

# LOGIC FOR COMPUTER SCIENCE

---

Steve Reeves  
and  
Mike Clarke

*Department of Computer Science  
Queen Mary and Westfield College  
University of London  
U.K.*

*Department of Computer Science  
University of Waikato  
New Zealand*

©1990 and 2003

The programs in this book have been included for their instructional value. They have been tested with care but are not guaranteed for any particular purpose. The authors and publishers do not offer any warranties or representations, nor do they accept any liabilities with respect to the programs.

The contents of this book were first published in 1990 by Addison-Wesley Publishers Ltd.

# Preface to 1990 edition

## Aims

The aim of this book is to give students of computer science a working knowledge of the relevant parts of logic. It is not intended to be a review of applications of logic in computer science, neither is it primarily intended to be a first course in logic for students of mathematics or philosophy, although we believe that much of the material will be increasingly relevant to both of these groups as computational ideas pervade their syllabuses.

Most controversial perhaps will be our decision to include modal and intuitionistic logic in an introductory text, the inevitable cost being a rather more summary treatment of some aspects of classical predicate logic. We believe, however, that a glance at the wide variety of ways in which logic is used in computer science fully justifies this approach. Certainly classical predicate logic is the basic tool of sequential program verification, but modal and temporal logics are increasingly being used for distributed and concurrent systems and intuitionistic logic provides a basis for expressing specifications and deriving programs. Horn clause logic and resolution underlie the very widespread use of logic programming, while algorithms for automated theorem proving have long been of interest to computer scientists for both their intrinsic interest and the applications in artificial intelligence.

One major (and deliberate) omission is the standard development of the logical basis of set theory and arithmetic. These theories are so well covered in a number of excellent and widely available texts (many of which are referenced in the text or are among the sources we acknowledge at the end of this preface) that we preferred to use the space for less well-exposed topics. Of course, the need to formalize arithmetic and set theory has led to major developments in logic and computer science and we have tried to give the historical perspective, while referring readers elsewhere for the detail.

Different disciplines have different motivations for studying logic and correspondingly different conventions of notation and rigour. To keep the within reasonable bounds we have decided to omit some of the lengthier explanations and proofs found in traditional logic texts in favour of introducing topics considered more ‘advanced’, that are central to modern computer science. In many cases, where proof methods have been specified by non-deterministic sets of rules, we have been more precise than usual by giving algorithms and programs; in other cases we have relied on the background of our students to keep routine formal development to a minimum.

Another major departure is that we present many of the definitions and algorithms as computer programs in, not just one but, two programming languages. We have chosen Prolog and SML, partly because they are both highly succinct and suitable languages for the procedures we want to express, but also because they have their roots, respectively in logic and the  $\lambda$ -calculus, two of the most important theoretical developments that underlie computer science and the theory of computability. Either of the languages is sufficient, but a student who carefully studies the programs in both languages will learn a lot about the theory and technique of declarative programming as well as about the logical definitions and algorithms that the programs express.

In Appendix A we give a brief introduction to the philosophy and facilities of both languages, but this is aimed to some extent at teachers and students with a considerable background in computer science. The less sophisticated will need access to one or other of the introductory texts that we recommend. That being said, the programs are designed to be readable and should relay some message even to non-programmers, perhaps helping them to realize that much of logic is inseparable from the notion of an effective algorithm, and even encourage them to start programming.

Overall, our aim has been to show how computer science and logic are closely linked. We hope that students will see that what they might have considered a dry subject without obvious applications is being put to good use and vigorously developed by computer scientists.

## Readership

Much of the material has been tested in a course given to first-year undergraduate students in computer science who, at that stage, have had an introductory course in discrete mathematics and a first programming course that emphasizes recursion, inductive proof and scope of definition. So they already have a fair grasp at a semiformal level of notions such as set, function, relation, formal

language, free and bounds variable and mathematical induction, and we believe that such a background will, if not already standard, soon become so for first-year students of computer science. The students, we are glad to say, bear out our conviction that an introductory logic course can successfully go beyond what is usually considered to be the appropriate level. They are able to actually do proofs using the methods we teach and are surprised and challenged by the idea of several logics. We feel that this is because computer science, properly taught, makes the student of logic easier, and vice versa. The activity of constructing and reasoning about programs is not all that different from the activity of constructing and reasoning about proofs.

## Acknowledgements

Our colleagues, also, have made a big contribution to the development of the course, and subsequently the book. We would single out for special mention, in no particular order, Peter Burton, Wilfrid Hodges, Doug Goldson, Peter Landin, Sarah Lloyd-Jones, Mike Hopkins, Keith Clarke, Richard Bornat, Steve Sommerville, Dave Saunders, Mel Slater, John Bell and Mark Christian, and well as those further away—Alan Bundy, Dov Gabbay—who have influenced our views on the more advanced topics.

Finally, it will be obvious that we have been strongly influenced, and greatly helped, by many other texts whose development for the subject we have studied, and in many instances borrowed. These have included Hodges (1977), *Logic*, Hamilton (1978), *Logic for Mathematicians*, Boolos and Jeffrey (1980), *Computability and Logic*, Scott et al. (1981), *Foundations of Logic Programming*, and Martin-Löf (1985), *Constructive Mathematics and Computer Programming*.

*Steve Reeves*  
*Mike Clarke*

QMW, University of London  
November, 1989

## Preface to 2003 edition

Since 1990 much has changed in our subject and many further chapters could be added to the book Mike and I wrote in 1989-1990. However, I think it is good to be able to say that all of the things we wrote about then are still relevant and being used in many areas of computer science today, which is something not many authors

of computer science texts looking back over 13 years from 2003 could say—we clearly chose well.

However, there are two reasons why the book has not changed. One is that no company, today, thinks it worth publishing (well, not Addison-Wesley anyhow—now part of Pearson). To some extent you can't blame them—computer science has become more and more a ticket to a good job rather than an intellectual undertaking (that is likely to lead to a good job) taught and studied by people who are interested in it. (many of our current students are not interested in the subject, or are not very good at it, so I hate to think what their working lives, in terms of self-fulfillment, are going to be like). The publishers look around at all the courses which teach short-term skills rather than lasting knowledge and see that logic has little place, and see that a book on logic for computer science does not represent an opportunity to make monetary profits.

Why, then, has the book re-appeared? Because of repeated demands from around the world (but mainly from the USA) for copies of it! There are no longer any (new) copies for sale, so given the demand something had to be done. Hence this ersatz edition. It's not as high quality as AW's was, but then I'm not a type-setter, printer, bookbinder, designer etc. It was produced from the original Word files we gave to AW (from which, after much re-typing and re-design, they produced the 1990 edition). Those files were written using a couple of Macintosh SEs. The files have traveled around the world with me, moving from computer to computer until the 2003 version has been produced on an eMac and a Titanium Powerbook. There is one constant in Word—it still crashes reliably about once a day!

The other reason the book has not been re-written is that Mike Clarke died in 1994, so the version before you stands as a memorial to him—he was a friend and a mentor, and you can't be more than that.

*Steve Reeves*

University of Waikato  
January 2003

---

# CONTENTS

---

<b>Preface to 1990 edition</b>	<b>iii</b>
<b>Preface to 2003 edition</b>	<b>v</b>
<b>CONTENTS</b>	<b>vii</b>
<b>Introduction</b>	<b>1</b>
<b>1.1. Aims and Objectives</b>	<b>1</b>
<b>1.2. Background history</b>	<b>2</b>
<b>1.3. Background terminology</b>	<b>2</b>
<b>1.4. Propositions, Beliefs and Declarative Sentences</b>	<b>5</b>
<b>1.5. Contradictions</b>	<b>6</b>
<b>1.6. Formalization</b>	<b>7</b>

<b>Formalizing the Language</b>	<b>9</b>
2.1 Informal Propositional Calculus	9
2.2 Arguments	20
2.3 Functional Completeness	27
2.4 Consistency, Inconsistency, Entailment.	28
2.5 Formal Propositional Calculus	33
2.6 Soundness and Completeness for propositional calculus	42
<b>Extending the language</b>	<b>49</b>
3.1 Informal predicate calculus	49
3.2 FDS for predicate calculus	60
3.3 Historical discussion	65
3.4 Models and Theories	68
<b>Semantic Tableaux</b>	<b>71</b>
4.1 Introduction	71
4.2 Semantic Tableaux for Propositional Calculus	72
4.3 Soundness and Completeness for Propositional Calculus	80
4.4 Semantic Tableaux for Predicate Calculus	89
4.5 Soundness and Completeness for Predicate Calculus	92
<b>Natural Deduction</b>	<b>99</b>
5.1 Rules and Proofs	99
5.2 The Sequent Calculus	110
5.3 Generalizing the logic	117
5.4 What is Logic Ultimately?	121

<b>Some Extended Examples</b>	<b>125</b>
6.1. Introduction	125
6.2. Theory examples	125
6.3. Gödel and the limits of formalization	144
<b>Logic Programming</b>	<b>147</b>
7.1. Introduction	147
7.2. Substitution and Unification	153
7.3. Resolution	159
7.4. Least Herbrand models and a declarative semantics for definite clause programs	162
<b>Non-Standard Logics</b>	<b>167</b>
8.1. Introduction	167
8.2. Necessity and Possibility	167
8.3. Possible world semantics	169
8.4. Frames, interpretations and models	170
8.5. Truth-functionality and modal logic	174
8.6. Systems of modal logic	175
8.7. A tableau system for S4	175
8.8. One use for modal logic in programming	184
8.9. Tableaux for Intuitionistic Logic	186
<b>Further Study</b>	<b>193</b>
9.1. Introduction	193
9.2. Connection method	193
9.3. LCF	197
9.4. Temporal and dynamic logics	204
9.5. Intuitionistic logic	210

<b>Introductions to Standard ML and Prolog</b>	<b>221</b>
<b>A.1. Introduction</b>	<b>221</b>
<b>A.2. Standard ML</b>	<b>221</b>
<b>A.3. Prolog</b>	<b>239</b>
<b>Programs in Standard ML and Prolog</b>	<b>255</b>
<b>B.1. Programs in SML</b>	<b>255</b>
<b>B.2. Programs in Prolog</b>	<b>279</b>
<b>Solutions to Selected Exercises</b>	<b>281</b>
<b>REFERENCES</b>	<b>293</b>
<b>INDEX</b>	<b>297</b>

# CHAPTER ONE

---

## Introduction

### 1.1. Aims and Objectives

This book will differ from most others with similar titles because we aim to give you not one or two ways of looking at Logic, but many. The forms of reasoning that are fundamental to Computer Science are not necessarily those most familiar from a study of Mathematics and this gives us the opportunity to develop the subject along two dimensions, looking not only at different methods for implementing one particular mode of reasoning, but also at different ways of formalizing the process of reasoning itself.

There are many reasons why a computer scientist should need to study logic. Not only has it historically formed the roots of computer science, both Church's and Turing's work being motivated by the decision problem for first-order logic, but nowadays we are finding conversely that computer science is generating an explosion of interest in logic, with the desire to automate reasoning and the necessity to prove programs correct.

Basically, logic is about formalizing language and reasoning, and computer science addresses similar problems with the extra task, having formalized them, of *expressing* those formalizations, in the technical sense of producing mechanisms which follow the rules that they lay down. This, indeed, has led to the recent use of computer science for investigating logics in an experimental way, exploring some of them much more thoroughly than was possible when the 'computer' was a person rather than a machine.

What we hope then to show is that computer science has grown out of logic. It is helping to suggest new ideas for logical analysis and these logical ideas are, in turn, allowing computer science to develop further. The two subjects have each contributed to the growth of the other and still are, and in combination they form an exciting and rapidly growing field of study.

## 1.2. Background history

In the middle of the last century Boole laid down what we now see as the mathematical basis for computer hardware and propositional logic, but the logics that we are going to look at really started towards the end of the century with the work of Gottlob Frege, a German mathematician working in relative obscurity. Frege aimed to derive all of mathematics from logical principles, in other words pure reason, together with some self-evident truths about sets. (Such as 'sets are identical if they have the same members' or 'every property determines a set'). In doing this he introduced new notation and language which forms the basis of the work that we shall be covering. Until Boole and Frege, logic had not fundamentally changed since Aristotle!

Frege's huge work was (terminally) criticized at its foundations by Bertrand Russell who found a basic flaw in it stemming from one of the 'self-evident' truths upon which the whole enterprise was based. However, Russell developed the work further by suggesting ways of repairing the damage. He also introduced Frege's work to the English-speaking mathematicians since not many of them, at that time, read German. Russell, who did read German, saw that the work was important and so publicized it.

## 1.3. Background terminology

We are going to be doing what is usually known as 'mathematical Logic' or 'symbolic Logic' or 'formal Logic'. That is, we are going to use ordinary, but careful, mathematical methods to study a branch of mathematics called Logic. Before we start to look at what Logic actually is we shall try to make the context in which we are working a bit clearer. To make the discussion concrete we can think in terms of the typical introductory programming course that you may have followed.

Such a programming course not only teaches you how to use the constructs of the language to produce the effects that you want when the program is executed, but it also teaches you the distinction between the language that you write programs in and the meaning of the statements of that language in terms of the effect that they have when executed by a computer. If the course was a good one, it will also have taught

you how to reason about programs - perhaps to show that two apparently different programs are equivalent. Logic is the study of formal (i.e. symbolic) systems of reasoning and of methods of attaching meaning to them. So there are strong parallels between formal computer science and logic. Both involve the study of formal systems and ways of giving them meaning (semantics). However in Logic you study a wider variety of formal systems than you do in Computer Science, so wide and so fundamental that Logic is used not only as one of the mathematical tools for studying programming, but also as a foundation for mathematics itself. This ought to set the alarm bells ringing, because we have already said that we were going to use mathematics to study Logic, so there is an apparent circularity here. It is certainly the case that circular or "self-referential" discussion like this is very easy to get wrong but the notion of self-reference is a central one in Computer Science and, in fact, is exploited rather than avoided.

In Logic we deal with the issue by putting the logic we are going to study in one compartment and the logic we are going to do the studying with in another. These compartments are realized by using different languages. The logic that is the object of our study will be expressed in one particular language that we call the object language. Our study of this logic and language is carried out in another language which we call the observer's language. (You might also see the word metalanguage for this.)

The idea should already be familiar to you from studying foreign or ancient languages. In this case Latin, for example, might be the object language and your native language, in which you might have discussed the details of Latin syntax or the meaning of particular Latin sentences, is the observer's language. In mathematics, the symbolism of calculus, set theory, graph theory and so on, provide the object language and again your native language, augmented perhaps with some specialised mathematical vocabulary, is used as the observer's language. In programming, the object language is a 'programming' language such as Pascal, Lisp or Miranda and the observer's language is again your native language augmented with the appropriate mathematical and operational notions.

### **Example 1.1**

Consider the statement

```
times 0 do print* od=donothing
```

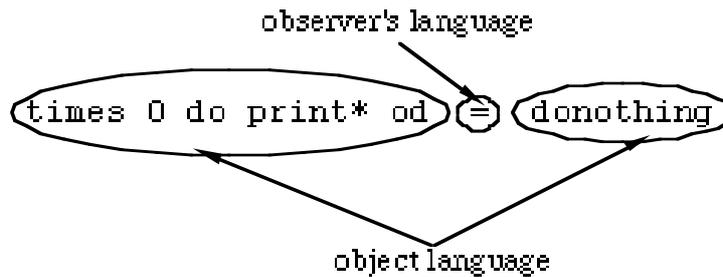


Figure 1

This, in fact, is a statement in the observer's language about the equivalence of two statements in one of our local programming languages. Although you may have guessed correctly, you have no means of saying with certainty which are the symbols of the object language and which are symbols of the observers language until the object language has been defined for you. In fact, the distinction is as shown in Figure 1.

**Exercise 1.1** Now you are invited to use your linguistic, mathematical and programming experience to do a similar analysis of the following statements into observer and object languages.

- (a) The sentence 'They feeds the cat' is ungrammatical in English.
- (b) The French translation of the English phrase 'Thank you very much' is 'Merci beaucoup'
- (c) The equation  $E=mc^2$  holds in Special Relativity.
- (d) There is no real value of  $x$  that satisfies  $x^2 - 2x + 2 = 0$
- (e) There is no real value of  $foo$  that satisfies  $x^2 - 2x + 2 = 0$
- (f) If  $x^2 - 2x + 1 = 0$  then  $x = 1$
- (g) If  $x^2 - 2x + 1 = 0$  then  $x$  must be 1
- (h) If  $x^2 - 2x + 1 = 0$  then  $x$  must be unity
- (i) "E=mc<sup>2</sup> holds in Special Relativity" cannot be proved.
- (j) The statements  $x:=x+1$ ;  $x:=x+1$ ; are equivalent to  $x:=x+2$ ; in Pascal.
- (k) "**if...then...else**" is a statement form in Pascal

You probably found that one or two of these exercises were borderline cases and caused you to point out, more or less forcibly, that it would be a lot easier if you

had an actual definition of the object language in front of you. This is the first thing we do when we embark on the development of propositional logic in Chapter 2.

## 1.4. Propositions, Beliefs and Declarative Sentences

The basic items that logic deals with are propositions. Philosophers have given a variety of answers to the question "What is a proposition?" but since we are dealing with the mathematics rather than the philosophy of logic it doesn't really matter for our purposes. One answer, however, is that a proposition is what is common to a set of declarative sentences in your native language that all say the same thing. Philosophers then have to argue about what "all say the same thing" means, but fortunately we don't.

Propositions communicate judgements or beliefs and since beliefs are themselves manifested as states of mind (it's hard to see what else they could be) the act of believing or the stating of propositions allows, with practice, the representation in your mind of complex objects both physical and abstract. We seem to be a long way from the limits of the human race, as a whole, in representing things mentally, and reasoning with them, and we are in the Stone Age when it comes to building ourselves tools for doing so. This is why the study of formal methods of manipulating propositions, Logic in other words, is so important.

Since Computer Science is one discipline in which the objects that we want to reason about are extraordinarily complex, and often abstract and purely formal, the need for Logic here is especially clear.

Of course, the fact that beliefs are states of mind means that we cannot directly manipulate them, neither can we manipulate propositions, since they are expressions of those states of mind. What we do is to manipulate sentences in some language which *map on to* propositions and beliefs.

The language with which we, the authors, are most familiar for this task is the natural language called "English". We use it to express our beliefs as propositions, for the purpose of transferring them to each other, testing them and so on. When one of us says to the other "I believe that Moto Guzzi manufacture the best motorcycles in the world" he conveys part of his current state of mind, in particular a part that expresses a certain relation between himself and motorcycles.

In general, then, we use English to express our beliefs. However, we need to refine this statement since English is rather complicated and not all of English is used for this purpose. There are only certain sentences in English that convey beliefs, i.e. express propositions, and these are the declarative sentences.

**Definition 1.1**

A declarative sentence is a grammatically correct English sentence that can be put in place of '...' in the sentence "Is it true that ...?" with the effect that the resulting sentence is a grammatically correct English question.

One might expect further restrictions here, though. The definition has a rather syntactic bias to it, and English is notoriously expressive. We cannot go into it fully here, but a good introductory discussion can be found in Hodges (1977).

**Exercise 1.2** Decide whether the following are declarative sentences or not:

- (a) What is your name?
- (b) Close the door!
- (c) Grass is green.
- (d) Grass is red.
- (e) It is wrong.
- (f) I am honest.
- (g) You must not cheat.
- (h) It is false that grass is red.

## 1.5. Contradictions

By this stage you should have some feel for how beliefs are manipulated in natural language. But how are beliefs actually useful? What is their reason for existing? Basically beliefs give a description of the world as it is or might be. For example, if I have a system of beliefs about the laws of mechanics (a description of part of the world) I can generate beliefs about the Solar System without having to actually go out there and make measurements. If I have a system of beliefs about my friends, I can predict their behaviour in certain situations without the possible embarrassment of engineering and being in those situations. Again, I can have a set of beliefs about numbers and reason about the result of the sum  $2+2$ , without actually creating two different sets of cardinality 2, amalgamating and counting them.

So systems of belief allow decisions to be made, facts to be conjectured; it seems that they can do anything. However, there is one limitation. You cannot simultaneously hold two different beliefs which you know contradict one another. Since we have said that Logic is important because it allows us to manipulate beliefs, it follows that a fundamental task of Logic is to be able to decide whether or not a set of beliefs is contradictory. In simple cases, as we shall see, Logic can do this in a

mechanical way. But there are inherent limitations and it may be that, ultimately, even the most ingeniously programmed machine cannot do as well at manipulating propositions as the most careful person. This belief has not yet been contradicted!

## 1.6. Formalization

Formalization is the process of constructing an object language together with rules for manipulating sentences in the language. One aim in doing this is to promote clarity of thought and eliminate mistakes.

Another equally important issue, one that gives rise to the term "formalization" itself, is that we provide a means of manipulating objects of interest without having to understand what we are doing. This sounds at first like a retrograde step, but to give an example: arithmetic arose out of the formalization of counting. So we now have a set of rules which we can follow to add together numbers correctly without needing to understand what numbers are or what adding up is. Of course, we can always go back to the original physical act and see that adding up comes from the process of counting up to a particular number  $n$  with reference to one group of objects and then starting from  $n+1$  in counting a second group. The answer in this case is what we would formally call the sum of the numbers concretely represented by each group.

So the power of formalization is that, once formalized, an area of interest can be worked in without understanding. If the agent following the rules is a human being this might be a mixed blessing, since understanding at the intellectual level is a strong motivation for getting things done. But, if you want to write a computer program to reason, then formalization is essential. Equally essential, if the results are to be useful, is to be able to prove that, as long as the rules are correctly applied, the results will be correct.

For instance, a programmer employed in the financial sector may have, in the form of a set of beliefs that are related in complicated ways, an idea of how the Stock Exchange works. It is the abstract structure of these relationships which models the concrete structure of the Stock Exchange and forms a model of how the Stock Exchange works. The programmer will then formalize this model when writing a computer system to automatically deal in the Stock Exchange, say. Now, if you look at the program, it is clear that the names of the objects in the program do not matter. Nor does the language in which they are written. What matters is that the relationships in the real thing are faithfully and fully represented in the program. This

is the sense of formalization that we are concerned with: the program should model the form of the real thing in interaction between its parts.

In the next chapter we make a start by looking at a simple form of declarative sentence and we show how it can be used to formalize some basic instances of reasoning.

## Summary

- Mathematical logic began towards the end of the last century when Frege developed what is now the predicate calculus.
- Mathematical logic involves applying standard mathematical methods to the study of systems that themselves can be used to formalize mathematics. The apparent circularity is overcome by distinguishing between the *object* language, in which the formal system is expressed, and the *observer's* language in which properties of the formal system are expressed and reasoned about.
- The basic items that logic deals with are *propositions*. Propositions are used to express beliefs. In natural language they are represented by *declarative sentences*.
- The notion of belief is a very general one; nevertheless there are some restrictions on the way beliefs can be manipulated in mental reasoning. For example you *cannot simultaneously hold contradictory beliefs* (at least without being aware that something is wrong).
- The importance of formalization is that once a particular area of mathematics or computer science has been formalized, reasoning in it can be carried out purely by symbol manipulation, without reference to meaning or understanding, and mathematical properties of the reasoning process can be clearly stated and proved.

# CHAPTER TWO

---

## Formalizing the Language

### 2.1 Informal Propositional Calculus

#### 2.1.1 The language

We will use  $\wedge$ ,  $\vee$ ,  $\neg$  and  $\rightarrow$  as our standard symbols for the connectives. These symbols form part of the alphabet of the language of propositional logic. Other elements of the alphabet are the parentheses,  $)$  and  $($ , and a set of propositional variables, for instance  $\{p, q, r, s\}$ . We can now give a proper definition of the conditions that a sequence (string) of symbols must satisfy to be a sentence of propositional logic.

#### Definition 2.1

If  $P$  is a set of propositional variables then:

- 1) a propositional variable from the set  $P$  is a sentence,
- 2) if  $S$  and  $T$  are sentences then so are  $(\neg S)$ ,  $(S \wedge T)$ ,  $(S \vee T)$ ,  $(S \rightarrow T)$  and  $(S \leftrightarrow T)$ ,
- 3) no other sequences are sentences.

We can, for example, use the definition to show that  $p$ ,  $(p \wedge q)$ ,  $(p \wedge (\neg q))$  and  $((p \wedge q) \wedge r)$  are sentences, because  $p$  is a sentence by clause 1, since  $p$  is a propositional variable,  $(p \wedge q)$  is a sentence because  $p$  and  $q$  are sentences by clause 1 and hence, by the fourth condition in clause 2, the whole string of symbols is a sentence. The other cases follow similarly.

In practice, to keep the number of brackets to a minimum, there is a convention that  $\neg$  takes precedence over  $\vee$ , as it is sometimes put, "binds more tightly" than  $\vee$  and  $\wedge$ , which in turn bind more tightly than  $\rightarrow$  and  $\leftrightarrow$ . Also, outside parentheses can often be omitted without ambiguity. So  $(p \vee (\neg q))$  would usually be written as  $p \vee \neg q$  and  $((p \vee q) \wedge r)$  as  $p \vee q \wedge r$ .

Furthermore, we can see that  $\neg p$ , for instance, is not a sentence since, although we have that  $p$  is a sentence (clause 1), none of the other clauses makes  $\neg p$  a sentence so by clause 3 it is not a sentence.

The set of symbol sequences (strings) defined in this way is called the set of (well-formed) sentences or language of propositional logic. The form of the definition is important not only because it is the first of many that we shall be seeing, but also because it determines the property of "being a sentence of propositional logic" as being decidable. That is, the question "is this sequence of symbols, formed from the alphabet of propositional logic, a sentence of propositional logic?" can always be answered correctly either "yes" or "no". Later on we shall see some similarly structured questions which cannot be answered in all cases. These will be called undecidable questions.

There are two ways to be sure that this (or any) definition gives rise to a decidable property; you can either construct a proof that it is so or you can construct a program which always gives the correct answer to the question "is this string a sentence?". By "always gives the correct answer" here we mean that, whenever the question is asked, the program answers it correctly before it terminates - and it always terminates. Clearly, to implement the definition as a program involves much more work than only proving that the definition gives a decidable property, but for the extra work we gain a program that can always answer the question correctly without further work on our part.

With a suitably expressive programming language we can use the above definition, of sentences based on the set  $P$  of propositional variables, to give us almost directly a programmed decision procedure. First, though, we have to represent the forms of sentence defined by the grammar in the language that we will use.

In this book we use two programming languages, SML and Prolog, that are becoming widely used in computer science for implementing algebraic and logically based calculations. These languages are also theoretically interesting in their own right. SML is based on the  $\lambda$ -calculus and type inference, while Prolog is based on the notion of logic programming (see Chapter 7). An introduction to each of the languages is given in Appendix A. Using the datatype feature of SML makes it easy

to define all the possible forms of sentence. For instance, just as the definition above uses the phrase ‘...if  $S$  is a sentence then so are  $(\neg S)$  and ...’ then we can use the phrase ‘... $S = \text{Not of } S \mid \dots$ ’ in SML to represent the same idea. Notice that instead of using the symbol ‘ $\neg$ ’ we have used the symbol ‘Not’; this is done so that later on when we write programs to manipulate these sentences we do not get too many, possibly confusing, sequences of symbols, that is we prefer the words. So using datatypes the type `SENT`, which represents sentences of the language, can be defined in SML as:

```
Datatype SENT = Prop of string
                | Not of SENT
                | And of (SENT * SENT)
                | Or of (SENT * SENT)
                | Imp of (SENT * SENT)
                | Eq of (SENT * SENT);
```

This means that a sentence, that is a value of type `SENT`, is either of the form `Prop ("p")` or `Not (S)` where `S` is a value of type `SENT`, or `And (S,T)` where `S` and `T` are both values of type `SENT`, and so on. The way in which this declaration represents sentences as defined above should now be clear.

Of course, writing down sentences using the form described in this declaration is not as convenient for us as the form in the original definition since there is more to write. But we must remember that the language SML is fixed (and completely formal, of course) whereas we, as humans, have a certain amount of flexibility when it comes to adapting ourselves to other notations. So, since the programming language will not adapt, we have to.

However, it is usual to mitigate the somewhat verbose programming representation of the components of a language when, say, non-specialists have to use it by putting a piece of software called a parser between the user and the program being used. The task of the parser is to take a string of symbols from the user and, for those that are suitable, to transform them into the required form from the programmer’s point of view. Thus, we would, in any suite of programs to do things as yet unspecified with logical statement, expect to have to write a program which carried out this task. It turns out that to do this task properly is not a trivial thing. However, parsers are such important and ubiquitous pieces of software that a lot of effort has gone into making their design fairly routine. In the SML programs that we

write in the rest of the text we will be using just the internal form of the language, but in Appendix B we have given the text of a parser so that the interested reader may see what is required to implement such a program. It is not, however, necessary to understand how the parser works, or even to acknowledge its existence, in order to understand what follows, so the uninterested reader need not worry. (In fact, by defining the constructor symbols to be infix, we can circumvent the need for a parser somewhat, which is just what we do below in Prolog, but since this was a good place to bring to the reader's notice the idea of parsing we decided on the current presentation.)

Having represented the sentences we can now go on to describe how to do computations with them. First, consider the problem of deciding whether a string is a sentence based on a set of the definition above but given in SML:

```
fun decide P (Prop v) = v memberof P
| decide P (Not(l)) = decide P l
| decide P (And(l,r)) = (decide P l) andalso (decide P r)
| decide P (Or(l,r)) = (decide P l) andalso Pr)
| decide P (Imp(l,r)) = (decide P l) andalso (decide P r)
| decide P (Eq(l,r)) = (decide P l) andalso (decide P r);
```

We can see that the program always terminates since it either returns a value (true or false) immediately or, if a recursive call is made, the arguments of the recursive call are strictly smaller, as pieces of text, than the preceding number of recursions, so the program will always terminate. The correctness of its answer follows from the closeness of the program to the original definition. We conclude, therefore, that the property of being a sentence of propositional logic is decidable.

### 2.1.2 The Prolog version of 'decide' and the enumeration of sentences

In Prolog (and again see Appendix A for details of the language) the decision procedure can be expressed as

```
:-op(510, fx, [ ~ ]).
:-op(520, xfy, [ / \ ]).
:-op(530, xfy, [ \ / ]).
```

```

:-op(540,xfx, [→]).
:-op(550,xfx, [↔]).
member(X,[Y|Z]):-X = Y;member(X,Z).
decide(S):-member(S,[p,q,r,s]).
decide(~S):-decide(S).
decide(S):-((S=Q)/ \ R;S = Q \ / R;S=Q→R;S=Q↔R),
           decide(Q),decide(R).

```

The major difference between the SML and Prolog versions is that with Prolog we define a relation rather than a function, but it should nevertheless be apparent that the programs are essentially the same operationally and what was said above about the recursive calls, termination and decidability applies equally here.

