

Final Year Project Report

A Theorem Proving Assistant

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A thesis submitted in part fulfilment of the degree of
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Project Specification

General Information

Calculational Theorem Proving is the name given to a particular style of mathematical proof which was developed during the 1980s by Feijen and Dijkstra. It emphasises the syntactic manipulation of expressions rather than manipulation based on an interpretation of the expression. In doing so it tries to let the notation do the work.

In order to do so the choice of notation and the layout of the proofs are important.

This style of proof has been taught in a number of our undergraduate modules over the last 10 years and is probably quite familiar to all of our undergraduates. An example proof would have been included here but the special symbols for the boolean operators were not available.

The aim of this project is to develop a tool which will assist the person proving the theorem by performing basic housekeeping tasks. So for example, the user should be able to select a sub-expression, select an appropriate rule to transform it, and have the system carry out the transformation and record the appropriate hint to show which rule was used and what the variable bindings were. It is important to mention that we are not interested in automatic theorem proving, the user will still be required to drive the proof but the system will perform the matching and applying of the rules.

It should be possible to store and retrieve partial or complete proofs. It should be possible to undo a series of steps and select different rules to apply. Once a theorem is proved it should be possible to add it to the rule base so it can be used in future proofs.

Mandatory Requirements

- The design of algorithms to a selected sub-expression with a subexpression of a rule.
- The design of an interface to allow users to select subexpressions and rules to apply.
- The design of appropriate algorithms to allow partial and complete proofs to be stored and retrieved.
- The design of appropriate algorithms to allow the user to undo steps in a proof.
- The implementation of the above functionality.

Discretionary Requirements

- Incorporating quantified expressions and their manipulation rules in the system.

Exceptional Requirements

- Incorporating additional small calculi such as Max/Min, Floor/Ceiling and GCD/LCM into the system.

Suggested Reading

- <http://www.cs.utexas.edu/~EWD/>
- <http://www.mathmeth.com/>
- Program Construction by Roland Backhouse
- A logical approach to discrete maths by David Gries

Abstract

Context

This report introduces the reader to predicate calculus and theorem proving in the style used by Dijkstra. It highlights the features of it that lend themselves to a computer application. Proving boolean theorems is a pattern matching exercise without need for interpretation of the expression at each stage of the proof. This report explores issues and solutions for building a software package which facilitates theorem proving in a clear and easy manner. A software package written in Java is presented from both user experience and technical development points of view.

Methodology

An exploratory approach was taken to not only resolving the major issues but finding them as well. There is no road map to follow so a lot of time and resources were put into paths that led nowhere. In order to carry out this project algorithms were defined which were relied upon throughout, some of which have proven to be flawed and others invaluable. These will be discussed. A modular approach was taken to the software development, focusing completing small tasks and proving their correctness before moving on to the next.

Findings

Several major algorithms were defined to carry out the steps needed for theorem proving with the assistance of software. These algorithms were implemented in Java and a fully functioning software package was produced. It facilitates theorem proving over the predicate calculus with quantified expressions as well as other small calculi such as max/min and floor/ceiling.

Acknowledgments

Thank you kindly

Introduction to Dijkstra's Theorem Proving Style

Predicate calculus theorem proving works like this: given a set of axioms and theorems (rules) one can calculate, or derive, further theorems. Relying on those derived previously a full calculus can be evolved. This process relies heavily on pattern matching and this notion is vitally important. With each step of a proof a hint is given which tells the reader which rule was used and what assignment was made to each variable in that rule. Dijkstra states that the notation used is vitally important for a clear and easy to read proof [1].

Preliminaries

Before giving an example proof over the boolean domain we must set some conventions for notation and give information about operators.

- Upper case letters such as X, Y and Z will be used as boolean identifiers.
- For this brief introduction I am only going to introduce 3 operators:
 - Conjunction** - boolean multiplication: \wedge reads as "and".
 - Disjunction** - boolean addition: \vee reads as "or".
 - Equivalence** - boolean equals: \equiv reads as "equival".
- Equivalence holds the lowest precedence of the three operators and conjunction and disjunction share equal precedence meaning explicit bracketing must sometimes be used.
- Brackets can be introduced as long as precedence and operators operands are respected.
- Brackets can be removed under the same conditions as removal.
- Rules will be numbered and named and be referenced to by their number or name.
- Each new line of a proof will be preceded by an assignment and the corresponding rule. We call this "the hint".
 - eg. $\{(X, Y := Z, Y).(5)\}$ reads as X and Y are assigned the values Z and Y respectively in rule 5.
- Axioms will be denoted with a $*$ to the left of it's number and theorems with a \cdot .

