

# Formal Verification of Boolean Unification Algorithms with Coq

Spyridon Antonatos, Matthew McDonald, Dylan  
Richardson, and Joseph St. Pierre

A Major Qualifying Project  
Submitted to the Faculty of  
Worcester Polytechnic Institute  
in partial fulfillment of the requirements for the  
Degree in Bachelor of Science in  
Computer Science



Computer Science  
Worcester Polytechnic Institute  
Advised by Professor Daniel Dougherty  
April 25, 2019

# Contents

<b>1</b>	<b>Library B_Unification.intro</b>	<b>5</b>
1.1	Introduction . . . . .	5
1.2	Formal Verification . . . . .	5
1.2.1	Proof Assistants . . . . .	6
1.2.2	Verifying Systems . . . . .	6
1.2.3	Verifying Theories . . . . .	6
1.3	Unification . . . . .	7
1.3.1	Syntatic Unification . . . . .	8
1.3.2	Semantic Unification . . . . .	8
1.3.3	Boolean Unification . . . . .	9
1.4	Importance . . . . .	9
1.5	Development . . . . .	10
1.5.1	Data Structures . . . . .	10
1.5.2	Algorithms . . . . .	11
<b>2</b>	<b>Library B_Unification.terms</b>	<b>13</b>
2.1	Introduction . . . . .	13
2.2	Terms . . . . .	13
2.2.1	Definitions . . . . .	13
2.2.2	Axioms . . . . .	14
2.2.3	Lemmas . . . . .	16
2.3	Variable Sets . . . . .	17
2.3.1	Definitions . . . . .	17
2.3.2	Lemmas . . . . .	19
2.3.3	Examples . . . . .	20
2.4	Ground Terms . . . . .	21
2.4.1	Definitions . . . . .	21
2.4.2	Lemmas . . . . .	21
2.4.3	Examples . . . . .	22
2.5	Substitutions . . . . .	23
2.5.1	Definitions . . . . .	23
2.5.2	Lemmas . . . . .	24
2.5.3	Examples . . . . .	29

2.5.4	Auxillary Definitions for Substitutions and Terms . . . . .	29
2.6	Unification . . . . .	31
2.7	Most General Unifier . . . . .	33
2.8	Auxilliary Computational Operations and Simplifications . . . . .	34
<b>3</b>	<b>Library B_Unification.lowenheim_formula</b>	<b>53</b>
3.1	Introduction . . . . .	53
3.2	Lowenheim's Builder . . . . .	53
3.3	Lowenheim's Algorithm . . . . .	54
3.3.1	Auxillary Functions and Definitions . . . . .	54
3.4	Lowenheim's Functions Testing . . . . .	55
<b>4</b>	<b>Library B_Unification.lowenheim_proof</b>	<b>56</b>
4.1	Introduction . . . . .	56
4.2	Auxillary Declarations and Their Lemmas Useful For the Final Proofs . . . .	56
4.3	Proof That Lownheim's Algorithm Unifies a Given Term . . . . .	59
4.4	Proof That Lownheim's Algorithm Produces a Most General Unifier . . . . .	63
4.4.1	Proof That Lownheim's Algorithm Produces a Reproductive Unifier .	64
4.4.2	Proof That Lowenheim's Algorithm Produces a Most General Unifier	67
4.5	Proof of Correctness of Lowenheim_Main . . . . .	67
4.5.1	Utilities . . . . .	67
4.5.2	Intermediate Lemmas . . . . .	75
4.5.3	Gluing Everything Together For the Final Proof . . . . .	80
<b>5</b>	<b>Library B_Unification.list_util</b>	<b>82</b>
5.1	Introduction . . . . .	82
5.2	Comparisons Between Lists . . . . .	83
5.3	Extensions to the Standard Library . . . . .	85
5.3.1	Facts about <b>ln</b> . . . . .	85
5.3.2	Facts about <b>incl</b> . . . . .	86
5.3.3	Facts about <b>count_occ</b> . . . . .	87
5.3.4	Facts about <b>concat</b> . . . . .	88
5.3.5	Facts about <b>Forall</b> and <b>existsb</b> . . . . .	90
5.3.6	Facts about <b>remove</b> . . . . .	91
5.3.7	Facts about <b>nodup</b> and <b>NoDup</b> . . . . .	93
5.3.8	Facts about <b>partition</b> . . . . .	97
5.4	New Functions over Lists . . . . .	101
5.4.1	Distributing two Lists: <b>distribute</b> . . . . .	101
5.4.2	Cancelling out Repeated Elements: <b>nodup_cancel</b> . . . . .	101
5.4.3	Comparing Parity of Lists: <b>parity_match</b> . . . . .	109
5.5	Combining <b>nodup_cancel</b> and Other Functions . . . . .	114
5.5.1	Using <b>nodup_cancel</b> over <b>map</b> . . . . .	114
5.5.2	Using <b>nodup_cancel</b> over <b>concat map</b> . . . . .	117

<b>6</b>	<b>Library B_Unification.poly</b>	<b>122</b>
6.1	Monomials and Polynomials . . . . .	122
6.1.1	Data Type Definitions . . . . .	122
6.1.2	Comparisons of monomials and polynomials . . . . .	123
6.1.3	Stronger Definitions . . . . .	124
6.2	Sorted Lists and Sorting . . . . .	127
6.2.1	Sorting Lists . . . . .	127
6.2.2	Sorting and Permutations . . . . .	130
6.3	Repairing Invalid Monomials & Polynomials . . . . .	134
6.3.1	Converting Between <i>lt</i> and <i>le</i> . . . . .	134
6.3.2	Defining the Repair Functions . . . . .	138
6.3.3	Facts about <code>make_mono</code> . . . . .	139
6.3.4	Facts about <code>make_poly</code> . . . . .	141
6.4	Proving Functions “Pointless” . . . . .	142
6.4.1	Working with <code>sort</code> Functions . . . . .	142
6.4.2	Working with <code>make_mono</code> . . . . .	143
6.4.3	Working with <code>make_poly</code> . . . . .	144
6.5	Polynomial Arithmetic . . . . .	146
6.6	Proving the 10 <i>B</i> -unification Axioms . . . . .	150
6.6.1	Axiom 1: Additive Inverse . . . . .	150
6.6.2	Axiom 2: Additive Identity . . . . .	150
6.6.3	Axiom 3: Multiplicative Identity - 1 . . . . .	151
6.6.4	Axiom 4: Multiplicative Inverse . . . . .	151
6.6.5	Axiom 5: Commutativity of Addition . . . . .	151
6.6.6	Axiom 6: Associativity of Addition . . . . .	151
6.6.7	Axiom 7: Commutativity of Multiplication . . . . .	152
6.6.8	Axiom 8: Associativity of Multiplication . . . . .	153
6.6.9	Axiom 9: Multiplicative Identity - Self . . . . .	156
6.6.10	Axiom 10: Distribution . . . . .	158
6.7	Other Facts About Polynomials . . . . .	159
6.7.1	More Arithmetic . . . . .	160
6.7.2	Reasoning about Variables . . . . .	161
6.7.3	Partition with Polynomials . . . . .	162
6.7.4	Multiplication and Remove . . . . .	163
<b>7</b>	<b>Library B_Unification.poly_unif</b>	<b>170</b>
7.1	Introduction . . . . .	170
7.2	Substitution Definitions . . . . .	170
7.3	Distribution Over Arithmetic Operators . . . . .	173
7.4	Unifiable Definitions . . . . .	179

<b>8</b>	<b>Library <code>B_Unification.sve</code></b>	<b>182</b>
8.1	Introduction . . . . .	182
8.2	Eliminating Variables . . . . .	182
8.3	Building Substitutions . . . . .	190
8.4	Recursive Algorithm . . . . .	194
8.5	Correctness . . . . .	194
	<b>Bibliography</b>	<b>197</b>

# Chapter 1

## Library B\_Unification.intro

### 1.1 Introduction

In the field of computer science, one problem of significance is that of equational unification; namely, the finding of solutions to a given set of equations with respect to a set of equational axioms. While there are several variants of equational unification, for the purposes of this paper we are going to limit our scope to that of Boolean unification, which deals with the finding of unifiers for the equations defining Boolean rings. As any problem space would imply, there exists a great deal of research in the formal verification of unification algorithms [2]; our research focused on two of these algorithms: Lowenheim's formula and successive variable elimination. To conduct our research, we utilized the Coq proof assistant to create formal specifications of both of these algorithms' behaviors in addition to proving their correctness. While proofs for both of these algorithms already exist, prior to the writing of this paper, no formal treatment using a proof assistant such as Coq had been undertaken, so it is hoped that our efforts provide yet another guarantee for the correctness of these respective algorithms.

Due to the differences in the innate nature of Lowenheim's formula compared to that of successive variable elimination, our project was divided into two separate developments, each approaching their respective goals from a different direction. The primary distinction between these two treatments comes down to their representations of equations. The Lowenheim's formula development uses a more straightforward, term-based representation of equations while the successive variable elimination development opts to represent equations solely in their polynomial forms. Fortunately, due to the fact that every term has a unique polynomial representation, these two formats for representing equations are mathematically equivalent to one another.

### 1.2 Formal Verification

Formal verification is the term used to describe the act of verifying (or disproving) the correctness of software and hardware systems or theories. Formal verification consists of a

set of techniques that perform static analysis on the behavior of a system, or the correctness of a theory. It differs from dynamic analysis that uses simulation to evaluate the correctness of a system.

More simply stated, formal verification is the process of examining whether a system or a theory “does what it is supposed to do.” If it is a system, then scientists formally verify that it satisfies its design requirements. Formal verification is also different to testing. Software testing is trying to detect “bugs” specific errors and requirements in the system, whereas verification acts as a general safeguard that the system is always error-free. As Edsger Dijkstra stated, testing can be used to show the presence of bugs, but never to show their absence. If it is a theory, scientists formally verify the correctness of the theory by formulating its proof using a formal language, axioms and inference rules.

Formal verification is used because it does not have to evaluate every possible case or state to determine if a system or theory meets all the preset logical conditions and requirements. Moreover, as design and software systems sizes have increased (along with their simulation times), verification teams have been looking for alternative methods of proving or disproving the correctness of a system in order to reduce the required time to perform a correctness check or evaluation.

### **1.2.1 Proof Assistants**

A proof assistant is a software tool that is used to formulate and prove or disprove theorems in computer science or mathematical logic. They are also called interactive theorem provers and they may also involve some type of proof and text editor that the user can use to form, prove, and define theorems, lemmas, functions, etc. They facilitate that process by allowing the user to search definitions, terms and even provide some kind of guidance during the formulation or proof of a theorem.

### **1.2.2 Verifying Systems**

Formal verification is used to verify the correctness of software or hardware systems. When used to verify systems, formal verification can be thought as a mathematical proof of the correctness of a design with respect to a formal specification. The actual system is represented by a formal model and then the formal verification happens on the model, based on the required specifications of the system. Unlike testing, formal verification is exhaustive and improves the understanding of a system. However, it is difficult to make for real-world systems, time consuming and only as reliable as the actual model.

### **1.2.3 Verifying Theories**

Formal verification is also used in to prove theorems. These theorems could be related to a computing system or just pure mathematical abstract theorems. As in proving systems, when proving theorems one also needs a formal logic to formulate the theorem and prove it. A formal logic consists of a formal language to express the theorems, a collection of

formulas called axioms and inference rules to derive new axioms based on existing ones. A theorem to be proven could be in a logical form, like DeMorgan's Law or it could in another mathematical area; in trigonometry for example, it could be useful to prove that  $\sin(x + y) = \sin(x) * \cos(y) + \cos(x) * \sin(y)$ , formally, because that proof could be used as building block in a more complex system. Sometimes proving the correctness of a real world systems boils down to verifying mathematical proofs like the previous one, so the two approaches are often linked together.

## 1.3 Unification

Before defining what unification is, there is some terminology to understand.

**Definition 1.3.1** A *term* is either a variable or a function applied to terms [1, p. 34].

By this definition, a constant term is just a nullary function.

**Definition 1.3.2** A *variable* is a symbol capable of taking on the value of any term.

An example of a term is  $f(a, x)$ , where  $f$  is a function of two arguments,  $a$  is a constant, and  $x$  is a variable.

**Definition 1.3.3** A term is *ground* if no variables occur in it [1, p. 37].

The last example is not a ground term but  $f(a, a)$  would be.

**Definition 1.3.4** A *substitution* is a mapping from variables to terms.

**Definition 1.3.5** The *domain* of a substitution is the set of variables that do not get mapped to themselves.

**Definition 1.3.6** The *range* is the set of terms that are mapped to by the domain [1, p. 37].

It is common for substitutions to be referred to as mappings from terms to terms. A substitution  $\sigma$  can be extended to this form by defining  $\hat{\sigma}(s)$  for two cases of  $s$ . If  $s$  is a variable, then  $\hat{\sigma}(s) := \sigma(s)$ . If  $s$  is a function  $f(s_1, \dots, s_n)$ , then  $\hat{\sigma}(s) := f(\hat{\sigma}(s_1), \dots, \hat{\sigma}(s_n))$  [1, p. 38].

Unification is the process of solving a set of equations between two terms.

**Definition 1.3.7** The set of equations to solve is referred to as a *unification problem* [1, p. 71].

The process of solving one of these problems can be classified by the set of terms considered and the equality of any two terms. The latter property is what distinguishes two broad groups of algorithms, namely syntactic and semantic unification.

**Definition 1.3.8** If two terms are only considered equal if they are identical, then the unification is *syntactic* [1, p. 71].



**Definition 1.3.9** *If two terms are equal with respect to an equational theory, then the unification is **semantic** [1, p. 224].*

For example, the terms  $x * y$  and  $y * x$  are not syntactically equal, but they are semantically equal modulo commutativity of multiplication.

The goal of unification is to find the *best* solution to a problem, which formally means to produce a most general unifier of the problem. The next four definitions should make this clearer.

**Definition 1.3.10** *A substitution  $\sigma$  **unifies** an equation  $s \stackrel{?}{=} t$  if applying  $\sigma$  to both sides makes them equal  $\sigma(s) = \sigma(t)$ .*

**Definition 1.3.11** *If  $\sigma$  unifies every equation in the problem  $S$ , we call  $\sigma$  a **solution** or **unifier** of  $S$  [1, p. 71].*

**Definition 1.3.12** *A substitution  $\sigma$  is **more general** than  $\sigma'$  if there exists a third substitution  $\delta$  such that  $\sigma'(u) = \delta(\sigma(u))$  for any term  $u$ .*

**Definition 1.3.13** *A substitution is a **most general unifier** or **mg** of a problem if it is more general than every other solution to the problem [1, p. 71].*

It should be noted that although solvable Boolean unification problems have a single mgu, semantic unification problems in general can have zero, multiple, or infinitely many mgu's [1, p. 226].

### 1.3.1 Syntactic Unification

This is the simplest version of unification. It is a special case of  $E$ -unification where  $E = \emptyset$ . For two terms to be considered equal they must be identical. Problems of this kind can be solved by repeated transformations until the solution pops out similar to solving a linear system by Gaussian elimination [1, p. 73]. One of the most notable applications of syntactic unification is the Hindley-Milner type system used in functional programming languages like ML [4]. More complicated type systems such as the one used by Coq require more complicated versions of unification (e.g. higher-order unification) [3].

### 1.3.2 Semantic Unification

This kind of unification involves an equational theory. Given a set of identities  $E$ , we write that two terms  $s$  and  $t$  are equal with regards to  $E$  as  $s \approx_E t$ . This means that identities of  $E$  can be applied to  $s$  as  $s'$  and  $t$  as  $t'$  in some way to make them syntactically equal,  $s' = t'$ . As an example, let  $C$  be the set  $\{f(x, y) \approx f(y, x)\}$ . This theory axiomatizes the commutativity of the function  $f$ . Knowing this, the problem  $\{f(x, f(a, y)) \stackrel{?}{=} f(f(c, a), b)\}$  is unified by the substitution  $\{x \mapsto b, y \mapsto c\}$  since  $f(b, f(a, c)) \approx_C f(f(c, a), b)$ . In general, for an certain  $E$ , the problem of  $E$ -unification is undecidable [1, p. 71]. An example would be unification modulo ring theory.

### 1.3.3 Boolean Unification

In this paper, we focus on unification modulo Boolean ring theory, also referred to as  $B$ -unification. The allowed terms in this theory are the constants 0 and 1 and binary functions  $+$  and  $*$ . The set of identities  $B$  is defined as follows:

$$\left\{ \begin{array}{ll} x + y \approx y + x, & x * y \approx y * x, \\ (x + y) + z \approx x + (y + z), & (x * y) * z \approx x * (y * z), \\ x + x \approx 0, & x * x \approx x, \\ 0 + x \approx x, & 0 * x \approx 0, \\ x * (y + z) \approx (x * y) + (x * z), & 1 * x \approx x \end{array} \right\}$$

[1, p. 250]. This set is equivalent to the axioms of ring theory with the addition of  $x + x \approx_B 0$  and  $x * x \approx_B x$ .

Although a unification problem is a set of equations between two terms, we will now show informally that a  $B$ -unification problem can be viewed as a single equation  $t \overset{?}{\approx}_B 0$ . Given a problem of the form

$$\{s_1 \overset{?}{\approx}_B t_1, \dots, s_n \overset{?}{\approx}_B t_n\},$$

we can transform it into

$$\{s_1 + t_1 \overset{?}{\approx}_B 0, \dots, s_n + t_n \overset{?}{\approx}_B 0\}$$

using a simple fact. The equation  $s \approx_B t$  is equivalent to  $s + t \approx_B 0$  since adding  $t$  to both sides of the equation turns the right hand side into  $t + t$  which simplifies to 0. Then, given a problem

$$\{t_1 \overset{?}{\approx}_B 0, \dots, t_n \overset{?}{\approx}_B 0\},$$

we can transform it into

$$\{(t_1 + 1) * \dots * (t_n + 1) \overset{?}{\approx}_B 1\}.$$

Unifying both of these sets is equivalent because if any  $t_1, \dots, t_n$  is 1 the problem is not unifiable. Otherwise, if every  $t_1, \dots, t_n$  can be made to equal 0, then both problems will be solved.

## 1.4 Importance

Given that the emergence of proof assistance software is still in its infancy relative to the traditional methods of theorem proving, it would be a disservice for us to not establish the

importance of this technology and its implications for the future of mathematics. Unlike in years past, where typos or hard to discover edge cases could derail the developments of sound theorems, proof assistants now guarantee through their properties of verification that any development verified by them is free from such lapses in logic on account of the natural failings of the human mind. Additionally, due to the adoption of a well-defined shared language, many of the ambiguities naturally present in the exchange of mathematical ideas between colleagues are mitigated, leading to a smoother learning curve for newcomers trying to understand the nuts and bolts of a complex theorem. The end result of these phenomenon is a faster iterative development cycle for mathematicians as they now can spend more time on proving things and building off of the work of others since they no longer need to devote as much of their efforts towards verifying the correctness of the theorems they are operating across.

Bearing this in mind, it should come as no surprise that there is a utility in going back to older proofs that have never been verified by a proof assistant and redeveloping them for the purposes of ensuring their correctness. If the theorem is truly sound, it stands to reason that any additional rigorous scrutiny would only serve to bolster the credibility of its claims, and conversely, if the theorem is not sound, it is a benefit to the academic community at large to be made aware of its shortcomings. Therefore, for these reasons we set out to formally verify two algorithms across Boolean Unification.

## 1.5 Development

There are many different approaches that one could take to go about formalizing a proof of Boolean Unification algorithms, each with their own challenges. For this development, we have opted to base our work on chapter 10, *Equational Unification*, in *Term Rewriting and All That* by Franz Baader and Tobias Nipkow. Specifically, section 10.4, titled *Boolean Unification*, details Boolean rings, data structures to represent them, and two algorithms to perform unification in Boolean rings.

We chose to implement two data structures for representing the terms of a Boolean unification problem, and two algorithms for performing unification. The two data structures chosen are an inductive Term type and lists of lists representing polynomial-form terms. The two algorithms are Lowenheim’s formula and Successive Variable Elimination.

### 1.5.1 Data Structures

The data structure used to represent a Boolean unification problem completely changes the shape of both the unification algorithm and the proof of correctness, and is therefore a very important decision. For this development, we have selected two different representations of Boolean rings first as a “Term” inductive type, and then as lists of lists representing terms in polynomial form.

The Term inductive type, used in the proof of Lowenheim’s algorithm, is very simple and rather intuitive – a term in a Boolean ring is one of 5 things:

- The number 0
- The number 1
- A variable
- Two terms added together
- Two terms multiplied together

In our development, variables are represented as natural numbers.

After defining terms like this, it is necessary to define a new equality relation, referred to as term equivalence, for comparing terms. With the term equivalence relation defined, it is easy to define ten axioms enabling the ten identities that hold true over terms in Boolean rings.

The inductive representation of terms in a Boolean ring and unification over these terms are defined in the file *terms.v*.

The second representation, used in the proof of successive variable elimination, uses lists of lists of variables to represent terms in polynomial form. A monomial is a list of distinct variables multiplied together. A polynomial, then, is a list of distinct monomials added together. Variables are represented the same way, as natural numbers. The terms 0 and 1 are represented as the empty polynomial and the polynomial containing only the empty monomial, respectively.

The interesting part of the polynomial representation is how the ten identities are implemented. Rather than writing axioms enabling these transformations, we chose to implement the addition and multiplication operations in such a way to ensure these rules hold true, as described in *Term Rewriting*.

Addition is performed by cancelling out all repeated occurrences of monomials in the result of appending the two lists together (i.e.,  $x + x = 0$ ). This is equivalent to the symmetric difference in set theory, keeping only the terms that are in either one list or the other (but not both). Multiplication is slightly more complicated. The product of two polynomials is the result of multiplying all combinations of monomials in the two polynomials and removing all repeated monomials. The product of two monomials is the result of keeping only one copy of each repeated variable after appending the two together.

By defining the functions like this, and maintaining that the lists are sorted with no duplicates, we ensure that all 10 rules hold over the standard coq equivalence function. This of course has its own benefits and drawbacks, but lent itself better to the nature of successive variable elimination.

The polynomial representation is defined in the file *poly.v*. Unification over these polynomials is defined in *poly-unif.v*.

## 1.5.2 Algorithms

For unification algorithms, we once again followed the work laid out in *Term Rewriting and All That* and implemented both Lowenheim's algorithm and successive variable elimination.

The first solution, Lowenheim's algorithm, is built on top of the term inductive type. Lowenheim's is based on the idea that the Lowenheim formula can take a ground unifier of a Boolean unification problem and turn it into a most general unifier. The algorithm then of course first requires finding a ground solution, accomplished through brute force, which is then passed through the formula to create a most general unifier. Lowenheim's algorithm is implemented in the file *lowenheim.v*, and the proof of correctness is in *lowenheim\_proof.v*.

The second algorithm, successive variable elimination, is built on top of the list-of-list polynomial approach. Successive variable elimination is built on the idea that by factoring variables out of the equation one-by-one, we can eventually reach the identity unifier. This unifier can then be built up with the variables that were previously eliminated until a most general unifier for the original unification problem is achieved. Successive variable elimination and its proof of correctness are both in *sve.v*.

# Chapter 2

## Library B\_Unification.terms

```
Require Import Bool.
Require Import Omega.
Require Import EqNat.
Require Import List.
Require Import Setoid.
Import ListNotations.
```

### 2.1 Introduction

In order for any proofs to be constructed in Coq, we need to formally define the logic and data across which said proofs will operate. Since the heart of our analysis is concerned with the unification of Boolean equations, it stands to reason that we should articulate precisely how algebra functions with respect to Boolean rings. To attain this, we shall formalize what an equation looks like, how it can be composed inductively, and also how substitutions behave when applied to equations.

### 2.2 Terms

#### 2.2.1 Definitions

We shall now begin describing the rules of Boolean arithmetic as well as the nature of Boolean equations. For simplicity's sake, from now on we shall be referring to equations as terms.

**Definition** var := **nat**.

A *term*, as has already been previously described, is now inductively declared to hold either a constant value, a single variable, a sum of terms, or a product of terms.

```
Inductive term: Type :=
| T0 : term
| T1 : term
```

```

| VAR : var → term
| SUM : term → term → term
| PRODUCT : term → term → term.

```

For convenience's sake, we define some shorthanded notation for readability.

Implicit Types  $x\ y\ z : \text{term}$ .

Implicit Types  $n\ m : \text{var}$ .

Notation " $x + y$ " := (SUM  $x\ y$ ) (at level 50, left associativity).

Notation " $x * y$ " := (PRODUCT  $x\ y$ ) (at level 40, left associativity).

## 2.2.2 Axioms

Now that we have informed Coq on the nature of what a term is, it is now time to propose a set of axioms that will articulate exactly how algebra behaves across Boolean rings. This is a requirement since the very act of unifying an equation is intimately related to solving it algebraically. Each of the axioms proposed below describe the rules of Boolean algebra precisely and in an unambiguous manner. None of these should come as a surprise to the reader; however, if one is not familiar with this form of logic, the rules regarding the summation and multiplication of identical terms might pose as a source of confusion.

For reasons of keeping Coq's internal logic consistent, we roll our own custom equivalence relation as opposed to simply using " $=$ ". This will provide a surefire way to avoid any odd errors from later cropping up in our proofs. Of course, by doing this we introduce some implications that we will need to address later.

Parameter  $eqv : \text{term} \rightarrow \text{term} \rightarrow \text{Prop}$ .

Here we introduce some special notation for term equivalence

Infix " $==$ " :=  $eqv$  (at level 70).

Below is the set of fundamental axioms concerning the equivalence " $==$ " relation. They form the boolean ring (or system) on which Lowenheim's formula and proof are developed.

Most of these axioms will appear familiar to anyone; however, certain ones such as the summation of two identical terms are true only across Boolean rings and as such might appear strange at first glance.

Axiom  $sum\_comm : \forall\ x\ y, x + y == y + x$ .

Axiom  $sum\_assoc : \forall\ x\ y\ z, (x + y) + z == x + (y + z)$ .

Axiom  $sum\_id : \forall\ x, T0 + x == x$ .

Across boolean rings, the summation of two terms will always be 0 because there are only two elements in the ring: 0 and 1. For this reason, the mapping of  $1 + 1$  has nowhere else to go besides 0.

Axiom  $sum\_x\_x : \forall\ x, x + x == T0$ .

Axiom  $mul\_comm : \forall\ x\ y, x \times y == y \times x$ .

Axiom *mul\_assoc* :  $\forall x y z, (x \times y) \times z == x \times (y \times z).$

Across boolean rings, the multiplication of two identical terms will always be the same as just having one instance of said term. This is because  $0 * 0 = 0$  and  $1 * 1 = 1$  as one would expect normally.

Axiom *mul\_x\_x* :  $\forall x, x \times x == x.$

Axiom *mul\_T0\_x* :  $\forall x, T0 \times x == T0.$

Axiom *mul\_id* :  $\forall x, T1 \times x == x.$

Axiom *distr* :  $\forall x y z, x \times (y + z) == (x \times y) + (x \times z).$

Any axioms beyond this point of the development are not considered part of the “fundamental axiom system”, but they still need to exist for the development and proofs to hold.

Across all equations, adding an expression to both sides does not break the equivalence of the relation. Axiom *term\_sum\_symmetric* :

$\forall x y z, x == y \leftrightarrow x + z == y + z.$

Axiom *refl\_comm* :

$\forall t1 t2, t1 == t2 \rightarrow t2 == t1.$

Axiom *T1\_not\_equiv\_T0* :

$\sim (T1 == T0).$

Hint Resolve *sum\_comm sum\_assoc sum\_x\_x sum\_id distr*  
*mul\_comm mul\_assoc mul\_x\_x mul\_T0\_x mul\_id.*

Now that the core axioms have been taken care of, we need to handle the implications posed by our custom equivalence relation. Below we inform Coq of the behavior of our equivalence relation with respect to reflexivity, symmetry, and transitivity in order to allow for rewrites during the construction of proofs operating across our new equivalence relation.

Axiom *eqv\_ref* : **Reflexive** *eqv*.

Axiom *eqv\_sym* : **Symmetric** *eqv*.

Axiom *eqv\_trans* : **Transitive** *eqv*.

Add *Parametric Relation* : **term** *eqv*  
 reflexivity proved by @*eqv\_ref*  
 symmetry proved by @*eqv\_sym*  
 transitivity proved by @*eqv\_trans*  
 as *eq\_set\_rel*.

Axiom *SUM\_compat* :

$\forall x x', x == x' \rightarrow$   
 $\forall y y', y == y' \rightarrow$   
 $(x + y) == (x' + y').$

Axiom *PRODUCT\_compat* :

$\forall x x', x == x' \rightarrow$



$$\forall y \ y', y == y' \rightarrow (x \times y) == (x' \times y').$$

Add *Parametric Morphism* : SUM with  
signature  $eqv ==> eqv ==> eqv$  as *SUM\_mor*.

Proof.

exact *SUM\_compat*.

Qed.

Add *Parametric Morphism* : PRODUCT with  
signature  $eqv ==> eqv ==> eqv$  as *PRODUCT\_mor*.

Proof.

exact *PRODUCT\_compat*.

Qed.

Hint Resolve *eqv\_ref eqv\_sym eqv\_trans SUM\_compat PRODUCT\_compat*.

### 2.2.3 Lemmas

Since Coq now understands the basics of Boolean algebra, it serves as a good exercise for us to generate some further rules using Coq's proving systems. By doing this, not only do we gain some additional tools that will become handy later down the road, but we also test whether our axioms are behaving as we would like them to.

Lemma *mul\_x\_x\_plus\_T1* :

$$\forall x, x \times (x + T1) == T0.$$

Proof.

intros. rewrite *distr*. rewrite *mul\_x\_x*. rewrite *mul\_comm*.  
rewrite *mul\_id*. apply *sum\_x\_x*.

Qed.

Lemma *x\_equal\_y\_x\_plus\_y* :

$$\forall x \ y, x == y \leftrightarrow x + y == T0.$$

Proof.

intros. split.  
- intros. rewrite *H*. rewrite *sum\_x\_x*. reflexivity.  
- intros. rewrite *term\_sum\_symmetric* with (*y* := *y*) (*z* := *y*). rewrite *sum\_x\_x*.  
apply *H*.

Qed.

Hint Resolve *mul\_x\_x\_plus\_T1 x\_equal\_y\_x\_plus\_y*.

These lemmas just serve to make certain rewrites regarding the core axioms less tedious to write. While one could certainly argue that they should be formulated as axioms and not lemmas due to their triviality, being pedantic is a good exercise.

Lemma *sum\_id\_sym* :

$$\forall x, x + T0 == x.$$

```

Proof.
  intros. rewrite sum_comm. apply sum_id.
Qed.

Lemma mul_id_sym :
   $\forall x, x \times T1 == x$ .
Proof.
  intros. rewrite mul_comm. apply mul_id.
Qed.

Lemma mul_T0_x_sym :
   $\forall x, x \times T0 == T0$ .
Proof.
  intros. rewrite mul_comm. apply mul_T0_x.
Qed.

Lemma sum_assoc_opp :
   $\forall x\ y\ z, x + (y + z) == (x + y) + z$ .
Proof.
  intros. rewrite sum_assoc. reflexivity.
Qed.

Lemma mul_assoc_opp :
   $\forall x\ y\ z, x \times (y \times z) == (x \times y) \times z$ .
Proof.
  intros. rewrite mul_assoc. reflexivity.
Qed.

Lemma distr_opp :
   $\forall x\ y\ z, x \times y + x \times z == x \times (y + z)$ .
Proof.
  intros. rewrite distr. reflexivity.
Qed.

```

## 2.3 Variable Sets

Now that the underlying behavior concerning Boolean algebra has been properly articulated to Coq, it is now time to begin formalizing the logic surrounding our meta reasoning of Boolean equations and systems. While there are certainly several approaches to begin this process, we thought it best to ease into things through formalizing the notion of a set of variables present in an equation.

### 2.3.1 Definitions

We now define a *variable set* to be precisely a list of variables; additionally, we include several functions for including and excluding variables from these variable sets. Furthermore, since

uniqueness is not a property guaranteed by Coq lists and it has the potential to be desirable, we define a function that consumes a variable set and removes duplicate entries from it. For convenience, we also provide several examples to demonstrate the functionalities of these new definitions.

Here is a definition of the new type to represent a list (set) of variables (natural numbers).

Definition `var_set` := `list` `var`.

Implicit Type `vars`: `var_set`.

Here is a simple function to check to see if a variable is in a variable set. Fixpoint

`var_set_includes_var` (`v` : `var`) (`vars` : `var_set`) : `bool` :=

```
match vars with
| nil => false
| n :: n' => if (beq_nat v n) then true
              else var_set_includes_var v n'
end.
```

Here is a function to remove all instances of var `v` from a list of vars. Fixpoint

`var_set_remove_var` (`v` : `var`) (`vars` : `var_set`) : `var_set` :=

```
match vars with
| nil => nil
| n :: n' => if (beq_nat v n) then (var_set_remove_var v n')
              else n :: (var_set_remove_var v n')
end.
```

Next is a function to return a unique `var_set` without duplicates. Found vars should be empty for correctness guarantee. Fixpoint `var_set_create_unique` (`vars` : `var_set`): `var_set`

```
:=
match vars with
| nil => nil
| n :: n' =>
    if (var_set_includes_var n n') then var_set_create_unique n'
    else n :: var_set_create_unique n'
end.
```

Function to check if a given `var_set` is unique Fixpoint `var_set_is_unique` (`vars` : `var_set`):

```
bool :=
match vars with
| nil => true
| n :: n' =>
    if (var_set_includes_var n n') then false
    else var_set_is_unique n'
end.
```

Function to get the variables of a term as a `var_set` Fixpoint `term_vars` (`t` : `term`) : `var_set` :=

```
match t with
```

```

| T0 ⇒ nil
| T1 ⇒ nil
| VAR x ⇒ x :: nil
| PRODUCT x y ⇒ (term_vars x) ++ (term_vars y)
| SUM x y ⇒ (term_vars x) ++ (term_vars y)
end.

```

This is a function to generate a list of unique variables that make up a given term.

Definition `term_unique_vars` ( $t : \text{term}$ ) : `var_set` :=  
`var_set_create_unique` (`term_vars`  $t$ ).

### 2.3.2 Lemmas

Now that we have established the functionality for variable sets, let us prove some properties about them. Lemma `vs_includes_true` :  $\forall (x : \text{var}) (lvar : \text{list var})$ ,  
`var_set_includes_var`  $x$   $lvar$  = `true`  $\rightarrow$  `In`  $x$   $lvar$ .

Proof.

```

intros.
induction lvar.
- simpl; intros. discriminate.
- simpl in H. remember (beq_nat x a) as H2. destruct H2.
  + simpl. left. symmetry in HeqH2. pose proof beq_nat_true as H7.
    specialize (H7 x a HeqH2). symmetry in H7. apply H7.
  + specialize (IHlvar H). simpl. right. apply IHlvar.

```

Qed.

Lemma `vs_includes_false` :  $\forall (x : \text{var}) (lvar : \text{list var})$ ,  
`var_set_includes_var`  $x$   $lvar$  = `false`  $\rightarrow$   $\neg$  `In`  $x$   $lvar$ .

Proof.

```

intros.
induction lvar.
- simpl; intros. unfold not. intros. destruct H0.
- simpl in H. remember (beq_nat x a) as H2. destruct H2. inversion H.
  specialize (IHlvar H). firstorder. intuition. apply IHlvar. simpl in H0.
  destruct H0.
  + inversion HeqH2. symmetry in H2. pose proof beq_nat_false as H7.
    specialize (H7 x a H2). rewrite H0 in H7. destruct H7. intuition.
  + apply H0.

```

Qed.

Lemma `in_dup_and_non_dup` :  $\forall (x : \text{var}) (lvar : \text{list var})$ ,  
`In`  $x$   $lvar$   $\leftrightarrow$  `In`  $x$  (`var_set_create_unique`  $lvar$ ).

Proof.

```

intros. split.
- induction lvar.

```

```

+ intros. simpl in H. destruct H.
+ intros. simpl. remember (var_set_includes_var a lvar) as C. destruct C.
  × symmetry in HeqC. pose proof vs_includes_true as H7.
    specialize (H7 a lvar HeqC). simpl in H. destruct H.
    - rewrite H in H7. specialize (IHlvar H7). apply IHlvar.
    - specialize (IHlvar H). apply IHlvar.
  × symmetry in HeqC. pose proof vs_includes_false as H7.
    specialize (H7 a lvar HeqC). simpl in H. destruct H.
    - simpl. left. apply H.
    - specialize (IHlvar H). simpl. right. apply IHlvar.
- induction lvar.
+ intros. simpl in H. destruct H.
+ intros. simpl in H. remember (var_set_includes_var a lvar) as C.
  destruct C.
  × symmetry in HeqC. pose proof vs_includes_true as H7.
    specialize (H7 a lvar HeqC). specialize (IHlvar H). simpl.
    right. apply IHlvar.
  × symmetry in HeqC. pose proof vs_includes_false as H7.
    specialize (H7 a lvar HeqC). simpl in H. destruct H.
    - simpl. left. apply H.
    - specialize (IHlvar H). simpl. right. apply IHlvar.
Qed.

```

### 2.3.3 Examples

Below are some examples of the behaviors of variable sets.

Example `var_set_create_unique_ex1` :

```
var_set_create_unique [0;5;2;1;1;2;2;9;5;3] = [0;1;2;9;5;3].
```

Proof.

```
simpl. reflexivity.
```

Qed.

Example `var_set_is_unique_ex1` :

```
var_set_is_unique [0;2;2;2] = false.
```

Proof.

```
simpl. reflexivity.
```

Qed.

Example `term_vars_ex1` :

```
term_vars (VAR 0 + VAR 0 + VAR 1) = [0;0;1].
```

Proof.

```
simpl. reflexivity.
```

Qed.

```

Example term_vars_ex2 :
  In 0 (term_vars (VAR 0 + VAR 0 + VAR 1)).
Proof.
  simpl. left. reflexivity.
Qed.

```

## 2.4 Ground Terms

Seeing as we just outlined the definition of a variable set, it seems fair to now formalize the definition of a ground term, or in other words, a term that has no variables and whose variable set is the empty set.

### 2.4.1 Definitions

A *ground term* is a recursively defined proposition that is only true if and only if no variable appears in it; otherwise it will be a false proposition and no longer a ground term.

In this subsection we declare definitions related to ground terms, including functions and lemmas.

This is a function to check if a given term is a ground term (i.e. has no vars). **Fixpoint** `ground_term (t : term) : Prop :=`

```

  match t with
  | VAR x ⇒ False
  | SUM x y ⇒ ground_term x ∧ ground_term y
  | PRODUCT x y ⇒ ground_term x ∧ ground_term y
  | _ ⇒ True
end.

```

### 2.4.2 Lemmas

Our first real lemma (shown below), articulates an important property of ground terms: all ground terms are equivalent to either 0 or 1. This curious property is a direct result of the fact that these terms possess no variables and additionally because of the axioms of Boolean algebra.

This is a lemma (trivial, intuitively true) that proves that if the function `ground_term` returns true then it is either T0 or T1. **Lemma** `ground_term_equiv_T0_T1 : ∀ x,`

`ground_term x → x == T0 ∨ x == T1.`

**Proof.**

```

  intros. induction x.
  - left. reflexivity.
  - right. reflexivity.
  - contradiction.
  - inversion H. destruct IHx1; destruct IHx2; auto. rewrite H2. left.

```

```

rewrite sum_id. apply H3. rewrite H2. rewrite H3. rewrite sum_id. right.
reflexivity. rewrite H2. rewrite H3. right. rewrite sum_comm.
rewrite sum_id. reflexivity. rewrite H2. rewrite H3. rewrite sum_x_x. left.
reflexivity.
- inversion H. destruct IHx1; destruct IHx2; auto. rewrite H2. left.
  rewrite mul_T0_x. reflexivity. rewrite H2. left. rewrite mul_T0_x.
  reflexivity. rewrite H3. left. rewrite mul_comm. rewrite mul_T0_x.
  reflexivity. rewrite H2. rewrite H3. right. rewrite mul_id. reflexivity.
Qed.

```

This lemma, while intuitively obvious by definition, nonetheless provides a formal bridge between the world of ground terms and the world of variable sets. `Lemma ground_term_has_empty_var_set`  
`:  $\forall x$ ,`

`ground_term  $x \rightarrow$  term_vars  $x = []$ .`

Proof.

```

intros. induction x.
- simpl. reflexivity.
- simpl. reflexivity.
- contradiction.
- firstorder. unfold term_vars. unfold term_vars in H2. rewrite H2.
  unfold term_vars in H1. rewrite H1. simpl. reflexivity.
- firstorder. unfold term_vars. unfold term_vars in H2. rewrite H2.
  unfold term_vars in H1. rewrite H1. simpl. reflexivity.

```

Qed.

### 2.4.3 Examples

Here are some examples to show that our ground term definition is working appropriately.

Example `ex_gt1` :

`ground_term (T0 + T1).`

Proof.

```

simpl. split.
- reflexivity.
- reflexivity.

```

Qed.

Example `ex_gt2` :

`ground_term (VAR 0  $\times$  T1)  $\rightarrow$  False.`

Proof.

```

simpl. intros. destruct H. apply H.

```

Qed.

## 2.5 Substitutions

It is at this point in our Coq development that we begin to officially define the principal action around which the entirety of our efforts are centered: the act of substituting variables with other terms. While substitutions alone are not of great interest, their emergent properties as in the case of whether or not a given substitution unifies an equation are of substantial importance to our later research.

### 2.5.1 Definitions

In this subsection we make the fundamental definitions of substitutions, basic functions for them, accompanying lemmas and some propositions.

Here we define a *substitution* to be a list of ordered pairs where each pair represents a variable being mapped to a term. For sake of clarity these ordered pairs shall be referred to as *replacements* from now on and as a result, substitutions should really be considered to be lists of replacements.

Definition replacement := **prod** var **term**.

Definition subst := **list** replacement.

Implicit Type s : subst.

Our first function, `find_replacement`, is an auxilliary to `apply_subst`. This function will search through a substitution for a specific variable, and if found, returns the variable's associated term. **Fixpoint** `find_replacement (x : var) (s : subst) : term :=`

```
match s with
| nil ⇒ VAR x
| r :: r' ⇒
    if beq_nat (fst r) x then snd r
    else find_replacement x r'
end.
```

The `apply_subst` function will take a term and a substitution and will produce a new term reflecting the changes made to the original one. **Fixpoint** `apply_subst (t : term) (s : subst) : term :=`

```
match t with
| T0 ⇒ T0
| T1 ⇒ T1
| VAR x ⇒ find_replacement x s
| PRODUCT x y ⇒ PRODUCT (apply_subst x s) (apply_subst y s)
| SUM x y ⇒ SUM (apply_subst x s) (apply_subst y s)
end.
```

For reasons of completeness, it is useful to be able to generate *identity substitutions*; namely, substitutions that map the variables of a term to themselves.

**Fixpoint** `build_id_subst (lvar : var_set) : subst :=`



```

match lvar with
| nil  $\Rightarrow$  nil
| v :: v'  $\Rightarrow$  (v , (VAR v)) :: build_id_subst v'
end.

```

Since we now have the ability to generate identity substitutions, we should now formalize a general proposition for testing whether or not a given substitution is an identity substitution of a given term.

```

Definition subst_equiv (s1 s2: subst) : Prop :=
   $\forall$  t, apply_subst t s1 == apply_subst t s2.

```

```

Definition subst_is_id_subst (t : term) (s : subst) : Prop :=
  apply_subst t s == t.

```

Given we now have definitions for substitutions, we should now introduce the idea of a substitution composing another one.

```

Fixpoint subst_compose (s s' : subst) : subst :=
  match s' with
  | []  $\Rightarrow$  s
  | (x, t) :: s''  $\Rightarrow$  (x, apply_subst t s) :: (subst_compose s s'')
  end.

```

Here we define the domain of a substitution, namely the list of variables for which the substitution has a mapping (replacement). Essentially this acts as a list of all the first parts of the replacement.

```

Definition subst_domain (sig : subst) : list var :=
  map (fun r  $\Rightarrow$  (fst r)) sig.

```

```

Definition sub_dmn_list (l1 : list var) (l2 : list var) : Prop :=
   $\forall$  (x : var), In x l1  $\rightarrow$  In x l2.

```

## 2.5.2 Lemmas

Having now outlined the functionality of a substitution, let us now begin to analyze some implications of its form and composition by proving some lemmas.

Given that we have a definition for identity substitutions, we should prove that identity substitutions do not modify a term.

```

Lemma id_subst:  $\forall$  (t : term) (l : var_set),
  apply_subst t (build_id_subst l) == t.

```

Proof.

```

intros. induction t.
- simpl. reflexivity.
- simpl. reflexivity.
- simpl. induction l.
  + simpl. reflexivity.

```

```

+ simpl. destruct (beq_nat a v) eqn: e.
  × apply beq_nat_true in e. rewrite e. reflexivity.
  × apply IHL.
- simpl. rewrite IHt1. rewrite IHt2. reflexivity.
- simpl. rewrite IHt1. rewrite IHt2. reflexivity.
Qed.

```

These are helper lemmes for the `apply_subst` properties.

Lemma `sum_comm_compat`  $t1\ t2$ :  $\forall (sigma: subst),$   
`apply_subst (t1 + t2) sigma == apply_subst (t2 + t1) sigma.`  
Proof.

```
intros. simpl. auto.
```

Qed.

Hint Resolve `sum_comm_compat`.

Lemma `sum_assoc_compat`  $t1\ t2\ t3$ :  $\forall (sigma: subst),$   
`apply_subst ((t1 + t2) + t3) sigma == apply_subst (t1 + (t2 + t3)) sigma.`  
Proof.

```
intros. simpl. auto.
```

Qed.

Hint Resolve `sum_assoc_compat`.

Lemma `sum_id_compat`  $t$ :  $\forall (sigma: subst),$   
`apply_subst (T0 + t) sigma == apply_subst t sigma.`  
Proof.

```
intros. simpl. auto.
```

Qed.

Hint Resolve `sum_id_compat`.

Lemma `sum_x_x_compat`  $t$ :  $\forall (sigma: subst),$   
`apply_subst (t + t) sigma == apply_subst T0 sigma.`  
Proof.

```
intros. simpl. auto.
```

Qed.

Hint Resolve `sum_x_x_compat`.

Lemma `mul_comm_compat`  $t1\ t2$ :  $\forall (sigma: subst),$   
`apply_subst (t1 × t2) sigma == apply_subst (t2 × t1) sigma.`  
Proof.

```
intros. simpl. auto.
```

Qed.

Hint Resolve `mul_comm_compat`.

Lemma `mul_assoc_compat`  $t1\ t2\ t3$ :  $\forall (sigma: subst),$   
`apply_subst ((t1 × t2) × t3) sigma == apply_subst (t1 × (t2 × t3)) sigma.`  
Proof.

```
intros. simpl. auto.
```

Qed.

Hint Resolve *mul\_assoc\_compat*.

Lemma *mul\_x\_x\_compat*  $t$ :  $\forall (sigma: subst),$   
 $apply\_subst (t \times t) sigma == apply\_subst t sigma.$

Proof.

intros. simpl. auto.

Qed.

Hint Resolve *mul\_x\_x\_compat*.

Lemma *mul\_T0\_x\_compat*  $t$ :  $\forall (sigma: subst),$   
 $apply\_subst (T0 \times t) sigma == apply\_subst T0 sigma.$

Proof.

intros. simpl. auto.

Qed.

Hint Resolve *mul\_T0\_x\_compat*.

Lemma *mul\_id\_compat*  $t$ :  $\forall (sigma: subst),$   
 $apply\_subst (T1 \times t) sigma == apply\_subst t sigma.$

Proof.

intros. simpl. auto.

Qed.

Hint Resolve *mul\_id\_compat*.

Lemma *distr\_compat*  $t1\ t2\ t3$ :  $\forall (sigma: subst),$   
 $apply\_subst (t1 \times (t2 + t3)) sigma ==$   
 $apply\_subst ((t1 \times t2) + (t1 \times t3)) sigma.$

Proof.

intros. simpl. auto.

Qed.

Hint Resolve *distr\_compat*.

Lemma *refl\_comm\_compat*  $t1\ t2$ :  $\forall (sigma: subst),$   
 $apply\_subst t1 sigma == apply\_subst t2 sigma \rightarrow$   
 $apply\_subst t2 sigma == apply\_subst t1 sigma.$

Proof.

intros. simpl. auto.

Qed.

Hint Resolve *refl\_comm\_compat*.

Lemma *trans\_compat*  $t1\ t2\ t3$  :  $\forall (sigma: subst),$   
 $apply\_subst t1 sigma == apply\_subst t2 sigma \rightarrow$   
 $apply\_subst t2 sigma == apply\_subst t3 sigma \rightarrow$   
 $apply\_subst t1 sigma == apply\_subst t3 sigma.$

Proof.

intros. eauto.

Qed.

Hint `Resolve trans_compat`.

Lemma `trans_compat2 c1 c2 c3` :

$c1 == c2 \rightarrow$

$c2 == c3 \rightarrow$

$c1 == c3$ .

Proof.

`intros. eauto.`

Qed.

This is an axiom that states that if two terms are equivalent then applying any substitution on them will also produce equivalent terms. The reason we axiomatized this and we did not prove it as a lemma is because the set of our fundamental axioms is not an inductive relation, so it would be impossible to prove the lemma below with our fundamental axioms in the current format.

Axiom `apply_subst_compat` :  $\forall (t \ t' : \text{term})$ ,

$t == t' \rightarrow$

$\forall (\text{sigma} : \text{subst}), \text{apply\_subst } t \text{ sigma} == \text{apply\_subst } t' \text{ sigma}.$

Add *Parametric Morphism* : `apply_subst` with

$\text{signature eqv} \Rightarrow \text{eq} \Rightarrow \text{eqv}$  as `apply_subst_mor`.

Proof.

`exact apply_subst_compat.`

Qed.

This is a simple lemma that states that an empty substitution cannot modify a term.

Lemma `subst_empty_no_change` :

$\forall (t : \text{term}), (\text{apply\_subst } t \ \square) == t.$

Proof.

`intros. induction t.`

- `simpl. reflexivity.`

- `simpl. reflexivity.`

- `simpl. reflexivity.`

- `simpl. rewrite IHt1. rewrite IHt2. reflexivity.`

- `simpl. rewrite IHt1. rewrite IHt2. reflexivity.`

Qed.

This is a lemma that states that sequentially applying two substitutions on a term produces the same term as applying the composed substitutions on the term.

Lemma `subst_compose_eqv` :

$\forall (t : \text{term}) (\text{sig1} : \text{subst}) (\text{sig2} : \text{subst}),$

$(\text{apply\_subst } t (\text{subst\_compose } \text{sig1 } \text{sig2})) == (\text{apply\_subst } (\text{apply\_subst } t \text{ sig2}) \text{ sig1}).$

Proof.

`intros. induction t.`

- `simpl. reflexivity.`

- `simpl. reflexivity.`

```

- simpl. induction sig2.
  + simpl. reflexivity.
  + simpl. induction sig1.

```

*Admitted.*

An intuitive thing to prove for ground terms is that they cannot be modified by applying substitutions to them. This will later prove to be very relevant when we begin to talk about unification.

This is a helpful lemma for showing substitutions do not affect ground terms. **Lemma** `ground_term_cannot_subst` :  $\forall x$ ,

```

ground_term x →
  ∀ s, apply_subst x s == x.

```

*Proof.*

```

intros. induction s.
- apply ground_term_equiv_T0_T1 in H. destruct H.
  + rewrite H. simpl. reflexivity.
  + rewrite H. simpl. reflexivity.
- apply ground_term_equiv_T0_T1 in H. destruct H. rewrite H.
  + simpl. reflexivity.
  + rewrite H. simpl. reflexivity.

```

*Qed.*

A fundamental property of substitutions is their distributivity across the summation and multiplication of terms. Again the importance of these proofs will not become apparent until we talk about unification.

This is a useful lemma for showing the distributivity of substitutions across term summation. **Lemma** `subst_sum_distribution` :  $\forall s \ x \ y$ ,

```

apply_subst x s + apply_subst y s == apply_subst (x + y) s.

```

*Proof.*

```

intro. induction s.
- simpl. intros. reflexivity.
- intros. simpl. reflexivity.

```

*Qed.*

This is a lemma to prove the distributivity of the `apply_subst` function across term multiplication. **Lemma** `subst_mul_distribution` :  $\forall s \ x \ y$ ,

```

apply_subst x s × apply_subst y s == apply_subst (x × y) s.

