Automated Reasoning
Exercise Sheet 5: Induction and Hoare Logic

Exercise 1: Induction

Consider the following (Isabelle) datatype definition:

```
datatype 'a TREE = LEAF 'a | NODE 'a "'a TREE" "'a TREE"
```

1. Give an induction rule appropriate for proofs by (structural) induction involving the `TREE` datatype.
2. Define a function `MIRROR` that recursively flips the nodes in the left and right subtrees of a tree as defined above.
3. Formalize your definition of `MIRROR` in Isabelle and give a structured (Isar) proof that `MIRROR`(`MIRROR` t) $= t$.

Exercise 2: Pen-and-Paper Hoare Logic Proof

Construct the natural deduction proof of the following Hoare Logic triple (taken from the factorial example in the lecture), on paper:

$$\{Y = 1 \wedge Z = 0\}\,\texttt{WHILE}\ Z \neq X\ \texttt{DO}\ Z := Z + 1\,; Y := Y \times Z\ \texttt{OD}\ \{Y = X!\}$$

You may use any of the FOL natural deduction rules and the Hoare Logic rules. Additionally, you may use the following 4 lemmas:

$$\frac{\neg\neg X}{X}\ notnotD \qquad \frac{b = a}{a = b}\ sym \qquad \frac{}{0! = 1}\ fact\_0$$

$$\frac{}{x! \times (x+1) = (x+1)!}\ fact\_plus\_1 \qquad \frac{s = t \quad P\,s}{P\,t}\ subst$$

Exercise 3: Introduction to Hoare Logic in Isabelle

In the following exercise, you will formally verify the correctness of some simple programs using Isabelle's *Hoare_Logic* library. This library allows you to formalise the specifications of programs of a simple programming language in the form of Hoare triples.

The supported programming language includes the following constructs:

- Local variable declaration: `VARS x y z`
- Sequence: `p ; q`
- Skip (do nothing): `SKIP`
- Variable assignment: `x := 0`
- Conditional: `IF cond THEN p ELSE q FI`
- Loop: `WHILE cond INV { invariant } DO p OD`

A program `X` with precondition `P` and postcondition `Q` can be specified as the Hoare triple:

Each Hoare triple in Isabelle must begin with a local variable declaration @text VARS including at least one local variable, i.e. the triple shown above can be specified in Isabelle as follows:

```
"VARS a P X Q"
```

Note that a loop invariant must be explicitly specified for each while loop using the `INV` operator.

You can use any pre-defined Isabelle type or function in the *program specification*.

The automated tactic `vcg`, can be used to extract verification conditions from the Hoare triples and convert them to Isabelle subgoals. The tactic `vcg_simp` combines the capabilities of `vcg` with simplification.

Verification Problems

Using the *Hoare_Logic* library, verify the correctness of the following programs. Some of the examples require that you introduce the appropriate invariant `Inv`.

Make sure your theory has the following imports statement:

```
imports Main Binomial "~~/src/HOL/Hoare/Hoare_Logic"
```

- The minimum of two integers `x` and `y`:

```
lemma Min: "VARS (z :: int)
    {True}
    IF x ≤ y THEN z := x ELSE z := y FI
    { z = min x y }"
```

- Iteratively copy an integer variable `x` to `y`:

```
lemma Copy: "VARS (a :: int) y
    {0 ≤ x}
    a := x; y := 0;
    WHILE a ≠ 0
    INV { Inv }
    DO y := y + 1 ; a := a - 1 OD
    {x = y}"
-- "Replace Inv with your invariant."
```

- Iteration multiplication through addition:

```
lemma Multi: "VARS (a :: int) z
    {0 ≤ y}
    a := 0; z := 0;
    WHILE a ≠ y
    INV { Inv }
    DO
       z := z + x ;
       a := a + 1
    OD
    {z = x * y}"
-- "Replace Inv with your invariant."
```

- A factorial algorithm:

```
lemma DownFact: "VARS (z :: nat) (y::nat)
    {True}
    z := x; y := 1;
    WHILE z > 0
    INV { Inv }
    DO
       y := y * z ;
       z := z - 1
    OD
    y = fact x"
   -- "Replace Inv with your invariant."
```

- Integer division of x by y:

```
lemma Div: "VARS (r :: int) d
    {y ≠ 0}
    r := x; d := 0;
    WHILE y ≤ r
    INV { Inv }
    DO
    r := r - y;
    d := d + 1
    OD
    { Postcondition }"
-- "Replace Inv with your invariant."
-- "Replace Postcondition with an appropriate postcondition that reflects
the expected behaviour of the algorithm."
```