Prolog allows you to define your own infix operators and this program is complete and can be used as it stands, without the need for an additional parser. We have taken the opportunity to invent some symbols for the logical connectives that we use in this book. The first five lines of the program are system-defined predicates for specifying the precedence and associativity of the operators and you will find an explanation of this in Appendix A or any good book on Prolog.

Prolog programs are used by expressing a request for a computation as a goal (again, see Appendix A for more practical, and Chapter 7 for more theoretical, detail). For example to use the program above to check whether or not the string of symbols  $p/\wedge q \rightarrow r$  is a sentence of the language, you type

```
?-decide(p/\q -> r).
```

to which the prolog interpreter would output 'yes', whereas for

```
?-decide(p+q).
```

you would get the output 'no', and for

```
?-decide(->p).
```

you would be told that there is a syntax error because the connective  $\rightarrow$  is defined to take two arguments.

As well as the question of decidability another important property is that the sentences of propositional logic are enumerable, that is all the sentences that get the answer ‘yes’ can be arranged in a list with a first member, a second member, and so on. With a little experience of Prolog one might think that the backtracking mechanism could be used to generate this list by repeatedly satisfying the goal

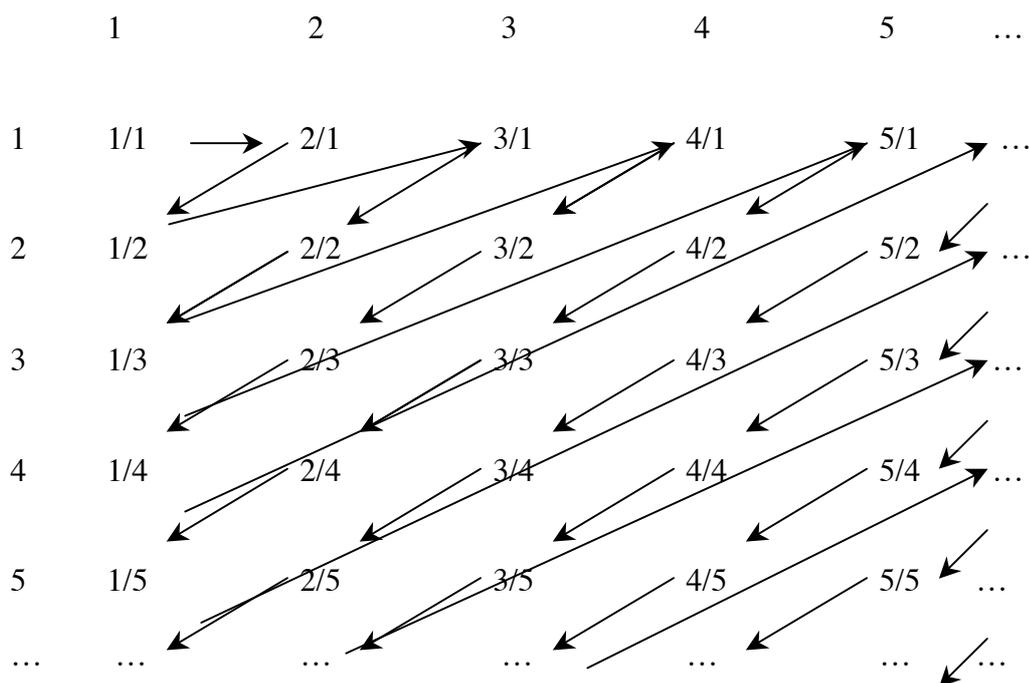
`?-decide(S).`

However, this does not work because of the fixed-order, depth-first nature of Prolog’s execution model. With two propositional variables  $p$  and  $q$  you would, in fact, get the output

```
p;
q;
~p;
~q;
~~p;
~~q;
~~~p;
```

and so on *ad infinitum*. Because the program clauses dealing with  $\sim$  come before those dealing with the other connectives, a formula such as  $p/\wedge q$  can never be generated. It is clear that simply reordering the clauses will not help either.

One way to get round this is to use an idea invented around 1880 by Georg Cantor. Cantor wanted to find out if all infinite sets are the same size (they are not in fact), and he defined a set as enumerably infinite if it could be put into one-to-one correspondence with the positive integers. He noticed a similar problem to the one we have encountered here arises with the rationals, that is numbers of the form  $i/j$  where  $i$  and  $j$  are positive integers. If you start listing them in the order  $1/1, 2/1, 3/1, \dots$  you will never, for example, get to  $1/2$ . Cantor’s way around this was to imagine the rationals arranged in a two-dimensional array in which  $i/j$  is in the  $i$ th column and the  $j$ th row (the diagram following shows the idea.)



The idea is to enumerate the elements of the array by starting at the top left-hand corner with  $1/1$  and following the path shown to give the list  $1/1, 2/1, 1/2, 3/1, 2/2, 1/3, 4/1, 3/2, \dots$ . It is intuitively clear that by doing this you eventually get to any point  $i/j$ . If intuition does not satisfy you, as indeed it should not if you are going to study logic, then it is straightforward by elementary algebra to show that  $i/j$  is in position  $(i + j - 2)(i + j - 1)/2 + j$  in the list. Conversely, we can invert the mapping to show that the  $n$ th rational in the list is  $i/j$  where  $j = n - (k - 2)(k - 1)/2$ ,  $i = k - j$  and  $k = \lfloor (3 + \sqrt{8n - 7})/2 \rfloor$ .

We can use the same idea to enumerate logical formulas. To keep things simple for the moment suppose we have only one connective,  $\rightarrow$  say. Then, following the recursive scheme given above, we know that any formula is either a sentence letter or of the form  $(S \rightarrow T)$  where  $S$  and  $T$  are both formulas. Now we do exactly the same as for the rationals.  $(S \rightarrow T)$  is in the column corresponding to  $S$  and the row corresponding to  $T$ .

The propositional variables count as formulas, of course. If they are finite in number then they can be listed before all the compound formulas. If we have an infinite supply of propositional variables then there is a slight complication because we must ensure that any given one is eventually brought into use. One way round this is to place the propositional variables at odd numbers in the list, with compound formulas at the even-numbered positions. The top left-hand corner of the array of

compound formulas would then, for propositional variables  $p, q, r, \dots$  be as in the following diagram (we have as usual omitted the outermost pair of parentheses).

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

We can now use exactly the same scheme of enumeration as we did for the rationals to generate the list of formulas  $p \rightarrow p, (p \rightarrow p) \rightarrow p, p \rightarrow (p \rightarrow p), \dots$  which, when merged with the sentence letters, will be in positions 2, 4, 6,  $\dots$ . We can imagine this mapping to be a code, a function  $c$  say, that takes integers to formulas. As above it is straightforward to show that

$$c(S \rightarrow T) = (c(S) + c(T) - 2)(c(S) + c(T) - 1) + 2c(T)$$

and, for  $n$  even,  $d(n)$  is  $d(i) \rightarrow d(j)$  where  $j = (n - (k - 2)(k - 1))/2$ ,  $i = k - j$  and  $k = \lfloor (3 + \sqrt{4n - 7})/2 \rfloor$ .

We can then write these functions as Prolog predicates and, by enumerating the integers in increasing order and decoding them into formulas, we can realize our original goal of demonstrating an effective procedure for enumerating all the sentences of the language—or in practical terms, as many as we want.

```
:-op(540,xfx,[->]).
int(1).
int(K) :- int(J), K is J+1.
split(N,I,J) :- int(K), L is K * (K-1), L>=N,!,
                J is (N-(K-2) * (K-1))/2, I is K-J.
code(S,N) :- atom(S), name(S,[I]),N is 2 * I - 193.
code(S->T,N) :- code(S,I),code(T,J),
                N is (I+J-2)*(I+J-1)+2*J.
```