```

*Proof.*

```

intro. induction s.
- intros. reflexivity.
- intros. simpl. reflexivity.

```

*Qed.*

Here is a lemma to prove the opposite of summation distributivity of the `apply_subst` function across term summation. **Lemma** `subst_sum_distr_opp` :  $\forall s \ x \ y$ ,

`apply_subst (x + y) s == apply_subst x s + apply_subst y s.`

Proof.

`intros.`

`apply refl_comm.`

`apply subst_sum_distribution.`

Qed.

This is a lemma to prove the opposite of multiplication distributivity of the `apply_subst` function across term summation. **Lemma** `subst_mul_distr_opp` :  $\forall s x y,$

`apply_subst (x × y) s == apply_subst x s × apply_subst y s.`

Proof.

`intros.`

`apply refl_comm.`

`apply subst_mul_distribution.`

Qed.

An intuitive lemmas to apply a single replacement substitution on a VAR term. **Lemma** `var_subst`:  $\forall (v : \text{var}) (ts : \text{term}),$

`apply_subst (VAR v) [(v , ts)] == ts.`

Proof.

`intros. simpl. destruct (beq_nat v v) eqn: e.`

`- apply beq_nat_true in e. reflexivity.`

`- apply beq_nat_false in e. firstorder.`

Qed.

### 2.5.3 Examples

Here are some examples showcasing the nature of applying substitutions to terms.

Example `subst_ex1` :

`apply_subst (T0 + T1) [] == T0 + T1.`

Proof.

`intros. reflexivity.`

Qed.

Example `subst_ex2` :

`apply_subst (VAR 0 × VAR 1) [(0, T0)] == T0.`

Proof.

`intros. simpl. apply mul_T0_x.`

Qed.

### 2.5.4 Auxillary Definitions for Substitutions and Terms

In this section we define more helper functions and lemmas related to substitutions and ground terms. Specifically we are defining a ground term, a ground substitution, a “01” term, a “01” substitution, and a substitution composition. The terms that are used more in

the future proofs are the “01” term and “01” substitution. A “01” term is a term that is either equal to T0 or T1. A “01” substitution is a substitution in which each variable (or the first part of each replacement) is mapped to a “01” term. A “01” term is not necessarily a ground term (but it might be) and a “01” substitution is not necessarily a ground substitution (but it might be). In the proof file, we are mostly using the “01” term and substitution terminology.

```
Fixpoint ground_subst (sig : subst) : Prop :=
  match sig with
  | [] => True
  | r :: r' => ground_term (snd r) ∧ ground_subst r'
  end.
```

This is a function to determine whether a term is a ground term. Fixpoint is\_ground\_term (t : term) : bool :=

```
match t with
| T0 => true
| T1 => true
| VAR x => false
| SUM a b => (is_ground_term a) && (is_ground_term b)
| PRODUCT a b => (is_ground_term a) && (is_ground_term b)
end.
```

This is a function to determine whether a substitution is a ground substitution. Fixpoint is\_ground\_subst (sig : subst) : bool := existsb is\_ground\_term (map snd sig).

This is a function to determine whether a term is a T0 or T1 term by returning a boolean. Definition is\_01\_term (t : term) : bool :=

```
match t with
| T0 => true
| T1 => true
| _ => false
end.
```

This is a function to determine whether a substitution is a “01” substitution by returning a boolean, meaning that each second part of every replacement is either a T0 or a T1 term. Fixpoint is\_01\_subst (sig : subst) : bool :=

```
existsb is_01_term (map snd sig).
```

This is a function to determine whether a term is a T0 or T1 term by returning a proposition.

```
Fixpoint _01_term (t : term) : Prop :=
  match t with
  | T0 => True
  | T1 => True
  | _ => False
  end.
```

This is a function to determine whether a substitution is a “01” substitution by returning a proposition, meaning that each second part of every replacement is either a T0 or a T1 substitution. `Fixpoint _01_subst (sig : subst) : Prop :=`

```
match sig with
| [] => True
| r :: r' => _01_term (snd r) ∧ _01_subst r'
end.
```

## 2.6 Unification

Now that we have established the concept of term substitutions in Coq, it is time for us to formally define the concept of Boolean unification. *Unification*, in its most literal sense, refers to the act of applying a substitution to terms in order to make them equivalent to each other. In other words, to say that two terms are *unifiable* is to really say that there exists a substitution such that the two terms are equal. Interestingly enough, we can abstract this concept further to simply saying that a single term is unifiable if there exists a substitution such that the term will be equivalent to 0. By doing this abstraction, we can prove that equation solving and unification are essentially the same fundamental problem.

Below is the initial definition for unification, namely that two terms can be unified to be equivalent to one another. By starting here we will show each step towards abstracting unification to refer to a single term.

**Definition** `unifies (a b : term) (s : subst) : Prop :=`  
`apply_subst a s == apply_subst b s.`

Here is a simple example demonstrating the concept of testing whether two terms are unified by a substitution.

**Example** `ex_unif1 :`  
`unifies (VAR 0) (VAR 1) [(0, T1); (1, T1)].`

**Proof.**

```
unfold unifies. simpl. reflexivity.
```

**Qed.**

Now we are going to show that moving both terms to one side of the equivalence relation through addition does not change the concept of unification.

**Definition** `unifies_T0 (a b : term) (s : subst) : Prop :=`  
`apply_subst a s + apply_subst b s == T0.`

**Lemma** `unifies_T0_equiv : ∀ x y s,`  
`unifies x y s ↔ unifies_T0 x y s.`

**Proof.**

```
intros. split.
- intros. unfold unifies_T0. unfold unifies in H. rewrite H.
  rewrite sum_x_x. reflexivity.
```



```

- intros. unfold unifies_T0 in H. unfold unifies.
  rewrite term_sum_symmetric with (x := apply_subst x s + apply_subst y s)
  (z := apply_subst y s) in H. rewrite sum_id in H.
  rewrite sum_comm in H.
  rewrite sum_comm with (y := apply_subst y s) in H.
  rewrite ← sum_assoc in H.
  rewrite sum_x_x in H.
  rewrite sum_id in H.
  apply H.

```

Qed.

Now we can define what it means for a substitution to be a unifier for a given term.

Definition unifier ( $t : \mathbf{term}$ ) ( $s : \mathbf{subst}$ ) : Prop :=  
 apply\_subst  $t$   $s$  == T0.

Example unifier\_ex1 :  
 unifier (VAR 0) [(0, T0)].

Proof.

```

  unfold unifier. simpl. reflexivity.

```

Qed.

To ensure our efforts were not in vain, let us now prove that this last abstraction of the unification problem is still equivalent to the original.

Lemma unifier\_distribution :  $\forall x y s$ ,  
 unifies\_T0  $x y s \leftrightarrow$  unifier ( $x + y$ )  $s$ .

Proof.

```

  intros. split.
- intros. unfold unifies_T0 in H. unfold unifier.
  rewrite ← H. symmetry. apply subst_sum_distribution.
- intros. unfold unifies_T0. unfold unifier in H.
  rewrite ← H. apply subst_sum_distribution.

```

Qed.

Lastly let us define a term to be unifiable if there exists a substitution that unifies it.

Definition unifiable ( $t : \mathbf{term}$ ) : Prop :=  
 $\exists s$ , unifier  $t s$ .

Example unifiable\_ex1 :  
 $\exists x$ , unifiable ( $x + T1$ ).

Proof.

```

   $\exists$  T1. unfold unifiable. unfold unifier.
   $\exists$  []. simpl. rewrite sum_x_x. reflexivity.

```

Qed.

## 2.7 Most General Unifier

In this subsection we define propositions, lemmas and examples related to the most general unifier.

While the property of a term being unifiable is certainly important, it should come as no surprise that not all unifiers are created equal; in fact, certain unifiers possess the desirable property of being *more general* than others. For this reason, let us now formally define the concept of a *most general unifier* (mgu): a unifier such that with respect to a given term, all other unifiers are instances of it, or in other words, less general than it.

The first step towards establishing the concept of a mgu requires us to formalize the notion of a unifier being more general than another. To accomplish this goal, let us formulate the definition of a substitution composing another one; or in other words, to say that a substitution is more general than another one.

This is a proposition of sequential substitution application. **Definition** `substitution_factor_through`  $(s \ s' \ \text{delta} : \text{subst}) : \text{Prop} :=$

$$\forall (x : \text{var}), \text{apply\_subst} (\text{apply\_subst} (\text{VAR } x) s) \ \text{delta} == \text{apply\_subst} (\text{VAR } x) s' .$$

This is the definition of a more general substitution. **Definition** `more_general_substitution`  $(s \ s' : \text{subst}) : \text{Prop} :=$

$$\exists \ \text{delta}, \text{substitution\_factor\_through} \ s \ s' \ \text{delta} .$$

Now that we have articulated the concept of composing substitutions, let us now formulate the definition for a most general unifier.

This is the definition of a Most General Unifier (mgu): A Most General Unifier (MGU) takes in a term and a substitution and tells whether or not said substitution is an mgu for the given term. **Definition** `most_general_unifier`  $(t : \text{term}) (s : \text{subst}) : \text{Prop} :=$

$$\begin{aligned} & \text{unifier } t \ s \wedge \\ & \forall (s' : \text{subst}), \\ & \text{unifier } t \ s' \rightarrow \\ & \text{more\_general\_substitution } s \ s'. \end{aligned}$$

While this definition of a most general unifier is certainly valid, we can also characterize a unifier by other similar properties. For this reason, let us now define an alternative definition called a *reproductive unifier*, and then prove it to be equivalent to our definition of a most general unifier. This will make our proofs easier to formulate down the road as the task of proving a unifier to be reproductive is substantially easier than proving it to be most general directly. **Definition** `reproductive_unifier`  $(t : \text{term}) (sig : \text{subst}) : \text{Prop} :=$

$$\begin{aligned} & \text{unifier } t \ sig \wedge \\ & \forall (tau : \text{subst}) (x : \text{var}), \\ & \text{unifier } t \ tau \rightarrow \\ & \text{apply\_subst} (\text{apply\_subst} (\text{VAR } x) sig) \ tau == \text{apply\_subst} (\text{VAR } x) \ tau. \end{aligned}$$

This is a lemma to show that a reproductive unifier is a most general unifier. Since the ultimate goal is to prove that a specific algorithm produces an mgu then if we could prove

it is a reproductive unifier then we could use this lemma to arrive at the desired conclusion.

Lemma reproductive\_is\_mgu :  $\forall (t : \text{term}) (u : \text{subst}),$   
 reproductive\_unifier  $t\ u \rightarrow$   
 most\_general\_unifier  $t\ u$ .

Proof.

```
intros. unfold most_general_unifier. unfold reproductive_unifier in H.
unfold more_general_substitution . destruct H. split.
- apply H.
- intros. specialize (H0 s').  $\exists\ s'$ . unfold substitution_factor_through.
  intros. specialize (H0 x).
  specialize (H0 H1). apply H0.
```

Qed.

This is a lemma to show that if two terms are equivalent then for any substitution that is an mgu of one of the terms, then it is an mgu of the other term as well. Lemma

most\_general\_unifier\_compat :  $\forall (t\ t' : \text{term}),$   
 $t == t' \rightarrow$   
 $\forall (\text{sigma} : \text{subst}),$   
 most\_general\_unifier  $t\ \text{sigma} \leftrightarrow$  most\_general\_unifier  $t'\ \text{sigma}$ .

Proof.

```
intros. split.
- intros. unfold most_general_unifier. unfold unifier in H0.
  unfold unifier in *. split.
  + unfold most_general_unifier in H0. destruct H0. unfold unifier in H0.
    rewrite H in H0. apply H0.
  + intros. unfold most_general_unifier in H0. destruct H0.
    specialize (H2 s'). unfold unifier in H0. symmetry in H. rewrite H in H1.
    unfold unifier in H2. specialize (H2 H1). apply H2.
- unfold most_general_unifier. intros. destruct H0 . split.
  + symmetry in H. unfold unifier in H0. rewrite H in H0. unfold unifier.
    apply H0.
  + intros. specialize (H1 s'). unfold unifier in H2. rewrite H in H2.
    unfold unifier in H1. specialize (H1 H2). apply H1.
```

Qed.

## 2.8 Auxilliary Computational Operations and Simplifications

These functions below will come in handy later during the Lowenheim formula proof. They mainly lay the groundwork for providing the computational nuts and bolts for Lowenheim's algorithm for finding most general unifiers.

This is a function to check if two terms are exactly identical. Fixpoint identical (a b:

```

term) : bool :=
  match a , b with
  | T0, T0 ⇒ true
  | T0, _ ⇒ false
  | T1 , T1 ⇒ true
  | T1 , _ ⇒ false
  | VAR x , VAR y ⇒ if beq_nat x y then true else false
  | VAR x, _ ⇒ false
  | PRODUCT x y, PRODUCT x1 y1 ⇒ identical x x1 && identical y y1
  | PRODUCT x y, _ ⇒ false
  | SUM x y, SUM x1 y1 ⇒ identical x x1 && identical y y1
  | SUM x y, _ ⇒ false
  end.

```

This is basic addition for terms. Definition `plus_one_step (a b : term) : term :=`

```

match a, b with
| T0, T0 ⇒ T0
| T0, T1 ⇒ T1
| T1, T0 ⇒ T1
| T1 , T1 ⇒ T0
| _ , _ ⇒ SUM a b
end.

```

This is basic multiplication for terms. Definition `mult_one_step (a b : term) : term :=`

```

match a, b with
| T0, T0 ⇒ T0
| T0, T1 ⇒ T0
| T1, T0 ⇒ T0
| T1 , T1 ⇒ T1
| _ , _ ⇒ PRODUCT a b
end.

```

This is a function to simplify a term in very apparent and basic ways. They are only simplified if they are ground terms. Fixpoint `simplify (t : term) : term :=`

```

match t with
| T0 ⇒ T0
| T1 ⇒ T1
| VAR x ⇒ VAR x
| PRODUCT x y ⇒ mult_one_step (simplify x) (simplify y)
| SUM x y ⇒ plus_one_step (simplify x) (simplify y)
end.

```

Some lemmas follow to prove intuitive facts for the basic multiplication and addition of terms, leading up to proving the `simplify_eqv` lemma.

Lemma pos\_left\_sum\_compat :  $\forall (t \ t1 \ t2 : \mathbf{term}),$   
 $t == t1 \rightarrow \text{plus\_one\_step } t1 \ t2 == \text{plus\_one\_step } t \ t2.$

Proof.

```

intros. induction t1.
- induction t.
  + reflexivity.
  + apply T1_not_equiv_T0 in H. inversion H.
  + induction t2.
    × simpl. rewrite H. rewrite sum_x_x. reflexivity.
    × simpl. rewrite H. rewrite sum_id. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
  + induction t2.
    × simpl. rewrite H. rewrite sum_x_x. reflexivity.
    × simpl. rewrite H. rewrite sum_id. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
  + induction t2.
    × simpl. rewrite H. rewrite sum_x_x. reflexivity.
    × simpl. rewrite H. rewrite sum_id. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
- induction t.
  + induction t2.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
  + induction t2.
    × simpl. reflexivity.
    × simpl. reflexivity.
    × simpl. reflexivity.
    × simpl. reflexivity.
    × simpl. reflexivity.
  + induction t2.
    × simpl. rewrite H. rewrite sum_comm. rewrite sum_id. reflexivity.
    × simpl. rewrite H. rewrite sum_x_x. reflexivity.
    × simpl. rewrite H. reflexivity.

```

```

    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
+ induction t2.
    × simpl. rewrite H. rewrite sum_comm. rewrite sum_id. reflexivity.
    × simpl. rewrite H. rewrite sum_x_x. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
+ induction t2.
    × simpl. rewrite H. rewrite sum_comm. rewrite sum_id. reflexivity.
    × simpl. rewrite H. rewrite sum_x_x. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
- induction t.
+ induction t2.
    × simpl. rewrite H. rewrite sum_x_x. rewrite H. reflexivity.
    × simpl. rewrite  $\leftarrow$  H. rewrite sum_id. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
+ induction t2.
    × simpl. rewrite  $\leftarrow$  H. rewrite sum_comm. rewrite sum_id. reflexivity.
    × simpl. rewrite H. rewrite sum_x_x. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
+ induction t2.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
+ induction t2.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
+ induction t2.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.

```

```

    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
- induction t.
+ induction t2.
    × simpl. rewrite ← H. rewrite sum_x_x. reflexivity.
    × simpl. rewrite ← H. rewrite sum_id. reflexivity.
    × simpl. rewrite ← H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
+ induction t2.
    × simpl. rewrite ← H. rewrite sum_comm. rewrite sum_id. reflexivity.
    × simpl. rewrite H. rewrite sum_x_x. reflexivity.
    × simpl. rewrite ← H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
+ induction t2.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
+ induction t2.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
+ induction t2.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
- induction t.
+ induction t2.
    × simpl. rewrite ← H. rewrite sum_x_x. reflexivity.
    × simpl. rewrite ← H. rewrite sum_id. reflexivity.
    × simpl. rewrite ← H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
+ induction t2.

```

```

× simpl. rewrite ← H. rewrite sum_comm. rewrite sum_id. reflexivity.
× simpl. rewrite H. rewrite sum_x_x. reflexivity.
× simpl. rewrite ← H. reflexivity.
× simpl. rewrite ← H. reflexivity.
× simpl. rewrite ← H. reflexivity.
+ induction t2.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite H. reflexivity.
+ induction t2.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite H. reflexivity.
+ induction t2.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite H. reflexivity.

```

Qed.

Lemma pos\_right\_sum\_compat :  $\forall (t \ t1 \ t2 : \text{term}),$   
 $t == t2 \rightarrow \text{plus\_one\_step } t1 \ t2 == \text{plus\_one\_step } t1 \ t.$

Proof.

intros. induction t1.

```

- induction t.
  + induction t2.
    × simpl. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. rewrite sum_x_x. apply H.
    × simpl. rewrite ← H. rewrite sum_x_x. reflexivity.
    × simpl. rewrite ← H. rewrite sum_x_x. reflexivity.
  + induction t2.
    × simpl. rewrite H. reflexivity.
    × simpl. reflexivity.
    × simpl. rewrite H. rewrite sum_id. reflexivity.
    × simpl. rewrite H. rewrite sum_id. reflexivity.
    × simpl. rewrite ← H. rewrite sum_id. reflexivity.
  + induction t2.

```



```

× simpl. rewrite H. rewrite sum_x_x. reflexivity.
× simpl. rewrite H. rewrite sum_id. reflexivity.
× simpl. rewrite H. rewrite sum_id. reflexivity.
× simpl. rewrite H. rewrite sum_id. reflexivity.
× simpl. rewrite ← H. rewrite sum_id. reflexivity.
+ induction t2.
× simpl. rewrite H. rewrite sum_x_x. reflexivity.
× simpl. rewrite H. rewrite sum_id. reflexivity.
× simpl. rewrite H. rewrite sum_id. reflexivity.
× simpl. rewrite H. rewrite sum_id. reflexivity.
× simpl. rewrite ← H. rewrite sum_id. reflexivity.
+ induction t2.
× simpl. rewrite H. rewrite sum_x_x. reflexivity.
× simpl. rewrite H. rewrite sum_id. reflexivity.
× simpl. rewrite H. rewrite sum_id. reflexivity.
× simpl. rewrite H. rewrite sum_id. reflexivity.
× simpl. rewrite ← H. rewrite sum_id. reflexivity.
- induction t.
+ induction t2.
× simpl. reflexivity.
× simpl. rewrite H. reflexivity.
× simpl. rewrite ← H. rewrite sum_comm. rewrite sum_id. reflexivity.
× simpl. rewrite ← H. rewrite sum_comm. rewrite sum_id. reflexivity.
× simpl. rewrite ← H. rewrite sum_comm. rewrite sum_id. reflexivity.
+ induction t2.
× simpl. rewrite H. reflexivity.
× simpl. reflexivity.
× simpl. rewrite H. rewrite sum_x_x. reflexivity.
× simpl. rewrite H. rewrite sum_x_x. reflexivity.
× simpl. rewrite ← H. rewrite sum_x_x. reflexivity.
+ induction t2.
× simpl. rewrite H. rewrite sum_comm. rewrite sum_id. reflexivity.
× simpl. rewrite H. rewrite sum_x_x. reflexivity.
× simpl. rewrite H. reflexivity.
× simpl. rewrite H. reflexivity.
× simpl. rewrite ← H. reflexivity.
+ induction t2.
× simpl. rewrite H. rewrite sum_comm. rewrite sum_id. reflexivity.
× simpl. rewrite H. rewrite sum_x_x. reflexivity.
× simpl. rewrite H. reflexivity.
× simpl. rewrite H. reflexivity.
× simpl. rewrite ← H. reflexivity.

```

```

+ induction t2.
  × simpl. rewrite H. rewrite sum_comm. rewrite sum_id. reflexivity.
  × simpl. rewrite H. rewrite sum_x_x. reflexivity.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite ← H. reflexivity.
- induction t.
  + induction t2.
    × simpl. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
  + induction t2.
    × simpl. rewrite H. reflexivity.
    × simpl. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
  + induction t2.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
  + induction t2.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
  + induction t2.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
- induction t.
  + induction t2.
    × simpl. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite ← H. reflexivity.

```

```

    × simpl. rewrite ← H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
+ induction t2.
    × simpl. rewrite H. reflexivity.
    × simpl. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
+ induction t2.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
+ induction t2.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
+ induction t2.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
- induction t.
+ induction t2.
    × simpl. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
+ induction t2.
    × simpl. rewrite H. reflexivity.
    × simpl. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
+ induction t2.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.

```

```

    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
+ induction t2.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
+ induction t2.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite ← H. reflexivity.

```

Qed.

Lemma pos\_left\_mul\_compat :  $\forall (t \ t1 \ t2 : \text{term}),$   
 $t == t1 \rightarrow \text{mult\_one\_step } t1 \ t2 == \text{mult\_one\_step } t \ t2.$

Proof.

```

intros. induction t1.
- induction t.
  + reflexivity.
  + apply T1_not_equiv_T0 in H. inversion H.
  + induction t2.
    × simpl. rewrite H. rewrite mul_x_x. reflexivity.
    × simpl. rewrite H. rewrite mul_T0_x. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
  + induction t2.
    × simpl. rewrite H. rewrite mul_x_x. reflexivity.
    × simpl. rewrite H. rewrite mul_T0_x. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
  + induction t2.
    × simpl. rewrite H. rewrite mul_x_x. reflexivity.
    × simpl. rewrite H. rewrite mul_T0_x. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
- induction t.

```

```

+ induction t2.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite H. reflexivity.
+ induction t2.
  × simpl. reflexivity.
  × simpl. reflexivity.
  × simpl. reflexivity.
  × simpl. reflexivity.
  × simpl. reflexivity.
+ induction t2.
  × simpl. rewrite H. rewrite mul_comm. rewrite mul_T0_x. reflexivity.
  × simpl. rewrite H. rewrite mul_x_x. reflexivity.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite H. reflexivity.
+ induction t2.
  × simpl. rewrite H. rewrite mul_comm. rewrite mul_T0_x. reflexivity.
  × simpl. rewrite H. rewrite mul_x_x. reflexivity.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite H. reflexivity.
+ induction t2.
  × simpl. rewrite H. rewrite mul_comm. rewrite mul_T0_x. reflexivity.
  × simpl. rewrite H. rewrite mul_x_x. reflexivity.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite H. reflexivity.
- induction t.
  + induction t2.
    × simpl. rewrite H. rewrite mul_x_x. reflexivity.
    × simpl. rewrite ← H. rewrite mul_T0_x. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
  + induction t2.
    × simpl. rewrite ← H. rewrite mul_comm. rewrite mul_T0_x. reflexivity.
    × simpl. rewrite H. rewrite mul_x_x. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.

```

```

    × simpl. rewrite H. reflexivity.
+ induction t2.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
+ induction t2.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
+ induction t2.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
- induction t.
+ induction t2.
    × simpl. rewrite ← H. rewrite mul_x_x. reflexivity.
    × simpl. rewrite ← H. rewrite mul_T0_x. reflexivity.
    × simpl. rewrite ← H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
+ induction t2.
    × simpl. rewrite ← H. rewrite mul_comm. rewrite mul_T0_x. reflexivity.
    × simpl. rewrite H. rewrite mul_x_x. reflexivity.
    × simpl. rewrite ← H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
+ induction t2.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
+ induction t2.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.

```

```

    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
+ induction t2.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
- induction t.
+ induction t2.
    × simpl. rewrite ← H. rewrite mul_x_x. reflexivity.
    × simpl. rewrite ← H. rewrite mul_T0_x. reflexivity.
    × simpl. rewrite ← H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
+ induction t2.
    × simpl. rewrite ← H. rewrite mul_comm. rewrite mul_T0_x. reflexivity.
    × simpl. rewrite H. rewrite mul_x_x. reflexivity.
    × simpl. rewrite ← H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
+ induction t2.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
+ induction t2.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
+ induction t2.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.

```

Qed.

Lemma pos\_right\_mul\_compat :  $\forall (t \ t1 \ t2 : \text{term}),$   
 $t == t2 \rightarrow \text{mult\_one\_step } t1 \ t2 == \text{mult\_one\_step } t1 \ t.$

Proof.

intros. induction *t1*.

- induction *t*.

+ induction *t2*.

× simpl. reflexivity.

× simpl. rewrite *H*. reflexivity.

× simpl. rewrite *H*. rewrite *mul\_x\_x*. reflexivity.

× simpl. rewrite ← *H*. rewrite *mul\_x\_x*. reflexivity.

× simpl. rewrite ← *H*. rewrite *mul\_x\_x*. reflexivity.

+ induction *t2*.

× simpl. reflexivity.

× simpl. reflexivity.

× simpl. rewrite *mul\_T0\_x*. reflexivity.

× simpl. rewrite *mul\_T0\_x*. reflexivity.

× simpl. rewrite *mul\_T0\_x*. reflexivity.

+ induction *t2*.

× simpl. rewrite *mul\_T0\_x*. reflexivity.

× simpl. rewrite *mul\_T0\_x*. reflexivity.

× simpl. rewrite *mul\_T0\_x*. rewrite *mul\_T0\_x*. reflexivity.

× simpl. rewrite *mul\_T0\_x*. rewrite *mul\_T0\_x*. reflexivity.

× simpl. rewrite *mul\_T0\_x*. rewrite *mul\_T0\_x*. reflexivity.

+ induction *t2*.

× simpl. rewrite *mul\_T0\_x*. reflexivity.

× simpl. rewrite *mul\_T0\_x*. reflexivity.

× simpl. rewrite *mul\_T0\_x*. rewrite *mul\_T0\_x*. reflexivity.

× simpl. rewrite *mul\_T0\_x*. rewrite *mul\_T0\_x*. reflexivity.

× simpl. rewrite *mul\_T0\_x*. rewrite *mul\_T0\_x*. reflexivity.

+ induction *t2*.

× simpl. rewrite *mul\_T0\_x*. reflexivity.

× simpl. rewrite *mul\_T0\_x*. reflexivity.

× simpl. rewrite *mul\_T0\_x*. rewrite *mul\_T0\_x*. reflexivity.

× simpl. rewrite *mul\_T0\_x*. rewrite *mul\_T0\_x*. reflexivity.

× simpl. rewrite *mul\_T0\_x*. rewrite *mul\_T0\_x*. reflexivity.

- induction *t*.

+ induction *t2*.

× simpl. reflexivity.

× simpl. rewrite *H*. reflexivity.

× simpl. rewrite ← *H*. rewrite *mul\_comm*. rewrite *mul\_T0\_x*. reflexivity.

× simpl. rewrite ← *H*. rewrite *mul\_comm*. rewrite *mul\_T0\_x*. reflexivity.

× simpl. rewrite ← *H*. rewrite *mul\_comm*. rewrite *mul\_T0\_x*. reflexivity.

+ induction *t2*.

× simpl. rewrite *H*. reflexivity.



```

    × simpl. reflexivity.
    × simpl. rewrite H. rewrite mul_x_x. reflexivity.
    × simpl. rewrite H. rewrite mul_x_x. reflexivity.
    × simpl. rewrite ← H. rewrite mul_x_x. reflexivity.
+ induction t2.
    × simpl. rewrite H. rewrite mul_comm. rewrite mul_T0_x. reflexivity.
    × simpl. rewrite H. rewrite mul_x_x. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
+ induction t2.
    × simpl. rewrite H. rewrite mul_comm. rewrite mul_T0_x. reflexivity.
    × simpl. rewrite H. rewrite mul_x_x. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
+ induction t2.
    × simpl. rewrite H. rewrite mul_comm. rewrite mul_T0_x. reflexivity.
    × simpl. rewrite H. rewrite mul_x_x. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
- induction t.
+ induction t2.
    × simpl. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
+ induction t2.
    × simpl. rewrite H. reflexivity.
    × simpl. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
+ induction t2.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
+ induction t2.
    × simpl. reflexivity.
    × simpl. rewrite H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
    × simpl. rewrite ← H. reflexivity.
    × simpl. rewrite ← H. reflexivity.

```

```

    × simpl. rewrite  $H$ . reflexivity.
    × simpl. rewrite  $H$ . reflexivity.
    × simpl. rewrite  $H$ . reflexivity.
    × simpl. rewrite  $H$ . reflexivity.
    × simpl. rewrite  $\leftarrow H$ . reflexivity.
+ induction  $t2$ .
    × simpl. rewrite  $H$ . reflexivity.
    × simpl. rewrite  $H$ . reflexivity.
    × simpl. rewrite  $H$ . reflexivity.
    × simpl. rewrite  $H$ . reflexivity.
    × simpl. rewrite  $\leftarrow H$ . reflexivity.
- induction  $t$ .
+ induction  $t2$ .
    × simpl. reflexivity.
    × simpl. rewrite  $H$ . reflexivity.
    × simpl. rewrite  $\leftarrow H$ . reflexivity.
    × simpl. rewrite  $\leftarrow H$ . reflexivity.
    × simpl. rewrite  $\leftarrow H$ . reflexivity.
+ induction  $t2$ .
    × simpl. rewrite  $H$ . reflexivity.
    × simpl. reflexivity.
    × simpl. rewrite  $H$ . reflexivity.
    × simpl. rewrite  $H$ . reflexivity.
    × simpl. rewrite  $\leftarrow H$ . reflexivity.
+ induction  $t2$ .
    × simpl. rewrite  $H$ . reflexivity.
    × simpl. rewrite  $H$ . reflexivity.
    × simpl. rewrite  $H$ . reflexivity.
    × simpl. rewrite  $H$ . reflexivity.
    × simpl. rewrite  $\leftarrow H$ . reflexivity.
+ induction  $t2$ .
    × simpl. rewrite  $H$ . reflexivity.
    × simpl. rewrite  $H$ . reflexivity.
    × simpl. rewrite  $H$ . reflexivity.
    × simpl. rewrite  $H$ . reflexivity.
    × simpl. rewrite  $\leftarrow H$ . reflexivity.
+ induction  $t2$ .
    × simpl. rewrite  $H$ . reflexivity.
    × simpl. rewrite  $H$ . reflexivity.
    × simpl. rewrite  $H$ . reflexivity.
    × simpl. rewrite  $H$ . reflexivity.
    × simpl. rewrite  $\leftarrow H$ . reflexivity.

```

```

- induction t.
+ induction t2.
  × simpl. reflexivity.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite ← H. reflexivity.
  × simpl. rewrite ← H. reflexivity.
  × simpl. rewrite ← H. reflexivity.
+ induction t2.
  × simpl. rewrite H. reflexivity.
  × simpl. reflexivity.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite ← H. reflexivity.
+ induction t2.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite ← H. reflexivity.
+ induction t2.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite ← H. reflexivity.
+ induction t2.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite H. reflexivity.
  × simpl. rewrite ← H. reflexivity.

```

Qed.

Being able to simplify a term can be a useful tool. Being able to use the simplified version of the term as the equivalent version of the original term can also be useful since many of our functions simplify the term first.

Lemma `simplify_eqv` :  $\forall (t : \text{term})$ ,

`simplify t == t`.

Proof.

```

intros. induction t.
- simpl. reflexivity.
- simpl. reflexivity.
- simpl. reflexivity.

```

```

- simpl. pose proof pos_left_sum_compat.
  specialize (H t1 (simplify t1) (simplify t2)).
  symmetry in IHt1. specialize (H IHt1). rewrite H.
  pose proof pos_right_sum_compat. specialize (H0 (simplify t2) t1 t2).
  specialize (H0 IHt2). symmetry in H0. rewrite H0.
  induction t1.
+ induction t2.
  × simpl. rewrite sum_x_x. reflexivity.
  × simpl. rewrite sum_id. reflexivity.
  × simpl. reflexivity.
  × simpl. reflexivity.
  × simpl. reflexivity.
+ induction t2.
  × simpl. rewrite sum_id_sym. reflexivity.
  × simpl. rewrite sum_x_x. reflexivity.
  × simpl. reflexivity.
  × simpl. reflexivity.
  × simpl. reflexivity.
+ simpl. reflexivity.
+ simpl. reflexivity.
+ simpl. reflexivity.
- simpl. pose proof pos_left_mul_compat.
  specialize (H t1 (simplify t1) (simplify t2)).
  symmetry in IHt1. specialize (H IHt1). rewrite H.
  pose proof pos_right_mul_compat. specialize (H0 (simplify t2) t1 t2).
  specialize (H0 IHt2). symmetry in H0. rewrite H0.
  induction t1.
+ induction t2.
  × simpl. rewrite mul_x_x. reflexivity.
  × simpl. rewrite mul_T0_x. reflexivity.
  × simpl. reflexivity.
  × simpl. reflexivity.
  × simpl. reflexivity.
+ induction t2.
  × simpl. rewrite mul_T0_x_sym. reflexivity.
  × simpl. rewrite mul_x_x. reflexivity.
  × simpl. reflexivity.
  × simpl. reflexivity.
  × simpl. reflexivity.
+ simpl. reflexivity.
+ simpl. reflexivity.
+ simpl. reflexivity.

```

Qed.

This is an intuitive lemma that states when a term is equivalent to  $T0$  and it is also a ground term then simplifying it gives a term exactly equal to  $T0$ . This intuitively follows from the fact that since  $t$  is a ground term then all its terms are either  $T0$  or  $T1$  and since it is equivalent to  $T0$ , simplifying it will also give a single final ground term  $T0$ . Lemma

`simplify_eq_T0 :  $\forall (t : \text{term}),$   
     $t == T0 \wedge (\text{is\_ground\_term } t) = \text{true} \rightarrow$   
     $\text{simplify } t = T0.$`

Proof.

```
intros. destruct H. induction t.  
- reflexivity.  
- simpl in H. apply T1_not_equiv_T0 in H. destruct H.  
- unfold simplify. simpl in H0. inversion H0.  
- simpl. simpl in H0. apply andb_prop in H0. destruct H0.
```

*Admitted.*

# Chapter 3

## Library

### B\_Unification.lowenheim\_formula

Require Export terms.

Require Import List.

Import ListNotations.

#### 3.1 Introduction

In this section we formulate Lowenheim’s algorithm using the data structures and functions defined in the `terms` library. The final occurring main function, `Lowenheim_Main`, takes as input a term and produces a substitution that unifies the given term. The resulting substitution is said to be a most general unifier and not a mere substitution, but that statement is proven in the `lowenheim_proof` file. In this section we focus on the formulation of the algorithm itself, without any proofs about the properties of the formula or the algorithm.

#### 3.2 Lowenheim’s Builder

In this subsection we are implementing the main component of Lowenheim’s algorithm, which is the “builder” of Lowenheim’s substitution for a given term. This implementation strictly follows as close as possible the formal, mathematical format of Lowenheim’s algorithm.

Here is a skeleton function for building a substitution on the format  $\sigma(x) := (s+1)*\sigma_1(x) + s*\sigma_2(x)$ , each variable of a given list of variables, a given term  $s$  and substitutions  $\sigma_1$  and  $\sigma_2$ . This skeleton function is a more general format of Lowenheim’s builder.

```
Fixpoint build_on_list_of_vars (list_var : var_set) (s : term) (sig1 : subst)
                               (sig2 : subst) : subst :=
```

```
  match list_var with
  | [] => []
```

```

| v' :: v ⇒ (v', (s + T1) × apply_subst (VAR v') sig1 +
               s × apply_subst (VAR v') sig2)
:: build_on_list_of_vars v s sig1 sig2
end.

```

This is the function to build a Lowenheim substitution for a term  $t$ , given the term  $t$  and a unifier of  $t$ , using the previously defined skeleton function. The list of variables is the variables within  $t$  and the substitutions are the identical substitution and the unifier of the term. This function will often be referred in the rest of the document as our “Lowenheim builder” or the “Lowenheim substitution builder”, etc.

```

Definition build_lowenheim_subst (t : term) (tau : subst) : subst :=
  build_on_list_of_vars (term_unique_vars t) t
    (build_id_subst (term_unique_vars t)) tau.

```

### 3.3 Lowenheim’s Algorithm

In this subsection we enhance Lowenheim’s builder to the level of a complete algorithm that is able to find ground substitutions before feeding them to the main formula to generate a most general unifier

#### 3.3.1 Auxillary Functions and Definitions

This is a function to update a term, after it applies to it a given substitution and simplifies it.

```

Definition update_term (t : term) (s' : subst) : term :=
  simplify (apply_subst t s').

```

Here is a function to determine if a term is the ground term T0.

```

Definition term_is_T0 (t : term) : bool :=
  identical t T0.

```

In this development we have the need to be able to represent both the presence and the absence of a substitution. In case for example our `find_unifier` function cannot find a unifier for an input term, we need to be able to return a `subst nil` type, like a substitution option that states no substitution was found. We are using the built-in `Some` and `None` inductive options (that are used as `Some`  $\sigma$  and `None`) to represent some substitution and no substitution respectively. The type of the two above is the inductive `option {A:type}` that can be attached to any type; in our case it is `option subst`.

Our Lowenheim builder works when we provide an already existing unifier of the input term  $t$ . For our implementation to be complete we need to be able to generate that initial unifier ourselves. That is why we first need to define a function to find all possible “01” substitutions (substitutions where each variable gets mapped to T0 or T1).

```

Fixpoint all_01_substs (vars : var_set) : list subst :=

```

```

match vars with
| [] ⇒ []
| v :: v' ⇒ (map (fun s ⇒ (v, T0) :: s) (all_01_substs v')) ++
              (map (fun s ⇒ (v, T1) :: s) (all_01_substs v'))
end.

```

Next is a function to find an initial “ground unifier” for our Lowenheim builder function. It finds a substitution with ground terms that makes the given input term equivalent to T0.

```

Fixpoint find_unifier (t : term) : option subst :=
  find (fun s ⇒ match update_term t s with
    | T0 ⇒ true
    | _ ⇒ false
  end) (all_01_substs (term_unique_vars t)).

```

Here is the main Lowenheim’s formula; given a term, produce an MGU (a most general substitution that when applied on the input term, it makes it equivalent to T0), if there is one. Otherwise, return **None**. This function is often referred in the rest of the document as “Lowenheim Main” function or “Main Lowenheim” function, etc.

```

Definition Lowenheim_Main (t : term) : option subst :=
  match find_unifier t with
  | Some s ⇒ Some (build_lowenheim_subst t s)
  | None ⇒ None
  end.

```

### 3.4 Lowenheim’s Functions Testing

In this subsection we explore ways to test the correctness of our Lowenheim’s functions on specific inputs.

Here is a function to test the correctness of the output of the `find_unifier` helper function defined above. True means expected output was produced, false otherwise.

```

Definition Test_find_unifier (t : term) : bool :=
  match find_unifier t with
  | Some s ⇒ term_is_T0 (update_term t s)
  | None ⇒ true
  end.

```

Here is a function to apply Lowenheim’s substitution on the term - the substitution produced by the Lowenheim main function.

```

Definition apply_lowenheim_main (t : term) : term :=
  match Lowenheim_Main t with
  | Some s ⇒ apply_subst t s
  | None ⇒ T1
  end.

```



# Chapter 4

## Library

### B\_Unification.lowenheim\_proof

```
Require Export lowenheim_formula.  
Require Import List.  
Import ListNotations.  
Require Export EqNat.  
Require Import List.  
Import ListNotations.  
Import Coq.Init.Tactics.  
Require Export Classical_Prop.
```

#### 4.1 Introduction

In this chapter we provide a proof that our `Lowenheim_Main` function defined in `lowenheim_formula` provides a unifier that is most general. Our final top level proof (found at the end of this file) proves two statements: 1) If a term is unifiable, then our own defined `Lowenheim_Main` function produces a most general unifier (mgu). 2) If a term is not unifiable, then our own defined `Lowenheim_Main` function produces a `None` substitution. We prove the above statements with a series of proofs and sub-groups of proofs that help us get to the final top-level statements mentioned above.

#### 4.2 Auxillary Declarations and Their Lemmas Useful For the Final Proofs

In this section we provide definitions and proofs of helper functions, propositions, and lemmas that will be later used in other proofs.

This is the definition of an `under_term`. An `under_term` is a proposition, or a relationship between two terms. When a term  $t$  is an `under_term` of a term  $t'$  then each of the unique variables found within  $t$  are also found within the unique variables of  $t'$ .

Definition `under_term` ( $t : \text{term}$ ) ( $t' : \text{term}$ ) : Prop :=

$\forall (x : \text{var}),$   
 $\text{In } x (\text{term\_unique\_vars } t) \rightarrow \text{In } x (\text{term\_unique\_vars } t').$

This is a simple lemma for `under_terms` that states that a term is an `under_term` of itself.

Lemma `under_term_id` :  $\forall (t : \text{term}),$   
`under_term`  $t$   $t$ .

Proof.

`intros. firstorder.`

Qed.

This is a lemma to prove the summation distribution property of the function `term_vars`: the `term_vars` of a sum of two terms is equal to the concatenation of the `term_vars` of each individual term of the original sum.

Lemma `term_vars_distr` :  $\forall (t1\ t2 : \text{term}),$   
`term_vars` ( $t1 + t2$ ) = `term_vars`  $t1$  ++ `term_vars`  $t2$ .

Proof.

`intros.`  
`induction t2; auto.`

Qed.

This is a lemma to prove an intuitive statement: if a variable is within the `term_vars` (list of variables) of a term, then it is also within the `term_vars` of the sum of that term and any other term.

Lemma `tv_h1`:  $\forall (t1\ t2 : \text{term}) (x : \text{var}),$   
 $\text{In } x (\text{term\_vars } t1) \rightarrow \text{In } x (\text{term\_vars } (t1 + t2)).$

Proof.

`intros. induction t2.`  
`- simpl. rewrite app_nil_r. apply H.`  
`- simpl. rewrite app_nil_r. apply H.`  
`- simpl. pose proof in_or_app as H1. specialize (H1 var (term_vars t1) [v] x).`  
`firstorder.`  
`- rewrite term_vars_distr. apply in_or_app. left. apply H.`  
`- rewrite term_vars_distr. apply in_or_app. left. apply H.`

Qed.

This is a lemma similar to the previous one, to prove an intuitive statement: if a variable is within the `term_vars` (list of variables) of a term, then it is also within the `term_vars` of the sum of that term and any other term, but being added from the left side.

Lemma `tv_h2`:  $\forall (t1\ t2 : \text{term}) (x : \text{var}),$   
 $\text{In } x (\text{term\_vars } t2) \rightarrow \text{In } x (\text{term\_vars } (t1 + t2)).$

Proof.

```

intros. induction t1.
- simpl. apply H.
- simpl. apply H.
- simpl. pose proof in_or_app as H1. right. apply H.
- rewrite term_vars_distr. apply in_or_app. right. apply H.
- rewrite term_vars_distr. apply in_or_app. right. apply H.

```

Qed.

This is a helper lemma for the `under_term` relationship : if the sum of two terms is a subterm of another term  $t'$ , then the left component of the sum is also a subterm of the other term  $t'$ .

Lemma helper\_2a:  $\forall (t1\ t2\ t' : \text{term}),$   
 $\text{under\_term } (t1 + t2)\ t' \rightarrow \text{under\_term } t1\ t'.$

Proof.

```

intros. unfold under_term in *. intros. specialize (H x).
pose proof in_dup_and_non_dup as H10. unfold term_unique_vars.
unfold term_unique_vars in *. pose proof tv_h1 as H7. apply H.
specialize (H7 t1 t2 x). specialize (H10 x (term_vars (t1 + t2))).
destruct H10. apply H1. apply H7. pose proof in_dup_and_non_dup as H10.
specialize (H10 x (term_vars t1)). destruct H10. apply H4. apply H0.

```

Qed.

This is a helper lemma for the `under_term` relationship : if the sum of two terms is a subterm of another term  $t'$ , then the right component of the sum is also a subterm of the other term  $t'$ .

Lemma helper\_2b:  $\forall (t1\ t2\ t' : \text{term}),$   
 $\text{under\_term } (t1 + t2)\ t' \rightarrow \text{under\_term } t2\ t'.$

Proof.

```

intros. unfold under_term in *. intros. specialize (H x).
pose proof in_dup_and_non_dup as H10. unfold term_unique_vars.
unfold term_unique_vars in *. pose proof tv_h2 as H7. apply H.
specialize (H7 t1 t2 x). specialize (H10 x (term_vars (t1 + t2))).
destruct H10. apply H1. apply H7. pose proof in_dup_and_non_dup as H10.
specialize (H10 x (term_vars t2)). destruct H10. apply H4. apply H0.

```

Qed.

This is a helper lemma for lists and their elements: if a variable is a member of a list, then it is equal to the first element of that list or it is a member of the rest of the elements of that list.

Lemma elt\_in\_list:  $\forall (x: \text{var}) (a : \text{var}) (l : \text{list var}),$   
 $\text{In } x\ (a :: l) \rightarrow$   
 $x = a \vee \text{In } x\ l.$

Proof.

```

intros.
pose proof in_inv as H1.
specialize (H1 var a x l H).
destruct H1.
- left. symmetry in H0. apply H0.
- right. apply H0.
Qed.

```

This is a similar lemma to the previous one, for lists and their elements: if a variable is not a member of a list, then it is not equal to the first element of that list and it is not a member of the rest of the elements of that list.

Lemma `elt_not_in_list`:  $\forall (x : \text{var}) (a : \text{var}) (l : \text{list var}),$   
 $\neg \text{In } x (a :: l) \rightarrow$   
 $x \neq a \wedge \neg \text{In } x l.$

```

Proof.
  intros.
  pose proof not_in_cons. specialize (H0 var x a l). destruct H0.
  specialize (H0 H). apply H0.
Qed.

```

This is a lemma for an intuitive statement for the variables of a term: a variable  $x$  belongs to the list of unique variables (`term_unique_vars`) found within the variable-term that is constructed by variable itself `VAR x`.

Lemma `in_list_of_var_term_of_var`:  $\forall (x : \text{var}),$   
 $\text{In } x (\text{term\_unique\_vars } (\text{VAR } x)).$

```

Proof.
  intros. simpl. left. intuition.
Qed.

```

This is an intuitive lemma to prove that every element either belongs in any list or does not. Lemma `var_in_out_list`:  $\forall (x : \text{var}) (lvar : \text{list var}),$

$\text{In } x lvar \vee \neg \text{In } x lvar.$

```

Proof.
  intros.
  pose proof classic as H1. specialize (H1 (In x lvar)). apply H1.
Qed.

```

## 4.3 Proof That Lowenheim's Algorithm Unifies a Given Term

In this section, we prove that our own defined Lowenheim builder from `lowenheim_formula` (`build_lowenheim_subst`), produces a unifier; that is, given unifiable term and one unifier of the term, it also produces another unifier of this term (and as explained in the `terms` library,

a unifier is a substitution that when applied to term it produces a term equivalent to the ground term T0.

This is a helper lemma for the skeleton function defined in `lowenheim_formula`: If we apply a substitution on a term-variable VAR  $x$ , and that substitution is created by the skeleton function `build_on_list_of_vars` applied on a single input variable  $x$ , then the resulting term is equivalent to: the resuting term from applying a substitution on a term-variable VAR  $x$ , and that substitution being created by the skeleton function `build_on_list_of_vars` applied on an input list of variables that contains variable  $x$ .

Lemma helper1\_easy:  $\forall (x: \text{var}) (lvar : \text{list var})$   
 $(sig1 \ sig2 : \text{subst}) (s : \text{term}),$

`In x lvar →`  
`apply_subst (VAR x) (build_on_list_of_vars lvar s sig1 sig2) ==`  
`apply_subst (VAR x) (build_on_list_of_vars [x] s sig1 sig2).`

Proof.

```

intros.
induction lvar.
- simpl. simpl in H. destruct H.
- apply elt_in_list in H. destruct H.
  + simpl. destruct (beq_nat a x) as [eqn:?].
    × apply beq_nat_true in Heqb. destruct (beq_nat x x) as [eqn:?].
      - rewrite H. reflexivity.
      - apply beq_nat_false in Heqb.
        ++ destruct Heqb.
        ++ rewrite Heqb. apply Heqb0.
    × simpl in IHlvar. apply IHlvar. symmetry in H. rewrite H in Heqb.
      apply beq_nat_false in Heqb. destruct Heqb. intuition.
  + destruct (beq_nat a x) as [eqn:?].
    × apply beq_nat_true in Heqb. symmetry in Heqb. rewrite Heqb in IHlvar.
      rewrite Heqb. simpl in IHlvar. simpl. destruct (beq_nat a a) as [eqn:?].
      - reflexivity.
      - apply IHlvar. rewrite Heqb in H. apply H.
    × apply beq_nat_false in Heqb. simpl. destruct (beq_nat a x) as [eqn:?].
      - apply beq_nat_true in Heqb0. rewrite Heqb0 in Heqb. destruct Heqb.
        intuition.
      - simpl in IHlvar. apply IHlvar. apply H.

```

Qed.

This is another helper lemma for the skeleton function `build_on_list_of_vars` and it can be rephrased this way: applying two different substitutions on the same term-variable give the same result. One subsitution containing only one replacement, and for its own variable. The other subsitution contains the previous replacement but also more replacements for other variables (that are obviously not in the variables of our term-variable). So, the replacements for the extra variables do not affect the application of the subsitution - hence the resulting

term.

```

Lemma helper_1: ∀ (t' s : term) (v : var) (sig1 sig2 : subst),
  under_term (VAR v) t' →
  apply_subst (VAR v)
    (build_on_list_of_vars (term_unique_vars t') s sig1 sig2) ==
  apply_subst (VAR v)
    (build_on_list_of_vars (term_unique_vars (VAR v)) s sig1 sig2).

```

Proof.

```

intros. unfold under_term in H. specialize (H v).
pose proof in_list_of_var_term_of_var as H3. specialize (H3 v).
specialize (H H3). pose proof helper1_easy as H2.
specialize (H2 v (term_unique_vars t') sig1 sig2 s). apply H2. apply H.

```

Qed.

Lemma 10.4.5 from 'Term Rewriting and All That' book on page 254-255. This a very significant lemma used later for the proof that our Lownheim builder function (not the Main function, but the builder function), gives a unifier (not necessarily an mgu, which would be a next step of the proof). It states that if a term  $t$  is an `under_term` of another term  $t'$ , then applying a substitution—a substitution created by giving the list of variables of term  $t'$  on the skeleton function `build_list_of_vars`—, on the term  $t$ , a term that has the same format:  $(s + 1) * \sigma_1(t) + s * \sigma_2(t)$  as each replacement of each variable on any substitution created by skeleton function:  $(s + 1) * \sigma_1(x) + s * \sigma_2(x)$ .

```

Lemma subs_distr_vars_ver2 : ∀ (t t' s : term) (sig1 sig2 : subst),
  under_term t t' →
  apply_subst t (build_on_list_of_vars (term_unique_vars t') s sig1 sig2) ==
  (s + T1) × apply_subst t sig1 + s × apply_subst t sig2.

```

Proof.

```

intros. generalize dependent t'. induction t.
- intros t'. repeat rewrite ground_term_cannot_subst.
  + rewrite mul_comm with (x := s + T1). rewrite distr.
    repeat rewrite mul_T0_x. rewrite mul_comm with (x := s).
    rewrite mul_T0_x. repeat rewrite sum_x_x. reflexivity.
  + unfold ground_term. reflexivity.
  + unfold ground_term. reflexivity.
  + unfold ground_term. reflexivity.
- intros t'. repeat rewrite ground_term_cannot_subst.
  + rewrite mul_comm with (x := s + T1). rewrite mul_id.
    rewrite mul_comm with (x := s). rewrite mul_id.
    rewrite sum_comm with (x := s).
    repeat rewrite sum_assoc. rewrite sum_x_x.
    rewrite sum_comm with (x := T1). rewrite sum_id. reflexivity.
  + unfold ground_term. reflexivity.
  + unfold ground_term. reflexivity.

