout << mooreLambda.at(s);
  while (tSy != eot) {      // eot = end of tape
    s = delta[s][tSy];
    if (!defined(s))
      return false;         // s undefined, so no acceptance
    cout << mooreLambda.at(s);
    i++;
    tSy = tape[i];          // fetch next symbol
  } // while
  cout << " ";
  return F.contains(s);     // accepted <==> s element of F
} // MooreDFA::accepts

// end of MooreDFA.cpp
//======================================================================
```

Tests:

```
  cout << "2.b) MooreDFA" << endl;
  cout << "------" << endl;
  cout << endl;

  fab = new FABuilder();
  fab->setStartState("S").
    addFinalState("B").
    addFinalState("Z").
    addTransition("S", 'b', "B").
    addTransition("B", 'b', "B").
    addTransition("B", 'z', "Z").
    addTransition("Z", 'z', "Z").
    addTransition("Z", 'b', "B").
    setSetMooreLambda({
      {"S", ' '},
      {"B", 'c'},
      {"Z", 'd'}
    });

  MooreDFA* mooreDfa = fab->buildMooreDFA();

  cout << "mooreDfa->accepts(\"bzb\") = " << boolalpha << mooreDfa->accepts("bzb")
<< endl;
  cout << "mooreDfa->accepts(\"bbbbzbzz\") = " << boolalpha << mooreDfa-
>accepts("bbbbzbzz") << endl;
  cout << "mooreDfa->accepts(\"zbb\")   = " << boolalpha << mooreDfa->accepts("z")
<< endl;
  cout << endl;
```

```
vizualizeFA("mooreDfa", mooreDfa);

delete mooreDfa;
delete fab;
```



mooreDfa:

```
PROBLEMS    OUTPUT    DEBUG CONSOLE    TERMINAL

2.b) MooreDFA
------

mooreDfa->accepts("bzb")       =  cdc true
mooreDfa->accepts("bbbbzbzz")  =  ccccdcdd true
mooreDfa->accepts("zbb")       =  false