In order to give a sample proof I provide the following set of axioms and theorems.

$*$ (0) $[(X \equiv (Y \equiv Z)) \equiv ((X \equiv Y) \equiv Z)]$	\equiv associative
$*$ (1) $[X \equiv Y \equiv Y \equiv X]$	\equiv symmetric
$*$ (2) $[X \equiv true \equiv X]$	\equiv identity
\cdot (3) $[X \equiv X]$	\equiv reflexive
\cdot (4) $[true]$	true
$*$ (5) $[X \vee Y \equiv Y \vee X]$	\vee symmetric
$*$ (6) $[X \vee (Y \vee Z) \equiv (X \vee Y) \vee Z]$	\vee associative
$*$ (7) $[X \vee X \equiv X]$	\vee idempotent
$*$ (8) $[X \vee (Y \equiv Z) \equiv X \vee Y \equiv X \vee Z]$	\vee / \equiv

A Sample Proof

We will now attempt to prove that disjunction distributes over its self.

$$\begin{aligned}
& (X \vee Y) \vee (X \vee Z) \\
\equiv & \quad \{(X, Y, Z := (X \vee Y), X, Z).(6)\} \\
& ((X \vee Y) \vee X) \vee Z \\
\equiv & \quad \{(X, Y := (X \vee Y), X).(5)\} \\
& (X \vee (X \vee Y)) \vee Z \\
\equiv & \quad \{(X, Y, Z := (X, X, Y).(6)\} \\
& ((X \vee X) \vee Y) \vee Z \\
\equiv & \quad \{(X := X).(7)\} \\
& ((X) \vee Y) \vee Z \\
\equiv & \quad \{remove\ brackets\} \\
& (X \vee Y) \vee Z \\
\equiv & \quad \{(X, Y, Z := (X, Y, Z).(6)\} \\
& X \vee (Y \vee Z)
\end{aligned}$$

This has yielded a new theorem so we shall record it so it is available for use in future proofs.

$$\cdot (9) [(X \vee Y) \vee (X \vee Z) \equiv X \vee (Y \vee Z)] \quad \vee/\vee$$

Note that in the above proof no interpretation of any of the boolean expressions was done. It is purely a pattern matching exercise. At each step of the proof we used a single theorem to replace a section of an expression with an equivalent section. The theorem proving assistant functions by exploiting this feature of the proof style.

A second proof is provided here for demonstration. It proves that $P \vee true \equiv true$.

$$\begin{aligned}
& P \vee true \\
\equiv & \quad \{(X := P).(2)\} \\
& P \vee (P \equiv P) \\
\equiv & \quad \{(X, Y, Z := P, P, P).(6)\} \\
& P \vee P \equiv P \vee P \\
\equiv & \quad \{(X := P).(7)\} \\
& P \equiv P \vee P \\
\equiv & \quad \{(X := P).(7)\} \\
& P \equiv P \\
\equiv & \quad \{(X := P).(2)\} \\
& true
\end{aligned}$$

Again we record the proof:

$$\cdot (10) [P \vee true \equiv true] \quad \vee zero$$

Further Notation and Calculi

Other Boolean Operators

blah

Quantified Expressions

blah

The Floor/Ceiling Calculus

blah

Lattice Theory

blah

The Max/Min Calculus

blah

Introduction to The Theorem Proving Assistant

The Software

The theorem proving assistant is a user friendly software environment for assisting in proving predicate calculus theorems. It is not be an automated tool, but one which provides the user with a comprehensive and robust environment in which theorems can be proved. The software takes care of the "housework", such as automating the generation of the hint between each step.

The user is presented with an environment in which they prove theorems. To start a theorem the user needs an expression to work from. This is typed in in a psuedo language `****APENDIX FOR PSEUDO LANGUAGE****` and after clicking start a parser will transform the input into the correct form. For example: "X and Y" will be transformed into the expression $X \wedge Y$.

The expression which the user is working with at any one time will be referred to as the current expression. In order to carry out steps of the proof the following steps are carried out by the user:

1. Select a theorem (or sub-expression of a theorem) to use as the current expression.
2. Select a sub-expression in the current expression (the software ensures that only a valid subexpression can be chosen).
3. Choose a theorem to apply.
4. Make a selection of which replacement/assignment to use from that theorem from a list of options.
5. View the new expression generated with a hint step describing which theorem and what assignment was used.
6. Continue to carry out steps the new expression as the current expression until a conclusion has been drawn.
7. Save the proven theorem as a new theorem for future use.

