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Thomas Genet, Jørgen Villadsen

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A Short Isabelle Tutorial for the Functional Programmer

Thomas Genet (genet@irisa.fr) and Jørgen Villadsen (jovi@dtu.dk)

Abstract
The objective of this very short tutorial is to help any functional programmer to quickly put their hand on Isabelle/HOL and catch a glimpse of its power. If you want some more afterward, please refer to the official Isabelle/HOL tutorial and the documentation available in the tool.

1 Installing and Starting Isabelle/HOL
Download Isabelle/HOL from https://isabelle.in.tum.de/ This tutorial is based on the 2022 version. If your operating system is neither old nor exotic, installation should be straightforward. Otherwise, you should refer to the installation instructions https://isabelle.in.tum.de/installation.html.

When Isabelle’s main window opens, it should be divided into a number of frames. The largest frame is used to enter programs and lemmas. Let us call it the Theory frame. The frame on the leftmost position gathers all built-in Isabelle documentation. The frame at the bottom is for output of all program runs and proof goals. If the Output frame is not visible, click on the “Output” button on the bottom left of the window to make it visible.

2 Defining and Running Programs
In the Theory frame type the following:

theory Scratch
  imports Main
begin
end

where the name of the theory (here Scratch) should match with the file name (check that it is Scratch.thy in the leftmost topmost bar over the Theory frame). Then, between begin and end, we can define the elements of our theory: functions, tests, lemmas, etc. Let’s start with our first program. Below begin and above end, type in the following code:

fun remove :: "'a => 'a list => 'a list"
  where
    "remove x [] = []" |
    "remove x (y#ys) = (if x=y then ys else y#(remove x ys))"

Note that, unlike many programming languages, Isabelle does not use double quotes to denote strings but to delimitate function definitions, lemmas, etc. While typing this program you can notice two things. First, Isabelle replaces all combinations => by the nicer symbol ⇒. Second, in the Output frame, Isabelle has automatically proven the termination of your program, by finding a termination order denoted by "(λp. length (snd p)) <*mlex*> {}". Roughly, termination of remove is guaranteed because the length of the second parameter (i.e. the list) decreases for each recursive call. If no termination order is found, then you will see in the Output frame a red warning saying that automatic termination proof failed. The fun construct defines a function named remove, taking two parameters of type ‘a (any type) and ‘a list (list of elements of type ‘a) and whose result is of type ‘a list. The function is then defined using (possibly recursive) equations. Lists can be built using the empty list [] and the “cons” operator denoted by #. Lists can also be defined using shortcuts. For instance, the list [1,2,3] is a shortcut for 1#(2#(3#[])). Now let’s try our function remove, which should remove all occurrences of an element from a list. Below the definition of remove, enter a simple test where (* ... *) is the syntax for comments:

value "remove 2 [1,2,3]" (* this is a simple test *)

In the Output frame, you will see a red warning saying that there is a “Wellsortedness” problem. This is due to the fact that, by default in Isabelle, symbols “0”, “1”, etc. are not uniquely associated to the type int. Thus, evaluating value "1" will result in the same “Wellsortedness” problem. To denote the integer 1, we need to annotate the symbol “1” by the desired type: value "(1::int)" results in the integer 1. Let’s try again on our example:
value "remove (2::int) [1,2,3]"

Now, we have the expected result in the Output panel: "[1, 3] :: "int list". Note that specifying the type of one parameter was enough for the desired type to be inferred for the whole expression.

3 Automate the Search for Bugs

The next step is to check if our function contains errors. We could write more tests using value and verify, test after test, that the result fulfills our expectations. Instead, we define a property that our function is supposed to have, using a logical formula. For instance, type in the following sentence, where the ¬ logical symbol stands for “not”. To get the ¬ operator, type the ~ character: you can then use the “Tab” key to select the symbol inside the selection box that opens.

lemma "¬ (List.member (remove e l) e)"

The function List.member:: 'a list ⇒ 'a ⇒ bool is part of Isabelle's List library and results in the boolean True if the list contains the given element, and False otherwise. The formula states that the result of remove e 1 should not contain the element e. Since we provide no information on e or l, they are free variables. Thus, the formula we just defined is supposed to hold for all possible values of e (of type 'a) and l (of type 'a list).