writing    mooreDfa to mooreDfa.gv ...
rendering  mooreDfa.gv to mooreDfa.gv.svg ...
displaying mooreDfa.gv.svg ...
```

3. NFA, Transformation NFA -> DFA und Zustandsminimierung

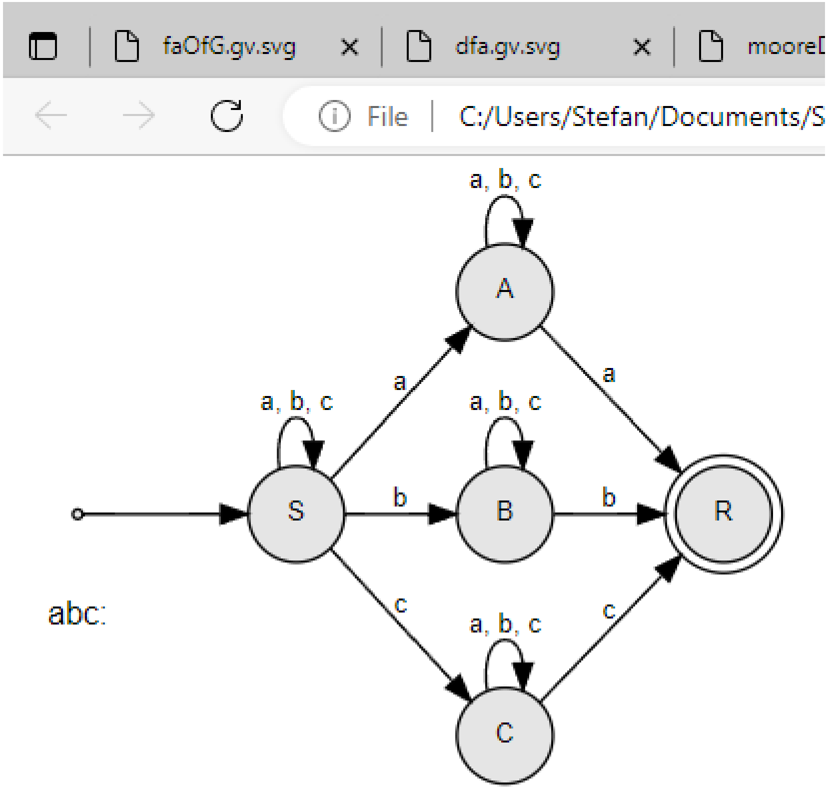
a)

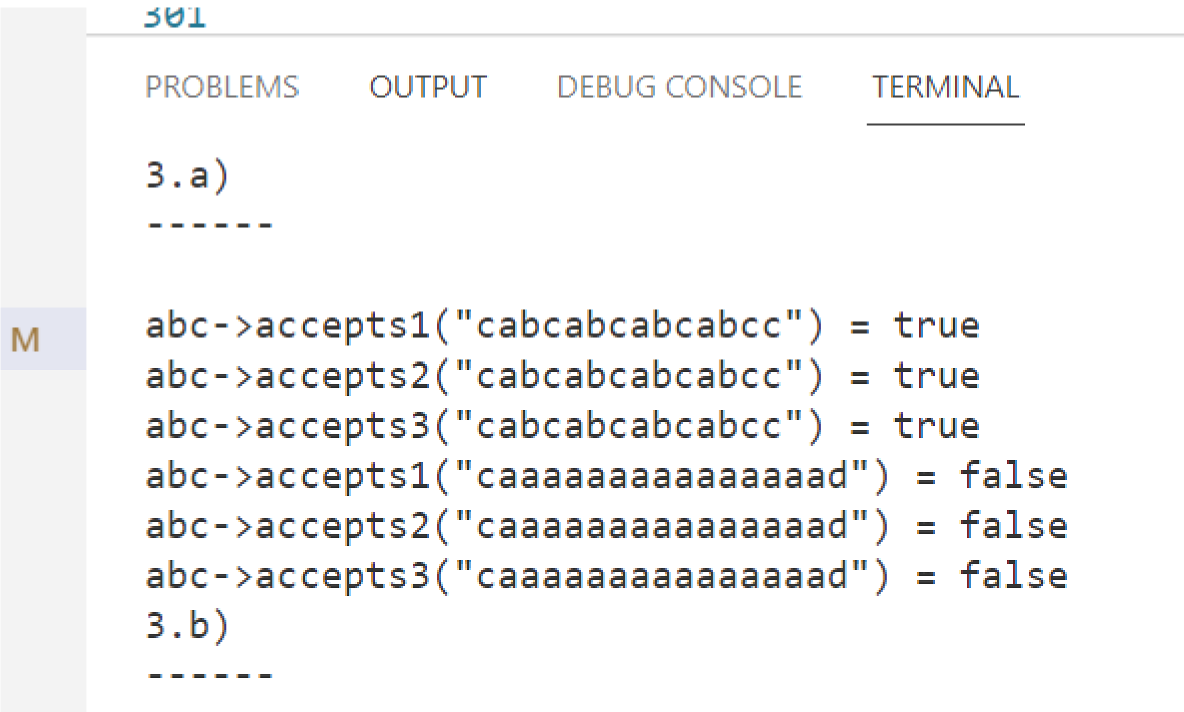
Code:

```
cout << "3.a)" << endl;
cout << "------" << endl;
```

```
  cout << endl;

  fab = new FABuilder();
  fab->setStartState("S").
    addFinalState("R").
    addTransition("S", 'a', "S").
    addTransition("S", 'b', "S").
    addTransition("S", 'c', "S").
    addTransition("S", 'a', "A").
    addTransition("S", 'b', "B").
    addTransition("S", 'c', "C").
    addTransition("A", 'a', "A").
    addTransition("A", 'b', "A").
    addTransition("A", 'c', "A").
    addTransition("B", 'a', "B").
    addTransition("B", 'b', "B").
    addTransition("B", 'c', "B").
    addTransition("C", 'a', "C").
    addTransition("C", 'b', "C").
    addTransition("C", 'c', "C").
    addTransition("A", 'a', "R").
    addTransition("B", 'b', "R").
    addTransition("C", 'c', "R");