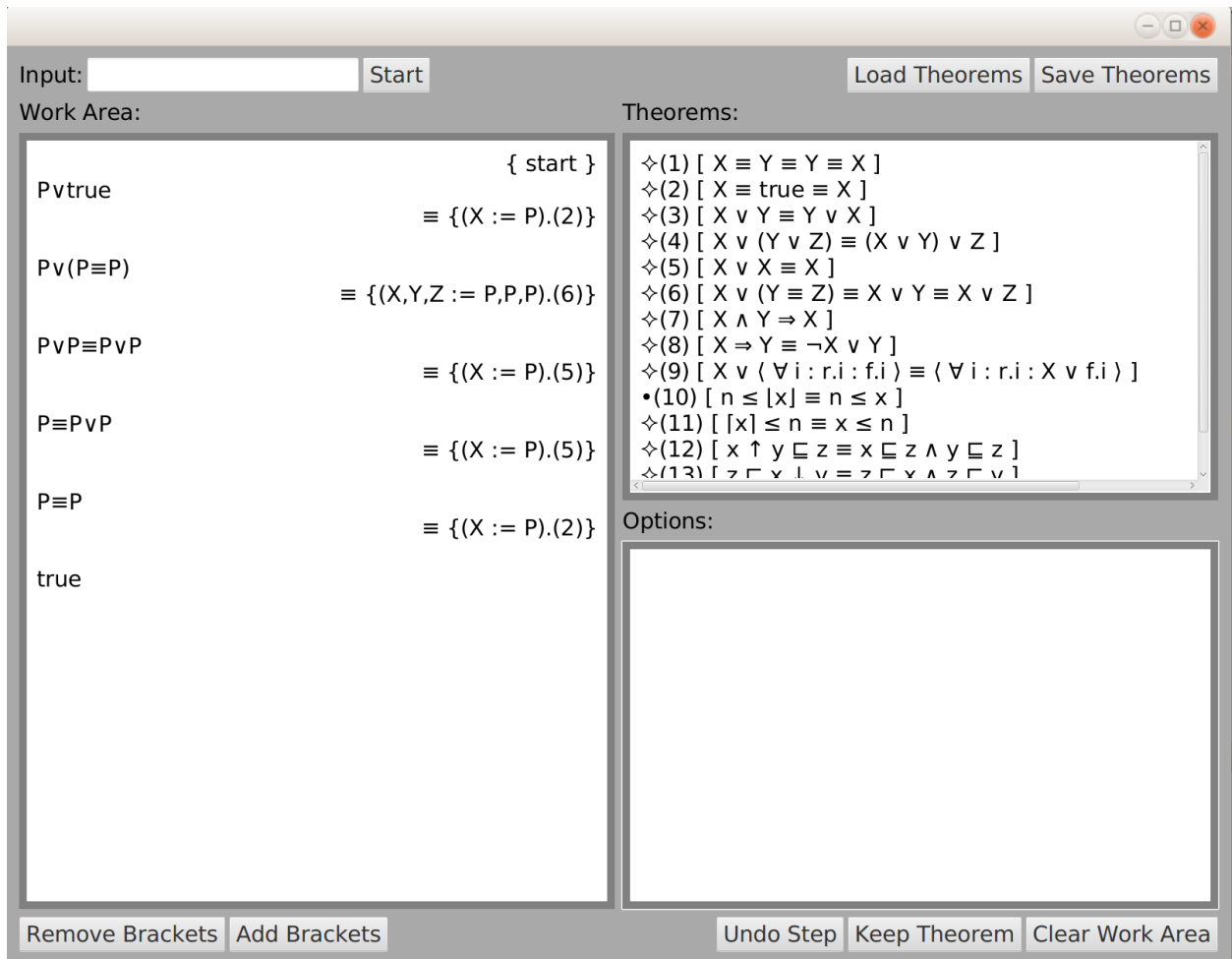
Further functionality allows the user to add and remove brackets where appropriate, undo a step, clear the work area and load or save theorem sets.

The Interface

The interface consists of three distinct areas. The left hand side is referred to as the work area. It is here where the current expression and all steps taken to derive it will be displayed. It is here that a user will select a sub-expression of the current expression as described in step 2 above.

The righthand side of the interface will consist of both an area where a list of numbered theorems are displayed and also an area for replacement options to be displayed. The list of theorems will be made up of loaded axioms as well as theorems that have been previously derived and saved by the user. It is here that a theorem will be chosen as described in step 3 above and the replacement options generated will be displayed in the options area. The user also has the ability to explore a theorem by clicking on it when the work area is clear. This "exploration" shows the theorem's derivation and which steps were taken in order to derive it as well as giving the option to either delete a theorem or continue work on it.