```

```

+ unfold ground_term. reflexivity.
- intros. rewrite helper_1.
+ unfold term_unique_vars. unfold term_vars. unfold var_set_create_unique.
  unfold var_set_includes_var. unfold build_on_list_of_vars.
  rewrite var_subst. reflexivity.
+ apply H.
- intros. specialize (IHt1 t'). specialize (IHt2 t').
  repeat rewrite subst_sum_distr_opp. rewrite IHt1. rewrite IHt2.
+ rewrite distr. rewrite distr. repeat rewrite sum_assoc.
  rewrite sum_comm with (x := (s + T1) × apply_subst t2 sig1)
    (y := s × apply_subst t1 sig2 + s × apply_subst t2 sig2).
  repeat rewrite sum_assoc.
  rewrite sum_comm with (x := s × apply_subst t2 sig2)
    (y := (s + T1) × apply_subst t2 sig1).
  repeat rewrite sum_assoc. reflexivity.
+ pose helper_2b as H2. specialize (H2 t1 t2 t'). apply H2. apply H.
+ pose helper_2a as H2. specialize (H2 t1 t2 t'). apply H2. apply H.
- intros. specialize (IHt1 t'). specialize (IHt2 t').
  repeat rewrite subst_mul_distr_opp. rewrite IHt1. rewrite IHt2.
+ rewrite distr.
  rewrite mul_comm with (y := (s + T1) × apply_subst t2 sig1).
  rewrite distr. rewrite mul_comm with (y := s × apply_subst t2 sig2).
  rewrite distr. repeat rewrite mul_assoc.
  repeat rewrite mul_comm with (x := apply_subst t2 sig1).
  repeat rewrite mul_assoc.
  rewrite mul_assoc_opp with (x := s + T1) (y := s + T1). rewrite mul_x_x.
  rewrite mul_assoc_opp with (x := s + T1) (y := s).
  rewrite mul_comm with (x := s + T1) (y := s). rewrite distr.
  rewrite mul_x_x. rewrite mul_id_sym. rewrite sum_x_x. rewrite mul_T0_x.
  repeat rewrite mul_assoc.
  rewrite mul_comm with (x := apply_subst t2 sig2).
  repeat rewrite mul_assoc.
  rewrite mul_assoc_opp with (x := s) (y := s + T1). rewrite distr.
  rewrite mul_x_x. rewrite mul_id_sym. rewrite sum_x_x. rewrite mul_T0_x.
  repeat rewrite sum_assoc. rewrite sum_assoc_opp with (x := T0) (y := T0).
  rewrite sum_x_x. rewrite sum_id. repeat rewrite mul_assoc.
  rewrite mul_comm with (x := apply_subst t2 sig2)
    (y := s × apply_subst t1 sig2).
  repeat rewrite mul_assoc. rewrite mul_assoc_opp with (x := s).
  rewrite mul_x_x. reflexivity.
+ pose helper_2b as H2. specialize (H2 t1 t2 t'). apply H2. apply H.
+ pose helper_2a as H2. specialize (H2 t1 t2 t'). apply H2. apply H.

```

Qed.

This is an intermediate lemma occurring by the previous lemma 10.4.5. Utilizing lemma 10.4.5 and also using two substitutions for the skeleton function *build\_on\_list\_vars* gives a substitution that unifies the term; the two substitutions being a known unifier of the term and the identity substitution.

Lemma *specific\_sigmas\_unify*:  $\forall (t : \mathbf{term}) (tau : \mathbf{subst}),$   
 $\mathbf{unifier} \ t \ tau \rightarrow$   
 $\mathbf{apply\_subst} \ t \ (\mathbf{build\_on\_list\_of\_vars}$   
 $\quad (\mathbf{term\_unique\_vars} \ t) \ t \ (\mathbf{build\_id\_subst} \ (\mathbf{term\_unique\_vars} \ t))$   
 $\quad tau) ==$

T0.

Proof.

intros.  
 rewrite *subs\_distr\_vars\_ver2*.  
 - rewrite *id\_subst*. rewrite *mul\_comm* with  $(x := t + T1)$ . rewrite *distr*.  
   rewrite *mul\_x\_x*. rewrite *mul\_id\_sym*. rewrite *sum\_x\_x*. rewrite *sum\_id*.  
   unfold *unifier* in *H*. rewrite *H*. rewrite *mul\_T0\_x\_sym*. reflexivity.  
 - apply *under\_term\_id*.

Qed.

This is the resulting lemma from this subsection: Our Lowenheim's substitution builder produces a unifier for an input term; namely, a substitution that unifies the term, given that term is unifiable and we know an already existing unifier  $\tau$ .

Lemma *lowenheim\_unifies*:  $\forall (t : \mathbf{term}) (tau : \mathbf{subst}),$   
 $\mathbf{unifier} \ t \ tau \rightarrow$   
 $\mathbf{apply\_subst} \ t \ (\mathbf{build\_lowenheim\_subst} \ t \ tau) == T0.$

Proof.

intros. unfold *build\_lowenheim\_subst*. apply *specific\_sigmas\_unify*. apply *H*.

Qed.

## 4.4 Proof That Lowenheim's Algorithm Produces a Most General Unifier

In the previous section we proved that our Lowenheim builder produces a unifier, if we already know an existing unifier of the term. In this section we prove that that unifier is a most general unifier.



### 4.4.1 Proof That Lowenheim's Algorithm Produces a Reproductive Unifier

In this subsection we will prove that our Lowenheim builder gives a unifier that is reproductive; this will help us in the proof that the resulting unifier is an mgu, since a reproductive unifier is a “stronger” property than an mgu.

This is a lemma for an intuitive statement for the skeleton function *build\_on\_list\_vars*: if a variable  $x$  is in a list  $l$ , and we apply a substitution created by the *build\_on\_list\_vars* function given input list  $l$ , on the term-variable  $\text{VAR } x$ , then we get the replacement for that particular variable that was contained in the original substitution. So basically if *build\_on\_list\_of\_vars* is applied on a list of variables  $l$  ( $x_1, x_2, x_3, \dots, x_n$ ), then the resulting substitution is in the format  $x_i \mapsto (s+1) * \sigma_1(x_i) + s * \sigma_2(x_i)$  for each  $x_i$ . If we apply that substitution on the term-variable  $x_1$ , *wewillgettheinitialformatofthereplacement* :  $(s + 1) \backslash \text{ast } \backslash \text{sigma}\{1\}(x\{1\}) + s \backslash \text{ast } \backslash \text{sigma}\{2\}(x\{1\})$ . *It can be thought as “reverse application” of the skeleton function.*

Lemma lowenheim\_rephrase1\_easy :  $\forall (l : \text{list var}) (x : \text{var})$   
 $(sig1 \ sig2 : \text{subst}) (s : \text{term}),$

$\text{In } x \ l \rightarrow$   
 $\text{apply\_subst } (\text{VAR } x) (\text{build\_on\_list\_of\_vars } l \ s \ sig1 \ sig2) ==$   
 $(s + \text{T1}) \times \text{apply\_subst } (\text{VAR } x) \ sig1 + s \times \text{apply\_subst } (\text{VAR } x) \ sig2.$

Proof.

intros.  
induction l.  
- simpl. unfold  $\text{In}$  in  $H$ . destruct  $H$ .  
- apply elt\_in\_list in  $H$ . destruct  $H$ .  
+ simpl. destruct ( $\text{beq\_nat } a \ x$ ) as  $\llbracket eqn \rrbracket ?$ .  
 $\times$  rewrite  $H$ . reflexivity.  
 $\times$  pose proof  $\text{beq\_nat\_false}$  as  $H2$ . specialize ( $H2 \ a \ x$ ).  
specialize ( $H2 \ Heqb$ ). intuition. symmetry in  $H$ . specialize ( $H2 \ H$ ).  
inversion  $H2$ .  
+ simpl. destruct ( $\text{beq\_nat } a \ x$ ) as  $\llbracket eqn \rrbracket ?$ .  
 $\times$  symmetry in  $Heqb$ . pose proof  $\text{beq\_nat\_eq}$  as  $H2$ . specialize ( $H2 \ a \ x$ ).  
specialize ( $H2 \ Heqb$ ). rewrite  $H2$ . reflexivity.  
 $\times$  apply  $IHL$ . apply  $H$ .

Qed.

This is a helper lemma for an intuitive statement: if a variable  $x$  is found in a list of variables  $l$ , then applying the substitution created by the *build\_id\_subst* function given input list  $l$ , on the term-variable  $\text{VAR } x$ , we will get the same  $\text{VAR } x$  back.

Lemma helper\_3a:  $\forall (x : \text{var}) (l : \text{list var}),$

$\text{In } x \ l \rightarrow$   
 $\text{apply\_subst } (\text{VAR } x) (\text{build\_id\_subst } l) == \text{VAR } x.$

Proof.

intros. induction l.

```

- unfold build_id_subst. simpl. reflexivity.
- apply elt_in_list in H. destruct H.
  + simpl. destruct (beq_nat a x) as [eqn:?.
    × rewrite H. reflexivity.
    × pose proof beq_nat_false as H2. specialize (H2 a x).
      specialize (H2 Heqb). intuition. symmetry in H. specialize (H2 H).
      inversion H2.
  + simpl. destruct (beq_nat a x) as [eqn:?.
    × symmetry in Heqb. pose proof beq_nat_eq as H2. specialize (H2 a x).
      specialize (H2 Heqb). rewrite H2. reflexivity.
    × apply IHL. apply H.

```

Qed.

This is a lemma for an intuitive statement for the Lowenheim builder, very similar to lemma `lowenheim_rephrase1_easy`: applying Lowenheim's substitution given an input term  $t$ , on any term-variable of the term  $t$ , gives us the initial format of the replacement for that variable (Lowenheim's reverse application).

Lemma `lowenheim_rephrase1` :  $\forall (t : \text{term}) (tau : \text{subst}) (x : \text{var}),$   
 $\text{unifier } t \text{ tau} \rightarrow$   
 $\text{In } x (\text{term\_unique\_vars } t) \rightarrow$   
 $\text{apply\_subst } (\text{VAR } x) (\text{build\_lowenheim\_subst } t \text{ tau}) ==$   
 $(t + \text{T1}) \times (\text{VAR } x) + t \times \text{apply\_subst } (\text{VAR } x) \text{ tau}.$

Proof.

```

intros.
unfold build_lowenheim_subst. pose proof lowenheim_rephrase1_easy as H1.
specialize (H1 (term_unique_vars t) x
  (build_id_subst (term_unique_vars t)) tau t).
rewrite helper_3a in H1.
- apply H1. apply H0.
- apply H0.

```

Qed.

This is a lemma for an intuitive statement for the skeleton function `build_on_list_vars` that resembles a lot of `lowenheim_rephrase1_easy`: if a variable  $x$  is not in a list  $l$ , and we apply a substitution created by the `build_on_list_vars` function given input list  $l$ , on the term-variable `VAR  $x$` , then we get the term-variable `VAR  $x$`  back; that is expected since the replacements in the substitution should not contain any entry with variable  $x$ .

Lemma `lowenheim_rephrase2_easy` :  $\forall (l : \text{list var}) (x : \text{var})$   
 $(sig1 \text{ sig2} : \text{subst}) (s : \text{term}),$   
 $\neg (\text{In } x l) \rightarrow$   
 $\text{apply\_subst } (\text{VAR } x) (\text{build\_on\_list\_of\_vars } l s \text{ sig1 sig2}) ==$   
 $\text{VAR } x.$

Proof.

```

intros. unfold not in H.
induction l.
- simpl. reflexivity.
- simpl. pose proof elt_not_in_list as H2. specialize (H2 x a l).
  unfold not in H2. specialize (H2 H). destruct H2.
  destruct (beq_nat a x) as [eqn:?].
  + symmetry in Heqb. apply beq_nat_eq in Heqb. symmetry in Heqb.
    specialize (H0 Heqb). destruct H0.
  + simpl in IHL. apply IHL. apply H1.

```

Qed.

This is a lemma for an intuitive statement for the Lowenheim builder, very similar to lemma `lowenheim_rephrase2_easy` and `lowenheim_rephrase1`: applying Lowenheim's substitution given an input term  $t$ , on any term-variable not of the ones of term  $t$ , gives us back the same term-variable.

```

Lemma lowenheim_rephrase2 : ∀ (t : term) (tau : subst) (x : var),
  unifier t tau →
  ¬ (In x (term_unique_vars t)) →
  apply_subst (VAR x) (build_lowenheim_subst t tau) ==
  VAR x.

```

Proof.

```

intros. unfold build_lowenheim_subst.
pose proof lowenheim_rephrase2_easy as H2.
specialize (H2 (term_unique_vars t) x
  (build_id_subst (term_unique_vars t)) tau t).
specialize (H2 H0). apply H2.

```

Qed.

This is the resulting lemma of the section: our Lowenheim builder `build_lowenheim_subst` gives a reproductive unifier.

```

Lemma lowenheim_reproductive: ∀ (t : term) (tau : subst),
  unifier t tau →
  reproductive_unifier t (build_lowenheim_subst t tau).

```

Proof.

```

intros. unfold reproductive_unifier. intros.
pose proof var_in_out_list. split.
- apply lowenheim_unifies. apply H.
- intros. specialize (H0 x (term_unique_vars t)). destruct H0.
  + rewrite lowenheim_rephrase1.
    × rewrite subst_sum_distr_opp. rewrite subst_mul_distr_opp.
      rewrite subst_mul_distr_opp. unfold unifier in H1. rewrite H1.
      rewrite mul_T0_x. rewrite subst_sum_distr_opp. rewrite H1.
      rewrite ground_term_cannot_subst.

```

```

    - rewrite sum_id. rewrite mul_id. rewrite sum_comm. rewrite sum_id.
      reflexivity.
    - unfold ground_term. intuition.
  × apply H.
  × apply H0.
+ rewrite lowenheim_rephrase2.
  × reflexivity.
  × apply H.
  × apply H0.

```

Qed.

#### 4.4.2 Proof That Lowenheim’s Algorithm Produces a Most General Unifier

In this subsection we will prove that our Lowenheim builder gives a unifier that is most general; this will help us a lot in the top-level proof that the *Main\_Lownheim* function gives an mgu.

Here is the subsection’s resulting lemma. Given a unifiable term  $t$ , a unifier of  $t$ , then our Lowenheim builder (*build\_lowenheim\_subst*) gives a most general unifier (mgu).

Lemma *lowenheim\_most\_general\_unifier*:  $\forall (t : \mathbf{term}) (tau : \mathbf{subst}),$   
     unifier  $t \ tau \rightarrow$   
     most\_general\_unifier  $t (build\_lowenheim\_subst \ t \ tau).$

Proof.

```

  intros. apply reproductive_is_mgu. apply lowenheim_reproductive. apply H.

```

Qed.

### 4.5 Proof of Correctness of Lowenheim\_Main

In this section we prove that our own defined Lowenheim function satisfies its two main requirements: 1) If a term is unifiable, then *Lowenheim\_Main* function produces a most general unifier (mgu). 2) If a term is not unifiable, then *Lownheim\_Main* function produces a **None** substitution. The final top-level proof is at the end of this section. To get there, we prove a series of intermediate lemmas that are needed for the final proof.

#### 4.5.1 Utilities

In this section we provide helper “utility” lemmas and functions that are used in the proofs of intermediate lemmas that are in turn used in the final proof.

## General Utilities Used in the Final Proof Steps

This is a function that converts an **option** subst to a **subst**. It is designed to be used mainly for **option** substs that are **Some**  $\sigma$ . If the input **option** subst is not **Some** and is **None** then it returns the **nil** substitution, but that case should not normally be considered. This function is useful because many functions and lemmas are defined for the substitution type not the option substitution type.

Definition `convert_to_subst` ( $so : \text{option subst}$ ) : **subst** :=

```
match so with
| Some s  $\Rightarrow$  s
| None  $\Rightarrow$  []
end.
```

This is an intuitive helper lemma that proves that if an empty substitution is applied on any term  $t$ , then the resulting term is the same input term  $t$ .

Lemma `empty_subst_on_term`:  $\forall (t : \text{term})$ ,

`apply_subst t [] == t`.

Proof.

```
intros. induction t.
- reflexivity.
- simpl. reflexivity.
- simpl. reflexivity.
- simpl. rewrite IHt1. rewrite IHt2. reflexivity.
- simpl. rewrite IHt1. rewrite IHt2. reflexivity.
```

Qed.

This another intuitive helper lemma that states that if the empty substitution is applied on any term  $t$ , and the resulting term is equivalent to the ground term `T0`, then the input term  $t$  must be equivalent to the ground term `T0`.

Lemma `app_subst_T0`:  $\forall (t : \text{term})$ ,

`apply_subst t [] == T0  $\rightarrow$  t == T0`.

Proof.

```
intros. rewrite empty_subst_on_term in H. apply H.
```

Qed.

This is another intuitive lemma that uses classical logic for its proof. It states that any term  $t$ , can be equivalent to the ground term `T0` or it cannot be equivalent to it.

Lemma `T0_or_not_T0`:  $\forall (t : \text{term})$ ,

$t == T0 \vee \neg t == T0$ .

Proof.

```
intros. pose proof classic. specialize (H (t == T0)). apply H.
```

Qed.

This is another intuitive helper lemma that states: if applying a substitution  $\sigma$  on a term  $t$  gives a term equivalent to `T0` then there exists a substitution that applying it to term

$t$  gives a term equivalent to  $T0$  (which is obvious since we already know  $\sigma$  exists for that task).

Lemma exists\_subst:  $\forall (t : \text{term}) (sig : \text{subst}),$   
 $\text{apply\_subst } t \text{ sig} == T0 \rightarrow \exists s, \text{apply\_subst } t s == T0.$

Proof.

intros.  $\exists sig. \text{apply } H.$

Qed.

Lemma t\_id\_eqv :  $\forall (t : \text{term}),$   
 $t == t.$

Proof.

intros. reflexivity.

Qed.

This a helper lemma that states: if two *options* **subst**s (specifically **Some**) are equal then the substitutions contained within the **option subst** are also equal.

Lemma eq\_some\_eq\_subst ( $s1 \ s2 : \text{subst}$ ) :  
 $\text{Some } s1 = \text{Some } s2 \rightarrow s1 = s2.$

Proof.

intros. congruence.

Qed.

This a helper lemma that states: if the **find\_unifier** function (the one that tries to find a ground unifier for term  $t$ ) does not find a unifier (returns **None**) for an input term  $t$  then it not **True** (true not in “boolean format” but as a proposition) that the **find\_unifier** function produces a **Some subst**. This lemma and the following ones that are similar, are very useful for the intermediate proofs because we are able to convert a proposition about the return type of the **find\_unifier** function to an equivalent one, e.g. from **None subst** to **Some subst** and vice versa.

Lemma None\_is\_not\_Some ( $t : \text{term}$ ):  
 $\text{find\_unifier } t = \text{None} \rightarrow$   
 $\forall (sig : \text{subst}), \neg \text{find\_unifier } t = \text{Some } sig.$

Proof.

intros. congruence.

Qed.

This a helper lemma similar to the previous one that states: if the **find\_unifier** function (the one that tries to find a ground unifier for term  $t$ ) finds a unifier (returns **Some  $\sigma$** ) for an input term  $t$  then it is not **True** (true not in “boolean format” but as a proposition) that the **find\_unifier** function produces a **None subst**.

Lemma Some\_is\_not\_None ( $sig : \text{subst}$ ) ( $t : \text{term}$ ):  
 $\text{find\_unifier } t = \text{Some } sig \rightarrow \neg \text{find\_unifier } t = \text{None}.$

Proof.

intros. congruence.

Qed.

This is a helper lemma similar to the previous ones that states: if the `find_unifier` function (the one that tries to find a ground unifier for term  $t$ ) does not find a unifier that returns `None` for an input term  $t$  then it is **True** (true not in “boolean format” but as a proposition) that the `find_unifier` function produces a `Some` subst.

Lemma `not_None_is_Some` ( $t$ : **term**) :

$\neg \text{find\_unifier } t = \text{None} \rightarrow$   
 $\exists \text{ sig} : \text{subst}, \text{find\_unifier } t = \text{Some sig}.$

Proof.

`intros H.`  
`destruct (find_unifier t) as [ti | ].`  
`-  $\exists ti$ . firstorder.`  
`- congruence.`

Qed.

This is an intuitive helper lemma that uses classical logic to prove the validity of an alternate version of the contrapositive proposition: if  $p$  then  $q$  implies if not  $q$  then not  $p$ , but with each entity (proposition  $q$  and  $p$ ) negated.

Lemma `contrapositive_opposite` :  $\forall p q$ ,

$(\neg p \rightarrow \neg q) \rightarrow$   
 $q \rightarrow p.$

Proof.

`intros. apply NNPP. firstorder.`

Qed.

This is an intuitive helper lemma that uses classical logic to prove the validity of the contrapositive proposition: if  $p$  then  $q$  implies not  $q$  then not  $p$ .

Lemma `contrapositive` :  $\forall (p q : \text{Prop})$ ,

$(p \rightarrow q) \rightarrow$   
 $(\neg q \rightarrow \neg p).$

Proof.

`intros. firstorder.`

Qed.

The following five lemmas are also helper lemmas.

Lemma `None_not_Some`  $\{T U : \text{Type}\} (f : U \rightarrow \text{option } T) (x : U)$ :

$(f x) = \text{None} \rightarrow (\forall (t : T), \neg (f x) = \text{Some } t).$

Proof.

`intros H1 H2 H3.`  
`congruence.`

Qed.

Lemma `Some_not_None`  $\{T U : \text{Type}\} (f : U \rightarrow \text{option } T) (x : U) (t : T)$ :

$(f x) = \text{Some } t \rightarrow \neg (f x) = \text{None}.$

Proof.

intros *H1 H2*.

congruence.

Qed.

Lemma not\_None\_Some {*T U*: Type} (*f* : *U* → option *T*) (*x*: *U*) :  
¬ (*f* *x* = None) → ∃ *t* : *T*, *f* *x* = Some *t*.

Proof.

intros *H*.

destruct (*f* *x*) as [*t* | ].

- ∃ *t*; *easy*.

- congruence.

Qed.

Lemma not\_Some\_None {*T U*: Type} (*f* : *U* → option *T*) (*x*: *U*) :  
(¬ ∃ *t* : *T*, *f* *x* = Some *t*) → *f* *x* = None.

Proof.

apply contrapositive\_opposite.

intros *H*.

apply not\_None\_Some in *H*.

tauto.

Qed.

Lemma existsb\_find {*T*: Type} (*f*: *T* → bool) (*l* : list *T*) :  
existsb *f* *l* = true →  
∃ (*a*: *T*), find *f* *l* = Some *a*.

Proof.

intros *H*.

apply NNPP.

intros *H1*.

apply not\_Some\_None in *H1*.

assert (*A1*:= find\_none *f* *l*).

assert (*A2*:= *A1* *H1*).

assert (*A3*:= existsb\_exists *f* *l*).

destruct *A3* as [*A31 A32*].

assert (*A4*:= *A31* *H*).

destruct *A4* as [*t A41*]. destruct *A41* as [*A411 A412*].

assert (*A21*:= *A2* *t* *A411*).

rewrite *A412* in *A21*.

congruence.

Qed.



## Utilities Used in the Final Proof Case That $t$ is Unifiable

In this section we are defining a number of functions and lemmas that are used in the proof of the `unif_some_subst` lemma in the intermediate lemmas section that follows this utilities section. We are focusing on connecting the concept of a “01” substitution with any given substitution. We are attempting to create a “01” substitution given any input substitution, and then prove facts about the new “01” substitution.

This is a function to build a `T0 subst`, a substitution that maps each variable to `T0`, given an input list of variables. **Definition** `build_T0_subst` ( $lvar : \text{list var}$ ) : `subst` :=

```
map (fun v => (v, T0)) lvar.
```

Next is a function to build a `T0 subst`, given an input term  $t$ . **Definition** `build_T0_subst_from_t` ( $t : \text{term}$ ) : `subst` :=

```
build_T0_subst (term_unique_vars t).
```

With the following four helper functions, we are trying to create a final function that does the following: 1) Given any substitution, it produces a “01” substitution building off the given substitution. 2) It does that by composing two substitutions  $s1$  and  $s1b$  into a new one,  $s2$ . 3) It creates  $s1b$  from  $s1$ .  $s1b$  is a “01” substitution and so is  $s2$ .

Here is the function to create the  $s1b$  “01” substitution, by mapping all the second parts of each replacement of the substitution using the following rules: 1) All the variables of non-ground terms are mapped to `T0` and all ground terms are mapped to their simplified “01” version. Therefore the substitution occurring from this function is a “01” substitution.

**Fixpoint** `make_unif_subst` ( $\tau : \text{subst}$ ) : `subst` :=

```
match tau with
| [] => []
| (first, second) :: rest' =>
  if is_ground_term second
  then (first, simplify second) :: (make_unif_subst rest')
  else (build_T0_subst_from_t second) ++ (make_unif_subst rest')
end.
```

This function creates a list of identity replacements, for all the variables of the  $lvar$  list input that are not in  $lvar\_s$  list input. The  $lvar\_s$  list input is supposedly the list with the variables of a substitution and we are trying eventually to augment the substitution with an identity substitution. **Fixpoint** `augment_with_id` ( $lvar\_s : \text{list var}$ ) ( $lvar : \text{list var}$ ) : `subst` :=

```
match lvar with
| [] => []
| v :: v' =>
  if var_set_includes_var v lvar_s
  then augment_with_id lvar_s v'
  else (v, VAR v) :: (augment_with_id lvar_s v')
end.
```

This function adds the identity substitution to the input substitution. **Definition**

```

add_id_subst (t : term) (tau : subst) : subst :=
  augment_with_id (subst_domain tau) (term_unique_vars t) ++ tau.

```

This is the resulting function that given any substitution for a term, produces a “01” substitution. Even though this function is not directly called by name, its implementation is directly used. So whenever in the future comments there is a reference to a `convert_to_01_subst`, what is meant is essentially the composition of the `make_unif_subst` substitution and the input substitution `tau` - or the resulting substitution `s2`, by composing `s1` and `s1b`. Definition

```

convert_to_01_subst (tau : subst) (t : term) : subst :=
  subst_compose (make_unif_subst (add_id_subst t tau)) (add_id_subst t tau).

```

The following lemmas are about facts for the “01” substitutions and our `convert_to_01_subst` function. These lemmas are very important for the intermediate lemmas section where in the `unifiable t` case we are trying to prove that when there exists any substitution for a term `t`, then there exists a “01” substitution.

This is an intuitive lemma that states that adding an identity substitution to an existing unifier of a term gives another unifier. Lemma `add_id_unf` :  $\forall (t : \text{term}) (sig1 : \text{subst})$ ,

```

unifier t sig1 →
unifier t (add_id_subst t sig1).

```

Proof.

```

intros. induction sig1.
- induction t.
  + unfold unifier in *. simpl in *. apply H.
  + unfold unifier in *. simpl in *. apply H.
  + unfold unifier in *. simpl in *. destruct PeanoNat.Nat.eqb. apply H.
    apply H.
  + unfold unifier in *. simpl in *. unfold add_id_subst. simpl.

```

*Admitted.*

This lemma states two facts, given a term `t` and a unifier `sig1` of `t`: 1) The `convert_to_01_subst` substitution is also a unifier. 2) Applying the `convert_to_01_subst` substitution on the term results in a term that is ground. Lemma `unif_grnd_unif` :  $\forall (t : \text{term}) (sig1 : \text{subst})$ ,

```

unifier t sig1 →
(unifier t (subst_compose (make_unif_subst (add_id_subst t sig1))
  (add_id_subst t sig1))) ∧
(is_ground_term
  (apply_subst t (subst_compose (make_unif_subst (add_id_subst t sig1))
    (add_id_subst t sig1)))) = true.

```

Proof.

```

intros. split.
- unfold unifier. unfold unifier in H. rewrite subst_compose_eqv.
  pose proof add_id_unf. specialize (H0 t sig1). unfold unifier in H0.
  specialize (H0 H). rewrite H0. simpl. reflexivity.
- admit.

```

*Admitted.*

If a substitution *sig1* is a “01” substitution and the domain of the substitution is a subset of a list of variable *l1* then the substitution *sig1* is an element of all the “01” substitutions of that list *l1*. Lemma `_01_in_all` :  $\forall (l1 : \text{list var}) (sig : \text{subst}),$

`is_01_subst sig = true  $\wedge$  sub_dmn_list l1 (subst_domain sig)  $\rightarrow$`   
`In sig (all_01_substs l1).`

Proof.

`intros. destruct H. unfold is_01_subst in H.`

*Admitted.*

Here is a specialized format of the `_01_in_all` lemma. Instead of *l1* we have `term_unique_vars t`. Lemma `_01_in_rec` :  $\forall (t : \text{term}) (sig : \text{subst}),$

`is_01_subst sig = true  $\wedge$`   
`sub_dmn_list (term_unique_vars t) (subst_domain sig)  $\rightarrow$`   
`In sig (all_01_substs (term_unique_vars t)).`

Proof.

`intros.`  
`pose proof _01_in_all.`  
`specialize (H0 (term_unique_vars t) sig).`  
`apply H0. apply H.`

Qed.

Here is a lemma to show that given a unifier *sig1* of *t*, then the `convert_to_01_subst` substitution is a “01” subst and also the variables of term *t* are a subset of the domain of the `convert_to_01_subst` substitution. Lemma `make_unif_is_01` :  $\forall (t : \text{term}) (sig1 : \text{subst}),$

`unifier t sig1  $\rightarrow$`   
`is_01_subst (subst_compose (make_unif_subst (add_id_subst t sig1))`  
`(add_id_subst t sig1)) = true  $\wedge$`   
`sub_dmn_list`  
`(term_unique_vars t)`  
`(subst_domain (subst_compose (make_unif_subst (add_id_subst t sig1))`  
`(add_id_subst t sig1))).`

Proof.

`intros.`

*Admitted.*

This is a lemma to show that given a unifier of term *t*, then there exists a substitution *sig2* that 1) belongs to all the “01” substitutions of term *t* and it also unifies *t*, by making *t* equal to T0 when applied on it (it is equal, not just equivalent because we want *sig2* to be a ground substitution too). Lemma `unif_exists_grnd_unif` :  $\forall (t : \text{term}) (sig1 : \text{subst}),$

`unifier t sig1  $\rightarrow$`   
 `$\exists$  sig2 : subst,`  
`In sig2 (all_01_substs (term_unique_vars t))  $\wedge$`   
`match update_term t sig2 with`

```

| T0 ⇒ true
| _ ⇒ false
end = true.

```

Proof.

```

intros. ∃ (subst_compose (make_unif_subst (add_id_subst t sig1))
  (add_id_subst t sig1)). split.
- pose proof _01_in_rec as H1.
  specialize (H1 t (subst_compose (make_unif_subst (add_id_subst t sig1))
    (add_id_subst t sig1))).
  pose proof make_unif_is_01 as H2. specialize (H2 t sig1).
  specialize (H2 H).
  specialize (H1 H2). apply H1.
- pose proof unif_grnd_unif. specialize (H0 t sig1 H). destruct H0.
  unfold unifier in H0. unfold update_term. pose proof simplify_eqv.
  specialize (H2 (apply_subst t (subst_compose (make_unif_subst
    (add_id_subst t sig1)) (add_id_subst t sig1)))).
  symmetry in H2. pose proof trans_compat2. symmetry in H0.
  specialize (H3 T0 (apply_subst t (subst_compose (make_unif_subst
    (add_id_subst t sig1)) (add_id_subst t sig1))) (simplify (apply_subst t
    (subst_compose (make_unif_subst (add_id_subst t sig1))
    (add_id_subst t sig1)))).
  specialize (H3 H0 H2). symmetry in H3. pose proof simplify_eq_T0.
  specialize (H4 (apply_subst t (subst_compose (make_unif_subst
    (add_id_subst t sig1)) (add_id_subst t sig1)))).
  symmetry in H0. rewrite H4.
+ reflexivity.
+ split.
  × apply H0.
  × apply H1.

```

Qed.

## 4.5.2 Intermediate Lemmas

In this subsection we prove a series of lemmas for each of the two statements of the final proof, which were: 1) if a term is unifiable, then `Lowenheim_Main` function produces a most general unifier (mgu). 2) if a term is not unifiable, then `Lowenheim_Main` function produces a `None` substitution.

### Not unifiable $t$ case

In this section we prove intermediate lemmas useful for the second statement of the final proof: if a term is not unifiable, then `Lowenheim_Main` function produces a `None` substitution.

This is a lemma to show that if `find_unifier` returns `Some subst`, the term is unifiable.  
 Lemma `some_subst_unifiable`:  $\forall (t : \text{term}),$   
 $(\exists \text{sig}, \text{find\_unifier } t = \text{Some sig}) \rightarrow$   
 unifiable  $t$ .

Proof.

```

intros.
destruct H as [sig1 H1].
induction t.
- unfold unifiable.  $\exists []$ . unfold unifier. simpl. reflexivity.
- simpl in H1. inversion H1.
- unfold unifiable.  $\exists \text{sig1}$ . unfold find_unifier in H1.
  apply find_some in H1. destruct H1.
  remember (update_term (VAR v) sig1) in H0.
  destruct t.
  + unfold update_term in Heqt. pose proof simplify_eqv.
    specialize (H1 (apply_subst (VAR v) sig1)). unfold unifier.
    symmetry in Heqt. rewrite Heqt in H1. rewrite H1. reflexivity.
  + inversion H0.
  + inversion H0.
  + inversion H0.
  + inversion H0.
- unfold unifiable.  $\exists \text{sig1}$ . unfold find_unifier in H1.
  apply find_some in H1. destruct H1.
  remember (update_term (t1 + t2) sig1) in H0.
  destruct t.
  + unfold update_term in Heqt. pose proof simplify_eqv.
    specialize (H1 (apply_subst (t1 + t2) sig1)).
    symmetry in Heqt. unfold unifier. rewrite Heqt in H1. rewrite H1.
    reflexivity.
  + inversion H0.
  + inversion H0.
  + inversion H0.
  + inversion H0.
- unfold unifiable.  $\exists \text{sig1}$ . unfold find_unifier in H1.
  apply find_some in H1. destruct H1.
  remember (update_term (t1  $\times$  t2) sig1) in H0.
  destruct t.
  + unfold update_term in Heqt. pose proof simplify_eqv.
    specialize (H1 (apply_subst (t1  $\times$  t2) sig1)).
    symmetry in Heqt. unfold unifier. rewrite Heqt in H1. rewrite H1.
    reflexivity.
  + inversion H0.
```

```

+ inversion H0.
+ inversion H0.
+ inversion H0.

```

Qed.

This lemma shows that if no substitution makes `find_unifier` to return `Some subst`, then it returns `None`. Lemma `not_Some_is_None (t: term) :`

```

¬ (∃ sig, find_unifier t = Some sig) →
find_unifier t = None.

```

Proof.

```

apply contrapositive_opposite.
intros H.
apply not_None_is_Some in H.
tauto.

```

Qed.

This is a lemma to show that if a term  $t$  is not unifiable, the `find_unifier` function returns `None` with  $t$  as input. Lemma `not_unifiable_find_unifier_none_subst : ∀ (t : term),`

```

¬ unifiable t → find_unifier t = None.

```

Proof.

```

intros.
pose proof some_subst_unifiable.
specialize (H0 t).
pose proof contrapositive.
specialize (H1 (∃ sig : subst, find_unifier t = Some sig) (unifiable t)).
specialize (H1 H0). specialize (H1 H).
pose proof not_Some_is_None.
specialize (H2 t H1).
apply H2.

```

Qed.

## Unifiable $t$ Case

In this section we prove intermediate lemmas useful for the first statement of the final proof: if a term is unifiable, then `Lowenheim_Main` function produces a most general unifier (mgu).

Lemma to show that if `find_unifier` on an input term  $t$  returns `Some  $\sigma$` , then  $\sigma$  is a unifier of  $t$ . Lemma `Some_subst_unifiable : ∀ (t : term) (sig : subst),`

```

find_unifier t = Some sig → unifier t sig.

```

Proof.

```

intros. unfold find_unifier in H.
induction t.
- simpl in H. apply eq_some_eq_subst in H. symmetry in H. rewrite H.
  unfold unifier. simpl. reflexivity.
- simpl in H. inversion H.

```

```

- unfold find_unifier in H. apply find_some in H. destruct H.
  remember (update_term (VAR v) sig) in H0.
  destruct t.
  + unfold unifier. unfold update_term in Heqt. pose proof simplify_eqv.
    specialize (H1 (apply_subst (VAR v) sig) ). symmetry in Heqt.
    rewrite Heqt in H1. rewrite H1. reflexivity.
  + inversion H0.
  + inversion H0.
  + inversion H0.
  + inversion H0.
- unfold find_unifier in H. apply find_some in H. destruct H.
  remember (update_term (t1 + t2) sig) in H0.
  destruct t.
  + unfold unifier. unfold update_term in Heqt. pose proof simplify_eqv.
    specialize (H1 (apply_subst (t1 + t2) sig) ). symmetry in Heqt.
    rewrite Heqt in H1. rewrite H1. reflexivity.
  + inversion H0.
  + inversion H0.
  + inversion H0.
  + inversion H0.
- unfold find_unifier in H. apply find_some in H. destruct H.
  remember (update_term (t1 × t2) sig) in H0.
  destruct t.
  + unfold unifier. unfold update_term in Heqt. pose proof simplify_eqv.
    specialize (H1 (apply_subst (t1 × t2) sig) ). symmetry in Heqt.
    rewrite Heqt in H1. rewrite H1. reflexivity.
  + inversion H0.
  + inversion H0.
  + inversion H0.
  + inversion H0.

```

Qed.

This lemma is the one using all the utilities defined in the utilities section for the **unifiable** **t** case. It states that if there is a unifier *sig1* for term *t* then there exists some substitution *sig2* for which the **find\_unifier** function returns **Some** *sig2*. Here is the main outline of the proof: As done in the utilities section, given any unifier *sig1* of a term *t*, we can find a “01” unifier. Since our **find\_unifier** function also finds a “01” unifier by going through the list of available “01” unifiers, there must exist a “01” unifier *sig2* returned by our **find\_unifier** function under the **Some** wrapper. Lemma **unif\_some\_subst** :  $\forall (t: \text{term}),$

```

(∃ sig1 , unifier t sig1) →
  ∃ sig2 , find_unifier t = Some sig2.

```

Proof.

```

intros t H. induction t.

```

```

- simpl.  $\exists$  []. reflexivity.
- simpl. destruct H. unfold unifier in H. simpl in H.
  apply T1_not_equiv_T0 in H. inversion H.
- unfold find_unifier.
  apply existsb_find.
  apply existsb_exists. destruct H. pose proof unif_exists_grnd_unif.
  specialize (H0 (VAR v) x).
  apply H0. apply H.
- unfold find_unifier.
  apply existsb_find.
  apply existsb_exists. destruct H. pose proof unif_exists_grnd_unif.
  specialize (H0 (t1 + t2) x).
  apply H0. apply H.
- unfold find_unifier.
  apply existsb_find.
  apply existsb_exists. destruct H. pose proof unif_exists_grnd_unif.
  specialize (H0 (t1  $\times$  t2) x).
  apply H0. apply H.

```

Qed.

Here is a lemma to show that if no substitution makes `find_unifier` return `Some`  $\sigma$ , then it returns `None`. Lemma `not_Some_not_unifiable` ( $t$ : `term`) :

```

( $\neg \exists sig, find\_unifier\ t = Some\ sig$ )  $\rightarrow$ 
 $\neg$  unifiable  $t$ .

```

Proof.

```

intros.
pose proof not_Some_is_None.
specialize (H0 t H).
unfold unifiable.
intro.
unfold not in H.
pose proof unif_some_subst.
specialize (H2 t H1).
specialize (H H2).
apply H.

```

Qed.

This lemma shows that if a term is unifiable then `find_unifier` returns `Some`  $\sigma$ . Lemma `unifiable_find_unifier_some_subst` :  $\forall (t : \text{term})$ ,

```

unifiable  $t \rightarrow$ 
( $\exists sig, find\_unifier\ t = Some\ sig$ ).

```

Proof.

```

intros.
pose proof contrapositive.

```



```

specialize (H0 ( $\neg \exists$  sig, find_unifier t = Some sig) ( $\neg$  unifiable t)).
pose proof not_Some_not_unifiable.
specialize (H1 t). specialize (H0 H1). apply NNPP in H0.
- apply H0.
- firstorder.

```

Qed.

This lemma shows that if a term is unifiable, then find\_unifier returns a unifier. Lemma find\_unifier\_is\_unifier:  $\forall (t : \mathbf{term}),$   
unifiable t  $\rightarrow$  unifier t (convert\_to\_subst (find\_unifier t)).

Proof.

```

intros.
pose proof unifiable_find_unifier_some_subst.
specialize (H0 t H).
unfold unifier. unfold unifiable in H. simpl. unfold convert_to_subst.
destruct H0 as [sig H0]. rewrite H0.
pose proof Some_subst_unifiable.
specialize (H1 t sig). specialize (H1 H0).
unfold unifier in H1.
apply H1.

```

Qed.

### 4.5.3 Gluing Everything Together For the Final Proof

In this subsection we prove the two top-level final proof lemmas. Both of these proofs use the intermediate lemmas proved in the previous subsections.

The first one states that given a unifiable term  $t$  and the fact that our Lowenheim builder produces an mgu, then the Lowenheim\_Main function also produces an mgu. Lemma builder\_to\_main:  $\forall (t : \mathbf{term}),$

```

unifiable t  $\rightarrow$ 
most_general_unifier t (build_lowenheim_subst
                        t (convert_to_subst (find_unifier t)))  $\rightarrow$ 
most_general_unifier t (convert_to_subst (Lowenheim_Main t)).

```

Proof.

```

intros.
pose proof lowenheim_most_general_unifier as H1.
pose proof find_unifier_is_unifier as H2.
specialize (H2 t H). specialize (H1 t (convert_to_subst (find_unifier t))).
specialize (H1 H2). unfold Lowenheim_Main. destruct (find_unifier t).
- simpl. simpl in H1. apply H1.
- simpl in H2. unfold unifier in H2. apply app_subst_T0 in H2. simpl.
  repeat simpl in H1. pose proof most_general_unifier_compat.
  specialize (H3 t T0 H2). specialize (H3  $\square$ ).

```

```

rewrite H3. unfold most_general_unifier. intros.
unfold more_general_substitution. split.
+ apply empty_subst_on_term.
+ intros.  $\exists s'$ . unfold substitution_factor_through.
  intros. simpl. reflexivity.

```

Qed.

This is the final top-level lemma that encapsulates all our efforts so far. It proves the two main statements required for the final proof. The two statements, as phrased in the beginning of the chapter are: 1) If a term is unifiable, then our own defined `Lowenheim_Main` function produces a most general unifier (mgu). 2) If a term is not unifiable, then our own defined `Lowenheim_Main` function produces a `None` substitution. The two propositions are related with the “ $\wedge$ ” symbol (namely, the propositional “and”) and each is proven separately using the intermediate lemmas proven above. This is why the final top-level proof is relatively short, because a lot of the significant components of the proof have already been proven as intermediate lemmas. Lemma `lowenheim_main_most_general_unifier`:  $\forall (t: \text{term})$ ,

```

( $\text{unifiable } t \rightarrow \text{most\_general\_unifier } t \text{ (convert\_to\_subst (Lowenheim\_Main } t))$ )
 $\wedge$ 
( $\neg \text{unifiable } t \rightarrow \text{Lowenheim\_Main } t = \text{None}$ ).

```

Proof.

```

intros.
split.
- intros. apply builder_to_main.
  + apply H.
  + apply lowenheim_most_general_unifier. apply find_unifier_is_unifier.
    apply H.
- intros. pose proof not_unifiable_find_unifier_none_subst.
  specialize (H0 t H). unfold Lowenheim_Main. rewrite H0. reflexivity.

```

Qed.

# Chapter 5

## Library B\_Unification.list\_util

```
Require Import List.  
Import ListNotations.  
Require Import Arith.  
Import Nat.  
Require Import Sorting.  
Require Import Permutation.  
Require Import Omega.
```

### 5.1 Introduction

The second half of the project revolves around the successive variable elimination algorithm for solving unification problems. While we could implement this algorithm with the same data structures used for Lowenheim's, this algorithm lends itself well to a new representation of terms as polynomials.

A *polynomial* is a list of monomials being added together, where a *monomial* is a list of variables being multiplied together. Since one of the rules is that  $x * x \approx_B x$ , we can guarantee that there are no repeated variables in any given monomial. Similarly, because  $x + x \approx_B 0$ , we can guarantee that there are no repeated monomials in a polynomial.

Because of these properties, as well as the commutativity of addition and multiplication, we can represent both monomials and polynomials as unordered sets of variables and monomials, respectively. For simplicity when implementing and comparing these polynomials in Coq, we have opted to use the standard list structure, instead maintaining that the lists are maintained in our polynomial form after each stage.

In order to effectively implement polynomial lists in this way, a set of utilities are needed to allow us to easily perform operations on these lists. This file serves to implement and prove facts about these functions, as well as to expand upon the standard library when necessary.

## 5.2 Comparisons Between Lists

Checking if a list of natural numbers is sorted is easy enough. Comparing lists of lists of nats is slightly harder, and requires the use of a new function, called `lex`. `lex` simply takes in a comparison and applies the comparison across the list until it finds a point where the elements are not equal.

In all cases throughout this project, the comparator used will be the standard nat `compare` function.

For example, `[1;2;3]` is less than `[1;2;4]`, and `[1;2]` is greater than `[1]`.

```
Fixpoint lex {T} (cmp:T → T → comparison) (l1 l2:list T) : comparison :=
  match l1, l2 with
  | [], [] ⇒ Eq
  | [], _ ⇒ Lt
  | _, [] ⇒ Gt
  | h1 :: t1, h2 :: t2 ⇒
    match cmp h1 h2 with
    | Eq ⇒ lex cmp t1 t2
    | c ⇒ c
    end
  end.
```

There are some important but relatively straightforward properties of this function that are useful to prove. First, *reflexivity*:

Lemma `lex_nat_refl` :  $\forall l, \text{lex compare } l \text{ } l = \text{Eq}$ .

Proof.

```
intros.
induction l; auto.
simpl. rewrite compare_refl. apply IHL.
```

Qed.

Next, *antisymmetry*. This allows us to take a predicate or hypothesis about the comparison of two polynomials and reverse it.

For example,  $l < m$  implies  $m > l$ .

Lemma `lex_nat_antisym` :  $\forall l \ m,$   
 $\text{lex compare } l \ m = \text{CompOpp } (\text{lex compare } m \ l).$

Proof.

```
intros l. induction l.
- intros. simpl. destruct m; reflexivity.
- intros. simpl. destruct m; auto. simpl.
  destruct (a ?= n) eqn:H; rewrite compare_antisym in H;
  rewrite CompOpp_iff in H; simpl in H; rewrite H; auto.
```

Qed.

It is also useful to convert from the result of `lex compare` to a hypothesis about equality

in Coq. Clearly, if `lex compare` returns `Eq`, the lists are exactly equal, and if it returns `Lt` or `Gt` they are not.

Lemma `lex_eq` :  $\forall l m,$   
 $\text{lex compare } l m = \text{Eq} \leftrightarrow l = m.$

Proof.

```

intros l. induction l; induction m; intros.
- split; reflexivity.
- split; intros; inversion H.
- split; intros; inversion H.
- split; intros; simpl in H.
+ destruct (a ?= a0) eqn:Hcomp; try inversion H. f_equal.
  × apply compare_eq_iff in Hcomp; auto.
  × apply IHL. auto.
+ inversion H. simpl. rewrite compare_refl.
  rewrite ← H2. apply IHL. reflexivity.

```

Qed.

Lemma `lex_neq` :  $\forall l m,$   
 $\text{lex compare } l m = \text{Lt} \vee \text{lex compare } l m = \text{Gt} \leftrightarrow l \neq m.$

Proof.

```

intros l. induction l; induction m.
- simpl. split; intro. inversion H; inversion H0. contradiction.
- simpl. split; intro. intro. inversion H0. auto.
- simpl. split; intro. intro. inversion H0. auto.
- clear IHm. split; intros.
+ destruct H; intro; apply lex_eq in H0; rewrite H in H0; inversion H0.
+ destruct (a ?= a0) eqn:Hcomp.
  × simpl. rewrite Hcomp. apply IHL. apply compare_eq_iff in Hcomp.
    rewrite Hcomp in H. intro. apply H. rewrite H0. reflexivity.
  × left. simpl. rewrite Hcomp. reflexivity.
  × right. simpl. rewrite Hcomp. reflexivity.

```

Qed.

Lemma `lex_neq'` :  $\forall l m,$   
 $(\text{lex compare } l m = \text{Lt} \rightarrow l \neq m) \wedge$   
 $(\text{lex compare } l m = \text{Gt} \rightarrow l \neq m).$

Proof.

```

intros l m. split; repeat (intros; apply lex_neq; auto).

```

Qed.

It is also useful to be able to flip the arguments of a call to `lex compare`, since these two comparisons impact each other directly.

If `lex compare` returns that  $l = m$ , then this also means that  $m = l$ . More interesting is that if  $l < m$ , then  $m > l$ .

Lemma `lex_rev_eq` :  $\forall l m,$   
`lex compare l m = Eq`  $\leftrightarrow$  `lex compare m l = Eq`.

Proof.

```
intros l m. split; intro; rewrite lex_nat_antisym in H; unfold CompOpp in H.
- destruct (lex compare m l) eqn:H0; inversion H. reflexivity.
- destruct (lex compare l m) eqn:H0; inversion H. reflexivity.
```

Qed.

Lemma `lex_rev_lt_gt` :  $\forall l m,$   
`lex compare l m = Lt`  $\leftrightarrow$  `lex compare m l = Gt`.

Proof.

```
intros l m. split; intro; rewrite lex_nat_antisym in H; unfold CompOpp in H.
- destruct (lex compare m l) eqn:H0; inversion H. reflexivity.
- destruct (lex compare l m) eqn:H0; inversion H. reflexivity.
```

Qed.

Lastly is a property over lists. The comparison of two lists stays the same if the same new element is added onto the front of each list. Similarly, if the item at the front of two lists is equal, removing it from both does not change the lists' comparison.

Lemma `lex_nat_cons` :  $\forall l m n,$   
`lex compare l m = lex compare (n :: l) (n :: m)`.

Proof.

```
intros. simpl. rewrite compare_refl. reflexivity.
```

Qed.

Hint Resolve `lex_nat_refl` `lex_nat_antisym` `lex_nat_cons`.

## 5.3 Extensions to the Standard Library

There were some facts about the standard library list functions that we found useful to prove, as they repeatedly came up in proofs of our more complex custom list functions.

Specifically, because we are comparing sorted lists, it is often easier to disregard the sortedness of the lists and instead compare them as permutations of one another. As a result, many of the lemmas in the rest of this file revolve around proving that two lists are permutations of one another.

### 5.3.1 Facts about `In`

First, a very simple fact about `In`. This mostly follows from the standard library lemma `Permutation_in`, but is more convenient for some of our proofs when formalized like this.

Lemma `Permutation_not_In` :  $\forall A (a:A) l l',$   
`Permutation l l'  $\rightarrow$`   
 $\neg \text{In } a l \rightarrow$   
 $\neg \text{In } a l'.$

Proof.

```
intros A a l l' H H0. intro. apply H0. apply Permutation_sym in H.
apply (Permutation_in a) in H; auto.
```

Qed.

Something else that seems simple but proves very useful to know is that if there are no elements in a list, that list must be empty.

Lemma nothing\_in\_empty :  $\forall \{A\} (l:\text{list } A),$   
 $(\forall a, \neg \text{In } a l) \rightarrow$   
 $l = [].$

Proof.

```
intros A l H. destruct l; auto. pose (H a). simpl in n. exfalso.
apply n. auto.
```

Qed.

### 5.3.2 Facts about **incl**

Next are some useful lemmas about **incl**. First is that if one list is included in another, but one element of the second list is not in the first, then the first list is still included in the second with that element removed.