  NFA* abc = fab->buildNFA();
  cout << "abc->accepts1(\"cabcabcabcabcc\") = " << abc-
>accepts1("cabcabcabcabcc") << endl;
  cout << "abc->accepts2(\"cabcabcabcabcc\") = " << abc-
>accepts2("cabcabcabcabcc") << endl;
  cout << "abc->accepts3(\"cabcabcabcabcc\") = " << abc-
>accepts3("cabcabcabcabcc") << endl;

  cout << "abc->accepts1(\"caaaaaaaaaaaaaaad\") = " << abc-
>accepts1("caaaaaaaaaaaaaaad") << endl;
  cout << "abc->accepts2(\"caaaaaaaaaaaaaaad\") = " << abc-
>accepts2("caaaaaaaaaaaaaaad") << endl;
  cout << "abc->accepts3(\"caaaaaaaaaaaaaaad\") = " << abc-
>accepts3("caaaaaaaaaaaaaaad") << endl;

  delete abc;
  delete fab;
```

Tests:




```
301
PROBLEMS    OUTPUT    DEBUG CONSOLE    TERMINAL

3.a)
------

M   abc->accepts1("cabcabcabcabcc") = true
    abc->accepts2("cabcabcabcabcc") = true
    abc->accepts3("cabcabcabcabcc") = true
    abc->accepts1("caaaaaaaaaaaaaad") = false
    abc->accepts2("caaaaaaaaaaaaaad") = false
    abc->accepts3("caaaaaaaaaaaaaad") = false
    3.b)
    ------
```

b)

Code:

```
void TimeAccept(NFA* abc, void (*func)(NFA* abc)) {
  stopwatch::Stopwatch sw{}; // not going to post this entire class here
  sw.start();
  func(abc);
  cout << "Elapsed time: " << sw.elapsed<TimeFormat::MICROSECONDS>() << " micro
```

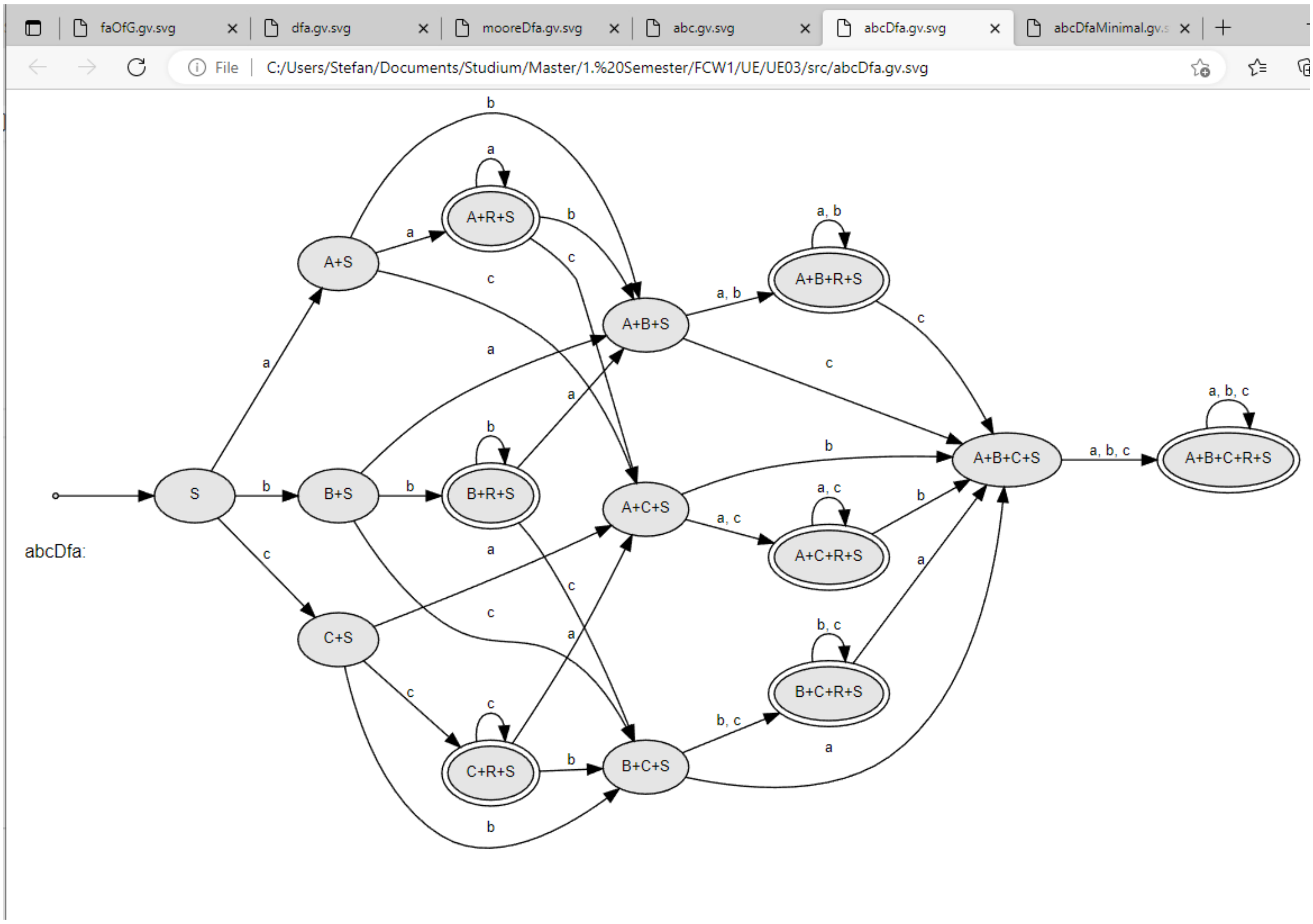
```
sec" << endl;
  }