The 3 areas are surrounded by several buttons as well as the input box for generating the starting step of a proof. The buttons are used to access the functionality of the theorem proving assistant.



Functionality Overview

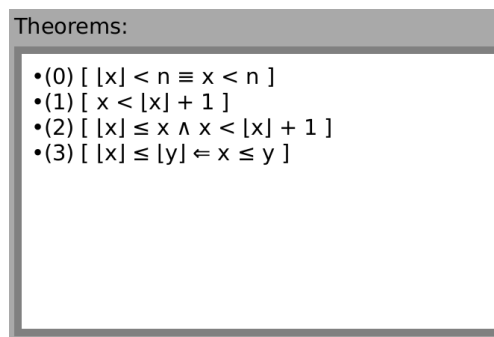
In this section the functionality of the Theorem proving assistant is explained. The steps are demonstrated with varying calculi to illustrate the versatility of the Theorem Proving Assistant.

Creating/Loading a Theorem Set

Theorem files are stored in a JSON format but can be added to or created by writing theorems in a plain text psuedo language. A $*$ or a $-$ is used to indicate whether this theorem should be interpreted as an axiom or not. Each theorem is placed on a separate line and the software will automatically handle their indexes. For example, if the user wants to use boolean theorems relating to the Floor/Ceiling calculus the following would be added to a theorem file.

```
- |_ x _| < n == x < n
- x < |_ x _| + 1
- |_ x _| <= x and x < |_ x _| + 1
- |_ x _| <= |_ y _| <- x <= y
```

After clicking the Load Theorems button and selecting a file the theorems will be loaded into the theorems area.

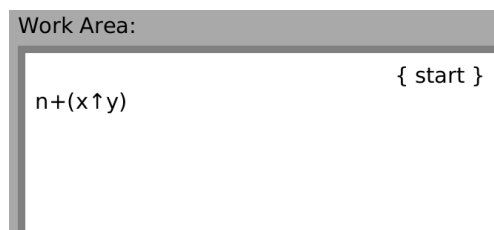


Starting a Proof

To start a proof the user types the starting expression into the input box in plain text. The following example is taken from the Max/Min calculus.

Input:

After clicking Start the input is parsed and presented to the user as the first proof step.



Performing a Proof Step

To perform a proof step it consists of 3 distinct operations. This example demonstrates permuting a boolean term within a quantified expression.

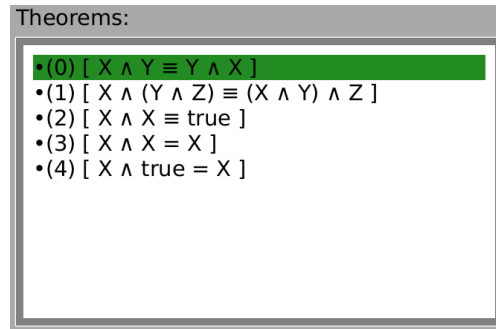
Select A subexpression

To select valid sub expressions the user needs to select the operator around which the expression pivots. This is the lowest precedence operator in the required subexpression. If multiple option are available, clicking multiple times will cycle the selection. Below shows the highlighting of several subexpressions within the current expression.



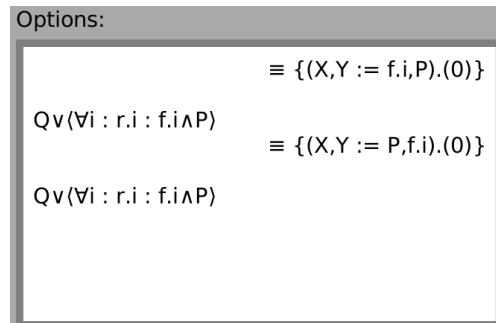
Select A Theorem

After choosing a subexpression the user then needs to choose the theorem that they wish to apply. In this case we wish to commute P and $f.i$ around the \wedge operator so we choose rule (0).

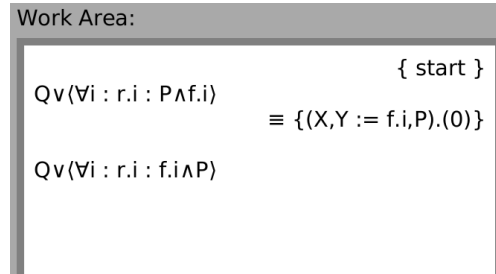


Select An Option

The list of options is automatically generated after clicking a theorem. Each option shows what the new current expression will be along with the hint which informs the user of the assignment and the rule used. In this case, after choosing theorem (0) only two options are available. The both yield the same end result but the assignment of variables in the hint is different.