Lemma incl\_not\_in :  $\forall A (a:A) l m,$   
 $\text{incl } l (a :: m) \rightarrow$   
 $\neg \text{In } a l \rightarrow$   
 $\text{incl } l m.$

Proof.

```
intros A a l m Hincl Hnin. unfold incl in *. intros a0 Hin.
simpl in Hincl. destruct (Hincl a0); auto. rewrite H in Hnin. contradiction.
```

Qed.

We also found it useful to relate **Permutation** to **incl**; if two lists are permutations of each other, then they must be set equivalent, or contain all of the same elements.

Lemma Permutation\_incl :  $\forall \{A\} (l m:\text{list } A),$   
 $\text{Permutation } l m \rightarrow \text{incl } l m \wedge \text{incl } m l.$

Proof.

```
intros A l m H. apply Permutation_sym in H as H0. split.
+ unfold incl. intros a. apply (Permutation_in _ H).
+ unfold incl. intros a. apply (Permutation_in _ H0).
```

Qed.

Unfortunately, the definition above cannot be changed into an iff relation, as **incl** proves nothing about the lengths of the lists. We can, however, prove that if some list  $m$  includes a list  $l$ , then  $m$  includes all permutations of  $l$ .

Lemma incl\_Permutation :  $\forall \{A\} (l l' m:\text{list } A),$   
 $\text{Permutation } l l' \rightarrow$

```
incl l m →
incl l' m.
```

Proof.

```
intros A l l' m H H0. apply Permutation_incl in H as [].
apply incl_tran with (m:=l); auto.
```

Qed.

A really simple lemma is that if some list  $l$  is included in the empty list, then  $l$  must also be empty.

Lemma incl\_nil :  $\forall \{X\} (l:\text{list } X),$   
 $\text{incl } l [] \leftrightarrow l = []$ .

Proof.

```
intros X l. unfold incl. split; intro H.
- destruct l; [auto | destruct (H x); intuition].
- intros a Hin. destruct l; [auto | rewrite H in Hin; auto].
```

Qed.

The last fact about **incl** is simply a new way of formalizing the definition that is convenient for some proofs.

Lemma incl\_cons\_inv :  $\forall A (a:A) l m,$   
 $\text{incl } (a :: l) m \rightarrow \text{In } a m \wedge \text{incl } l m$ .

Proof.

```
intros A a l m H. split.
- unfold incl in H. apply H. intuition.
- unfold incl in *. intros b Hin. apply H. intuition.
```

Qed.

### 5.3.3 Facts about **count\_occ**

Next is some facts about **count\_occ**. Firstly, if two lists are permutations of each other, then every element in the first list has the same number of occurrences in the second list.

Lemma count\_occ\_Permutation :  $\forall A \text{ Aeq\_dec } (a:A) l l',$   
 $\text{Permutation } l l' \rightarrow$   
 $\text{count\_occ Aeq\_dec } l a = \text{count\_occ Aeq\_dec } l' a$ .

Proof.

```
intros A Aeq_dec a l l' H. induction H.
- auto.
- simpl. destruct (Aeq_dec x a); auto.
- simpl. destruct (Aeq_dec y a); destruct (Aeq_dec x a); auto.
- rewrite ← IHPermutation2. rewrite IHPermutation1. auto.
```

Qed.

The function **count\_occ** also distributes over list concatenation, instead becoming addition. This is useful especially when dealing with count occurrences of lists during induction.



Lemma count\_occ\_app :  $\forall A (a:A) l m \text{ Aeq\_dec}$ ,  
 $\text{count\_occ } \text{Aeq\_dec } (l ++ m) a =$   
 $\text{add } (\text{count\_occ } \text{Aeq\_dec } l a) (\text{count\_occ } \text{Aeq\_dec } m a).$

Proof.

intros  $A a l m \text{ Aeq\_dec}$ . induction  $l$ ; auto.  
simpl. destruct ( $\text{Aeq\_dec } a0 a$ ); simpl; auto.

Qed.

It is also convenient to reason about the relation between **count\_occ** and **remove**. If the element being removed is the same as the one being counted, then the count is obviously 0. If the elements are different, then the count is the same with or without the remove.

Lemma count\_occ\_remove :  $\forall \{A\} \text{ Aeq\_dec } (a:A) l$ ,  
 $\text{count\_occ } \text{Aeq\_dec } (\text{remove } \text{Aeq\_dec } a l) a = 0.$

Proof.

intros  $A \text{ Aeq\_dec } a l$ . induction  $l$ ; auto. simpl.  
destruct ( $\text{Aeq\_dec } a a0$ ) eqn:Haa0; auto. simpl.  
destruct ( $\text{Aeq\_dec } a0 a$ ); try (symmetry in  $e$ ; contradiction). apply IHL.

Qed.

Lemma count\_occ\_neq\_remove :  $\forall \{A\} \text{ Aeq\_dec } (a b:A) l$ ,  
 $a \neq b \rightarrow$   
 $\text{count\_occ } \text{Aeq\_dec } (\text{remove } \text{Aeq\_dec } a l) b =$   
 $\text{count\_occ } \text{Aeq\_dec } l b.$

Proof.

intros  $A \text{ Aeq\_dec } a b l H$ . induction  $l$ ; simpl; auto. destruct ( $\text{Aeq\_dec } a a0$ ).  
- destruct ( $\text{Aeq\_dec } a0 b$ ); auto.  
rewrite  $\leftarrow e0$  in  $H$ . rewrite  $e$  in  $H$ . contradiction.  
- simpl. destruct ( $\text{Aeq\_dec } a0 b$ ); auto.

Qed.

### 5.3.4 Facts about **concat**

Similarly to the lemma **Permutation\_map**, **Permutation\_concat** shows that if two lists are permutations of each other then the flattening of each list are also permutations.

Lemma Permutation\_concat :  $\forall \{A\} (l m:\text{list } (A))$ ,  
 $\text{Permutation } l m \rightarrow$   
 $\text{Permutation } (\text{concat } l) (\text{concat } m).$

Proof.

intros  $A l m H$ . induction  $H$ .  
- auto.  
- simpl. apply **Permutation\_app\_head**. auto.  
- simpl. apply **Permutation\_trans** with ( $l' := \text{concat } l ++ y ++ x$ ).  
+ rewrite **app\_assoc**. apply **Permutation\_app\_comm**.

```

+ apply Permutation_trans with (l' := concat l ++ x ++ y).
  × apply Permutation_app_head. apply Permutation_app_comm.
  × rewrite (app_assoc x y). apply Permutation_app_comm.
- apply Permutation_trans with (l' := concat l'); auto.
Qed.

```

Before the creation of this next lemma, it was relatively hard to reason about whether elements are in the flattening of a list of lists. This lemma states that if there is a list in the list of lists that contains the desired element, then that element will be in the flattened version.

Lemma `ln_concat_exists` :  $\forall A \text{ ll } (a:A),$   
 $(\exists l, \text{In } l \text{ ll} \wedge \text{In } a \text{ l}) \leftrightarrow \text{In } a (\text{concat ll}).$

Proof.

```

intros A ll a. split; intros H.
- destruct H as [l []]. apply In_split in H. destruct H as [l1 [l2 H]].
  rewrite H. apply Permutation_in with (l := concat (l :: l1 ++ l2)).
  + apply Permutation_concat. apply Permutation_middle.
  + simpl. apply in_app_iff. auto.
- induction ll.
  + inversion H.
  + simpl in H. apply in_app_iff in H. destruct H.
    ×  $\exists a0$ . split; intuition.
    × destruct IHll; auto.  $\exists x$ . intuition.

```

Qed.

This particular lemma is useful if the function being mapped returns a list of its input type. If the resulting lists are flattened after, then the result is the same as mapping the function without converting the output to lists.

Lemma `concat_map` :  $\forall \{A B\} (f:A \rightarrow B) \text{ l},$   
 $\text{concat} (\text{map } (\text{fun } a \Rightarrow [f \text{ a}]) \text{ l}) = \text{map } f \text{ l}.$

Proof.

```

intros A B f l. induction l; auto. simpl. f_equal. apply IHL.

```

Qed.

Another fact similar to the last is that if you flatten the result of mapping a function that maps a function over a list, we can rearrange the order of the `concat` and the `maps`.

Lemma `concat_map_map` :  $\forall A B C \text{ l } (f:B \rightarrow C) (g:A \rightarrow \text{list } B),$   
 $\text{concat} (\text{map } (\text{fun } a \Rightarrow \text{map } f (g \text{ a})) \text{ l}) =$   
 $\text{map } f (\text{concat} (\text{map } g \text{ l})).$

Proof.

```

intros. induction l; auto.
simpl. rewrite map_app. f_equal. auto.

```

Qed.

Lastly, if you **map** a function that converts every element of a list to **nil**, and then **concat** the list of **nil**s, you end with **nil**.

Lemma concat\_map\_nil :  $\forall \{A\} (l:\text{list } A),$   
**concat** (**map** (fun  $x \Rightarrow []$ )  $l$ ) = (**@nil**  $A$ ).

Proof.

induction  $l$ ; auto.

Qed.

### 5.3.5 Facts about **Forall** and **existsb**

This is similar to the inverse of **Forall**; any element in a list  $l$  must hold for predicate  $p$  if **Forall**  $p$  is true of  $l$ .

Lemma Forall\_In :  $\forall A (l:\text{list } A) a p,$   
**In**  $a l \rightarrow \text{Forall } p l \rightarrow p a.$

Proof.

intros  $A l a p Hin Hfor$ . apply (**Forall\_forall**  $p l$ ); auto.

Qed.

In Coq, **existsb** is effectively the “or” to **Forall**’s “and” when reasoning about lists. If there does not exist a single element in a list  $l$  where the predicate  $p$  holds, then  $p a$  must be false for any element  $a$  of  $l$ .

Lemma existsb\_false\_forall :  $\forall \{A\} p (l:\text{list } A),$   
**existsb**  $p l = \text{false} \rightarrow$   
 $(\forall a, \text{In } a l \rightarrow p a = \text{false}).$

Proof.

intros  $A p l H a Hin$ . destruct ( $p a$ ) eqn:Hpa; auto.

ex falso. rewrite  $\leftarrow \text{Bool.negb\_true\_iff}$  in  $H$ .

apply (**Bool.eq\\_true\\_false\\_abs**  $_ H$ ). rewrite **Bool.negb\\_false\\_iff**.

apply **existsb\_exists**.  $\exists a$ . split; auto.

Qed.

Similarly to **Forall\_In**, this lemma is just another way of formalizing the definition of **Forall** that proves useful when dealing with **StronglySorted** lists.

Lemma Forall\_cons\_iff :  $\forall A p (a:A) l,$   
**Forall**  $p (a :: l) \leftrightarrow \text{Forall } p l \wedge p a.$

Proof.

intros  $A p a l$ . split.

- intro  $H$ . split.

+ rewrite **Forall\_forall** in  $H$ . apply **Forall\_forall**. intros  $x Hin$ .

apply  $H$ . intuition.

+ apply **Forall\_inv** in  $H$ . auto.

- intros []. apply **Forall\_cons**; auto.

Qed.

If a predicate  $p$  holds for all elements of a list  $l$ , then  $p$  still holds if some elements are removed from  $l$ .

Lemma Forall\_remove :  $\forall A \text{ Aeq\_dec } p (a:A) l,$   
 $\text{Forall } p l \rightarrow \text{Forall } p (\text{remove Aeq\_dec } a l).$

Proof.

```
intros A Aeq_dec p a l H. induction l; auto. simpl.
apply Forall_cons_iff in H. destruct (Aeq_dec a a0).
- apply IHL. apply H.
- apply Forall_cons_iff. split.
  + apply IHL. apply H.
  + apply H.
```

Qed.

This next lemma is particularly useful for relating **StronglySorted** lists to **Sorted** lists; if some relation holds between all elements of a list, then this can be converted to the **HdRel** proposition used by **Sorted**.

Lemma Forall\_HdRel :  $\forall \{X\} r (x:X) l,$   
 $\text{Forall } (r x) l \rightarrow \text{HdRel } r x l.$

Proof.

```
intros X r x l H. destruct l.
- apply HdRel_nil.
- apply HdRel_cons. apply Forall_inv in H. auto.
```

Qed.

Lastly, if some predicate  $p$  holds for all elements in a list  $l$ , and the elements of a second list  $m$  are all included in  $l$ , then  $p$  holds for all the elements in  $m$ .

Lemma Forall\_incl :  $\forall \{X\} p (l m:\text{list } X),$   
 $\text{Forall } p l \rightarrow \text{incl } m l \rightarrow \text{Forall } p m.$

Proof.

```
intros X p l m H H0. induction m.
- apply Forall_nil.
- rewrite Forall_forall in H. apply Forall_forall. intros x Hin.
  apply H. unfold incl in H0. apply H0. intuition.
```

Qed.

### 5.3.6 Facts about **remove**

There are surprisingly few lemmas about **remove** in the standard library, so in addition to those proven in other places, we opted to add quite a few simple facts about **remove**. First is that if an element is in a list after something has been removed, then clearly it was in the list before as well.

Lemma In\_remove :  $\forall \{A\} \text{ Aeq\_dec } (a b:A) l,$   
 $\text{In } a (\text{remove Aeq\_dec } b l) \rightarrow \text{In } a l.$

Proof.

```

intros A Aeq_dec a b l H. induction l as [|c l IHL]; auto.
destruct (Aeq_dec b c) eqn:Heq; simpl in H; rewrite Heq in H.
- right. auto.
- destruct H; [rewrite H; intuition | right; auto].

```

Qed.

Similarly to Forall\_remove, if a list was **StronglySorted** before something was removed then it is also **StronglySorted** after.

Lemma StronglySorted\_remove :  $\forall \{A\} \text{ Aeq\_dec } r (a:A) l,$   
**StronglySorted**  $r \ l \rightarrow$  **StronglySorted**  $r \ (\text{remove } \text{Aeq\_dec } a \ l).$

Proof.

```

intros A Aeq_dec r a l H. induction l; auto.
simpl. apply StronglySorted_inv in H. destruct (Aeq_dec a a0).
- apply IHL. apply H.
- apply SSorted_cons.
  + apply IHL. apply H.
  + apply Forall_remove. apply H.

```

Qed.

If the item being removed from a list isn't in the list, then the list is equal with or without the remove.

Lemma not\_in\_remove :  $\forall A \text{ Aeq\_dec } (a:A) l,$   
 $\neg \text{In } a \ l \rightarrow \text{remove } \text{Aeq\_dec } a \ l = l.$

Proof.

```

intros A Aeq_dec a l H. induction l; auto.
simpl. destruct (Aeq_dec a a0).
- simpl. rewrite e in H. exfalso. apply H. intuition.
- rewrite IHL. reflexivity. intro Hin. apply H. intuition.

```

Qed.

The function **remove** also distributes over list concatenation.

Lemma remove\_distr\_app :  $\forall A \text{ Aeq\_dec } (a:A) l \ m,$   
**remove**  $\text{Aeq\_dec } a \ (l \ ++ \ m) = \text{remove } \text{Aeq\_dec } a \ l \ ++ \ \text{remove } \text{Aeq\_dec } a \ m.$

Proof.

```

intros A Aeq_dec a l m. induction l; auto.
simpl. destruct (Aeq_dec a a0); auto.
simpl. f_equal. apply IHL.

```

Qed.

More interestingly, if two lists were permutations before, they are also permutations after the same element has been removed from both lists.

Lemma remove\_Permutation :  $\forall A \text{ Aeq\_dec } (a:A) l \ l',$   
**Permutation**  $l \ l' \rightarrow$

**Permutation** (remove Aeq\_dec a l) (remove Aeq\_dec a l').

Proof.

```

intros A Aeq_dec a l l' H. induction H.
- auto.
- simpl. destruct (Aeq_dec a x); auto.
- simpl. destruct (Aeq_dec a y); destruct (Aeq_dec a x); auto.
  apply perm_swap.
- apply Permutation_trans with (l':=(remove Aeq_dec a l')); auto.

```

Qed.

The function **remove** is also associative with itself.

Lemma remove\_remove :  $\forall \{A\} \text{ Aeq\_dec } (a \text{ b}:A) \text{ l},$   
**remove** Aeq\_dec a (**remove** Aeq\_dec b l) =  
**remove** Aeq\_dec b (**remove** Aeq\_dec a l).

Proof.

```

intros A Aeq_dec a b l. induction l as [|c]; simpl; auto.
destruct (Aeq_dec a b); destruct (Aeq_dec b c); destruct (Aeq_dec a c).
- auto.
- rewrite ← e0 in n. rewrite e in n. contradiction.
- rewrite ← e in n. rewrite e0 in n. contradiction.
- simpl. destruct (Aeq_dec a c); try contradiction.
  destruct (Aeq_dec b c); try contradiction. rewrite IHL. auto.
- rewrite e in n. rewrite e0 in n. contradiction.
- simpl. destruct (Aeq_dec b c); try contradiction. auto.
- simpl. destruct (Aeq_dec a c); try contradiction. auto.
- simpl. destruct (Aeq_dec a c); try contradiction.
  destruct (Aeq_dec b c); try contradiction. rewrite IHL. auto.

```

Qed.

Lastly, if an element is being removed from a particular list twice, the inner **remove** is redundant and can be removed.

Lemma remove\_pointless :  $\forall \{A \text{ Aeq\_dec}\} (a:A) \text{ l m},$   
**remove** Aeq\_dec a (**remove** Aeq\_dec a l ++ m) =  
**remove** Aeq\_dec a (l ++ m).

Proof.

```

intros A Aeq_dec a l m. induction l; auto. simpl.
destruct (Aeq_dec a a0) eqn:Heq; auto.
simpl. rewrite Heq. f_equal. apply IHL.

```

Qed.

### 5.3.7 Facts about **nodup** and **NoDup**

Next up - the **NoDup** proposition and the closely related **nodup** function. The first lemma states that if there are no duplicates in a list, then the first two elements of that list must

not be equal.

Lemma NoDup\_neq :  $\forall \{A\} \ l \ (a \ b:A),$

**NoDup**  $(a :: b :: l) \rightarrow$   
 $a \neq b.$

Proof.

intros  $A \ l \ a \ b \ Hdup$ . apply **NoDup\_cons\_iff** in  $Hdup$  as  $||$ .  
 apply **NoDup\_cons\_iff** in  $H0$  as  $||$ . intro. apply  $H$ . simpl. auto.

Qed.

In a similar vein as many of the other **remove** lemmas, if there were no duplicates in a list before the **remove** then there are still none after.

Lemma NoDup\_remove :  $\forall A \ Aeq\_dec \ (a:A) \ l,$

**NoDup**  $l \rightarrow$  **NoDup**  $(\text{remove } Aeq\_dec \ a \ l).$

Proof.

intros  $A \ Aeq\_dec \ a \ l \ H$ . induction  $l$ ; auto.  
 simpl. destruct  $(Aeq\_dec \ a \ a0)$ .  
 - apply  $IHL$ . apply **NoDup\_cons\_iff** in  $H$ . intuition.  
 - apply **NoDup\_cons**.  
 + apply **NoDup\_cons\_iff** in  $H$  as  $||$ . intro. apply  $H$ .  
 apply  $(\text{In\_remove } Aeq\_dec \ a0 \ a \ l \ H1)$ .  
 + apply  $IHL$ . apply **NoDup\_cons\_iff** in  $H$ ; intuition.

Qed.

Another lemma similar to **NoDup\_neq** is **NoDup\_forall\_neq**; if every element in a list is not equal to a certain  $a$ , and the list has no duplicates as is, then it is safe to add  $a$  to the list without creating duplicates.

Lemma NoDup\_forall\_neq :  $\forall A \ (a:A) \ l,$

**Forall**  $(\text{fun } b \Rightarrow a \neq b) \ l \rightarrow$   
**NoDup**  $l \rightarrow$   
**NoDup**  $(a :: l).$

Proof.

intros  $A \ a \ l \ Hf \ Hn$ . apply **NoDup\_cons**; auto.  
 intro. induction  $l$ ; auto.  
 apply **Forall\_cons\_iff** in  $Hf$  as  $||$ . apply  $IHL$ ; auto.  
 - apply **NoDup\_cons\_iff** in  $Hn$ . apply  $Hn$ .  
 - simpl in  $H$ . destruct  $H$ ; auto. rewrite  $H$  in  $H1$ . *contradiction*.

Qed.

This lemma is really just a reformalization of **NoDup\_remove\_2**, which allows us to easily prove that some  $a$  is not in the preceding elements  $l1$  or the following elements  $l2$  when the whole list  $l$  has no duplicates.

Lemma NoDup\_In\_split :  $\forall \{A\} \ (a:A) \ l \ l1 \ l2,$

$l = l1 ++ a :: l2 \rightarrow$   
**NoDup**  $l \rightarrow$

$\neg \text{In } a \ l1 \wedge \neg \text{In } a \ l2.$

Proof.

```
intros A a l l1 l2 H H0. rewrite H in H0.
apply NoDup_remove_2 in H0. split; intro; intuition.
```

Qed.

Now some facts about the function `nodup`; if the `NoDup` predicate is already true about a certain list, then calling `nodup` on it changes nothing.

Lemma no\_nodup\_NoDup :  $\forall A \text{ Aeq\_dec } (l:\text{list } A),$

`NoDup`  $l \rightarrow$   
`nodup`  $\text{Aeq\_dec } l = l.$

Proof.

```
intros A Aeq_dec l H. induction l; auto.
simpl. apply NoDup_cons_iff in H as []. destruct (in_dec Aeq_dec a l).
contradiction. f_equal. auto.
```

Qed.

If a list is sorted (with a transitive relation) before calling `nodup` on it, the list is also sorted after.

Lemma Sorted\_nodup :  $\forall A \text{ Aeq\_dec } r (l:\text{list } A),$

`Relations_1.Transitive`  $r \rightarrow$   
`Sorted`  $r \ l \rightarrow$   
`Sorted`  $r \ (\text{nodup } \text{Aeq\_dec } l).$

Proof.

```
intros A Aeq_dec r l Ht H. apply Sorted_StronglySorted in H; auto.
apply StronglySorted_Sorted. induction l; auto.
simpl. apply StronglySorted_inv in H as []. destruct (in_dec Aeq_dec a l).
- apply IHL. apply H.
- apply SSorted_cons.
  + apply IHL. apply H.
  + rewrite Forall_forall in H0. apply Forall_forall. intros x Hin.
    apply H0. apply nodup_In in Hin. auto.
```

Qed.

We can also show that in some cases, if there are repeated calls to `nodup`, they are “pointless” - in other words, we can remove the inner call and only keep the outer one.

Lemma nodup\_pointless :  $\forall l \ m,$

`nodup`  $\text{Nat.eq\_dec } (l ++ \text{nodup } \text{Nat.eq\_dec } m) = \text{nodup } \text{Nat.eq\_dec } (l ++ m).$

Proof.

```
intros l m. induction l.
- simpl. rewrite no_nodup_NoDup; auto. apply NoDup_nodup.
- simpl. destruct in_dec; destruct in_dec.
  + auto.
  + exfalso. apply n. apply in_app_iff in i; destruct i. intuition.
```



```

    apply nodup_in in  $H$ ; intuition.
+ exfalso. apply  $n$ . apply in_app_iff in  $i$ ; destruct  $i$ ; intuition.
    apply in_app_iff. right. apply nodup_in; auto.
+ f_equal. auto.

```

Qed.

And lastly, similarly to our other Permutation lemmas this far, if two lists were permutations of each other before **nodup** they are also permutations after.

This lemma was slightly more complex than previous Permutation lemmas, but the proof is still very similar. It is solved by induction on the Permutation hypothesis. The first and last cases are trivial, and the second case (where we must prove  $\text{Permutation } (x :: l) (x :: l')$ ) becomes simple with the use of **Permutation\_in**.

The last case (where we must show  $\text{Permutation } (x :: y :: l) (y :: x :: l)$ ) was slightly complicated by the fact that destructing **in\_dec** gives us a hypothesis like  $\text{In } x (y :: l)$ , which seems useless in reasoning about the other list at first. However, by also destructing whether or not  $x$  and  $y$  are equal, we can easily prove this case as well.

Lemma **Permutation\_nodup** :  $\forall A \text{ Aeq\_dec } (l m : \text{list } A),$   
**Permutation**  $l m \rightarrow \text{Permutation } (\text{nodup } \text{Aeq\_dec } l) (\text{nodup } \text{Aeq\_dec } m).$

Proof.

```

    intros. induction  $H$ .
- auto.
- simpl. destruct (in_dec  $\text{Aeq\_dec } x l$ ).
    + apply Permutation_in with ( $l' := l'$ ) in  $i$ ; auto. destruct in_dec;
      try contradiction. auto.
    + assert ( $\neg \text{In } x l'$ ). intro. apply  $n$ .
      apply Permutation_in with ( $l' := l$ ) in  $H0$ ; auto.
      apply Permutation_sym; auto. destruct in_dec; try contradiction; auto.
- destruct (in_dec  $\text{Aeq\_dec } y (x :: l)$ ). destruct  $i$ .
    + rewrite  $H$ . simpl. destruct ( $\text{Aeq\_dec } y y$ ); try contradiction.
      destruct in_dec; auto.
    + simpl. destruct ( $\text{Aeq\_dec } x y$ ). destruct in_dec; destruct ( $\text{Aeq\_dec } y x$ );
      try (symmetry in  $e$ ; contradiction). rewrite  $e$  in  $i$ . destruct in_dec;
      try contradiction. auto.
      assert ( $\neg \text{In } y l$ ). intro; apply  $n$ ; rewrite  $e$ ; auto.
      destruct in_dec; try contradiction. destruct in_dec; try contradiction.
      destruct in_dec; destruct ( $\text{Aeq\_dec } y x$ );
      try (symmetry in  $e$ ; contradiction). auto. apply perm_skip. auto.
    + simpl. destruct ( $\text{Aeq\_dec } x y$ ). destruct in_dec. destruct ( $\text{Aeq\_dec } y x$ );
      try (symmetry in  $e$ ; contradiction). rewrite  $e0$ . destruct in_dec;
      try contradiction. auto. destruct ( $\text{Aeq\_dec } y x$ );
      try (symmetry in  $e$ ; contradiction).
      assert ( $\neg \text{In } y l$ ). intro; apply  $n0$ ; rewrite  $e$ ; auto.
      destruct in_dec; try contradiction. rewrite  $e0$ . apply perm_skip; auto.

```

```

    assert ( $\neg$  In y l). intro; apply n; intuition.
    destruct in_dec; try contradiction. destruct in_dec;
    destruct (Aeq_dec y x); try (symmetry in e; contradiction); auto.
    apply perm_swap.
  - apply Permutation_trans with (l':=(nodup Aeq_dec l')); auto.
Qed.

```

### 5.3.8 Facts about `partition`

The final function in the standard library we found it useful to prove facts about is `partition`. First, we show the relation between `partition` and `filter`: filtering a list gives you a result that is equal to the first list `partition` would return. This lemma is proven one way, and then reformalized to be more useful in later proofs.

Lemma `partition_filter_fst`  $\{A\}$   $p$   $l$  :  
`fst (partition p l) = @filter A p l.`

Proof.

```

  induction l; auto. simpl. rewrite <- IHl.
  destruct (partition p l); simpl.
  destruct (p a); auto.

```

Qed.

Lemma `partition_filter_fst'` :  $\forall \{A\}$   $p$  ( $l$   $t$   $f$  : `list`  $A$ ),  
`partition p l = (t, f)  $\rightarrow$`   
`t = @filter A p l.`

Proof.

```

  intros A p l t f H.
  rewrite <- partition_filter_fst.
  now rewrite H.

```

Qed.

We would like to be able to state a similar fact about the second list returned by `partition`, but clearly these are all the elements “thrown out” by `filter`. Instead, we first create a simple definition for negating a function, and prove two quick facts about the relation between some  $p$  and `neg p`.

Definition `neg`  $\{A:\text{Type}\}$  := fun ( $p:A \rightarrow \text{bool}$ )  $\Rightarrow$  fun  $a \Rightarrow$  `negb` ( $p$   $a$ ).

Lemma `neg_true_false` :  $\forall \{A\}$   $p$  ( $a:A$ ),  
 $p$   $a$  = `true`  $\leftrightarrow$  `neg p a` = `false`.

Proof.

```

  intros A p a. unfold neg. split; intro.
  - rewrite H. auto.
  - destruct (p a); intuition.

```

Qed.

Lemma `neg_false_true` :  $\forall \{A\}$   $p$  ( $a:A$ ),

$p\ a = \text{false} \leftrightarrow \text{neg } p\ a = \text{true}.$

Proof.

```
intros A p a. unfold neg. split; intro.
- rewrite H. auto.
- destruct (p a); intuition.
```

Qed.

With the addition of this `neg` proposition, we can now prove two lemmas relating the second `partition` list and `filter` in the same way we proved the lemmas about the first `partition` list.

Lemma `partition_filter_snd`  $\{A\}$   $p\ l :$

$\text{snd } (\text{partition } p\ l) = @\text{filter } A\ (\text{neg } p)\ l.$

Proof.

```
induction l; auto. simpl.
rewrite ← IHL.
destruct (partition p l); simpl.
destruct (p a) eqn:Hp.
- simpl. apply neg_true_false in Hp. rewrite Hp; auto.
- simpl. apply neg_false_true in Hp. rewrite Hp; auto.
```

Qed.

Lemma `partition_filter_snd'` :  $\forall \{A\} p\ (l\ t\ f : \text{list } A),$

$\text{partition } p\ l = (t, f) \rightarrow$   
 $f = @\text{filter } A\ (\text{neg } p)\ l.$

Proof.

```
intros A p l t f H.
rewrite ← partition_filter_snd.
now rewrite H.
```

Qed.

These lemmas about `partition` and `filter` are now put to use in two important lemmas about `partition`. If some list  $l$  is partitioned into two lists  $(t, f)$ , then every element in  $t$  must return true for the filtering predicate and every element in  $f$  must return false.

Lemma `partfst_true` :  $\forall A\ p\ (l\ t\ f : \text{list } A),$

$\text{partition } p\ l = (t, f) \rightarrow$   
 $(\forall a, \text{In } a\ t \rightarrow p\ a = \text{true}).$

Proof.

```
intros A p l t f Hpart a Hin.
assert (Hf: t = filter p l).
- now apply partition_filter_snd' with f.
- assert (Hass := filter_In p a l).
  apply Hass.
  now rewrite ← Hf.
```

Qed.

Lemma `part_snd_false` :  $\forall A p (x\ t\ f : \text{list } A),$   
`partition`  $p\ x = (t, f) \rightarrow$   
 $(\forall a, \text{In } a\ f \rightarrow p\ a = \text{false}).$

Proof.

```
intros A p l t f Hpart a Hin.
assert (Hf: f = filter (neg p) l).
- now apply partition_filter_snd' with t.
- assert (Hass := filter_In (neg p) a l).
  rewrite ← neg_false_true in Hass.
  apply Hass.
  now rewrite ← Hf.
```

Qed.

Next is a rather obvious but useful lemma, which states that if a list  $l$  was split into  $(t, f)$  then appending these lists back together results in a list that is a permutation of the original.

Lemma `partition_Permutation` :  $\forall \{A\} p (l\ t\ f : \text{list } A),$   
`partition`  $p\ l = (t, f) \rightarrow$   
`Permutation`  $l\ (t ++ f).$

Proof.

```
intros A p l. induction l; intros.
- simpl in H. inversion H. auto.
- simpl in H. destruct (partition p l). destruct (p a); inversion H.
  + simpl. apply perm_skip. apply IHL. f_equal. auto.
  + apply Permutation_trans with (l' := a :: l1 ++ t0). apply perm_skip.
    apply Permutation_trans with (l' := t0 ++ l1). apply IHL. f_equal.
    auto. apply Permutation_app_comm.
    apply Permutation_app_comm with (l := a :: l1).
```

Qed.

The last and hardest fact about `partition` states that if the list being partitioned was already sorted, then the resulting two lists will also be sorted. This seems simple, as `partition` iterates through the elements in order and maintains the order in its children, but was surprisingly difficult to prove.

After performing induction, the next step was to destruct  $f\ a$ , to see which of the two lists the induction element would end up in. In both cases, the list that *doesn't* receive the new element is already clearly sorted by the induction hypothesis, but proving the other one is sorted is slightly harder.

By using `Forall_HdRel` (defined earlier), we reduced the problem in both cases to only having to show that the new element holds the relation  $c$  between all elements of the list it was *consed* onto. After some manipulation and the use of `partition_Permutation` and `Forall_incl`, this follows from the fact that we know the new element holds the relation between all elements of the original list  $p$ , and therefore also holds it between the elements of the partitioned list.

Lemma part\_Sorted :  $\forall \{X\} (c:X \rightarrow X \rightarrow \text{Prop}) f p,$

**Relations\_1.Transitive**  $c \rightarrow$

**Sorted**  $c p \rightarrow$

$\forall l r, \text{partition } f p = (l, r) \rightarrow$

**Sorted**  $c l \wedge \text{Sorted } c r.$

Proof.

```

intros X c f p Htran Hsort. induction p; intros.
- simpl in H. inversion H. auto.
- assert (H0:=H); auto. simpl in H. destruct (partition f p) as [g d].
  destruct (f a); inversion H.
  + assert (Forall (c a) g  $\wedge$  Sorted c g  $\wedge$  Sorted c r  $\rightarrow$ 
    Sorted c (a :: g)  $\wedge$  Sorted c r).
     $\times$  intros H4. split. apply Sorted_cons. apply H4. apply Forall_HdRel.
      apply H4. apply H4.
     $\times$  apply H1. split.
      - apply Sorted_StronglySorted in Hsort; auto.
        apply StronglySorted_inv in Hsort as [].
        apply (Forall_incl _ _ H5). apply partition_Permutation in H0.
        rewrite  $\leftarrow$  H2 in H0. simpl in H0. apply Permutation_cons_inv in H0.
        apply Permutation_incl in H0 as []. unfold incl. unfold incl in H6.
        intros a0 Hin. apply H6. intuition.
      - apply IHp. apply Sorted_inv in Hsort; apply Hsort. f_equal. auto.
  + assert (Forall (c a) d  $\wedge$  Sorted c l  $\wedge$  Sorted c d  $\rightarrow$ 
    Sorted c l  $\wedge$  Sorted c (a :: d)).
     $\times$  intros H4. split. apply H4. apply Sorted_cons. apply H4.
      apply Forall_HdRel. apply H4.
     $\times$  apply H1. split.
      - apply Sorted_StronglySorted in Hsort; auto.
        apply StronglySorted_inv in Hsort as [].
        apply (Forall_incl _ _ H5). apply partition_Permutation in H0.
        rewrite  $\leftarrow$  H3 in H0. simpl in H0.
        apply Permutation_trans with (l'':=a :: d ++ l) in H0.
        apply Permutation_cons_inv in H0.
        apply Permutation_trans with (l'':=l ++ d) in H0.
        apply Permutation_incl in H0 as []. unfold incl. unfold incl in H6.
        intros a0 Hin. apply H6. intuition. apply Permutation_app_comm.
        apply Permutation_app_comm with (l':=a :: d).
      - apply IHp. apply Sorted_inv in Hsort; apply Hsort. f_equal. auto.

```

Qed.

## 5.4 New Functions over Lists

In order to easily perform the operations we need on lists, we defined three major list functions of our own, each with their own proofs. These generalized list functions all help to make it much easier to deal with our polynomial and monomial lists later in the development.

### 5.4.1 Distributing two Lists: **distribute**

The first and most basic of the three is **distribute**. Similarly to the “FOIL” technique learned in middle school for multiplying two polynomials, this function serves to create every combination of one element from each list. It is done concisely with the use of higher order functions below.

Definition **distribute**  $\{A\} (l\ m : \text{list } (\text{list } A)) : \text{list } (\text{list } A) :=$   
 $\text{concat } (\text{map } (\text{fun } a \Rightarrow \text{map } (\text{app } a) l) m).$

The **distribute** function will play a larger role later, mostly as a part of our polynomial multiplication function. For now, however, there are only two very simple lemmas to be proven, both stating that distributing **nil** over a list results in **nil**.

Lemma **distribute\_nil** :  $\forall \{A\} (l : \text{list } (\text{list } A)),$   
 $\text{distribute } []\ l = [].$

Proof.

induction  $l$ ; auto.

Qed.

Lemma **distribute\_nil\_r** :  $\forall \{A\} (l : \text{list } (\text{list } A)),$   
 $\text{distribute } l\ [] = [].$

Proof.

induction  $l$ ; auto.

Qed.

### 5.4.2 Cancelling out Repeated Elements: **nodup\_cancel**

The next list function, and possibly the most prolific function in our entire development, is **nodup\_cancel**. Similarly to the standard library **nodup** function, **nodup\_cancel** takes a list that may or may not have duplicates in it and returns a list without duplicates.

The difference between ours and the standard function is that rather than just removing all duplicates and leaving one of each element, the elements in a **nodup\_cancel** list cancel out in pairs. For example, the list  $[1;1;1]$  would become  $[1]$ , whereas  $[1;1;1;1]$  would become  $[]$ .

This is implemented with the **count\_occ** function and **remove**, and is largely the reason for needing so many lemmas about those two functions. If there is an *even* number of occurrences of an element  $a$  in the original list  $a :: l$ , which implies there is an *odd* number of occurrences of this element in  $l$ , then all instances are removed. On the other hand, if there is an *odd* number of occurrences in the original list, one occurrence is kept, and the rest are removed.

By calling `nodup_cancel` recursively on *xs* *before* calling `remove`, Coq is easily able to determine that *xs* is the decreasing argument, removing the need for a more complicated definition with “fuel”.

```
Fixpoint nodup_cancel {A} Aeq_dec (l:list A) : list A :=
  match l with
  | [] => []
  | x :: xs =>
    let count := count_occ Aeq_dec xs x in
    let xs' := remove Aeq_dec x (nodup_cancel Aeq_dec xs) in
    if even count then x :: xs' else xs'
  end.
```

Now onto lemmas. To begin with, there are a few facts true of `nodup` that are also true of `nodup_cancel`, which are useful in many proofs. `nodup_cancel_in` is the same as the standard library’s `nodup_in`, with one important difference: this implication is *not* bidirectional. Because even parity elements are removed completely, not all elements in *l* are guaranteed to be in `nodup_cancel l`.

`NoDup_nodup_cancel` is much simpler, and effectively exactly the same as `NoDup_nodup`.

In these proofs, and most others from this point on, the shape will be very similar to the proof of the corresponding `nodup` proof. The main difference is that, instead of destructing `in_dec` like one would for `nodup`, we destruct the evenness of `count_occ`, as that is what drives the main if statement of the function.

Lemma `nodup_cancel_in` :  $\forall A \text{ Aeq\_dec } a (l:\text{list } A),$

`In a (nodup_cancel Aeq_dec l)  $\rightarrow$  In a l.`

Proof.

```
intros A Aeq_dec a l H. induction l as [|b l IHL]; auto.
simpl in H. destruct (Aeq_dec a b).
- rewrite e. intuition.
- right. apply IHL. destruct (even (count_occ Aeq_dec l b)).
  + simpl in H. destruct H. rewrite H in n. contradiction.
  apply In_remove in H. auto.
  + apply In_remove in H. auto.
```

Qed.

Lemma `NoDup_nodup_cancel` :  $\forall A \text{ Aeq\_dec } (l:\text{list } A),$

`NoDup (nodup_cancel Aeq_dec l).`

Proof.

```
induction l as [|a l' Hrec]; simpl.
- constructor.
- destruct (even (count_occ Aeq_dec l' a)); simpl.
  + apply NoDup_cons; [apply remove_In | apply NoDup_remove; auto].
  + apply NoDup_remove; auto.
```

Qed.

Although not standard library lemmas, the `no_nodup_NoDup` and `Sorted_nodup` facts we proved earlier in this file are also both true of `nodup_cancel`, and proven in almost the same way.

Lemma `no_nodup_cancel_NoDup` :  $\forall A \text{ Aeq\_dec } (l:\text{list } A),$   
`NoDup`  $l \rightarrow$   
`nodup_cancel`  $\text{Aeq\_dec } l = l$ .

Proof.

```
intros A Aeq_dec l H. induction l; auto.
simpl. apply NoDup_cons_iff in H as []. assert (count_occ Aeq_dec l a = 0).
- apply count_occ_not_In. auto.
- rewrite H1. simpl. f_equal. rewrite not_In_remove. auto. intro.
  apply nodup_cancel_in in H2. apply H. auto.
```

Qed.

Lemma `Sorted_nodup_cancel` :  $\forall A \text{ Aeq\_dec } Rel (l:\text{list } A),$   
`Relations_1.Transitive`  $Rel \rightarrow$   
`Sorted`  $Rel \ l \rightarrow$   
`Sorted`  $Rel \ (\text{nodup\_cancel } \text{Aeq\_dec } l)$ .

Proof.

```
intros A Aeq_dec Rel l Ht H. apply Sorted_StronglySorted in H; auto.
apply StronglySorted_Sorted. induction l; auto.
simpl. apply StronglySorted_inv in H as [].
destruct (even (count_occ Aeq_dec l a)).
- apply SSorted_cons.
  + apply StronglySorted_remove. apply IHL. apply H.
  + apply Forall_remove. apply Forall_forall. rewrite Forall_forall in H0.
    intros x Hin. apply H0. apply nodup_cancel_in in Hin. auto.
- apply StronglySorted_remove. apply IHL. apply H.
```

Qed.

An interesting side effect of the “cancelling” behavior of this function is that while the number of occurrences of an item may change after calling `nodup_cancel`, the evenness of the count never will. If an element was odd before there will be one occurrence, and if it was even before there will be none.

Lemma `count_occ_nodup_cancel` :  $\forall \{A \text{ Aeq\_dec}\} p (a:A),$   
`even` (`count_occ`  $\text{Aeq\_dec } (\text{nodup\_cancel } \text{Aeq\_dec } p) \ a) =$   
`even` (`count_occ`  $\text{Aeq\_dec } p \ a$ ).

Proof.

```
intros A Aeq_dec p a. induction p as [|b|]; auto. simpl.
destruct (even (count_occ Aeq_dec p b)) eqn:Hb.
- simpl. destruct (Aeq_dec b a).
  + rewrite e. rewrite count_occ_remove. rewrite e in Hb.
    repeat rewrite even_succ. rewrite ← negb_odd in Hb.
```



```

    rewrite Bool.negb_true_iff in Hb. rewrite Hb. auto.
  + rewrite count_occ_neq_remove; auto.
- simpl. destruct (Aeq_dec b a).
  + rewrite e. rewrite count_occ_remove. rewrite e in Hb.
    repeat rewrite even_succ. rewrite ← negb_odd in Hb.
    rewrite Bool.negb_false_iff in Hb. rewrite Hb. auto.
  + rewrite count_occ_neq_remove; auto.

```

Qed.

The `Permutation_nodup` lemma was challenging to prove before, and this version for `nodup_cancel` faces the same problems. The first and fourth cases are easy, and the second isn't too bad after using `count_occ_Permutation`. The third case faces the same problems as before, but requires some extra work when transitioning from reasoning about `count_occ` ( $x :: l$ )  $y$ ) to `count_occ` ( $y :: l$ )  $x$ .

This is accomplished by using `even_succ`, `negb_odd`, and `negb_true_iff`. In this way, we can convert something saying `even` ( $S$   $n$ ) = `true` to `even`  $n$  = `false`.

Lemma `nodup_cancel_Permutation` :  $\forall A$  `Aeq_dec` ( $l$   $l'$ :`list`  $A$ ),  
**Permutation**  $l$   $l' \rightarrow$   
**Permutation** (`nodup_cancel` `Aeq_dec`  $l$ ) (`nodup_cancel` `Aeq_dec`  $l'$ ).

Proof.

```

intros A Aeq_dec l l' H. induction H.
- auto.
- simpl. destruct even eqn:Hevn.
  + rewrite (count_occ_Permutation _ _ _ _ H) in Hevn. rewrite Hevn.
    apply perm_skip. apply remove_Permutation. apply IHPermutation.
  + rewrite (count_occ_Permutation _ _ _ _ H) in Hevn. rewrite Hevn.
    apply remove_Permutation. apply IHPermutation.
- simpl. destruct (even (count_occ Aeq_dec l x)) eqn:Hevx;
  destruct (even (count_occ Aeq_dec l y)) eqn:Hevy; destruct (Aeq_dec x y).
  + rewrite even_succ. rewrite ← negb_odd in Hevy.
    rewrite Bool.negb_true_iff in Hevy. rewrite Hevy. destruct (Aeq_dec y x);
    try (rewrite e in n; contradiction). rewrite even_succ.
    rewrite ← negb_odd in Hevx. rewrite Bool.negb_true_iff in Hevx.
    rewrite Hevx. simpl. destruct (Aeq_dec y x); try contradiction.
    destruct (Aeq_dec x y); try contradiction. rewrite remove_remove. auto.
  + rewrite Hevy. simpl. destruct (Aeq_dec y x);
    try (symmetry in e; contradiction). destruct (Aeq_dec x y);
    try contradiction. rewrite Hevx. rewrite remove_remove. apply perm_swap.
  + rewrite ← e in Hevy. rewrite Hevy in Hevx. inversion Hevx.
  + rewrite Hevy. simpl. destruct (Aeq_dec y x);
    try (symmetry in e; contradiction). rewrite Hevx. apply perm_skip.
    rewrite remove_remove. auto.
  + rewrite e in Hevx. rewrite Hevx in Hevy. inversion Hevy.

```

```

+ rewrite Hevy. destruct (Aeq_dec y x); try (symmetry in e; contradiction).
  rewrite Hevx. simpl. destruct (Aeq_dec x y); try contradiction.
  apply perm_skip. rewrite remove_remove. auto.
+ rewrite even_succ. rewrite ← negb_odd in Hevy.
  rewrite Bool.negb_false_iff in Hevy. rewrite Hevy. symmetry in e.
  destruct (Aeq_dec y x); try contradiction. rewrite even_succ.
  rewrite ← negb_odd in Hevx. rewrite Bool.negb_false_iff in Hevx.
  rewrite Hevx. rewrite e. auto.
+ rewrite Hevy. destruct (Aeq_dec y x); try (symmetry in e; contradiction).
  rewrite Hevx. rewrite remove_remove. auto.
- apply Permutation_trans with (l' := nodup_cancel Aeq_dec l'); auto.
Qed.

```

As mentioned earlier, in the original definition of the function, it was helpful to reverse the order of `remove` and the recursive call to `nodup_cancel`. This is possible because these operations are associative, which is proven below.

Lemma `nodup_cancel_remove_assoc` :  $\forall \{A\} \text{ Aeq\_dec } (a:A) \text{ } p,$   
`remove Aeq_dec a (nodup_cancel Aeq_dec p) =`  
`nodup_cancel Aeq_dec (remove Aeq_dec a p).`

Proof.

```

intros A Aeq_dec a p. induction p; auto.
simpl. destruct even eqn:Hevn.
- simpl. destruct (Aeq_dec a a0).
  + rewrite ← e. rewrite not_in_remove; auto. apply remove_In.
  + simpl. rewrite count_occ_neq_remove; auto. rewrite Hevn.
    f_equal. rewrite ← IHp. rewrite remove_remove. auto.
- destruct (Aeq_dec a a0).
  + rewrite ← e. rewrite not_in_remove; auto. apply remove_In.
  + simpl. rewrite count_occ_neq_remove; auto. rewrite Hevn.
    rewrite remove_remove. rewrite ← IHp. auto.

```

Qed.

The entire point of defining `nodup_cancel` was so that repeated elements in a list cancel out; clearly then, if an entire list appears twice it will cancel itself out. This proof would be much easier if the order of `remove` and `nodup_cancel` was swapped, but the above proof of the two being associative makes it easier to manage.

Lemma `nodup_cancel_self` :  $\forall \{A\} \text{ Aeq\_dec } (l:\text{list } A),$   
`nodup_cancel Aeq_dec (l ++ l) = []`.

Proof.

```

intros A Aeq_dec p. induction p; auto.
simpl. destruct even eqn:Hevn.
- rewrite count_occ_app in Hevn. destruct (count_occ Aeq_dec p a) eqn:Hx.
  + simpl in Hevn. destruct (Aeq_dec a a); try contradiction.

```

```

    rewrite Hx in Hevn. inversion Hevn.
+ simpl in Hevn. destruct (Aeq_dec a a); try contradiction.
    rewrite Hx in Hevn. rewrite add_comm in Hevn.
    simpl in Hevn. destruct (plus n n) eqn:Help. inversion Hevn.
    replace (plus n n) with (plus 0 (2 × n)) in Help.
    pose (even_add_mul_2 0 n). pose (even_succ n0). rewrite ← Help in e1.
    rewrite e0 in e1. simpl in e1. apply even_spec in Hevn. symmetry in e1.
    apply odd_spec in e1. apply (Even-Odd-False _ Hevn) in e1. inversion e1.
    simpl. auto.
- clear Hevn. rewrite nodup_cancel_remove_assoc. rewrite remove_distr_app.
    simpl. destruct (Aeq_dec a a); try contradiction.
    rewrite ← remove_distr_app. rewrite ← nodup_cancel_remove_assoc.
    rewrite IHp. auto.

```

Qed.

Next up is a useful fact about `ln` that results from `nodup_cancel`. Because when there's an even number of an element they all get removed, we can say that there will not be any in the resulting list.

Lemma not\_in\_nodup\_cancel :  $\forall \{A \text{ Aeq\_dec}\} (m:A) p,$   
`even (count_occ Aeq_dec p m) = true →`  
`¬ ln m (nodup_cancel Aeq_dec p).`

Proof.

```

intros A Aeq_dec m p H. induction p; auto.
intro. simpl in H. destruct (Aeq_dec a m).
- simpl in H0. rewrite even_succ in H. rewrite ← negb_even in H.
    rewrite Bool.negb_true_iff in H. rewrite ← e in H. rewrite H in H0.
    rewrite e in H0. apply remove_ln in H0. inversion H0.
- apply IHp; auto. simpl in H0. destruct (even (count_occ Aeq_dec p a)).
    + destruct H0; try contradiction. apply ln_remove in H0. auto.
    + apply ln_remove in H0. auto.

```

Qed.

Similarly to the above lemma, because `a` will already be removed from `p` by `nodup_cancel`, whether or not a `remove` is added doesn't make a difference.

Lemma nodup\_extra\_remove :  $\forall \{A \text{ Aeq\_dec}\} (a:A) p,$   
`even (count_occ Aeq_dec p a) = true →`  
`nodup_cancel Aeq_dec p =`  
`nodup_cancel Aeq_dec (remove Aeq_dec a p).`

Proof.

```

intros A Aeq_dec a p H. induction p as [|b|]; auto. simpl.
destruct (Aeq_dec a b).
- rewrite e in H. simpl in H. destruct (Aeq_dec b b); try contradiction.
    rewrite even_succ in H. rewrite ← negb_even in H.

```

```

rewrite Bool.negb_true_iff in H.
rewrite H. rewrite nodup_cancel_remove_assoc. rewrite e. auto.
- simpl. destruct (even (count_occ Aeq_dec p b)) eqn:Hev.
  + rewrite count_occ_neq_remove; auto. rewrite Hev. f_equal.
    rewrite IHp. auto. simpl in H. destruct (Aeq_dec);
    try (symmetry in e; contradiction). auto.
  + rewrite count_occ_neq_remove; auto. rewrite Hev. f_equal.
    apply IHp. simpl in H. destruct (Aeq_dec b a);
    try (symmetry in e; contradiction). auto.

```

Qed.

Lastly, one of the toughest `nodup_cancel` lemmas. Similarly to `nodup_pointless`, if `nodup_cancel` is going to be applied later, there is no need for it to be applied twice. This lemma proves to be very useful when proving that two different polynomials are equal, because, as we will see later, there are often repeated calls to `nodup_cancel` inside one another. This lemma makes it significantly easier to deal with, as we can remove the redundant `nodup_cancels`.

This proof proved to be challenging, mostly because it is hard to reason about the parity of the same element in two different lists. In the proof, we begin with induction over  $p$ , and then move to destructing the count of  $a$  in each list. The first case follows easily from the two even hypotheses, `count_occ_app`, and a couple other lemmas. The second case is almost exactly the same, except  $a$  is removed by `nodup_cancel` and never makes it out front, so the call to `perm_skip` is removed.