// ... same as 3a)

  TimeAccept(abc, [](NFA* abc) {
    cout << "abc->accepts1(\"cabcabcabcabcc\") = " << abc-
>accepts1("cabcabcabcabcc") << endl;
  });
  TimeAccept(abc, [](NFA* abc) {
    cout << "abc->accepts2(\"cabcabcabcabcc\") = " << abc-
>accepts2("cabcabcabcabcc") << endl;
  });
  TimeAccept(abc, [](NFA* abc) {
    cout << "abc->accepts3(\"cabcabcabcabcc\") = " << abc-
>accepts3("cabcabcabcabcc") << endl;
  });

  TimeAccept(abc, [](NFA* abc) {
    cout << "abc->accepts1(\"caaaaaaaaaaaaaaad\") = " << abc-
>accepts1("caaaaaaaaaaaaaaad") << endl;
  });
  TimeAccept(abc, [](NFA* abc) {
    cout << "abc->accepts2(\"caaaaaaaaaaaaaaad\") = " << abc-
>accepts2("caaaaaaaaaaaaaaad") << endl;
  });
  TimeAccept(abc, [](NFA* abc) {
    cout << "abc->accepts3(\"caaaaaaaaaaaaaaad\") = " << abc-
>accepts3("caaaaaaaaaaaaaaad") << endl;
  });