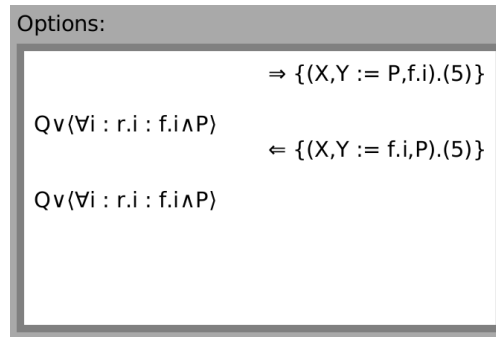


We choose the first option and the Work Area is updated with the new proof step. We are then free to select a subexpression of the new current expression and continue generating new proof steps until a conclusion has been drawn.

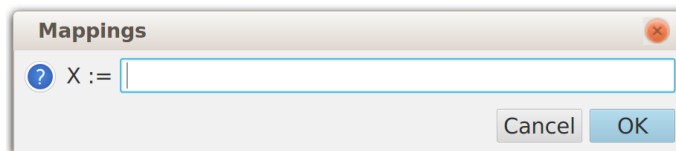


If the user is not satisfied with the options and clicks a different theorem, the software will generate a new list of options. This fast cycling and viewing of the options is the strongest point of the Theorem Proving Assistant. It allows easy and fast explorations of different options during a proof.

There are two points to highlight about the generation of options. Firstly note that the equivalence character is given with the hint, meaning that the current expression and the new generated expression are equivalent. This "transition" character is yielded from the rule. If the rule stated that $[X \wedge Y \Rightarrow Y \wedge X]$ then the transition character would be \Rightarrow . There is also a subtlety taken into consideration where non commutative transition characters such as implication where depending on the side of the rule which is used, the transition character must be pointing the correct direction. Below is the list of options generated from the given hypothetical theorem.

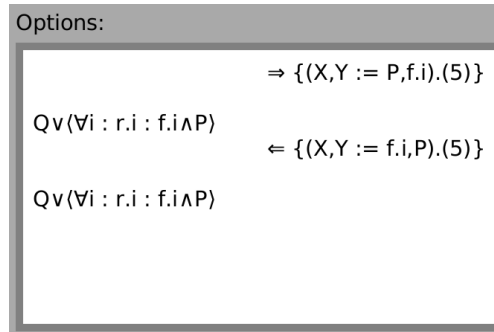


The second point to highlight is regarding unaccounted for Identifiers. Consider the below example where the selection is *true* and the user wishes to use the rule $[X \equiv X \equiv \text{true}]$. It is clear that the replacement is $X \equiv X$ but the replacements $P \equiv P$ and $Q \equiv Q$ are equally valid. Should this case arise the user is prompted with a dialog to enter the desired mapping.

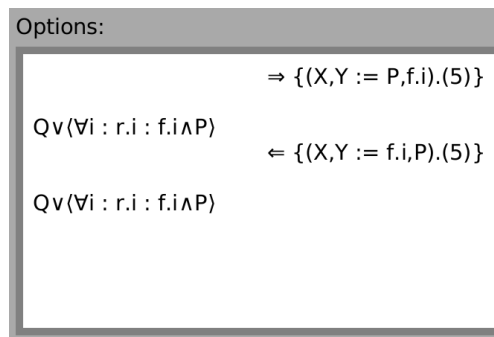


Keeping a Theorem

When a conclusion has been drawn such as the proof of Absorbition.0 $[X \wedge (X \vee Y) \equiv X]$ the user can save this theorem for future use. The Work Area below shows the entire proof.



After clicking the Keeper button the theorem is added to the list of theorems. Note that the equivalence operator (\equiv) is used to join the left and right sides of the theorem. If an operator of higher precedence was used within the proof, such as implication, then that operator would be used to join the two sides.



Saving all Theorems

great

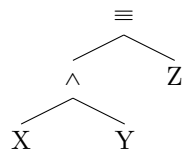
Backend Algorithms

Here I present work completed so far.

Expression Representation

When starting this project the only fact that was clear was the need to not represent expressions as strings. Immediate issues associated with a string based solution are the lack of sense of precedence, the lack of pivots to easily commute around and no easy way to identify the beginning and end of bracketed sections.