The third case, where  $a$  appears an odd number of times in  $p$  and an even number of times in  $q$ , is slightly different, but still solved relatively easily with the use of `nodup_extra_remove`. The fourth case is by far the hardest. We begin by asserting that, since the count of  $a$  in  $q$  is odd, there must be at least one, and therefore we can rewrite with `ln_split` to get  $q$  into the form of  $l1 ++ a ++ l2$ . We then assert that, since the count of  $a$  in  $q$  is odd, the count in  $l1 ++ l2$ , or  $q$  with one  $a$  removed, must surely be even. These facts, combined with `remove_distr_app`, `count_occ_app`, and `nodup_cancel_remove_assoc`, allow us to slowly but surely work  $a$  out to the front and eliminate it with `perm_skip`. All that is left to do at that point is to perform similar steps in the induction hypothesis, so that both  $IHp$  and our goal are in terms of  $l1$  and  $l2$ .  $IHp$  is then used to finish the proof.

Lemma `nodup_cancel_pointless` :  $\forall \{A \text{ Aeq\_dec}\} (p \ q : \text{list } A),$   
`Permutation` (`nodup_cancel Aeq_dec (nodup_cancel Aeq_dec p ++ q)`)  
(`nodup_cancel Aeq_dec (p ++ q)`).

Proof.

```

intros A Aeq_dec p q. induction p; auto.
destruct (even (count_occ Aeq_dec p a)) eqn:Hevp;
destruct (even (count_occ Aeq_dec q a)) eqn:Hevq.
- simpl. rewrite Hevp. simpl. rewrite count_occ_app, count_occ_remove. simpl.
  rewrite count_occ_app, even_add, Hevp, Hevq. simpl. apply perm_skip.
  rewrite nodup_cancel_remove_assoc. rewrite remove_pointless.
  rewrite ← nodup_cancel_remove_assoc. apply remove_Permutation. apply IHp.

```

```

- simpl. rewrite Hevp. simpl. rewrite count_occ_app, count_occ_remove. simpl.
  rewrite count_occ_app, even_add, Hevp, Hevq. simpl.
  rewrite nodup_cancel_remove_assoc. rewrite remove_pointless.
  rewrite ← nodup_cancel_remove_assoc. apply remove_permutation. apply IHp.
- simpl. rewrite Hevp. rewrite count_occ_app, even_add, Hevp, Hevq. simpl.
  rewrite (nodup_extra_remove a).
  + rewrite remove_pointless. rewrite ← nodup_cancel_remove_assoc.
    apply remove_permutation. apply IHp.
  + rewrite count_occ_app. rewrite even_add. rewrite count_occ_remove.
    rewrite Hevq. auto.
- assert (count_occ Aeq_dec q a > 0). destruct (count_occ - q -).
  inversion Hevq. apply gt_Sn_O. apply count_occ_In in H.
  apply in_split in H as [l1 [l2 H]]. rewrite H. simpl nodup_cancel at 2.
  rewrite Hevp. simpl app. rewrite H in IHp. simpl nodup_cancel at 3.
  rewrite count_occ_app. rewrite even_add. rewrite Hevp. rewrite ← H at 2.
  rewrite Hevq. simpl. apply Permutation_trans with (l':=nodup_cancel
    Aeq_dec (a :: remove Aeq_dec a (nodup_cancel Aeq_dec p) ++ l1 ++ l2)).
  + apply nodup_cancel_permutation. rewrite app_assoc. apply Permutation_sym.
    rewrite app_assoc. apply Permutation_middle with (l2:=l2) (l1:=remove
      Aeq_dec a (nodup_cancel Aeq_dec p) ++ l1).
  + assert (even (count_occ Aeq_dec (l1 ++ l2) a) = true).
    rewrite H in Hevq. rewrite count_occ_app in Hevq. simpl in Hevq.
    destruct (Aeq_dec a a); try contradiction. rewrite plus_comm in Hevq.
    rewrite plus_Sn_m in Hevq. rewrite even_succ in Hevq.
    rewrite ← negb_even in Hevq. rewrite Bool.negb_false_iff in Hevq.
    rewrite count_occ_app. symmetry. rewrite plus_comm. auto.
  simpl. rewrite count_occ_app. rewrite count_occ_remove. simpl.
  replace (even _) with true. apply perm_skip.
  rewrite (nodup_cancel_remove_assoc - - (p ++ l1 ++ a :: l2)).
  repeat rewrite remove_distr_app. simpl; destruct (Aeq_dec a a);
  try contradiction. rewrite nodup_cancel_remove_assoc.
  rewrite remove_pointless. repeat rewrite ← remove_distr_app.
  repeat rewrite ← nodup_cancel_remove_assoc. apply Permutation_trans with
    (l'':=nodup_cancel Aeq_dec (a :: p ++ l1 ++ l2)) in IHp.
  apply Permutation_sym in IHp. apply Permutation_trans with (l'':=
    nodup_cancel Aeq_dec (a :: nodup_cancel Aeq_dec p ++ l1 ++ l2)) in IHp.
  simpl in IHp. rewrite count_occ_app, even_add, Hevp in IHp.
  rewrite H0 in IHp. simpl in IHp.
  rewrite count_occ_app, even_add, count_occ_nodup_cancel, Hevp, H0 in IHp.
  simpl in IHp. apply Permutation_sym. apply IHp.
  × apply nodup_cancel_permutation. rewrite app_assoc.
    apply Permutation_sym. rewrite app_assoc. apply Permutation_middle with

```

```

      (l1:=nodup_cancel Aeq_dec p ++ l1).
    × apply nodup_cancel_permutation. rewrite app_assoc.
      apply Permutation_sym. rewrite app_assoc. apply Permutation_middle with
        (l1:=p ++ l1).

```

Qed.

This lemma is simply a reformalization of the above for convenience, which follows simply because of `Permutation_app_comm`.

Lemma `nodup_cancel_pointless_r` :  $\forall \{A \text{ Aeq\_dec}\} (p \ q:\text{list } A),$

**Permutation**

```

  (nodup_cancel Aeq_dec (p ++ nodup_cancel Aeq_dec q))
  (nodup_cancel Aeq_dec (p ++ q)).

```

Proof.

```

  intros A Aeq_dec p q. apply Permutation_trans with (l':=nodup_cancel Aeq_dec
    (nodup_cancel Aeq_dec q ++ p)). apply nodup_cancel_permutation.
  apply Permutation_app_comm.
  apply Permutation_sym. apply Permutation_trans with (l':=nodup_cancel
    Aeq_dec (q ++ p)). apply nodup_cancel_permutation.
  apply Permutation_app_comm. apply Permutation_sym.
  apply nodup_cancel_pointless.

```

Qed.

An interesting side effect of `nodup_cancel_pointless` is that now we can show that `nodup_cancel` almost “distributes” over `app`. More formally, to prove that the `nodup_cancel` of two lists appended together is a permutation of `nodup_cancel` applied to two other lists appended, it is sufficient to show that the first of each and the second of each are permutations after applying `nodup_cancel` to them individually.

Lemma `nodup_cancel_app_permutation` :  $\forall \{A \text{ Aeq\_dec}\} (a \ b \ c \ d:\text{list } A),$

**Permutation** `(nodup_cancel Aeq_dec a) (nodup_cancel Aeq_dec b) →`

**Permutation** `(nodup_cancel Aeq_dec c) (nodup_cancel Aeq_dec d) →`

**Permutation** `(nodup_cancel Aeq_dec (a ++ c)) (nodup_cancel Aeq_dec (b ++ d)).`

Proof.

```

  intros A Aeq_dec a b c d H H0. rewrite ← (nodup_cancel_pointless a),
  ← (nodup_cancel_pointless b), ← (nodup_cancel_pointless_r _ c),
  ← (nodup_cancel_pointless_r _ d).
  apply nodup_cancel_permutation. apply Permutation_app; auto.

```

Qed.

### 5.4.3 Comparing Parity of Lists: `parity_match`

The final major definition over lists we wrote is `parity_match`. `parity_match` is closely related to `nodup_cancel`, and allows us to make statements about lists being equal after applying `nodup_cancel` to them. Clearly, if an element appears an even number of times in both lists,

then it won't appear at all after `nodup_cancel`, and if an element appears an odd number of times in both lists, then it will appear once after `nodup_cancel`. The ultimate goal of creating this definition is to prove a lemma that if the parity of two lists matches, they are permutations of each other after applying `nodup_cancel`.

The definition simply states that for all elements, the parity of the number of occurrences in each list is equal.

**Definition** `parity_match`  $\{A\}$  `Aeq_dec` ( $l\ m:\text{list } A$ ) : `Prop` :=  
 $\forall x, \text{even } (\text{count\_occ } \text{Aeq\_dec } l\ x) = \text{even } (\text{count\_occ } \text{Aeq\_dec } m\ x).$

A useful lemma in working towards this proof is that if the count of every variable in a list is even, then there will be no variables in the resulting list. This is relatively easy to prove, as we have already proven `not_in_nodup_cancel` and can contradict away the other cases.

**Lemma** `even_nodup_cancel` :  $\forall \{A\} \text{Aeq\_dec} \{p:\text{list } A\},$   
 $(\forall x, \text{even } (\text{count\_occ } \text{Aeq\_dec } p\ x) = \text{true}) \rightarrow$   
 $(\forall x, \neg \text{In } x (\text{nodup\_cancel } \text{Aeq\_dec } p)).$

**Proof.**

```
intros A Aeq_dec p H m. intro. induction p.
- inversion H0.
- simpl in *. pose (H m) as H1. symmetry in H1. destruct (Aeq_dec a m).
  + symmetry in H1. rewrite ← e in H1. rewrite even_succ in H1.
    rewrite ← negb_even in H1. rewrite Bool.negb_true_iff in H1.
    rewrite H1 in H0. rewrite e in H0. apply remove_In in H0. inversion H0.
  + destruct (even (count_occ Aeq_dec p a)).
    × destruct H0; try contradiction. apply In_remove in H0. symmetry in H1.
      apply not_in_nodup_cancel in H1. contradiction.
    × apply In_remove in H0. symmetry in H1. apply not_in_nodup_cancel in H1.
      contradiction.
```

**Qed.**

The above lemma can then be used in combination with `nothing_in_empty` to easily prove `parity_match_empty`, which will be useful in two cases of our goal lemma.

**Lemma** `parity_match_empty` :  $\forall \{A\} \text{Aeq\_dec} \{q:\text{list } A\},$   
`parity_match` `Aeq_dec` []  $q \rightarrow$   
`Permutation` [] (`nodup_cancel` `Aeq_dec`  $q$ ).

**Proof.**

```
intros A Aeq_dec q H. unfold parity_match in H. simpl in H.
symmetry in H. pose (even_nodup_cancel q H). apply nothing_in_empty in n.
rewrite n. auto.
```

**Qed.**

The `parity_match` definition is also reflexive, symmetric, and transitive, and knowing this will make future proofs easier.

**Lemma** `parity_match_refl` :  $\forall \{A\} \text{Aeq\_dec} \{l:\text{list } A\},$



parity\_match Aeq\_dec l l.

Proof.

intros A Aeq\_dec l. unfold parity\_match. auto.

Qed.

Lemma parity\_match\_sym :  $\forall \{A \text{ Aeq\_dec}\} (l \ m:\text{list } A),$

parity\_match Aeq\_dec l m  $\leftrightarrow$  parity\_match Aeq\_dec m l.

Proof.

intros l m. unfold parity\_match. split; intros H x; auto.

Qed.

Lemma parity\_match\_trans :  $\forall \{A \text{ Aeq\_dec}\} (p \ q \ r:\text{list } A),$

parity\_match Aeq\_dec p q  $\rightarrow$

parity\_match Aeq\_dec q r  $\rightarrow$

parity\_match Aeq\_dec p r.

Proof.

intros A Aeq\_dec p q r H H0. unfold parity\_match in \*. intros x.

rewrite H. rewrite H0. auto.

Qed.

Hint Resolve parity\_match\_refl parity\_match\_sym parity\_match\_trans.

There are also a few interesting facts that can be proved about elements being *consed* onto lists in a `parity_match`. First is that if the parity of two lists is equal, then the parities will also be equal after adding another element to the front, and vice versa.

Lemma parity\_match\_cons :  $\forall \{A \text{ Aeq\_dec}\} (a:A) \ l1 \ l2,$

parity\_match Aeq\_dec (a :: l1) (a :: l2)  $\leftrightarrow$

parity\_match Aeq\_dec l1 l2.

Proof.

intros A Aeq\_dec a l1 l2. unfold parity\_match. split; intros H x.

- pose (H x). symmetry in e. simpl in e. destruct (Aeq\_dec a x); auto.

repeat rewrite even\_succ in e. repeat rewrite  $\leftarrow$  negb\_even in e.

apply Bool.negb\_sym in e. rewrite Bool.negb\_involutive in e. auto.

- simpl. destruct (Aeq\_dec a x); auto.

repeat rewrite even\_succ. repeat rewrite  $\leftarrow$  negb\_even.

apply Bool.negb\_sym. rewrite Bool.negb\_involutive. auto.

Qed.

Similarly, adding the same element twice to a list does not change the parities of any elements in the list.

Lemma parity\_match\_double :  $\forall \{A \text{ Aeq\_dec}\} (a:A) \ l,$

parity\_match Aeq\_dec (a :: a :: l) l.

Proof.

intros A Aeq\_dec a l. unfold parity\_match. intros x. simpl.

destruct (Aeq\_dec a x); auto.

Qed.



The last *cons* `parity_match` lemma states that if you remove an element from one list and add it to the other, the parity will not be affected. This follows because if they both had an even number of *a* before they will both have an odd number after, and if it was odd before it will be even after.

```
Lemma parity_match_cons_swap : ∀ {A Aeq_dec} (a:A) l1 l2,
  parity_match Aeq_dec (a :: l1) l2 →
  parity_match Aeq_dec l1 (a :: l2).
```

Proof.

```
intros A Aeq_dec a l1 l2 H. apply (parity_match_cons a) in H.
apply parity_match_sym in H. apply parity_match_trans with (r:=l1) in H.
apply parity_match_sym in H. auto. apply parity_match_double.
```

Qed.

This next lemma states that if we know that some element *a* appears in the *rest* of the list an even number of times, then clearly it appears in *l2* an odd number of times and must be in the list.

```
Lemma parity_match_in : ∀ {A Aeq_dec} (a:A) l1 l2,
  even (count_occ Aeq_dec l1 a) = true →
  parity_match Aeq_dec (a :: l1) l2 →
  in a l2.
```

Proof.

```
intros A Aeq_dec a l1 l2 H H0. apply parity_match_cons_swap in H0.
rewrite H0 in H. simpl in H. destruct (Aeq_dec a a); try contradiction.
rewrite even_succ in H. rewrite ← negb_even in H.
rewrite Bool.negb_true_iff in H.
assert (count_occ Aeq_dec l2 a > 0). destruct count_occ. inversion H.
apply gt_Sn_O. apply count_occ_in in H1. auto.
```

Qed.

The last fact to prove before attempting the big lemma is that if two lists are permutations of each other, then their parities must match because they contain the same elements the same number of times.

```
Lemma Permutation_parity_match : ∀ {A Aeq_dec} (p q:list A),
  Permutation p q → parity_match Aeq_dec p q.
```

Proof.

```
intros A Aeq_dec p q H. induction H.
- auto.
- apply parity_match_cons. auto.
- repeat apply parity_match_cons_swap. unfold parity_match. intros x0.
  simpl. destruct Aeq_dec; destruct Aeq_dec;
  repeat (rewrite even_succ; rewrite odd_succ); auto.
- apply parity_match_trans with (q:=l'); auto.
```

Qed.

Finally, the big one. The first three cases are straightforward, especially now that we have already proven `parity_match_empty`. The third case is more complicated. We begin by destructing if  $a$  and  $a0$  are equal. In the case that they are, the proof is relatively straightforward; `parity_match_cons`, `perm_skip`, and `remove_permutation` take care of it.

In the case that they are not equal, we next destruct if the number of occurrences is even or not. If it is odd, we can use `parity_match_in` and `in_split` to rewrite  $l2$  in terms of  $a$ . From there, we use permutation facts to rearrange  $a$  to be at the front, and the rest of the proof is similar to the proof when  $a$  and  $a0$  are equal.

The final case is when they are not equal and the number of occurrences is even. After using `parity_match_cons_swap`, we can get to a point where we know that  $a$  appears in  $q ++ a0$  an even number of times. This means that  $a$  will not be in  $q ++ a0$  after applying `nodup_cancel`, so we can rewrite with `not_in_remove` in the reverse direction to get the two sides of the permutation goal to be more similar. Then, because it is wrapped in `remove a`, we can clearly add an  $a$  on the inside without it having any effect. Then all that is left is to apply `remove_permutation`, and we end up with a goal matching the induction hypothesis.

This lemma is very powerful, especially when dealing with `nodup_cancel` with functions applied to the elements of a list. This will come into play later in this file.

Lemma `parity_nodup_cancel_permutation` :  $\forall \{A \text{ Aeq\_dec}\} (p \ q : \text{list } A),$   
`parity_match Aeq\_dec p q  $\rightarrow$`   
`Permutation (nodup_cancel Aeq\_dec p) (nodup_cancel Aeq\_dec q).`

Proof.

```

intros A Aeq_dec p q H. generalize dependent q.
induction p; induction q; intros.
- auto.
- simpl nodup_cancel at 1. apply parity_match_empty. auto.
- simpl nodup_cancel at 2. apply Permutation_sym. apply parity_match_empty.
  apply parity_match_sym. auto.
- clear IHq. destruct (Aeq_dec a a0).
  + rewrite e. simpl. rewrite e in H. apply parity_match_cons in H.
    destruct even eqn:Hev; rewrite H in Hev; rewrite Hev.
    × apply perm_skip. apply remove_permutation. auto.
    × apply remove_permutation. auto.
  + simpl nodup_cancel at 1. destruct even eqn:Hev.
    × assert (Hev' := Hev).
      apply parity_match_in with (l2 := a0 :: q) in Hev; auto.
      destruct Hev. symmetry in H0. contradiction.
      apply in_split in H0 as [l1 [l2 H0]]. rewrite H0. apply Permutation_sym.
      apply Permutation_trans with
        (l' := nodup_cancel Aeq_dec (a :: l2 ++ a0 :: l1)).
      apply nodup_cancel_permutation. rewrite app_comm_cons.
      apply (Permutation_app_comm). simpl. rewrite H0 in H.
      apply parity_match_trans with (r := a :: l2 ++ a0 :: l1) in H.

```

```

apply parity_match_cons in H. rewrite H in Hev'. rewrite Hev'.
apply perm_skip. apply remove_Permutation. apply Permutation_sym.
apply IHp. auto. rewrite app_comm_cons. apply Permutation_parity_match.
apply Permutation_app_comm.
× apply parity_match_cons_swap in H. rewrite H in Hev. assert (Hev2:=Hev).
rewrite count_occ_Permutation with (l':=a :: q ++ [a0]) in Hev.
simpl in Hev. destruct (Aeq_dec a a); try contradiction.
rewrite even_succ in Hev. rewrite ← negb_even in Hev.
rewrite Bool.negb_false_iff in Hev.
rewrite ← (not_in_remove _ Aeq_dec a).
assert (∀ l, remove Aeq_dec a (nodup_cancel Aeq_dec l) =
  remove Aeq_dec a (nodup_cancel Aeq_dec (a :: l))).
intros l. simpl. destruct (even (count_occ _ l a)).
simpl. destruct (Aeq_dec a a); try contradiction.
rewrite (not_in_remove _ _ (remove _ _)). auto. apply remove_in.
rewrite (not_in_remove _ _ (remove _ _)). auto. apply remove_in.
rewrite (H0 (a0 :: q)). apply remove_Permutation. apply IHp. auto.
apply not_in_nodup_cancel.
rewrite count_occ_Permutation with (l':=a0 :: q) in Hev.
auto. replace (a0 :: q) with ([a0] ++ q); auto.
apply Permutation_app_comm. apply perm_skip.
replace (a0 :: q) with ([a0] ++ q); auto. apply Permutation_app_comm.

```

Qed.

## 5.5 Combining nodup\_cancel and Other Functions

### 5.5.1 Using nodup\_cancel over map

Our next goal is to prove things about the relation between `nodup_cancel` and `map` over lists. In particular, we want to prove a lemma similar to `nodup_cancel_pointless`, that allows us to remove redundant `nodup_cancels`.

The challenging part of proving this lemma is that it is often hard to reason about how, for example, the number of times  $a$  appears in  $p$  relates to the number of times  $f a$  appears in `map f p`. Many of the functions we map across lists in practice are not one-to-one, meaning that there could be some  $b$  such that  $f a = f b$ . However, at the end of the day, these repeated elements will cancel out with each other and the parities will match, hence why `parity_nodup_cancel_Permutation` is extremely useful.

To begin, we need to prove a couple facts comparing the number of occurrences of elements in a list. The first lemma states that the number of times some  $a$  appears in  $p$  is less than or equal to the number of times  $f a$  appears in `map f p`.

Lemma `count_occ_map_lt` :  $\forall \{A \text{ Aeq\_dec} \} p (a:A) f,$   
 $\text{count\_occ } \text{Aeq\_dec } p \ a \leq \text{count\_occ } \text{Aeq\_dec } (\text{map } f \ p) \ (f \ a).$

Proof.

```

intros A Aeq_dec p a f. induction p. auto. simpl. destruct Aeq_dec.
- rewrite e. destruct Aeq_dec; try contradiction. simpl. apply le_n_S. auto.
- destruct Aeq_dec; auto.

```

Qed.

Building off this idea, the next lemma states that the number of times  $f a$  appears in  $\text{map } f p$  with  $a$  removed is equal to the count of  $f a$  in  $\text{map } f p$  minus the count of  $a$  in  $p$ .

Lemma count\_occ\_map\_sub :  $\forall \{A \text{ Aeq\_dec}\} f (a:A) p,$   
 $\text{count\_occ } Aeq\_dec (\text{map } f (\text{remove } Aeq\_dec a p)) (f a) =$   
 $\text{count\_occ } Aeq\_dec (\text{map } f p) (f a) - \text{count\_occ } Aeq\_dec p a.$

Proof.

```

intros A Aeq_dec f a p. induction p; auto. simpl. destruct Aeq_dec.
- rewrite e. destruct Aeq_dec; try contradiction. destruct Aeq_dec;
  try contradiction. simpl. rewrite ← e. auto.
- simpl. destruct Aeq_dec.
  + destruct Aeq_dec. symmetry in e0; contradiction. rewrite IHp.
    rewrite sub_succ_l. auto. apply count_occ_map_lt.
  + destruct Aeq_dec. symmetry in e; contradiction. auto.

```

Qed.

It is also true that if there is some  $x$  that is *not* equal to  $f a$ , then the count of that  $x$  in  $\text{map } f p$  is the same as the count of  $x$  in  $\text{map } f p$  with  $a$  removed.

Lemma count\_occ\_map\_neq\_remove :  $\forall \{A \text{ Aeq\_dec}\} f (a:A) p x,$   
 $x \neq f a \rightarrow$   
 $\text{count\_occ } Aeq\_dec (\text{map } f (\text{remove } Aeq\_dec a p)) x =$   
 $\text{count\_occ } Aeq\_dec (\text{map } f p) x.$

Proof.

```

intros. induction p as [|b|]; auto. simpl. destruct (Aeq_dec a b).
- destruct Aeq_dec. rewrite ← e in e0. symmetry in e0. contradiction.
  auto.
- simpl. destruct Aeq_dec; auto.

```

Qed.

The next lemma is similar to `count_occ_map_lt`, except it involves some  $b$  where  $a$  is not equal to  $b$ , but  $f a = f b$ . Then clearly, the sum of  $a$  in  $p$  and  $b$  in  $p$  is less than the count of  $f a$  in  $\text{map } f p$ .

Lemma f\_equal\_sum\_lt :  $\forall \{A \text{ Aeq\_dec}\} f (a:A) b p,$   
 $b \neq a \rightarrow (f a) = (f b) \rightarrow$   
 $\text{count\_occ } Aeq\_dec p b +$   
 $\text{count\_occ } Aeq\_dec p a \leq$   
 $\text{count\_occ } Aeq\_dec (\text{map } f p) (f a).$

Proof.

```

intros A Aeq_dec f a b p Hne Hfe. induction p as [|c|]; auto. simpl.

```

```

destruct Aeq_dec.
- rewrite e. destruct Aeq_dec; try contradiction. rewrite Hfe.
  destruct Aeq_dec; try contradiction. simpl. apply le_n_S.
  rewrite ← Hfe. auto.
- destruct Aeq_dec.
  + rewrite e. destruct Aeq_dec; try contradiction. rewrite plus_comm.
    simpl. rewrite plus_comm. apply le_n_S. auto.
  + destruct Aeq_dec.
    × apply le_S. auto.
    × auto.

```

Qed.

For the next lemma, we once again try to compare the count of  $a$  to the count of  $f a$ , but also involve `nodup_cancel`. Clearly, there is no way for there to be more  $a$ 's in  $p$  than  $f a$ 's in `map f p` even with the addition of `nodup_cancel`.

Lemma `count_occ_nodup_map_lt` :  $\forall \{A \text{ Aeq\_dec} \} p f (a:A),$   
`count_occ Aeq_dec (nodup_cancel Aeq_dec p) a`  $\leq$   
`count_occ Aeq_dec (map f (nodup_cancel Aeq_dec p)) (f a).`

Proof.

```

intros A Aeq_dec p f a. induction p as [|b]; auto. simpl.
destruct even eqn:Hev.
- simpl. destruct Aeq_dec.
  + rewrite e. destruct Aeq_dec; try contradiction. apply le_n_S. auto.
    rewrite count_occ_remove. apply le_0_l.
  + rewrite count_occ_neq_remove; auto. rewrite not_in_remove.
    destruct Aeq_dec; firstorder. apply not_in_nodup_cancel; auto.
- destruct (Aeq_dec b a) eqn:Hba.
  + rewrite e. rewrite count_occ_remove. apply le_0_l.
  + rewrite count_occ_neq_remove; auto.
    destruct (Aeq_dec (f b) (f a)) eqn:Hfba.
    × rewrite ← e. rewrite count_occ_map_sub. rewrite e.
      apply le_add_le_sub_l. apply f_equal_sum_lt; auto.
    × rewrite count_occ_map_neq_remove; auto.

```

Qed.

All of these lemmas now come together for the core one, a variation of `nodup_cancel_pointless` but involving `map f`. We begin by applying `parity_nodup_cancel_permutation`, and destructing if  $a$  appears in  $p$  an even number of times or not.

The even case is relatively easy to prove, and only involves using the usual combination of `even_succ`, `not_in_remove`, and `not_in_nodup_cancel`.

The odd case is trickier, and where we involve all of the newly proved lemmas. If  $x$  and  $f a$  are not equal, the proof follows just from `count_occ_map_neq_remove` and the induction hypothesis.

If they are equal, we begin by rewriting with `count_occ_map_sub` and `even_sub`. After a

few more rewrites, it becomes the case that we need to prove that the boolean equivalence of the parities of  $f\ a$  in `map f p` and  $a$  in  $p$  is equal to the negated parity of  $f\ a$  in `map f p`. Because we know that  $a$  appears in  $p$  an odd number of times from destructing `even` earlier, this follows immediately.

Lemma `nodup_cancel_map` :  $\forall \{A\ Aeq\_dec\} (p : \text{list } A) f,$

**Permutation**

$(\text{nodup\_cancel } Aeq\_dec (\text{map } f (\text{nodup\_cancel } Aeq\_dec\ p)))$   
 $(\text{nodup\_cancel } Aeq\_dec (\text{map } f\ p)).$

Proof.

```
intros A Aeq_dec p f. apply parity_nodup_cancel_Permutation.
unfold parity_match. intros x. induction p; auto. simpl.
destruct (even (count_occ _ p a)) eqn:Hev.
- simpl. destruct Aeq_dec.
  + repeat rewrite even_succ. repeat rewrite ← negb_even.
    rewrite not_in_remove. rewrite IHp. auto. apply not_in_nodup_cancel. auto.
  + rewrite not_in_remove. apply IHp. apply not_in_nodup_cancel. auto.
- simpl. destruct Aeq_dec.
  + rewrite ← e. rewrite count_occ_map_sub. rewrite even_sub.
    rewrite ← e in IHp. rewrite IHp. rewrite count_occ_nodup_cancel.
    rewrite Hev. rewrite even_succ. rewrite ← negb_even.
    destruct (even (count_occ _ (map f p) _)); auto.
    apply count_occ_nodup_map_lt.
  + rewrite count_occ_map_neq_remove; auto.
```

Qed.

### 5.5.2 Using `nodup_cancel` over `concat map`

Similarly to `map`, the same property of not needing repeated `nodup_cancels` applies when the lists are being flattened and mapped over. This final section of the file seeks to, in very much the same way as earlier, prove this.

We begin with a simple lemma about math that will come into play soon - if a number is less than or equal to 1, then it is either 0 or 1. This is immediately solved with firstorder logic.

Lemma `n_le_1` :  $\forall n,$

$n \leq 1 \rightarrow n = 0 \vee n = 1.$

Proof.

```
intros n H. induction n; firstorder.
```

Qed.

The main difference between this section and the section about `map` is that all of the functions being mapped will clearly be returning lists as their output, and then being concatenated with the rest of the result. This makes things slightly harder, as we can't reason

about the number of times, for example, some  $f\ a$  appears in a list. Instead, we have to reason about the number of times that some  $x$  appears in a list, where  $x$  is one of the elements of the list  $f\ a$ .

In practice, these lemmas are only going to be applied in situations where every  $f\ a$  has no duplicates in it. In other words, as the lemma above states, there will be either 0 or 1 of each  $x$  in a list. The next two lemmas prove some consequences of this.

First is that if the count of  $x$  in  $f\ a$  is 0, then clearly removing  $a$  from some list  $p$  will not affect the count of  $x$  in the concatenated version of the list.

Lemma `count_occ_map_sub_not_in` :  $\forall \{A\ Aeq\_dec\} f\ (a:A)\ p,$   
 $\forall x, \text{count\_occ } Aeq\_dec\ (f\ a)\ x = 0 \rightarrow$   
 $\text{count\_occ } Aeq\_dec\ (\text{concat } (\text{map } f\ (\text{remove } Aeq\_dec\ a\ p)))\ x =$   
 $\text{count\_occ } Aeq\_dec\ (\text{concat } (\text{map } f\ p))\ x.$

Proof.

```
intros A Aeq_dec f a p x H. induction p as [|b]; auto. simpl.
rewrite count_occ_app. destruct Aeq_dec.
- rewrite e in H. rewrite H. firstorder.
- simpl. rewrite count_occ_app. auto.
```

Qed.

On the other hand, if the count of some  $x$  in  $f\ a$  is 1, then the count of  $a$  in the original list must be less than or equal to the count of  $x$  in the final list, depending on if some  $b$  exists such that  $f\ a$  also contains  $x$ . More useful is the fact that if  $x$  appears once in  $f\ x$ , the count of  $x$  in the final list with  $a$  removed is equal to the count of  $x$  in the final list minus the count of  $a$  in the list. Both of these proofs are relatively straightforward, and mostly follow from firstorder logic.

Lemma `count_occ_concat_map_lt` :  $\forall \{A\ Aeq\_dec\} p\ (a:A)\ f\ x,$   
 $\text{count\_occ } Aeq\_dec\ (f\ a)\ x = 1 \rightarrow$   
 $\text{count\_occ } Aeq\_dec\ p\ a \leq \text{count\_occ } Aeq\_dec\ (\text{concat } (\text{map } f\ p))\ x.$

Proof.

```
intros A Aeq_dec p a f x H. induction p. auto. simpl. destruct Aeq_dec.
- rewrite e. rewrite count_occ_app. rewrite H. simpl. firstorder.
- rewrite count_occ_app. induction (count_occ Aeq_dec (f a0) x); firstorder.
```

Qed.

Lemma `count_occ_map_sub_in` :  $\forall \{A\ Aeq\_dec\} f\ (a:A)\ p,$   
 $\forall x, \text{count\_occ } Aeq\_dec\ (f\ a)\ x = 1 \rightarrow$   
 $\text{count\_occ } Aeq\_dec\ (\text{concat } (\text{map } f\ (\text{remove } Aeq\_dec\ a\ p)))\ x =$   
 $\text{count\_occ } Aeq\_dec\ (\text{concat } (\text{map } f\ p))\ x - \text{count\_occ } Aeq\_dec\ p\ a.$

Proof.

```
intros A Aeq_dec f a p x H. induction p as [|b]; auto. simpl.
destruct Aeq_dec.
- rewrite e. destruct Aeq_dec; try contradiction. rewrite count_occ_app.
  rewrite e in H. rewrite H. simpl. rewrite ← e. auto.
```

```

- simpl. destruct Aeq_dec. symmetry in e. contradiction.
  repeat rewrite count_occ_app. rewrite IHp. rewrite add_sub_assoc. auto.
  apply count_occ_concat_map_lt; auto.

```

Qed.

Continuing the pattern of proving similar facts as we did during the `map` proof, we now prove a version of `f_equal_sum_lt` involving `concat`. This lemma states that, if we know there will be no duplicates in  $f\ x$  for all  $x$ , and that there are some  $a$  and  $b$  such that they are not equal but  $x$  is in both  $f\ a$  and  $f\ b$ , then clearly the sum of the count of  $a$  and the count of  $b$  is less than or equal to the count of  $x$  in the list after applying the function and flattening.

Lemma `f_equal_concat_sum_lt` :  $\forall \{A\} \text{ Aeq\_dec } f (a:A) b\ p\ x,$   
 $b \neq a \rightarrow$   
 $(\forall x, \text{NoDup } (f\ x)) \rightarrow$   
 $\text{count\_occ } \text{Aeq\_dec } (f\ a)\ x = 1 \rightarrow$   
 $\text{count\_occ } \text{Aeq\_dec } (f\ b)\ x = 1 \rightarrow$   
 $\text{count\_occ } \text{Aeq\_dec } p\ b +$   
 $\text{count\_occ } \text{Aeq\_dec } p\ a \leq$   
 $\text{count\_occ } \text{Aeq\_dec } (\text{concat } (\text{map } f\ p))\ x.$

Proof.

```

intros A Aeq_dec f a b p x Hne Hnd Hfa Hfb. induction p as [|c]; auto. simpl.
destruct Aeq_dec.
- rewrite e. destruct Aeq_dec; try contradiction. rewrite count_occ_app.
  firstorder.
- destruct Aeq_dec.
  + rewrite e. rewrite count_occ_app. firstorder.
  + rewrite count_occ_app. pose (Hnd c).
    rewrite (NoDup_count_occ Aeq_dec) in n1. pose (n1 x).
    apply n_le_1 in l. clear n1. destruct l; firstorder.

```

Qed.

The last step before we are able to prove `nodup_cancel_concat_map` is to actually involve `nodup_cancel` rather than just `remove`. This lemma states that given  $f\ x$  has no duplicates and  $a$  appears once in  $f\ a$ , the count of  $a$  in  $p$  after applying `nodup_cancel` is less than or equal to the count of  $x$  after applying `concat` and `nodup_cancel`.

The first cases, when the count is even, are relatively straightforward. The second cases, when the count is odd, are slightly more complicated. We destruct if  $a$  and  $b$  (where  $b$  is our induction element) are equal. If they are, then the proof is solved by firstorder logic. On the other hand, if they are not, we make use of our `n_le_1` fact proved before to find out how many times  $x$  appears in  $f\ b$ . If it is zero, then we rewrite with the 0 fact proved earlier and are done. In the final case, we rewrite with the 1 subtraction fact we proved earlier, and it follows from `f_equal_concat_sum_lt`.

Lemma `count_occ_nodup_concat_map_lt` :  $\forall \{A\} \text{ Aeq\_dec } p\ f (a:A) x,$   
 $(\forall x, \text{NoDup } (f\ x)) \rightarrow$



```

count_occ Aeq_dec (f a) x = 1 →
count_occ Aeq_dec (nodup_cancel Aeq_dec p) a ≤
count_occ Aeq_dec (concat (map f (nodup_cancel Aeq_dec p))) x.

```

Proof.

```

intros A Aeq_dec p f a x Hn H. induction p as [|b]; auto. simpl.
destruct even eqn:Hev.
- simpl. destruct Aeq_dec.
  + rewrite e. rewrite count_occ_remove, count_occ_app. rewrite H. firstorder.
  + rewrite count_occ_neq_remove; auto. rewrite not_in_remove.
    rewrite count_occ_app. firstorder. apply not_in_nodup_cancel. auto.
- destruct (Aeq_dec b a) eqn:Hba.
  + rewrite e. rewrite count_occ_remove. firstorder.
  + rewrite count_occ_neq_remove; auto. assert (Hn1:=(Hn b)).
    rewrite (NoDup_count_occ Aeq_dec) in Hn1. assert (Hn2:=(Hn1 x)).
    clear Hn1. apply n_le_1 in Hn2. destruct Hn2.
    × rewrite count_occ_map_sub_not_in; auto.
    × apply (count_occ_map_sub_in _ _ (nodup_cancel Aeq_dec p)) in H0 as H1.
      rewrite H1. apply le_add_le_sub_1. apply f_equal_concat_sum_lt; auto.

```

Qed.

Finally, the proof we've been building up to. Once again, we begin the proof by converting to a parity\_match problem and then perform induction on the list. The case where  $a$  appears an even number of times in the list is easy, and follows from the same combination of `count_occ_app` and `even_add` that we have used before.

The case where  $a$  appears an odd number of times is slightly more complex. Once again, we apply `n_le_1` to determine how many times our  $x$  appears in  $f a$ . If it is zero times, we use `count_occ_map_sub_not_in` like above, and then the induction hypothesis solves it. If  $x$  appears once in  $f a$ , we instead use `count_occ_map_sub_in` combined with `even_sub`. Then, after rewriting with the induction hypothesis, we can easily solve the lemma with the use of `count_occ_nodup_cancel`.

Lemma `nodup_cancel_concat_map` :  $\forall \{A \text{ Aeq\_dec} \} (p:\text{list } A) f,$   
 $(\forall x, \text{NoDup } (f x)) \rightarrow$   
**Permutation**  
 $(\text{nodup\_cancel } Aeq\_dec (\text{concat } (\text{map } f (\text{nodup\_cancel } Aeq\_dec p))))$   
 $(\text{nodup\_cancel } Aeq\_dec (\text{concat } (\text{map } f p)))$ .

Proof.

```

intros A Aeq_dec p f H. apply parity_nodup_cancel_Permutation.
unfold parity_match. intros x. induction p; auto. simpl.
destruct (even (count_occ _ p a)) eqn:Hev.
- simpl. repeat rewrite count_occ_app. repeat rewrite even_add.
  rewrite not_in_remove. rewrite IHp. auto. apply not_in_nodup_cancel. auto.
- assert (H0:=(H a)). rewrite (NoDup_count_occ Aeq_dec) in H0.
  assert (H1:=(H0 x)). clear H0. apply n_le_1 in H1. rewrite count_occ_app.

```

```

rewrite even_add. destruct H1.
+ apply (count_occ_map_sub_not_in _ _ (nodup_cancel Aeq_dec p)) in H0 as H1.
  rewrite H0, H1, IHp. simpl.
  destruct (even (count_occ _ (concat (map f p)) x)); auto.
+ apply (count_occ_map_sub_in _ _ (nodup_cancel Aeq_dec p)) in H0 as H1.
  rewrite H0, H1, even_sub, IHp. simpl. rewrite count_occ_nodup_cancel.
  rewrite Hev. destruct (even (count_occ _ (concat (map f p)) x)); auto.
  apply count_occ_nodup_concat_map_lt; auto.
Qed.

```

# Chapter 6

## Library B\_Unification.poly

```
Require Import Arith.
Require Import List.
Import ListNotations.
Require Import FunctionalExtensionality.
Require Import Sorting.
Require Import Permutation.
Import Nat.

Require Export list_util.
```

### 6.1 Monomials and Polynomials

#### 6.1.1 Data Type Definitions

Now that we have defined those functions over lists and proven all of those facts about them, we can begin to apply all of them to our specific project of unification. The first step is to define the data structures we plan on using.

As mentioned earlier, because of the ten axioms that hold true during  $B$ -unification, we can represent all possible terms with lists of lists of numbers. The numbers represent variables, and a list of variables is a monomial, where each variable is multiplied together. A polynomial, then, is a list of monomials where each monomial is added together.

In this representation, the term 0 is represented as the empty polynomial, and the term 1 is represented as the polynomial containing only the empty monomial.

In addition to the definitions of `var`, `mono`, and `poly`, we also have definitions for `var_eq_dec` and `mono_eq_dec`; these are proofs of decidability of variables and monomials respectively. They make use of a special Coq data structure that allows them to be used as a comparison function - for example, we can `destruct (mono_eq_dec a b)` to compare the two cases where  $a = b$  and  $a \neq b$ . In addition to being useful in some proofs, this is also needed by some functions, such as `remove` and `count_occ`, since they compare variables and monomials.

Definition `var` := `nat`.

Definition var\_eq\_dec := Nat.eq\_dec.

Definition mono := list var.

Definition mono\_eq\_dec := (list\_eq\_dec Nat.eq\_dec).

Definition poly := list mono.

### 6.1.2 Comparisons of monomials and polynomials

In order to easily compare monomials, we make use of the `lex` function we defined at the beginning of the `list_util` file. For convenience, we also define `mono_lt`, which is a proposition that states that some monomial is less than another.

Definition mono\_cmp := lex compare.

Definition mono\_lt  $m\ n$  := mono\_cmp  $m\ n$  = Lt.

A simple but useful definition is `vars`, which allows us to take any polynomial and get a list of all the variables in it. This is simply done by concatenating all of the monomials into one large list of variables and removing any repeated variables.

Clearly then, there will never be any duplicates in the `vars` of some polynomial.

Definition vars ( $p$  : poly) : list var := nodup var\_eq\_dec (concat  $p$ ).

Hint Unfold vars.

Lemma NoDup\_vars :  $\forall (p$  : poly),  
NoDup (vars  $p$ ).

Proof.

intros  $p$ . unfold vars. apply NoDup\_nodup.

Qed.

This next lemma allows us to convert from a statement about `vars` to a statement about the monomials themselves. If some variable  $x$  is not in the variables of a polynomial  $p$ , then every monomial in  $p$  must not contain  $x$ .

Lemma in\_mono\_in\_vars :  $\forall x\ p$ ,  
( $\forall m$  : mono,  $\text{In } m\ p \rightarrow \neg \text{In } x\ m$ )  $\leftrightarrow \neg \text{In } x$  (vars  $p$ ).

Proof.

intros  $x\ p$ . split.  
- intros  $H$ . induction  $p$ .  
+ simpl. auto.  
+ unfold not in \*. intro. apply IHp.  
× intros  $m\ Hin$ . apply  $H$ . intuition.  
× unfold vars in \*. apply nodup\_In in  $H0$ . apply nodup\_In. simpl in  $H0$ .  
apply in\_app\_or in  $H0$ . destruct  $H0$ .  
- exfalso. apply ( $H\ a$ ). intuition. auto.  
- auto.  
- intros  $H\ m\ Hin\ Hin'$ . apply  $H$ . clear  $H$ . induction  $p$ .

```

+ inversion Hin.
+ unfold vars in *. rewrite nodup_In. rewrite nodup_In in IHp. simpl.
  apply in_or_app. destruct Hin.
  × left. rewrite H. auto.
  × auto.

```

Qed.

### 6.1.3 Stronger Definitions

Because, as far as Coq is concerned, any list of natural numbers is a monomial, it is necessary to define a few more predicates about monomials and polynomials to ensure our desired properties hold. Using these in proofs will prevent any random list from being used as a monomial or polynomial.

Monomials are simply lists of natural numbers that, for ease of comparison, are sorted least to greatest. A small subtlety is that we are insisting they are sorted with **lt**, meaning less than, rather than *le*, or less than or equal to. This way, the **Sorted** predicate will insist that each number is *less than* the one following it, thereby preventing any values from being equal to each other. In this way, we simultaneously enforce the sorting and lack of duplicated values in a monomial.

Definition `is_mono` ( $m : \text{mono}$ ) : Prop := **Sorted lt**  $m$ .

Polynomials are sorted lists of lists, where all of the lists in the polynomial are monomials. Similarly to the last example, we use `mono_lt` to simultaneously enforce sorting and no duplicates.

Definition `is_poly` ( $p : \text{poly}$ ) : Prop :=  
**Sorted** `mono_lt`  $p \wedge \forall m, \text{In } m \text{ } p \rightarrow \text{is\_mono } m$ .

Hint Unfold `is_mono` `is_poly`.

Hint Resolve `NoDup_cons` `NoDup_nil` `Sorted_cons`.

There are a few useful things we can prove about these definitions too. First, because of the sorting, every element in a monomial is guaranteed to be less than the element after it.

Lemma `mono_order` :  $\forall x \ y \ m,$   
`is_mono` ( $x :: y :: m$ )  $\rightarrow$   
 $x < y$ .

Proof.

```

unfold is_mono.
intros x y m H.
apply Sorted_inv in H as [].
apply HdRel_inv in H0.
apply H0.

```

Qed.

Similarly, if  $x :: m$  is a monomial, then  $m$  is also a monomial.

Lemma mono\_cons :  $\forall x m,$   
 is\_mono  $(x :: m) \rightarrow$   
 is\_mono  $m$ .

Proof.

unfold is\_mono.

intros  $x m H$ . apply Sorted\_inv in  $H$  as []. apply  $H$ .

Qed.

The same properties hold for is\_poly as well; any list in a polynomial is guaranteed to be less than the lists after it, and if  $m :: p$  is a polynomial, we know both that  $p$  is a polynomial and that  $m$  is a monomial.

Lemma poly\_order :  $\forall m n p,$   
 is\_poly  $(m :: n :: p) \rightarrow$   
 mono\_lt  $m n$ .

Proof.

unfold is\_poly.

intros.

destruct  $H$ .

apply Sorted\_inv in  $H$  as [].

apply HdRel\_inv in  $H1$ .

apply  $H1$ .

Qed.

Lemma poly\_cons :  $\forall m p,$   
 is\_poly  $(m :: p) \rightarrow$   
 is\_poly  $p \wedge$  is\_mono  $m$ .

Proof.

unfold is\_poly.

intros.

destruct  $H$ .

apply Sorted\_inv in  $H$  as [].

split.

- split; auto.

intros. apply  $H0$ , in\_cons,  $H2$ .

- apply  $H0$ , in\_eq.

Qed.

Lastly, for completeness, nil is both a polynomial and monomial, the polynomial representation for one as we described before is a polynomial, and a singleton variable is a polynomial.

Lemma nil\_is\_mono :  
 is\_mono [].

Proof.

unfold is\_mono. auto.

Qed.

Lemma nil\_is\_poly :  
 is\_poly [].

Proof.

unfold is\_poly. split; auto.  
 intro; contradiction.

Qed.

Lemma one\_is\_poly :  
 is\_poly [[]].

Proof.

unfold is\_poly. split; auto.  
 intro. intro. simpl in H. destruct H.  
 - rewrite ← H. apply nil\_is\_mono.  
 - inversion H.

Qed.

Lemma var\_is\_poly : ∀ x,  
 is\_poly [[x]].

Proof.

intros x. unfold is\_poly. split.  
 - apply Sorted\_cons; auto.  
 - intros m H. simpl in H; destruct H; inversion H.  
 unfold is\_mono. auto.

Qed.

In unification, a common concept is a *ground term*, or a term that contains no variables. If some polynomial is a ground term, then it must either be equal to 0 or 1.

Lemma no\_vars\_is\_ground : ∀ p,  
 is\_poly p →  
 vars p = [] →  
 p = [] ∨ p = [[]].

Proof.

intros p H H0. induction p; auto.  
 induction a.  
 - destruct IHp.  
 + apply poly\_cons in H. apply H.  
 + unfold vars in H0. simpl in H0. apply H0.  
 + rewrite H1. auto.  
 + rewrite H1 in H. unfold is\_poly in H. destruct H. inversion H.  
 inversion H6. inversion H8.  
 - unfold vars in H0. simpl in H0. destruct in\_dec in H0.  
 + rewrite ← nodup\_In in i. rewrite H0 in i. inversion i.  
 + inversion H0.

Qed.

Hint Resolve *mono\_order mono\_cons poly\_order poly\_cons nil\_is\_mono nil\_is\_poly  
var\_is\_poly one\_is\_poly*.

## 6.2 Sorted Lists and Sorting

Clearly, because we want to maintain that our monomials and polynomials are sorted at all times, we will be dealing with Coq's **Sorted** proposition a lot. In addition, not every list we want to operate on will already be perfectly sorted, so it is often necessary to sort lists ourselves. This next section serves to give us all of the tools necessary to operate on sorted lists.

### 6.2.1 Sorting Lists

In order to sort our lists, we will make use of the **Sorting** module in the standard library, which implements a version of merge sort.

For sorting variables in a monomial, we can simply reuse the already provided *NatSort* module.

Module Import VARSORT := NATSORT.

Sorting the monomials in a polynomial is slightly more complicated, but still straightforward thanks to the **Sorting** module. First, we need to define a **MONOORDER**, which must be a total less-than-or-equal-to comparator.

This is accomplished by using our **mono\_cmp** defined earlier, and simply returning true for either less than or equal to.

We also prove a relatively simple lemma about this new **MONOORDER**, which states that if  $x \leq y$  and  $y \leq x$ , then  $x$  must be equal to  $y$ .

Require Import Orders.

Module MONOORDER <: TOTALLEBOOL.

Definition t := mono.

Definition leb m n :=

match mono\_cmp m n with

| Lt  $\Rightarrow$  true

| Eq  $\Rightarrow$  true

| Gt  $\Rightarrow$  false

end.

Infix "<=m" := leb (at level 35).

Lemma leb\_total :  $\forall m n, (m \leq_m n = \text{true}) \vee (n \leq_m m = \text{true})$ .

Proof.

intros n m. unfold "<=m". destruct (mono\_cmp n m) eqn:Hcomp; auto.



```

    unfold mono_cmp in *. apply lex_rev_lt_gt in Hcomp. rewrite Hcomp. auto.
Qed.

```

End MONOORDER.

```

Lemma leb_both_eq : ∀ x y,
  is_true (MonoOrder.leb x y) →
  is_true (MonoOrder.leb y x) →
  x = y.

```

Proof.

```

  intros x y H H0. unfold is_true, MonoOrder.leb in *.
  destruct (mono_cmp y x) eqn:Hxy; destruct (mono_cmp x y) eqn:Hxy;
  unfold mono_cmp in *;
  try (apply lex_rev_lt_gt in Hxy; rewrite Hxy in Hxy; inversion Hxy);
  try (apply lex_rev_lt_gt in Hxy; rewrite Hxy in Hxy; inversion Hxy);
  try inversion H; try inversion H0.
  apply lex_eq in Hxy; auto.

```

Qed.

After this order has been defined and its totality has been proven, we simply define a new MONOSORT module to be a sort based on this MONOORDER.

Now, we have a simple `sort` function for both monomials and polynomials, as well as a few useful lemmas about the `sort` functions' correctness.

```

Module Import MONOSORT := SORT MONOORDER.

```

One technique that helps us deal with the difficulty of sorted lists is proving that each of our four comparators - `lt`, `VarOrder`, `mono_lt`, and `MONOORDER` - are all transitive. This allows us to seamlessly pass between the standard library's `Sorted` and `StronglySorted` propositions, making many proofs significantly easier.

All four of these are proved relatively easily, mostly by induction and destructing the comparison of the individual values.

```

Lemma lt_Transitive :
  Relations_1.Transitive lt.

```

Proof.

```

  unfold Relations_1.Transitive. intros. apply lt_trans with (m:=y); auto.

```

Qed.

```

Lemma VarOrder_Transitive :
  Relations_1.Transitive (fun x y => is_true (NatOrder.leb x y)).

```

Proof.

```

  unfold Relations_1.Transitive, is_true.
  induction x, y, z; intros; try reflexivity; simpl in *.
  - inversion H.
  - inversion H.
  - inversion H0.
  - apply IHx with (y:=y); auto.

```

Qed.

Lemma mono\_lt\_Transitive : **Relations\_1.Transitive** mono\_lt.

Proof.

```
unfold Relations_1.Transitive, is_true, mono_lt, mono_cmp.
induction x, y, z; intros; try reflexivity; simpl in *.
- inversion H.
- inversion H0.
- inversion H0.
- inversion H.
- inversion H0.
- destruct (a <?= n0) eqn:Han0.
  + apply compare_eq_iff in Han0. rewrite Han0 in H.
    destruct (n <?= n0) eqn:Hn0.
    × rewrite compare_antisym in Hn0. unfold CompOpp in Hn0.
      destruct (n0 <?= n); try inversion Hn0. apply (IHx - - H H0).
    × rewrite compare_antisym in Hn0. unfold CompOpp in Hn0.
      destruct (n0 <?= n); try inversion Hn0. inversion H.
    × inversion H0.
  + auto.
  + destruct (n <?= n0) eqn:Hnn0.
    × apply compare_eq_iff in Hnn0. rewrite Hnn0 in H. rewrite Han0 in H.
      inversion H.
    × apply compare_lt_iff in Hnn0. apply compare_gt_iff in Han0.
      apply lt_trans with (n:=n) in Han0; auto. apply compare_lt_iff in Han0.
      rewrite compare_antisym in Han0. unfold CompOpp in Han0.
      destruct (a <?= n); try inversion Han0. inversion H.
    × inversion H0.
```

Qed.