// ... same as 3a)
```

```
PROBLEMS    OUTPUT    DEBUG CONSOLE    TERMINAL

abc->accepts2("caaaaaaaaaaaaaaad") = false
abc->accepts3("caaaaaaaaaaaaaaad") = false
3.b)
------

abc->accepts1("cabcabcabcabcc") = true
Elapsed time: 7849 micro sec
abc->accepts2("cabcabcabcabcc") = true
Elapsed time: 383 micro sec
abc->accepts3("cabcabcabcabcc") = true
Elapsed time: 482 micro sec
abc->accepts1("caaaaaaaaaaaaaaad") = false
Elapsed time: 9202 micro sec
abc->accepts2("caaaaaaaaaaaaaaad") = false
Elapsed time: 396 micro sec
abc->accepts3("caaaaaaaaaaaaaaad") = false
Elapsed time: 467 micro sec
3.c)
------
```

c)

Code:

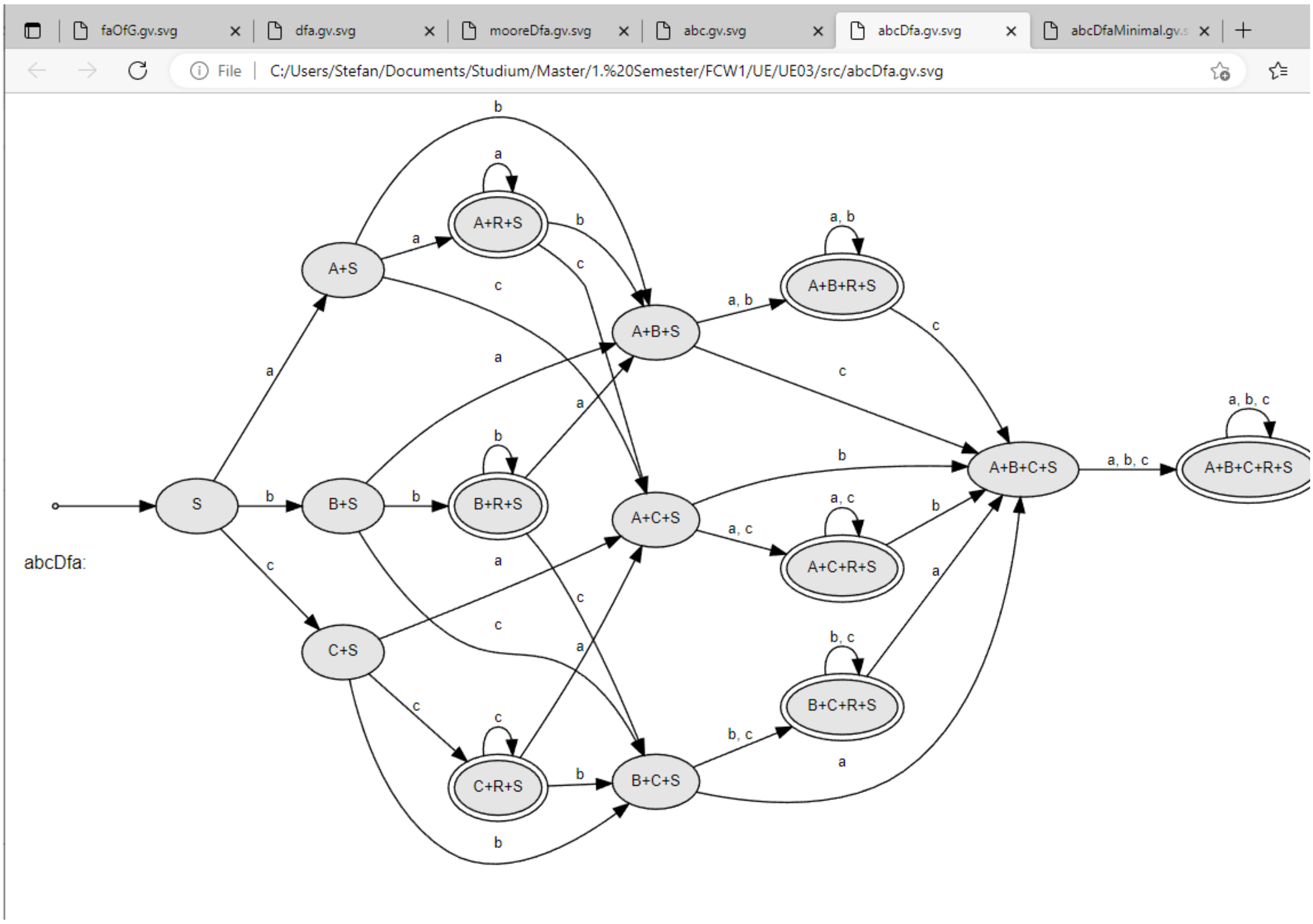
```
// ... same as 3a)