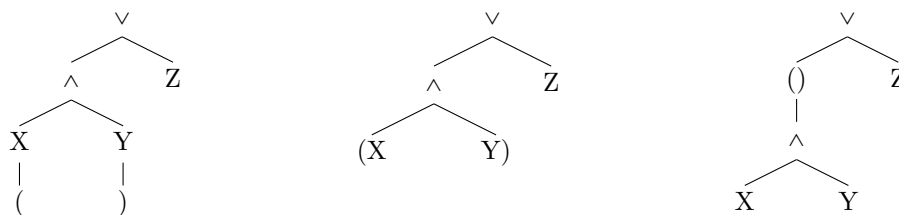
Syntax trees are a commonly used solution [2]. Leaves would be identifiers and nodes operators. Below I demonstrate an example with a simple boolean expression: $X \wedge Y \equiv Z$.



In order to yield the boolean expression from the tree we need only to perform an in-order traversal, printing the leaf or node's identifier or operator as we visit them. As a human we can read the expression from the tree by reading the identifiers and operators from left to right.

Depth is used to indicate precedence. One can see how precedence is maintained as the conjunction operator is at a deeper level than the equivalence. The two operators are commutative and swapping the left and right children of either node will yield an equivalent (in terms of ultimate value) tree.

Bracketing sections proved to be more of an issue. Below I demonstrate several options that were considered with the boolean expression $(X \wedge Y) \vee Z$.



The decision as to which option to use was made for me when I turned my attention the defining a valid substring.

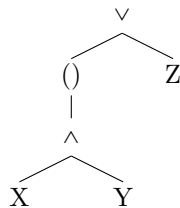
A Valid Sub-expression

A valid sub-expression is a fundamental part of the project. It is what a user will first select in order to carry out a replacement. For a sub-expression to be valid when selecting it we must respect precedence, bracketing and the number of operands associated with an operator. These requirements indicate that maybe a formal grammar will need to be defined but up until a parser is needed I wish to avoid this. I fear that having a grammar at this stage will steer me towards string based solutions. Initially I would like to stick to purely tree based solutions due to the issues associated with string manipulation.

To demonstrate valid and invalid sub-expressions of $X \wedge Y \equiv Z$ I present the table below.

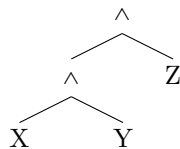
Valid	Invalid
$X \wedge Y$	$Y \equiv Z$
X	$\wedge Y$
Z	$\equiv Z$

Validating the selection of a sub-expression has to be a simple task. After drawing some syntax trees it became clear that any node's subtree is a valid sub-expression. For this reason the right most bracket option was chosen. Any node of that tree can be selected and its subtree is a valid sub-expression. We list the valid sub-expressions of $(X \wedge Y) \vee Z$ beside the tree and the correlation becomes clear.



$(X \wedge Y) \vee Z$
$(X \wedge Y) \vee Z$
$(X \wedge Y)$
$X \wedge Y$
X
Y
Z

Initially this simple approach of using a node's subtree to define a sub-expression appeared comprehensive but when I went to extract all valid sub-expressions of an expression with associative operators I realised this was not possible. We use the expression $X \wedge Y \wedge Z$ to demonstrate this. Consider the following tree representation and list of valid sub-expressions as defined above.



$X \wedge Y \wedge Z$
$X \wedge Y \wedge Z$
$X \wedge Y$
X
Y
Z

$Y \wedge Z$ is a valid sub-expression of $X \wedge Y \wedge Z$ but is not attainable from the above tree in its current state. We need to permute the syntax tree to "re-shuffle" it so $Y \wedge Z$ can exist as a subtree while still maintaining the value of the boolean expression.

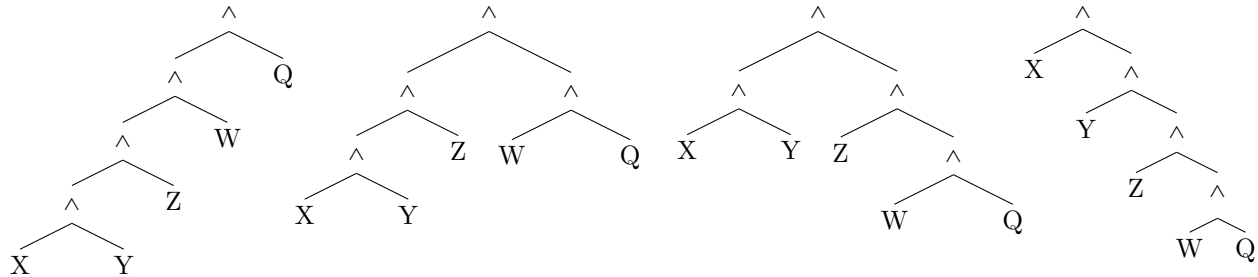
Permutations of a Syntax Tree

In order to achieve this re-shuffling of a tree we need to rely on a tree rotation algorithm called zigging [3]. Performing the zig operation on the deeper conjunction node will rotate the tree clockwise, causing the node to be the new root. X will be the left child of the new root with the previous root as its right child. The old roots right child, Z , persists, and the temporarily orphaned Y becomes Z 's sibling. The following two trees present two permutations of a tree for $X \wedge Y \wedge Z$ attainable by zigging the left or right child of the root.