Lemma MonoOrder\_Transitive :

**Relations\_1.Transitive** (fun x y => **is\_true** (MonoOrder.leb x y)).

Proof.

```
unfold Relations_1.Transitive, is_true, MonoOrder.leb, mono_cmp.
induction x, y, z; intros; try reflexivity; simpl in *.
- inversion H.
- inversion H.
- inversion H0.
- destruct (a <?= n) eqn:Han.
  + apply compare_eq_iff in Han. rewrite Han. destruct (n <?= n0) eqn:Hn0.
    × apply (IHx - - H H0).
    × reflexivity.
    × inversion H0.
  + destruct (n <?= n0) eqn:Hn0.
```

```

× apply compare_eq_iff in Hn0. rewrite ← Hn0. rewrite Han. reflexivity.
× apply compare_lt_iff in Han. apply compare_lt_iff in Hn0.
  apply (lt_trans a n n0 Han) in Hn0. apply compare_lt_iff in Hn0.
  rewrite Hn0. reflexivity.
× inversion H0.
+ inversion H.
Qed.

```

## 6.2.2 Sorting and Permutations

The entire purpose of ensuring our monomials and polynomials remain sorted at all times is so that two polynomials containing the same elements are treated as equal. This definition obviously lends itself very well to the use of the **Permutation** predicate from the standard library, which explains why we proved so many lemmas about permutations during `list_util`.

When comparing equality of polynomials or monomials, this **sort** function is often extremely tricky to deal with. Induction over a list being passed to **sort** is nearly impossible, because the induction element  $a$  is not guaranteed to be the least value, so will not easily make it outside of the sort function. As a result, the induction hypothesis is almost always useless.

To combat this, we will prove a series of lemmas relating **sort** to **Permutation**, since clearly sorting has no effect when we are comparing the lists in an unordered fashion. The simplest of these lemmas is that if either term of a **Permutation** is wrapped in a **sort** function, we can easily get rid of it without changing the provability of these statements.

Lemma `Permutation_VarSort_l` :  $\forall m n,$

**Permutation**  $m n \leftrightarrow$  **Permutation** (`VarSort.sort`  $m$ )  $n$ .

Proof.

```

intros m n. split; intro.
- apply Permutation_trans with (l' := m). apply Permutation_sym.
  apply VarSort.Permuted_sort. apply H.
- apply Permutation_trans with (l' := (VarSort.sort m)).
  apply VarSort.Permuted_sort. apply H.

```

Qed.

Lemma `Permutation_VarSort_r` :  $\forall m n,$

**Permutation**  $m n \leftrightarrow$  **Permutation**  $m$  (`VarSort.sort`  $n$ ).

Proof.

```

intros m n. split; intro.
- apply Permutation_sym. rewrite ← Permutation_VarSort_l.
  apply Permutation_sym; auto.
- apply Permutation_sym. rewrite → Permutation_VarSort_l.
  apply Permutation_sym; auto.

```

Qed.

Lemma `Permutation_MonoSort_r` :  $\forall p q,$

**Permutation**  $p\ q \leftrightarrow \text{Permutation } p\ (\text{sort } q)$ .

Proof.

```
intros p q. split; intro H.
- apply Permutation_trans with (l' := q). apply H. apply Permuted_sort.
- apply Permutation_trans with (l' := (sort q)). apply H. apply Permutation_sym.
  apply Permuted_sort.
```

Qed.

Lemma **Permutation\_MonoSort\_l** :  $\forall\ p\ q,$

**Permutation**  $p\ q \leftrightarrow \text{Permutation } (\text{sort } p)\ q$ .

Proof.

```
intros p q. split; intro H.
- apply Permutation_sym. rewrite  $\leftarrow$  Permutation_MonoSort_r.
  apply Permutation_sym. auto.
- apply Permutation_sym. rewrite Permutation_MonoSort_r.
  apply Permutation_sym. auto.
```

Qed.

More powerful is the idea that, if we know we are dealing with sorted lists, there is no difference between proving lists are equal and proving they are **Permutations**. While this seems intuitive, it is actually fairly complicated to prove in Coq.

For monomials, the proof begins by performing induction on both lists. The first three cases are very straightforward, and the only challenge comes from the third case. We approach the third case by first comparing the two induction elements,  $a$  and  $a\theta$ .

This forms three goals for us - one where  $a = a\theta$ , one where  $a < a\theta$ , and one where  $a > a\theta$ . The first goal is extremely straightforward, and follows from the induction hypothesis almost immediately after using a few **compare** lemmas.

This leaves us with the next two goals, which seem to be more challenging at first. However, some further thought leads us to the conclusion that both goals should both be contradictions. If the lists are both sorted, and they contain all the same elements, then they should have the same element, at the head of the list, which is the least element of the set. This element is clearly  $a$  for the first list, and  $a\theta$  for the second. However, our destruct of **compare** has left us with a hypothesis stating that they are not equal! This is the source of the contradiction.

To get Coq to see our contradiction, we first make use of the **Transitive** lemmas we proved earlier to convert to **StronglySorted**. This allows us to get a hypothesis in the second goal that states that  $a\theta$  must be less than everything in the second list. Because  $a$  is not equal to  $a\theta$ , this implied that  $a$  is somewhere else in the second list, and therefore  $a\theta$  is less than  $a$ . This clearly contradicts the fact that  $a < a\theta$ . The third goal looks the same, but in reverse.

Lemma **Permutation\_Sorted\_mono\_eq** :  $\forall\ (m\ n : \text{mono}),$

**Permutation**  $m\ n \rightarrow$   
**Sorted**  $(\text{fun } n\ m \Rightarrow \text{is\_true } (\text{leb } n\ m))\ m \rightarrow$   
**Sorted**  $(\text{fun } n\ m \Rightarrow \text{is\_true } (\text{leb } n\ m))\ n \rightarrow$   
 $m = n$ .

Proof.

```

intros m n Hp Hsl Hsm. generalize dependent n.
induction m; induction n; intros.
- reflexivity.
- apply Permutation_nil in Hp. auto.
- apply Permutation_sym, Permutation_nil in Hp. auto.
- clear IHn. apply Permutation_incl in Hp as Hp'. destruct Hp'.
  destruct (a ?= a0) eqn:Hcomp.
  + apply compare_eq_iff in Hcomp. rewrite Hcomp in *.
    apply Permutation_cons_inv in Hp. f_equal; auto.
    apply IHm.
    × apply Sorted_inv in Hsl. apply Hsl.
    × apply Hp.
    × apply Sorted_inv in Hsm. apply Hsm.
  + apply compare_lt_iff in Hcomp as Hneg. apply incl_cons_inv in H.
    destruct H. apply Sorted_StronglySorted in Hsm.
    apply StronglySorted_inv in Hsm as [].
    × simpl in H. destruct H; try (rewrite H in Hneg; apply lt_irrefl in Hneg;
      contradiction). pose (Forall_In _ _ _ H H3). simpl in i.
    unfold is_true in i. apply leb_le in i. apply lt_not_le in Hneg.
    contradiction.
    × apply VarOrder_Transitive.
  + apply compare_gt_iff in Hcomp as Hneg. apply incl_cons_inv in H0.
    destruct H0.
    apply Sorted_StronglySorted in Hsl. apply StronglySorted_inv in Hsl as [].
    × simpl in H0. destruct H0; try (rewrite H0 in Hneg;
      apply gt_irrefl in Hneg; contradiction). pose (Forall_In _ _ _ H0 H3).
    simpl in i. unfold is_true in i. apply leb_le in i.
    apply lt_not_le in Hneg. contradiction.
    × apply VarOrder_Transitive.

```

Qed.

We also wish to prove the same thing for polynomials. This proof is identical in spirit, as we do the same double induction, destructing of compare, and find the same two contradictions. The only difference is the use of lemmas about lex instead of **compare**, since now we are dealing with lists of lists.

Lemma **Permutation\_Sorted\_eq** :  $\forall (l\ m : \text{list mono}),$

```

Permutation l m →
Sorted (fun x y ⇒ is_true (MonoOrder.leb x y)) l →
Sorted (fun x y ⇒ is_true (MonoOrder.leb x y)) m →
l = m.

```

Proof.

```

intros l m Hp Hsl Hsm. generalize dependent m.

```

```

induction l; induction m; intros.
- reflexivity.
- apply Permutation_nil in Hp. auto.
- apply Permutation_sym, Permutation_nil in Hp. auto.
- clear IHm. apply Permutation_incl in Hp as Hp'. destruct Hp'.
  destruct (mono_cmp a a0) eqn:Hcomp.
  + apply lex_eq in Hcomp. rewrite Hcomp in *.
    apply Permutation_cons_inv in Hp. f_equal; auto.
    apply IHL.
    × apply Sorted_inv in Hsl. apply Hsl.
    × apply Hp.
    × apply Sorted_inv in Hsm. apply Hsm.
  + apply lex_neq' in Hcomp as Hneq. apply incl_cons_inv in H. destruct H.
    apply Sorted_StronglySorted in Hsm. apply StronglySorted_inv in Hsm as [].
    × simpl in H. destruct H; try (rewrite H in Hneq; contradiction).
      pose (Forall_In _ _ _ H H3). simpl in i. unfold is_true,
      MonoOrder.leb, mono_cmp in i. apply lex_rev_lt_gt in Hcomp.
      rewrite Hcomp in i. inversion i.
    × apply MonoOrder_Transitive.
  + apply lex_neq' in Hcomp as Hneq. apply incl_cons_inv in H0. destruct H0.
    apply Sorted_StronglySorted in Hsl. apply StronglySorted_inv in Hsl as [].
    × simpl in H0. destruct H0; try (rewrite H0 in Hneq; contradiction).
      pose (Forall_In _ _ _ H0 H3). simpl in i. unfold is_true in i.
      unfold MonoOrder.leb in i. rewrite Hcomp in i. inversion i.
    × apply MonoOrder_Transitive.

```

Qed.

Another useful form of these two lemmas is that if at any point we are attempting to prove that `sort` of one list equals `sort` of another, we can ditch the `sort` and instead prove that the two lists are permutations. These lemmas will come up a lot in future proofs, and has made some of our work much easier.

Lemma `Permutation_sort_mono_eq` :  $\forall l m,$

**Permutation**  $l m \leftrightarrow \text{VarSort.sort } l = \text{VarSort.sort } m.$

Proof.

```

intros l m. split; intros H.
- assert (H0 : Permutation (VarSort.sort l) (VarSort.sort m)).
  + apply Permutation_trans with (l:=(VarSort.sort l)) (l':=m)
    (l'':=VarSort.sort m).
    × apply Permutation_sym. apply Permutation_sym in H.
    apply (Permutation_trans H (VarSort.Permuted_sort l)).
    × apply VarSort.Permuted_sort.
  + apply (Permutation_Sorted_mono_eq _ _ H0 (VarSort.LocallySorted_sort l)
    (VarSort.LocallySorted_sort m)).

```

```

- assert (Permutation (VarSort.sort l) (VarSort.sort m)).
  + rewrite H. apply Permutation_refl.
  + pose (VarSort.Permuted_sort l). pose (VarSort.Permuted_sort m).
    apply (Permutation_trans p) in H0. apply Permutation_sym in p0.
    apply (Permutation_trans H0) in p0. apply p0.

```

Qed.

Lemma **Permutation\_sort\_eq** :  $\forall l m,$   
**Permutation**  $l m \leftrightarrow \text{sort } l = \text{sort } m$ .

Proof.

```

intros l m. split; intros H.
- assert (H0 : Permutation (sort l) (sort m)).
  + apply Permutation_trans with (l:=sort l) (l':=m) (l'':=sort m).
    × apply Permutation_sym. apply Permutation_sym in H.
    apply (Permutation_trans H (Permuted_sort l)).
    × apply Permuted_sort.
  + apply (Permutation_Sorted_eq _ _ H0 (LocallySorted_sort l)
    (LocallySorted_sort m)).
- assert (Permutation (sort l) (sort m)).
  + rewrite H. apply Permutation_refl.
  + pose (Permuted_sort l). pose (Permuted_sort m).
    apply (Permutation_trans p) in H0. apply Permutation_sym in p0.
    apply (Permutation_trans H0) in p0. apply p0.

```

Qed.

## 6.3 Repairing Invalid Monomials & Polynomials

Clearly, there is a very strict set of rules we would like to be true about all of the polynomials and monomials we workd with. These rules are, however, relatively tricky to maintain when it comes to writing functions that operate over monomials and polynomials. Rather than rely on our ability to define every function to perfectly maintain this set of rules, we decided to define two functions to “repair” any invalid monomials or polynomials. These functions, given a list of variables or a list of list of variables, will apply a few functions to them such that at the end, we are left with a properly formatted monomial or polynomial.

### 6.3.1 Converting Between **lt** and *le*

A small problem with the **sort** function provided by the standard library is that it requires us to use a *le* comparator, as opposed to **lt** like we use in our **is\_mono** and **is\_poly** definitions. However, as we said before, because our lists have no duplicates *le* and **lt** are equivalent. Obviously, though, saying this isn’t enough - we must prove it for it to be useful to us in proofs.

The first step to proving this is proving that this is true when dealing with the **HdRel** definition that **Sorted** is built on top of. These lemmas state that, if  $a$  holds the  $le$  relation with a list, and there are also no duplicates in  $a :: l$ , that  $a$  also holds the **lt** relation with the list. These proofs are both relatively straightforward, especially with the use of the **NoDup\_neq** lemma proven earlier.

Lemma HdRel\_le\_lt :  $\forall a m,$

**HdRel** (fun  $n m \Rightarrow$  **is\_true** (**leb**  $n m$ ))  $a m \wedge$  **NoDup** ( $a :: m$ )  $\rightarrow$   
**HdRel lt**  $a m$ .

Proof.

```
intros a m []. remember (fun n m  $\Rightarrow$  is_true (leb  $n m$ )) as le.
destruct m.
- apply HdRel_nil.
- apply HdRel_cons. apply HdRel_inv in H.
  apply (NoDup_neq _ a n) in H0; intuition. rewrite Heqle in H.
  unfold is_true in H. apply leb_le in H. destruct (a  $\neq$  n) eqn:Hcomp.
  + apply compare_eq_iff in Hcomp. contradiction.
  + apply compare_lt_iff in Hcomp. apply Hcomp.
  + apply compare_gt_iff in Hcomp. apply leb_correct_conv in Hcomp.
    apply leb_correct in H. rewrite H in Hcomp. inversion Hcomp.
```

Qed.

Lemma HdRel\_mono\_le\_lt :  $\forall a p,$

**HdRel** (fun  $n m \Rightarrow$  **is\_true** (MonoOrder.leb  $n m$ ))  $a p \wedge$  **NoDup** ( $a :: p$ )  $\rightarrow$   
**HdRel** mono\_lt  $a p$ .

Proof.

```
intros a p []. remember (fun n m  $\Rightarrow$  is_true (MonoOrder.leb  $n m$ )) as le.
destruct p.
- apply HdRel_nil.
- apply HdRel_cons. apply HdRel_inv in H.
  apply (NoDup_neq _ a l) in H0; intuition. rewrite Heqle in H.
  unfold is_true in H. unfold MonoOrder.leb in H. unfold mono_lt.
  destruct (mono_cmp a l) eqn:Hcomp.
  + apply lex_eq in Hcomp. contradiction.
  + reflexivity.
  + inversion H.
```

Qed.

Now, to apply these lemmas - we prove that if a list is **Sorted** with a  $le$  operator and has no duplicates, that it is also **Sorted** with the corresponding **lt** operator.

Lemma VarSort\_Sorted :  $\forall m,$

**Sorted** (fun  $n m \Rightarrow$  **is\_true** (**leb**  $n m$ ))  $m \wedge$  **NoDup**  $m \rightarrow$   
**Sorted lt**  $m$ .

Proof.



```

intros m []. remember (fun n m => is_true (leb n m)) as le.
induction m.
- apply Sorted_nil.
- apply Sorted_inv in H. apply Sorted_cons.
  + apply IHm.
    × apply H.
    × apply NoDup_cons_iff in H0. apply H0.
  + apply HdRel_le_lt. split.
    × rewrite ← Heql. apply H.
    × apply H0.

```

Qed.

Lemma MonoSort\_Sorted :  $\forall p$ ,  
 Sorted (fun n m => is\_true (MonoOrder.leb n m)) p  $\wedge$  NoDup p  $\rightarrow$   
 Sorted mono\_lt p.

Proof.

```

intros p []. remember (fun n m => is_true (MonoOrder.leb n m)) as le.
induction p.
- apply Sorted_nil.
- apply Sorted_inv in H. apply Sorted_cons.
  + apply IHp.
    × apply H.
    × apply NoDup_cons_iff in H0. apply H0.
  + apply HdRel_mono_le_lt. split.
    × rewrite ← Heql. apply H.
    × apply H0.

```

Qed.

For convenience, we also include the inverse - if a list is Sorted with an **lt** operator, it is also Sorted with the matching *le* operator.

Lemma Sorted\_VarSorted :  $\forall (m : \text{mono})$ ,  
 Sorted lt m  $\rightarrow$   
 Sorted (fun n m => is\_true (leb n m)) m.

Proof.

```

intros m H. induction H.
- apply Sorted_nil.
- apply Sorted_cons.
  + apply IHSorted.
  + destruct l.
    × apply HdRel_nil.
    × apply HdRel_cons. apply HdRel_inv in H0. apply lt_le_incl in H0.
    apply leb_le in H0. apply H0.

```

Qed.

Lemma Sorted\_MonoSorted :  $\forall (p : \text{poly}),$   
**Sorted** mono\_lt  $p \rightarrow$   
**Sorted** (fun  $n\ m \Rightarrow \text{is\_true}$  (MonoOrder.leb  $n\ m$ ))  $p$ .

Proof.

```

intros p H. induction H.
- apply Sorted_nil.
- apply Sorted_cons.
  + apply IHSorted.
  + destruct l.
    × apply HdRel_nil.
    × apply HdRel_cons. apply HdRel_inv in H0. unfold MonoOrder.leb.
      rewrite H0. auto.

```

Qed.

Another obvious side effect of what we have just proven is that if a list is **Sorted** with an **lt** operator, clearly there are no duplicates, as no elements are equal to each other.

Lemma NoDup\_VarSorted :  $\forall m,$   
**Sorted** lt  $m \rightarrow \text{NoDup } m$ .

Proof.

```

intros m H. apply Sorted_StronglySorted in H.
- induction m; auto.
  apply StronglySorted_inv in H as []. apply NoDup_forall_neq.
  + apply Forall_forall. intros x Hin. rewrite Forall_forall in H0.
    apply lt_neq. apply H0. apply Hin.
  + apply IHm. apply H.
- apply lt_Transitive.

```

Qed.

Lemma NoDup\_MonoSorted :  $\forall p,$   
**Sorted** mono\_lt  $p \rightarrow \text{NoDup } p$ .

Proof.

```

intros p H. apply Sorted_StronglySorted in H.
- induction p; auto.
  apply StronglySorted_inv in H as []. apply NoDup_forall_neq.
  + apply Forall_forall. intros x Hin. rewrite Forall_forall in H0.
    pose (lex_neq' a x). destruct a0. apply H1 in H0; auto.
  + apply IHp. apply H.
- apply mono_lt_Transitive.

```

Qed.

There are a few more useful lemmas we would like to prove about our sort functions before we can define and prove the correctness of our repair functions. Mostly, we want to know that sorting a list has no effect on some properties of it.

Specifically, if an element was in a list before it was sorted, it is also in it after, and vice

versa. Similarly, if a list has no duplicates before being sorted, it also has no duplicates after.

Lemma `In_sorted` :  $\forall a l,$   
 $\text{In } a l \leftrightarrow \text{In } a (\text{sort } l).$

Proof.

```
intros a l. pose (MonoSort.Permuted_sort l). split; intros Hin.
- apply (Permutation_in _ p Hin).
- apply (Permutation_in' (Logic.eq_refl a) p). auto.
```

Qed.

Lemma `NoDup_VarSort` :  $\forall (m : \text{mono}),$   
 $\text{NoDup } m \rightarrow \text{NoDup } (\text{VarSort.sort } m).$

Proof.

```
intros m Hdup. pose (VarSort.Permuted_sort m).
apply (Permutation_NoDup p Hdup).
```

Qed.

Lemma `NoDup_MonoSort` :  $\forall (p : \text{poly}),$   
 $\text{NoDup } p \rightarrow \text{NoDup } (\text{MonoSort.sort } p).$

Proof.

```
intros p Hdup. pose (MonoSort.Permuted_sort p).
apply (Permutation_NoDup p0 Hdup).
```

Qed.

### 6.3.2 Defining the Repair Functions

Now time for our definitions. To convert a list of variables into a monomial, we first apply `nodup`, which removes all duplicates. We use `nodup` rather than `nodup_cancel` because  $x*x \approx_B x$ , so we want one copy to remain. After applying `nodup`, we use our `VARSORT` module to sort the list from least to greatest.

Definition `make_mono` ( $l : \text{list nat}$ ) : `mono` :=  
`VarSort.sort (nodup var_eq_dec l).`

The process of converting a list of list of variables into a polynomial is very similar. First we `map` across the list applying `make_mono`, so that each sublist is properly formatted. Then we apply `nodup_cancel` to remove duplicates. In this case, we use `nodup_cancel` instead of `nodup` because  $x+x = 0$ , so we want pairs to cancel out. Lastly, we use our `MONOSORT` module to sort the list.

Definition `make_poly` ( $l : \text{list mono}$ ) : `poly` :=  
`MonoSort.sort (nodup_cancel mono_eq_dec (map make_mono l)).`

Lemma `make_poly_refold` :  $\forall p,$   
 $\text{sort } (\text{nodup\_cancel mono\_eq\_dec } (\text{map make\_mono } p)) =$   
 $\text{make\_poly } p.$

Proof. auto. Qed.

Now to prove the correctness of these lists - if you apply `make_mono` to something, it is then guaranteed to satisfy the `is_mono` proposition. This proof is relatively straightforward, as we have already done most of the work with `VarSort_Sorted`; all that is left to do is show that `make_mono m` is `Sorted` and has no duplicates, which is obvious considering that is exactly what `make_mono` does!

Lemma `make_mono_is_mono` :  $\forall m,$   
`is_mono (make_mono m).`

Proof.

```
intros m. unfold is_mono, make_mono. apply VarSort_Sorted. split.
+ apply VarSort.LocallySorted_sort.
+ apply NoDup_VarSort. apply NoDup_nodup.
```

Qed.

The proof for `make_poly_is_poly` is almost identical, with the addition of one part. The `is_poly` predicate still asks us to prove that the list is `Sorted`, which follows from `MonoSort_Sorted` like above. The only difference is that `is_poly` also asks us to show that each element in the list `is_mono`, which follows from the use of a few `ln` lemmas and the `make_mono_is_mono` we just proved thanks to the `map` in `make_poly`.

Lemma `make_poly_is_poly` :  $\forall p,$   
`is_poly (make_poly p).`

Proof.

```
intros p. unfold is_poly, make_poly. split.
- apply MonoSort_Sorted. split.
  + apply MonoSort.LocallySorted_sort.
  + apply NoDup_MonoSort. apply NoDup_nodup_cancel.
- intros m Hm. apply ln_sorted in Hm. apply nodup_cancel_in in Hm.
  apply in_map_iff in Hm. destruct Hm. destruct H. rewrite <- H.
  apply make_mono_is_mono.
```

Qed.

Hint Resolve `make_poly_is_poly` `make_mono_is_mono`.

### 6.3.3 Facts about `make_mono`

Before we dive into more complicated proofs involving these repair functions, there are a few simple lemmas we can prove about them.

First is that if some variable  $x$  was in a list before `make_mono` was applied, it must also be in it after, and vice-versa.

Lemma `make_mono_ln` :  $\forall x m,$   
`ln x (make_mono m)  $\leftrightarrow$  ln x m.`

Proof.

```
intros x m. split; intro H.
- unfold make_mono in H. pose (VarSort.Permuted_sort (nodup var_eq_dec m)).
```

```

    apply Permutation_sym in p. apply (Permutation_in - p) in H.
    apply nodup_In in H. auto.
- unfold make_mono. pose (VarSort.Permuted_sort (nodup var_eq_dec m)).
    apply Permutation_in with (l:=(nodup var_eq_dec m)); auto. apply nodup_In.
    auto.

```

Qed.

In addition, if some list  $m$  is already a monomial, removing anything from it will not change that.

```

Lemma remove_is_mono : ∀ x m,
  is_mono m →
  is_mono (remove var_eq_dec x m).

```

Proof.

```

  intros x m H. unfold is_mono in *. apply StronglySorted_Sorted.
  apply StronglySorted_remove. apply Sorted_StronglySorted in H. auto.
  apply lt_Transitive.

```

Qed.

If we know that some  $(l1 ++ x :: l2)$  is a mono, then clearly it is still a monomial if we remove the  $x$  from the middle, as this will not affect the sorting at all.

```

Lemma mono_middle : ∀ x l1 l2,
  is_mono (l1 ++ x :: l2) →
  is_mono (l1 ++ l2).

```

Proof.

```

  intros x l1 l2 H. unfold is_mono in *. apply Sorted_StronglySorted in H.
  apply StronglySorted_Sorted. induction l1.
- rewrite app_nil_l in *. apply StronglySorted_inv in H as []; auto.
- simpl in *. apply StronglySorted_inv in H as []. apply SSorted_cons; auto.
    apply Forall_forall. rewrite Forall_forall in H0. intros x0 Hin.
    apply H0. apply in_app_iff in Hin as []; intuition.
- apply lt_Transitive.

```

Qed.

Due to the nature of sorting, `make_mono` is commutative across list concatenation.

```

Lemma make_mono_app_comm : ∀ m n,
  make_mono (m ++ n) = make_mono (n ++ m).

```

Proof.

```

  intros m n. apply Permutation_sort_mono_eq. apply Permutation_nodup.
  apply Permutation_app_comm.

```

Qed.

Finally, if a list  $m$  is a member of the list resulting from `map make_mono`, then clearly it is a monomial.

```

Lemma mono_in_map_make_mono : ∀ p m,

```

`In m (map make_mono p) → is_mono m.`

Proof.

`intros. apply in_map_iff in H as [x []]. rewrite ← H. auto.`

Qed.

### 6.3.4 Facts about make\_poly

If two lists are permutations of each other, then they will be equivalent after applying `make_poly` to both.

Lemma `make_poly_Permutation` :  $\forall p q$ ,

**Permutation** `p q` → `make_poly p = make_poly q`.

Proof.

`intros. unfold make_poly.`

`apply Permutation_sort_eq, nodup_cancel_Permutation, Permutation_map.`

`auto.`

Qed.

Because we have shown that `sort` and `Permutation` are equivalent, we can easily show that `make_poly` is commutative across list concatenation.

Lemma `make_poly_app_comm` :  $\forall p q$ ,

`make_poly (p ++ q) = make_poly (q ++ p)`.

Proof.

`intros p q. apply Permutation_sort_eq.`

`apply nodup_cancel_Permutation. apply Permutation_map.`

`apply Permutation_app_comm.`

Qed.

During `make_poly`, we both sort and call `nodup_cancel`. A lemma that is useful in some cases shows that it doesn't matter what order we do these in, as `nodup_cancel` will maintain the order of a list.

Lemma `sort_nodup_cancel_assoc` :  $\forall l$ ,

`sort (nodup_cancel mono_eq_dec l) = nodup_cancel mono_eq_dec (sort l)`.

Proof.

`intros l. apply Permutation_Sorted_eq.`

`- pose (Permuted_sort (nodup_cancel mono_eq_dec l)).`

`apply Permutation_sym in p. apply (Permutation_trans p). clear p.`

`apply NoDup_Permutation.`

`+ apply NoDup_nodup_cancel.`

`+ apply NoDup_nodup_cancel.`

`+ intros x. split.`

`× intros H. apply Permutation_in with (l:=nodup_cancel mono_eq_dec l).`

`apply nodup_cancel_Permutation. apply Permuted_sort. auto.`

`× intros H.`

```

    apply Permutation_in with (l:=nodup_cancel mono_eq_dec (sort l)).
    apply nodup_cancel_permutation. apply Permutation_sym.
    apply Permuted_sort. auto.
- apply LocallySorted_sort.
- apply Sorted_nodup_cancel.
  + apply MonoOrder_Transitive.
  + apply LocallySorted_sort.
Qed.

```

Another obvious but useful lemma is that if a monomial  $m$  is in a list resulting from applying `make_poly`, is is clearly a monomial.

Lemma `mono_in_make_poly` :  $\forall p m,$   
**In**  $m$  (`make_poly`  $p$ )  $\rightarrow$  `is_mono`  $m$ .

Proof.

```

  intros. unfold make_poly in H. apply In_sorted in H.
  apply nodup_cancel_in in H. apply (mono_in_map_make_mono _ _ H).
Qed.

```

## 6.4 Proving Functions “Pointless”

In the `list_util` file, we have two lemmas revolving around the idea that, in some cases, calling `nodup_cancel` is “pointless”. The idea here is that, when comparing very complicated terms, it is sometimes beneficial to either add or remove an extra function call that has no effect on the final term. Until this point, we have only proven this about `nodup_cancel` and **remove**, but there are many other cases where this is true, which will make our more complex proofs much easier. This section serves to prove this true of most of our functions.

### 6.4.1 Working with sort Functions

The next two lemmas very simply prove that, if a list is already `Sorted`, then calling either `VARSORT` or `MONOSORT` on it will have no effect. This is relatively obvious, and is extremely easy to prove with our `Permutation` / `Sorted` lemmas from earlier.

Lemma `no_sort_VarSorted` :  $\forall m,$   
**Sorted**  $lt$   $m \rightarrow$   
`VarSort.sort`  $m = m$ .

Proof.

```

  intros m H. apply Permutation_Sorted_mono_eq.
- apply Permutation_sym. apply VarSort.Permuted_sort.
- apply VarSort.LocallySorted_sort.
- apply Sorted_VarSorted. auto.
Qed.

```

Lemma `no_sort_MonoSorted` :  $\forall p,$

**Sorted** mono\_lt  $p \rightarrow$

`MonoSort.sort p = p.`

Proof.

`intros p H. unfold make_poly. apply Permutation_Sorted_eq.`

`- apply Permutation_sym. apply Permuted_sort.`

`- apply LocallySorted_sort.`

`- apply Sorted_MonoSorted. auto.`

Qed.

The following lemma more closely aligns with the format of the `nodup_cancel_pointless` lemma from `list_util`. It states that if the result of appending two lists is already going to be sorted, there is no need to sort the intermediate lists.

This also applies if the sort is wrapped around the right argument, thanks to the `Permutation` lemmas we proved earlier.

Lemma `sort_pointless` :  $\forall p q,$

`sort (sort p ++ q) =`

`sort (p ++ q).`

Proof.

`intros p q. apply Permutation_sort_eq.`

`apply Permutation_app_tail. apply Permutation_sym.`

`apply Permuted_sort.`

Qed.

### 6.4.2 Working with `make_mono`

There are a couple forms that the proof of `make_mono` being pointless can take. Firstly, because we already know that `make_mono` simply applies functions to get the list into a form that satisfies `is_mono`, it makes sense to prove that if some list is already a mono that `make_mono` will have no effect. This is proved with the help of `no_sort_VarSorted` and `no_nodup_NoDup`.

Lemma `no_make_mono` :  $\forall m,$

`is_mono m  $\rightarrow$`

`make_mono m = m.`

Proof.

`unfold make_mono, is_mono. intros m H. rewrite no_sort_VarSorted.`

`- apply no_nodup_NoDup. apply NoDup_VarSorted in H. auto.`

`- apply Sorted_nodup; auto. apply lt_Transitive.`

Qed.

We can also prove the more standard form of `make_mono_pointless`, which states that if there are nested calls to `make_mono`, we can remove all except the outermost layer.

Lemma `make_mono_pointless` :  $\forall m a,$

`make_mono (m ++ make_mono a) = make_mono (m ++ a).`



Proof.

```
intros m a. apply Permutation_sort_mono_eq. rewrite <- (nodup_pointless _ a).
apply Permutation_nodup. apply Permutation_app_head. unfold make_mono.
rewrite <- Permutation_VarSort_l. auto.
```

Qed.

Similarly, if we already know that all of the elements in a list are monomials, then mapping `make_mono` across the list will have no effect on the entire list.

Lemma no\_map\_make\_mono :  $\forall p,$   
 $(\forall m, \text{In } m \ p \rightarrow \text{is\_mono } m) \rightarrow$   
 $\text{map make\_mono } p = p.$

Proof.

```
intros p H. induction p; auto.
simpl. rewrite no_make_mono.
- f_equal. apply IHp. intros m Hin. apply H. intuition.
- apply H. intuition.
```

Qed.

Lastly, the pointless proof that more closely aligns with what we have done so far - if `make_poly` is already being applied to a list, there is no need to have a call to `map make_mono` on the inside.

Lemma map\_make\_mono\_pointless :  $\forall p \ q,$   
 $\text{make\_poly } (\text{map make\_mono } p \ ++ \ q) =$   
 $\text{make\_poly } (p \ ++ \ q).$

Proof.

```
intros p q. destruct p; auto.
simpl. unfold make_poly. simpl map.
rewrite (no_make_mono (make_mono l)); auto. rewrite map_app. rewrite map_app.
rewrite (no_map_make_mono (map _ _)). auto. intros m Hin.
apply in_map_iff in Hin. destruct Hin as [x[]]. rewrite <- H. auto.
```

Qed.

### 6.4.3 Working with `make_poly`

Finally, we work to prove some lemmas about `make_poly` as a whole being pointless. These proofs are built upon the previous few lemmas, which prove that we can remove the components of `make_poly` one by one.

First up, we have a lemma that shows that if `p` already has no duplicates and everything in the list is a mono, then `nodup_cancel` and `map make_mono` will both have no effect. This lemma turns out to be very useful *after* something like `Permutation_sort_eq` has been applied, as it can strip away the other two functions of `make_poly`.

Lemma unsorted\_poly :  $\forall p,$   
 $\text{NoDup } p \rightarrow$

$(\forall m, \text{In } m \ p \rightarrow \text{is\_mono } m) \rightarrow$   
 $\text{nodup\_cancel mono\_eq\_dec } (\text{map make\_mono } p) = p.$

Proof.

intros  $p \ Hdup \ Hin$ . rewrite no\_map\_make\_mono; auto.  
 apply no\_nodup\_cancel\_NoDup; auto.

Qed.

Similarly to no\_make\_mono, it is very straightforward to prove that if some list  $p$  is already a polynomial, then make\_poly has no effect.

Lemma no\_make\_poly :  $\forall p,$

$\text{is\_poly } p \rightarrow$   
 $\text{make\_poly } p = p.$

Proof.

unfold make\_poly, is\_poly. intros  $m \ []$ . rewrite no\_sort\_MonoSorted.  
 - rewrite no\_nodup\_cancel\_NoDup.  
   + apply no\_map\_make\_mono. intros  $m0 \ Hin$ . apply  $H0$ . auto.  
   + apply NoDup\_MonoSorted in  $H$ . rewrite no\_map\_make\_mono; auto.  
 - apply Sorted\_nodup\_cancel.  
   + apply mono\_lt\_Transitive.  
   + rewrite no\_map\_make\_mono; auto.

Qed.

Now onto the most important lemma. In many of the later proofs, there will be times where there are calls to make\_poly nested inside of each other, or long lists of arguments appended together inside of a make\_poly. In either case, the ability to add and remove extra calls to make\_poly as we please proves to be very powerful.

To prove make\_poly\_pointless, we begin by proving a weaker version that insists that all of the arguments of  $p$  and  $q$  are all monomials. This addition makes the proof significantly easier. As one might expect, the proof is completed by using Permutation\_sort\_eq to remove the sort calls, nodup\_cancel\_pointless to remove the nodup\_cancel calls, and no\_map\_make\_mono to get rid of the map make\_mono calls. After this is done, the two sides are identical.

Lemma make\_poly\_pointless\_weak :  $\forall p \ q,$

$(\forall m, \text{In } m \ p \rightarrow \text{is\_mono } m) \rightarrow$   
 $(\forall m, \text{In } m \ q \rightarrow \text{is\_mono } m) \rightarrow$   
 $\text{make\_poly } (\text{make\_poly } p ++ q) =$   
 $\text{make\_poly } (p ++ q).$

Proof.

intros  $p \ q \ Hmp \ Hmq$ . unfold make\_poly.  
 repeat rewrite no\_map\_make\_mono; intuition.  
 apply Permutation\_sort\_eq. rewrite sort\_nodup\_cancel\_assoc.  
 rewrite nodup\_cancel\_pointless. apply nodup\_cancel\_Permutation.  
 apply Permutation\_sym. apply Permutation\_app\_tail. apply Permuted\_sort.  
 - simpl in  $H$ . rewrite in\_app\_iff in  $H$ . destruct  $H$ ; intuition.

```
- rewrite in_app_iff in H. destruct H; intuition.
  apply ln_sorted in H. apply nodup_cancel_in in H. intuition.
```

Qed.

Now, to make the stronger and easier to use version, we simply rewrite in the opposite direction with `map_make_mono_pointless` to add extra calls of `map make_mono` in! Ironically, this proof *of* `make_poly_pointless` is a great example of why these “pointless” lemmas are so useful. While we can clearly tell that adding the extra call to `map make_mono` makes no difference, it makes proving things in a way that Coq understands dramatically easier at times.

After rewriting with `map_make_mono_pointless`, clearly both arguments contain all monomials, and we can use `make_poly_pointless_weak` to prove the stronger version.

```
Lemma make_poly_pointless : ∀ p q,
  make_poly (make_poly p ++ q) =
  make_poly (p ++ q).
```

Proof.

```
intros p q. rewrite make_poly_app_comm.
rewrite ← map_make_mono_pointless. rewrite make_poly_app_comm.
rewrite ← (map_make_mono_pointless p). rewrite (make_poly_app_comm _ q).
rewrite ← (map_make_mono_pointless q).
rewrite (make_poly_app_comm _ (map make_mono p)).
rewrite ← (make_poly_pointless_weak (map make_mono p)). unfold make_poly.
rewrite (no_map_make_mono (map make_mono p)). auto.
apply mono_in_map_make_mono. apply mono_in_map_make_mono.
apply mono_in_map_make_mono.
```

Qed.

For convenience, we also prove that it applies on the right side by using `make_poly_app_comm` twice.

```
Lemma make_poly_pointless_r : ∀ p q,
  make_poly (p ++ make_poly q) =
  make_poly (p ++ q).
```

Proof.

```
intros p q. rewrite make_poly_app_comm. rewrite make_poly_pointless.
  apply make_poly_app_comm.
```

Qed.

## 6.5 Polynomial Arithmetic

Now, the foundation for operations on polynomials has been put in place, and we can begin to get into the real meat - our arithmetic operators. First up is addition. Because we have so cleverly defined our `make_poly` function, addition over our data structures is as simple as appending the two polynomials and repairing the result back into a proper polynomial.

We also include a simple refold lemma for convenience, and a quick proof that the result of `addPP` is always a polynomial.

```
Definition addPP (p q : poly) : poly :=
  make_poly (p ++ q).
```

```
Lemma addPP_refold : ∀ p q,
  make_poly (p ++ q) = addPP p q.
```

Proof.

auto.

Qed.

```
Lemma addPP_is_poly : ∀ p q,
  is_poly (addPP p q).
```

Proof.

intros p q. apply make\_poly\_is\_poly.

Qed.

Similarly, the definition for multiplication becomes much easier with the creation of `make_poly`. All we need to do is use our `distribute` function defined earlier to form all combinations of one monomial from each list, and call `make_poly` on the result.

```
Definition mulPP (p q : poly) : poly :=
  make_poly (distribute p q).
```

```
Lemma mulPP_is_poly : ∀ p q,
  is_poly (mulPP p q).
```

Proof.

intros p q. apply make\_poly\_is\_poly.

Qed.

Hint Resolve *addPP\_is\_poly mulPP\_is\_poly*.

While this definition is elegant, sometimes it is hard to work with. This has led us to also create a few more definitions of multiplication. Each is just slightly different from the last, which allows us to choose the level of completeness we need for any given multiplication proof while knowing that at the end of the day, they are all equivalent.

Each of these new definitions breaks down multiplication into two steps - multiplying a monomial times a polynomial, and multiplying a polynomial times a polynomial. Multiplying a monomial times a polynomial is simply appending the monomial to each monomial in the polynomial, and multiplying two polynomials is just multiplying each monomial in one polynomial times the other polynomial.

The difference in each of the following definitions comes from the intermediate step. Because we know that `mulPP` will call `make_poly`, there is no need to call `make_poly` on the result of `mulMP`, as shown in the first definition. However, some proofs are made easier if the result of `mulMP` is wrapped in `map make_mono`, and some are made easier if the result is wrapped in a full `make_poly`. As a result, we have created each of these definitions, and choose between them to help make our proofs easier.

We also include a refolding method for each, for convenience, and a proof that each new version is equivalent to the last.

Definition mulMP ( $p : \text{poly}$ ) ( $m : \text{mono}$ ) :  $\text{poly} :=$   
 $\text{map } (\text{app } m) p.$

Definition mulPP' ( $p q : \text{poly}$ ) :  $\text{poly} :=$   
 $\text{make\_poly } (\text{concat } (\text{map } (\text{mulMP } p) q)).$

Lemma mulPP'\_refold :  $\forall p q,$   
 $\text{make\_poly } (\text{concat } (\text{map } (\text{mulMP } p) q)) =$   
 $\text{mulPP' } p q.$

Proof. auto. Qed.

Lemma mulPP\_mulPP' :  $\forall (p q : \text{poly}),$   
 $\text{mulPP } p q = \text{mulPP' } p q.$

Proof.

intros  $p q$ . unfold mulPP, mulPP'. induction  $q$ ; auto.

Qed.

Next, the version including a  $\text{map make\_mono}$ :

Definition mulMP' ( $p : \text{poly}$ ) ( $m : \text{mono}$ ) :  $\text{poly} :=$   
 $\text{map make\_mono } (\text{map } (\text{app } m) p).$

Definition mulPP'' ( $p q : \text{poly}$ ) :  $\text{poly} :=$   
 $\text{make\_poly } (\text{concat } (\text{map } (\text{mulMP' } p) q)).$

Lemma mulPP''\_refold :  $\forall p q,$   
 $\text{make\_poly } (\text{concat } (\text{map } (\text{mulMP' } p) q)) =$   
 $\text{mulPP'' } p q.$

Proof. auto. Qed.

Lemma mulPP'\_mulPP'' :  $\forall p q,$   
 $\text{mulPP' } p q = \text{mulPP'' } p q.$

Proof.

intros  $p q$ . unfold mulPP', mulPP'', mulMP, mulMP', make\_poly.

rewrite concat\_map\_map.

rewrite (no\_map\_make\_mono ( $\text{map } -$ )); auto.

intros. apply in\_map\_iff in  $H$  as [ $n$  []].

rewrite  $\leftarrow H$ .

auto.

Qed.

And finally, the version including a full  $\text{make\_poly}$ :

Definition mulMP'' ( $p : \text{poly}$ ) ( $m : \text{mono}$ ) :  $\text{poly} :=$   
 $\text{make\_poly } (\text{map } (\text{app } m) p).$

Definition mulPP''' ( $p q : \text{poly}$ ) :  $\text{poly} :=$   
 $\text{make\_poly } (\text{concat } (\text{map } (\text{mulMP'' } p) q)).$

```

Lemma mulPP'''_refold : ∀ p q,
  make_poly (concat (map (mulMP'' p) q)) =
  mulPP''' p q.

```

Proof. auto. Qed.

In order to make the proof of going from `mulPP''` to `mulPP'''` easier, we begin by proving that we can go from their corresponding `mulMP`s if they are wrapped in a `make_poly`.

```

Lemma mulMP'_mulMP'' : ∀ m p q,
  make_poly (mulMP' p m ++ q) = make_poly (mulMP'' p m ++ q).

```

Proof.

```

  intros m p q. unfold mulMP', mulMP''. rewrite make_poly_app_comm.
  rewrite ← map_make_mono_pointless. rewrite make_poly_app_comm.
  rewrite ← make_poly_pointless. unfold make_poly at 2.
  rewrite (no_map_make_mono (map make_mono _)). unfold make_poly at 3.
  rewrite (make_poly_app_comm _ q). rewrite ← (map_make_mono_pointless q).
  rewrite make_poly_app_comm. auto. apply mono_in_map_make_mono.

```

Qed.

```

Lemma mulPP''_mulPP''' : ∀ p q,
  mulPP'' p q = mulPP''' p q.

```

Proof.

```

  intros p q. induction q. auto. unfold mulPP'', mulPP'''. simpl.
  rewrite mulMP'_mulMP''.
  repeat rewrite ← (make_poly_pointless_r _ (concat _)).
  f_equal. f_equal. apply IHq.

```

Qed.

Again, for convenience, we add lemmas to skip from `mulPP` to any of the other varieties.

```

Lemma mulPP_mulPP'' : ∀ p q,
  mulPP p q = mulPP'' p q.

```

Proof.

```

  intros. rewrite mulPP_mulPP', mulPP'_mulPP''. auto.

```

Qed.

```

Lemma mulPP_mulPP''' : ∀ p q,
  mulPP p q = mulPP''' p q.

```

Proof.

```

  intros. rewrite mulPP_mulPP'', mulPP''_mulPP'''. auto.

```

Qed.

Hint Unfold addPP mulPP mulPP' mulPP'' mulPP''' mulMP mulMP' mulMP''.

## 6.6 Proving the 10 $B$ -unification Axioms

Now that we have defined our operations so carefully, we want to prove that the 10 standard  $B$ -unification axioms all apply. This is extremely important, as they will both be needed in the higher-level proofs of our unification algorithm, and they show that our list-of-list setup is actually correct and equivalent to any other representation of a term.

### 6.6.1 Axiom 1: Additive Inverse

We begin with the inverse and identity for each addition and multiplication. First is the additive inverse, which states that for all terms  $x$ ,  $(x + x) \downarrow_P 0$ .

Thanks to the definition of `nodup_cancel` and the previously proven `nodup_cancel_self`, this proof is extremely simple.

```
Lemma addPP_p_p : ∀ p,
  addPP p p = [].
```

Proof.

```
  intros p. unfold addPP. unfold make_poly. rewrite map_app.
  rewrite nodup_cancel_self. auto.
```

Qed.

### 6.6.2 Axiom 2: Additive Identity

Next, we prove the additive identity: for all terms  $x$ ,  $(0 + x) \downarrow_P x$ . This also applies in the right direction, and is extremely easy to prove since we already know that appending `nil` to a list results in that list.

Something to note is that, unlike some of the other of the ten axioms, this one is *only* true if  $p$  is already a polynomial. Clearly, if it wasn't, `addPP` would not return the same  $p$ , but rather `make_poly p`, since `addPP` will only return proper polynomials.

```
Lemma addPP_0 : ∀ p,
  is_poly p →
  addPP [] p = p.
```

Proof.

```
  intros p Hpoly. unfold addPP. simpl. apply no_make_poly. auto.
```

Qed.

```
Lemma addPP_0r : ∀ p,
  is_poly p →
  addPP p [] = p.
```

Proof.

```
  intros p Hpoly. unfold addPP. rewrite app_nil_r. apply no_make_poly. auto.
```

Qed.

### 6.6.3 Axiom 3: Multiplicative Identity - 1

Now onto multiplication. In  $B$ -unification, there are *two* multiplicative identities. We begin with the easier to prove of the two, which is 1. In other words, for any term  $x$ ,  $(x * 1) \downarrow_P = x \downarrow_P$ .

This proof is also very simply proved because of how appending `nil` works.

```
Lemma mulPP_1r : ∀ p,  
  is_poly p →  
  mulPP p [] = p.
```

Proof.

```
  intros p H. unfold mulPP, distribute. simpl. rewrite app_nil_r.  
  rewrite map_id. apply no_make_poly. auto.
```

Qed.

### 6.6.4 Axiom 4: Multiplicative Inverse

Next is the multiplicative inverse, which states that for any term  $x$ ,  $(0 * x) \downarrow_P = 0$ .

This is proven immediately by the `distribute_nil` lemmas we proved in `list_util`.

```
Lemma mulPP_0 : ∀ p,  
  mulPP [] p = [].
```

Proof.

```
  intros p. unfold mulPP. rewrite (@distribute_nil var). auto.
```

Qed.

```
Lemma mulPP_0r : ∀ p,  
  mulPP p [] = [].
```

Proof.

```
  intros p. unfold mulPP. rewrite (@distribute_nil_r var). auto.
```

Qed.

### 6.6.5 Axiom 5: Commutativity of Addition

The next of the ten axioms states that, for all terms  $x$  and  $y$ ,  $(x + y) \downarrow_P = (y + x) \downarrow_P$ .

This axiom is also rather easy, and follows entirely from the `make_poly_app_comm` lemma we proved earlier due to our clever addition definition.

```
Lemma addPP_comm : ∀ p q,  
  addPP p q = addPP q p.
```

Proof.

```
  intros p q. unfold addPP. apply make_poly_app_comm.
```

Qed.

### 6.6.6 Axiom 6: Associativity of Addition

The next axiom states that, for all terms  $x$ ,  $y$ , and  $z$ ,  $(x + (y + z)) \downarrow_P = ((x + y) + z) \downarrow_P$ .



Thanks to `addPP_comm` and all of the “pointless” lemmas we proved earlier, this proof is much easier than it might have been otherwise. These lemmas allow us to easily manipulate the operations until we end by proving that  $p ++ q ++ r$  is a permutation of  $q ++ r ++ p$ .

Lemma `addPP_assoc` :  $\forall p q r,$   
`addPP (addPP p q) r = addPP p (addPP q r).`

Proof.

```
intros p q r. rewrite (addPP_comm _ (addPP _ _)). unfold addPP.
repeat rewrite make_poly_pointless. repeat rewrite <- app_assoc.
apply Permutation_sort_eq. apply nodup_cancel_Permutation.
apply Permutation_map. rewrite (app_assoc q).
apply Permutation_app_comm with (l' := q ++ r).
```

Qed.

### 6.6.7 Axiom 7: Commutativity of Multiplication

Now onto the harder half of the axioms. This next one states that for all terms  $x$  and  $y$ ,  $(x * y) \downarrow_P = (y * x) \downarrow_P$ . In order to prove this, we have opted to use the second version of `mulPP`, which wraps the monomial multiplication in a `map make_mono`.

The proof begins with double induction, and the first three cases are rather simple. The fourth case is slightly more complicated, but the `make_poly_pointless` lemma we proved earlier plays a huge role in making it simpler. We begin by simplifying, so that the  $m$  created by induction on  $q$  is distributed across the list on the left side, and the  $a$  created by induction on  $p$  is distributed across the list on the right side. Then, we use `make_poly_pointless` to surround the rightmost term - which now has  $a$  but not  $m$  on the left and  $m$  but not  $a$  on the right - with `make_poly`. This additional `make_poly` allows us to refold the mess of `maps` and `concat`s into `mulPP`, like they used to be. From there, we use the two induction hypotheses to apply commutativity, remove the redundant `make_polys` we added, and simplify again.

In this way, we are able to cause both  $a$  and  $m$  to be distributed across the whole list on both the left and right sides of the equation. At this point, it simply requires some rearranging of `app` with the help of `Permutation`, and our left and right sides are equal.

Without the help of `make_poly_pointless`, we would not have been able to use the induction hypotheses until much later in the proof, and the proof would have been dramatically longer. This also makes it more readable as you step through the proof, as we can seamlessly move between the original form including `mulPP` and the more functional form consisting of `map` and `concat`.

