Formal Methods in Computer Science SS 2016:
Optional Exercise Sheet (Induction)

This exercise sheet provides some training material for the optional tutorial.

1.) Show that any natural number above 11 can be written as a sum of 4's and 5's.

2.) Show that for any $n \in \mathbb{N}_0$, the number $\ell_n = 4^{n+2} + 5^{2n+1}$ is divisible by 21.

3.) Prove the following: *If a tree has $n \geq 1$ vertices, then it has $n - 1$ edges.*

4.) Let I, I' be interpretations with domains $\mathcal{U}$, $\mathcal{U}'$. We say that I is *isomorphic* to I' if there exists a bijection $\chi : \mathcal{U} \to \mathcal{U}'$ such that the following conditions are fulfilled:

(a) $\chi(I(c)) = I'(c)$ for every constant symbol c.

(b) $\chi(I(f)(p_1, \ldots, p_n)) = I'(f)(\chi(p_1), \ldots, \chi(p_n))$ for every n-ary function symbol f $(n > 0)$ and all $p_1, \ldots, p_n \in \mathcal{U}$.

χ is called *isomorphism* between I and I'.

Now let χ be an isomorphism between I and I'. Prove that for all closed (i.e., variable-free) terms t we have $I'(t) = \chi(I(t))$.

Hint: Prove the statement by structural induction on t.

5.) We define the set L of all lists as follows:

$$L ::= nil \mid (c : L)$$

nil denotes the empty list containing no element. We define the function *append* by $append(nil, y) = y$ and $append((c : x), y) = (c : append(x, y))$. Show that, for all lists ℓ, $append(\ell, nil) = \ell$ holds.

6.) Recall from former lectures the definition of *Fibonacci numbers*: $F(0) = 0$, $F(1) = 1$, and for all integers $k \geq 0$, $F(k + 2) = F(k + 1) + F(k)$. Show that, for all integers $n \geq 0$, $F(n) < 2^n$ holds.

7.) Recall from former lectures the definition of *Fibonacci numbers*: $F(0) = 0$, $F(1) = 1$, and for all integers $k \geq 0$, $F(k + 2) = F(k + 1) + F(k)$. Show that, for all integers $n \geq 0$, $\sum_{i=0}^{n-1} F(i) < F(n + 1)$ holds.

8.) Recall from former lectures the definition of *Fibonacci numbers*: $F(0) = 0$, $F(1) = 1$, and for all integers $k \geq 0$, $F(k+2) = F(k+1) + F(k)$. Show that, for all integers $n \geq 3$, $\alpha^{n-2} < F(n)$ holds, where $\alpha = (1+\sqrt{5})/2$.

Remark: α is called the *golden ratio* and it can be proved that $\lim_{n\to\infty} F_{n+1}/F_n = \alpha$.

9.) What is wrong with the following proof of the statement: *for any positive real x and any natural number n, $x^n = 1$ holds*?

Let $\mathcal{P}(n)$ denote $x^n = 1$. The proof is by mathematical induction on n.

Base case. For $n = 0$, $\mathcal{P}(n)$ is true because $x^0 = 1$.

Induction hypothesis. Assume $\mathcal{P}(n)$ is true for some $n \geq 0$.

Induction step. We want to show that $\mathcal{P}(n+1)$ is true. We derive:

$$\begin{aligned} x^{n+1} &= \frac{x^n \cdot x^n}{x^{n-1}} \\ &= \frac{1 \cdot 1}{1} \qquad \text{(from above by the induction hypothesis)} \\ &= 1\,. \end{aligned}$$

Hence, $\mathcal{P}(n+1)$ is true. □

10.) Let $\mathcal{P}(n)$ denote the statement $n! > 2^n$. Show that there is a smallest natural number n_0 such that $\mathcal{P}(n)$ holds for all natural numbers $n \geq n_0$.