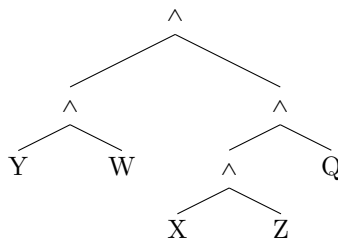


Now by unioning the the set of sub-expressions yielded from the two trees we have a complete set. This simple approach however does not scale. An algorithm combining commuting nodes, zigging nodes and zigging nodes from a depth of two is needed in order yield all valid sub-expressions of any tree. It is at this point that I must introduce the caveat that commutativity is taken for granted. The algorithm will not only yield all sub-expressions permissable by the associativity of the operators, but also those permissable by the commutativity of the operators. Expressions such as $X \wedge Y$ and $Y \wedge X$ will be considered equivalent.

Consider the following series of tree representations of $X \wedge Y \wedge Z \wedge W \wedge Q$ and one can see how the whole tree is being "dragged" through the root node by performing the zig operation on the roots left child.



After each zig if we either do or do not commute the roots children and continue until no new trees are generated we will create every possible permutation. When the algorithm stops we will have yielded all 5! equivalent tree permutations. The following tree is one of them which will be produced at some point during permuting algorithm (I am not going to list all 5! of them!).



Recursively calling the described permute algorithm on the children of the root of each permutation will ultimately yield all valid sub-expressions. When attempting to identify valid sub-expressions of an expression all permutations of that expressions's tree must exist simulatiously; all possible tree arrangements for a given expression must be considered when validating or refuting an operation on an expression.

Matching, Mapping and Replacing

At this point I introduce a new theorem but no longer in terms of X and Y but P and Q.

$$\cdot [P \wedge (P \vee Q) \equiv P] \quad \text{absorbtion0}$$

We consider a state half way through a proof where the user's current expression is $X \wedge (X \vee Y) \equiv X \wedge Y$ and wishes to use absorbtion0 to replace the entire left hand side of the expression with X. The action is documented below with the notation we defined.

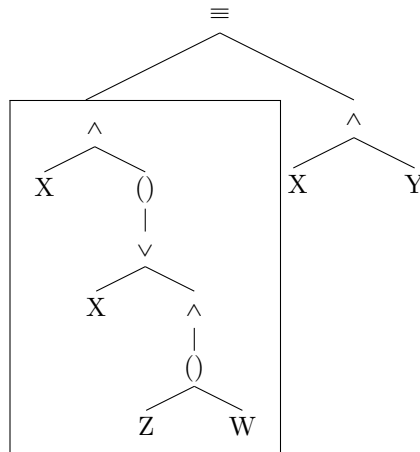
$$\begin{aligned} & X \wedge (X \vee Y) \equiv X \wedge Y \\ = & \quad \{(P, Q := X, Y).(\text{absorbtion0})\} \\ & X \equiv X \wedge Y \end{aligned}$$

As humans we can easily map P to X and Q to Y and do the replacement as it is in our nature to look for patterns and repetition. To design algorithms for a computer to do this is an complex task. To further complicate the matter we change the the boolean identifier Y on the left hand side of the expression to a boolean expression consisting of several operands. We redine the current expression and application of absorbtion0 as follows.

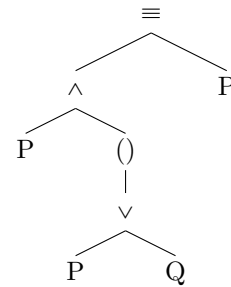
$$\begin{aligned} & X \wedge (X \vee (Z \wedge W)) \equiv X \wedge Y \\ = & \quad \{(P, Q := X, (Z \wedge W)).(\text{absorbtion0})\} \\ & X \equiv X \wedge Y \end{aligned}$$

In looking to match the users selection $(X \wedge (X \vee (Z \wedge W)))$ with a sub-expression of absorbtion0 we must compare it to every valid sub-expression of absorbtion0. Not only that, but we must handle the fact that the boolean identifiers in the rule and current expression are completely different. We start by drawing a tree representation of the current expression with the current expression highlighted and the rule, absorbtion0. Note that I have conveniently chosen to draw the correct permutation the rule. A software program will have to iterate through all permutations in attempts to find matches.