The effect of the lemma command is to define the property and, at the same time, to switch Isabelle into proof mode. Below lemma, Isabelle waits for proof commands. In this mode you can no longer define functions nor state new lemmas. On the current lemma, we can first search for small finite counterexamples. AutoQuickcheck may already have shown you a counterexample in the Output frame. Otherwise, this can be obtained by typing the nitpick command below the lemma line. While typing the first letters of the word nitpick, a selection appears in which one you can select the command you want to insert using the arrows of your keyboard and the “Tab” key. Once the nitpick command is inserted, it finds a counterexample to our lemma. With values l = [a1,a1] and e = a1, the lemma we stated is false. In other words, for any list l with two occurrences of the same element, the lemma is false. Let's check remove's behavior on a similar example. Typing in value "remove (1::int) [1,1]" permits to see that remove does not do the job: the result is [1] and our function is wrong. Click on the definition of remove and correct it. In the “then” part of the second equation, one should recursively call remove on ys, i.e. the second equation should be: "remove x (y#ys) = (if x=y then (remove x ys) else y#(remove x ys))". Once corrected, you can click on the value line to check that the result is the expected one, and click on the nitpick line to check that no more counterexamples are to be found.

Now, let's try to define a second property. You first have to close the ongoing proof. There are three ways to close the proof of a lemma: done when the proof is finished, sorry when you think that the lemma is correct but have not completed the proof, and oops to close the proof mode when the lemma was shown to be false (if a counterexample is still found, for instance). In our case, we corrected the function, the lemma is likely to be true, but we do not yet have the proof. Thus, we type sorry below the nitpick command. With our last lemma we expect to show that remove e 1 removes all occurrences of e in l but what about the other elements in the list? Below sorry, enter the following lemma which checks that all the other elements have not disappeared from the list:

lemma "(length l) = (length (remove e l)) + (count l e)"

Note that you have to type a space character between (length l) and "=" to avoid Isabelle replacing the combination "$e$" by the symbol "$\geq$". In this lemma, the function length::'a list ⇒ nat returns the number of elements in a list (nat stands for natural numbers, i.e. non-negative integers) and count::'a list ⇒ 'a ⇒ nat counts the number of occurrences of a given element in a list. Thus, this lemma states that the number of elements in l is equal to the number of elements in (remove e l) plus the number of occurrences of e in l. Again, the first thing to check is that there is no counterexample. Below the lemma, type nitpick. It finds a counterexample where count is considered as a free variable, as l and e. Furthermore, free variables are colored in blue, and so are l, e and count. Note that this is not the case for length and remove. The reason is that the function count is unknown. In fact, the function name in the library is count_list. This time, the counterexample is not due to a bug in the function but to an error in the lemma: it states a property on an unknown function count and nitpick invents a value for this function, falsifying the lemma. This permits to detect misspelling and such in the formulas. If you modify the lemma as follows, nitpick no longer finds counterexamples.

lemma "(length l) = (length (remove e l)) + (count_list l e)"
4 No More Bugs? Let’s Go for a Proof!

The fact that nitpick finds no counterexample does not imply that the property is true. To be sure that it holds we need to prove it using Isabelle proof commands. First, we try to prove this last lemma on remove, length and count_list. Since we know that there are no more simple counterexamples on the lemma, we can remove the nitpick command. Click on the lemma line and check the “Proof state” box on top of the output frame. The proof state consists, for the moment, of a unique proof subgoal which is exactly the lemma we stated. We are going to apply the main Isabelle proof command auto to see if this goal can be automatically simplified. Under the lemma, type apply auto. In the output frame, we can see that auto failed to simplify the proof goal. This is not surprising since e and 1 are free variables. In particular, we do not know if we can apply the first equation of the definition of remove since we do not know whether 1 is [] or not. To give more information to Isabelle about 1, before the apply auto line, type apply (induct 1). Applying induction on 1 has split the proof goal in two subgoals:

1. length [] = length (remove e []) + count_list [] e
2. ∀ a 1. length l = length (remove e l) + count_list l e ⇒ length (a # 1) = length (remove e (a # 1)) + count_list (a # 1) e

The first subgoal corresponds to the case where 1 is known to be [], i.e. 1 has been replaced by [] in the subgoal. In the second subgoal, a and 1 become new fresh variables, local to this formula. This is the meaning of the notation “∀ a 1.” on the leftmost part of the formula. This second subgoal is built with Isabelle’s deduction symbol “⇒”. To solve a goal of the form A ⇒ B, the objective is to prove B using the additional hypothesis A. This time, apply auto knows how to simplify those two goals. Click on the apply auto line below apply (induct 1) to see its effect: there are no proof subgoals left. This concludes your first proof. You can now proudly close it using the done command. The complete lemma and proof should look like this in the Theory frame:

lemma "(length 1) = (length (remove e 1)) + (count_list 1 e)"
  apply (induct 1)
  apply (auto)
  done

Now, let’s go back to the first lemma we wrote on List.member and remove, and prove it. You can remove the nitpick command and the sorry command. As above, an apply auto would not succeed because the definition of remove cannot be used to simplify the proof goal. Type apply (induct 1) and then apply auto. This time, apply auto did not succeed to fully solve the subgoals. If you click on the apply (induct 1) line and the apply auto line you can compare the subgoals to see the effect of apply auto. In the two subgoals, the expressions built on remove have been simplified but not the expressions built on List.member. This is due to the fact that the equations defining member are not visible for auto, because they are outside of the current theory. We could search in Isabelle theories for the name of the definition or lemma to apply. Instead of this, we can delegate this job to Sledgehammer. Sledgehammer can find and use function definitions and lemmas outside of the current theory and call external theorem provers to solve proof goals. Click on the apply auto line, then click on the “Sledgehammer” button on the bottom left of the window to make it visible. In this Sledgehammer window, you find the list of automatic provers that are going to be used to solve your goal: cvc4, vampire, verit, etc. Click on the “Apply” button. After some seconds, you can see proofs proposed by the external theorem provers. In particular, you should see this result:

Try this: apply (simp add: member_rec(2))

By clicking on the proposed proof command apply (simp add: member_rec(2)), it is added to your proof and solves the first subgoal. Proofs obtained from Sledgehammer use either simp,metis, smt, . . . proof commands and lemma or definition names. Here, the proof command simp uses the second equation of the member definition to solve the goal. By clicking on the “Output” button, you can check that the first subgoal was solved. The last subgoal can be solved in the same way using Sledgehammer again. The last proof command introduced by Sledgehammer should be of the form by (simp add: member_rec(1)), where by is a proof command that also closes the proof mode like done. Let’s finish this part by proving a last lemma (where the implication symbol → can be obtained by typing →→):

lemma "(length (remove e 1)) = (length 1) → ¬ (List.member 1 e)"

This property means that if the length of (remove e 1) and 1 are equal, then e should not appear in 1. Nitpick does not find any counterexample. We can start the proof by apply (induct 1) and apply auto as usual. We end up with four subgoals. Sledgehammer can solve the first one, but not the second one. So we are stuck with 3 subgoals. Let’s carefully look at the first remaining subgoal:
1. \[ \text{length (remove e l) = Suc (length l)} \implies \text{List.member (e # l) e = False} \]

This goal is of the form \( A \implies B \implies \text{False} \). In other words, with assumptions \( A \) and \( B \) we have to prove \( \text{False} \). The only solution for this subgoal to hold is if the assumptions, separately or together, are false. Here, the first assumption is clearly false: \( \text{length (remove e l)} \) cannot be equal to \( (\text{length l})+1 \) (\( \text{Suc i} \) stands for the successor of natural \( i \)). In fact, we already know, from the previous lemma, how \( \text{length (remove e l)} \) and \( (\text{length l}) \) relate. However, for Sledgehammer to use this lemma, we need to name it. Click back on the definition of the previous lemma and add a name to it with a colon. For instance:

\[
\text{lemma count_remove: } "(\text{length l}) = (\text{length (remove e l)}) + (\text{count_list l e})"
\]