```

decode(N,S) :- 1 is N mod 2,!,
               I is (N+193)//2,name(S,[I]).
decode(N,S->T) :- split(N,I,J),
                  decode(I,S),decode(J,T).
enumerate(N) :- int(K),L is 2*K,
                decode(L,X),write(X),nl,K>=N.

```

This is a complete program for coding, decoding and enumerating sentences that will work as it stands. It will be seen that it includes some features of Prolog that are of no logical interest, but are necessary to manipulate numbers and symbols at a basic level. The `name` predicate for example is a system utility for splitting an atom into a list of characters. It is used here to generate propositional variables starting at the letter 'a' (193 being twice the internal numerical code for 'a' minus one). The `split` predicate does the square root computation by a method of testing that uses only interger arithmetic. It could be replaced in most Prolog systems by the system's square root operator.

Of course, enumerating all possible sentences is not much practical use but, in the theoretical study of what the limits of computation are, it is important to show that you can in principle carry out such an enumeration . Furthermore, the idea that you can code formulas using arithmetic is an important one in its own right, quite apart from its use here for enumeration. In one of the most significant results in the history of mathematics Gödel used the idea to show, in 1931, that any logical basis for arithmetic is bound to be inadequate in a certain technical sense. We shall say a little more about this later.

### Exercise 2.1

- (a) Work out how you might modify the Prolog program for enumerating sentences with `->` so that it could handle the complete set of connectives `~`, `/\`, `\/`, `->`, `<->`.
- (b) Calculate by hand what the 1000<sup>th</sup> compound sentence is, that is what  $d(2000)$  is.
- (c) Write a similar program for enumerating sentences in SML.

### 2.1.3. *Giving meaning to the language*

So far we have defined the form of the language that we are studying. We can now decide whether or not a string of symbols from the alphabet is a well-formed sentence of this language. However, we do not yet have a way of giving any meaning or semantics to these sentences. It is as if you had been given a manual for Pascal with the part that gives the meaning, usually a set of rules that tell you how a given statement is executed (known as operational semantics), omitted from the manual. You would be in a position to write programs that were correctly formed, as far as the Pascal syntax is concerned, but you would not know what the program denotes or what its effect would be. You would not know its meaning.

At this point we are in a similar position with propositional logic; we can write well-formed sentences but we cannot say what they mean or relate them to any other language.

To give a meaning to a language we first have to associate the sentences of the language with some class of objects. For instance, in English, we begin our acquisition of language with simple utterances that consist of single words: "Dog!", "Cat!", "Car!" etc. Our understanding of the meaning of these words is judged by our use of them. That is, we say that someone understands the word "cat" if they point to a cat as they say it. If someone points to a cat and says "Dog!" then we conclude that they do not understand the meaning of the word.

At this simple level, at least, we can imagine that there is a mapping between the words and the objects that they denote. Then, as our natural language develops, we understand words for verbs, adjectives, relations and so on. Again, our understanding is demonstrated by our use of the words in certain situations. Of course, a natural language like English is far more complicated than any artificial language (such as a programming language or a logical language) and, although our methods will allow us to give a semantics to the languages that we shall study in this book, it is not yet, and may never be, possible to give a semantics to English in the same manner (if only because the language is not static).

So we have first to decide what objects, perhaps in an abstract sense, we are to have our sentences denoting. For the moment we are going to make an assumption that will mean our semantics is classical. The assumption is that any sentence is - has for its meaning something that is - either true or false. To make the meaning of 'true' and 'false' absolutely clear we can do what we do when telling someone the meaning of any other word - we can point to an instance. In this case, to explain our usage of 'true' and 'false', we refer you to statements that we can confidently assume you will

recognise as true and false. Every reader can be assumed to know that the numbers one and zero are not equal. So we can say that what a sentence refers to will either be the same thing that the arithmetic statement " $0=0$ " refers to or it will be the same thing that the arithmetic statement " $0=1$ " refers to. Here we are taking a view of semantics that is called denotational - we say what each sentence in the language denotes. Contrast this with what was said earlier about Pascal, where we spoke of the semantics of the language being specified by the actions that can be attributed to a particular sentence of the language, known as operational semantics. As it happens, Pascal is a simple enough language for it to be given a denotational semantics too, although quite a lot of work had to be done before the underlying mathematics was properly worked out.

We could contemplate giving an operational semantics to our propositional logic in which, perhaps, one action was performed and called 'true' and another was performed and called 'false' depending on whether the result of testing a value in a computer register is what we conventionally call true or false. It turns out, however, that such an operational approach is too cumbersome when all we really want to work with are abstract notions such as truth and falsity. The idea of letting truth reside in a particular action involves all the detail of how the action is carried out, how long it takes and what happens if it goes wrong. For other purposes, particular those involving getting an effect when you execute a program, like an invoice being printed or a line drawn on a screen, the operational detail is vital; but here it just complicates matters, so we take the denotational approach.

Every sentence of the language is either true or false, so we need rules for calculating which of these two values a given sentence has. The situation here is similar to the usual algebra of arithmetic where we have operations like multiplication and addition, symbolized by  $*$  and  $+$ , and letters such as  $x$  and  $y$  which are understood to stand in place of numbers. In propositional logic we have five operation symbols and a quantity of sentence variables that can stand in place of sentences. Just as we can give a meaning to an algebraic statement in terms of the meanings, or denotations, of the operation symbols, which operate on numbers, so we can give a meaning to the logical operators, which here we call connectives, by saying how they act on the denotations of sentences, i.e. on truth and falsity.

## 2.2 Arguments

### 2.2.1 Informal arguments

A notion that is central to our work is that of argument. The language that we introduced above will allow us to express, and show valid, arguments such as

If Socrates is a man then Socrates is mortal.

Socrates is a man.

Therefore, Socrates is mortal.

It should not allow us to show valid the argument

Socrates is a man.

Therefore, Socrates is mortal.

even though, by knowing the meaning of the words, we would say that the conclusion holds. If the textual form of the argument is changed to

If Ssss is an xxxx then Ssss is a yyyy.

Ssss is an xxxx.

Therefore Ssss is a yyyy.

we can guarantee that you cannot make an assessment of the argument from its meaning, yet we anticipate that you will accept it as valid by virtue of its structure.

So we are going to judge the validity of arguments by their form, not their meaning. This means that even the following argument is valid:

Paris is in Australia and Australia is below the equator

Therefore, Paris is in Australia

because its form is that of a valid argument, even though your geographical knowledge tells you the conclusion is false. Also, the following argument is not valid despite all the statements, including the conclusion, being true:

The Eiffel Tower is in Paris or Paris is in France

Therefore, the Eiffel Tower is in Paris

So, the correctness of an argument is not governed by its content, or its meaning, but by its logical form. We are going to make this idea much more precise and at the same time abstract away from the particular statements involved in the arguments, which makes the form much clearer.

### Exercise 2.2

- 1) Say whether each of the following arguments is valid or not.
  - a) The Eiffel Tower is in Australia and Australia is below the equator  
Therefore, The Eiffel Tower is in Australia
  - b) The Eiffel Tower is in Paris or Paris is in France  
Therefore, the Eiffel Tower is in Paris
  - c) The Eiffel Tower is in Australia or Australia is below the equator  
Therefore, the Eiffel Tower is in Australia
  - d) The Eiffel Tower is in Paris and Paris is in France  
Therefore, the Eiffel Tower is in Paris
  - e) The Eiffel Tower is in Australia and Paris is in France  
Therefore, Paris is in France
  - f) The Eiffel Tower is in Australia or France is in Australia  
Therefore, the Eiffel Tower is in Australia
  - g) The Eiffel Tower is in Australia or France is in Australia  
Therefore, the Eiffel Tower is in Paris
- 2) For each of the above use your knowledge of English and geography to say whether
  - i) the premise, i.e. the sentence before the 'therefore', is true
  - ii) the conclusion, i.e. the sentence after the 'therefore', is true
- 3) Can you construct a valid argument with true premise and false conclusion?

### 2.2.2 Formalizing arguments

The argument forms of the first two Socrates examples can be abstracted to

	if $p$ then $q$
	$p$
	therefore
	$q$
and	
	$p$
	therefore
	$q$

How to represent in logic the natural language form 'if  $S$  then  $T$ ', where  $S$  and  $T$  are arbitrary statements, has been the subject of heated debate among logicians. It turns out that simple examples of the kind we have here can be written unproblematically as  $S \square T$  where  $\square$  is one of the connectives we introduced in the alphabet for propositional logic and  $S$  and  $T$  stand for arbitrary sentences of propositional logic. There are other commonly occurring natural language forms, some of which we have seen above, that correspond to the remaining connectives.

<u>natural language</u>	<u>propositional logic</u>
$S$ and $T$	$S \square T$
$S$ or $T$	$S \vee T$
not $S$	$\neg S$
$S$ if and only if $T$	$S \square T$

We shall see that the correctness of an argument in the propositional calculus is decidable, in other words there are effective procedures for determining whether or not a given argument is correct. One such a procedure is the method of truth-tables which we now describe.

The Socrates argument can be transcribed into the formal language as

$$((p \square q) \square p) \square q \tag{1}$$

i.e. if it is the case both that  $p$  is true, and also that if  $p$  is true then  $q$  is true, then it is the case that  $q$  is true.

We have said we are going to assume that every proposition is either true or false and that this is one of the basic assumptions of "classical" logic - the oldest form of logic and the one that we are studying to start with. Because we are only interested in the form of arguments and the truth-values (true or false) of propositions, rather than their more subtle meanings in the everyday world, we use sentence variables to stand for arbitrary interpreted sentences that can take the values true (t) or false (f) alone.

From these we can build up more complicated formulae (with corresponding forms of natural language argument) using the connectives such as those for "if..then" and "and" as shown above.

In elementary algebra, if we know that if  $a=2$  and  $b=3$ , we can calculate the value of  $a+b$  as 5 without knowing or caring whether  $a$  stands for 2 apples or 2 houses. Similarly, in classical logic the truth-value of a compound formula can be calculated solely from the truth-values of its constituent sentence variables, independently of how these were determined or of any other aspects of their meaning in the real world. Logics with this property are called truth-functional and their connectives are sometimes called truth-functors.

Classical logic has, although as we shall see it does not necessarily need, the five connectives listed above. The rules for using them in truth-value calculations can be conveniently expressed in the form of truth-tables - the same idea as the multiplication tables of elementary arithmetic, but of course the rules are different.

□	t	f
t	t	f
f	t	t

□	t	f
t	t	f
f	f	f

	t	f
t	t	t
f	t	f

$\square$	t	f
t	t	f
f	f	t

$\neg$	
t	f
f	t

To find, for example, the truth-value of  $p \square q$  when the truth-value of  $p$  is t and the truth-value of  $q$  is f we look along the row marked t for  $p$  and down the column marked f for  $q$ . The corresponding table entry in the t row and f column is f for  $p=t$  and  $q=f$ .

Note that for  $\square$  it matters which of its arguments is the row and which the column; we would have got a different answer if we had taken  $q$  as the row and  $p$  as the column. Some of the truth-functores commute and some do not.

With the truth-tables for the connectives the argument (1) can be shown correct as follows:

$p$	$q$	$p \square q$	$(p \square q) \square p$	$((p \square q) \square p) \square q$
t	t	t	t	t
t	f	f	f	t
f	t	t	f	t
f	f	t	f	t

What we have done is to build up a truth table for the formula that we want to check by using the rules for the connectives to compute the truth values of all subformulas. We see that for any possible combination of truth-values for  $p$  and  $q$ , i.e. for all lines in the truth-table, the argument is true. The assignment of truth-values to propositional variables - each line of the truth-table - is called a valuation. The formula (1) is true in any valuation and we say therefore that (1) is valid. Another word often used for formulas that are true in all valuations is tautology.

For a two-argument truth-functor there can only be  $2^4 = 16$  different truth-tables because for two sentence variables there are only 4 different combinations of truth-values and each of these can only correspond to one of two truth-values.

In classical logic, i.e. the logic based on these truth-tables, the connectives we have introduced can be defined in terms of each other. For example  $S \sqsupset T$  is truth-functionally equivalent to  $\neg S \vee T$ . We can show this by the truth-table

$S$	$T$	$S \sqsupset T$	$\neg S \vee T$
t	t	t	t
t	f	f	f
f	t	t	t
f	f	t	t

where you see that the column headed  $S \sqsupset T$  is the same as that given above for  $\neg S \vee T$ .

It can easily be checked from the truth-table for  $\sqsupset$  that  $S$  is truth-functionally equivalent to  $T$  if and only if  $S \sqsupset T$  is a tautology, so equivalences are a special kind of tautology in which the principle connective is  $\sqsupset$ . They are useful in the transformation of statements into logically equivalent statements of different, perhaps simpler or more useful, form.

### Exercise 2.3

- a) Using the propositional variable  $r$  to mean 'it is raining',  $s$  to mean 'it is snowing' and  $f$  to mean 'it is freezing' translate the following into our logical notation:
- (i) It is raining and it is freezing
  - (ii) It is either raining or snowing, and it is freezing
  - (iii) It is raining but not snowing
  - (iv) If it is freezing then it is snowing
  - (v) It is neither raining nor snowing
  - (vi) If it is freezing or snowing then it is not raining
- b) How many different  $n$ -argument truth-functors are there?
- c) Many other equivalences are known. Here are some. You should check as many as you have the patience for.

(i)  $(\mathcal{P} * \mathcal{P}) \equiv \mathcal{P}$  idempotence

(ii)  $(\mathcal{P} * \mathcal{Q}) \equiv (\mathcal{Q} * \mathcal{P})$  commutativity

(iii)  $(\mathcal{P} * (\mathcal{Q} * \mathcal{R})) \equiv ((\mathcal{P} * \mathcal{Q}) * \mathcal{R})$  associativity

where  $*$  can be either  $\wedge$  or  $\vee$ , but not  $\rightarrow$ , in (ii) and (iii), and either  $\wedge$  or  $\vee$  in (i).

(iv) Which of (i), (ii) and (iii) does  $\rightarrow$  satisfy? Is it for example associative?

Here are some more equivalences.

(v)  $(\mathcal{P} \wedge (\mathcal{Q} \vee \mathcal{R})) \equiv ((\mathcal{P} \wedge \mathcal{Q}) \vee (\mathcal{P} \wedge \mathcal{R}))$

(vi)  $(\mathcal{P} \vee (\mathcal{Q} \wedge \mathcal{R})) \equiv ((\mathcal{P} \vee \mathcal{Q}) \wedge (\mathcal{P} \vee \mathcal{R}))$

(vii)  $(\mathcal{P} \wedge \neg \mathcal{P}) \equiv \perp$  a special propositional constant that is false in every valuation (to be pronounced "absurdity", "falsity" or "bottom").

(viii)  $(\mathcal{P} \vee \neg \mathcal{P}) \equiv \top$  a constant that is true in every valuation. This tautology is often called "excluded middle" or historically, in Latin, "tertium non datur".

(ix)  $\neg \neg \mathcal{P} \equiv \mathcal{P}$

(x)  $\neg(\mathcal{P} \wedge \mathcal{Q}) \equiv (\neg \mathcal{P} \vee \neg \mathcal{Q})$

(xi)  $\neg(\mathcal{P} \vee \mathcal{Q}) \equiv (\neg \mathcal{P} \wedge \neg \mathcal{Q})$

d) Use truth-tables to check that the following pairs of sentences are equivalent:

(i)  $p$  and  $p \vee (p \wedge q)$

(ii)  $p$  and  $p \wedge (p \vee q)$

(iii)  $p \wedge q$  and  $p$

If I now tell you that  $p$  means 'everyone loves everyone' and  $q$  means 'everyone loves themselves', why is it that given these meanings  $p \supset q$  and  $p$  have the same truth-values?

(iv) Use the laws of equivalence above to show that the pairs of sentences in (i) and (ii) are equivalent.

e) Formalize the arguments from the previous section and use truth-tables to check the assessments of validity that you gave there.

f) Use truth-tables to determine, for each of the following sentences, whether it is a tautology, a contradiction or contingent, i.e. neither a tautology nor a contradiction.

i)  $(p \supset (q \supset p))$

ii)  $((p \supset \neg q) \supset q)$

iii)  $((p \supset (q \supset r)) \supset ((p \supset q) \supset (p \supset r)))$

iv)  $((p \supset q) \supset (\neg(q \supset p)))$

v)  $((\neg p \supset \neg q) \supset (q \supset p))$

vi)  $\neg((p \supset q) \supset p) \supset p$

## 2.3 Functional Completeness

The logical connectives  $\neg$ ,  $\supset$ ,  $\wedge$ , and  $\vee$  are chosen for the fairly natural way that their truth-tables correspond to common usage in argument, but it is not mathematically necessary to have so many.

In fact it can be shown that a single connective is sufficient to represent all classical truth-functores. Such a "functionally complete" connective is the Sheffer stroke, written  $|$ , whose truth table is the same as that for  $\neg(S \supset \mathcal{T})$ .

Another connective with this property of being functionally complete is "NOR", which is equivalent to  $\neg(S \vee \mathcal{T})$ . This has important consequences in hardware design. A digital circuit can be built to realize any possible truth-functor from NOR gates alone (circuits which realize NOR).

**Exercise 2.4**

a) Show that

$$(i) \neg S \sqsupset S \mid S$$

$$(ii) S \sqsupset T \sqsupset (S \mid T) \mid (S \mid T)$$

b) How can  $S \sqsupset T$  and  $S \sqsupset \neg T$  be written in terms of  $\mid$  alone?

**2.4 Consistency, Inconsistency, Entailment.****Definition 2.2**

A valuation is an assignment of truth-values to the propositional variables.

Thus a valuation is a function  $v : P \rightarrow \{t, f\}$ , where  $P$  is the set of propositional variables.

**Definition 2.3**

A sentence is valid iff it is true (evaluates to t) for all valuations. A valid sentence is also be called a tautology.

**Definition 2.4**

Suppose you have a set  $G = \{S_1, \dots, S_n\}$  of sentences. In some valuations (lines of the truth-table) some of the  $S_i$  will be true and some false. If there is at least one line in which all the  $S_i \in G$  are true then we say that  $G$  is semantically consistent. If no valuation makes all the  $S_i$  true then  $G$  is inconsistent.

An example of inconsistency is the set  $\{S, \neg S\}$ .

**Definition 2.5**

A set of sentences  $G$  semantically entails a sentence  $T$ , written as  $G \vDash T$ , iff there is no valuation that makes all of the sentences in  $G$  true and makes  $T$  false, i.e. assuming the truth of all  $S_i \in G$  has the consequence that  $T$  is true.

If we now adopt the convention that we write  $\vDash \mathcal{T}$  in the case where  $G$  is the empty set then we can use  $\vDash \mathcal{T}$  as a neat notation for saying that  $\mathcal{T}$  is a tautology because if  $G$  is empty then the definition of semantic entailment says that there is no valuation which makes  $\mathcal{T}$  false, so  $\mathcal{T}$  is true in all valuations. Also, if  $\mathcal{T}$  is omitted, then the definition can be read as saying that there is no valuation which makes all of the sentences in  $G$  true, so we can write  $G \vDash$  for  $G$  is inconsistent.

With this convention  $\vDash$  (which of course is a symbol in the observer's language for a relation between sentences and sets of sentences in the object language) behaves rather like the  $=$  sign in algebraic equations. We have  $G \vDash \mathcal{T}$  iff  $G, \neg \mathcal{T} \vDash$  where  $G, \neg \mathcal{T}$  is a convenient abbreviation for  $G \sqcup \{\neg \mathcal{T}\}$ .

We can think of this as formalizing the idea that, given the assumptions in  $G$ , then the conclusion  $\mathcal{T}$  is true, or  $\mathcal{T}$  follows from the assumptions.

As examples, we look at the sets  $\{p, \neg p\}$  and  $\{(p \sqcup q) \sqcup q, \neg p \sqcup \neg q, p\}$  and try to decide on their consistency. To do this we write out the truth-tables, which enumerate all possible valuations for the propositional variables  $p$  and  $q$ , to see whether or not there is at least one row in the truth-tables which has t in each place, i.e. to see whether or not all the sentences can simultaneously be true.

In the first case we get

$p$	$\neg p$
t	f
f	t

and here we can clearly see that no row has t everywhere, so the sentences in  $\{p, \neg p\}$  are inconsistent. Next we get

$p$	$q$	$(p \sqcup q)$	$\neg p$	$\neg q$	$(p \sqcup q) \sqcup q$	$(\neg p \sqcup \neg q)$
t	t	t	f	f	t	f
t	f	f	f	t	t	t
f	t	f	t	f	t	t
f	f	f	t	t	t	t

and we can see that the set  $\{(p \sqcup q) \sqcup q, \neg p \sqcup \neg q, p\}$  is consistent because the second line of the truth-table shows that all three sentences in the set have value t.

We next give some examples of deciding the correctness of questions of semantic entailment. Remember that  $G \vDash \mathcal{S}$  iff there is no valuation which, while

making all of the sentences in  $G$ , true makes  $S$  false. This, again, can be decided by writing out truth-tables so as to enumerate all possible valuations.

Consider the examples  $\{p\} \models p$ ,  $\{p \sqcap q, p\} \models q$  and  $\{p, \neg p\} \models q$ . The first is trivial since the truth-table is just

$p$
t
f

and here everywhere  $p$  has value t then  $p$  has value t. The second case gives the truth-table

$p$	$q$	$p \sqcap q$
t	t	t
t	f	f
f	t	t
f	f	t

and we can see that in the single case, in the first line, where the assumptions are both true then the conclusion is too, so the entailment is valid. Finally we have

$p$	$q$	$\neg p$
t	t	f
t	f	f
f	t	t
f	f	t

and we can see that nowhere do the assumptions both have value t and this means that the conclusion never has the value f when all the assumptions have the value t. Hence, the entailment is valid.

Note that this would always be the outcome if the assumptions are  $\{p, \neg p\}$  since, as we saw above, this set is inconsistent, so it is never the case that both sentences have value t simultaneously. Any entailment therefore, no matter what the

conclusion, would be valid with these assumptions. We can sum this up by saying that "anything follows from inconsistent assumptions".

### Exercise 2.5

- a) Work out which of the following sets of sentences are semantically consistent and which are semantically inconsistent:

i)  $\{p \sqcap q, \neg q\}$

ii)  $\{p \sqcap q, \neg q \sqcap r, p \sqcap \neg r\}$

iii)  $\{(p \sqcap q) \sqcap r, \neg((\neg p \sqcap \neg q) \sqcap r)\}$

- b) Work out which of the following semantic entailments are correct and which are not .

i)  $\{p \sqcap q\} \vDash (\neg q \sqcap \neg p)$

ii)  $\{p \sqcap q\} \vDash q$

iii)  $\{(p \sqcap q) \sqcap r, \neg r\} \vDash \neg p$

iv)  $\vDash ((p \sqcap q) \sqcap p) \sqcap p$

- c) Rewrite  $(a \sqcap b) \sqcap (a \sqcap c)$  to a logically equivalent sentence containing no connectives other than  $\neg$  and  $\sqcap$  .

- d) If  $\mathcal{A}$  and  $\mathcal{B}$  are any sentences and  $T$  is a set of sentences then show that  $T \sqcap \{\mathcal{A}\} \vDash \mathcal{B}$  if and only if  $T \vDash \mathcal{A} \sqcap \mathcal{B}$ .

- e) Here are some facts about entailment; you should prove that they follow from the definition.  $\mathcal{R}, \mathcal{S}$  and  $\mathcal{T}$  are any sentences and  $G$  and  $D$  are any sets of sentences. Recall that  $G, D$  means  $G \sqcap D$  and  $G, \mathcal{T}$  means  $G \sqcap \{\mathcal{T}\}$ .

i)  $G, \mathcal{T} \vDash \mathcal{T}$

ii) if  $G \vDash \mathcal{T}$  then  $G, D \vDash \mathcal{T}$  (Monotonicity)

iii) if  $G \vDash \mathcal{T}$  and  $G, \mathcal{T} \vDash \mathcal{S}$  then  $G \vDash \mathcal{S}$  (called the Cut Theorem)

iv) if  $\mathcal{T} \vDash \mathcal{S}$  and  $\mathcal{S} \vDash \mathcal{R}$  then  $\mathcal{T} \vDash \mathcal{R}$  (Transitivity)

v)  $G \vDash \neg T$  iff  $G, T \vDash$

vi)  $G \vDash T$  and  $G \vDash S$  iff  $G \vDash (T \Box S)$

vii)  $G, T \vDash \mathcal{R}$  and  $G, S \vDash \mathcal{R}$  iff  $G, (T \Box S) \vDash \mathcal{R}$

viii)  $G, T \vDash S$  iff  $G \vDash T \Box S$

ix)  $G, T \vDash S$  and  $G, S \vDash T$  iff  $G \vDash T \Box S$

f) Use the properties of  $\vDash$  listed in question five to show, without using truth-tables, that:

i)  $\vDash p \Box (q \Box p)$

ii)  $\vDash (p \Box q) \Box ((q \Box r) \Box (p \Box r))$

g) Three people  $A$ ,  $B$  and  $C$  are apprehended on suspicion of cruelty to mice in the computer lab.

$A$  says: " $B$  did it;  $C$  is innocent"

$B$  says: "If  $A$  is guilty then so is  $C$ "

$C$  says: "I didn't do it; one of the others did"

i) Are the statements consistent?

ii) Assuming that everyone is innocent of the dastardly deed, who told lies?

iii) Assuming that everyone's statement is true, who is innocent and who is guilty?

Hint: let  $I_A$  stand for " $A$  is innocent",  $I_B$  for " $B$  is innocent" and  $I_C$  for " $C$  is innocent". Then  $A$ 's statement can be written as  $\neg I_A \Box I_C$ , which we call  $S_A$ , and so on.

For each valuation of  $I_A$ ,  $I_B$  and  $I_C$  determine the truth-values of  $S_A$ ,  $S_B$  and  $S_C$ . All these answers can be determined from the truth-table.

- h) The Cut Theorem, which is one of the facts about entailment that you were invited to prove above, says:

if  $G \vDash T$  and  $G, T \vDash S$  then  $G \vDash S$

where  $T$  and  $S$  are sentences and  $G$  is a set of sentences. Give a counter-example, i.e. examples of  $G$ ,  $T$  and  $S$ , which shows that if  $G, T \vDash S$  then  $G \vDash S$  does not always hold.

## 2.5 Formal Propositional Calculus

Up to now we have been working with informal systems. We now re-express all of the above in more formal terms and then go on to introduce our first formal system. That will mean that the person using the system no longer has to know the meaning of the symbols in the language or the meaning behind any rule—the only thing communicated is the form of the expressions and rules, and the relations between them. To use a formal system correctly, and hence to make arguments correctly, we need only follow the rules correctly. If this can be done then, because the rules are completely specified, it follows that a program can be written which can construct correct proofs.

To show that an argument is correct, in other words to assess its validity or otherwise, we first need to give a formal interpretation for the symbols of the language. This is where the notion of valuation, as already introduced, will be used. But then a further development will be to construct a valid argument step by step without knowing the meaning of the expressions and rules. This is where we will turn to the formal deductive system.

### 2.5.1 The language of Propositions

We will first elaborate some of the definitions which were given fairly informally in previous sections.

#### Definition 2.6

A propositional language is based on two components, an alphabet and a grammar.

- a) The alphabet consists of three sets:

- i) a set of connective symbols  $\{ \neg, \square, \square, \square, \square \}$ ,
  - ii) a set of punctuation symbols  $\{ (, ) \}$ ,
  - iii) a set of propositional variables  $P$ .
- b) The grammar, which defines what counts as being a sentence based on  $P$ :
- i) each of the elements of  $P$  is a sentence based on  $P$ ,
  - ii) if  $S$  and  $T$  are sentences based on  $P$  then so are  $(\neg S)$ ,  $(S \square T)$ ,  
 $(S \square T)$ ,  $(S \square T)$  and  $(S \square T)$ ,
  - iv) nothing else is a sentence based on  $P$ .

### Definition 2.7

The set of sentences based on  $P$  is called the propositional language based on  $P$ , which we write as  $L(P)$ . We often refer to the elements of  $P$  as atomic sentences.

We have already seen one particular way, based on truth-tables, of giving a meaning to the symbols in a language. We are now going to be more abstract so, instead of tying ourselves to one particular way of giving meaning, we simply present a general definition of what it is to give meaning to a language. The truth-tables can be seen as a particular example of this.

Recall that a valuation is a function  $v$  from a set of propositional variables to the set  $\{t, f\}$ . If the domain of  $v$  is  $P$  then we say that  $v$  is a  $P$ -valuation.

We can now extend  $v$  into a new function which gives meaning not only to the members of  $P$ , as  $v$  does, but to any member of  $L(P)$ . This extended function,  $\text{truthvalue}_v : L(P) \rightarrow \{t, f\}$ , is defined below by cases based on the structure of members of  $L(P)$ . By convention, we drop the  $v$  subscript where it is clear which valuation we are basing our definition on.

### Definition 2.8

- i)  $\text{truthvalue}(S) = v(S)$  if  $S$  is atomic.
- ii)  $\text{truthvalue}(\neg S) = t$  if  $\text{truthvalue}(S) = f$  and  
 $\text{truthvalue}(\neg S) = f$  if  $\text{truthvalue}(S) = t$ .
- iii)  $\text{truthvalue}(S \square T) = t$  if  $\text{truthvalue}(S) = t$  and  $\text{truthvalue}(T) = t$ ,  
and  $\text{truthvalue}(S \square T) = f$  otherwise.
- iv)  $\text{truthvalue}(S \square T) = t$  if  $\text{truthvalue}(S) = t$  or  $\text{truthvalue}(T) = t$ , or  
both, and  $\text{truthvalue}(S \square T) = f$  otherwise.
- v)  $\text{truthvalue}(S \square T) = f$  if  $\text{truthvalue}(S) = t$  and  $\text{truthvalue}(T) = f$

and  $\text{truthvalue}(S \sqcap \bar{T}) = t$  otherwise.

- vi)  $\text{truthvalue}(S \sqcap \bar{T}) = t$  if  $\text{truthvalue}(S) = \text{truthvalue}(T)$  and  
 $\text{truthvalue}(S \sqcap \bar{T}) = f$  otherwise.

As an example, consider the sentence  $(\neg(p \sqcap q) \sqcap (r \sqcap p))$  in a context where we have a valuation  $v$  such that  $v(p) = t$ ,  $v(q) = f$  and  $v(r) = t$ . We have

$\text{truthvalue}((\neg(p \sqcap q) \sqcap (r \sqcap p)))$  depends on  
 $\text{truthvalue}(\neg(p \sqcap q))$  which depends on  
 $\text{truthvalue}(p \sqcap q)$  which depends on  
 $\text{truthvalue}(p) = v(p) = t$   
or  $\text{truthvalue}(q) = v(q) = f$   
so  $\text{truthvalue}(p \sqcap q) = t$   
so  $\text{truthvalue}(\neg(p \sqcap q)) = f$   
and  $\text{truthvalue}(r \sqcap p)$  which depends on  
 $\text{truthvalue}(r) = v(r) = t$   
and  $\text{truthvalue}(p) = v(p) = t$   
so  $\text{truthvalue}(r \sqcap p) = t$   
so  $\text{truthvalue}((\neg(p \sqcap q) \sqcap (r \sqcap p))) = t$ .

Now this computation of the truth-value of a sentence, in the context of a certain valuation, clearly follows the same pattern as the computation which sets out to decide whether or not a sequence of symbols from the alphabet is a member of the language.

If we recall the definition of sentencehood above, and use it on the same sentence  $(\neg(p \sqcap q) \sqcap (r \sqcap p))$  as above we get

$\text{decide}((\neg(p \sqcap q) \sqcap (r \sqcap p)))$  depends on  
 $\text{decide}(\neg(p \sqcap q))$  which depends on  
 $\text{decide}(p \sqcap q)$  which depends on  
 $\text{decide}(p)$  which is true, since  $p \sqcap P$   
and  $\text{decide}(q)$  which is true, since  $q \sqcap P$   
so  $\text{decide}(p \sqcap q)$  is true  
so  $\text{decide}(\neg(p \sqcap q))$  is true  
and  $\text{decide}(r \sqcap p)$  which depends on  
 $\text{decide}(r)$  which is true, since  $r \sqcap P$

and  $\text{decide}(p)$  is true, since  $p \in P$   
 so  $\text{decide}(r \wedge p)$  is true  
 so  $\text{decide}(\neg(p \wedge q) \wedge (r \wedge p))$  is true.

This similarity of computations should come as no surprise, since their patterns are governed by the grammar, which is the same in each case.

### Exercise 2.6

- a) How many sentences are there for the alphabet which has  $P = \{q\}$ ?
- b) How many sentences are there in the language which has  $P = \{p_1, p_2, \dots\}$ , i.e. a countably infinite set?
- c) For each of the following sentences, and given the valuation  $v$  where  $v(p) = t$ ,  $v(q) = f$  and  $v(r) = t$ , find the truth-values of
  - i)  $(p \wedge \neg p)$
  - ii)  $(p \wedge \neg p)$
  - iii)  $(p \wedge \neg \neg p)$
  - iv)  $((p \wedge q) \wedge (p \wedge q))$
  - v)  $((p \wedge q) \wedge r) \wedge (q \wedge p)$

### 2.5.2 More definitions

#### Definition 2.9

If  $v$  is a  $P$ -valuation we say that  $v$  satisfies a sentence  $S$  of  $L(P)$  if  $\text{truthvalue}_v(S) = t$ , which is also written  $\models_v S$ . A  $P$ -valuation  $v$  satisfies a set of sentences  $\{S_1, \dots, S_n\}$  if  $\text{truthvalue}_v(S_i) = t$  for all  $i$  between 1 and  $n$ . Note that this is the same as saying  $\text{truthvalue}_v(S_1 \wedge \dots \wedge S_n) = t$ .

If  $G$  and  $D$  are two sets of sentences then  $v$  satisfies  $G \wedge D$  if and only if  $v$  satisfies both  $G$  and  $D$ . To make this work in general we say that any  $P$ -valuation satisfies the empty set.

**Definition 2.10**

A  $P$ -valuation  $v$  is a model for a set of sentences iff  $v$  satisfies the set of sentences.

**Definition 2.11**

If  $S \in L(P)$  then  $S$  is a tautology if and only if  $\text{truthvalue}_v(S) = t$  for all  $v$ . Equivalently,  $S$  is a tautology if and only if  $\vDash_v S$  for all  $v$ . As before we write this simply as  $\vDash S$ .

**2.5.3 Formal Deductive Systems****Definition 2.12**

A formal system has the following components:

- a) an alphabet of symbols,
- b) rules for building sentences, the grammar,
- c) a set of sentences, the axioms,
- d) a finite set of rules for generating new sentences from old, the rules of deduction.

The main characteristic of a formal system is that the behaviour and properties of the symbols in the alphabet are given entirely by the rules of inference. The symbols themselves have no meaning so the notion of valuation, which we were using above, does not arise. However, as we shall see later, a desirable property of a formal deductive system is that it bears a particular relationship to any valuation.

**2.5.4 Formal deductive system for propositional calculus**

The alphabet and grammar components will be just as they were in the previous sections. The two new components are the axioms and the rules of inference. The axiom system that we give here is not the only one possible. A set of axiom schemas for propositional calculus was first given by Frege; it contained six sentences. The set that we have chosen was given, and shown to do the same job as Frege's, by Lukasiewicz. Yet another, this time with four axiom schemas, was given by Hilbert and Ackermann. In fact, the one we give is not the smallest possible: Nicod used the Sheffer stroke to give a set consisting of just one schema, though instead of Modus Ponens he used a slightly more complicated variant of it.

- a) the alphabet
- b) the grammar
- c) the axioms: if  $S, T$  and  $R$  are any sentences then

$$A1) \quad (S \sqsupset (T \sqsupset S))$$

$$A2) \quad ((S \sqsupset (T \sqsupset R)) \sqsupset ((S \sqsupset T) \sqsupset (S \sqsupset R)))$$

$$A3) \quad (((\neg S) \sqsupset (\neg T)) \sqsupset (T \sqsupset S))$$

are axiom schemas, which generate the axioms in the same way as the clauses of the grammar generate the sentences.

d) rule of deduction, which for historical reasons is called Modus Ponens, often abbreviated to MP: from  $S$  and  $(S \sqsupset T)$ , for  $S$  and  $T$  any sentences, we obtain  $T$  as a direct consequence.

So we actually have infinitely many axioms since  $S, T$  and  $R$  can be any sentences and the number of sentences is infinite. Clearly, though, there are more sentences than there are axioms. For example  $(p \sqsupset p)$  is certainly a sentence but it is not an axiom. Just as clearly, all the axioms are sentences. These two facts together mean that the set of axioms is a proper subset of the set of sentences, yet both are infinitely large. However, this is not such a strange situation; the natural numbers form an infinite set and the even natural numbers form another infinite set which is a proper subset of the natural numbers. The similarity can be seen if we give their set definitions:

$$\text{Ax}(P) = \{ S \mid S \sqsupset L(P) \text{ and axiom}(S) \}$$

$$\text{Evens} = \{ n \mid n \sqsupset N \text{ and even}(n) \}$$

Here  $\text{axiom}(S)$  is true whenever  $S$  is an axiom, and  $\text{even}(n)$  is true whenever there is a natural number  $k$  such that  $n = 2k$ . We can see that  $\text{even}$  is decidable, but can we define  $\text{axiom}$  so that it is decidable too? Well, once again we can look to the structure of the definition of the axiom schemas for an answer. The definition above can be recast so that  $\text{axiom}$  is

$\text{axiom } P \text{ sentence} = \text{axiom1 } P \text{ sentence or axiom2 } P \text{ sentence or axiom3 } P \text{ sentence}$

where

$$\text{axiom1 } P (S \sqsupset (T \sqsupset R)) = \text{true if decide } P \text{ } S \text{ and decide } P \text{ } T \text{ and } S=R$$

$\text{axiom2 } P ((S \sqcap (T \sqcap R)) \sqcap ((S \sqcap T) \sqcap (S'' \sqcap R))) = \text{true}$  if  $\text{decide}^P S$  and  $\text{decide}^P T$  and  $\text{decide}^P R$  and  $S=S'$  and  $R=R'$  and  $T=T'$  and  $S=S''$   
 $\text{axiom3 } P (((\neg S) \sqcap (\neg T)) \sqcap (T \sqcap S')) = \text{true}$  if  $\text{decide}^P S$  and  $\text{decide}^P T$   
 and  $S=S'$  and  $T=T'$

and axiom is false for all other sentences ( $P$  is the set of propositional variables in the alphabet). Finally, since  $\text{decide}$  is decidable it follows that axiom is too.

There is another way of deciding whether or not a sentence is an axiom and that is by introducing the idea of instances. First, we need some definitions and notation.

Let  $P$  and  $Q$  be two sets of propositional variables. Then these give rise to two propositional languages  $L(P)$  and  $L(Q)$ .

Let  $\text{vars}_P$  be a function which takes an element of a propositional language as argument and returns as result the set of all those propositional variables that appear in the sentence. So, for example, if  $P = \{p_1, p_2\}$  then  $\text{vars}_P(p_1 \sqcap (p_2 \sqcap p_2)) = \{p_1, p_2\}$ .

We can give a method for calculating  $\text{vars}_P$  which, again, is based on the structure of sentences:

$$\begin{aligned} \text{vars}_P(S) &= \{S\} \text{ if } S \sqcap P \\ &\text{ or } \text{vars}_P(T) \text{ if } S = \neg T \\ &\text{ or } \text{vars}_P(T) \sqcup \text{vars}_P(R) \text{ if } S = T \sqcap R \text{ or } T \sqcup R \text{ or } T \sqsupset R \text{ or } T \sqsupseteq R \end{aligned}$$

Now, if  $\text{vars}_P(S) = \{p_1, \dots, p_k\}$  then  $S[b_1/p_1, \dots, b_k/p_k]$ , where  $b_i \sqcap L(Q)$ , is the sentence of  $L(Q)$  that results from simultaneously substituting  $b_i$  for  $p_i$  for all  $i$  from 1 to  $k$ . We say that  $S[b_1/p_1, \dots, b_k/p_k]$  is a  $Q$ -instance of  $S$ , which is a sentence based on  $P$ . (As usual, when there is sufficient context we omit the reference to the sets  $P$  and  $Q$ ).

Now, to get back to our axioms, let  $\mathcal{P} = \{S, T, R\}$ . Consider the axiom schemas above as the (only) three sentences of a language based on  $\mathcal{P}$ , which we call  $l(\mathcal{P})$ . Then the axioms as defined above are simply all the  $P$ -instances of all the elements of  $l(\mathcal{P})$ . That is

$$\begin{aligned} \text{Ax}(P) &= \{S[S_1/p_1, \dots, S_n/p_n] \sqcap L(P) \mid S \sqcap l(\mathcal{P}) \text{ and } \text{vars}_{\mathcal{P}}(S) = \{S_1, \dots, S_n\} \\ &\text{ and } p_1, \dots, p_n \sqcap L(P)\} \end{aligned}$$

The idea of an instance is probably quite an intuitive one. In fact, we have been using it implicitly all along by using curly letters to range over all sentences. What we were doing, we can now see, was to express results, definitions and questions in a language based on an alphabet of curly letters and to assume that it was clear how to apply these general results in particular cases, i.e. how the results, definitions and questions related to all instances over an appropriate alphabet.

### 2.5.5 Proofs

#### Definition 2.14

A proof in a Formal Deductive System (FDS) is a sequence of sentences  $S_1, \dots, S_n$  such that, for all  $i \leq n$ , either  $S_i$  is an axiom or there are two members  $S_j, S_k$  of the sequence, with  $j, k < i$ , which have  $S_i$  as a direct consequence by Modus Ponens (MP).  $S_n$  is then a theorem of the FDS, and the sequence  $S_1, \dots, S_n$  is a proof of  $S_n$ .

Note that, in such a proof, any of the  $S_i$  are theorems since we can truncate the proof at  $S_i$ , giving a proof of  $S_i$ .

#### Definition 2.15

If  $G$  is a set of sentences then a sequence  $S_1, \dots, S_n$  is a deduction from  $G$  if, for each  $i \leq n$

- either a)  $S_i$  is an axiom
- or b)  $S_i \in G$
- or c)  $S_i$  follows from two earlier members of the sequence as a direct consequence of MP.

We can think of a deduction from  $G$  as being like a proof with the elements of  $G$  as temporary axioms.

#### Definition 2.16

If  $G$  is a set of sentences and  $S_1, \dots, S_n$  is a deduction from  $G$  then  $S_n$  is deducible from  $G$ , and this is written  $G \vdash S_n$ .

" $S$  is a theorem" can therefore be written as  $\vdash S$ , i.e.  $S$  is deducible from the empty set. And, as should be clear from the definition by now, we could write a

program which takes any sequence of sentences and decides whether or not the sequence is a proof. That is, proofhood is also decidable.

### Example 2.1

Here is an example of a proof of the sentence  $(p \supset p)$ . Note that the numbers on the left and the comments on the right are not part of the formal proof, they are annotations to help the reader see that the steps are justified.

- |  |                 |
|--|-----------------|
| 1. $((p \supset ((p \supset p) \supset p)) \supset ((p \supset (p \supset p)) \supset (p \supset p)))$ | instance of A2  |
| 2. $(p \supset ((p \supset p) \supset p))$   | instance of A1  |
| 3. $((p \supset (p \supset p)) \supset (p \supset p))$   | MP with 1 and 2 |
| 4. $(p \supset (p \supset p))$   | instance of A1  |
| 5. $(p \supset p)$   | MP with 3 and 4 |

Even this simple example shows that proofs in this system are difficult. This is mainly because very long sentences are generated and it is usually hard to see how to proceed correctly or what are the appropriate axiom instances to choose. Later we will see some far better syntactic proof methods, but we introduce the system here because it is easy to prove things about it (if not in it!).

### Example 2.2

Now we have an example of a proof that uses assumptions. Recall from above that the assumptions can be used in the same way as the axioms.

We show that  $\{p, (q \supset (p \supset r))\} \vdash (q \supset r)$ .

- |  |                 |
|--|-----------------|
| 1. $p$   | assumption      |
| 2. $(q \supset (p \supset r))$   | assumption      |
| 3. $(p \supset (q \supset p))$   | instance of A1  |
| 4. $(q \supset p)$   | MP with 1 and 3 |
| 5. $((q \supset (p \supset r)) \supset ((q \supset p) \supset (q \supset r)))$ | instance of A2  |
| 6. $((q \supset p) \supset (q \supset r))$                                     | MP with 2 and 5 |
| 7. $(q \supset r)$   | MP with 4 and 6 |

**Exercise 2.7**

- a) For each stage of the two proofs above, write down the substitutions used in the relevant axiom schemas to obtain the sentences in the proof.
- b) Construct proofs of the following:
- i)  $\vdash (a \supset (a \supset a))$
  - ii)  $\{a\} \vdash a \supset a$
  - iii)  $\{a\} \vdash a \supset a$ , but make it different from the proof you gave in (ii).
  - iv)  $\{a, a \supset b\} \vdash b$
  - v)  $\{a\} \vdash b \supset a$
  - vi)  $\{f \supset g, g \supset h\} \vdash f \supset h$
  - vii)  $\{f \supset (g \supset h), g\} \vdash f \supset h$
  - viii)  $\vdash \neg\neg f \supset f$
  - ix)  $\vdash f \supset \neg\neg f$

## 2.6 Soundness and Completeness for propositional calculus

Now that we have a system in which we can build proofs, we would like to be sure that the sentences we can find proofs for, the theorems, are indeed the tautologies that we previously characterised as valid. So, we have to show that the following is true:

*For any sentence  $S$ , if  $S$  is a theorem then  $S$  is a tautology  
and if  $S$  is a tautology then  $S$  is a theorem.*

This will allow us to claim that our formal system adequately characterizes our intuitive ideas about valid arguments, so we say that the italicized statement expresses the adequacy theorem for the formal system. The first part expresses the soundness of our formal system. It says that if we show that  $S$  is a theorem then it is a

tautology. In other words we only ever produce valid sentences as theorems. Conversely, the second sentence expresses completeness and says that any  $S$  which is a tautology will always be provable in the formal system.

### 2.6.1 The deduction theorem

This section introduces and proves a theorem that turns out to be very useful for both drastically shortening proofs within the formal system and also for easing the presentation of the completeness proof, which we do later.

#### Theorem

If  $G, S \vdash T$  then  $G \vdash S \supset T$ , where  $S$  and  $T$  are any sentences and  $G$  is any set of sentences.

#### Proof

Let  $\mathcal{T}_1, \dots, \mathcal{T}_n$  be a proof of  $T$  from assumptions  $G \cup \{S\}$ , so  $\mathcal{T}_n$  is  $T$ . We do induction on  $n$ .

If  $n=1$  then either  $T$  is in  $G$  or  $T$  is an instance of an axiom schema or  $T$  is  $S$ . In the first two cases  $G \vdash T$  so since  $\vdash T \supset (S \supset T)$  we have  $G \vdash S \supset T$ . In the final case since  $\vdash S \supset S$  we have  $G \vdash S \supset T$ .

Now assume that for any  $k$ ,  $1 \leq k < n$ , the result holds. There are four possibilities. Either  $T$  is in  $G$ , or  $T$  is an instance of an axiom schema, or  $T$  is  $S$ , or  $T$  follows as a direct consequence by Modus Ponens from  $\mathcal{T}_i$  and  $\mathcal{T}_j$ ,  $1 \leq i, j < n$ . In the first three cases we can argue as we did in the case where  $n=1$ .

In the fourth case  $\mathcal{T}_j$ , say, has the form  $\mathcal{T}_i \supset \mathcal{T}_n$ . By the assumption we have  $G \vdash S \supset \mathcal{T}_i$  and  $G \vdash S \supset (\mathcal{T}_i \supset \mathcal{T}_n)$ . But an instance of axiom schema A2 is  $\vdash (S \supset (\mathcal{T}_i \supset \mathcal{T}_n)) \supset ((S \supset \mathcal{T}_i) \supset (S \supset \mathcal{T}_n))$ , so we have by Modus Ponens, using  $G \vdash S \supset (\mathcal{T}_i \supset \mathcal{T}_n)$ , that  $G \vdash (S \supset \mathcal{T}_i) \supset (S \supset \mathcal{T}_n)$  and then by MP again, this time with  $G \vdash S \supset \mathcal{T}_i$ , that  $G \vdash S \supset \mathcal{T}_n$ . So, by induction on  $n$ , the theorem holds.

### The adequacy theorem

There are two parts to this proof since we have to show both if  $\vdash S$  then  $\vDash S$  and if  $\vDash S$  then  $\vdash S$ . We also use, and prove, a couple of lemmas.

#### Lemma 1

If  $S$  and  $(S \supset T)$  are both tautologies then  $T$  is a tautology.

**Proof**

Assume that  $\mathcal{T}$  is not a tautology. We will now deduce a contradiction, which will mean that our initial assumption is false, so  $\mathcal{T}$  must be a tautology. (This method of argument is known as 'reductio ad absurdum').

If  $\mathcal{T}$  is not a tautology, but both  $\mathcal{S}$  and  $(\mathcal{S} \square \mathcal{T})$  are, then there must be a valuation  $v$  such that  $v(\mathcal{S})=t$ ,  $v((\mathcal{S} \square \mathcal{T}))=t$  and  $v(\mathcal{T})=f$ .

If  $v((\mathcal{S} \square \mathcal{T}))=t$ , then  $v(\mathcal{S})=f$  or  $v(\mathcal{T})=t$  or both. If  $v(\mathcal{S})=f$  then this contradicts  $v(\mathcal{S})=t$ . If  $v(\mathcal{T})=t$  then this contradicts  $v(\mathcal{T})=f$ .

Either way we have a contradiction so  $\mathcal{T}$  must be a tautology.

With this, we can go on to give the Soundness theorem.

**Theorem**

If  $\vdash \mathcal{S}$  then  $\vDash \mathcal{S}$ , where  $\mathcal{S}$  is any sentence.

**Proof**

If  $\mathcal{S}$  is a theorem then there is a sequence  $\mathcal{S}_1, \dots, \mathcal{S}_n$  with  $\mathcal{S}_n = \mathcal{S}$  such that the sequence is a proof of  $\mathcal{S}$ . If  $\mathcal{S}$  is an axiom then there is nothing to prove since it can be shown by straightforward calculation of their truth-values that all our axioms are tautologies. If  $\mathcal{S}$  is not an axiom then we proceed by induction on the length of the proof of  $\mathcal{S}$ .

If  $n=1$  then  $\mathcal{S}$  is an axiom (by the definition of proof) and so  $\mathcal{S}$  is a tautology. If  $n>1$  then we proceed by assuming that all theorems with proofs of length less than  $n$  are tautologies.

Now, either  $\mathcal{S}$  is an axiom or the proof of  $\mathcal{S}$  contains two sentences  $\mathcal{S}_i$  and  $\mathcal{S}_j$ , with  $i, j < n$ , such that  $\mathcal{S}_j$  (say) is  $(\mathcal{S}_i \square \mathcal{S})$ .  $\mathcal{S}_i$  and  $\mathcal{S}_j$  are tautologies by hypothesis (since they have proofs of length less than  $n$ ) and so, by Lemma 1,  $\mathcal{S}$  is a tautology too. So the induction step is complete and the soundness theorem is proved.

Before we go on to the completeness theorem we need the other lemma.

**Lemma 2**

Let  $\mathcal{S}$  be any sentence and let  $\mathcal{S}_1, \dots, \mathcal{S}_n$  be the propositional variables that appear in  $\mathcal{S}$ . Let  $v$  be any valuation. Then if  $v(\mathcal{S}_i) = t$  let  $\mathcal{S}_i'$  be  $\mathcal{S}_i$  while if  $v(\mathcal{S}_i) = f$  let

$S_i'$  be  $\neg S_i$ . Also let  $S'$  be  $S$  if  $v(S) = t$  and  $S'$  be  $\neg S$  if  $v(S) = f$ . Then we have that  $\{S_1', \dots, S_n'\} \vdash S'$ .

### Proof

This is by induction on the structure of  $S$ . Let us assume that  $S$  has  $m$  occurrences of connectives.

In the case that  $m=0$ ,  $S$  is atomic and so consists of a single propositional variable. Clearly, if  $v(S) = t$  then we put  $S' = S$  and we have  $S' \vdash S'$  and if  $v(S) = f$  then we put  $S' = \neg S$  and so  $S' \vdash S'$ . So the theorem holds for this simplest case. Now assume that it holds for any  $j < m$ . There are several cases and sub-cases to deal with.

a) If  $S$  is of the form  $\mathcal{T}_1 \square \mathcal{T}_2$  then  $\mathcal{T}_1$  and  $\mathcal{T}_2$  have less than  $m$  connectives and so by the assumption we have  $\{S_1', \dots, S_k'\} \vdash \mathcal{T}_1'$  and  $\{S_1', \dots, S_k'\} \vdash \mathcal{T}_2'$ , where  $S_1', \dots, S_k'$  are the propositional variables in  $S$ .

i) If  $v(\mathcal{T}_1) = t$  then  $\mathcal{T}_1'$  is  $\mathcal{T}_1$  and if  $v(\mathcal{T}_2) = t$  then  $\mathcal{T}_2'$  is  $\mathcal{T}_2$ . Also we have  $v(\mathcal{T}_1 \square \mathcal{T}_2) = t$  and so  $S'$  is  $\mathcal{T}_1 \square \mathcal{T}_2$ . By the assumption, therefore,  $\{S_1', \dots, S_k'\} \vdash \mathcal{T}_2$  and since  $\vdash \mathcal{T}_2 \square (\mathcal{T}_1 \square \mathcal{T}_2)$  we have, by Modus Ponens, that  $\{S_1', \dots, S_k'\} \vdash \mathcal{T}_1 \square \mathcal{T}_2$ , i.e.  $\{S_1', \dots, S_k'\} \vdash S'$ .

ii) If  $v(\mathcal{T}_1) = t$  then  $\mathcal{T}_1'$  is  $\mathcal{T}_1$  and if  $v(\mathcal{T}_2) = f$  then  $\mathcal{T}_2'$  is  $\neg \mathcal{T}_2$ . Also we have  $v(\mathcal{T}_1 \square \mathcal{T}_2) = f$  and so  $S'$  is  $\neg(\mathcal{T}_1 \square \mathcal{T}_2)$ . By the assumption, therefore,  $\{S_1', \dots, S_k'\} \vdash \neg \mathcal{T}_2$  and  $\{S_1', \dots, S_k'\} \vdash \mathcal{T}_1$  and since we can show that  $\vdash \mathcal{T}_1 \square (\neg \mathcal{T}_2 \square \neg(\mathcal{T}_1 \square \mathcal{T}_2))$  we have, by Modus Ponens twice, that  $\{S_1', \dots, S_k'\} \vdash \neg(\mathcal{T}_1 \square \mathcal{T}_2)$ , i.e.  $\{S_1', \dots, S_k'\} \vdash S'$ .

iii) If  $v(\mathcal{T}_1) = f$  then  $\mathcal{T}_1'$  is  $\neg \mathcal{T}_1$  and, whatever value  $v$  gives  $\mathcal{T}_2$ , we have  $v(\mathcal{T}_1 \square \mathcal{T}_2) = t$  and so  $S'$  is  $\mathcal{T}_1 \square \mathcal{T}_2$ . By the assumption, therefore,  $\{S_1', \dots, S_k'\} \vdash \neg \mathcal{T}_1$  and since  $\vdash \neg \mathcal{T}_1 \square (\mathcal{T}_1 \square \mathcal{T}_2)$  we have, by Modus Ponens, that  $\{S_1', \dots, S_k'\} \vdash \mathcal{T}_1 \square \mathcal{T}_2$ , i.e.  $\{S_1', \dots, S_k'\} \vdash S'$ .

b) If  $S$  is of the form  $\neg \mathcal{T}_1$  then  $\mathcal{T}_1$  has less than  $n$  connectives and so  $\{S_1', \dots, S_k'\} \vdash \mathcal{T}_1'$ , by the assumption.

i) If  $v(\mathcal{T}_1) = t$  then  $\mathcal{T}_1'$  is  $\mathcal{T}_1$  and  $v(\mathcal{S}) = f$  so  $\mathcal{S}'$  is  $\neg\mathcal{S}$ . Since  $\vdash \mathcal{T}_1 \square \neg\neg\mathcal{T}_1$  we have by MP that  $\{S_1', \dots, S_k'\} \vdash \neg\neg\mathcal{T}_1$ , i.e.  $\{S_1', \dots, S_k'\} \vdash \neg\mathcal{S}$ , i.e.  $\{S_1', \dots, S_k'\} \vdash \mathcal{S}'$ .

ii) If  $v(\mathcal{T}_1) = f$  then  $\mathcal{T}_1'$  is  $\neg\mathcal{T}_1$  and  $v(\mathcal{S}) = t$  so  $\mathcal{S}'$  is  $\mathcal{S}$ . Therefore  $\{S_1', \dots, S_k'\} \vdash \neg\mathcal{T}_1$ , i.e.  $\{S_1', \dots, S_k'\} \vdash \mathcal{S}'$ .

With that we have covered all cases and, by induction on  $n$ , the proof is complete.

### Theorem

If  $\vDash \mathcal{S}$  then  $\vdash \mathcal{S}$ , for any sentence  $\mathcal{S}$ .

### Proof

Assume that  $\vDash \mathcal{S}$ . Let  $S_1, \dots, S_n$  be the propositional variables in  $\mathcal{S}$ . By Lemma 2 we know that, for any valuation,  $\{S_1', \dots, S_n'\} \vdash \mathcal{S}$ . Note here that  $\mathcal{S}'$  is  $\mathcal{S}$  since  $\vDash \mathcal{S}$ , so for any valuation  $\mathcal{S}$  is true. Therefore we have that  $\{S_1', \dots, S_{n-1}', S_n\} \vdash \mathcal{S}$  and  $\{S_1', \dots, S_{n-1}', \neg S_n\} \vdash \mathcal{S}$ .

Using the deduction theorem we have  $\{S_1', \dots, S_{n-1}'\} \vdash S_n \square \mathcal{S}$  and  $\{S_1', \dots, S_{n-1}'\} \vdash \neg S_n \square \mathcal{S}$ . Since we can show  $\vdash (S_n \square \mathcal{S}) \square ((\neg S_n \square \mathcal{S}) \square \mathcal{S})$  we have, using MP twice,  $\{S_1', \dots, S_{n-1}'\} \vdash \mathcal{S}$ . By repeating this process  $n-1$  more times we have  $\vdash \mathcal{S}$  as required.

### Example 2.3

As an example of how this proof works, consider the case in which  $\mathcal{S}$  is  $(p \square (q \square p))$ . Then, by Lemma 2, we have  $\{p', q'\} \vdash (p \square (q \square p))$ . Writing this out in full we have

$$\begin{aligned} &\{p, q\} \vdash (p \square (q \square p)) \\ &\quad \text{and} \\ &\{p, \neg q\} \vdash (p \square (q \square p)) \\ &\quad \text{and} \\ &\{\neg p, q\} \vdash (p \square (q \square p)) \\ &\quad \text{and} \\ &\{\neg p, \neg q\} \vdash (p \square (q \square p)). \end{aligned}$$

So by the deduction theorem we have

$$\begin{aligned} & \{p\} \vdash (q \supset (p \supset (q \supset p))) \text{ and } \{p\} \vdash (\neg q \supset (p \supset (q \supset p))) \\ & \text{and} \\ & \{\neg p\} \vdash (q \supset (p \supset (q \supset p))) \text{ and } \{\neg p\} \vdash (\neg q \supset (p \supset (q \supset p))) \end{aligned}$$

The first two of these can be combined twice with

$$\vdash (q \supset (p \supset (q \supset p))) \supset ((\neg q \supset (p \supset (q \supset p))) \supset (p \supset (q \supset p)))$$

using Modus Ponens to give

$$\{p\} \vdash (p \supset (q \supset p))$$

and similarly for the second two to give

$$\{\neg p\} \vdash (p \supset (q \supset p))$$

This can then be repeated to give

$$\vdash (p \supset (q \supset p))$$

## Summary

- A logical *language* is defined by giving its *alphabet* and its *grammar*—a set of rules that says which strings of symbols from the alphabet are well-formed *sentences*. We give the alphabet and grammar of *propositional logic*. The property of being a sentence is *decidable* and there is a computationally effective method of *enumerating* the sentences of the language. We demonstrate this by giving SML and Prolog programs for decidability and enumeration.

- An important part of logic is the study of *arguments* - of which conclusions can correctly be said to follow from given premises. The validity of an argument is judged from its *form* not its meaning. A valid argument can have a false conclusion -

provided its premises are false - but a valid argument applied to true premises always gives a true conclusion. In classical propositional logic the validity of argument forms can be decided by *truth-tables*.

- Meaning is given to a language via a set of rules that enable you to calculate what the sentences of the language *denote*. Languages in which you can calculate the truth-value of a sentence from the truth-values of its sub-sentences are called *truth-functional*. Classical propositional logic is truth-functional and the calculation rules are given by truth-tables for each of the connectives. A truth-table can be constructed for any given sentence by listing all the ways in which truth-values can be assigned to its constituent propositional variables and, using the truth-tables for the connectives, calculating the value of the sentence in each case. An assignment of truth-values to propositional variables is called a *valuation*. A formula that is true in every valuation is said to be *valid*. Valid formulas in propositional logic are called *tautologies*.

- A set of sentences  $G$  *entails* a sentence  $S$ , written  $G \vDash S$  if every valuation that makes all the sentences in  $G$  true makes  $S$  true also. If no valuation makes all the sentences in  $G$  true then  $G$  is said to be *inconsistent*.

- A *formal system* enables the validity of arguments in a language to be decided without reference to the notions of true and false. As well as the alphabet and grammar of the language a formal system has *axioms* and *rules of inference*. A *proof* in such a system is a sequence of sentences each of which is either an axiom or is derived from earlier members of the sequence by using the rules of inference. The final sentence of such a sequence is said to be a *theorem* of the system. It can be shown that the formal system for classical propositional logic given in this chapter is *sound* and *complete* in the sense that all its theorems are tautologies and all tautologies are among its theorems.

# CHAPTER THREE

---

## Extending the language

### 3.1. Informal predicate calculus

The simplicity of the propositional calculus is also its worst shortcoming. A simple argument like

All men are mortal  
Socrates is a man  
therefore  
Socrates is mortal

is of the form

$A$   
 $M$   
therefore  
 $D$

or, in propositional logic

$(A \wedge M) \rightarrow D$

but this, as you can verify, is not a valid argument; the truth-table does not give 't' for every valuation. However, we would obviously like to characterize such arguments as valid. To do this we have to look at the internal structure of the propositions.

'All men are mortal' has the natural language form 'if  $x$  is a man then  $x$  is mortal, for all  $x$ '. We are going to define a language called predicate calculus in which this can be written formally as  $\forall x(M(x) \supset D(x))$ .

Here,  $x$  is a variable which is understood to stand for any object,  $\forall$  is a universal quantifier ('for all...') and  $M$  and  $D$  are one-place predicates. That is, they express properties that the objects which are their arguments have.

If we write 's' for Socrates we have  $M(s)$  and  $D(s)$  for the other two sentences in the argument. Now we can show the argument to be valid.

$\forall x(M(x) \supset D(x))$  says that, for any  $x$ ,  $(M(x) \supset D(x))$  so it is certainly true to say  $(M(s) \supset D(s))$ . But we are given  $M(s)$ , so by propositional logic we can deduce  $D(s)$ .

We now give the formal definition of the language.

### 3.1.1. Grammatical Definitions

#### Definition 3.1

A language of predicate calculus based on  $\langle P, N, F \rangle$ , written  $L(\langle P, N, F \rangle)$ , is defined by:

- a) the alphabet, which has the seven components:
  - i) a set of connective symbols  $\{ \neg, \wedge, \vee, \supset, \equiv \}$ ,
  - ii) a set of quantifier symbols  $\{ \forall, \exists \}$ ,
  - iii) a set of punctuation symbols  $\{ (, ), \cdot \}$ ,
  - iv) a set  $P$  of sets  $P_n$  of  $n$ -ary predicate symbols for each  $n \geq 0$ ,
  - v) a set  $N$  of names  $\{ a, b, c, \dots \}$ ,
  - vi) a set  $F$  of sets  $F_n$  of  $n$ -ary function symbols  $\{ f, g, \dots \}$  for each  $n \geq 0$ .

We call  $P$ ,  $N$  and  $F$  the parameters of the language.

Each language also contains (vii) a set  $V$  of variables  $\{ x, y, \dots, x_1, x_2, \dots \}$ . However, since this set is included in all languages there is no need to include it in the parameters that define the language.

- b) the grammar, which defines  $L(\langle P, N, F \rangle)$ , the set of sentences based on  $\langle P, N, F \rangle$ . It is given here informally by describing several kinds of object which go to make up sentences (and as before we will not mention the basis of the sentence and its parts explicitly unless it is not clear from the context what we are referring to).

A term based on  $\langle P, N, F \rangle$  is either a variable, or a name, or a function symbol followed in brackets, and separated by commas, by the correct number of terms for the function symbol's arity.

For example  $x$ ,  $a$  and  $f(x, a, g(y, z))$  are all terms if  $f$  has arity 3,  $g$  has arity 2,  $a$  is a name and  $x$ ,  $y$  and  $z$  are variables.

A formula based on  $\langle P, N, F \rangle$  is of the form

$$\neg F \text{ or } (F * G), \text{ or } QvF \text{ or } P(t_1, t_2, \dots, t_n),$$

where  $*$  is one of the binary logical connectives,  $F$  and  $G$  are formulas, called sub-formulas of the formula,  $Q$  is a quantifier,  $v$  is a variable and  $P(t_1, t_2, \dots, t_n)$  is an atomic formula consisting of a predicate symbol followed in brackets, and separated by commas, by the correct number of terms for its arity .

In the case  $QvF$  where  $F$  contains no quantifiers we say that any occurrence of  $v$  in  $F$  is bound by  $Q$  in  $F$ , and  $F$  is the scope of  $Q$ . If an occurrence of a variable  $v$  is bound by a quantifier then it is a bound occurrence and we say that the quantifier binds  $v$ . In the case of  $QvF$  where  $F$  does contain quantifiers then any occurrences of  $v$  in  $F$  which are not bound by any other quantifier in  $F$  are bound by  $Q$ . In this case the scope of  $Q$  consists of all sub-formulas of  $F$  that are not in the scope of a quantifier other than  $Q$  that binds  $v$ .

Note that no occurrence of a variable can be bound by more than one quantifier. If an occurrence of a variable  $v$  is not bound by any quantifier then that occurrence is a free occurrence.

A sentence based on  $\langle P, N, F \rangle$  is a formula in which no free variables occur. An atomic formula with no free variables is an atomic sentence.

For example, if  $a$  is a name and  $x$  is a variable then  $f(x, a)$  is a term, provided that  $f$  is a function symbol of arity two,  $(A \sqcap B(x, f(y, a)))$  is a formula in which  $x$  and  $y$  are free,  $\sqcap x \sqcap y (A \sqcap B(x, f(y, a)))$  is a sentence and  $R(a, b, c)$  is an atomic sentence.

One final definition in this section is of the notion of a term  $t$  being free for a variable  $v$ . This essentially means that no variables of  $t$  are 'captured' when  $t$  is substituted for  $v$  in a formula  $\mathcal{F}$ .

### Definition 3.2

If  $\mathcal{F}$  is a formula and  $v$  is a variable then the term  $t$  is free for  $v$  in  $\mathcal{F}$  iff there is no variable  $u$  in  $t$  such that  $v$  appears within the scope of a quantifier that binds  $u$ .

For example, if  $\exists x_1 A(x_1, x_2)$  is the formula in question, then  $f(x_1, x_3)$  is not free for  $x_1$ . Since  $x_2$  appears within the scope, namely  $A(x_1, x_2)$ , of a quantifier that binds  $x_1$ , the  $x_1$  in  $f(x_1, x_3)$  is captured by the quantifier. However,  $f(x_2, x_3)$  is free for  $x_2$  in the same formula since the only quantifier binds  $x_1$  and this variable does not appear in  $f(x_2, x_3)$ .

Now we can extend the SML declarations that define the language in the previous section. The extensions that we need are to do with the terms, and the addition of predicates and quantifiers to the language. First, we have to decide on how to represent the terms. From the definition a term is either a variable or a name or a function whose parameter places are filled with the correct number of terms for its arity. So the following SML datatype can be used:

```
datatype TERM = Var of string
              | Name of string
              | app of (string * TERM list)
              | empty;
```

So, the term which is the name "a" will be represented as `Name "a"`; the variable "x" will be represented as `Var "x"`; the application of a function to its arguments as in "g(a,b)" will be represented by `app("g", [Name "a", Name "b"])` and so on.

Having represented the terms we can extend the declaration of SENT, for the sentences:

```
datatype SENT = Prop of string
              | Not of SENT
              | And of (SENT * SENT)
              | Or of (SENT * SENT)
              | Imp of (SENT * SENT)
              | Eq of (SENT * SENT)
              | Forall of (TERM * SENT)
```

```
| Exists of (TERM * SENT)
| Pred of (string * TERM list);
```

### 3.1.2. Interpretations

We now go on to define the meaning of the sentences of the language. This is done by introducing the notion of interpretation:

#### Definition 3.3

An interpretation of a language  $L(\langle P, N, F \rangle)$  - and we will shorten this to just  $L$  in this section - over a universe  $U$  is a pair

$$I_U = \langle \square_U, \square_U \rangle^L$$

where

$U$  is a non-empty set of objects, which the terms refer to, called the universe  
 $\square_U : P_n \rightarrow \wp U^n$  maps, for each  $P_n$  in  $P$ , the  $n$ -ary predicate symbols to  $n$ -ary relations over  $U$

$\square_U : N \rightarrow U$  maps the names to objects in the universe

$\square_U : F_n \rightarrow (U^n \rightarrow U)$  maps, for each  $F_n$  in  $F$ , the  $n$ -ary function symbols to  $n$ -ary functions over the universe.

Note that  $\square_U$  is overloaded, i.e. the symbol stands for two operations. However, this is not ambiguous because, when it is applied, we can always tell from its argument which operation to use.

$\square_U$  maps  $n$ -ary predicate symbols to the relations which they denote. We think of a relation as given by the set of tuples of objects from  $U$  which are in the relation to one another (which you may see called its extension). For instance, in mathematics the symbol " $<$ " as a relation over the universe of the positive integers  $\{1, 2, 3, \dots\}$  has, as its extension, the set of ordered pairs  $\{(1, 2), (1, 3), (2, 3), \dots\}$  because 1 is less than 2, 1 is less than 3, 2 is less than 3 and so on.

We have to extend  $\square_U$  so that, when applied to an element from the set of terms  $T$ ,  $\square_U$  produces as its value an object from  $U$ . So, we define

$$\square_U(g(t_1, \dots, t_m)) = \square_U(g)(\square_U(t_1), \dots, \square_U(t_m))$$

for each  $g \in F_m, t_i \in T$ .

Finally, to make such a  $\mathcal{I}_U$  complete, each variable must also denote an object in  $U$ . This is done by considering  $\mathcal{I}_U$  to be, in fact, a set of functions, which we call assignments and which we denote by  $\mathcal{A}_U$ . All assignments  $\mathcal{A}_U$  in the set  $\mathcal{A}_U$  agree on the names and function symbols and they all obey the equation above. So, on the names and function symbols we are justified in thinking of just one assignment, since all the elements of the set of assignments behave in the same way for these arguments. However, they differ on what they map the variables to and there are enough of them to allow a given variable to be mapped to each of the objects in the universe.

The name "assignment" for such functions varies between authors. Some (Hamilton (1978) for example) use the word "valuation" (and in the way we used it previously, which is rather confusing) and Mendelson uses "sequence" for part of it. Some use no name at all. Hodges (1977) seems to use "assignment" too.

We are now in a position to give a hierarchy by which the truth of a sentence in a particular language  $L$  can be determined.

#### Definition 3.4

An assignment  $\mathcal{A}_U$  satisfies a formula in an interpretation  $\mathcal{I}_U^L$  according to the following, where  $\mathcal{F}$  and  $\mathcal{G}$  are any formulas:

- 1) for any predicate  $Q \in P_n$ ,  $\mathcal{A}_U$  satisfies  $Q(t_1, \dots, t_n)$ , for any  $t_i \in T$ , iff  $(\mathcal{A}_U(t_1), \dots, \mathcal{A}_U(t_n)) \in \mathcal{I}_U(Q)$
- 2)  $\mathcal{A}_U$  satisfies  $\neg \mathcal{F}$  iff  $\mathcal{A}_U$  does not satisfy  $\mathcal{F}$
- 3)  $\mathcal{A}_U$  satisfies  $(\mathcal{F} \wedge \mathcal{G})$  iff  $\mathcal{A}_U$  satisfies both  $\mathcal{F}$  and  $\mathcal{G}$ ,
- 4)  $\mathcal{A}_U$  satisfies  $(\mathcal{F} \vee \mathcal{G})$  iff  $\mathcal{A}_U$  satisfies either  $\mathcal{F}$  or  $\mathcal{G}$ , or both,
- 5)  $\mathcal{A}_U$  satisfies  $(\mathcal{F} \rightarrow \mathcal{G})$  iff  $\mathcal{A}_U$  satisfies  $(\neg \mathcal{F} \vee \mathcal{G})$ ,
- 6)  $\mathcal{A}_U$  satisfies  $(\mathcal{F} \leftrightarrow \mathcal{G})$  iff  $\mathcal{A}_U$  satisfies  $(\mathcal{F} \rightarrow \mathcal{G}) \wedge (\neg \mathcal{F} \rightarrow \neg \mathcal{G})$
- 7)  $\mathcal{A}_U$  satisfies  $\exists x \mathcal{F}$  iff there is an element  $a$  of  $U$  such that there is some assignment  $\mathcal{A}'_U$  from  $\mathcal{I}_U^L$ , which is the same as  $\mathcal{A}_U$  except perhaps at  $x$  where  $\mathcal{A}'_U(x) = a$ , which satisfies  $\mathcal{F}$ .
- 8)  $\mathcal{A}_U$  satisfies  $\forall x \mathcal{F}$  iff  $\mathcal{A}_U$  satisfies  $\neg \exists x \neg \mathcal{F}$ . This is the same as saying that there is no element  $a$  of  $U$  such that there is some assignment  $\mathcal{A}'_U$  from  $\mathcal{I}_U^L$  which is the same as  $\mathcal{A}_U$ , except perhaps at  $x$  where  $\mathcal{A}'_U(x) = a$ , which does not satisfy  $\mathcal{F}$ . This, in turn, says that for every element  $a$  in  $U$  all assignments  $\mathcal{A}'_U$ , which are the same as  $\mathcal{A}_U$ , except perhaps at  $x$  where  $\mathcal{A}'_U(x) = a$ , satisfy  $\mathcal{F}$ .

The fact that variables are only allowed to range over members of the universe leads to other names for the language that we are studying. In full we should call it a first-order predicate language. In the same vein, the propositional language, where quantifiers ranged over nothing (since there were none) might be called a zero-order predicate language. So, the order of the language refers to the "level" of the objects up to and including which the quantifiers can range over. You can think of the level as being the place that the objects come in the series which starts

nothing	zeroth-order
the universe	first-order
relations over the universe (i.e. predicates)	second-order
relations over relations	third-order
etc.	etc.

We will use the term "predicate logic" or "predicate calculus" to refer only to the first-order case, so there is no ambiguity. Sometimes we may talk of "first-order logic" or "first-order language" when we refer to this same level.

### Definition 3.5

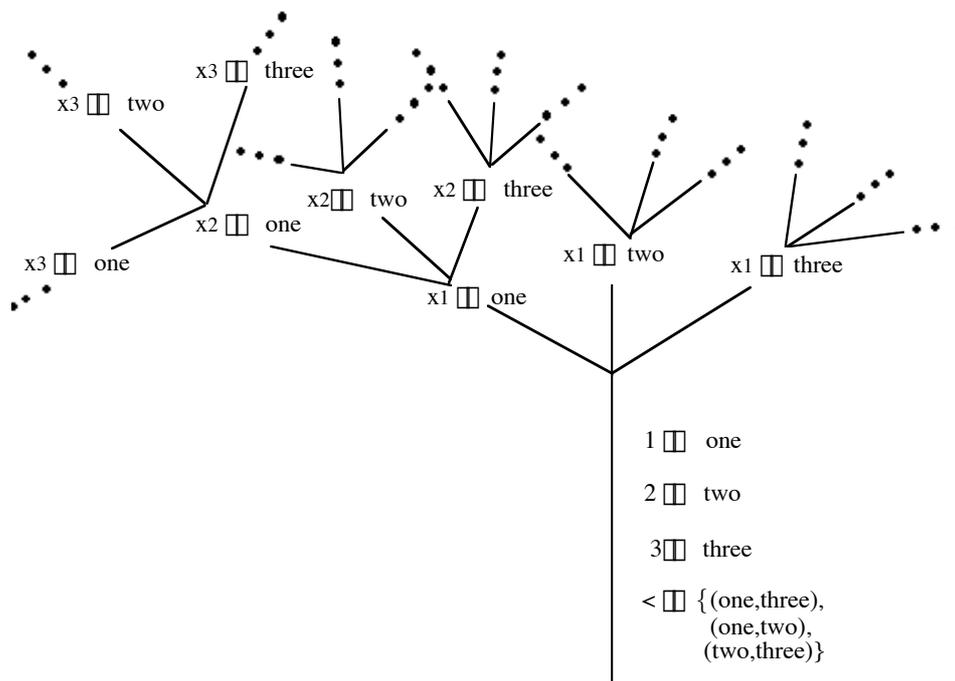
A formula is true in an interpretation  $I_U^L$  iff all the assignments in  $I_U^L$  satisfy it. A formula is valid iff it is true in every interpretation of its language  $L$ . Conversely, a formula is false in an interpretation  $I_U^L$  iff no assignment in  $I_U^L$  satisfies it and it is unsatisfiable iff it is false in every interpretation. Formulas that are not unsatisfiable are satisfiable.

Note that in the propositional case, since there are no terms, the assignment functions are redundant and then an interpretation collapses to what we called a valuation (as long as we equate the propositions with nullary predicates).

Note that the definition implies that if we wish to see whether a sentence is true in some interpretation then we have to show that it is satisfied by all assignments in the interpretation. This, clearly, may involve a lot of work (especially if the number of assignments is infinite!). However, it can be proved that a sentence is satisfied by all assignments in an interpretation iff it is satisfied by at least one assignment in the interpretation, which means that the amount of work required to see whether a sentence is true in an interpretation can be vastly reduced.

### 3.1.3. Examples on interpretations

1) The sentence  $\exists x_1 (1 < x_1)$  is true in the interpretation which makes '1' denote the number one and '<', which is an infix predicate symbol in the formal language, denote the less-than relation over the integers {one, two, three}. To see this in a graphical way imagine all the possible assignments in this interpretation displayed as a tree. The common part of all the assignments maps 1 to one, 2 to two, 3 to three and < to the relation whose extension is {(one,two), (one,three), (two,three)}. This is shown on the trunk of the tree. The branches then show all the possible extensions which give all the possible assignments:



We can see that for an arbitrary assignment (path up the tree) there is an assignment that is the same everywhere except possibly at  $x_1$ , where it maps  $x_1$  to two. This means that the assignment satisfies the existential sentence and so it meets the condition for being satisfied by any assignment and so it is true under the interpretation.

2) The sentence

$$1 < 2 \mapsto \exists x(x < 2)$$

is valid. We can think of this as saying that "in those assignments where the left-hand side is satisfied, the right-hand side is too". This is the case since any assignment which satisfies  $1 < 2$  will clearly (trivially) satisfy  $\forall x(x < 2)$ . This argument then extends to any interpretation, which might be clearer if we use a less suggestive language and write the sentence as

$$P(a,b) \iff \forall x P(x,b)$$

3) In the same interpretation as above

$$\forall x(x < 1)$$

is a false sentence. This is so because, for an arbitrary assignment, there is no assignment which is the same, except perhaps at  $x_1$ , such that  $x_1$  is mapped to an element of the universe which is in the relation less-than to 1.

4) An example of an unsatisfiable sentence is  $1 < 2 \iff \forall x \neg(x < 2)$ .

5) The sentence

$$\forall x \forall y \forall z (x < y \iff y < z \iff x < z)$$

is satisfiable. It is true if ' $<$ ' is less-than over the natural numbers, and it is false if ' $<$ ' denotes "is the square-root of" over the same universe, since, for instance, we have  $2 < 4$  and  $4 < 16$  but not  $2 < 16$ .

In general, to prove validity, we must show that an arbitrary assignment in an arbitrary interpretation satisfies the sentence concerned.

On the other hand, to prove a sentence non-valid we must be ingenious enough to actually construct an interpretation in which there is a assignment which does not satisfy the sentence.

In the sequel we will usually omit the references to  $L$  and  $U$  when they are clear from the context.

6) For a more extended example we consider a language with parameters as follows.

The set of predicate symbols is  $\{M, S\}$ , both symbols having arity two; the set of function symbols is  $\{f, m'\}$ , both with arity one; the set of names is  $\{a, b, c, d, e, f, g\}$ . This defines the language so that the following are all sentences:

$$\begin{aligned} &M(a,b) \\ &M(a,b) \sqcap M(b,a) \\ &\neg M(c,d) \\ &\sqcap x M(a,x) \\ &\sqcap x M(a,x) \\ &M(f'(a), m'(c)) \end{aligned}$$

However, even though we know that these are sentences, we still have no way of knowing their meaning. For this we need an interpretation. One interpretation, which we call  $I$ , is as follows:

$$\begin{aligned} I = \langle \sqcap_U, \sqcap_U \rangle \text{ where } U = \{ &\text{Albert, Brian, Cynthia, Dougal, Ermintrude,} \\ &\text{Florence, Georgina} \} \\ \sqcap_U(M) = \{ &(\text{Cynthia, Brian}), (\text{Brian, Cynthia}) \} \\ \sqcap_U(S) = \{ &(\text{Ermintrude, Dougal}), (\text{Dougal, Ermintrude}) \} \\ \sqcap_U(f') = \{ &(\text{Cynthia, Albert}), (\text{Florence, Brian}) \} \\ \sqcap_U(m') = \{ &(\text{Florence, Cynthia}), (\text{Ermintrude, Florence}), (\text{Dougal, Florence}) \} \end{aligned}$$

Given this interpretation we can work out the truth-values of some of the sentences above. For example we have, for  $M(a, b)$ , that  $(\sqcap_U(a), \sqcap_U(b)) = (\text{Albert, Brian}) \sqcap \{(\text{Cynthia, Brian}), (\text{Brian, Cynthia})\} = \sqcap_U(M)$ , so  $M(a, b)$  is not true since any completion of  $\sqcap_U$  will behave the same way.

7) As another example, we can give a different interpretation,  $J$ , to the same language as above. We define  $J$  as follows:

$$\begin{aligned} J = \langle \sqcap_V, \sqcap_V \rangle \text{ where } V = \{ &\text{Anne, Bill, Charles, Diana, Elizabeth, Fred,} \\ &\text{Gertrude} \} \\ \sqcap_V(M) = \{ &(\text{Anne, Bill}), (\text{Bill, Anne}), (\text{Fred, Gertrude}), (\text{Gertrude, Fred}) \} \\ \sqcap_V(S) = \{ &(\text{Charles, Diana}), (\text{Diana, Charles}), (\text{Bill, Elizabeth}), (\text{Elizabeth,} \\ &\text{Bill}) \} \\ \sqcap_V(f') = \{ &(\text{Diana, Bill}), (\text{Charles, Bill}), (\text{Bill, Fred}), (\text{Elizabeth, Fred}) \} \end{aligned}$$

$$\mathcal{I}(m') = \{(Elizabeth, Gertrude), (Bill, Gertrude), (Charles, Anna), (Diana, Anna)\}$$

Given this interpretation we have, for  $M(a,b)$ , that  $(\mathcal{I}(a), \mathcal{I}(b)) = (Anne, Bill) \in \{(Anne, Bill), (Bill, Anne), (Fred, Gertrude), (Gertrude, Fred)\} = \mathcal{I}(M)$ , so  $M(a,b)$  is true.

### Exercise 3.1

1) Work out whether the following are true in each of the interpretations  $I$  and  $J$  given in the previous section:

a)  $M(a,c)$

b)  $M(a,b) \wedge M(b,a)$

c)  $S(e,d)$

d)  $S(e,d) \wedge S(d,e)$

e)  $\exists x \exists y (M(x,y) \wedge M(y,x))$

f)  $\exists z M(f'(c), b)$

2) From your knowledge of family relationships and the legalities of marriage etc., choose suitable denotations for the function symbols  $f'$  and  $m'$ , and the predicate symbols  $M$  and  $S$  in the examples above. Draw the family trees that the interpretations  $I$  and  $J$  describe.

3) A first-order language  $L$  has the usual connectives and punctuation symbols, together with variable symbols  $x$  and  $y$ , a constant symbol  $a$ , a unary function symbol  $t$  and two binary predicate symbols  $=$  and  $<$ , both used in infix form.

The domain of an interpretation  $I$  for  $L$  is the set of integers  $D = \{0, 1, 2\}$ . The denotation of  $a$  is the number 0. The denotation of  $t$  is the function from  $D$  to  $D$  that, for any  $n \in D$ , maps  $n$  to the remainder on dividing  $(n+2)$  by 3. The denotation of  $<$  is the binary relation on  $D$  whose extension is  $\{<0,1>, <1,2>, <2,0>\}$  and the denotation of  $=$  is the usual identity relation over integers.

For each of the following strings of symbols say whether or not it is a formula of  $L$ . If it is, say whether the formula is true, satisfiable, or false in  $I$ . Justify your statement briefly. The first one has been completed for you as an example.

- a)  $t(t(a))=a$  is a formula of  $L$  and is false, because  $t(a)$  denotes the number 2, so  $t(t(a))$  denotes the number  $(2+2) \bmod 3 = 1$  and 1 is not the same number as 0.
- b)  $t(a)<a$  is .....
- c)  $\Box x(x>t(x))$  is .....
- d)  $\Box x( t(t(t(x))) =x )$  is .....
- e)  $\Box x\Box y(t(x)<t(y))$  is .....
- f)  $\Box x(t(x)<t(y))$  is .....
- g)  $\Box x((t(x)<t(y)) \Box \neg(x=y))$  is .....

### 3.2. FDS for predicate calculus

We have already seen an alphabet and (informal) grammar for this system. The following is a possible collection of axiom schemas:

Let  $\mathcal{S}, \mathcal{T}$  and  $\mathcal{R}$  be sentences of the language. Then:

P1)  $(\mathcal{S} \Box (\mathcal{T} \Box \mathcal{S}))$

P2)  $((\mathcal{S} \Box (\mathcal{T} \Box \mathcal{R})) \Box ((\mathcal{S} \Box \mathcal{T}) \Box (\mathcal{S} \Box \mathcal{R})))$

P3)  $((\neg\mathcal{S}) \Box (\neg\mathcal{T}) \Box (\mathcal{T} \Box \mathcal{S}))$

P4)  $(\Box x_i \mathcal{S} \Box \mathcal{S})$ , if  $x_i$  does not occur free in  $\mathcal{S}$

P5)  $(\Box x_i \mathcal{S} \Box \mathcal{S}[t/x_i])$ , if  $\mathcal{S}$  is a formula of the language in which  $x_i$  may appear free and  $t$  is free for  $x_i$  in  $\mathcal{S}$

P6)  $(\Box x_i (\mathcal{S} \Box \mathcal{T}) \Box (\mathcal{S} \Box \Box x_i \mathcal{T}))$ , if  $x_i$  does not occur free in  $\mathcal{S}$ .

Rules of deduction

- 1) Modus Ponens (MP), from  $\mathcal{S}$  and  $(\mathcal{S} \Box \mathcal{T})$  deduce  $\mathcal{T}$  where  $\mathcal{S}$  and  $\mathcal{T}$  are any formulas of the language.
- 2) Generalization, from  $\mathcal{S}$  deduce  $\Box x_i \mathcal{S}$ , where  $\mathcal{S}$  is any formula of the language.

Note that since the rules and axioms given above include those of the propositional calculus it is clear that any sentence that is a theorem of propositional calculus is also a theorem of predicate calculus.

One important fact about this new logic is that the deduction theorem does not go through quite as before. This time we need an extra condition in the premise of the theorem.

### **Theorem**

Let  $S$  and  $T$  be any sentences and let  $G$  be any set of sentences.

Then, if  $G, S \vdash T$ , and no use was made of Generalization involving a free variable of  $S$ , it is the case that  $G \vdash S \supset T$ .

It can be shown that predicate calculus has the same soundness and completeness properties that we proved for propositional calculus, although in this case we shall not give the proofs since they are even more involved than was the case for propositional calculus, though they follow the same lines.

One property that predicate calculus does not have is that of decidability. That is, the question "Is this sentence valid or not?" cannot be answered if we use any method which, essentially, can be programmed. We say that predicate calculus is undecidable (though we will be able to refine this statement later on). The lack of an answer does not depend on how clever the method is, or how long we set it to work for. It is simply that for some sentences there is no answer.

#### *3.2.1. Deciding on Proofhood*

Even though there are bounds to what is possible computationally, we can extend some of the programs that we had in the sections on propositional logic to the predicate case since, although deciding on validity is not possible in general, deciding on proofhood is. This is because a proof is simply a finite sequence of finite sentences, each of which has to have some decidable property that we can check.

We saw above how the language can be extended to include terms, quantifiers and predicates. In order to be able to check a sequence of sentences to see whether it satisfies the definition of a proof in predicate logic, as we did for propositional logic, we first need some programs for checking for free variables, deciding on axiomhood etc. The first function we define tests to see if a given variable occurs in a given term and of course the program follows the definition of the structure of a term:

```

infix occurs_in;
fun v occurs_in ((Name n)::t)      = false orelse (v occurs_in t)
  | v occurs_in ((Var w)::t)       = (v = w) orelse (v occurs_in t)
  | v occurs_in (app(f,terms)::t) = (v occurs_in terms) orelse
                                     (v occurs_in t);

infix free_in;
fun v free_in (And(s,t)) = (v free_in s) orelse (v free_in t)
  | v free_in (Or(s,t))  = (v free_in s) orelse (v free_in t)
  | v free_in (Imp(s,t)) = (v free_in s) orelse (v free_in t)
  | v free_in (Eq(s,t))  = (v free_in s) orelse (v free_in t)
  | v free_in (Not(s))   = (v free_in s) orelse (v free_in t)
  | v free_in (Forall(Var y,s)) = if v = Var y
                                   then false
                                   else v free_in s
  | v free_in (Exists(Var y,s)) = if v = Var y
                                   then false
                                   else v free_in s
  | v free_in (Pred(p,terms)) = v occurs_in terms
  | v free_in (Prop p) = false;

```

This may look rather complicated but in fact the computation, as before, simply follows the structure of the sentence being tested. As we can see, for each of the connectives we just test for the variable being free in each sub-sentence. For the quantifiers, if the bound variable is the same as the variable then clearly it is not free. The only interesting case, really, is the atomic sentence of the form  $P(t_1, \dots, t_n)$ . Here we just test to see if the variable occurs in any of  $t_1$  to  $t_n$ . Finally, if the sentence is propositional then clearly the variable does not occur, so it does not occur free.

In order to test for axiomhood we also need a test to see whether a term is free for a variable in a sentence, but we assume that we have such a function, which we call `free_for` (and leave its development as an exercise).

We can now go on to give functions for the three new axiom schemas P4, P5 and P6:

```

fun axiom1 (Imp(S, Imp(T, S'))) = S=S'
  | axiom1 s                    = false;

fun axiom2 (Imp(Imp(S, Imp(T, R)), Imp(Imp(S', T'), Imp(S'', R')))) =
  (S=S') andalso (T=T') andalso (R=R') andalso (S=S'')
  | axiom2 s = false;

fun axiom3 (Imp(Imp(Not S, Not T), Imp(T', S'))) = (S=S') andalso (T=T')
  | axiom3 s = false;

fun axiom4 (Imp(Forall(x, S), S')) = not(x free_in S)
  | axiom4 _ = false;

fun axiom5 (Imp(Forall(x, S), S')) =
  let val (ok, t) = forms_match (x, S) S' in

```

```

        if ok then t free_for (x,S) else false
      end
    | axiom5 _ = false;

fun axiom6 (Imp(Forall(x, Imp(S,T)), Imp(S', Forall(x', T')))) =
  S=S' andalso T=T' andalso x=x' andalso not(x free_in S)
  | axiom6 _ = false;

fun axiom s = axiom1 s orelse axiom2 s orelse axiom3 s
  orelse axiom4 s orelse axiom5 s orelse axiom6 s;

```

The function `forms_match` is again left as an exercise, and it essentially takes two sentences and a variable and returns true if the sentences match up to occurrences of the variable and also the term that appears in place of the variable where the variable does not itself appear. For instance we have that `forms_match` applied to the formulae  $P(x)$  and  $P(f(a))$  and the variable  $x$  returns true, since the sentences are the same up to the occurrence of  $x$ , together with  $f(a)$ , since that is the term that appears in the place of  $x$ . If we apply it to  $Q(x,x)$  and  $Q(f(b),f(a))$  then it returns false since the formulas do not match because the terms in place of  $x$  are not the same.

The final part we need is to check for a correct use of the rule of generalization. This means that if a sentence of the form  $\forall x.S$  appears in the sequence of sentences that we are testing for proofhood then we also need to see if a sentence of the form  $S$  appears before it in the sequence. The following SML function does just that:

```

fun generalization l (Forall(x,S)) = S memberof l
  | generalization _ _ = false;

```

We can then adapt and extend the function `proof` as given before to give a proof-checker for predicate logic too. This is again left as an exercise.

### Exercise 3.2

- 1) Which of the following statements are correct and which incorrect?

In the sentence  $\forall x_1 A(x_2)$

- i)  $x_2$  is free for  $x_2$
- ii)  $x_2$  is free for  $x_1$
- iii)  $x_1$  is free for  $x_2$

iv)  $x_7$  is free for  $x_2$

v)  $f(x_1, x_7)$  is free for  $x_2$

2) In the sentences and formulae below, is the term  $f(x_1, x_3)$  free for  $x_2$  or not?

i)  $\exists x_2(A(x_1, x_2) \wedge A(x_2, a))$

ii)  $\exists x_1 \exists x_3(A(x_1, x_2) \wedge B(x_3))$

iii)  $\exists x_2 A(f(x_2)) \wedge \exists x_3 B(x_1, x_2, x_3)$

iv)  $\neg \neg A(x_2) \wedge \exists x_5 A(x_2)$

v)  $\exists x_2 A(x_2)$

3) Show that

i)  $x_i$  is free for  $x_i$  in any formula

ii) any term is free for  $x_i$  in a formula  $S$  if  $S$  contains no free occurrences of  $x_i$ .

4) Write an SML or Prolog program which tests whether a given term is free for a given variable in a given formula.

5) Construct proofs of the following theorems of predicate calculus:

a)  $\exists x_1 \exists x_2 A \vdash \exists x_2 \exists x_1 A$

b)  $\exists x_1 \exists x_2 A(x_1, x_2) \vdash \exists x_1 A(x_1, x_1)$

6) The word "theorem" is used in two different ways in chapter two. Give one example of each of these two uses of "theorem", from sections five or six.

7) Write an SML or Prolog program which implements the `forms_match` function needed for this section.

8) Adapt and extend the program for proof in the previous chapter so that it works on proofs in predicate logic too.

### 3.3. Historical discussion

The undecidability of predicate logic is one of the fundamental results for Computer Science as well as for Logic and it links our subject with the work of some of the greatest mathematicians and logicians of the modern era. First, the German mathematician David Hilbert, who was celebrated as the greatest mathematician of his time, being something of an all-rounder, proposed 23 problems at a congress of mathematicians from all over the world in 1900. (See (Reid, 1970) for his bibliography). He stated in the introduction to these problems that he was convinced that every mathematical problem could be answered, either with a solution or with a proof that it had no solution. He even referred to "this axiom of solvability". The problems that he listed (and, even though there were 23, he only described 10 in the lecture, since the talk was considered long enough already) lead, as he had hoped when he propounded them, to some of the greatest discoveries in mathematics.

Unfortunately for Hilbert, as we now know and have said above, his "axiom of solvability" is not valid. We now know that even completely rigorously stated problems, i.e. problems expressed in the completely formal language of logic, cannot, in general, be solved. That is, there are logical sentences whose validity cannot be determined by any general procedure or process. This contradicts Hilbert's statement in his lecture when he said of some of the great unsolved problems: "However unapproachable these problems may seem to us and however helpless we stand before them, we have, nevertheless, the firm conviction that their solution must follow by a finite number of purely logical processes". The problem of finding a method which tells whether a sentence is valid or not was formulated in *Grundzüge der Theoretischen Logik* (Hilbert and Ackermann, 1950) and is known as the Entscheidungsproblem.

The discovery that there is no such method was due to two people working independently (one in the USA, the other in England). The remarkable thing was, as often seems to happen with problems of this sort, that they both seemed to make the discovery, by different methods, at the same time, around 1936. These two formalisms are very different: one deals with functions defined by application and abstraction: the other deals with an abstract machine which was taken as the model for the first ever stored-program computer. Nevertheless they were both used to produce the same result.

### 3.3.1. Church and functions

The person working in the USA was Alonzo Church. He introduced what we are now familiar with as the  $\lambda$ -calculus (a good introduction is Henson (1987)) as the vehicle for his proof that predicate calculus is undecidable. The  $\lambda$ -calculus has had a huge impact on Computer Science and we mention some of its effects here. Details of the proof are in (Church, 1936).

There has been a long history of using the ideas on abstraction and application that the  $\lambda$ -calculus formalizes as a basis for programming languages. The first well-known language with this basis was Lisp, as developed by John McCarthy (McCarthy, 1960). Later, in the 1960s, Peter Landin (Landin, 1965) initiated the idea of using  $\lambda$ -calculus as a basis for describing programming languages. This work was taken up by Strachey and his followers and developed into a method for giving denotational semantics for programming languages, and is well presented by Stoy (Stoy, 1977). It was also taken as a basis for new programming languages, which lead to ISWIM (If you See What I Mean, Landin, 1966), which in turn has been further developed by others. The influence of ISWIM can be seen in languages like SML (though SML was originally just ML and used for a particular purpose; for more on this see chapter nine on LCF) and the "blackboard notation" initially developed by Landin and developed as a more complete programming notation in (Bornat, 1987).

### 3.3.2. Turing and mechanism

The person working in England was Alan Turing, and his method for the unsolvability of the Entscheidungsproblem involved the introduction of what we now know as Turing machines. A good introduction, which also gives a proof of the undecidability, is in Boolos and Jeffrey (1980). Turing's original paper (Turing, 1936) is very clear (though it contains mistakes in the detail which he later corrected). Turing's proof is based on showing that there are certain completely specifiable problems, like "does this computation ever print a 0?", which cannot be answered by algorithmic means, in other words by following a finite set of rules precise enough to be executed mechanically. He showed that if it were possible to decide validity in predicate logic then we would be able to answer questions like the one above. This is clearly a contradictory state of affairs. Since the reasoning that leads to these conclusions is clearly sound the only way out of the contradiction is to deny the truth of the assumption that gave rise to it. Namely, we have to conclude that the validity problem is undecidable.

A direct link between  $\lambda$ -calculus and mechanism was provided in a paper of Landin's (Landin, 1964) which introduced the SECD machine (the Store, Environment, Control, Dump machine) and showed that the  $\lambda$ -calculus could be given a completely mechanical, i.e. operational, semantics which coincides exactly with the semantics given by Church, which was in terms of re-writing expressions. This work has also had a lasting impact in that it has formed the basis of work on implementation of the so-called functional languages, languages based on a "sugaring" (to use a term of Landin's) of the somewhat terse language of the  $\lambda$ -calculus itself.

### 3.3.3. Computability

We have referred to the link between  $\lambda$ -calculus and mechanism provided by the SECD machine. It was known long before 1964 that the  $\lambda$ -calculus and Turing machines pick out exactly the same class of functions, which are what we call the computable functions or recursive functions or effective functions. By "effective functions" we mean "the functions which it is in principle possible for someone to calculate". Of course this is not a very exact definition, and it never can be since it is not clear how to define exactly a notion that depends on the possibilities of human calculation; to paraphrase Russell, we would need to formalize something which seems to be just a medical fact.

However, it is now commonly held to be the case that the class of functions definable by Turing machines or  $\lambda$ -calculus (or one of many other methods) does indeed coincide exactly with what is in principle calculable. That is, we have no evidence against this and much in favour of it. But, because we cannot formally define what we mean by terms like "calculable in principle" we cannot hope to prove a theorem. However, the correspondence is recorded as a thesis, a statement that is believed to be true. This is known as the Church-Turing Thesis:

*the class of effectively calculable functions is the same as the class of Turing computable (or  $\lambda$ -definable or recursive) functions.*

So, we have seen that there are problems which can be specified or described in completely formal detail, yet which no one has ever or will ever write a program to solve. This is at once exciting, in that it gives us insight into a fundamental limit to computation, mysterious, in that it raises the question of whether human beings have

the same kind of inherent limitation, and depressing since for the first time it seems that there is a definite bound to the tasks that computation can solve.

### 3.4. Models and Theories

A sentence in a first-order language is just a collection of symbols put together according to certain syntactic rules. To give meaning to the sentences of a language we have first to identify the objects about which we are talking. We have called this collection of objects the universe, taken to be non-empty. Over the universe we have certain relations between objects. If our universe is a collection of people then such a relation might be ' $p$  is the father of  $q$ '. We might take a particular person and identify that person's father. So, to say useful things about a universe we also want to be able to express relationships and generate new objects. This is where predicates and functions are used. We can express the relation above as  $F(p,q)$  or, given a person  $q$ , we can identify the father by applying a function,  $f(p)$ , where  $f$  is the 'father producing' function. This is the idea behind interpretations as defined above.

So, the interpretations give a basis upon which to judge the truth or falsity of a sentence in a particular language. In a given interpretation each predicate has a truth-value when its parameters are replaced by names. Such sentences are called ground atoms. Each ground atom has a value of true or false, i.e. if  $L$  is a ground atom then either  $\neg L$  is true or  $L$  is true. The truth-values calculated from the ground atoms are then combined by the connectives according to their usual meanings to finally give a truth-value for the whole sentence. From these ideas we can define the notion of a model.

#### Definition 3.6

A model is an interpretation of a sentence which makes the sentence true. We also extend this to sets of sentences,  $G$ , and say that  $M$  is a model of  $G$  iff  $M$  is a model for every sentence in  $G$ .

#### Definition 3.7

A theory is a set of sentences in a language which are true in a class of interpretations.

A set  $G$  of sentences determines a class of interpretations  $I$ , i.e. all those interpretations that are models of  $G$ , and  $I$  determines a further set of sentences that are true in all the interpretations in  $I$ . We write the set of sentences that are true in all models of  $G$  as  $\text{Th}(G)$ , i.e. the theory based on  $G$ .

### Definition 3.8

We call a set such as  $G$  the axioms (of the theory). The sentences which are elements of the theory we call the theorems.

If  $\mathcal{S}$  is a theorem of the theory determined by the set of axioms  $G$  then we write  $G \vDash \mathcal{S}$ , which we have introduced already as entailment, since here theoremhood is determined semantically.

Theories provide the starting point for the use of logic in formalizing reasoning in other areas of mathematics and computer science, and we shall be giving some examples in chapter six. To apply logic, however, you have to be able to prove theorems. We have already seen one method of doing this with axiom systems. In the next two chapters we look at some other, more powerful, proof methods.

## Summary

- As a means of formalizing arguments propositional calculus lacks expressive power because there is no way of referring to individuals or stating that propositions apply to some or all individuals. Predicate calculus is an extension of propositional calculus with names, variables, function symbols, predicate symbols and quantifiers.

- In predicate calculus individuals are denoted by *terms*. A term is either a name, a variable symbol or a function symbol applied to terms. The propositional variables of the propositional calculus are extended to *atomic formulas* which have the form of predicate symbols applied to terms. The quantifiers *bind* variables in the formulas over which their *scope* extends. The notions of scope and *free* and *bound variable* are similar to those in computer science. The other logical connectives are the same as in propositional logic and the recursive definition of compound formulas is similar.

- The simple truth-tables of propositional calculus no longer suffice to give a semantics for predicate calculus. The notion of *interpretation* is introduced. An interpretation consists of a universe of objects, an assignment function that specifies which objects in the universe the terms of the language denote, and a function that maps predicate symbols in the language to relations over the universe. The denotation of a term (the element of the universe that it denotes) is calculated by means of the recursively defined assignment function which maps names and variable symbols to elements of the universe and function symbols to functions over the universe.

- For each of the logical connectives and quantifiers, rules are given specifying when a well-formed formula in which they are the principal connective is *satisfied* for a given assignment in a given interpretation. Atomic formulas are satisfied if the denotation of their arguments is in the relation denoted by their predicate symbol. A formula of predicate calculus is *true* in an interpretation if it is satisfied for all assignments in that interpretation and it is *valid* if it is true in all interpretations.

- A formal deductive system for predicate calculus is given as an extension of that for propositional calculus. The notion of proof as a sequence of formulas in which each element is either an axiom or is derived from earlier members of the sequence by rules of inference is also similar.

- Whereas propositional calculus is *decidable* - any sentence can be shown either valid or not valid in a finite number of steps by the method of truth-tables - this is not the case for the full predicate calculus. There can be no mechanical method for deciding that an arbitrary formula of predicate calculus is not valid. This fundamental result was proved in two different ways, by Church who invented the lambda calculus to do it, and by Turing who modelled the notion of computability with an idealised machine that turned out to be the forerunner of the stored-program computer as we know it today.

- A *theory* is a set of sentences all of which are true in a class of interpretations. A *model* is an interpretation that makes all the sentences of a theory true. Theories and models provide the starting point for the use of logic in formalizing areas of mathematics such as arithmetic and set theory, and data abstractions in computer science such as lists and trees (see chapter six).

# CHAPTER FOUR

---

## Semantic Tableaux

### 4.1. Introduction

In this chapter we introduce one of the main methods that we will be using in the rest of the book to judge validity and consistency.

Semantic tableaux will turn out to be much more expressive and easy to use than truth-tables, though that is not the reason for their introduction.

In any model for  $G$ , a set of sentences, each element  $g_i$  of  $G$  is true. Thus the conjunction  $\bigwedge_i g_i$  is also true. Our problem, in proving that  $G \vDash S$  for some sentence  $S$ , is to show that if  $\bigwedge_i g_i$  is true then  $S$  is true whatever model of  $G$  we choose. That is we must show that

$$(\bigwedge_i g_i \rightarrow S) \tag{1}$$

is valid.

We can think of this as working by saying that the 'if  $\bigwedge_i g_i \dots$ ' picks out all the models from all the interpretations of its language and then passes these on to the '...then  $S$ '.

Because of the definition of implication, if a given interpretation is not a model of  $\bigwedge_i g_i$  then this will be false and so the whole of (1) is true; and if the given interpretation of  $\bigwedge_i g_i$  is a model then the truth of (1) depends on the truth of  $S$ . Thus (1) expresses the statement that  $S$  is a theorem of the theory generated by  $G$ , i.e.  $G \vDash S$ .

As it happens (1) does not express this in quite the way that we wish. However, consider the following argument. If  $(\bigwedge_i g_i \rightarrow S)$  is valid then for each interpretation in its language

1) if  $\bigwedge_i g_i$  is true then  $S$  must be true (by the definition of implication) so  $(\bigwedge_i g_i \wedge \neg S)$  must be false for every such interpretation

2) if  $\bigwedge_i g_i$  is false then the value of  $S$ , true or false, has no effect and  $(\bigwedge_i g_i \wedge \neg S)$  is false for every such interpretation

3) for each interpretation only 1 or 2 holds, since  $\bigwedge_i g_i$  can only be true or false, thus  $(\bigwedge_i g_i \wedge \neg S)$  is unsatisfiable.

This final sentence is the form that is most suitable for our purpose.  $S$  is a theorem of the theory generated by  $G$  if and only if  $(\bigwedge_i g_i \wedge \neg S)$  is unsatisfiable.

This argument forms the basis of the method of semantic tableaux. Given that we are required to prove  $G \vDash S$  then we must attempt to show that  $(\bigwedge_i g_i \wedge \neg S)$  is unsatisfiable. The basic idea is to allow this sentence to be elaborated in every possible way that expresses its satisfiability. If we find that no such way exists then we conclude that it is unsatisfiable, i.e. there is no assignment which will allow it to be true. Then we know that  $G \vDash S$  from the preceding argument.

Of course, this is just another way of saying that  $G \vDash S$  iff  $G \wedge \{\neg S\} \vDash$ , which we have seen before in chapter two.

## 4.2. Semantic Tableaux for Propositional Calculus

In this section we will be dealing only with a propositional language. As we saw in chapter two for such a language the notion of interpretation becomes trivial. It is simply a mapping from propositional letters to the truth-values t and f, i.e. it is what we called a valuation before.

Given a set of sentences of the form  $G \wedge \{\neg S\}$  we want to show that no model for it exists, i.e. no valuation satisfies it. We say that the semantic tableau method is a 'proof by refutation' method. We want to refute the existence of a model of  $G \wedge \{\neg S\}$ .

We display the evolution of the refutation in the form of a binary tree. We use the terms root, leaf and path with their usual meanings.

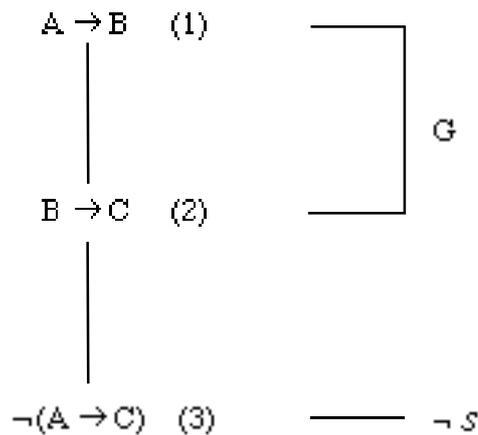


Figure 4.1

**Definition 4.1**

We have that a binary tree is given by a pair  $B = \langle s, N \rangle$  where  $s$  is a successor function and  $N$  is a set of nodes. Given an  $n \in N$ ,  $s(n) \subseteq N$  is the successor set of  $N$ , i.e. the set of nodes which come 'below'  $n$  in the tree. Since  $B$  is binary  $s(n)$ , for any  $n$ , has at most two members. Since  $B$  is a tree any node appears in at most one successor set. The root node of  $B$  is the unique node which is in the successor set of no node. A leaf is a node which has an empty successor set. A path is a sequence of nodes  $\langle n_i \rangle_{\{i \geq 0\}}$  such that  $n_{i+1} \in s(n_i)$ ,  $i \geq 0$ .

We also have a labeling function which maps nodes to their labels, which will be sentences. Consider the set of sentences shown in figure 4.1. Here we have a tree with the node set  $\{n_0, n_1, n_2\}$  and  $s(n_0) = \{n_1\}$ ,  $s(n_1) = \{n_2\}$  and  $s(n_2) = \{\}$ . The labeling function  $l$  is given by  $l(n_0) = A \rightarrow B$ ,  $l(n_1) = B \rightarrow C$  and  $l(n_2) = \neg(A \rightarrow C)$ . Note here that our set of propositional letters has  $\{A, B, C\}$  as a sub-set.

Sentences listed vertically beneath one another are, by definition, understood to be conjugated together.

It is easily seen that  $G \vDash S$  so how do we use the tableau method to prove it? Well, we must show that the above set is unsatisfiable. i.e. that it has no model.

**Definition 4.2**

The sentences in  $G \sqcup \{\neg S\}$  are the initial sentences of the tableau.  $G \vDash S$  is the entailment represented by the initial sentences given by  $G \sqcup \{\neg S\}$ .

Referring to figure 4.1, we take sentence (1) first. According to what we said before, the sentence must be allowed to express its validity in every possible way. We can see the possible ways that (1) can be valid by looking at the truth-table for the connective  $\rightarrow$

$\rightarrow$	t	f
t	t	f
f	t	t

If we take the cases where the antecedent  $A$  is false together with those where the consequent  $B$  is true then we have the cases which are exactly those which make  $A \rightarrow B$  true. The fact that there is some redundancy here is not important. All that we require is that the tableau expresses all the possible ways that  $A \rightarrow B$  can be true.

Referring now to figure 4.2, the the fork in the tableau denotes a disjunction between  $A$  and  $B$ .  $A \rightarrow B$  is true iff  $A$  is false or  $B$  is true (or both).

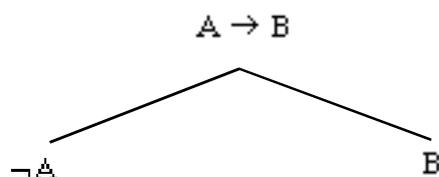


Figure 4.2

The tableau is now as shown in figure 4.3 and we mark sentence (1) with a  $\checkmark$  to show that all its cases have been covered already. We use the same argument with sentence (2) to get the tableau shown in figure 4.4.

Note that the path with  $+$  at its leaf contains the sentences  $A \rightarrow B$ ,  $B \rightarrow C$ ,  $\neg(A \rightarrow C)$ ,  $B$  and  $\neg B$ . The last two form a contradiction so we close the path, i.e. we mark it with  $+$  to show that it should take no further part in the refutation. There is no possible interpretation that could allow this path to be satisfiable.

### Definition 4.3

We say that a path is closed iff it contains a sentence and its negation. A tableau is closed iff all its paths are closed.

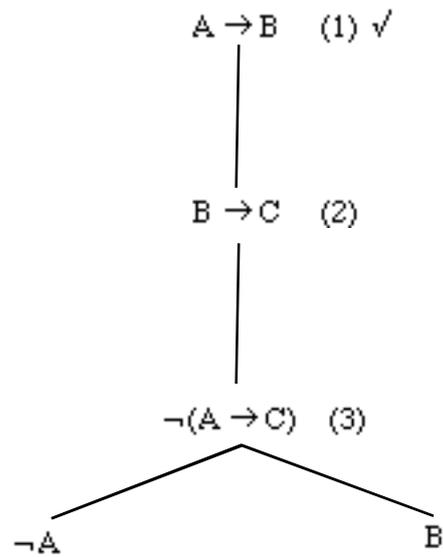


Figure 4.3

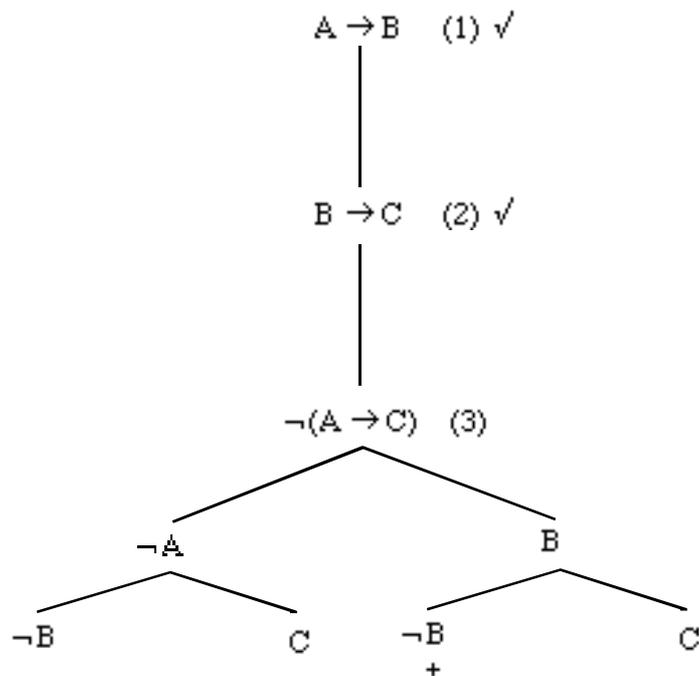


Figure 4.4

We have now to deal with sentence (3). For  $\neg(A \rightarrow C)$  to be true  $A \rightarrow C$  must be false and by referring to the above truth-table (with B as C) we see that to make this so

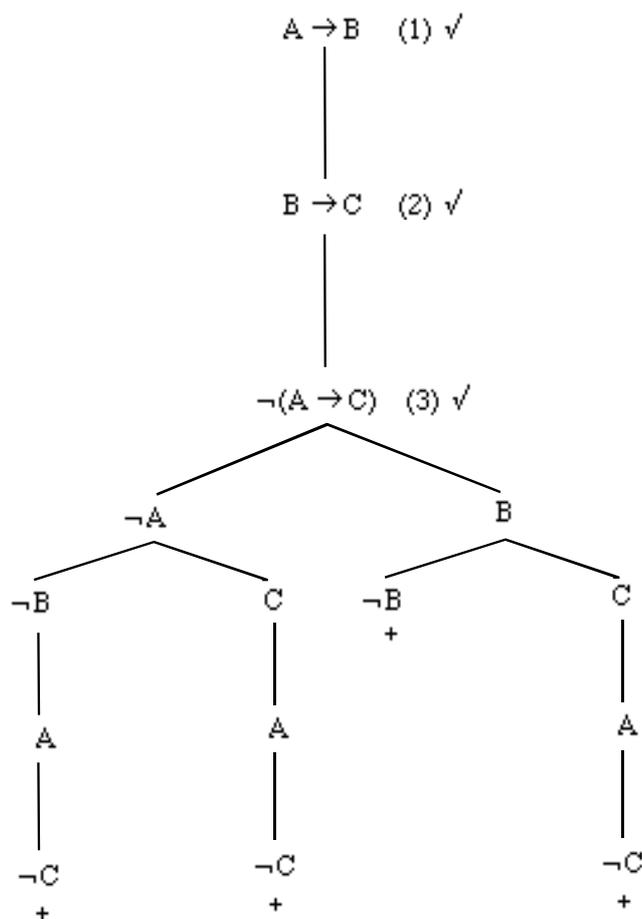


Figure 4.5

A must be true and B false so we add a new path to the still open paths of the tableau to get the tableau in figure 4.5, so the whole tableau is now closed.

We can now say that our initial entailment  $G \vDash S$  is valid. This is because the methods used to expand the sentences covered all the possible ways in which each could be true. However, we have seen that every path is unsatisfiable so there is no way for all the initial sentences to be true, i.e. they form an unsatisfiable set. So no model exists for  $G \cup \{\neg S\}$ .

If we use this method on an entailment  $G \vDash S$  which is not valid then we will reach a stage when no more sentences can be expanded but the tableau is unclosed. In this case each unclosed path forms a model which satisfies  $G \cup \{\neg S\}$  since, by the method of construction, we have that the sentences on an open path form a satisfiable set of sentences. Hence, there is a valuation under which all the sentences on an open

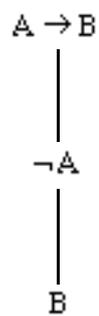


Figure 4.6

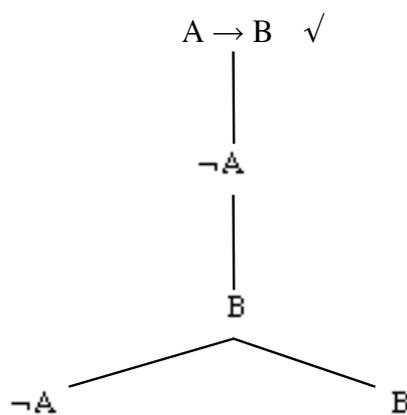


Figure 4.7

path are true. It follows that, since the initial sentences are on every path, there is some valuation under which they are all true. The simplest such valuation is one where each sentence that appears negated has the value *f* and any others, i.e. the un-negated ones, have value *t*. For example the initial tableau in figure 4.6 produced the completed tableau in figure 4.7, which says that a valuation  $\nu$  such that  $\nu(A) = f$  and  $\nu(B) = t$  satisfies the initial sentences, as you can easily check.

So,  $G \cup \{\neg S\}$  is satisfiable so  $G \vDash S$  is an invalid entailment, i.e.  $\{A \rightarrow B, \neg A\}$  does not imply  $\neg B$ .

You should compare this with the truth-table that we would get for this entailment:

A	B	$\neg A$	$\neg B$	$A \rightarrow B$
t	t	f	f	t
t	f	f	t	f
f	t	t	f	t
f	f	t	t	t

and here we can see that in the third line we have the premises true while the conclusion is false. That is, the entailment is invalid, since the conclusion is not true everywhere that the premises are, and on this line we see that A has value f and B has value t, just as with the tableau above.

The method given here can be extended to handle the other connectives and the relevant direct extensions are shown in figure 4.8. We call these the (schemas for) splitting rules (for connectives) of the tableau method. They may be verified as for  $\rightarrow$  by comparing with the usual truth tables for the connectives.

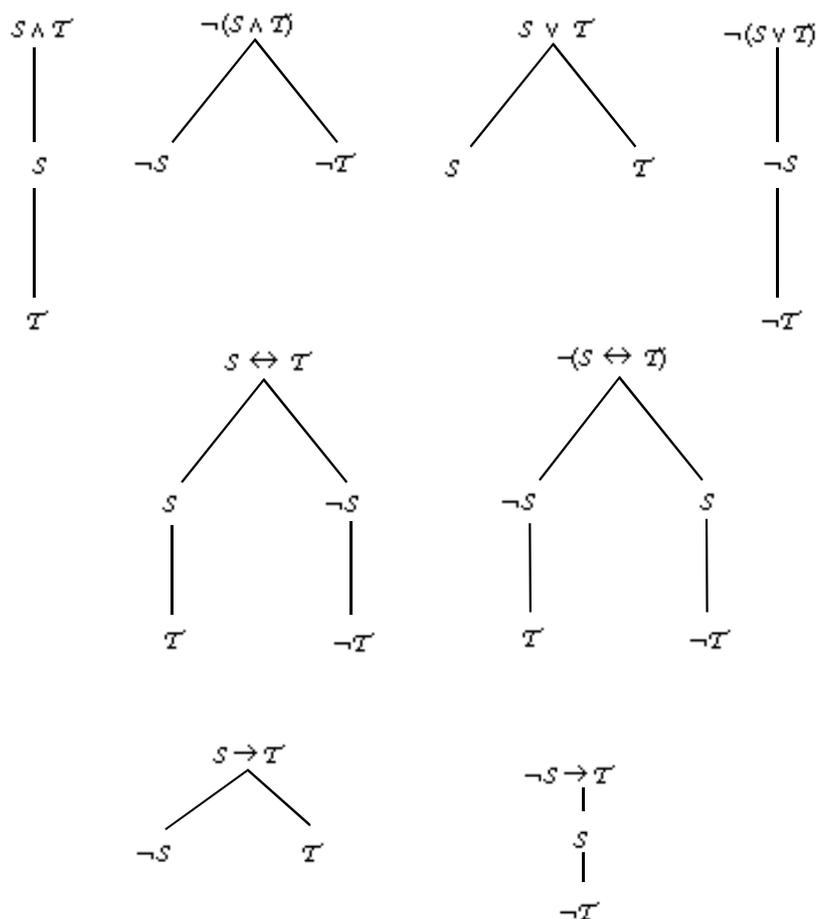


Figure 4.8



**Exercise 4.1**

Use truth-tables and tableaux to decide on the status of the following entailments:

- (a)  $\vDash A \leftrightarrow (A \sqcup B)$
- (b)  $\vDash (A \sqcup B) \leftrightarrow (B \sqcup A)$
- (c)  $A \leftrightarrow B, A \sqcup B \vDash A \sqcup B$
- (d)  $A \vDash A \sqcup B$
- (e)  $A, B \vDash A \sqcup B$
- (f)  $A \sqcup B \vDash A$
- (g)  $A \sqcup B, A \sqcup (B \sqcup C) \vDash A \sqcup C$

### 4.3. Soundness and Completeness for Propositional Calculus

We can now do a soundness and completeness proof for semantic tableaux. That is, we can prove, as we did for the formal system for propositional calculus in chapter two, that a sentence is provable by tableaux iff it is a tautology.

**Definition 4.6**

A sentence  $S$  of the form  $A \sqcup B$ ,  $\neg(A \sqcup B)$  or  $\neg(A \rightarrow B)$  will be called a sentence of type  $\sqcup$ . If  $S$  is of the form  $A \sqcup B$  then  $\sqcup 1$  denotes  $A$  and  $\sqcup 2$  denotes  $B$ . If  $S$  is of the form  $\neg(A \sqcup B)$  then  $\sqcup 1$  denotes  $\neg A$  and  $\sqcup 2$  denotes  $\neg B$ . If  $S$  is of the form  $\neg(A \rightarrow B)$  then  $\sqcup 1$  denotes  $A$  and  $\sqcup 2$  denotes  $\neg B$ .

A sentence  $S$  of the form  $A \sqcup B$ ,  $\neg(A \sqcup B)$ ,  $A \leftrightarrow B$ ,  $A \rightarrow B$  or  $\neg(A \leftrightarrow B)$  will be called a sentence of type  $\leftrightarrow$ . If  $S$  is of the form  $A \sqcup B$  then  $\leftrightarrow 1$  denotes  $A$  and  $\leftrightarrow 2$  denotes  $B$ . If  $S$  is of the form  $\neg(A \sqcup B)$  then  $\leftrightarrow 1$  denotes  $\neg A$  and  $\leftrightarrow 2$  denotes  $\neg B$ . If  $S$  is of the form  $A \rightarrow B$  then  $\leftrightarrow 1$  denotes  $\neg A$  and  $\leftrightarrow 2$  denotes  $B$ . If  $S$  is of the form  $A \leftrightarrow B$  then  $\leftrightarrow 1$  denotes  $A \sqcup B$  and  $\leftrightarrow 2$  denotes  $\neg A \sqcup \neg B$ . If  $S$  is of the form  $\neg(A \leftrightarrow B)$  then  $\leftrightarrow 1$  denotes  $\neg A \sqcup B$  and  $\leftrightarrow 2$  denotes  $A \sqcup \neg B$ .

**Lemma**

For any valuation  $v$  the following hold, by the usual definition of the connectives :

C<sub>1</sub>: a sentence of the form  $\Box$  is true iff both  $\Box_1$  and  $\Box_2$  are true.

C<sub>2</sub>: a sentence of the form  $\Box$  is true iff  $\Box_1$  or  $\Box_2$  is true.

**Definition 4.7**

A path  $p$  in a tableau  $T$  is true under a valuation  $v$  iff all the sentences on  $p$  are true under  $v$ .  $T$  is true iff at least one of its paths is true.

**Definition 4.8**

A tableau  $T_2$  is a direct extension of a tableau  $T_1$  if it can be obtained from  $T_1$  by application of one of the following rules, where  $p_1$  is a path in  $T_1$ :

D<sub>1</sub>) if some  $\Box$  occurs on path  $p_1$  with leaf  $l$ , then join  $\Box_1$  to  $l$  and  $\Box_2$  to  $\Box_1$  to get  $T_2$ .

D<sub>2</sub>) if some  $\Box$  occurs on path  $p_1$  with leaf  $l$  then add  $\Box_1$  as the left successor of  $l$  and  $\Box_2$  as the right successor of  $l$  to get  $T_2$ .

**Lemma**

For any satisfiable set  $G$  of sentences the following hold:

(i) S<sub>1</sub>: if  $\Box \Box G$  then  $G \cup \{\Box_1, \Box_2\}$  is satisfiable.

S<sub>2</sub>: if  $\Box \Box G$  then  $G \cup \{\Box_1\}$  or  $G \cup \{\Box_2\}$  is satisfiable.

(ii) If a tableau  $T_2$  is a direct extension of a tableau  $T_1$  which is true under  $v$  then  $T_2$  is true under  $v$ .

**Proof**

(i) S<sub>1</sub> and S<sub>2</sub> follow from C<sub>1</sub> and C<sub>2</sub>.

(ii) If  $T_1$  is true under  $v$  then it contains at least one true path, say  $p$ , on which the set of sentences  $G$  appears, all members of which are true under  $v$ .  $T_2$  is a direct extension of  $T_1$ , so it was obtained by one of the steps D<sub>1</sub> or D<sub>2</sub> above applied to a path  $p'$  of  $T_1$ . If  $p'$  is different from  $p$  then  $p$  is still a path of  $T_2$  and hence  $T_2$  is true under  $v$ .

If  $p'$  is the same as  $p$  then we have two cases which are proved by use of S<sub>1</sub> and S<sub>2</sub>.

For instance, if  $p$  was extended by  $D_1$  then some  $\Box$  appeared on  $p$  so by  $S_1$  the sentences in  $G \cup \{\Box 1, \Box 2\}$  are true under  $v$  and appear on  $p'$ , so  $p'$  is true too. The proof of the other case is similar.

### Corollary

If the initial sentences of a tableau  $T$  generated by  $D_1$  and  $D_2$  are satisfied then  $T$  must be true.

### Definition 4.9

$G \vDash S$  is provable iff there is a tableau with initial sentences  $G \cup \{\neg S\}$  which has an extension which is closed.

### Soundness Theorem

Any entailment provable by a tableau must be valid.

### Proof

A closed tableau cannot be true under any valuation. Hence, by the corollary, the initial sentences cannot be satisfiable. Thus, the entailment represented by the initial sentences is valid.

### Definition 4.10

$G$  is a model set in the following cases:

H0: No proposition symbol and its negation are both in  $G$

H1: if  $\Box \Box G$ , then  $\Box 1, \Box 2 \Box G$

H2: if  $\Box \Box G$ , then  $\Box 1 \Box G$  or  $\Box 2 \Box G$  or both

### Lemma

If  $G$  is a model set then  $G$  is satisfiable.

### Proof

We prove this by constructing a model for  $G$ . Let  $v$  be a valuation of the sentences in  $G$ . Let  $p$  be a propositional letter that occurs in at least one element of  $G$ . Then if  $p \Box G$  we put  $v(p) = t$ , if  $\neg p \Box G$  then  $v(p) = f$  and if neither then we arbitrarily give  $v(p)$  the value  $t$ .

Now, take an arbitrary element  $X$  of  $G$ . Let  $X$  have  $n > 0$  connective symbols in it. Suppose that all elements of  $G$  with  $m < n$  connectives in them are true under  $v$ .

Then  $X$  is true under  $v$  also. We show this by induction. If  $X$  is an  $\Box$  then  $\Box 1$  and  $\Box 2$  must also be in  $G$ , by  $H_1$ .  $\Box 1$  and  $\Box 2$  both contain less than  $n$  connectives and so are true. Thus,  $X$  is true. The case for  $X$  being a  $\Diamond$  is similar.

It is clear, then, that we have constructed a model for  $G$ , so  $G$  is satisfiable.

**Definition 4.11**

A path  $p$  in a tableau is complete iff

- i) for every  $\Box$  on  $p$ , both  $\Box 1$  and  $\Box 2$  are on  $p$
- ii) for every  $\Diamond$  on  $p$ , at least one of  $\Diamond 1$  or  $\Diamond 2$  is on  $p$ .

**Definition 4.12**

A tableau is completed iff every path is either closed or complete.

We can describe one particular way of repeatedly directly extending a tableau so as to give a sound and complete proof method as follows:

```

begin
  repeat
    changes:=false
    close each path that contains a sentence and
      its negation
    if all paths are closed
    then deliver "correct entailment"
    else
      changes:=true
      apply the appropriate rule
      mark the sentence as used
    until not changes
    deliver "incorrect entailment"
end

```

This algorithm can be seen to achieve the required soundness and completeness conditions by noticing that at the beginning of each time around the loop the tableau is open and 'changes' is true. At the end of the loop either (i) all the paths are closed and we deliver "correct entailment" or (ii) a splitting rule has been

applied (and at least one path is open) or (iii) no splitting rule is applicable (and at least one path is open).

In case (i) we are obviously finished since the tableau is closed and by the soundness theorem the entailment must be valid. In case (ii) we added a finite number of sentences to the tableau, each of which had one less connective than the split sentence that produced them. In case (iii) we have again finished, but this time by the completeness theorem we do not have a valid entailment.

Thus, we only re-enter the loop in case (ii). Clearly, the number of occurrences of connectives in unmarked sentences is strictly decreasing so we will eventually reach a stage where no connectives appear in unmarked sentences, thus the algorithm always terminates. We expected this since the propositional calculus is decidable.

Notice that this is only one possible algorithm since the theory does not specify an order for direct extensions, so we can change the algorithm by imposing different orders on the selection of sentences to be split. Decisions about which ordering, if any, to impose on the use of rules will be guided by how efficient we want the procedure to be. That is, how much work it takes to actually decide on the status of given sentence. In general we can show that any procedure will be very inefficient on many sentences and the development of more or less efficient procedures for deciding logical status comes under the remit of people doing research in automated reasoning. We will not go into these matters further here, but suffice to say that there is a huge body of research on this topic which is still growing very rapidly.

The algorithm above was written in a sort of procedural English, and is sometimes called pseudo-code. This is done to suggest the how such an algorithm might be written in your favoured programming language. Below we give SML and Prolog versions of, essentially, this algorithm so that you can compare how these languages would go about implementing it.

The first language we use is SML. The following first collection of functions carries out the operations on sentences that are needed. In particular, `apply_rule` takes a sentence and returns its sub-sentences as used by the connective rules:

```
fun Neg (Not(sent)) = sent
  | Neg sent = Not(sent);

fun alpha(And(s,t)) = true
  | alpha(Not(Imp(s,t))) = true
  | alpha(Not(Or(s,t))) = true
  | alpha(s) = false;
```

```

fun composite(Var s) = false
  | composite(Not(Var s))= false
  | composite(s) = true;

fun apply_rule (Imp(s,t)) = (Neg(s),t)
  | apply_rule (Eq(s,t)) = (And(s,t),And(Neg(s),Neg(t)))
  | apply_rule(And(s,t)) = (s,t)
  | apply_rule(Or(s,t)) = (s,t)
  | apply_rule(Not(Imp(s,t))) = (s,Neg(t))
  | apply_rule(Not(Eq(s,t))) = (And(Neg(s),t),And(s,Neg(t)))
  | apply_rule(Not(And(s,t))) = (Neg(s),Neg(t))
  | apply_rule(Not(Or(s,t)))= (Neg(s),Neg(t));

```

Now we need to introduce a type that will model the tableau. We define three kinds of node: a `Leaf`; a `Onenode`, i.e. a node with one successor; a `Twonode`, i.e. a node with two successors. Then, as we will see later on, we can use these three kinds of node to describe what action to do on any tableau. Each node, of whichever kind, also contains information to say whether it has been `Closed` or `Used`:

```

type nodeinfo = {Closed : bool, Used : bool};
datatype Tableau = Leaf of (SENT * nodeinfo) |
                  Onenode of (SENT * nodeinfo * Tableau) |
                  Twonode of (SENT * nodeinfo * Tableau * Tableau);

```

These next functions do the building up of the tableau; `initinfo` builds the first part of the tableau from the initial sentences:

```

val initinfo = {Closed=false,Used=false};

fun initialize (nil,goal) = Leaf(Neg(goal),initinfo)
  | initialize (premise::nil,Null) =Leaf(premise,initinfo)
  | initialize (premise :: rest,goal) =
    Onenode(premise,initinfo,initialize (rest,goal));

val useup = {Closed=false,Used=true};
val useable = (fn a => fn b:nodeinfo =>
               not(#Used(b)) andalso composite(a));

fun extend(Leaf(S,N),sent)=
  if not(#Closed(N))
  then let val (f,s) = apply_rule(sent) in
    if alpha(sent)
    then Onenode(S,N,
                 Onenode(f,initinfo,
                          Leaf(s,initinfo)))
    else Twonode(S,N,
                 next(Leaf(f,initinfo)),
                 next(Leaf(s,initinfo)))
  end

```

```

        end
        else (Leaf(S,N))
| extend(Onenode(S,N,T),sent) =
        if not (#Closed(N))
        then Onenode(S,N,extend(T,sent))
        else Onenode(S,N,T)
| extend(Twonode(S,N,T1,T2),sent) =
        if not (#Closed(N))
        then Twonode(S,N,
                extend(T1,sent),extend(T2,sent))
        else Twonode(S,N,T1,T2)

and next(Leaf(S,N)) =
        if (useable S N)
        then extend(Leaf(S,useup),S)
        else (Leaf(S,N))
| next(Onenode(S,N,T)) =
        if (useable S N)
        then extend(Onenode(S,useup,T),S)
        else (Onenode(S,N,next T))
| next(Twonode(S,N,T1,T2))=
        if (useable S N)
        then extend(Twonode(S,useup,T1,T2),S)
        else (Twonode(S,N,next T1,next T2));

```

The next functions are used to see whether or not the tableau is closed:

```

val closeit =
        fn N:nodeinfo => {Closed=true,Used=#Used(N)};

fun cleaves(Leaf(S,N))= Leaf(S,closeit N)
| cleaves(Onenode(S,N,T))= Onenode(S,closeit N,cleaves(T))
| cleaves(Twonode(S,N,T1,T2))=
        Twonode(S,closeit N,cleaves(T1),cleaves(T2));

fun close'(S,Leaf(S',N))= if S=S'
        then cleaves(Leaf(S',N))
        else Leaf(S',N)
| close'(S,Onenode(S',N,T))=
        if S=S'
        then cleaves(Onenode(S',N,T))
        else Onenode(S',N,close'(S,T))
| close'(S,Twonode(S',N,T1,T2))=
        if S=S'
        then cleaves(Twonode(S',N,T1,T2))
        else Twonode(S',N,
                close'(S,T1),close'(S,T2));

```

```

fun Close (Leaf(S,N)) = close'(Neg(S),Leaf(S,N))
  | Close(Onenode(S,N,T)) = Onenode(S,N,close'(Neg(S),Close(T)))
  | Close(Twonode(S,N,T1,T2))=
      Twonode(S,N,close'(Neg(S),Close(T1)),
              close'(Neg(S),Close(T2)));

fun closed (Leaf(S,N)) = #Closed(N)
  | closed (Onenode(S,N,T)) = #Closed(N) orelse closed T
  | closed (Twonode(S,N,T1,T2)) = #Closed(N) orelse
      ((closed T1) andalso
       (closed T2));

```

Finally, we can write a function for the main algorithm. Note that here instead of using a value "changes" as we did in the psuedo-code above here we test for any changes by seeing whether or not the tableau is unchanged by comparing it with the result of applying another round of direct extensions, via `next`, to itself. This is, of course, very inefficient. However, what we have been trying to do here is to present the clearest SML version of something close to the algorithm above. There are more efficient versions given in appendix 2. The reader will see that, as so often, we trade simplicity of algorithm for efficiency of computation.

```

fun make_tableau T = let val T' = next T in
    if T' = T
    then T
    else make_tableau(Close T')
end;

infix entails;
fun asstlist entails goal =
    let val start_tableau = initialize(asstlist,goal) in
        if initalclosed start_tableau
        then output std_out "\ncorrect\n"
        else
            let val final_tableau =
                make_tableau(start_tableau) in

```

```

        if closed(final_tableau)
        then output std_out "\ncorrect\n"
        else output std_out "\nincorrect\n"
    end
end;

```

Next, we give the Prolog program for the same algorithm.

```

:-op(500,xfx, [ : ]).
:-op(510, fy, [ ~ ]).
:-op(520,xfy, [ /\ ]).
:-op(530,xfy, [ \/ ]).
:-op(540,xfy, [ -> ]).
:-op(550,xfx, [ ? ]).

Assumptions?Goal:-set_up(Assumptions,Goal,[ ],open,Start_tree,R),!,
    ((R=clsd,!,write('valid'));maketab(Start_tree,[ ],Final_tree),
    ((closed(Final_tree),!,write('valid'));write('not valid')))).

set_up([ ],G,B,X,tr(NotG:U,Y),R):- literal(~G,NotG:U),
    ((X=clsd;closes(NotG,B)),Y=clsd);Y=open),R=Y.
set_up([H|S],G,B,X,tr(A:U,[T]),R):-literal(H,A:U),
    ((X=clsd;closes(A,B)),Y=clsd);Y=open),set_up(S,G,[A|B],Y,T,R).

maketab(tr(X,clsd),_,tr(X,clsd)).
maketab(tr(F:Used,open),B,tr(F:yes,T)):-
    (Used=yes,T=open);(Used=no,apply_rule(F,[F|B],T)).
maketab(tr(F:Used,[T]),B,tr(F:yes,[NewT])):-
    (Used=no,extend(T,B,F,Ta),maketab(Ta,[F|B],NewT));
    (Used=yes, maketab(T,[F|B],NewT)).
maketab(tr(F:Used,[L,R]),B,tr(F:yes,[NewL,NewR])):-
    (Used=no,extend(L,B,F,La),extend(R,B,F,Ra),
    maketab(La,[F|B],NewL),maketab(Ra,[F|B],NewR));
    (Used=yes,maketab(L,[F|B],NewL),maketab(R,[F|B],NewR)).

extend(tr(F:U,clsd),_,_,tr(F:U,clsd)).
extend(tr(F:U,open),B,X,tr(F:U,T)):-apply_rule(X,[F|B],T).
extend(tr(F:U,[T]),B,X,tr(F:U,[NewT])):- extend(T,[F|B],X,NewT).
extend(tr(F:U,[L,R]),B,X,tr(F:U,[NewL,NewR])):-
    extend(L,[F|B],X,NewL),
    extend(R,[F|B],X,NewR).

apply_rule( A/\B ,Branch,Newtree):- alpha( A, B,Branch,Newtree).
apply_rule( A\B ,Branch,Newtree):- beta( A, B,Branch,Newtree).
apply_rule( A->B ,Branch,Newtree):- beta( ~A, B,Branch,Newtree).
apply_rule(~(A/\B),Branch,Newtree):- beta( ~A,~B,Branch,Newtree).
apply_rule(~(A\B),Branch,Newtree):- alpha( ~A,~B,Branch,Newtree).
apply_rule(~(A->B),Branch,Newtree):- alpha( A,~B,Branch,Newtree).

alpha(U,V,B,[tr(X:G,[tr(Y:H,T)])]):-literal(U,X:G),literal(V,Y:H),
    (((closes(X,B),!;closes(Y,[X|B])),!,T=clsd);T=open).

beta(U,V,B,[tr(X:G,L),tr(Y:H,R)]):-literal(U,X:G),literal(V,Y:H),
    ((closes(X,B),!,L=clsd);L=open),((closes(Y,B),!,R=clsd);R=open).

```

```

literal(X,Y:U):-
    dblneg(X,Y),(((atomic(Y);(Y=~Z,atomic(Z))),U=yes);U=no).

dblneg(X,Y):- (X= ~(~Z),!,dblneg(Z,Y));Y=X.

closes(F,[H|T]):- F= ~H,!; ~F=H,!;closes(F,T).