Current Expr:



Absorbtion0:



The matching algorithm first requests all valid sub-expressions of the rule with a root node that was a child of an equivl node and has an operator which matches the root of the selection. In this case, all permutations of the subtree which starts at absorbtion0's single conjunction operator.

We walk each of these subtrees along side the current selection tree checking equivalence at each step. If a discrepancy is found (such as operators that don't match) that subtree is discarded and we examine the

next. During the walk if an identifier is found in the rule's subtree, that identifier is added to a look-up table with the corresponding node from the selection. This lookup table will define the mapping used in the hint.

During the walk of the example trees provided there are three identifiers to be found in the subtree of *absorb0*.

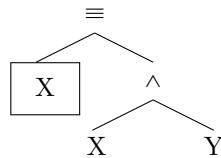
1. On discovery of P (the left child of the subtrees root), it will map directly to the corresponding X in the current expression. $P \rightarrow X$ will be added to the look up table.
2. On discovery of the second P we must be sure that this new mapping we are about to define corresponds with the mapping defined in step 1. If there is a discrepancy this permutation of the subtree of the rule is not valid and thus discarded.
3. On discovery of the identifier Q we note that it does not correspond to another identifier, but a whole expression. That is not a problem and we add $Q \rightarrow (Z \wedge W)$ to the look-up table.

If the walk of any subtree of the rule that is checked completes, then we add that subtree and its look-up table to a list. This list will be the list of possible uses of a rule on a selection. Be aware that there may be multiple uses of a rule on a selection. In the example given the list will contain only one element, the following subtree and lookup table.



To complete the replacement step there are a few small steps to take. None of which pose a large issue. We now need to remove the subtree from the permutation of the rule that contained it. In this case it will leave just the P node. Once we have the rule without the matched subtree we need to walk it and use the lookup table to replace its identifiers with their new nodes. If when walking we encounter an identifier not present in the look-up table we can use any identifier not present in the current expression.

In this example the rule without the matching subtree, P, will be walked and have its node replaced with its counterpart from the lookup table, X. At this point the matching and mapping is complete and we can return to the original expression we were working on and replace the current selection with the new tree (in this case, just an identifier node).



The replacement step has been performed, we know what rule we used and we also know what assignments were made into the rule. We can use this information to generate the needed hint and present the user with the outcome they expect. Here I re-express the replacement step from the start of this section to conclude the calculation of the step.

$$\begin{aligned}
 & X \wedge (X \vee (Z \wedge W)) \equiv X \wedge Y \\
 = & \quad \quad \{(P, Q := X, (Z \wedge W)).(absorb0)\} \\
 & X \equiv X \wedge Y
 \end{aligned}$$

Frontend Algorithms

The Parser

Design Details and Implementation

yada

Tools Used

Java

JavaFX

IntelliJ

Git

Gson

UML Diagrams

It's bleeding HUGE

Testing And Evaluation

yada

Test method used throughout build process

test etst etst

Proving Correctness

:/ (hope)

Conclusion

Progress So Far

At this point of the project I have implemented (in Java) the algorithms described in this report. I have test cases written for each individual component aswell as test cases carrying out processes relying on several components such as finding all matches for a given sub-expression in a given rule. The test cases take no input as all trees are hard coded and they output to the console. All operations must be performed programatically.

It is not a requirement of this report to submit any implemented code but anything written so far is available for viewing on <https://github.com/jj05y/Final-Year-Project-Theorem-Proving-Assitant>. Note that this is a work in progress, attempts to download and run any code at this point will most likely end in heartache.

Next Steps

I next intend on focusing my efforts on two areas.

The GUI

The end result of this project will be a graphical user interface to allow a user to carry out the steps defined in this report. I need to research what is the best way to approach this. At the moment I am considering Java's Swing package or C# forms.

The GUI will need to add extra functionality seperate to the util of the theorem proving assistant such as load/save functionality, an undo stack and a smooth and clear interface.

The Grammar and The Parser

As well as a user having the ability to load a workspace with a set of hard-coded axioms to work with, I would like a user to be able to define their own workspace. For this a grammar and parser would be needed to translate an arbitrary input language into syntax trees. I am yet to give any thought to defining a grammar or the parser which will suit it.

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