Come back to the proof and click on the line where Sledgehammer was failing. Now, Sledgehammer succeeds on this goal, and you can see that the found proof uses the \text{count_remove} lemma. Note that, for a lemma \( A \) to be used in the proof of lemma \( B \), the definition of \( A \) should come before the definition of \( B \). To prove the two remaining subgoals, and conclude the proof, you can use Sledgehammer again.

5 Datatypes

Let’s define the algebraic datatype of polymorphic binary trees with two constructors \text{Leaf} and \text{Node}. Pay attention to the double quotes. Then, construct an object of this type and associate it to the constant name \text{myTree}. Finally, define two functions on trees:

\[
\begin{align*}
\text{datatype } 'a \text{ tree} &= \text{Leaf} \mid \text{Node } 'a \ "'a tree" "'a tree" \\
\text{definition } "\text{myTree} = \text{Node } (1::\text{int}) \ (\text{Leaf} \ \text{Leaf}) \ (\text{Node} \ \text{Leaf} \ \text{Leaf})"
\end{align*}
\]

\[
\begin{align*}
\text{fun numNodes:: } "'a\text{ tree} \Rightarrow \text{nat}" & \text{ where} \\
"\text{numNodes Leaf} = 0" & \mid \\
"\text{numNodes } (\text{Node } e \ t1 \ t2) = 1+(\text{numNodes } t1)+(\text{numNodes } t2)"
\end{align*}
\]

\[
\begin{align*}
\text{fun subTree:: } "'a\text{ tree} \Rightarrow \ 'a\text{ tree} \Rightarrow \ \text{bool}" & \text{ where} \\
"\text{subTree Leaf Leaf} = \text{True}" & \mid \\
"\text{subTree } t \ \text{Leaf} = \text{False}" & \mid \\
"\text{subTree } t \ (\text{Node } e \ t1 \ t2) = ((t=(\text{Node } e \ t1 \ t2)) \vee (\text{subTree } t \ t1) \vee (\text{subTree } t \ t2))"
\end{align*}
\]

The function \text{numNodes} counts the number of nodes in a binary tree and the function \text{subTree} checks if a tree is a sub-tree of another, where the symbol “\( \vee \)” (denoting “or”) is obtained by typing \( \backslash / \). Note that, in the definition, the order of equations matters. For instance, to evaluate a call to the function \text{subTree} definition, the second equation is tried only if the first one does not apply, etc. We can test those functions on the constant we just defined:

\[
\text{value } "\text{numNodes myTree}"
\]

\[
\text{value } "\text{subTree } (\text{Node } 3 \ \text{Leaf} \ \text{Leaf}) \ \text{myTree}"
\]

The following lemma states the following property: if a tree \( t1 \) is a sub-tree of \( t2 \), then the number of nodes of \( t1 \) is lesser or equal to the number of nodes of \( t2 \). Note that the symbol \( \leq \) is obtained by typing \( \backslash = \).

\[
\text{lemma subNum: } "(\text{subTree } t1 \ t2) \implies (\text{numNodes } t1) \leq (\text{numNodes } t2)"
\]

To prove this lemma, we need to perform a proof by induction on trees because functions \text{numNodes} and \text{subTree} are recursively defined on trees. We have the choice between an induction on \( t1 \) or on \( t2 \). However, since \text{subTree} is recursively defined on the second parameter, induction on \( t2 \) is more likely to succeed. The proof can be carried out using \text{apply (induct } t2), then \text{apply auto} and Sledgehammer.

6 Code Exportation

You can export the code of Isabelle functions into various programming languages (Haskell, OCaml, Scala and Standard ML) using the \text{export_code} directive. For instance, below all the function definitions and outside of a proof, you can type: \text{export_code remove in Haskell} whose effect is to export all the necessary material for the function \text{remove} to run in Haskell.
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