  DFA* abcDfa = abc->dfaOf();
  vizualizeFA("abcDfa", abcDfa);
  delete abcDfa;

// ... same as 3a)
```

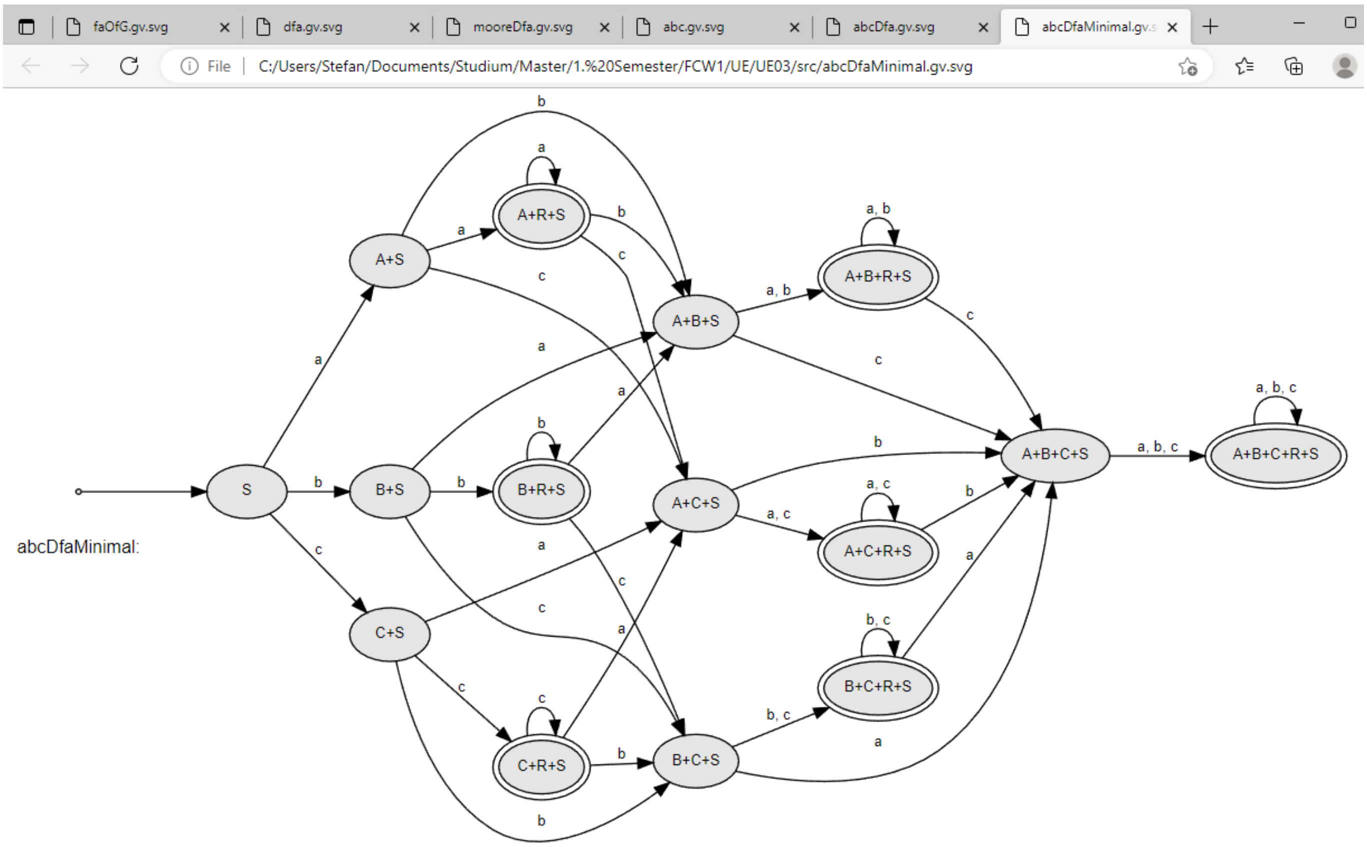


d)

Code:

```
// ... same as 3a)

  abcDfa = abc->dfaOf();
  DFA* abcDfaMinimal = abcDfa->minimalOf();

  vizualizeFA("abcDfa", abcDfa);
  vizualizeFA("abcDfaMinimal", abcDfaMinimal);

  delete abcDfaMinimal;
  delete abcDfa;

// ... same as 3a)
```





abcDfa war bereits minimal, da sich **abcDfa** nach der Minimierung nicht verändert hat.

4. Kellerautomat und erweiterter Kellerautomat

a)

```
Declaration     -> VAR | VAR VarDeclList .
VarDeclList     -> VarDecl ";" | VarDecl ";" VarDeclList .
VarDecl         -> IdentList ":" Type .
IdentList       -> ident | ident "," IdentList .
Type            -> ARRAY "(" number ")" OF TypeIdent | TypeIdent .
TypeIdent       -> INTEGER | BOOLEAN | CHAR .
```

b)

```
DKA = (Z, VT , V, d, z1 , S, F)
VT = {VAR, ident, number, ";", ":", ",", ")", "(", OF, ARRAY, INTEGER, BOOLEAN,
CHAR}
V = {Declaration, VarDeclList, VarDecl, IdentList, Type, TypeIdent}
Z = {z1}
S = Declaration
F = {z1}
```

```
S1:
d(Z, e, Declaration)    = (Z, VAR)
d(Z, e, Declaration)    = (Z, VarDeclList VAR)
d(Z, e, VarDeclList)    = (Z, ";" VarDecl)
d(Z, e, VarDeclList)    = (Z, VarDeclList ";" VarDecl)
d(Z, e, VarDecl)        = (Z, Type ":" IdentList)
d(Z, e, IdentList)      = (Z, ident)
d(Z, e, IdentList)      = (Z, IdentList "," ident)
d(Z, e, Type)           = (Z, TypeIdent OF ")" number "(" ARRAY)
d(Z, e, Type)           = (Z, TypeIdent)
d(Z, e, TypeIdent)      = (Z, INTEGER)
d(Z, e, TypeIdent)      = (Z, BOOLEAN)
d(Z, e, TypeIdent)      = (Z, CHAR)

S2:
d(Z, VAR, VAR)          = (Z, e)
d(Z, ";", ";")          = (Z, e)
d(Z, ident, ident)      = (Z, e)
d(Z, ":", ":")          = (Z, e)
d(Z, ",", ",")          = (Z, e)
d(Z, ARRAY, ARRAY)      = (Z, e)
d(Z, number, number)    = (Z, e)
d(Z, OF, OF)            = (Z, e)
d(Z, ")", ")")          = (Z, e)
d(Z, "(", "(")          = (Z, e)
```

```
d(Z, INTEGER, INTEGER)  = (Z, e)
d(Z, BOOLEAN, BOOLEAN)  = (Z, e)
d(Z, CHAR, CHAR)        = (Z, e)
```

c)

```
DKA = (Z, VT , V, d, z1 , S, F)
VT = {VAR, ident, number, ";", ":", ",", ")", "(", OF, ARRAY, INTEGER, BOOLEAN,
CHAR}
V = {Declaration, VarDeclList, VarDecl, IdentList, Type, TypeIdent, $(nur am
Start)}
Z = {z1}
S = Declaration
F = {z1}
```