11.) For sets $A_1, A_2, \ldots$ and $B_1, B_2, \ldots$, define $B_1 = A_1$ and $B_n = A_n \setminus (\bigcup_{i=1}^{n-1} A_i)$ for $n > 1$.

Prove: $\bigcup_{i=1}^{n} B_i = \bigcup_{i=1}^{n} A_i$.

12.) Recall the induction scheme (given below) and the procedure how universal statements and implications are proved! Discuss the role of the latter procedure when you state the induction hypothesis and when you perform the induction step.

$$\big[P(1) \land \forall k \in \mathbb{N}\,(P(k) \to P(k+1))\big] \to \forall n \in \mathbb{N}\,P(n)$$

13.) Let us define the *Fermat* numbers $F_n = 2^{(2^n)} + 1$ for all natural numbers $n \geq 1$. Prove that for all $n \geq 1$, $F_n = (F_0 \cdot F_1 \cdot \cdots \cdot F_{n-1}) + 2$.

14.) This exercise is taken from Hopcroft, J.E., Motwani, R. and Ullman, J.D.: *Introduction to Automata Theory, Languages, and Computation*, 3rd ed., Pearson, 2007. It requires some background from automata theory.

A non-deterministic finite automaton A is a quintuple $(Q, \Sigma, \delta, q_0, F)$, where Q is a finite set of states, Σ is a finite set of input symbols, $q_0 \in Q$ is the start state, and $F \subseteq Q$ is the set of final (or accepting) states. The transition function δ takes a state from Q and an input symbol from Σ as arguments and returns a subset of Q.

The set of all strings over Σ is denoted by Σ^*. Let x and y be two strings. Then xy is the concatenation of them. The length of a string w (i.e., the number of symbol occurrences in w) is denoted by $|w|$. ϵ is the empty string which is of length 0.

We denote by $\hat{\delta}$ the extension of δ to strings.

$$\hat{\delta}(q, w) = \begin{cases} \{q\} & \text{if } w = \epsilon \text{ (the empty string);} \\ \bigcup_{p \in \hat{\delta}(q,x)} \delta(p, a) & \text{if } w = xa,\ x \in \Sigma^* \text{ and } a \in \Sigma. \end{cases}$$

The language accepted by A, $L(A)$, is $\{w \mid \hat{\delta}(q_0, w) \cap F \neq \{\}\}$.

Let $A = (\{q_0, q_1, q_2\}, \{0, 1\}, \delta, q_0, \{q_2\})$, where $\delta(q_0, 0) = \{q_0, q_1\}$, $\delta(q_0, 1) = \{q_0\}$, $\delta(q_1, 0) = \{\}$, $\delta(q_1, 1) = \{q_2\}$, and $\delta(q_2, 0) = \delta(q_2, 1) = \{\}$. Show that $L(A) = \{w \mid w \text{ ends in } 01\}$.

Hint. Use mutual induction on the following statements:

(a) $\hat{\delta}(q_0, w)$ contains q_0 for every w.
(b) $\hat{\delta}(q_0, w)$ contains q_1 if and only if w ends in 0.
(c) $\hat{\delta}(q_0, w)$ contains q_2 if and only if w ends in 01.

15.) Consider a (generalized) chess board of size $2^n \times 2^n$, where one position is cut out. Take an L-tile made of three positions and show for all natural numbers $n \geq 1$ that the chess board can be covered using the L-tiles. Compute the number of required L-tiles.

16.) You have a bag with red, yellow and blue chips. If only one chip remains in the bag, you put it out. Otherwise you remove two chips at random:

(a) If one of the removed chips is red, you do not put any chips in the bag.
(b) If both of the removed chips are yellow, you put one yellow chip and five blue chips in the bag.
(c) If one of the chips is blue and the other is not red, you put ten red chips in the bag.

Show that any sequence of moves applied to an arbitrary bag always terminates or provide a non-terminating sequence of moves.