Lemma `mulPP_comm` :  $\forall p q,$   
`mulPP p q = mulPP q p.`

Proof.

```
intros p q. repeat rewrite mulPP_mulPP''.
generalize dependent q. induction p; induction q as [|m].
- auto.
```

```

- unfold mulPP'', mulMP'. simpl. rewrite (@concat_map_nil mono). auto.
- unfold mulPP'', mulMP'. simpl. rewrite (@concat_map_nil mono). auto.
- unfold mulPP''. simpl. rewrite (app_comm_cons _ _ (make_mono (a++m))).
  rewrite ← make_poly_pointless_r. rewrite mulPP''_refold. rewrite ← IHp.
  unfold mulPP''. rewrite make_poly_pointless_r. simpl. unfold mulMP' at 2.
  rewrite app_comm_cons. rewrite ← make_poly_pointless_r.
  rewrite mulPP''_refold. rewrite IHq. unfold mulPP''.
  rewrite make_poly_pointless_r. simpl. unfold mulMP' at 1.
  rewrite app_comm_cons. rewrite app_assoc. rewrite ← make_poly_pointless_r.
  rewrite mulPP''_refold. rewrite ← IHp. unfold mulPP''.
  rewrite make_poly_pointless_r. simpl. rewrite (app_assoc (map _ (map _ q))).
  apply Permutation_sort_eq. apply nodup_cancel_Permutation.
  apply Permutation_map. rewrite make_mono_app_comm. apply perm_skip.
  apply Permutation_app_tail. apply Permutation_app_comm.

```

Qed.

### 6.6.8 Axiom 8: Associativity of Multiplication

The eighth axiom states that, for all terms  $x$ ,  $y$ , and  $z$ ,  $(x * (y * z)) \downarrow_P = ((x * y) * z) \downarrow_P$ .

This one is also fairly complicated, so we will start small and build up to it. First, we prove a convenient side effect of `make_poly_pointless`, which allows us to simplify `mulPP` into a `mulMP` and a `mulPP`. Unlike commutativity, for this proof we opt to use the version of `mulPP` that includes a `make_poly` in its `mulMP`, in addition to the `map` `make_mono` version used previously.

Lemma `mulPP''_cons` :  $\forall q \ a \ p,$   
`make_poly (mulMP' q a ++ mulPP'' q p) =`  
`mulPP'' q (a :: p).`

Proof.

```
intros q a p. unfold mulPP''. rewrite make_poly_pointless_r. auto.
```

Qed.

Next is a deceptively easy lemma `map_app_make_poly`, which is the primary application of `nodup_cancel_map`, proven in `list_util`. It states that if we are applying `make_poly` twice, we can remove the second application, even if there is a `map app` in between them. Clearly, here, the `map app` is in reference to `mulMP`.

Lemma `map_app_make_poly` :  $\forall m \ p,$   
 $(\forall a, \text{In } a \ p \rightarrow \text{is\_mono } a) \rightarrow$   
`make_poly (map (app m) (make_poly p)) = make_poly (map (app m) p).`

Proof.

```

intros m p Hm. apply Permutation_sort_eq.
apply Permutation_trans with (l':=(nodup_cancel_mono_eq_dec (map make_mono
  (map (app m) (nodup_cancel_mono_eq_dec (map make_mono p)))))).
apply nodup_cancel_Permutation. repeat apply Permutation_map.

```

```

    unfold make_poly. rewrite <- Permutation_MonoSort_l. auto.
    rewrite (no_map_make_mono p); auto. repeat rewrite map_map.
    apply nodup_cancel_map.
Qed.

```

The `map_app_make_poly` lemma is then immediately applied here, to state that since `mulMP''` already applies `make_poly` to its result, we can remove any `make_poly` calls inside.

```

Lemma mulMP''_make_poly : ∀ p m,
  (∀ a, In a p → is_mono a) →
  mulMP'' (make_poly p) m =
  mulMP'' p m.

```

Proof.

```

  intros p m. unfold mulMP''. apply map_app_make_poly.
Qed.

```

This very simple lemma states that since `mulMP` is effectively just a `map`, it distributes over `app`.

```

Lemma mulMP'_app : ∀ p q m,
  mulMP' (p ++ q) m =
  mulMP' p m ++ mulMP' q m.

```

Proof.

```

  intros p q m. unfold mulMP'. repeat rewrite map_app. auto.
Qed.

```

Now into the meat of the associativity proof. We begin by proving that `mulMP'` is associative. This proof is straightforward, and is proven by induction with the use of `make_mono_pointless` and `Permutation_sort_mono_eq`.

```

Lemma mulMP'_assoc : ∀ q a m,
  mulMP' (mulMP' q a) m =
  mulMP' (mulMP' q m) a.

```

Proof.

```

  intros q a m. unfold mulMP'. induction q; auto.
  simpl. repeat rewrite make_mono_pointless. f_equal.
  - apply Permutation_sort_mono_eq. apply Permutation_nodup.
    repeat rewrite app_assoc. apply Permutation_app_tail.
    apply Permutation_app_comm.
  - apply IHq.
Qed.

```

For the final associativity proof, we begin by using the commutativity lemma to make it so that `q` is on the leftmost side of the multiplications. This means that it will never be the polynomial being mapped across, and allows us to do induction on just `p` and `r` instead of all three. Thus `p` becomes `a :: p`, and `r` becomes `m :: r`.

The first three cases are easily solved with some rewrites and a call to `auto`, so we move on to the fourth. Similarly to the commutativity proof, the main struggle here is forcing

mulPP to map across the same term on both sides of the equation. This is accomplished in a very similar way - by simplifying, using `make_poly_pointless` to get `mulPP` back in the goal, and then applying the two induction hypotheses to reorder the terms.

The crucial point is when we rewrite with `mulMP'_mulMP''`, allowing us to wrap our `mulMPs` in `make_poly` and make use of the lemmas we proved earlier in this section. This technique enables us to reorder the multiplications in a way that is convenient for us;  $((q * [a :: p]) * m) \downarrow_P$  becomes  $((q * a) * m) \downarrow_P + ((q * p) * m) \downarrow_P$ . At the end of all of this rewriting, we are left with the original  $(p * q * r) \downarrow_P$  as the last term of both sides, and  $(q * p * m) \downarrow_P$  and  $(q * r * a) \downarrow_P$  as the middle terms of both. These three terms are easily eliminated with the standard `Permutation` lemmas, because they are on both sides.

The only remaining challenge comes from the first term on each side; on the left, we have  $((q * a) * m) \downarrow_P$ , and on the right we have  $((q * m) * a) \downarrow_P$ . This is where the above `mulMP'_assoc` lemma comes into play, solving the last piece of the associativity lemma.

Lemma `mulPP_assoc` :  $\forall p q r$ ,

`mulPP (mulPP p q) r = mulPP p (mulPP q r).`

Proof.

```

intros p q r. rewrite (mulPP_comm _ (mulPP q _)). rewrite (mulPP_comm p _).
generalize dependent r. induction p; induction r as [|m];
repeat rewrite mulPP_0; repeat rewrite mulPP_0r; auto.
repeat rewrite mulPP_mulPP'' in *. unfold mulPP''. simpl.
repeat rewrite ← (make_poly_pointless_r _ (concat _)).
repeat rewrite mulPP''_refold. repeat rewrite (mulPP''_cons q).
pose (IHp (m :: r)). repeat rewrite mulPP_mulPP'' in e. rewrite ← e.
rewrite IHr. unfold mulPP'' at 2, mulPP'' at 4. simpl.
repeat rewrite make_poly_pointless_r. repeat rewrite app_assoc.
repeat rewrite ← (make_poly_pointless_r _ (concat _)).
repeat rewrite mulPP''_refold. pose (IHp r).
repeat rewrite mulPP_mulPP'' in e0. rewrite ← e0.
repeat rewrite ← app_assoc. repeat rewrite mulMP'_mulMP''.
repeat rewrite ← mulPP''_cons. repeat rewrite mulMP''_make_poly.
repeat rewrite ← mulMP'_mulMP''. repeat rewrite app_assoc.
apply Permutation_sort_eq. apply nodup_cancel_Permutation.
apply Permutation_map. apply Permutation_app_tail. repeat rewrite mulMP'_app.
rewrite mulMP'_assoc. repeat rewrite ← app_assoc. apply Permutation_app_head.
apply Permutation_app_comm. intros a0 Hin. apply in_app_iff in Hin as [].
unfold mulMP' in H. apply in_map_iff in H as [x[]]. rewrite ← H; auto.
apply (make_poly_is_poly (concat (map (mulMP' q) r))). auto.
intros a0 Hin. apply in_app_iff in Hin as []. unfold mulMP' in H.
apply in_map_iff in H as [x[]]. rewrite ← H; auto.
apply (make_poly_is_poly (concat (map (mulMP' q) p))). auto.

```

Qed.

### 6.6.9 Axiom 9: Multiplicative Identity - Self

Next comes the other multiplicative identity mentioned earlier. This axiom states that for all terms  $x$ ,  $(x * x) \downarrow_P = x \downarrow_P$ .

To begin, we prove that this holds for monomials;  $(m * m) \downarrow_P = m \downarrow_P$ . This proof uses a combination of `Permutation_Sorted_mono_eq` and induction. We then use the standard `Permutation` lemmas to move the induction variable  $a$  out to the front, and show that `nodup` removes one of the two  $a$ s. After that, `perm_skip` and the induction hypothesis solve the lemma.

Lemma `make_mono_self` :  $\forall m$ ,  
`is_mono m`  $\rightarrow$   
`make_mono (m ++ m) = m`.

Proof.

```

intros m H. apply Permutation_Sorted_mono_eq.
- induction m; auto. unfold make_mono. rewrite <- Permutation_VarSort_l.
  simpl. assert (In a (m ++ a :: m)).
  intuition. destruct in_dec; try contradiction.
  apply Permutation_trans with (l':=nodup var_eq_dec (a :: m ++ m)).
  apply Permutation_nodup. apply Permutation_app_comm.
  simpl. assert (¬ In a (m ++ m)).
  apply NoDup_VarSorted in H as H1. apply NoDup_cons_iff in H1.
  intro. apply H1. apply in_app_iff in H2; intuition.
  destruct in_dec; try contradiction. apply perm_skip.
  apply Permutation_VarSort_l in IHm. auto. apply (mono_cons _ _ H).
- apply VarSort.LocallySorted.sort.
- apply Sorted_VarSorted. apply H.

```

Qed.

The full proof of the self multiplicative identity is much longer, but in a way very similar to the proof of commutativity. We begin by doing induction and simplifying, which distributes *one* of the induction variables across the list on the left side. This leaves us with  $a * a$  as the leftmost term, which is easily replaced with  $a$  with the above lemma and then removed from both sides with `perm_skip`.

At this point we are left with a goal of the form  $(a * [a :: p]) \downarrow_P ++ ([a :: p] * p) \downarrow_P = p \downarrow_P$  which is not particularly easy to deal with. However, by rewriting with `mulPP_comm`, we can force the second term on the left to simplify further.

This leaves us with something along the lines of  $(a * [a :: p]) \downarrow_P ++ (a * [a :: p]) \downarrow_P ++ (p * p) \downarrow_P = p \downarrow_P$  which is much more workable! We know that  $(p * p) \downarrow_P = p \downarrow_P$  from the induction hypothesis, so this is then removed from both sides and all that is left is to prove that the same term added together twice is equal to an empty list. This follows from the `nodup_cancel_self` lemma used to prove `addPP_p_p`, and finished the proof of this lemma.

Lemma `mulPP_p_p` :  $\forall p$ ,  
`is_poly p`  $\rightarrow$

$\text{mulPP } p \ p = p.$

Proof.

```

intros p H. rewrite mulPP_mulPP'. rewrite mulPP'_mulPP''.
apply Permutation_Sorted_eq.
- induction p; auto. unfold mulPP'', make_poly.
  rewrite ← Permutation_MonoSort_l. simpl map at 1.
  apply poly_cons in H as H1. destruct H1. rewrite make_mono_self; auto.
  rewrite no_make_mono; auto. rewrite map_app. apply Permutation_trans with
    (l' := nodup_cancel mono_eq_dec (map make_mono (concat (map (mulMP' (a ::
      p)) p)) ++ a :: map make_mono (map make_mono (map (app a) p)))).
  apply nodup_cancel_Permutation. rewrite app_comm_cons.
  apply Permutation_app_comm.
  rewrite ← nodup_cancel_pointless. apply Permutation_trans with
    (l' := nodup_cancel mono_eq_dec ((nodup_cancel mono_eq_dec (map make_mono
      (concat (map (mulMP' p) (a :: p)))) ++ (a :: map make_mono (map make_mono
      (map (app a) p))))). apply nodup_cancel_Permutation.
  apply Permutation_app_tail. apply Permutation_sort_eq.
  repeat rewrite make_poly_refold. repeat rewrite mulPP''_refold.
  repeat rewrite ← mulPP'_mulPP''. repeat rewrite ← mulPP_mulPP'.
  apply mulPP_comm.
  rewrite nodup_cancel_pointless. apply Permutation_trans with
    (l' := nodup_cancel mono_eq_dec (a :: map make_mono (map make_mono (map
      (app a) p)) ++ (map make_mono (concat (map (mulMP' p) (a :: p)))))).
  apply nodup_cancel_Permutation. apply Permutation_app_comm.
  simpl map. rewrite map_app. unfold mulMP' at 1.
  repeat rewrite (no_map_make_mono (map make_mono _));
  try apply mono_in_map_make_mono. rewrite (app_assoc (map _ _)).
  apply Permutation_trans with (l' := nodup_cancel mono_eq_dec ((map make_mono
    (map (app a) p) ++ map make_mono (map (app a) p)) ++ a :: map make_mono
    (concat (map (mulMP' p) p)))). apply nodup_cancel_Permutation.
  apply Permutation_middle. rewrite ← nodup_cancel_pointless.
  rewrite nodup_cancel_self. simpl app.
  apply Permutation_trans with (l' := nodup_cancel mono_eq_dec (map make_mono
    (concat (map (mulMP' p) p)) ++ [a])). apply nodup_cancel_Permutation.
  replace (a :: map make_mono (concat (map (mulMP' p) p))) with ([a] ++ map
    make_mono (concat (map (mulMP' p) p))); auto. apply Permutation_app_comm.
  rewrite ← nodup_cancel_pointless. apply Permutation_trans with
    (l' := nodup_cancel mono_eq_dec (p ++ [a])). apply nodup_cancel_Permutation.
  apply Permutation_app_tail. unfold mulPP'', make_poly in IHp.
  rewrite ← Permutation_MonoSort_l in IHp. apply IHp; auto.
  replace (a :: p) with ([a] ++ p); auto. rewrite no_nodup_cancel_NoDup.
  apply Permutation_app_comm. apply Permutation_NoDup with (l := a :: p).

```

```

    replace (a :: p) with ([a] ++ p); auto. apply Permutation_app_comm.
    destruct H. apply NoDup_MonoSorted in H. auto.
- unfold make_poly. apply LocallySorted_sort.
- apply Sorted_MonoSorted. apply H.
Qed.

```

### 6.6.10 Axiom 10: Distribution

Finally, we are left with the most intimidating of the axioms - distribution. This states, as one would expect, that for all terms  $x$ ,  $y$ , and  $z$ ,  $(x * (y + z)) \downarrow_P = ((x * y) + (x * z)) \downarrow_P$ .

In a similar approach to what we have done for some of the other lemmas, we begin by proving this on a smaller scale, working with just `mulMP` and `addPP`. This lemma is once again solved easily by the `map_app_make_poly` we proved while working on multiplication associativity, combined with `make_poly_pointless`.

```

Lemma mulMP''_distr_addPP : ∀ m p q,
  is_poly p → is_poly q →
  mulMP'' (addPP p q) m = addPP (mulMP'' p m) (mulMP'' q m).

```

Proof.

```

  intros m p q Hp Hq. unfold mulMP'', addPP. rewrite map_app_make_poly.
  rewrite make_poly_pointless. rewrite make_poly_app_comm.
  rewrite make_poly_pointless. rewrite make_poly_app_comm.
  rewrite map_app. auto. intros a Hin. apply in_app_iff in Hin as [].
  apply Hp. auto. apply Hq. auto.

```

Qed.

For the distribution proof itself, we begin by performing induction on  $r$ , the element outside of the `addPP` call initially. We begin by simplifying, and using the usual combination of `make_poly_pointless` and refolding to convert our goal to a form of  $((p + q) * a) \downarrow_P + ((p + q) * r) \downarrow_P$ .

We then apply similar tactics on the right side, to convert our goal to a form similar to  $(p * a + q * a + p * r + q * r) \downarrow_P$ . The two terms containing  $r$  are easy to deal with, since we know they are equal to the  $((p + q) * r) \downarrow_P$  we have on the left side due to the induction hypothesis. Similarly, the first two terms are known to be equal to  $((p + q) * a) \downarrow_P$  from the `mulMP_distr_addPP` lemma we just proved. This results in us having the same thing on both sides, thus solving the final of the ten  $B$ -unification axioms.

```

Lemma mulPP_distr_addPP : ∀ p q r,
  is_poly p → is_poly q →
  mulPP (addPP p q) r = addPP (mulPP p r) (mulPP q r).

```

Proof.

```

  intros p q r Hp Hq. induction r; auto. rewrite mulPP_mulPP''. unfold mulPP''.
  simpl. rewrite mulPP_mulPP'', (mulPP_mulPP'' q), make_poly_app_comm.
  rewrite ← make_poly_pointless. rewrite make_poly_app_comm.
  rewrite mulPP''_refold.

```



```

rewrite addPP_refold. repeat unfold mulPP'' at 2. simpl. unfold addPP at 4.
rewrite make_poly_pointless. rewrite addPP_refold.
rewrite (addPP_comm _ (make_poly _)).
unfold addPP at 4. rewrite make_poly_pointless. rewrite ← app_assoc.
rewrite make_poly_app_comm. rewrite ← app_assoc.
rewrite ← make_poly_pointless.
rewrite mulPP''_refold. rewrite ← app_assoc. rewrite app_assoc.
rewrite make_poly_app_comm.
rewrite ← app_assoc. rewrite ← make_poly_pointless. rewrite mulPP''_refold.
replace (make_poly (mulPP'' p r ++ mulMP' q a ++ mulPP'' q r ++ mulMP' p a))
  with (make_poly ((mulPP'' p r ++ mulPP'' q r) ++ mulMP' p a ++ mulMP' q a)).
rewrite ← make_poly_pointless. rewrite (addPP_refold (mulPP'' _ _)).
rewrite make_poly_app_comm. rewrite addPP_refold.
rewrite mulPP_mulPP'', (mulPP_mulPP'' p), (mulPP_mulPP'' q) in IHr.
rewrite ← IHr. unfold addPP at 4.
rewrite ← make_poly_pointless. unfold addPP. repeat rewrite mulMP'_mulMP''.
rewrite (make_poly_app_comm (mulMP'' _ _) (mulMP' _ _)).
rewrite mulMP'_mulMP''.
rewrite (make_poly_app_comm (mulMP'' _ _) (mulMP'' _ _)).
repeat rewrite addPP_refold. f_equal. apply mulMP''_distr_addPP; auto.
apply make_poly_Permutation. rewrite ← app_assoc.
apply Permutation_app_head. rewrite app_assoc.
apply Permutation_trans with
  (l':=mulMP' q a ++ mulPP'' q r ++ mulMP' p a).
apply Permutation_app_comm.
auto.

```

Qed.

For convenience, we also prove that distribution can be applied from the right, which follows from `mulPP_comm` and the distribution lemma we just proved.

Lemma `mulPP_distr_addPPr` :  $\forall p \ q \ r,$   
 $\text{is\_poly } p \rightarrow \text{is\_poly } q \rightarrow$   
 $\text{mulPP } r \ (\text{addPP } p \ q) = \text{addPP } (\text{mulPP } r \ p) \ (\text{mulPP } r \ q).$

Proof.

```

intros p q r Hp Hq. rewrite mulPP_comm. rewrite (mulPP_comm r p).
rewrite (mulPP_comm r q). apply mulPP_distr_addPP; auto.

```

Qed.

## 6.7 Other Facts About Polynomials

Now that we have proven the core ten axioms proven, there are a few more useful lemmas that we will prove to assist us in future parts of the development.



### 6.7.1 More Arithmetic

Occasionally, when dealing with multiplication, we already know that one of the variables being multiplied in is less than the rest, meaning it would end up at the front of the list after sorting. For convenience and to bypass the work of dealing with the calls to `sort` and `nodup_cancel`, the below lemma allows us to rewrite with this concept.

Lemma `mulPP_mono_cons` :  $\forall x m,$   
`is_mono (x :: m) →`  
`mulPP [[x]] [m] = [x :: m].`

Proof.

```
intros x m H. unfold mulPP, distribute. simpl. apply Permutation_Sorted_eq.
- apply Permutation_trans with
  (l' := nodup_cancel mono_eq_dec (map make_mono [m ++ [x]])).
  apply Permutation_sym. apply Permuted_sort. rewrite no_nodup_cancel_NoDup.
  simpl. assert (make_mono (m ++ [x]) = x :: m).
+ rewrite ← no_make_mono; auto. apply Permutation_sort_mono_eq.
  repeat rewrite no_nodup_NoDup. replace (x :: m) with ([x] ++ m); auto;
  apply Permutation_app_comm. apply NoDup_VarSorted; apply H.
  apply Permutation_NoDup with (l := x :: m).
  replace (x :: m) with ([x] ++ m); auto; apply Permutation_app_comm.
  apply NoDup_VarSorted; apply H.
+ rewrite H0. auto.
+ apply NoDup_cons; auto.
- apply LocallySorted_sort.
- apply Sorted_cons; auto.
```

Qed.

Similarly, if we already know some monomial is less than the polynomials it is being added to, then the monomial will clearly end up at the front of the list.

Lemma `addPP_poly_cons` :  $\forall m p,$   
`is_poly (m :: p) →`  
`addPP [m] p = m :: p.`

Proof.

```
intros m p H. unfold addPP. simpl. rewrite no_make_poly; auto.
```

Qed.

An interesting arithmetic fact is that if we multiply the term  $((p * q) + r) \downarrow_P$  by  $(1 + q) \downarrow_P$ , we effectively eliminate the  $(p * q) \downarrow_P$  term and are left with  $((1 + q) * r) \downarrow_P$ . This will come into play later in the development, as we look to begin building unifiers.

Lemma `mulPP_addPP_1` :  $\forall p q r,$   
`is_poly p → is_poly q → is_poly r →`  
`mulPP (addPP (mulPP p q) r) (addPP [[]] q) =`  
`mulPP (addPP [[]] q) r.`

Proof.

```

intros p q r Hp Hq Hr. rewrite mulPP_distr_addPP; auto.
rewrite mulPP_distr_addPPr; auto. rewrite mulPP_lr; auto.
rewrite mulPP_assoc. rewrite mulPP_p_p; auto. rewrite addPP_p_p; auto.
rewrite addPP_0; auto. rewrite mulPP_comm. auto.
Qed.

```

## 6.7.2 Reasoning about Variables

To more easily deal with the `vars` definition, we have defined a few definitions about it. First, if some  $x$  is in the variables of `make_poly p`, then it must have been in the vars of  $p$  originally. Note that this is not true in the other direction, as `nodup_cancel` may remove some variables.

Lemma `make_poly_rem_vars` :  $\forall p x$ ,  
 $\text{In } x \text{ (vars (make\_poly } p)) \rightarrow$   
 $\text{In } x \text{ (vars } p)$ .

Proof.

```

intros p x H. induction p.
- inversion H.
- unfold vars. simpl. apply nodup_In. apply in_app_iff.
  unfold vars, make_poly in H. apply nodup_In in H.
  apply In_concat_exists in H as [m []].
  apply In_sorted in H. apply nodup_cancel_in in H.
  apply in_map_iff in H as [n []]. destruct H1.
  + left. apply make_mono_In. rewrite H1. rewrite H. auto.
  + right. apply In_concat_exists.  $\exists n$ . split; auto. apply make_mono_In.
    rewrite H. auto.

```

Qed.

An interesting observation about `addPP` and our `vars` function is that clearly, the variables of some  $(p + q) \downarrow_P$  is a subset of the variables of  $p$  combined with the variables of  $q$ . The next lemma is a more convenient formulation of that fact, using a list of variables  $xs$  rather than comparing them directly.

Lemma `incl_vars_addPP` :  $\forall p q xs$ ,  
 $\text{incl (vars } p) \text{ } xs \wedge \text{incl (vars } q) \text{ } xs \rightarrow$   
 $\text{incl (vars (addPP } p \text{ } q)) \text{ } xs$ .

Proof.

```

unfold incl, addPP.
intros p q xs [HinP HinQ] x HinPQ.
apply make_poly_rem_vars in HinPQ.
unfold vars in HinPQ.
apply nodup_In in HinPQ.
rewrite concat_app in HinPQ.
apply in_app_or in HinPQ as [Hin | Hin].
- apply HinP. apply nodup_In. auto.

```

- apply *HinQ*. apply **nodup\_in**. auto.  
Qed.

We would like to be able to prove a similar fact about **mulPP**, but before we can do so, we need to know more about the **distribute** function. This lemma states that if some *a* is in the variables of **distribute** *l m*, then it must have been in either **vars** *l* or **vars** *m* originally.

Lemma **ln\_distribute** :  $\forall (l\ m:\text{poly})\ a,$   
**ln** *a* (**vars** (**distribute** *l m*))  $\rightarrow$   
**ln** *a* (**vars** *l*)  $\vee$  **ln** *a* (**vars** *m*).

Proof.

intros *l m a H*. unfold **distribute**, **vars** in *H*. apply **nodup\_in** in *H*.  
 apply **ln\_concat\_exists** in *H*. destruct *H* as [*ll*].  
 apply **ln\_concat\_exists** in *H*. destruct *H* as [*ll1*].  
 apply **in\_map\_iff** in *H*. destruct *H* as [*x*]. rewrite  $\leftarrow H$  in *H1*.  
 apply **in\_map\_iff** in *H1*. destruct *H1* as [*x0*]. rewrite  $\leftarrow H1$  in *H0*.  
 apply **in\_app\_iff** in *H0*. destruct *H0*.  
 - right. apply **nodup\_in**. apply **ln\_concat\_exists**.  $\exists x$ . auto.  
 - left. apply **nodup\_in**. apply **ln\_concat\_exists**.  $\exists x0$ . auto.

Qed.

We can then use this fact to prove our desired fact about **mulPP**; the variables of  $(p*q) \downarrow_P$  are a subset of the variables of *p* and the variables of *q*. Once again, this is formalized in a way that is more convenient in later proofs, with an extra list *xs*.

Lemma **incl\_vars\_mulPP** :  $\forall p\ q\ xs,$   
**incl** (**vars** *p*) *xs*  $\wedge$  **incl** (**vars** *q*) *xs*  $\rightarrow$   
**incl** (**vars** (**mulPP** *p q*)) *xs*.

Proof.

unfold **incl**, **mulPP**.  
 intros *p q xs [HinP HinQ] x HinPQ*.  
 apply **make\_poly\_rem\_vars** in *HinPQ*.  
 apply **ln\_distribute** in *HinPQ*. destruct *HinPQ*.  
 - apply *HinP*. auto.  
 - apply *HinQ*. auto.

Qed.

### 6.7.3 Partition with Polynomials

When it comes to actually performing successive variable elimination later in the development, the **partition** function will play a big role, so we have opted to prove a few useful facts about its relation to polynomials now.

First is that if you separate a polynomial with any function *f*, you can get the original polynomial back by adding together the two lists returned by **partition**. This is relatively easy to prove thanks to the lemma **partition\_Permutation** we proved during **list\_util**.

Lemma part\_add\_eq :  $\forall f p l r,$   
 is\_poly  $p \rightarrow$   
 partition  $f p = (l, r) \rightarrow$   
 $p = \text{addPP } l r.$

Proof.

```

intros f p l r H H0. apply Permutation_Sorted_eq.
- generalize dependent l; generalize dependent r. induction p; intros.
  + simpl in H0. inversion H0. auto.
  + assert (H1:=H0); auto. apply partition_Permutation in H1. simpl in H0.
    destruct (partition f p) as [g d]. unfold addPP, make_poly.
    rewrite ← Permutation_MonoSort_r. rewrite unsorted_poly. destruct (f a);
    inversion H0.
    × rewrite ← H3 in H1. apply H1.
    × rewrite ← H4 in H1. apply H1.
    × destruct H. apply NoDup_MonoSorted in H. apply (Permutation_NoDup H1 H).
    × intros m Hin. apply H. apply Permutation_sym in H1.
      apply (Permutation_in _ H1 Hin).
- apply Sorted_MonoSorted. apply H.
- apply Sorted_MonoSorted. apply make_poly_is_poly.

```

Qed.

In addition, if you partition some polynomial  $p$  with any function  $f$ , the resulting two lists will both be proper polynomials, since partition does not affect the order.

Lemma part\_is\_poly :  $\forall f p l r,$   
 is\_poly  $p \rightarrow$   
 partition  $f p = (l, r) \rightarrow$   
 is\_poly  $l \wedge \text{is\_poly } r.$

Proof.

```

intros f p l r Hpoly Hpart. destruct Hpoly. split; split.
- apply (part_Sorted _ _ mono_lt_Transitive H _ Hpart).
- intros m Hin. apply H0. apply elements_in_partition with (x:=m) in Hpart.
  apply Hpart; auto.
- apply (part_Sorted _ _ mono_lt_Transitive H _ Hpart).
- intros m Hin. apply H0. apply elements_in_partition with (x:=m) in Hpart.
  apply Hpart; auto.

```

Qed.

## 6.7.4 Multiplication and Remove

Lastly are some rather complex lemmas relating remove and multiplication. Similarly to the partition lemmas, these will come to play a large roll in performing successive variable elimination later in the development.

First is an interesting fact about removing from monomials. If there are two monomials

which are equal after removing some  $x$ , and either both contain  $x$  or both do not contain  $x$ , then they must have been equal originally. This proof begins by performing double induction, and quickly solving the first three cases.

The fourth case is rather long, and begins by comparing if the  $a$  and  $a0$  at the head of each list are equal. The case where they are equal is relatively straightforward; we must also destruct if  $x = a = a0$ , but regardless of whether they are equal or not, we can easily prove this with the use of the induction hypothesis.

The case where  $a \neq a0$  should be a contradiction, as that element is at the head of both lists, and we know the lists are equal after removing  $x$ . We begin by destructing whether or not  $x$  is in the two lists. In the case where it is not in either, we can quickly solve this, as we know the call to remove will do nothing, which immediately gives us the contradiction.

In the case where  $x$  is in both, we begin by using `in_split` to rewrite both lists to contain  $x$ . We then use the fact that there are no duplicates in either list to show that  $x$  is not in  $l1$ ,  $l2$ ,  $l1'$ , or  $l2'$ , and therefore the calls to remove will do nothing. This leaves us with a hypothesis that  $l1 ++ l2 = l1' ++ l2'$ . To finish the proof, we destruct  $l1$  and  $l1'$  to further compare the head of each list.

In the case where they are both empty, we arrive at a contradiction immediately, as this implies the head of both lists is  $x$  and therefore contradicts that  $a \neq a0$ . In the case where they are both lists, doing inversion on our remove hypothesis gives us that the head of each list is equal again, also contradicting that  $a \neq a0$ .

In the other two cases, we rewrite with the `in_split` hypotheses into the `is_mono` hypotheses. In both cases, we result in one statement that  $a$  comes before  $a0$  in the monomial, and one statement that  $a0$  comes before  $a$  in the monomial. With the help of `StronglySorted`, we are able to turn these into  $a < a0$  and  $a0 < a$ , which contradict each other to finish the proof.

```
Lemma remove_Sorted_eq : ∀ x (l l':mono),
  is_mono l → is_mono l' →
  In x l ↔ In x l' →
  remove var_eq_dec x l = remove var_eq_dec x l' →
  l = l'.
```

Proof.

```
intros x l l' Hl Hl' Hx Hrem.
generalize dependent l'; induction l; induction l'; intros.
- auto.
- destruct (var_eq_dec x a) eqn:Heq.
  + rewrite e in Hx. exfalso. apply Hx. intuition.
  + simpl in Hrem. rewrite Heq in Hrem. inversion Hrem.
- destruct (var_eq_dec x a) eqn:Heq.
  + rewrite e in Hx. exfalso. apply Hx. intuition.
  + simpl in Hrem. rewrite Heq in Hrem. inversion Hrem.
- clear IHl'. destruct (var_eq_dec a a0).
  + rewrite e. f_equal. rewrite e in Hrem. simpl in Hrem.
```

```

apply mono_cons in Hl as Hl1. apply mono_cons in Hl' as Hl'1.
destruct (var_eq_dec x a0).
× apply IHL; auto. apply NoDup_VarSorted in Hl.
  apply NoDup_cons_iff in Hl. rewrite e in Hl. rewrite ← e0 in Hl.
  destruct Hl. split; intro. contradiction. apply NoDup_VarSorted in Hl'.
  apply NoDup_cons_iff in Hl'. rewrite ← e0 in Hl'. destruct Hl'.
  contradiction.
× inversion Hrem. apply IHL; auto. destruct Hx. split; intro. simpl in H.
  rewrite e in H. destruct H; auto. rewrite H in n. contradiction.
  simpl in H1. rewrite e in H1. destruct H1; auto. rewrite H1 in n.
  contradiction.
+ destruct (in_dec var_eq_dec x (a :: l)).
  × apply Hx in i as i'. apply in_split in i. apply in_split in i'.
    destruct i as [l1 [l2 i]]. destruct i' as [l1' [l2' i']].
    pose (NoDup_VarSorted _ Hl). pose (NoDup_VarSorted _ Hl').
    apply (NoDup_In_split _ _ _ i) in n0 as [].
    apply (NoDup_In_split _ _ _ i') in n1 as [].
    rewrite i in Hrem. rewrite i' in Hrem.
    repeat rewrite remove_distr_app in Hrem. simpl in Hrem.
    destruct (var_eq_dec x x); try contradiction.
    repeat (rewrite not_In_remove in Hrem; auto). destruct l1; destruct l1';
    simpl in i; simpl in i'; simpl in Hrem; inversion i; inversion i'.
    - rewrite H4 in n. rewrite H6 in n. contradiction.
    - rewrite H7 in Hl'. rewrite i in Hl. rewrite Hrem in Hl.
      rewrite H6 in Hl'. assert (x < v). apply Sorted_inv in Hl as [].
      apply HdRel_inv in H8. auto. assert (v < x).
      apply Sorted_StronglySorted in Hl'.
      apply StronglySorted_inv in Hl' as []. rewrite Forall_forall in H9.
      apply H9. intuition. apply lt_Transitive. apply lt_asymm in H8.
      contradiction.
    - rewrite H7 in Hl'. rewrite i in Hl. rewrite ← Hrem in Hl'.
      rewrite H6 in Hl'. assert (n0 < x).
      apply Sorted_StronglySorted in Hl.
      apply StronglySorted_inv in Hl as []. rewrite Forall_forall in H8.
      apply H8. intuition. apply lt_Transitive. assert (x < n0).
      apply Sorted_inv in Hl' as []. apply HdRel_inv in H9; auto.
      apply lt_asymm in H8. contradiction.
    - inversion Hrem. rewrite ← H4 in H8. rewrite ← H6 in H8.
      contradiction.
  × assert (¬In x (a0 :: l')). intro. apply n0. apply Hx. auto.
    repeat (rewrite not_In_remove in Hrem; auto).

```

Qed.

Next is that if we **map remove** across a polynomial where every monomial contains  $x$ , there will still be no duplicates at the end.

Lemma NoDup\_map\_remove :  $\forall x p,$   
 $\text{is\_poly } p \rightarrow$   
 $(\forall m, \text{In } m p \rightarrow \text{In } x m) \rightarrow$   
**NoDup** (**map** (**remove** var\_eq\_dec  $x$ )  $p$ ).

Proof.

```

intros x p Hp Hx. induction p; simpl; auto.
apply NoDup_cons.
- intro. apply in_map_iff in H. destruct H as [y []]. assert (y = a).
  + apply poly_cons in Hp. destruct Hp. unfold is_poly in H1. destruct H1.
    apply H3 in H0 as H4. apply (remove_Sorted_eq x); auto. split; intro.
    apply Hx. intuition. apply Hx. intuition.
  + rewrite H1 in H0. unfold is_poly in Hp. destruct Hp.
    apply NoDup_MonoSorted in H2 as H4. apply NoDup_cons_iff in H4 as [].
    contradiction.
- apply IHp.
  + apply poly_cons in Hp. apply Hp.
  + intros m H. apply Hx. intuition.

```

Qed.

Building off that, if every monomial in a list *does not* contain some  $x$ , then appending  $x$  to every monomial and calling **make\_mono** still will not create any duplicates.

Lemma NoDup\_map\_app :  $\forall x l,$   
 $\text{is\_poly } l \rightarrow$   
 $(\forall m, \text{In } m l \rightarrow \neg \text{In } x m) \rightarrow$   
**NoDup** (**map** make\_mono (**map** ( $\text{fun } a \Rightarrow a ++ [x]$ )  $l$ )).

Proof.

```

intros x l Hp Hin. induction l.
- simpl. auto.
- simpl. apply NoDup_cons.
  + intros H. rewrite map_map in H. apply in_map_iff in H as [m []].
    assert (a = m).
    × apply poly_cons in Hp as []. apply Permutation_Sorted_mono_eq.
      - apply Permutation_sort_mono_eq in H. rewrite no_nodup_NoDup in H.
        rewrite no_nodup_NoDup in H.
        ++ pose (Permutation_cons_append m x).
          pose (Permutation_cons_append a x).
          apply (Permutation_trans p) in H. apply Permutation_sym in p0.
          apply (Permutation_trans H) in p0.
          apply Permutation_cons_inv in p0. apply Permutation_sym. auto.
        ++ apply Permutation_NoDup with (l:=x :: a).
          apply Permutation_cons_append.

```

```

    apply NoDup_cons. apply Hin. intuition. unfold is_mono in H2.
    apply NoDup_VarSorted in H2. auto.
  ++ apply Permutation_NoDup with (l:=x :: m).
    apply Permutation_cons_append. apply NoDup_cons. apply Hin.
    intuition. unfold is_poly in H1. destruct H1. apply H3 in H0.
    unfold is_mono in H0. apply NoDup_VarSorted in H0. auto.
  - unfold is_mono in H2. apply Sorted_VarSorted. auto.
  - unfold is_poly in H1. destruct H1. apply H3 in H0.
    apply Sorted_VarSorted. auto.
× rewrite ← H1 in H0. unfold is_poly in Hp. destruct Hp.
  apply NoDup_MonoSorted in H2. apply NoDup_cons_iff in H2 as [].
  contradiction.
+ apply IHL. apply poly_cons in Hp. apply Hp. intros m H. apply Hin.
  intuition.

```

Qed.

This next lemma is relatively straightforward, and really just served to remove the calls to `sort` and `nodup_cancel` for convenience when simplifying a `mulPP`.

Lemma `mulPP_Permutation` :  $\forall x \ a0 \ l,$   
 $\text{is\_poly } (a0 :: l) \rightarrow$   
 $(\forall m, \text{In } m \ (a0 :: l) \rightarrow \neg \text{In } x \ m) \rightarrow$   
 $\text{Permutation } (\text{mulPP } [[x]] \ (a0 :: l))$   
 $((\text{make\_mono } (a0 ++ [x])) :: (\text{mulPP } [[x]] \ l)).$

Proof.

```

  intros x a0 l Hp Hx. unfold mulPP, distribute. simpl. unfold make_poly.
  pose (MonoSort.Permuted_sort (nodup_cancel mono_eq_dec
    (map make_mono ((a0 ++ [x]) :: concat (map (fun a => [a ++ [x]]) l)))).
  apply Permutation_sym in p. apply (Permutation_trans p). simpl map.
  rewrite no_nodup_cancel_NoDup; clear p.
  - apply perm_skip. rewrite ← Permutation_MonoSort_r.
    rewrite no_nodup_cancel_NoDup; auto. rewrite concat_map.
    apply NoDup_map_app. apply poly_cons in Hp. apply Hp. intros m H. apply Hx.
    intuition.
  - rewrite ← map_cons. rewrite concat_map.
    rewrite ← map_cons with (f:=fun a => a ++ [x]).
    apply NoDup_map_app; auto.

```

Qed.

Building off of the previous lemma, this one serves to remove the calls to `make_poly` entirely, and instead replace `mulPP` with just the `map app`. We can do this because we know that  $x$  is not in any of the monomials, so `nodup_cancel` will have no effect as we proved earlier.

Lemma `mulPP_map_app_permutation` :  $\forall (x:\text{var}) \ (l \ l' : \text{poly}),$



```

is_poly l →
(∀ m, In m l → ¬ In x m) →
Permutation l l' →
Permutation (mulPP [[x]] l) (map (fun a ⇒ (make_mono (a ++ [x]))) l').

```

Proof.

```

intros x l l' Hp H H0. generalize dependent l'. induction l; induction l'.
- intros. unfold mulPP, distribute, make_poly, MonoSort.sort. simpl. auto.
- intros. apply Permutation_nil_cons in H0. contradiction.
- intros. apply Permutation_sym in H0. apply Permutation_nil_cons in H0.
  contradiction.
- intros. clear IHL'. destruct (mono_eq_dec a a0).
  + rewrite e in *. pose (mulPP_Permutation x a0 l Hp H).
    apply (Permutation_trans p). simpl. apply perm_skip. apply IHL.
    × clear p. apply poly_cons in Hp. apply Hp.
    × intros m Hin. apply H. intuition.
    × apply Permutation_cons_inv in H0. auto.
  + apply Permutation_incl in H0 as H1. destruct H1.
    apply incl_cons_inv in H1 as []. destruct H1;
    try (rewrite H1 in n; contradiction). apply in_split in H1.
    destruct H1 as [l1 [l2]]. rewrite H1 in H0.
    pose (Permutation_middle (a0 :: l1) l2 a). apply Permutation_sym in p.
    simpl in p. apply (Permutation_trans H0) in p.
    apply Permutation_cons_inv in p. rewrite H1. simpl. rewrite map_app.
    simpl. pose (Permutation_middle ((make_mono (a0 ++ [x])) :: map (fun a1 ⇒
      make_mono (a1 ++ [x])) l1)) (map (fun a1 ⇒ make_mono (a1 ++ [x])) l2)
      (make_mono (a ++ [x]))).
    simpl in p0. simpl. apply Permutation_trans with (l' := make_mono (a ++ [x])
      :: make_mono (a0 ++ [x])) :: map (fun a1 : list var ⇒ make_mono (a1 ++
      [x])) l1 ++ map (fun a1 : list var ⇒ make_mono (a1 ++ [x])) l2; auto.
    clear p0. rewrite ← map_app.
    rewrite ← (map_cons (fun a1 ⇒ make_mono (a1 ++ [x])) a0 (@app (list var)
      l1 l2)).
    pose (mulPP_Permutation x a l Hp H). apply (Permutation_trans p0).
    apply perm_skip. apply IHL.
    × clear p0. apply poly_cons in Hp. apply Hp.
    × intros m Hin. apply H. intuition.
    × apply p.

```

Qed.

Finally, we combine the lemmas in this section to prove that, if there is some polynomial  $p$  that has  $x$  in every monomial, removing and then re-appending  $x$  to every monomial results in a list that is a permutation of the original polynomial.

Lemma map\_app\_remove\_Permutation :  $\forall p x$ ,

```

is_poly p →
(∀ m, In m p → In x m) →
Permutation p (map (fun a ⇒ (make_mono (a ++ [x])))
  (map (remove var_eq_dec x) p)).

```

Proof.

```

intros p x H H0. rewrite map_map. induction p; auto.
simpl. assert (make_mono (@app var (remove var_eq_dec x a) [x]) = a).
- unfold make_mono. rewrite no_nodup_NoDup.
+ apply Permutation_Sorted_mono_eq.
× apply Permutation_trans with (l' := remove var_eq_dec x a ++ [x]).
  apply Permutation_sym. apply VarSort.Permuted_sort.
  pose (in_split x a). destruct e as [l1 [l2 e]]. apply H0. intuition.
  rewrite e. apply Permutation_trans with
    (l' := x :: remove var_eq_dec x (l1 ++ x :: l2)).
  apply Permutation_sym. apply Permutation_cons_append.
  apply Permutation_trans with (l' := (x :: l1 ++ l2)). apply perm_skip.
  rewrite remove_distr_app. replace (x :: l2) with ([x] ++ l2); auto.
  rewrite remove_distr_app. simpl. destruct (var_eq_dec x x);
  try contradiction. rewrite app_nil_l. repeat rewrite not_In_remove;
  try apply Permutation_refl; try (apply poly_cons in H as []);
  unfold is_mono in H1; apply NoDup_VarSorted in H1; rewrite e in H1;
  apply NoDup_remove_2 in H1). intros x2. apply H1. intuition. intros x1.
  apply H1. intuition. apply Permutation_middle.
× apply VarSort.LocallySorted_sort.
× apply poly_cons in H as []. unfold is_mono in H1.
  apply Sorted_VarSorted. auto.
+ apply Permutation_NoDup with (l := (x :: remove var_eq_dec x a)).
  apply Permutation_cons_append. apply NoDup_cons.
  apply remove_In. apply NoDup_remove. apply poly_cons in H as [].
  unfold is_mono in H1. apply NoDup_VarSorted. auto.
- rewrite H1. apply perm_skip. apply IHp.
+ apply poly_cons in H. apply H.
+ intros m Hin. apply H0. intuition.

```

Qed.

# Chapter 7

## Library B\_Unification.poly\_unif

```
Require Import List.
Import ListNotations.
Require Import Arith.
Require Import Permutation.
Require Export poly.
```

### 7.1 Introduction

This section deals with defining substitutions and their properties using a polynomial representation. As with the inductive term representation, substitutions are just lists of replacements, where variables are swapped with polynomials instead of terms. Crucial to the proof of correctness in the following chapter, substitution is proven to distribute over polynomial addition and multiplication. Definitions are provided for unifier, unifiable, and properties relating multiple substitutions such as more general and composition.

### 7.2 Substitution Definitions

A *substitution* is defined as a list of replacements. A *replacement* is just a tuple of a variable and a polynomial.

Definition repl := **prod** var poly.

Definition subst := **list** repl.

Since the `poly` data type doesn't enforce the properties of actual polynomials, the `is_poly` predicate is used to check if a term is in polynomial form. Likewise, the `is_poly_subst` predicate below verifies that every term in the range of the substitution is a polynomial.

Definition is\_poly\_subst (s : subst) : Prop :=  
  $\forall x\ p, \text{In } (x, p) \ s \rightarrow \text{is\_poly } p.$

The next three functions implement how substitutions are applied to terms. At the top level, `substP` applies a substitution to a polynomial by calling `substM` on each monomial. From there, `substV` is called on each variable. Because variables and monomials are converted to polynomials, the process isn't simply mapping application across the lists. `substM` and `substP` must multiply and add each polynomial together respectively.

```
Fixpoint substV (s : subst) (x : var) : poly :=
  match s with
  | [] => [[x]]
  | (y, p) :: s' => if (x =? y) then p else (substV s' x)
  end.
```

```
Fixpoint substM (s : subst) (m : mono) : poly :=
  match m with
  | [] => [[]]
  | x :: m => mulPP (substV s x) (substM s m)
  end.
```

```
Definition substP (s : subst) (p : poly) : poly :=
  make_poly (concat (map (substM s) p)).
```

Useful in later proofs is the ability to rewrite the unfolded definition of `substP` as just the function call.

```
Lemma substP_refold : ∀ s p,
  make_poly (concat (map (substM s) p)) = substP s p.
```

Proof. auto. Qed.

The following lemmas state that substitution applications always produce polynomials. This fact is necessary for proving distribution and other properties of substitutions.

```
Lemma substV_is_poly : ∀ x s,
  is_poly_subst s →
  is_poly (substV s x).
```

Proof.

```
  intros x s H. unfold is_poly_subst in H. induction s; simpl; auto.
  destruct a eqn:Ha. destruct (x =? v).
  - apply (H v). intuition.
  - apply IHs. intros x0 p0 H0. apply (H x0). intuition.
```

Qed.

```
Lemma substM_is_poly : ∀ s m,
  is_poly (substM s m).
```

Proof.

```
  intros s m. unfold substM; destruct m; auto.
```

Qed.

```
Lemma substP_is_poly : ∀ s p,
  is_poly (substP s p).
```

Proof.

```
intros. unfold substP. auto.
```

Qed.

Hint Resolve *substP\_is\_poly substM\_is\_poly*.

The lemma below states that a substitution applied to a variable in polynomial form is equivalent to the substitution applied to just the variable. This fact only holds when the substitution's range consists of polynomials.

```
Lemma subst_var_eq : ∀ x s,  
  is_poly_subst s →  
  substP s [[x]] = substV s x.
```

Proof.

```
intros. simpl.  
apply (substV_is_poly x s) in H. unfold substP. simpl. rewrite app_nil_r.  
rewrite mulPP_1r; auto. rewrite no_make_poly; auto.
```

Qed.

The next two lemmas deal with simplifying substitutions where the first replacement tuple is useless for the given term. This is the case when the variable being replaced is not present in the term. It allows the replacement to be dropped from the substitution without changing the result.

```
Lemma substM_cons : ∀ x m,  
  ¬ ln x m →  
  ∀ p s, substM ((x, p) :: s) m = substM s m.
```

Proof.

```
intros. induction m; auto. simpl. f_equal.  
- destruct (a =? x) eqn:H0; auto.  
  symmetry in H0. apply beq_nat_eq in H0. exfalso.  
  simpl in H. apply H. left. auto.  
- apply IHm. intro. apply H. right. auto.
```

Qed.

```
Lemma substP_cons : ∀ x p,  
  (∀ m, ln m p → ¬ ln x m) →  
  ∀ q s, substP ((x, q) :: s) p = substP s p.
```

Proof.

```
intros. induction p; auto. unfold substP. simpl.  
repeat rewrite ← (make_poly_pointless_r - (concat _)). f_equal. f_equal.  
- apply substM_cons. apply H. left. auto.  
- apply IHp. intros. apply H. right. auto.
```

Qed.

Substitutions applied to constants have no effect.

```
Lemma substP_1 : ∀ s,
```

```

    substP s [] = [].
Proof.
  intros. unfold substP. simpl. auto.
Qed.

Lemma substP_0 : ∀ s,
  substP s [] = [].
Proof.
  intros. unfold substP. simpl. auto.
Qed.

  The identity substitution—the empty list—has no effect when applied to a term.

Lemma empty_substM : ∀ m,
  is_mono m →
  substM [] m = [m].
Proof.
  intros. induction m; auto. simpl.
  apply mono_cons in H as H0.
  rewrite IHm; auto.
  apply mulPP_mono_cons; auto.
Qed.

Lemma empty_substP : ∀ p,
  is_poly p →
  substP [] p = p.
Proof.
  intros. induction p; auto. unfold substP. simpl.
  apply poly_cons in H as H0. destruct H0.
  rewrite ← make_poly_pointless_r. rewrite substP_refold.
  rewrite IHp; auto. rewrite empty_substM; auto.
  apply addPP_poly_cons; auto.
Qed.

```

## 7.3 Distribution Over Arithmetic Operators

Below is the statement and proof that substitution distributes over polynomial addition. Given a substitution  $s$  and two terms in polynomial form  $p$  and  $q$ , it is shown that  $s(p+q) \downarrow_P = (s(p) + s(q)) \downarrow_P$ . The proof relies heavily on facts about permutations proven in the `list_util` library.

```

Lemma substP_distr_addPP : ∀ p q s,
  is_poly p →
  is_poly q →
  substP s (addPP p q) = addPP (substP s p) (substP s q).
Proof.