```
S1:
d(Z, e, VAR)                                    = (Z, Declaration)
d(Z, e, VAR VarDeclList)                        = (Z, Declaration)
d(Z, e, VarDecl ";")                            = (Z, VarDeclList)
d(Z, e, VarDecl ";" VarDeclList)                = (Z, VarDeclList)
d(Z, e, IdentList ":" Type)                     = (Z, VarDecl)
d(Z, e, ident)                                  = (Z, IdentList)
d(Z, e, ident "," IdentList)                    = (Z, IdentList)
d(Z, e, ARRAY "(" number ")" OF TypeIdent)  = (Z, Type)
d(Z, e, TypeIdent)                              = (Z, Type)
d(Z, e, INTEGER)                                = (Z, TypeIdent)
d(Z, e, BOOLEAN)                                = (Z, TypeIdent)
d(Z, e, CHAR)                                   = (Z, TypeIdent)

S2:
d(Z, VAR, $)            = (Z, $ VAR)
d(Z, ";", $)            = (Z, $ ";")
d(Z, ident, $)          = (Z, $ ident)
d(Z, ":", $)            = (Z, $ ":")
d(Z, ",", $)            = (Z, $ ",")
d(Z, ARRAY, $)          = (Z, $ ARRAY)
d(Z, number, $)         = (Z, $ number)
d(Z, OF, $)             = (Z, $ OF)
d(Z, ")", $)            = (Z, $ ")")
d(Z, "(", $)            = (Z, $ "(")
d(Z, INTEGER, $)        = (Z, $ INTEGER)
d(Z, BOOLEAN, $)        = (Z, $ BOOLEAN)
d(Z, CHAR, $)           = (Z, $ CHAR)
d(Z, VAR, Declaration)  = (Z, Declaration VAR)
d(Z, ";", Declaration)  = (Z, Declaration ";")
+ 76 more

(|VT| * |V| == 13 * 7 == 91 mögliche Kombinationen, um Papier zu sparen,
enumeriere ich die jetzt nicht)
```

```
S3:
S(Z, e, $Declaration) = (R, e)
```

d)

für b) (nur erfolgreiche Züge)

```
(Z, Declaration                    .VAR a, b: INTEGER;) |--
(Z, VarDeclList VAR                .VAR a, b: INTEGER;) |--
(Z, VarDeclList                    .a, b: INTEGER;) |--
(Z, ; VarDecl                      .a, b: INTEGER;) |--
(Z, ; Type : IdentList             .a, b: INTEGER;) |--
(Z, ; Type : IdentList , ident     .a, b: INTEGER;) |--
(Z, ; Type : IdentList ,           ., b: INTEGER;) |--
(Z, ; Type : IdentList             .b: INTEGER;) |--
(Z, ; Type : ident                 .b: INTEGER;) |--
(Z, ; Type :                       .: INTEGER;) |--
(Z, ; Type                         .INTEGER;) |--
(Z, ; TypeIdent                    .INTEGER;) |--
(Z, ;                              .;) |--
(Z,                                .) erkannt! (Keller leer)
```

für c) (nur erfolgreiche Züge)

```
(Z, $                              .VAR a, b: INTEGER;) |--
(Z, $VAR                           .a, b: INTEGER;) |--
(Z, $VAR a                         ., b: INTEGER;) |--
(Z, $VAR ident                     ., b: INTEGER;) |--
(Z, $VAR ident,                    . b: INTEGER;) |--
(Z, $VAR ident, b                  .: INTEGER;) |--
(Z, $VAR ident, ident              .: INTEGER;) |--
(Z, $VAR ident, IdentList          .: INTEGER;) |--
(Z, $VAR IdentList                 .: INTEGER;) |--
(Z, $VAR IdentList :               .INTEGER;) |--
(Z, $VAR IdentList : INTEGER       .;) |--
(Z, $VAR IdentList : Type          .;) |--
(Z, $VAR VarDecl                   .;) |--
(Z, $VAR VarDecl ;                 .) |--
(Z, $VAR VarDeclList               .) |--
(Z, $Declaration                   .) |--
(R,                                .) erkannt!
```

5. Term. Anfänge/Nachfolger, LL(k)-Bedingung u. Transformation