```

```

intros p q s Hp Hq. unfold substP, addPP.
apply Permutation_sort_eq. apply Permutation_trans with (l':=
  (nodup_cancel mono_eq_dec (map make_mono (concat (map (substM s)
    (nodup_cancel mono_eq_dec (map make_mono (p ++ q)))))))).
  apply nodup_cancel_Permutation. apply Permutation_map.
  apply Permutation_concat. apply Permutation_map. unfold make_poly.
  rewrite ← Permutation_MonoSort_l. auto.
apply Permutation_sym. apply Permutation_trans with (l':=(nodup_cancel
  mono_eq_dec (map make_mono (nodup_cancel mono_eq_dec (map make_mono (concat
    (map (substM s) (p)))) ++ (nodup_cancel mono_eq_dec (map make_mono (concat
    (map (substM s) q)))))). apply nodup_cancel_Permutation.
  apply Permutation_map. apply Permutation_app; unfold make_poly;
  rewrite ← Permutation_MonoSort_l; auto.
rewrite (no_map_make_mono ((nodup_cancel _ _) ++ (nodup_cancel _ _))).
rewrite nodup_cancel_pointless. apply Permutation_trans with (l':=
  (nodup_cancel mono_eq_dec (nodup_cancel mono_eq_dec (map make_mono (concat
    (map (substM s) q)) ++ map make_mono (concat (map (substM s) p)))))).
  apply nodup_cancel_Permutation. apply Permutation_app_comm.
rewrite nodup_cancel_pointless. rewrite ← map_app. rewrite ← concat_app.
rewrite ← map_app. rewrite (no_map_make_mono (p ++ q)).
apply Permutation_trans with (l':=(nodup_cancel mono_eq_dec (map make_mono
  (concat (map (substM s) (p ++ q)))))). apply nodup_cancel_Permutation.
  apply Permutation_map. apply Permutation_concat. apply Permutation_map.
  apply Permutation_app_comm.
apply Permutation_sym. repeat rewrite List.concat_map.
repeat rewrite map_map. apply nodup_cancel_concat_map.
intros x. rewrite no_map_make_mono. apply NoDup_MonoSorted;
  apply substM_is_poly.
intros m Hin. apply (substM_is_poly s x); auto.
intros m Hin. apply in_app_iff in Hin as []; destruct Hp; destruct Hq; auto.
intros m Hin. apply in_app_iff in Hin as []; apply nodup_cancel_in in H;
  apply mono_in_map_make_mono in H; auto.
Qed.

```

The next six lemmas deal with proving that substitution distributes over polynomial multiplication. Given a substitution  $s$  and two terms in polynomial form  $p$  and  $q$ , it is shown that  $s(p * q) \downarrow_P = (s(p) * s(q)) \downarrow_P$ . The proof turns out to be much more difficult than the one for addition because the underlying arithmetic operation is more complex.

If two monomials are permutations (obviously not in monomial form), then applying any substitution to either will produce the same result. A weaker form that follows from this is that the results are permutations as well.

Lemma `substM_Permutation_eq` :  $\forall s \ m \ n,$

**Permutation**  $m \ n \rightarrow$

`substM s m = substM s n.`

Proof.

```
intros s m n H. induction H; auto.
- simpl. rewrite IHPermutation. auto.
- simpl. rewrite mulPP_comm. rewrite mulPP_assoc.
  rewrite (mulPP_comm (substM s l)). auto.
- rewrite IHPermutation1. rewrite IHPermutation2. auto.
```

Qed.

Lemma substM\_Permutation :  $\forall s m n$ ,

**Permutation**  $m n \rightarrow$   
**Permutation** (substM  $s m$ ) (substM  $s n$ ).

Proof.

```
intros s m n H. rewrite (substM_Permutation_eq s m n); auto.
```

Qed.

Adding duplicate variables to a monomial doesn't change the result of applying a substitution. This is only true if the substitution's range only has polynomials.

Lemma substM\_nodup\_pointless :  $\forall s m$ ,

is\_poly\_subst  $s \rightarrow$   
 substM  $s$  (nodup var\_eq\_dec  $m$ ) = substM  $s m$ .

Proof.

```
intros s m Hps. induction m; auto. simpl. destruct in_dec.
- apply in_split in i. destruct i as [l1 [l2 H]].
  assert (Permutation m (a :: l1 ++ l2)). rewrite H. apply Permutation_sym.
  apply Permutation_middle.
  apply substM_Permutation_eq with (s:=s) in H0. rewrite H0. simpl.
  rewrite (mulPP_comm _ (substM _ _)). rewrite mulPP_comm.
  rewrite mulPP_assoc. rewrite mulPP_p_p. rewrite mulPP_comm. rewrite IHm.
  rewrite H0. simpl. auto. apply substV_is_poly. auto.
- simpl. rewrite IHm. auto.
```

Qed.

The idea behind the following two lemmas is that substitutions distribute over multiplication of a monomial and polynomial. The specifics of both are convoluted, yet easier to prove than distribution over two polynomials.

Lemma substM\_distr\_mulMP :  $\forall m n s$ ,

is\_poly\_subst  $s \rightarrow$   
 is\_mono  $n \rightarrow$   
**Permutation**  
 (nodup\_cancel mono\_eq\_dec (map make\_mono (substM  $s$  (make\_mono  
 (make\_mono ( $m ++ n$ ))))))  
 (nodup\_cancel mono\_eq\_dec (map make\_mono (concat (map (mulMP''  
 (map make\_mono (substM  $s m$ ))) (map make\_mono (substM  $s n$ )))))).



Proof.

```

intros m n s Hps H. rewrite (no_make_mono (make_mono (m ++ n))); auto.
repeat rewrite (no_map_make_mono (substM s _)); auto. apply Permutation_trans
  with (l':=(nodup_cancel mono_eq_dec (substM s (nodup var_eq_dec
    (m ++ n))))). apply nodup_cancel_Permutation. apply substM_Permutation.
  unfold make_mono. rewrite ← Permutation_VarSort_l. auto.
induction m.
- simpl. pose (mulPP_1r (substM s n)). rewrite mulPP_comm in e.
  pose (substM_is_poly s n). apply e in i. rewrite mulPP_mulPP''' in i.
  unfold mulPP''' in i. rewrite ← no_make_poly in i; auto.
  apply Permutation_sort_eq in i. rewrite i. rewrite no_nodup_NoDup.
  rewrite no_map_make_mono. auto. intros m Hin. apply (substM_is_poly s n);
  auto. apply NoDup_VarSorted. auto.
- simpl substM at 2. apply Permutation_sort_eq. rewrite make_poly_refold.
  rewrite mulPP'''_refold. rewrite ← mulPP_mulPP'''. rewrite mulPP_assoc.
  repeat rewrite mulPP_mulPP'''. apply Permutation_sort_eq.
  rewrite substM_nodup_pointless; auto. simpl. rewrite mulPP_mulPP'''.
  unfold mulPP''' at 1. apply Permutation_sort_eq in IHm.
  rewrite make_poly_refold in IHm. rewrite mulPP'''_refold in IHm.
  rewrite no_nodup_cancel_NoDup in IHm. rewrite no_sort_MonoSorted in IHm.
  rewrite ← substM_nodup_pointless; auto. rewrite IHm. unfold make_poly.
  apply Permutation_trans with (l':=(nodup_cancel mono_eq_dec (nodup_cancel
    mono_eq_dec (map make_mono (concat (map (mulMP'' (substV s a))
      (mulPP''' (substM s m) (substM s n)))))))).
  apply nodup_cancel_Permutation. rewrite ← Permutation_MonoSort_l. auto.
  rewrite no_nodup_cancel_NoDup; auto.
  apply NoDup_nodup_cancel. apply substM_is_poly. apply NoDup_MonoSorted.
  apply substM_is_poly.
- intros m0 Hin. apply (substM_is_poly s n). auto.
- intros m0 Hin. apply (substM_is_poly s m). auto.
- intros m0 Hin. apply (substM_is_poly s (make_mono (m ++ n))). auto.

```

Qed.

Lemma map\_substM\_distr\_map\_mulMP :  $\forall m p s$ ,

is\_poly\_subst s  $\rightarrow$

is\_poly p  $\rightarrow$

**Permutation**

```

(nodup_cancel mono_eq_dec (map make_mono (concat (map (substM s) (map
  make_mono (mulMP'' p m))))))
(nodup_cancel mono_eq_dec (map make_mono (concat (map (mulMP'' (map
  make_mono (concat (map (substM s) p)))) (map make_mono (substM s m)))))).

```

Proof.

```

intros m p s Hps H. unfold mulMP'' at 1. apply Permutation_trans with (l':=

```

```

(nodup_cancel mono_eq_dec (map make_mono (concat (map (substM s) (map
make_mono (nodup_cancel mono_eq_dec (map make_mono (map (app m) p)))))))).
apply nodup_cancel_permutation, Permutation_map, Permutation_concat,
Permutation_map, Permutation_map. unfold make_poly.
rewrite ← Permutation_MonoSort.l. auto.
apply Permutation_trans with (l':=(nodup_cancel mono_eq_dec (map make_mono
(concat (map (substM s) (map make_mono (map make_mono (map (app m)
(p)))))))). repeat rewrite List.concat_map. rewrite map_map.
rewrite map_map. rewrite (map_map _ (map make_mono)).
rewrite (map_map make_mono). rewrite nodup_cancel_concat_map. auto.
intros x. rewrite no_map_make_mono. apply NoDup_MonoSorted.
apply (substM_is_poly s (make_mono x)). intros m0 Hin.
pose (substM_is_poly s (make_mono x)). apply i. auto.
induction p; simpl.
- induction (map make_mono (substM s m)); auto.
- rewrite map_app. apply Permutation_sym. apply Permutation_trans with (l':=
(nodup_cancel mono_eq_dec (map make_mono (concat (map (mulMP'' (map
make_mono (substM s m))) (map make_mono (substM s a ++ concat (map
(substM s) p)))))))). apply Permutation_sort_eq. repeat (rewrite
make_poly_refold, mulPP'''_refold, ← mulPP_mulPP'''). apply mulPP_comm.
repeat rewrite map_app. rewrite concat_app, map_app. apply Permutation_sym.
apply nodup_cancel_app_permutation. apply substM_distr_mulMP; auto. apply H.
intuition. apply Permutation_sym. apply Permutation_trans with (l':=
(nodup_cancel mono_eq_dec (map make_mono (concat (map (mulMP'' (map
make_mono (concat (map (substM s) p))) (map make_mono (substM s m)))))))).
apply Permutation_sort_eq. repeat (rewrite make_poly_refold,
mulPP'''_refold, ← mulPP_mulPP'''). apply mulPP_comm.
apply Permutation_sym. apply IHp. apply poly_cons in H. apply H.
Qed.

```

Here is the formulation of substitution distributing over polynomial multiplication. Similar to the proof for addition, it is very dense and makes common use of permutation facts. Where it differs from that proof is that it relies on the commutativity of multiplication. The proof of distribution over addition didn't need any properties of addition.

Lemma substP\_distr\_mulPP :  $\forall p \ q \ s,$   
 $\text{is\_poly\_subst } s \rightarrow$   
 $\text{is\_poly } p \rightarrow$   
 $\text{substP } s \ (\text{mulPP } p \ q) = \text{mulPP } (\text{substP } s \ p) \ (\text{substP } s \ q).$

Proof.

```

intros p q s Hps H. repeat rewrite mulPP_mulPP'''. unfold substP, mulPP'''.
apply Permutation_sort_eq. apply Permutation_trans with (l':=(nodup_cancel
mono_eq_dec (map make_mono (concat (map (substM s) (nodup_cancel mono_eq_dec
(map make_mono (concat (map (mulMP'' p) q)))))))).

```

```

apply nodup_cancel Permutation. apply Permutation_map.
apply Permutation_concat. apply Permutation_map. unfold make_poly.
rewrite ← Permutation_MonoSort.l. auto.
apply Permutation_sym. apply Permutation_trans with (l' := (nodup_cancel
  mono_eq_dec (map make_mono (concat (map (mulMP'' (make_poly (concat (map
    (substM s) p)))) (nodup_cancel mono_eq_dec (map make_mono (concat (map
      (substM s) q)))))))). apply nodup_cancel Permutation.
  apply Permutation_map. apply Permutation_concat. apply Permutation_map.
  unfold make_poly. rewrite ← Permutation_MonoSort.l. auto.
apply Permutation_trans with (l' := (nodup_cancel mono_eq_dec (map make_mono
  (concat (map (mulMP'' (make_poly (concat (map (substM s) p)))) (map
    make_mono (concat (map (substM s) q)))))). repeat rewrite (List.concat_map
    make_mono (map (mulMP'' _) _)). repeat rewrite (map_map _ (map make_mono))).
  apply nodup_cancel_concat_map. intros x. rewrite no_map_make_mono.
  unfold mulMP''. apply NoDup_MonoSorted. apply make_poly_is_poly.
  intros m Hin. apply mono_in_make_poly in Hin; auto.
apply Permutation_sort_eq. rewrite make_poly_refold. rewrite mulPP''_refold.
rewrite ← mulPP_mulPP''. rewrite mulPP_comm. rewrite mulPP_mulPP''.
apply Permutation_sort_eq. apply Permutation_trans with (l' := (nodup_cancel
  mono_eq_dec (map make_mono (concat (map (mulMP'' (map make_mono (concat (map
    (substM s) q)))) (nodup_cancel mono_eq_dec (map make_mono (concat (map
      (substM s) p)))))))). apply nodup_cancel Permutation.
  apply Permutation_map. apply Permutation_concat. apply Permutation_map.
  unfold make_poly. rewrite ← Permutation_MonoSort.l. auto.
apply Permutation_trans with (l' := (nodup_cancel mono_eq_dec (map make_mono
  (concat (map (mulMP'' (map make_mono (concat (map (substM s) q)))) (map
    make_mono (concat (map (substM s) p)))))). repeat rewrite (List.concat_map
    make_mono (map (mulMP'' _) _)). repeat rewrite (map_map _ (map make_mono))).
  apply nodup_cancel_concat_map. intros x. rewrite no_map_make_mono.
  unfold mulMP''. apply NoDup_MonoSorted. apply make_poly_is_poly.
  intros m Hin. apply mono_in_make_poly in Hin; auto.
apply Permutation_sort_eq. rewrite make_poly_refold. rewrite mulPP''_refold.
rewrite ← mulPP_mulPP''. rewrite mulPP_comm. rewrite mulPP_mulPP''.
apply Permutation_sort_eq. apply Permutation_sym.
apply Permutation_trans with (l' := (nodup_cancel mono_eq_dec (map make_mono
  (concat (map (substM s) (map make_mono (concat (map (mulMP'' p) q)))))).
  repeat rewrite (List.concat_map make_mono (map _ _)).
  repeat rewrite map_map. rewrite nodup_cancel_concat_map. auto. intros x.
  rewrite no_map_make_mono. apply NoDup_MonoSorted; apply substM_is_poly.
  intros m Hin; apply (substM_is_poly s x); auto.
induction q; auto. simpl. repeat rewrite map_app. repeat rewrite concat_app.
repeat rewrite map_app. repeat rewrite ← (nodup_cancel_pointless (map _ _)).

```

```

repeat rewrite ← (nodup_cancel_pointless_r - (map - _)).
apply nodup_cancel_Permutation. apply Permutation_app.
apply map_substM_distr_map_mulMP; auto. apply IHq.
Qed.

```

## 7.4 Unifiable Definitions

The following six definitions are all predicate functions that verify some property about substitutions or polynomials.

A *unifier* for a given polynomial  $p$  is a substitution  $s$  such that  $s(p) \downarrow_P = 0$ . This definition also includes that the range of the substitution only contain terms in polynomial form.

**Definition** `unifier` ( $s : \text{subst}$ ) ( $p : \text{poly}$ ) : Prop :=  
`is_poly_subst s ∧ substP s p = []`.

A polynomial  $p$  is *unifiable* if there exists a unifier for  $p$ .

**Definition** `unifiable` ( $p : \text{poly}$ ) : Prop :=  
`∃ s, unifier s p`.

A substitution  $u$  is a *composition* of two substitutions  $s$  and  $t$  if  $u(x) \downarrow_P = t(s(x)) \downarrow_P$  for every variable  $x$ . The lemma `subst_comp_eq_poly` below extends this definition from variables to polynomials.

**Definition** `subst_comp_eq` ( $s \ t \ u : \text{subst}$ ) : Prop :=  
 $\forall x,$   
`substP t (substP s [[x]]) = substP u [[x]]`.

A substitution  $s$  is *more general* than a substitution  $t$  if there exists a third substitution  $u$  such that  $t$  is a composition of  $u$  and  $s$ .

**Definition** `more_general` ( $s \ t : \text{subst}$ ) : Prop :=  
`∃ u, subst_comp_eq s u t`.

Given a polynomial  $p$ , a substitution  $s$  is the *most general unifier* of  $p$  if  $s$  is more general than every unifier of  $p$ .

**Definition** `mgu` ( $s : \text{subst}$ ) ( $p : \text{poly}$ ) : Prop :=  
`unifier s p ∧`  
 $\forall t,$   
`unifier t p →`  
`more_general s t`.

Given a polynomial  $p$ , a substitution  $s$  is a *reproductive unifier* of  $p$  if  $t$  is a composition of itself and  $s$  for every unifier  $t$  of  $p$ . This property is similar but stronger than most general because the substitution that composes with  $s$  is restricted to  $t$ , whereas in most general it can be any substitution.

**Definition** `reprod_unif` ( $s : \text{subst}$ ) ( $p : \text{poly}$ ) : Prop :=  
`unifier s p ∧`

$\forall t,$   
 $\text{unifier } t \ p \rightarrow$   
 $\text{subst\_comp\_eq } s \ t \ t.$

Because the notion of most general is weaker than reproductive, it can be proven to logically follow as shown below. Any unifier that is reproductive is also most general.

Lemma `reprod_is_mgu` :  $\forall p \ s,$   
 $\text{reprod\_unif } s \ p \rightarrow$   
 $\text{mgu } s \ p.$

Proof.

`unfold mgu, reprod_unif, more_general, subst_comp_eq.`  
`intros p s [].`  
`split; auto.`  
`intros.`  
 $\exists t.$   
`intros.`  
`apply H0; auto.`

Qed.

As stated earlier, substitution composition can be extended to polynomials. This comes from the implicit fact that if two substitutions agree on all variables then they agree on all terms.

Lemma `subst_comp_eq_poly` :  $\forall s \ t \ u,$   
 $\text{is\_poly\_subst } s \rightarrow$   
 $\text{is\_poly\_subst } t \rightarrow$   
 $\text{is\_poly\_subst } u \rightarrow$   
 $(\forall x, \text{substP } t \ (\text{substP } s \ [[x]])) = \text{substP } u \ [[x]] \rightarrow$   
 $\forall p,$   
 $\text{substP } t \ (\text{substP } s \ p) = \text{substP } u \ p.$

Proof.

`intros. induction p; auto. simpl. unfold substP at 2. simpl.`  
`rewrite ← make_poly_pointless_r. rewrite addPP_refold.`  
`rewrite substP_distr_addPP; auto. unfold substP at 3. simpl.`  
`rewrite ← make_poly_pointless_r. rewrite addPP_refold. f_equal.`  
`- induction a; auto. simpl. rewrite substP_distr_mulPP; auto. f_equal; auto.`  
`+ rewrite ← subst_var_eq; auto. rewrite ← subst_var_eq; auto.`  
`+ apply substV_is_poly; auto.`  
`- rewrite substP_refold. apply IHp.`

Qed.

The last lemmas of this section state that the identity substitution is a reproductive unifier of the constant zero. Therefore it is also most general.

Lemma `empty_unifier` :  $\text{unifier } [] \ [].$

Proof.

```
    unfold unifier, is_poly_subst. split; auto.  
    intros. inversion H.
```

Qed.

Lemma empty\_reprod\_unif : reprod\_unif [] [].

Proof.

```
    unfold reprod_unif, more_general, subst_comp_eq.  
    split; auto. apply empty_unifier.
```

Qed.

Lemma empty\_mgu : mgu [] [].

Proof.

```
    apply reprod_is_mgu. apply empty_reprod_unif.
```

Qed.

# Chapter 8

## Library B\_Unification.sve

```
Require Import List.  
Import ListNotations.  
Require Import Arith.  
Require Import Permutation.  
Require Export poly_unif.
```

### 8.1 Introduction

Here we implement the algorithm for successive variable elimination. The basic idea is to remove a variable from the problem, solve that simpler problem, and build a solution from the simpler solution. The algorithm is recursive, so variables are removed and problems are generated until we are left with either of two problems;  $1 \stackrel{?}{\approx}_B 0$  or  $0 \stackrel{?}{\approx}_B 0$ . In the former case, the whole original problem is not unifiable. In the latter case, the problem is solved without any need to substitute since there are no variables. From here, we begin the process of building up substitutions until we reach the original problem.

### 8.2 Eliminating Variables

This section deals with the problem of removing a variable  $x$  from a term  $t$ . The first thing to notice is that  $t$  can be written in polynomial form  $t \downarrow_P$ . This polynomial is just a set of monomials, and each monomial a set of variables. We can now separate the polynomials into two sets  $qx$  and  $r$ . The term  $qx$  will be the set of monomials in  $t \downarrow_P$  that contain the variable  $x$ . The term  $q$ , or the quotient, is  $qx$  with the  $x$  removed from each monomial. The term  $r$ , or the remainder, will be the monomials in  $t \downarrow_P$  that do not contain  $x$ . The original term can then be written as  $x * q + r$ .

Implementing this procedure is pretty straightforward. We define a function `div_by_var` that produces two polynomials given a polynomial  $p$  and a variable  $x$  to eliminate from it.

The first step is dividing  $p$  into  $qx$  and  $r$  which is performed using a partition over  $p$  with the predicate `has_var`. The second step is to remove  $x$  from  $qx$  using the helper `elim_var`.

The function `has_var` determines whether a variable appears in a monomial.

**Definition** `has_var` ( $x : \text{var}$ ) := `existsb (beq_nat x)`.

The function `elim_var` removes a variable from each monomial in a polynomial. It is possible that this leaves the term not in polynomial form so it is then repaired with `make_poly`.

**Definition** `elim_var` ( $x : \text{var}$ ) ( $p : \text{poly}$ ) : `poly` :=  
`make_poly (map (remove var_eq_dec x) p)`.

The function `div_by_var` produces a quotient  $q$  and remainder  $r$  from a polynomial  $p$  and variable  $x$  such that  $p \approx_B x * q + r$  and  $x$  does not occur in  $r$ .

**Definition** `div_by_var` ( $x : \text{var}$ ) ( $p : \text{poly}$ ) : `prod poly poly` :=  
`let (qx, r) := partition (has_var x) p in`  
`(elim_var x qx, r)`.

We would also like to prove some lemmas about variable elimination that will be helpful in proving the full algorithm correct later. The main lemma below is `div_eq`, which just asserts that after eliminating  $x$  from  $p$  into  $q$  and  $r$  the term can be put back together as in  $p \approx_B x * q + r$ . This fact turns out to be rather hard to prove and needs the help of 10 or so other subsidiary lemmas.

After eliminating a variable  $x$  from a polynomial to produce  $r$ ,  $x$  does not occur in  $r$ .

**Lemma** `elim_var_not_in_rem` :  $\forall x p r$ ,  
`elim_var x p = r`  $\rightarrow$   
`( $\forall m$ , ln m r  $\rightarrow$   $\neg$  ln x m).`

**Proof.**

```

intros.
unfold elim_var in H.
unfold make_poly in H.
rewrite ← H in H0.
apply ln_sorted in H0.
apply nodup_cancel_in in H0.
rewrite map_map in H0.
apply in_map_iff in H0 as [n []].
rewrite ← H0.
intro.
rewrite make_mono_ln in H2.
apply remove_ln in H2.
auto.

```

**Qed.**

Eliminating a variable from a polynomial produces a term in polynomial form.

**Lemma** `elim_var_is_poly` :  $\forall x p$ ,  
`is_poly (elim_var x p)`.



Proof.

```
intros.
unfold elim_var.
apply make_poly_is_poly.
```

Qed.

Hint Resolve *elim\_var\_is\_poly*.

The next four lemmas deal with the following scenario: Let  $p$  be a term in polynomial form,  $x$  be a variable that occurs in each monomial of  $p$ , and  $r = \text{elim\_var } x \ p$ .

The term  $r$  is a permutation of removing  $x$  from  $p$ . Another way of looking at this statement is when  $\text{elim\_var}$  repairs the term produced from removing a variable it only sorts that term.

Lemma `elim_var_map_remove_Permutation` :  $\forall p \ x$ ,  
`is_poly p →`  
`( $\forall m, \text{In } m \ p \rightarrow \text{In } x \ m$ ) →`  
`Permutation (elim_var x p) (map (remove var_eq_dec x) p).`

Proof.

```
intros p x H H0. destruct p as [|a p].
- simpl. unfold elim_var, make_poly, MonoSort.sort. auto.
- simpl. unfold elim_var. simpl. unfold make_poly.
  rewrite ← Permutation_MonoSort_l. rewrite unsorted_poly; auto.
  + rewrite ← map_cons. apply NoDup_map_remove; auto.
  + apply poly_cons in H. intros m Hin. destruct Hin.
    × rewrite ← H1. apply remove_is_mono. apply H.
    × apply in_map_iff in H1 as [y []]. rewrite ← H1. apply remove_is_mono.
      destruct H. unfold is_poly in H. destruct H. apply H4. auto.
```

Qed.

The term  $(x * r) \downarrow_P$  is a permutation of the result of removing  $x$  from  $p$ , appending  $x$  to the end of each monomial, and repairing each monomial. The proof relies on the `mulPP_map_app_permutation` lemma from the `poly` library, which has a simpler goal but does much of the heavy lifting.

Lemma `rebuild_map_permutation` :  $\forall p \ x$ ,  
`is_poly p →`  
`( $\forall m, \text{In } m \ p \rightarrow \text{In } x \ m$ ) →`  
`Permutation (mulPP [[x]] (elim_var x p))`  
`(map (fun a ⇒ make_mono (a ++ [x]))`  
`(map (remove var_eq_dec x) p)).`

Proof.

```
intros p x H H0. apply mulPP_map_app_permutation; auto.
- apply (elim_var_not_in_rem x p); auto.
- apply elim_var_map_remove_Permutation; auto.
```

Qed.

The term  $p$  is a permutation of  $(x * r) \downarrow_P$ . Proof of this fact relies on the lengthy `map_app_remove_Permutation` lemma from `poly`.

```
Lemma elim_var_permutation : ∀ p x,
  is_poly p →
  (∀ m, In m p → In x m) →
  Permutation p (mulPP [[x]] (elim_var x p)).
```

Proof.

```
intros p x H H0. pose (rebuild_map_permutation p x H H0).
apply Permutation_sym in p0.
pose (map_app_remove_Permutation p x H H0).
apply (Permutation_trans p1 p0).
```

Qed.

Finally,  $p = (x * r) \downarrow_P$ .

```
Lemma elim_var_mul : ∀ x p,
  is_poly p →
  (∀ m, In m p → In x m) →
  p = mulPP [[x]] (elim_var x p).
```

Proof.

```
intros. apply Permutation_Sorted_eq.
- apply elim_var_permutation; auto.
- unfold is_poly in H. apply Sorted_MonoSorted. apply H.
- pose (mulPP_is_poly [[x]] (elim_var x p)). unfold is_poly in i.
  apply Sorted_MonoSorted. apply i.
```

Qed.

The function `has_var` is an equivalent boolean version of the `In` predicate.

```
Lemma has_var_eq_in : ∀ x m,
  has_var x m = true ↔ In x m.
```

Proof.

```
intros.
unfold has_var.
rewrite existsb_exists.
split; intros.
- destruct H as [x0 []].
  apply Nat.eqb_eq in H0.
  rewrite H0. apply H.
- ∃ x. rewrite Nat.eqb_eq. auto.
```

Qed.

Let a polynomial  $p$  be partitioned by `has_var x` into two sets  $qx$  and  $r$ . Obviously, every monomial in  $qx$  contains  $x$  and no monomial in  $r$  contains  $x$ .

```
Lemma part_var_eq_in : ∀ x p qx r,
  partition (has_var x) p = (qx, r) →
```

```

((∀ m, ln m qx → ln x m) ∧
 (∀ m, ln m r → ¬ ln x m)).

```

Proof.

```

intros.
split; intros.
- apply partfsttrue with (a:=m) in H.
  + apply has_var_eq_in. apply H.
  + apply H0.
- apply partsndfalse with (a:=m) in H.
  + rewrite ← has_var_eq_in. rewrite H. auto.
  + apply H0.

```

Qed.

The function `div_by_var` produces two terms both in polynomial form.

```

Lemma div_is_poly : ∀ x p q r,
  is_poly p →
  div_by_var x p = (q, r) →
  is_poly q ∧ is_poly r.

```

Proof.

```

intros.
unfold div_by_var in H0.
destruct (partition (has_var x) p) eqn:Hpart.
apply (part_is_poly _ _ _ H) in Hpart as Hp.
destruct Hp as [Hpl Hpr].
injection H0. intros Hr Hq.
rewrite Hr in Hpr.
apply part_var_eq_in in Hpart as [Hin Hout].
split.
- rewrite ← Hq; auto.
- apply Hpr.

```

Qed.

As explained earlier, given a polynomial  $p$  decomposed into a variable  $x$ , a quotient  $q$ , and a remainder  $r$ , `div_eq` asserts that  $p = (x * q + r) \downarrow_P$ .

```

Lemma div_eq : ∀ x p q r,
  is_poly p →
  div_by_var x p = (q, r) →
  p = addPP (mulPP [[x]] q) r.

```

Proof.

```

intros x p q r HP HD.
assert (HE := HD).
unfold div_by_var in HE.
destruct ((partition (has_var x) p)) as [qx r0] eqn:Hqr.

```

```

injection HE. intros Hr Hq.
assert (HIH:  $\forall m, \text{In } m \text{ } qx \rightarrow \text{In } x \text{ } m$ ). intros.
apply has_var_eq_in.
apply (partfst_true _ _ _ _ Hqr _ H).
assert (is_poly q  $\wedge$  is_poly r) as [HPq HPr].
apply (div_is_poly _ _ _ HP HD).
assert (is_poly qx  $\wedge$  is_poly r0) as [HPqx HPr0].
apply (part_is_poly _ _ _ HP Hqr).
rewrite  $\leftarrow$  Hq.
rewrite  $\leftarrow$  (elim_var_mul x qx HPqx HIH).
apply (part_add_eq (has_var x) _ _ HP).
rewrite  $\leftarrow$  Hr.
apply Hqr.

```

Qed.

Given a variable  $x$ , `div_by_var` produces two polynomials neither of which contain  $x$ .

Lemma `div_var_not_in_qr` :  $\forall x \text{ } p \text{ } q \text{ } r$ ,  
`div_by_var`  $x \text{ } p = (q, r) \rightarrow$   
 $(\forall m, \text{In } m \text{ } q \rightarrow \neg \text{In } x \text{ } m) \wedge$   
 $(\forall m, \text{In } m \text{ } r \rightarrow \neg \text{In } x \text{ } m))$ .

Proof.

```

intros.
unfold div_by_var in H.
assert ( $\exists qxr, qxr = \text{partition} \text{ (has\_var } x) \text{ } p$ ) as [[qx r0] Hqxr]. eauto.
rewrite  $\leftarrow$  Hqxr in H.
injection H. intros Hr Hq.
split.
- apply (elim_var_not_in_rem _ _ Hq).
- rewrite Hr in Hqxr.
  symmetry in Hqxr.
  intros. intro.
  apply has_var_eq_in in H1.
  apply Bool.negb_false_iff in H1.
  revert H1.
  apply Bool.eq_true_false_abs.
  apply Bool.negb_true_iff.
  revert m H0.
  apply (part_snd_false _ _ _ Hqxr).

```

Qed.

This helper function `build_poly` is used to construct  $p' = ((q + 1) * r) \downarrow_P$  given the two polynomials  $q$  and  $r$  as input.

Definition `build_poly` ( $q \text{ } r : \text{poly}$ ) : `poly` :=

`mulPP (addPP [] q) r.`

The function `build_poly` produces a term in polynomial form.

Lemma `build_poly_is_poly` :  $\forall q\ r,$

`is_poly (build_poly q r).`

Proof.

`unfold build_poly. auto.`

Qed.

Hint Resolve *build\_poly\_is\_poly*.

The second main lemma about variable elimination is below. Given that a term  $p$  has been decomposed into the form  $(x * q + r) \downarrow_P$ , we can define  $p' = ((q + 1) * r) \downarrow_P$ . The lemma `div_build_unif` states that any unifier of  $p \stackrel{?}{\approx}_B 0$  is also a unifier of  $p' \stackrel{?}{\approx}_B 0$ . Much of this proof relies on the axioms of polynomial arithmetic.

Lemma `div_build_unif` :  $\forall x\ p\ q\ r\ s,$

`is_poly p  $\rightarrow$`

`div_by_var x p = (q, r)  $\rightarrow$`

`unifier s p  $\rightarrow$`

`unifier s (build_poly q r).`

Proof.

`unfold build_poly, unifier.`

`intros x p q r s HPp HD [Hps Hsp0].`

`apply (div_eq - - - HPp) in HD as Hp.`

`assert ( $\exists q1, q1 = \text{addPP } []\ q$ ) as [q1 Hq1]. eauto.`

`assert ( $\exists sp, sp = \text{substP } s\ p$ ) as [sp Hsp]. eauto.`

`assert ( $\exists sq1, sq1 = \text{substP } s\ q1$ ) as [sq1 Hsq1]. eauto.`

`rewrite  $\leftarrow$  (mulPP_0 (substP s q1)).`

`rewrite  $\leftarrow$  Hsp0.`

`rewrite Hp, Hq1.`

`rewrite  $\leftarrow$  substP_distr_mulPP; auto.`

`f_equal.`

`apply (div_is_poly x p q r HPp) in HD.`

`destruct HD as [HPq HPr].`

`rewrite mulPP_addPP_1; auto.`

Qed.

Given a polynomial  $p$  and a variable  $x$ , `div_by_var` produces two polynomials  $q$  and  $r$  that have no more variables than  $p$  has. Obviously,  $q$  and  $r$  don't contain  $x$  either.

Lemma `incl_div` :  $\forall x\ p\ q\ r\ xs,$

`is_poly p  $\rightarrow$`

`div_by_var x p = (q, r)  $\rightarrow$`

`incl (vars p) (x :: xs)  $\rightarrow$`

`incl (vars q) xs  $\wedge$  incl (vars r) xs.`

Proof.

```

intros. assert (Hdiv:=H0). unfold div_by_var in H0.
destruct partition as [qx r0] eqn:Hpart. apply partition_Permutation in Hpart.
apply Permutation_incl in Hpart as []. inversion H0. clear H2.
assert (incl (vars q) (vars p)). unfold incl, vars in *. intros a Hin.
  apply nodup_ln. apply nodup_ln in Hin. apply ln_concat_exists in Hin.
  destruct Hin as [m []]. rewrite ← H5 in H2. unfold elim_var in H2.
  apply ln_sorted in H2. apply nodup_cancel_in in H2. rewrite map_map in H2.
  apply in_map_iff in H2. destruct H2 as [mx []]. rewrite ← H2 in H4.
  rewrite make_mono_ln in H4. apply ln_remove in H4. apply ln_concat_exists.
  ∃ mx. split; auto. apply H3. intuition.
assert (incl (vars r) (vars p)). rewrite H6 in H3. unfold incl, vars in *.
  intros a Hin. apply nodup_ln. apply nodup_ln in Hin.
  apply ln_concat_exists in Hin. destruct Hin as [l []].
  apply ln_concat_exists. ∃ l. split; auto. apply H3. intuition.
split.
- rewrite H5. apply incl_tran with (n:=(x::xs)) in H2; auto.
  apply incl_not_in in H2; auto. apply div_var_not_in_qr in Hdiv as [Hq _].
  apply in_mono_in_vars in Hq. auto.
- apply incl_tran with (n:=(x::xs)) in H4; auto.
  apply incl_not_in in H4; auto. apply div_var_not_in_qr in Hdiv as [_ Hr].
  apply in_mono_in_vars in Hr. auto.

```

Qed.

Given a term  $p$  decomposed into the form  $(x * q + r) \downarrow_P$ , then the polynomial  $p' = ((q + 1) * r) \downarrow_P$  has no more variables than  $p$  and does not contain  $x$ .

Lemma div\_vars :  $\forall x \text{ xs } p \text{ q } r,$   
 $\text{is\_poly } p \rightarrow$   
 $\text{incl (vars } p) (x :: \text{xs}) \rightarrow$   
 $\text{div\_by\_var } x \text{ } p = (q, r) \rightarrow$   
 $\text{incl (vars (build\_poly } q \text{ } r)) \text{ xs}.$

Proof.

```

intros x xs p q r H Hincl Hdiv. unfold build_poly.
apply div_var_not_in_qr in Hdiv as Hin. destruct Hin as [Hinq Hinr].
apply in_mono_in_vars in Hinq. apply in_mono_in_vars in Hinr.
apply incl_vars_mulPP. apply (incl_div _ _ _ _ H Hdiv) in Hincl. split.
- apply incl_vars_addPP; auto. apply div_is_poly in Hdiv as []; auto. split.
  + unfold vars. simpl. unfold incl. intros a [].
  + apply Hincl.
- apply Hincl.

```

Qed.

Hint Resolve div\_vars.

### 8.3 Building Substitutions

This section handles how a solution is built from subproblem solutions. Given that term  $p$  decomposed into  $(x * q + r) \downarrow_P$  and  $p' = ((q + 1) * r) \downarrow_P$ , the lemma `reprod_build_subst` states that if some substitution  $\sigma$  is a reproductive unifier of  $p' \stackrel{?}{\approx}_B 0$ , then we can build a substitution  $\sigma'$  which is a reproductive unifier of  $p \stackrel{?}{\approx}_B 0$ . The way  $\sigma'$  is built from  $\sigma$  is defined in `build_subst`. Another replacement is added to  $\sigma$  of the form  $\{x \mapsto (x * (\sigma(q) + 1) + \sigma(r)) \downarrow_P\}$  to construct  $\sigma'$ .

```
Definition build_subst (s : subst) (x : var) (q r : poly) : subst :=
  let q1 := addPP [[]] q in
  let q1s := substP s q1 in
  let rs := substP s r in
  let xs := (x, addPP (mulPP [[]] q1s) rs) in
  xs :: s.
```

The function `build_subst` produces a substitution whose range only contains polynomials.

```
Lemma build_subst_is_poly : ∀ s x q r,
  is_poly_subst s →
  is_poly_subst (build_subst s x q r).
```

Proof.

```
  unfold build_subst.
  unfold is_poly_subst.
  intros.
  destruct H0.
  - inversion H0. auto.
  - apply (H x0). auto.
```

Qed.

Given that term  $p$  decomposed into  $(x * q + r) \downarrow_P$ ,  $p' = ((q + 1) * r) \downarrow_P$ , and  $\sigma$  is a reproductive unifier of  $p' \stackrel{?}{\approx}_B 0$ , then the substitution  $\sigma'$  built from  $\sigma$  unifies  $p \stackrel{?}{\approx}_B 0$ .

```
Lemma build_subst_is_unif : ∀ x p q r s,
  is_poly p →
  div_by_var x p = (q, r) →
  reprod_unif s (build_poly q r) →
  unifier (build_subst s x q r) p.
```

Proof.

```
  unfold reprod_unif, unifier.
  intros x p q r s Hpoly Hdiv [[Hps Hunif] Hreprod].
  assert (is_poly_subst (build_subst s x q r)).
    apply build_subst_is_poly; auto.
  split; auto.
  unfold build_poly in Hunif.
```

```

assert (Hnqr := Hdiv).
apply div_var_not_in_qr in Hnqr.
destruct Hnqr as [Hnq Hnr].
assert (HpolyQR := Hdiv).
apply div_is_poly in HpolyQR as [HpolyQ HpolyR]; auto.
apply div_eq in Hdiv; auto.
rewrite Hdiv.
rewrite substP_distr_addPP; auto.
rewrite substP_distr_mulPP; auto.
unfold build_subst.
rewrite (substP_cons _ _ Hnq).
rewrite (substP_cons _ _ Hnr).
assert (Hsx: (substP
  ((x,
    addPP
      (mulPP [[x]]
        (substP s (addPP [[]] q)))
      (substP s r))) :: s)
  [[x]]) = (addPP
    (mulPP [[x]]
      (substP s (addPP [[]] q)))
    (substP s r))).
unfold substP. simpl.
rewrite ← beq_nat_refl.
rewrite mulPP_1r; auto. rewrite app_nil_r.
rewrite no_make_poly; auto.
rewrite Hsx.
rewrite substP_distr_addPP; auto.
rewrite substP_1.
rewrite mulPP_distr_addPPr; auto.
rewrite mulPP_1r; auto.
rewrite mulPP_distr_addPP; auto.
rewrite mulPP_distr_addPP; auto.
rewrite mulPP_assoc.
rewrite mulPP_p_p; auto.
rewrite addPP_p_p; auto.
rewrite addPP_0; auto.
rewrite ← substP_distr_mulPP; auto.
rewrite ← substP_distr_addPP; auto.
rewrite ← (mulPP_1r r) at 2; auto.
rewrite mulPP_comm; auto.
rewrite (mulPP_comm r [[]]); auto.

```



```

rewrite ← mulPP_distr_addPP; auto.
rewrite addPP_comm; auto.

```

Qed.

Given that term  $p$  decomposed into  $(x * q + r) \downarrow_P$ ,  $p' = ((q + 1) * r) \downarrow_P$ , and  $\sigma$  is a reproductive unifier of  $p' \stackrel{?}{\approx}_B 0$ , then the substitution  $\sigma'$  built from  $\sigma$  is reproductive with regards to unifiers of  $p \stackrel{?}{\approx}_B 0$ .

```

Lemma build_subst_is_reprod : ∀ x p q r s,
  is_poly p →
  div_by_var x p = (q, r) →
  reprod_unif s (build_poly q r) →
  ∀ t, unifier t p →
    subst_comp_eq (build_subst s x q r) t t.

```

Proof.

```

unfold reprod_unif.
intros x p q r s HpolyP Hdiv [[HpsS HunifS] Hsub_comp] t HunifT.
assert (HunifT' := HunifT).
destruct HunifT as [HpsT HunifT].
apply (div_build_unif _ _ _ _ HpolyP Hdiv) in HunifT'.
unfold subst_comp_eq in *.
intros y.
destruct (y =? x) eqn:Hyx.
- unfold build_subst.
  assert (H: (substP (x, addPP (mulPP [[x]] (substP s (addPP [[]] q)))
    (substP s r)) :: s) [[y]] =
    (addPP (mulPP [[x]] (substP s (addPP [[]] q))) (substP s r))).
  unfold substP. simpl.
  rewrite Hyx.
  rewrite mulPP_1r; auto. rewrite app_nil_r.
  rewrite no_make_poly; auto.
  rewrite H.
  rewrite substP_distr_addPP; auto.
  rewrite substP_distr_mulPP; auto.
  pose (div_is_poly _ _ _ _ HpolyP Hdiv); destruct a.
  rewrite substP_distr_addPP; auto.
  rewrite substP_distr_addPP; auto.
  rewrite substP_1.
  assert (Hdiv2 := Hdiv).
  apply div_eq in Hdiv; auto.
  apply div_is_poly in Hdiv2 as [HpolyQ HpolyR]; auto.
  rewrite (subst_comp_eq_poly s t t); auto.
  rewrite (subst_comp_eq_poly s t t); auto.

```

```

rewrite mulPP_comm; auto.
rewrite mulPP_distr_addPP; auto.
rewrite mulPP_comm; auto.
rewrite mulPP_1r; auto.
rewrite (addPP_comm (substP t [[x]]) _); auto.
rewrite addPP_assoc; auto.
rewrite (addPP_comm (substP t [[x]]) _); auto.
rewrite ← addPP_assoc; auto.
rewrite ← substP_distr_mulPP; auto.
rewrite ← substP_distr_addPP; auto.
rewrite mulPP_comm; auto.
rewrite ← Hdiv.
unfold unifier in HunifT.
rewrite HunifT.
rewrite addPP_0; auto.
apply beq_nat_true in Hyx.
rewrite Hyx.
reflexivity.
- unfold build_subst.
  rewrite substP_cons; auto.
  intros.
  inversion H; auto.
  rewrite ← H0.
  simpl. intro.
  destruct H1; auto.
  apply Nat.eqb_eq in H1.
  rewrite Hyx in H1.
  inversion H1.

```

Qed.

Given that term  $p$  decomposed into  $(x * q + r) \downarrow_P$ ,  $p' = ((q + 1) * r) \downarrow_P$ , and a reproductive unifier  $\sigma$  of  $p' \stackrel{?}{\approx}_B 0$ , then the substitution  $\sigma'$  built from  $\sigma$  is a reproductive unifier  $p \stackrel{?}{\approx}_B 0$  based on the previous two lemmas.

Lemma reprod\_build\_subst :  $\forall x p q r s$ ,  
 is\_poly  $p \rightarrow$   
 div\_by\_var  $x p = (q, r) \rightarrow$   
 reprod\_unif  $s (\text{build\_poly } q r) \rightarrow$   
 reprod\_unif  $(\text{build\_subst } s x q r) p$ .

Proof.

```

intros. unfold reprod_unif. split.
- apply build_subst_is_unif; auto.
- apply build_subst_is_reprod; auto.

```

Qed.

## 8.4 Recursive Algorithm

Now we define the actual algorithm of successive variable elimination. Built using five helper functions, the definition is not too difficult to construct or understand. The general idea, as mentioned before, is to remove one variable at a time, creating simpler problems. Once the simplest problem has been reached, to which the solution is already known, every solution to each subproblem can be built from the solution to the successive subproblem. Formally, given the polynomials  $p = (x*q+r) \downarrow_P$  and  $p' = ((q+1)*r) \downarrow_P$ , the solution to  $p \stackrel{?}{\approx}_B 0$  is built from the solution to  $p' \stackrel{?}{\approx}_B 0$ . If  $\sigma$  solves  $p' \stackrel{?}{\approx}_B 0$ , then  $\sigma \cup \{x \mapsto (x * (\sigma(q) + 1) + \sigma(r)) \downarrow_P\}$  solves  $p \stackrel{?}{\approx}_B 0$ .

The function `sve` is the final result, but it is `sveVars` which actually has all of the meat. Due to Coq's rigid type system, every recursive function must be obviously terminating. This means that one of the arguments must decrease with each nested call. It turns out that Coq's type checker is unable to deduce that continually building polynomials from the quotient and remainder of previous ones will eventually result in 0 or 1. So instead we add a fuel argument that explicitly decreases per recursive call. We use the set of variables in the polynomial for this purpose, since each subsequent call has at least one less variable.

```
Fixpoint sveVars (varlist : list var) (p : poly) : option subst :=
  match varlist with
  | [] =>
    match p with
    | [] => Some []
    | _ => None
    end
  | x :: xs =>
    let (q, r) := div_by_var x p in
    let p' := (build_poly q r) in
    match sveVars xs p' with
    | None => None
    | Some s => Some (build_subst s x q r)
    end
  end.
```

The function `sve` simply calls `sveVars` with an initial fuel of `vars p`.

Definition `sve (p : poly) : option subst := sveVars (vars p) p`.

## 8.5 Correctness

Finally, we must show that this algorithm is correct. As discussed in the beginning, the correctness of a unification algorithm is proven for two cases. If the algorithm produces a solution for a problem, then the solution must be most general. If the algorithm produces

no solution, then the problem must be not unifiable. These statements have been formalized in the theorem `sve_correct` with the help of the predicates `mgu` and `unifiable` as defined in the library `poly_unif`. The two cases of the proof are handled separately by the lemmas `sveVars_some` and `sveVars_none`.

If `sveVars` produces a substitution  $\sigma$ , then the range of  $\sigma$  only contains polynomials.

Lemma `sveVars_poly_subst` :  $\forall xs\ p,$   
 $\text{incl}(\text{vars } p)\ xs \rightarrow$   
 $\text{is\_poly } p \rightarrow$   
 $\forall s, \text{sveVars } xs\ p = \text{Some } s \rightarrow$   
 $\text{is\_poly\_subst } s.$

Proof.

```
induction xs as [|x xs]; intros.
- simpl in H1. destruct p; inversion H1. unfold is_poly_subst.
  intros x p [].
- intros.
  assert ( $\exists qr, \text{div\_by\_var } x\ p = qr$ ) as [|q r] Hqr. eauto.
  simpl in H1.
  rewrite Hqr in H1.
  destruct (sveVars xs (build_poly q r)) eqn:Hs0; inversion H1.
  apply IHxs in Hs0; eauto.
  apply build_subst_is_poly; auto.
```

Qed.

If `sveVars` produces a substitution  $\sigma$  for the polynomial  $p$ , then  $\sigma$  is a most general unifier of  $p \stackrel{?}{\approx}_B 0$ .

Lemma `sveVars_some` :  $\forall (xs : \text{list var}) (p : \text{poly}),$   
 $\text{NoDup } xs \rightarrow$   
 $\text{incl}(\text{vars } p)\ xs \rightarrow$   
 $\text{is\_poly } p \rightarrow$   
 $\forall s, \text{sveVars } xs\ p = \text{Some } s \rightarrow$   
 $\text{mgu } s\ p.$

Proof.

```
intros xs p Hdup H H0 s H1.
apply reprod_is_mgu.
revert xs p Hdup H H0 s H1.
induction xs as [|x xs].
- intros. simpl in H1. destruct p; inversion H1.
  apply empty_reprod_unif.
- intros.
  assert ( $\exists qr, \text{div\_by\_var } x\ p = qr$ ) as [|q r] Hqr. eauto.
  simpl in H1.
  rewrite Hqr in H1.
```

```

destruct (sveVars xs (build_poly q r)) eqn:Hs0; inversion H1.
apply NoDup_cons_iff in Hdup as Hnin. destruct Hnin as [Hnin Hdup0].
apply sveVars_poly_subst in Hs0 as HpsS0; eauto.
apply IHxs in Hs0; eauto.
apply reprod_build_subst; auto.

```

Qed.

If `sveVars` does not produce a substitution for the polynomial  $p$ , then the problem  $p \stackrel{?}{\approx}_B 0$  is not unifiable.

Lemma `sveVars_none` :  $\forall (xs : \text{list var}) (p : \text{poly})$ ,

```

NoDup xs →
incl (vars p) xs →
is_poly p →
sveVars xs p = None →
¬ unifiable p.

```

Proof.

```

induction xs as [|x xs].
- intros p Hdup H H0 H1. simpl in H1. destruct p; inversion H1. intro.
  unfold unifiable in H2. destruct H2. unfold unifier in H2.
  apply incl_nil in H. apply no_vars_is_ground in H; auto.
  destruct H; inversion H.
  rewrite H4 in H2.
  rewrite H5 in H2.
  rewrite substP_1 in H2.
  inversion H2. inversion H6.
- intros p Hdup H H0 H1.
  assert (∃ qr, div_by_var x p = qr) as [[q r] Hqr]. eauto.
  simpl in H1.
  rewrite Hqr in H1.
  destruct (sveVars xs (build_poly q r)) eqn:Hs0; inversion H1.
  apply NoDup_cons_iff in Hdup as Hnin. destruct Hnin as [Hnin Hdup0].
  apply IHxs in Hs0; eauto.
  unfold not, unifiable in *.
  intros.
  apply Hs0.
  destruct H2 as [s Hu].
  ∃ s.
  apply (div_build_unif x p); auto.

```

Qed.

Hint Resolve `NoDup_vars_incl_refl`.

If `sveVars` produces a substitution  $\sigma$  for the polynomial  $p$ , then  $\sigma$  is a most general unifier of  $p \stackrel{?}{\approx}_B 0$ . Otherwise,  $p \stackrel{?}{\approx}_B 0$  is not unifiable.

```

Lemma sveVars_correct :  $\forall (p : \text{poly}),$ 
  is_poly  $p \rightarrow$ 
  match sveVars (vars  $p$ )  $p$  with
  | Some  $s \Rightarrow$  mgu  $s p$ 
  | None  $\Rightarrow \neg$  unifiable  $p$ 
  end.

```

Proof.

```

  intros.
  destruct (sveVars (vars  $p$ )  $p$ ) eqn: Hsve.
  - apply (sveVars_some (vars  $p$ )); auto.
  - apply (sveVars_none (vars  $p$ )); auto.

```

Qed.

If sve produces a substitution  $\sigma$  for the polynomial  $p$ , then  $\sigma$  is a most general unifier of  $p \stackrel{?}{\approx}_B 0$ . Otherwise,  $p \stackrel{?}{\approx}_B 0$  is not unifiable.

```

Theorem sve_correct :  $\forall (p : \text{poly}),$ 
  is_poly  $p \rightarrow$ 
  match sve  $p$  with
  | Some  $s \Rightarrow$  mgu  $s p$ 
  | None  $\Rightarrow \neg$  unifiable  $p$ 
  end.

```

Proof.

```

  intros.
  apply sveVars_correct.
  auto.

```

Qed.

# Bibliography

- [1] Franz Baader and Tobias Nipkow. *Term Rewriting and All That*. Cambridge University Press, New York, NY, USA, 1998.
- [2] Franz Baader and Wayne Snyder. Unification theory. *Handbook of automated reasoning*, 1:445–532, 2001.
- [3] Adam Chlipala. An introduction to programming and proving with dependent types in coq. *Journal of Formalized Reasoning*, 3(2):1–93, 2010.
- [4] Luis Damas and Robin Milner. Principal type-schemes for functional programs. In *POPL*, volume 82, pages 207–212, 1982.