closed(tr(_:_ ,T):-
    T=clsd;(T=[X],closed(X));(T=[L,R],closed(L),closed(R)).

```

### Completeness Theorem

If  $G \vDash \mathcal{S}$  is valid then it is provable.

### Proof

Assume that  $G \vDash \mathcal{S}$  is valid. Then  $G \cup \{\neg \mathcal{S}\}$  is unsatisfiable. Let  $C(G, \mathcal{S})$  be a tableau produced by the algorithm above with initial sentences  $G \cup \{\neg \mathcal{S}\}$ . If some path  $p$  of  $C(G, \mathcal{S})$  is unclosed then, since it is complete, the sentences on  $p$  form a model set and thus are satisfiable.

Hence  $G \cup \{\neg \mathcal{S}\}$  is satisfiable, so it is not the case that  $G \vDash \mathcal{S}$ . Thus, no path of  $C(G, \mathcal{S})$  can be unclosed. Thus  $G \vDash \mathcal{S}$  is provable.

Since if every path of  $C(G, \mathcal{S})$  above must close then every path must be of finite length and  $C(G, \mathcal{S})$  is finitary, it follows that it will close after some finite number of steps. Thus we have

### Corollary

If  $G \vDash \mathcal{S}$  is valid then it is provable in a finite number of steps.

From the above it is clear that we have

### Correctness Theorem

The algorithm started with initial sentences  $G \cup \{\neg \mathcal{S}\}$  will terminate with "entailment is valid (invalid)" iff  $G \vDash \mathcal{S}$  (not  $G \vDash \mathcal{S}$ ).

## 4.4. Semantic Tableaux for Predicate Calculus

We now turn to the more complex problem of applying semantic tableaux to predicate calculus. Essentially we use exactly the same ideas that we used for propositional logic with two main extensions to deal with quantifiers.

Consider the sentence

$$\Box x(A(x) \vee B(x)) \rightarrow (\Box xA(x) \vee \Box xB(x))$$

which is valid as it stands, i.e.

$$\vDash \Box x(A(x) \vee B(x)) \rightarrow (\Box xA(x) \vee \Box xB(x))$$

We go about proving this by first negating it. The rule we need to apply first, since we have negated and inside the negation  $\rightarrow$  is the dominant connective, is the  $\neg\rightarrow$  rule.

Having applied it the tableau is as in figure 4.10. Now apply  $\neg\vee$  to (2) to get figure 4.11.

$$\neg(\Box x(A(x) \vee B(x)) \rightarrow (\Box xA(x) \vee \Box xB(x))) \quad \checkmark \quad (1)$$

$$\begin{array}{c} | \\ \neg(\Box xA(x) \vee \Box xB(x)) \quad (2) \\ | \\ \Box x(A(x) \vee B(x)) \quad (3) \end{array}$$

Figure 4.10

The next stage is to move the negations of (4) and (5) inwards. We do this by using the equivalences

$$\neg \Box xA \leftrightarrow \Box x\neg A$$

$$\neg \Box xA \leftrightarrow \Box x\neg A$$

$$\neg(\exists x(A(x) \vee B(x)) \rightarrow (\exists xA(x) \vee \exists xB(x))) \quad \checkmark \quad (1)$$

$$|$$

$$\neg(\exists xA(x) \vee \exists xB(x)) \quad \checkmark \quad (2)$$

$$|$$

$$\exists x(A(x) \vee B(x)) \quad (3)$$

$$|$$

$$\neg\exists xA(x) \quad (4)$$

$$|$$

$$\neg\exists xB(x) \quad (5)$$

Figure 4.11

which means that we add the fragment

$$\forall x\neg A(x) \quad (6)$$

$$|$$

$$\forall x\neg B(x) \quad (7)$$

to the tableau.

Now we are in the position of having no more rules to apply since the connective in (3) is not dominant. This is where we need some rules for dealing with  $\forall$  and  $\exists$ .

Remember that we are aiming to display a tableau in which every possible interpretation is given to any sentence appearing in it. Thus, when we meet a sentence saying 'there exists something such that...' it needs a name to form an

instance. However, it says that this something denotes an object with specific attributes i.e. in this case, A is true of it or B is true of it or both, thus, to preclude imposing these attributes on an object already mentioned, as will be the case in general, and of which they may not be true, we use an as yet unused name. Let us choose 'b'. Thus we now add

(A(b)    B(b))

as sentence 8 to the tableau. Since the sentence only demanded one such name we can mark it as used since it has been displayed according to our goal and that is all that is required.

Now we have (6) and (7) which say 'for all things...'. We must take every name which has so far appeared on the path, i.e. all objects that we know, so far, appear in the universe of the model that is being constructed, which includes the sentence with which we are dealing, and place an instance of the sentence, for each name, on the path. This ensures that the given sentence has been interpreted in every way possible in the model as so far constructed. And this brings out an important point. At some future stage some new names may be added to the possible universe which we are gradually constructing.

Therefore, to keep to the goal of allowing every possible interpretation of every sentence we must allow the possibility of different instances of the sentence being needed in the future. Thus we do not mark this sentence as having been used so that it may be taken into account in later stages. So we apply the  $\forall$ -rule to (6) and (7) with the name 'b'. Then we can apply the  $\exists$ -rule to (8) to get the tableau so far as in figure 4.12. We note that the paths both contain contradictions. So we can say that given the chance at each stage to produce a model we have failed. There is no model for our original negated sentence so  $\neg \forall x(A(x) \wedge B(x)) \leftrightarrow (\exists x A(x) \wedge \forall x B(x))$  is valid.

## 4.5. Soundness and Completeness for Predicate Calculus

We now collect together the rules we need and finally produce a simple algorithm for generating complete tableaux whenever possible in the predicate logic case.

**Definition 4.13**

The universal rule is:

Given a sentence of the form  $\forall xS$  with  $x$  free in  $S$  on an open path which contains names  $n_0, \dots, n_{m-1} \in N$ , add each of the sentences  $S[n_i/x]$  to the end of the path iff  $S[n_i/x]$  does not appear already on the path, where  $0 \leq i \leq m-1$ . Note for future use that the tableau has changed.

We note here that there may not be any names on the path when this rule is applied. In this case, since we are dealing with a non-empty universe, we take any name and apply the rule using this name. We shall usually take 'a' to be this first name.

**Definition 4.14**

The existential rule is:

Given a sentence of the form  $\exists xS$  with  $x$  free in  $S$  on an open path which contains names  $n_0, \dots, n_{m-1} \in N$ , mark the sentence as used and add the sentence  $S[n_m/x]$  where  $n_m \in N \setminus \{n_0, \dots, n_{m-1}\}$ . Note for future use that the tableau has changed.

Consider the sentence

$$\forall y \exists x P(x, y) \tag{1}$$

This is not valid. Almost any interpretation you are likely to think up will show this. For example  $U =$  natural numbers,  $\forall (P) =$  less-than. Then the sentence says 'there is a largest natural number'.

Now consider the following. Since sentences of the form  $\forall xS$  are never marked we can always apply them to new names and a new name is always produced by an application of  $\forall xS$  so a sentence like (1) will produce an infinite tableau which starts as in figure 4.13 and will go on and on growing. In this case after any finite time the tableau is not closed and we still have some sentences to apply, thus we continue. So, in our search for a counter-model it seems that we might, in some cases, never reach a conclusion since the process of building the tableau will never stop.

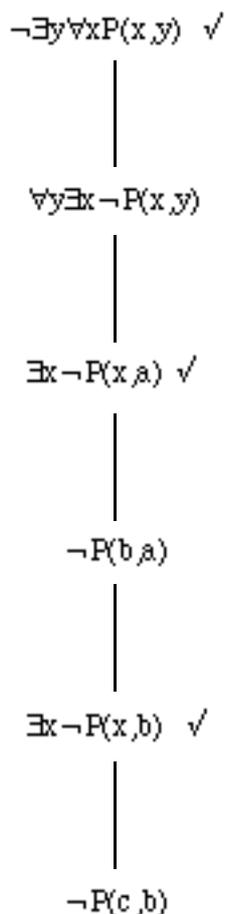


Figure 4.13

There are two points to make here. First, notice that by stepping outside of the algorithmic framework we were able to see that the sentence is in fact not valid. Thus, it is clear that algorithmic methods certainly are not the last word - which is comforting for humans (but not for expert systems salespeople). Secondly, this limitation is not specific to our method here.

Contrast this result with the propositional case where the tableau for any initial sentences always stops extending. This means that the question "does  $G$  entail  $S$ ?" can always be answered either "yes" or "no". We say that the validity question in propositional logic is decidable. It seems, however, that in the predicate calculus case we cannot hope for such a state of affairs.

But things are not as bad as they might seem. It is a central theorem of this subject that if a sentence is valid then there are methods for finding this out. In fact, the method of semantic tableaux is one such. We say that the validity question in predicate logic is semi-decidable. The following informal argument should help to justify this.

We can extend the algorithm in the section above to get:

```

begin
  repeat
    changes:=false
    close each path that contains a sentence
                                and its negation
  if all paths are closed
  then deliver "correct entailment"
  else
    if a connective rule can be applied
    then
      changes:=true
      apply the appropriate rule
      mark the sentence as used
    else
      apply the existential rule
      apply the universal rule
  until not changes
  deliver "incorrect entailment"
end

```

We can argue for the correctness of this algorithm in the same way as for the propositional case though with one big difference. Because a direct extension by the universal rule does not exhaust the sentence it is applied to, i.e. the sentence is not marked, we may never actually get a completed tableau in some cases. However, since any given universal sentence will always be dealt with after some finite time (since the preceding part of the algorithm deals only with the connectives, and they are always dealt with in a finite time) it is clear that any tableau makes progress towards being completed. So, even if some path is never closed it must come nearer and nearer to forming a model set. ((Smullyan, 1968) and (Jeffreys, 1967) give other examples of how to organize the rules so that they always lead to a model set if one is possible.)

From this discussion we can show a Soundness Theorem and a Completeness Theorem as before in the propositional case, though we will not give them here since

we are more interested in the computation side of the problem. However, see (Smullyan, 1968), for instance, for details.

### Correctness Theorem

The algorithm started with initial sentences  $G \cup \{\neg S\}$  will terminate with "entailment is valid" iff  $G \models S$ . If the algorithm terminates with "entailment is invalid" then not  $G \models S$ . But, it may not terminate if not  $G \models S$ .

What we are trying to do here is to establish theoremhood within a theory (which is a semantic notion, i.e. by choosing the 'right' substitution we are trying to decide on an assignment of elements of the universe to the variables like  $x$  and  $s$  which makes the sentences true, i.e. satisfied in the model) by purely syntactic means. Of course, this has been done rather informally above, i.e. we have resorted rather a lot to woolly justification, but the aim of this chapter is to introduce a completely formal procedure which will decide theoremhood in a given theory.

Even though we have succeeded in this task, we should also point out that following the algorithm, while guaranteed to lead to the correct answer (if there is one) is not always the best strategy if you want a short refutation. As you will find if you try the exercises below, following the algorithm will lead to a far longer proof than the strategy of looking at each stage of the development of the tableau and using your intelligence to plan how to proceed, keeping in mind that you want as short a refutation as possible. Another feature of this strategy, the first being that it requires intelligence and some idea of what a 'good' plan is, is that it gets better with practice, i.e. you also need to learn about what you are doing to be effective.

Now, our algorithm has none of these features and so we should expect it to be fairly ineffective for most of the time. However, since no one has yet succeeded in developing an algorithm which will learn in such a complex domain and which displays the sort of behaviour that we would call intelligent, we are left with largely ineffective algorithms. However, work in this area is developing new and (usually slightly) improved algorithms continuously. The most obvious strategy that we would like to add to our algorithm would give us some guidance as to which names to instantiate in universally quantified sentences in the universal rule. That is, instead of instantiating with every name, as we do here, is there a way of being sure of picking all and only those names needed to still give a sound and complete algorithm? The answer to this question is complicated and fairly subtle, so we will not go further into

it here. Also, later in the book, in the logic programming chapter, we will address essentially the same problem in a different setting.

Since in a given model the predicates and functions already have denotations the problem comes down to deciding on some assignment for the variables that appear in the sentence (as we did above) so that the sentence as a whole is true.

In appendix 2 we give SML and Prolog programs which extend the ones given earlier in this chapter and that implement the algorithm for the predicate case.

### Exercise 4.2

a) Use tableaux to decide on the status of the following entailments:

$$(i) \quad \forall y(H(y) \rightarrow A(y)) \vDash \forall x(\forall y(H(y) \wedge T(x,y)) \rightarrow \forall y(A(y) \wedge T(x,y)))$$

$$(ii) \quad \vDash \forall x(P(x) \rightarrow \forall xP(x))$$

$$(iii) \quad \vDash \forall x(P(x) \rightarrow \forall xP(x))$$

$$(iv) \quad \vDash \forall x\forall y(S(x,y) \leftrightarrow \neg S(y,y))$$

b) How would you express a)(iv) in English if  $S$  was the predicate "x shaves y"?

c) Express

"There is a man in town who shaves all the men in town who do not shave themselves" entails "Some man in town shaves himself"

as an entailment using predicate calculus. Then, use the tableau method to decide its status.

## Summary

- *Semantic tableaux* provide another method of determining validity and consistency in predicate calculus. Tableaux are more concise and can be constructed more mechanically than proofs in axiom systems and, even for propositional logic,

tableaux are much more efficient than truth-tables while giving exactly the same information.

- A tableau proof of  $G \vDash S$  starts with the set of sentences  $G \cup \{\neg S\}$ . The tableau itself is a binary tree constructed from this initial set of sentences by using rules for each of the logical connectives and quantifiers that specify how the tree branches. If the tableau *closes* then the initial set of sentences is unsatisfiable and the entailment  $G \cup S$  holds. A tableau closes if every branch closes. A branch closes if it contains  $F$  and  $\neg F$  for some sentence  $F$ .

- If a tableau does not close, and yet is complete because none of the rules can be applied to extend it, then the initial sentences are satisfiable and the unclosed branches give a model for them. In this case  $G \vDash S$  does not hold. So a tableau proof is a proof by *refutation*; the existence of a model for  $G \cup \{\neg S\}$  is refuted.

- For the propositional calculus semantic tableaux give a decision procedure (just as truth-tables do). For predicate calculus the rule for universal sentences, sentences of the form  $\Box xF$ , can be applied repeatedly. Methods of applying the rules can be given that are guaranteed to terminate with a closed tableau if and only if the initial set of sentences is unsatisfiable (i.e. the tableau method is *sound and complete*). However if the initial set is satisfiable (the corresponding entailment is not valid) the method may never terminate. It can be shown that no method could terminate with the correct answer for all cases of invalidity. Predicate calculus is *semi-decidable*.

# CHAPTER FIVE

---

## Natural Deduction

### 5.1. Rules and Proofs

Both of the methods given in previous chapters for constructing proofs have their disadvantages. Axiom systems are difficult to construct proofs in; their main uses are metalogical, the small number of rules making it easier to prove results about logic.

The tableau method on the other hand is easy to use mechanically but, because of the form of the connective rules and the fact that a tableau starts from the negation of the formula to be proved, the proofs that result are not a natural sequence of easily justifiable steps. Likewise, very few proofs in mathematics are from axiom systems directly. Mathematicians in practice usually reason in a more flexible way.

#### 5.1.1. Natural Deduction rules

Suppose that, on the assumption that some statement  $P$  is true,  $Q$  can be shown to hold, possibly via some intervening proof steps. Since, given  $P$ ,  $Q$  holds we can conclude (using the truth table for  $\rightarrow$ ) that  $P \rightarrow Q$  holds (given nothing). We can represent this sort of reasoning with a diagram

$$\begin{array}{c} \cancel{P} \\ \vdots \\ Q \\ \hline P \rightarrow Q \end{array}$$

where  $P$  is crossed through to remind us that, once  $P \rightarrow Q$  has been derived,  $P$  need no longer be considered an assumption,  $P \rightarrow Q$  is true outright. We say that the original assumption  $P$  has been discharged in the process of going from  $Q$  to  $P \rightarrow Q$ .

What we have, in effect, is a method for introducing  $\rightarrow$ , generating a new formula with  $\rightarrow$  as the principal connective. Similar introduction rules can be given for the other connectives and rules also for eliminating them. A set of rules that is adequate for deriving all theorems in predicate logic is given in figure 5.1. The rules for  $\exists$ I,  $\exists$ E and  $\forall$ I are straightforward, while  $\rightarrow$  E is Modus Ponens, however  $\rightarrow$  I requires some explanation. The rule is essentially that of analysis by cases, familiar from mathematics. Suppose we want to show that some theorem is true for all integers. One method of proceeding, for example if the theorem has something to do with division by two, would be to show that, if  $n$  is an even integer, the theorem holds, and then show that for  $n$  odd the theorem also holds. Since integers must be either odd or even the theorem therefore holds for all integers.

The truth of the conclusion does not depend on whether  $n$  is odd or even (even though the form of the proof perhaps does) so we are justified in discharging the assumptions we made to get the proof.

In a similar way the rule C expresses another frequently used pattern of reasoning, commonly known as *reductio ad absurdum* or proof by contradiction. Given a result to be proved we assume that the result is not true and then show that falsity follows. Either the result is true or it is not, the assumption that it is not true leads to a contradiction so the result must be true. Note that the validity of this argument depends on accepting that the result is either true or not true and so one could argue that the rule is really a special case of  $\rightarrow$  E applied to  $P \rightarrow \neg P$ . This makes the point that the set of rules we have given is not the only satisfactory set that could be given. We could have taken  $P \rightarrow \neg P$  as fundamental and got the effect of the rule C from this and  $\rightarrow$  E. The important thing about a set of rules is that it should be sound and complete. Sound because, by using the rules, you cannot do other than derive valid conclusions, complete because, if you are clever enough to see how, you can derive any valid conclusion. The set of rules that we give is both sound and complete, although we cannot give the rather technical proof of this here. For aesthetic reasons we also like our rules to be minimal, in the sense that if we left out any rule the set would no longer be complete. We carry the tools for the job, but we carry no more than strictly necessary. Naturally this places a burden on our ingenuity and as we gain experience of using the rules we add to our stock of tools in the form of lemmas

which, just as in mathematics, are small but useful results that we often find ourselves using. However, further discussion of strategy and technique must come later. For the moment we continue our discussion of the rules.

Natural Deduction Rules for Classical Predicate Logic

$\Box I \frac{S \quad \mathcal{T}}{S \Box \mathcal{T}}$	$\Box E \frac{S \Box \mathcal{T}}{S}$	$\Box E \frac{S \Box \mathcal{T}}{\mathcal{T}}$
$I \frac{S}{S \quad \mathcal{T}}$	$I \frac{\mathcal{T}}{S \quad \mathcal{T}}$	$E \frac{S \quad \mathcal{T} \quad \mathcal{R} \quad \mathcal{R}}{\mathcal{R}}$
$\rightarrow I \frac{\dot{\mathcal{T}}}{S \rightarrow \mathcal{T}}$	$\rightarrow E \frac{S \rightarrow \mathcal{T} \quad S}{\mathcal{T}}$	$\Box \frac{\Box}{S}$
$\forall I \frac{S(a)}{\forall x S(x)}$	provided that $a$ does not occur in $S(x)$ or any premise on which $S(a)$ may depend	
$\forall E \frac{\forall x S(x)}{S(a)}$	$\exists I \frac{S(a)}{\exists x S(x)}$	
$\Box E \frac{\Box x S(x) \quad \dot{\mathcal{T}}}{\mathcal{T}}$	provided that $a$ does not occur in $S(x)$ or $\mathcal{T}$ or any assumption other than $S(a)$ on which the derivation of $\mathcal{T}$ from $S(a)$ depends	

Notes:

1.  $S$ ,  $\mathcal{T}$  and  $\mathcal{R}$  stand for any sentence
2.  $\neg S$  is defined as  $S \rightarrow \Box$

Figure 5.1

It will be seen that we have chosen to define negation in terms of  $\perp$  which, it will be recalled, is the symbol for a proposition that is false in every valuation.  $P \rightarrow \perp$  is false when  $P$  is true and true when  $P$  is false, so  $P \rightarrow \perp$  and  $\neg P$  are logically equivalent. In the natural deduction system that we are using,  $\perp$  is fundamental and  $P \rightarrow \perp$  is the way you express negation, but for clarity and brevity we will allow negated formulas to appear in proofs on the understanding that  $\neg P$  stands at all points for  $P \rightarrow \perp$ . There are implicit introduction and elimination rules for negation because we have as instances of  $\rightarrow I$  and  $\rightarrow E$  the rules

$$\frac{\begin{array}{c} \cancel{P} \\ \vdots \\ \perp \end{array}}{P \rightarrow \perp} \qquad \frac{P \quad P \rightarrow \perp}{\perp}$$

Our rule  $\perp$  comes from the fact that an inconsistent set of formulas entails any formula. Note the difference between this and the rule C. The latter allows you to discharge the formula  $\neg P$ , the former does not.

Turning to the rules for the quantifiers, those for  $\exists E$  and  $\forall I$  are clearly sound, whatever the constant  $a$  denotes. The rule for  $\forall I$  depends on the constant  $a$  being "typical", hence the condition.

Mathematical proofs often start "take any integer  $a$  ....." and conclude "but the choice of  $a$  was arbitrary and so the result holds for all  $a$ ". If it turns out that the result about  $a$  (i.e.  $\mathcal{S}(a)$  in the rule) depends on  $a$  being prime, say, then you are not justified in concluding that the result holds for all  $a$ . The rule for  $\exists E$  contains a similar caveat. Suppose that  $\mathcal{S}(x)$  is some mathematical equation. We let the constant  $a$  be a solution to the equation and derive some other result  $\mathcal{T}$ . Now if there are other conditions that  $a$  has to satisfy and the derivation of  $\mathcal{T}$  from  $\mathcal{S}(a)$  depends on these as well, then it may turn out that no solution to the equation  $\mathcal{S}(x)$  satisfies these further conditions and so the proof is not valid.

It will be apparent from what we have said that unlike the axiom and tableau systems already discussed, these rules are designed to mimic fairly closely the patterns of reasoning that we use both in mathematics and everyday argument. For this reason the system is known as natural deduction. Its use in Computer Science has been found particularly appropriate where people collaborate with computers in an interactive way to construct proofs about programs. The LCF system (which we describe in chapter nine), for example, is based on natural deduction. Natural though

the rules may be, they still form part of a formal system in that they enable us to manipulate formulas in a purely syntactic way without regard to their meaning. As we indicated above the deductive system based on the rules can be shown sound and complete with respect to the semantics we gave in chapter three. They are therefore logically equivalent to the axiom and tableau methods covered already.

Natural deduction proofs are constructed by fitting the rules together to form a tree with the required formula at the root. Here for example is a demonstration of

$$\vdash P \rightarrow (Q \rightarrow (P \sqcap Q)).$$

$$\begin{array}{c} \begin{array}{c} \cancel{P}^2 \quad \cancel{Q}^1 \\ \hline \sqcap I \\ P \sqcap Q \end{array} \\ \begin{array}{c} \hline \sqcap I \quad 1 \\ Q \sqcap (P \sqcap Q) \end{array} \\ \begin{array}{c} \hline \sqcap I \quad 2 \\ P \sqcap (Q \sqcap (P \sqcap Q)) \end{array} \end{array}$$

The application of a rule is indicated by a horizontal line, on the left of which is the name of the rule used. For instance, in the example above, the first rule applied is  $\sqcap I$  (which in discussing it with someone else you would pronounce "and introduction"). Assumptions are identified with numbers as they are introduced and when they are discharged, i.e. used in a rule such as  $\rightarrow I$  which brings down the assumption as the antecedent of an introduced implication, then the corresponding number is written to the right of the discharging rule line and the assumption is crossed through to show that it has been discharged. Note that the rule names and numbers are not part of the proof; they are just annotations to make it easier to check that the rules have been followed.

Ideally you would have seen this proof develop as we wrote it down, while listening to the verbal explanation. Viewing the actual performance would also have given you some idea of how we went about inventing the proof, i.e. the proof strategy, as computer scientists call it. From the finished article you can't see whether we started at the top, the bottom or the middle. So here is the action replay.

We know that we have to end up with  $P \rightarrow (Q \rightarrow (P \sqcap Q))$  as the bottom line, so what could the rule application that gives this be? For the moment we are working backwards. We start by writing down

?

$$? \frac{}{P \supset (Q \supset (P \supset Q))}$$

Now  $\supset$ E and  $\supset$ I are not very likely because you would be coming from a more complicated formula that nevertheless still contains the formula you want.  $\supset$ C is a possibility, but we know by experience that this is something to try when all else fails (as we see several times later). The obvious choice is the introduction rule for the principal connective, namely  $\rightarrow$ I. So we write down

~~P~~<sup>1</sup>

?

$$\supset I \frac{Q \supset (P \supset Q)}{P \supset (Q \supset (P \supset Q))} 1$$

Now we are in the same position again and the same argument gives

~~P~~<sup>1</sup>      ~~Q~~<sup>2</sup>

?

$$\supset I \frac{P \supset Q}{Q \supset (P \supset Q)} 2$$

$$\supset I \frac{}{P \supset (Q \supset (P \supset Q))} 1$$

Now we see that things have worked out well for us because we have all the ingredients for an instance of  $\supset$ I, so we complete the proof as shown above.

Of course it doesn't always work out so easily. It can often be hard to see how to put the rules together to get the result you want, and even harder to legally discharge assumptions that you find it convenient to make. Ingenuity is often

required, but this must be confined to fitting the rules together and not to making up new rules of your own. For example we have seen in chapter two that

$$\neg \Box xP(x) \vdash \Box x\neg P(x).$$

A common mistake is to "prove" this by natural deduction with

$$\frac{\neg \Box xP(x)}{\neg P(a)} \quad \Box I \frac{}{\Box x\neg P(x)}$$

the point being that there is no rule among those we have given that sanctions the passage from  $\neg \Box xP(x)$  to  $\neg P(a)$ . (We give the correct proof below.)

### 5.1.2. Fitch box presentation

Before we look at some more examples we will just say something about presentation. We have chosen to show proofs as trees (albeit growing the right way up in contrast to the usual convention in computer science) but there are other ways of presenting natural deduction proofs that are sometimes more convenient typographically. The proofs are the same, only the presentation differs. One of these variants is due to Fitch. The idea is reminiscent of Chinese boxes, boxes-within-boxes. When you make an assumption you put a box round it. When you discharge the assumption the box is closed and the derived formula is written outside the box. You can imagine the box, if you like, as a machine, literally a black box, which verifies the formula and "outputs" it. The box is part of the world outside, so you can copy into the box any formula from outside it, but no formula from inside the box, which of course may depend on assumptions local to the box, may be copied to the outside. Here, then, is the example above done in the Fitch style.

P	Assumption						
<table style="width: 100%; border-collapse: collapse;"> <tr> <td style="padding: 5px;">Q</td> <td style="padding: 5px;">Assumption</td> </tr> <tr> <td style="padding: 5px;">P</td> <td style="padding: 5px;">From outer box</td> </tr> <tr> <td style="padding: 5px;">P <math>\wedge</math> Q</td> <td style="padding: 5px;"><math>\wedge</math> I</td> </tr> </table>		Q	Assumption	P	From outer box	P $\wedge$ Q	$\wedge$ I
Q	Assumption						
P	From outer box						
P $\wedge$ Q	$\wedge$ I						
Q $\wedge$ (P $\wedge$ Q)	$\wedge$ I						
P $\wedge$ (Q $\wedge$ (P $\wedge$ Q))	$\wedge$ I						

### 5.1.3. Natural and non-natural reasoning

One of the best methods of formulating proofs by natural deduction is to imagine how you would convince someone else, who didn't know any formal logic, of the validity of the entailment you are trying to demonstrate. Here is an example with quantifiers. We want to show

$$\{\forall x(F(x) \rightarrow G(x)), \forall x(G(x) \rightarrow H(x))\} \vdash \forall x(F(x) \rightarrow H(x))$$

If you were trying to convince someone of the validity of this you might say

Take an arbitrary object a  
 Suppose a is an F  
 Since all Fs are Gs, a is a G  
 Since all Gs are Hs, a is an H  
 So if a is an F then a is an H  
 But this argument works for any a  
 So all Fs are Hs

Note how the following natural deduction proof expresses this argument almost exactly



At this point the only current assumption is  $\neg(P \rightarrow \neg P)$ , so discharging this with the C rule we get the required result. In fact we obtained  $P \rightarrow \neg P$  in three places but only on the last occasion did it not depend on an undischarged assumption. One final point of presentation: we introduced  $\neg(P \rightarrow \neg P)$  as an assumption on two separate occasions but gave it the same number each time and discharged both occurrences at once. This is quite sound. It is only a single assumption written twice for purposes of presentation. It would be a different matter though if we had discharged the first occurrence before introducing the second.

We could of course have included  $P \rightarrow \neg P$  as a primitive rule and you may sometimes see natural deduction systems in which this or something similar is done. However, now that we have carried out the proof above, it is clear that any formula could have been consistently substituted for  $P$  and both the proof and result would be equally valid. So in several cases that follow we will allow ourselves to assume that this has been done and will quote an instance of  $P \rightarrow \neg P$  as a lemma.

Finally, observe that at the last step we could have used  $\rightarrow$  I to get  $\neg\neg(P \rightarrow \neg P)$ , showing that this can be derived without  $\square$  or C. This is an important point that we return to when we look at other logics.

Now here are some examples with quantifiers. First we show how to derive the basic equivalences between  $\square$  and  $\neg\square$ , starting with  $\{\neg\square xP(x)\} \vdash \square x\neg P(x)$ .

$$\begin{array}{c}
 \begin{array}{c}
 \cancel{P(a)} \quad 1 \\
 \square I \text{ ---} \\
 \square xP(x)
 \end{array}
 \qquad
 \neg\square xP(x) \\
 \square E \text{ ---} \\
 \square \\
 \square I \text{ ---} \quad 1 \\
 \neg P(a) \\
 \square I \text{ ---} \\
 \square x\neg P(x)
 \end{array}$$

Note that we have labeled the line marking the second rule application as  $\rightarrow$  E because the  $\neg\square xP(x)$  in the line above is a synonym for  $\square xP(x) \rightarrow \square$ , and a similar convention is used in reverse in the following line.

Two of the remaining three facts of this type namely  $\{\square x\neg P(x)\} \vdash \neg\square xP(x)$  and  $\{\square x\neg P(x)\} \vdash \neg\square xP(x)$  are straightforward and we leave them as exercises. However  $\{\neg\square xP(x)\} \vdash \square x\neg P(x)$  requires use of the C rule

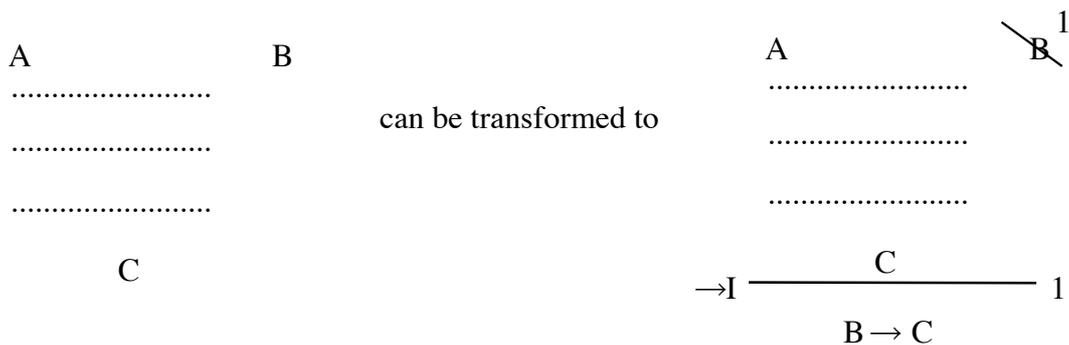


- b)  $\vdash \neg\neg P \rightarrow P$
- c)  $\vdash (\neg P \rightarrow Q) \rightarrow (\neg Q \rightarrow P)$
- d)  $\vdash (\forall x P(x) \rightarrow Q) \rightarrow \forall x (P(x) \rightarrow Q)$
- e)  $\neg P \vdash P \rightarrow Q$
- f)  $\{P \quad Q, \neg P\} \vdash Q$
- g)  $\{\forall x \neg P(x)\} \vdash \neg \forall x P(x)$
- h)  $\{\forall x \neg P(x)\} \vdash \neg \forall x P(x)$
- i)  $P \rightarrow Q \vdash \neg Q \rightarrow \neg P$

## 5.2. The Sequent Calculus

### 5.2.1. Natural Deduction rules as sequents

The tree format in which we have displayed natural deduction proofs is good for constructing proofs but not so good for reasoning about them. Suppose we want to demonstrate, for example, that from a derivation  $\{A, B\} \vdash C$  we can get  $\{A\} \vdash B \rightarrow C$  where A, B and C are any formulas, then we have to draw pictures to point out that a proof tree such as



What we need is a less pictorial, more formal, notation for manipulating derivations. This is provided by the notion of a sequent. A sequent is an expression of the form  $G \sqsubset H$  where H and G are sets of formulas. To start with we shall be talking about cases in which H is a single formula, A say, in which case we shall allow

ourselves to write  $G \cup \{A\}$  as  $G \cup A$ . We shall also for brevity write  $G \cup \{A\} \vdash B$  as  $G, A \vdash B$  and adopt the convention that  $G \cup \{A\}, G \cup A$  and  $G \cup A$  are all the same.

The use of the  $\vdash$ , instead of the  $\vdash$  that you might have expected, is designed to make an important distinction clear. If you assert  $G \vdash B$  you are saying, in the observer's language, that  $B$  can be derived from the set of assumptions  $G$  in some system of deduction, whereas  $G \cup A \vdash B$  is just a formula in the observer's language. Like a formula such as  $x+7$  in ordinary algebra, it doesn't make sense to say that it holds or doesn't hold—it is just there to be manipulated. We are going to put forward a set of rules that say how formulas involving  $\vdash$  can be manipulated and we will draw conclusions of the form "if  $G \cup A$  can be obtained by using the rules then  $G \vdash A$  in classical logic".

You may notice a similarity between this and the kind of statement we were making in the axiom systems we looked at earlier. This is no coincidence. In chapter two we were defining the notion of proof in a formal system, here we are formalizing the notion of entailment. Note by the way that  $\vdash$  does not necessarily have anything to do with the symbol  $\rightarrow$  in the language of predicate calculus, and there will be nothing in our rules that results in formulas such as  $A \vdash (B \vdash C)$  being obtained. The symbol  $\vdash$  will never be iterated.

Figure 5.2 above shows the natural deduction rules expressed in sequent notation. Note how the sets of formulas on the left of the  $\vdash$  are used to bundle together and make explicit the assumptions that were part of our verbal explanation above.

To make these complete we have had to add (at the beginning) two more rules that were also previously part of our verbal explanation. The first of them (which has been given the name "Assumption") gives you a way of getting started. You might think of it as (the only) axiom schema of this formal system for writing down derivations. The second is called "Thin" and the remainder are direct translations of the natural deduction rules we had earlier.

$$\begin{array}{c}
 \text{Assumption } \frac{}{S \sqsubseteq S} \\
 \\
 \text{Thin } \frac{H \sqsubseteq S}{G, H \sqsubseteq S} \\
 \\
 \begin{array}{ccc}
 \text{II} \frac{G \sqsubseteq S \quad H \sqsubseteq \mathcal{T}}{G, H \sqsubseteq S \sqsubseteq \mathcal{T}} & \text{IE} \frac{G \sqsubseteq S \sqsubseteq \mathcal{T}}{G \sqsubseteq S} & \text{IE} \frac{G \sqsubseteq S \sqsubseteq \mathcal{T}}{G \sqsubseteq \mathcal{T}} \\
 \\
 \text{I} \frac{G \sqsubseteq S}{G \sqsubseteq S \sqsubseteq \mathcal{T}} & \text{I} \frac{G \sqsubseteq \mathcal{T}}{G \sqsubseteq S \sqsubseteq \mathcal{T}} & \perp \frac{G \sqsubseteq \perp}{G \sqsubseteq S} \\
 \\
 \text{I} \frac{G \sqsubseteq S \quad \mathcal{T}, S, H \sqsubseteq \mathcal{R} \quad \mathcal{T}, F \sqsubseteq \mathcal{R}}{G, H, F \sqsubseteq \mathcal{R}} \\
 \\
 \rightarrow\text{I} \frac{S, G \sqsubseteq \mathcal{T}}{G \sqsubseteq S \rightarrow \mathcal{T}} & \rightarrow\text{E} \frac{G \sqsubseteq S \rightarrow \mathcal{T} \quad H \sqsubseteq S}{G, H \sqsubseteq \mathcal{T}} \\
 \\
 \text{II} \frac{G \sqsubseteq S(a)}{G \sqsubseteq \exists x S(x)} \quad \text{provided } a \text{ does not occur in } G \text{ or } S(x) \\
 \\
 \text{II} \frac{G \sqsubseteq \exists x S(x)}{G \sqsubseteq S(a)} & \text{II} \frac{G \sqsubseteq S(a)}{G \sqsubseteq \exists x S(x)} \\
 \\
 \text{II} \frac{G \sqsubseteq \exists x S(x) \quad S(a), H \sqsubseteq \mathcal{T}}{G, H \sqsubseteq \mathcal{T}} \quad \text{provided } a \text{ does not occur in } H, S(x) \text{ or } \mathcal{T}
 \end{array}
 \end{array}$$

Figure 5.2



### 5.2.3. *Classical sequent calculus*

Sequents were introduced by Gentzen (1934) who proposed a calculus in which elimination rules are replaced by introduction rules on the left of the  $\vdash$ . Gentzen proved the equivalence of his sequent calculus to natural deduction by adding the Cut Rule to his system, which makes relating it to natural deduction a lot easier. Then in a famous result known as Gentzen's Hauptsatz, he showed that any derivation involving the Cut rule could be converted to one that was Cut-free.

Gentzen's sequent calculus idea is a very powerful one for studying derivations and relating them to other systems such as the tableau method. A further generalization allows more than one formula on the right of the  $\vdash$ . Doing this, and bringing in rules for  $\neg$ , gives the following symmetrical system shown in Figure 5.3 which again can be shown equivalent to the natural deduction system for full predicate logic.

Assumption  $\frac{}{S \Box S}$

$$\text{Thin } \Box \frac{G \Box \Box}{S, G \Box \Box}$$

$$\Box \text{Thin} \frac{G \Box \Box}{G \Box \Box, T}$$

$$\Box \wedge \frac{G \Box H, S \quad G \Box H', T}{G, G \Box H, H', S \wedge T}$$

$$\wedge \Box \frac{S, T, G \Box H}{S \wedge T, G \Box H}$$

$$\Box \vee \frac{G \Box H, S}{G \Box H, S \vee T}$$

$$\Box \vee \frac{G \Box H, T}{G \Box H, S \vee T}$$

$$\vee \Box \frac{S, G \Box H \quad T, G \Box H'}{S \vee T, G, G \Box H, H'}$$

$$\Box \rightarrow \frac{S, G \Box H, T}{G \Box H, S \rightarrow T}$$

$$\rightarrow \Box \frac{G \Box H, S \quad T, G \Box H'}{S \rightarrow T, G, G \Box H, H'}$$

$$\Box \neg \frac{S, G \Box H}{G \Box H, \neg S}$$

$$\neg \Box \frac{G \Box H, S}{\neg S, G \Box H}$$

$$\Box \Box \frac{G \Box H, S(a)}{G \Box H, \forall x S(x)}$$

$$\Box \Box \frac{S(a), G \Box H}{\forall x S(x), G \Box H}$$

$$\Box \Box \frac{G \Box H, S(a)}{G \Box H, \exists x S(x)}$$

$$\Box \Box \frac{S(a), G \Box H}{\exists x S(x), G \Box H}$$

Note: in the rules  $\Rightarrow \forall$  and  $\exists \Rightarrow a$  must not be free in  $G$ ,  $H$  or  $S(x)$

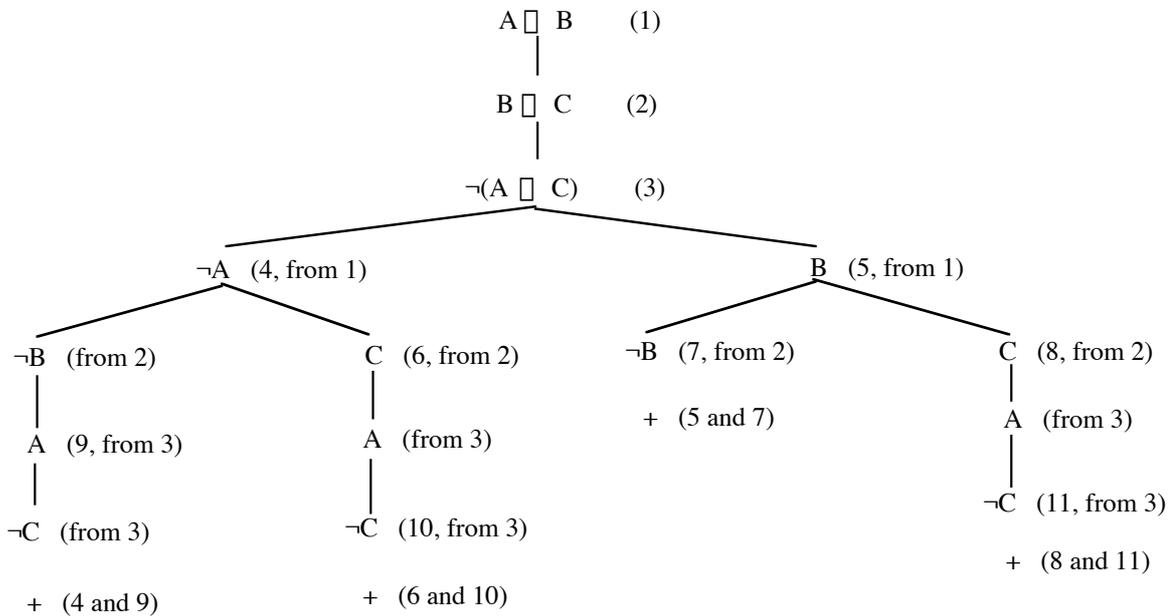
Figure 5.3

5.2.4. *Tableaux and sequents*

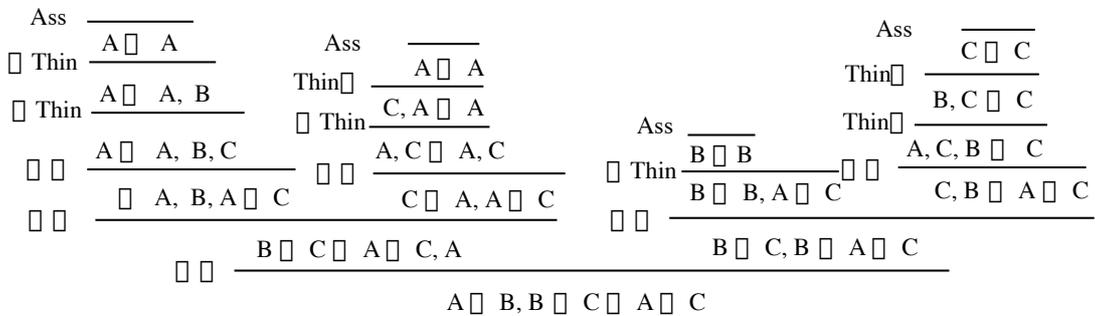
It can be shown that the statement "G  $\Box$  H can be derived in the system above" is equivalent to the statement "if all the formulas in G are true in an interpretation then at least one of the formulas in H is true". This can be used as the basis for a demonstration that the tableau and sequent calculus are equivalent. In fact closed tableaux are essentially sequent derivations in this system written upside down.

For instance, we have the following tableau proof of

$$\{A \rightarrow B, B \rightarrow C\} \vDash A \rightarrow C$$



and the following sequent proof of  $\{A \rightarrow B, B \rightarrow C\} \vDash A \rightarrow C$



Now, if we read each sequent as describing the unused sentences on each path of the tableau, with sentences on the left of the  $\sqsupset$  being un-negated and those on its right being negated and with branches in the tableau matching branches in the sequent proof, the similarity becomes quite clear. So, starting at the bottom, i.e. root, of the sequent proof we have sentences 1, 2 and 3 from the tableau. Then, moving up the leftmost branch, we have sentences 2, 3 and 4, i.e. the unused ones on the corresponding tableau branch. Then, moving up leftmost again, we have sentences 3, 4 and the  $\neg B$  from 2. Then we get, using  $\sqsupset \rightarrow$ , sentences 4, the  $\neg B$ , 9 and the  $\neg C$  from 3. This leads to a closure in the table of the leftmost path and, after some thinning, an assumption in the sequent proof.

The other paths can be seen to be equivalent to the corresponding tableau paths in the same way.

In fact, the original tableaux as introduced by Beth were even closer to the sequents since he used some notation to show whether, in sequent terms, a sentence was on the left or the right of the  $\sqsupset$ . Our tableaux are a subsequent specialization of Beth's to make the presentation, at least for the classical logics, clearer.

## 5.3. Generalizing the logic

### 5.3.1. Changing the Rules to get a different logic

Up to this point we have only talked about a single logic, called classical logic, the logic of two truth values and a truth-functional valuation system as described in chapter two and chapter three. In the introduction we promised to look not just at one logic but many. The sequent calculus with its many rules, each intended to capture in a straightforward way the behaviour of the logical connectives, gives us the opportunity to do this.

We have already seen that without the rule called C we are apparently unable to give a natural deduction proof of the propositional tautology  $P \rightarrow \neg\neg P$ . We now show that this is not just due to lack of inventiveness on our part. It provides a good illustration of the use of the sequent calculus for reasoning about derivations. However, to avoid some detail, we ask the reader to take on trust that the natural deduction system without C is equivalent to the sequent calculus system in which, for the rules  $\rightarrow$ ,  $\neg$  and  $\sqsupset$ , the set of formulas H on the right of the  $\sqsupset$  must be null.

Using this system we can derive  $\neg\neg(P \rightarrow \neg P)$  as follows



$$v_k(A \wedge B) = \min(v_k(A), v_k(B))$$

$$v_k(A \rightarrow B) = 1 \text{ if } v_k(A) \geq v_k(B) \text{ and } k \text{ if } v_k(A) < v_k(B)$$

We then have

$$v_k(\neg A) = v_k(A \rightarrow \perp) = 1 \text{ if } v_k(A) = k \text{ and } k \text{ if } v_k(A) < k$$

The rules have been chosen so that  $v_2$  reduces to the valuation function for classical propositional logic that we used in chapter two. We might hope that  $v_3$  would provide an adequate valuation function for the system that you get by omitting the C rule.

Now that we are talking about more than one logical system we must be careful to distinguish between them. We will call the full set of natural deduction rules C (either standing for "Classical" or "using Contradiction"), and the system derived from the full set by deleting the C rule we shall call I, for a reason to be revealed shortly. If a formula A can be derived from a set of formulas G in the full natural deduction system C then we will write  $G \vdash_C A$ , and if A can be derived from G in the system I then we will write  $G \vdash_I A$ .

By a lengthy but straightforward induction over the natural deduction proof tree (there are seven cases, one for each of the propositional rules) we can show that if  $G \vdash_I A$  then  $\max\{v_k(t_i) \mid t_i \in T\} \geq v_k(A)$  and hence if  $\vdash_I A$  then  $v_k(A) = 1$ . This shows that the system I is sound for any  $k \geq 2$ . We know that it is not complete for  $k=2$  because we have shown above that  $P \rightarrow \neg P$  is not a theorem of I whereas  $v_2(P \rightarrow \neg P) = 1$  for both possible values of  $v_2(P)$ . But what about  $k=3$ ?

Constructing the "truth-table" we get

$v_3(P)$	$v_3(\neg P)$	$v_3(P \rightarrow \neg P)$
1	3	1
2	3	2
3	1	1

so the stratagem seems to have worked in this case.  $P \rightarrow \neg P$  is not a tautology in the three-valued semantics and so the fact that it is not a theorem of I does not disprove the completeness of I.

Success is short-lived, however, because it is possible to show that whatever value of  $k$  is chosen, there are formulas  $A$  for which  $v_k(A) = 1$  in all valuations but it is not the case that  $\vdash_I A$ . In fact  $(\neg\neg P \vdash P) \rightarrow (P \vdash \neg P)$  is such a formula. We can leave it to the reader to show that  $v_k(A) = 1$  for all  $k$  and all values of  $v_k(P)$ . To show that it is not the case that  $\vdash_I A$  we have to wait until chapter eight. The conclusion is that a simple extension of the truth-table idea with a linearly ordered set, however large, is insufficient to give a semantic basis for the system of deduction I. In chapter eight we show what the correct semantic basis is.

### 5.3.3. Constructive ideas

In fact I is a system of deduction for a logic known as Intuitionistic logic. Historically it is important because it grew out of the work of Brouwer who originated the study of intuitionistic, for which you may read constructive, mathematics in the early part of this century. Brouwer rejected the law of the excluded middle, i.e.  $S \vee \neg S$  for any sentence  $S$ , and he and his followers set out to reconstitute mathematics on purely constructive lines. Constructivists would not, for example, admit existence proofs that rely on deriving a contradiction from the assumption that some mathematical entity does not exist. They said that for a proof of existence to have any meaning you have to actually produce an instance of the object in question. We can see an immediate connection here with the natural deduction system I.

In one of our earlier examples we showed that  $\{\neg \Box xP(x)\} \vdash_C \Box x\neg P(x)$ , which "says" that if it is not the case that every  $x$  has property  $P$ , then there must be some  $x$  that does not have property  $P$ . However we didn't do this by producing a particular object  $a$  such that  $\neg P(a)$  was true. We assumed  $\neg \Box xP(x)$ , derived  $\Box$ , and used the C rule. It is not hard to show that in the system I which does not have the C rule, you cannot prove  $\Box x\neg P(x)$  from  $\neg \Box xP(x)$ .

It was Heyting around 1930 who first gave an informal semantics for intuitionistic logic in terms of the notion of constructive proof and Gentzen a few years later who essentially formulated the natural deduction systems for both I and C, that we have been discussing in this chapter. We have just seen that a simplistic approach to giving the logic a mathematical semantics, using more than two truth-values, doesn't work. Tarski and Stone, working at about the same time as Gentzen, were the first to show the correct way to do it when they noticed similarities between intuitionistic logic and topology. However Kripke in 1963 proposed a semantics that

is much easier to work with, and since we explain this in chapter eight, we shall continue the discussion of intuitionistic logic there.

## 5.4. What is Logic Ultimately?

We made a point in our introduction of saying that we were going to look at not just one logic but many, and we have just shown you an example of this by examining the consequences of modifying the natural deduction rules for classical logic to get another important system. There is nothing sacred about classical logic. We can and will go on to look at other logics. But if we are going to do this where do we draw the line? Ultimately what is and what is not a logic?

Imagine I am showing you a computer program I have written. I place you in front of a terminal and invite you to type in things like

$$\{P, P \rightarrow Q\} \vdash Q$$

to which the machine answers "yes", or

$$\{\neg P \rightarrow Q\} \vdash \neg Q \rightarrow P$$

to which the machine answers "no", meaning that in whatever system of deduction my program implements,  $Q$  can be derived from  $P$  and  $P \rightarrow Q$ , but  $\neg Q \rightarrow P$  cannot be derived from  $\neg P \rightarrow Q$ .

The symbol  $\vdash$  denotes, in the observer's language, a relation, called a consequence relation, between formulas and sets of formulas of the object language. If you were to try out my program for a long time you would gradually build up some knowledge of what the consequence relation of my system was and you would start to get some idea of its properties. For example you might notice that it always said "yes" to questions of the form  $\{A\} \vdash A$ , whatever formula  $A$  was, or that whenever it said "yes" to  $G \vdash A$  it would always say "yes" to  $G, B \vdash A$ . Thinking back to chapter two you recall that the relation of semantic entailment  $\models$  possessed similar properties. If you observe that the program's consequence relation shares these properties then this increases your confidence that my program is implementing some kind of logic. This example is due to Dov Gabbay (1984).

Suppose however that I now tell you my program works by converting all the formulas to numbers and then says that  $G \vdash A$  if the number corresponding to  $A$ , call it  $n(A)$ , divides the product  $\prod n(g_i)$  of the numbers corresponding to the  $g_i$  in  $G$ . You

would probably want to say that a program that worked on a purely arithmetic basis such as this did not have anything to do with logic. Yet if the program did work like this it would have at least some of the properties of the systems described above because  $n(A)$  divides  $n(A)$  and so  $\{A\} \vdash A$  and if  $n(A)$  divides  $\Box n(g_i)$  then  $n(A)$  divides  $n(B) \Box n(g_i)$ , and so if  $G \vdash A$  then  $G, B \vdash A$ . If arithmetically-based programs like this can have logical properties then where do we draw the line on deduction rules? What is and what is not logic?

A relation  $\vdash$  between sets of formulas and formulas of some language  $L$  is the consequence relation of a logical deduction system based on  $L$  if it satisfies the three rules

Reflexivity	$\{A\} \vdash A$
Monotonicity	$G \vdash A$ implies $G, B \vdash A$
Transitivity (Cut)	$G \vdash A$ and $A, H \vdash B$ implies $G, H \vdash B$

plus another condition to cope with infinite sets. We leave the reader as an exercise to show by means of a counter-example that the arithmetically-based relation above does not always satisfy the transitivity condition.

## Summary

- Natural Deduction is a formal deductive system that models ordinary mathematical reasoning more closely than axiom systems or the tableau method do. A natural deduction system consists of rules for *introducing* and *eliminating* each of the logical connectives and quantifiers. Proofs are constructed by fitting the rules together in the form of a tree. As in ordinary reasoning, temporary assumptions may be made in the course of the proof and then *discharged* by incorporating them into the conclusion. Interactive proof systems for reasoning about programs in computer science are often based on natural deduction.

- The Sequent Calculus is a less pictorial, more algebraic, formulation of natural deduction in which the role of assumptions is more explicit. It provides a means of reasoning about proofs and axiomatizing deduction. A *sequent* is an expression of the form  $G \Box H$  where  $G$  and  $H$  are sets of formulas. A sequent calculus is a set of rules for manipulating sequents. Gentzen gave a set of sequent

rules for classical predicate calculus that he showed equivalent to natural deduction. The tableau method is shown to be essentially another way of writing sequent calculus derivations.

- Natural deduction and the sequent calculus give us the opportunity to generate different logics by varying the rules. Leaving out the Contradiction rule we get a logic, called *intuitionistic logic*, in which the 'law of the excluded middle',  $P \vee \neg P$ , is not a theorem. It is shown that this logic cannot have a semantics with two truth-values, or indeed any linearly ordered set of truth-values.

- If we can change the logic by changing the rules, how far can we go while still 'doing logic'? The rules of deduction determine a *consequence relation*. Consequence relations for logical deductive systems are reflexive, transitive and monotonic. Nowadays, however, the definition of what constitutes logical deduction is being pushed wider and wider, partly as a result of the impetus given by computer science.



# CHAPTER SIX

---

## Some Extended Examples

### 6.1. Introduction

In chapter three we introduced the fundamental notion of interpretation and said what it meant for an interpretation to be a model for a theory in a formal language. It should be clear that there is a use for interpretations in computer science. Either explicitly, when new programming languages are designed, or less explicitly when we invent data structures in solving some computational problem, we set up a relationship between parts of the language and the objects that we want to reason about. In both cases we can use the interpretation and the proof theory of the logic to state and derive properties of the programming language or the data structures.

### 6.2. Theory examples

In the next few sections we will give examples of theories and models. For this presentation our reasoning will be largely informal; that is we will not be working within the formal systems given in chapters two and three, though we will, of course, be respecting the meanings given there to the constants and other symbols that we introduced.

#### 6.2.1. A simple theory

Consider a language with one predicate symbol  $P$  and no function symbols or names, so in the notation of chapter three we have  $L(\langle\{P\},\{\},\{\}\rangle)$ . Let  $\mathcal{P}$  be the theory generated by the axioms

$$P_1 : \forall x \forall y \forall z ((P(x,y) \wedge P(y,z)) \rightarrow P(x,z))$$

$$P_2 : \forall x(\neg P(x,x))$$

To find models of  $\text{Th}(\{P_1, P_2\})$  we need only look for models of  $P_1$  and  $P_2$ , by definition. One such model would be the interpretation whose universe is the set  $\mathbf{Z}$  of positive and negative integers, and where  $P$  denotes the "less-than" relation over  $\mathbf{Z}$ .

It can get tedious using the strictly formal language when we have a particular interpretation in mind, so we will allow ourselves to write

$$P_1 : \forall x \forall y \forall z ((x < y \wedge y < z) \rightarrow x < z)$$

$$P_2 : \forall x (\neg x < x)$$

but we must remember that this is still a formal system and so we are still at liberty to take interpretations for these sentences that are "non-standard", i.e. in which  $<$  has some unusual denotation.

In one of the standard interpretations, where  $<$  is the usual arithmetic "less-than" relation over  $\mathbf{Z}$ , it is clear that many other sentences in addition to  $P_1$  and  $P_2$  are true. For example

$$\forall x \forall y (x < y \rightarrow \neg y < x)$$

but is this true in every model of  $P_1$  and  $P_2$ ?

We can reason informally to start with. Suppose there were elements in the universe (where we invent some names  $a$  and  $b$  to denote them) such that both  $a < b$  and  $b < a$  were the case. Then by  $P_1$  we would have  $a < a$ , which contradicts  $P_2$ . So it cannot be the case that such elements exist, and it would be the case that

$$\neg \forall x \forall y (x < y \wedge y < x)$$

which is equivalent to

$$\forall x \forall y \neg (x < y \wedge y < x)$$



To give a formal proof of the result, we can, for example, use the tableau method. As usual, in setting up the proof, the initial sentences are  $P_1$  and  $P_2$  together with the negation of the sentence that we wish to prove. The tableau we get is given in figure 6.1.

In examining this tableau you should bear in mind that the algorithms given in chapter four are not, in general, going to give the shortest proof, and an algorithm which orders use of the rules differently will give a different proof. When you have studied the tableau which solves this problem you should try using the rules in different orders, and also apply your intelligence, to get different, and perhaps better or less voluminous proofs.

### Exercise 6.1

- a) Find a model for  $\mathcal{P}$  which has a finite universe.
- b) If  $\mathcal{P}$  is interpreted as inequality over  $\mathbf{Z}$ , is  $P_2$  true? Is  $P_1$  true?
- c) Use natural deduction (chapter five) instead of the tableau method to give a formal proof that  $\forall x \forall y (x \neq y \rightarrow \neg y \neq x)$  is true in all models of  $\mathcal{P}$ .

#### 6.2.2. A theory for equality

Virtually all applications of logic need a predicate in the language whose denotation is what we normally understand by equality.

Strictly speaking we should use some neutral symbol of arity two, say  $Q$ , for this. Once again, to make our formulas and sentences easier to read and understand, we shall use the more intuitive informal symbol  $=$ , with the usual warning about being at liberty to give it non-standard interpretations if we wish.

Our theory for equality has one axiom

$$E_1 : \forall x (x = x)$$

and one axiom schema

$$E_2 : \forall x \forall y \forall z_1 \dots \forall z_n (x = y \rightarrow (S \rightarrow S[y/x]))$$

where  $S$  is any formula with free variables  $z_1, \dots, z_n$ ,  $x$  and possibly  $y$ .  $S[y/x]$  is the formula that results from putting  $y$  instead of one or more of the free occurrences of  $x$ . We need a schema like this since we do not know in advance what other predicate symbols will be in the language in addition to equality.

In particular we can use  $=$  as a predicate symbol in  $S$  and consider  $S$  to be the formula  $x=z_1$ . Then an instance of  $E_2$  would be

$$\Box x \Box y \Box z_1 (x = y \rightarrow (x=z_1 \rightarrow y=z_1)) \quad (1)$$

We can now use this together with  $E_1$  to prove other useful properties of  $=$ . For example we can prove that  $=$  is symmetric. Our informal reasoning is as follows. By the above we have

$$(a = b \rightarrow (a=a \rightarrow b=a)) \quad (2)$$

with  $a$  for  $x$  and  $z_1$  and  $b$  for  $y$ . Now assume that

$$a = b \quad (3)$$

then, by Modus Ponens on 2 and 3, we have that

$$a = a \rightarrow b = a \quad (4)$$

but, by  $E_1$ , we have

$$a = a \quad (5)$$

and so, by using Modus Ponens again on (4) and (5), we have

$$b = a$$

We have therefore shown that, if  $a=b$  is the case, then  $b=a$  is the case. So we have shown (see the beginning of chapter five) that

$$a = b \rightarrow b = a$$

and since  $a$  and  $b$  were arbitrary it follows that we have

$$\Box x \Box y (x = y \rightarrow y = x)$$

which is the formal language statement of the symmetry of = as required.

It should be apparent that the informal demonstration we have just given is very similar in style to the informal argument of chapter five (section 5.1.3) that was there the starting point for a formal proof using natural deduction. You should carry out a similar exercise and construct the formal proof by natural deduction that corresponds to the informal argument above. Again, we give the tableau proof in figure 6.2.

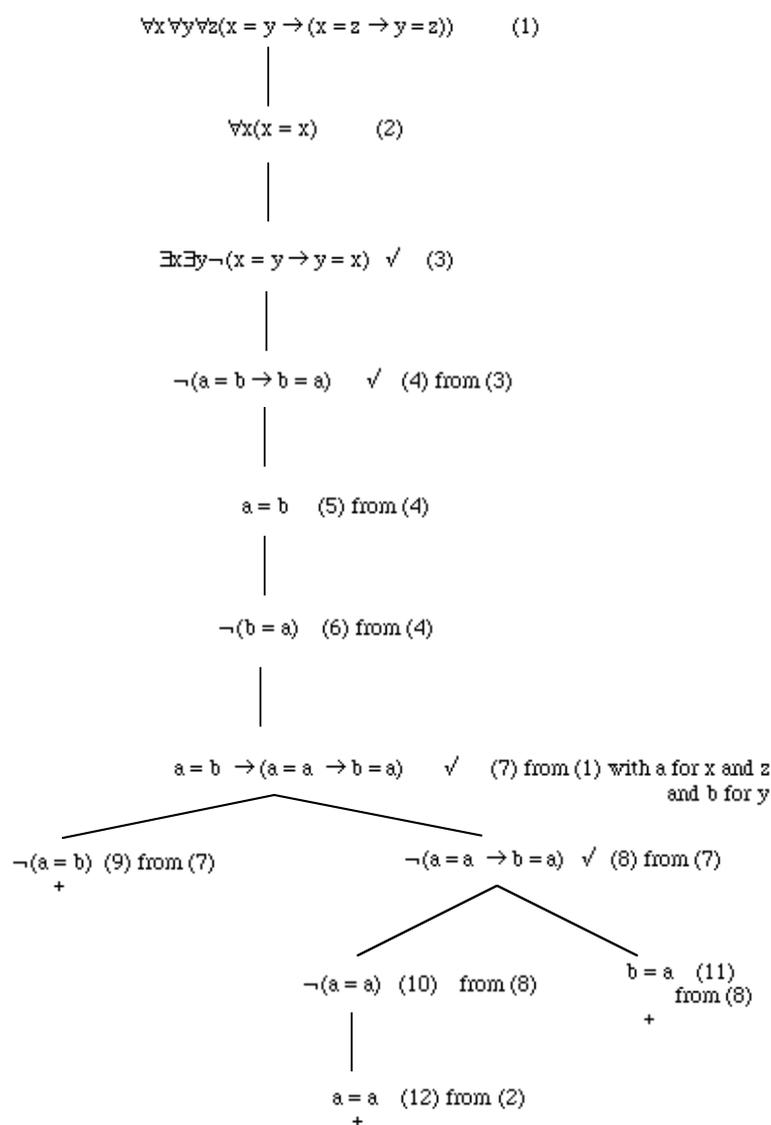


Figure 6.2

## Exercise 6.2

- 1) Show that transitivity of equality follows from  $E_1$  and an instance of  $E_2$ .
- 2) Give natural deduction proofs of the symmetry and transitivity of equality.

### 6.2.3. A theory for strings

In this case the intended interpretation is to be strings over a given alphabet of symbols, say  $\{\square, \square, \square\}$ , so that, for example,  $\square\square, \square\square, \square\square\square\square$  are in the universe, as is the empty string which we will denote by  $\square$

The formal language has the usual set of variables, connectives and punctuation plus a constant symbol, or name,  $e$  which denotes the empty string. The language has an infix function symbol  $'.'$  denoting the operation of attaching a single character on the left hand end of a string, and two predicate symbols  $C$  and  $S$ ,  $C(x)$  being true if the denotation of  $x$  is a single character string, and  $S(x)$  being true if  $x$  denotes a string.

Other names in the language are  $a, b$  and  $c$  (whose intended denotations are the single character strings  $\square, \square$  and  $\square$ ). In the notation of chapter three the language is  $L(\langle\{C,S\}, \{.\}, \{a, b, c, e\}\rangle)$ . Terms in the language therefore include  $a.(b.e)$ ,  $b, e$  (but not for example  $ab$ ). Different terms may denote the same string. The denotation of some terms may be undefined.

Now we consider the theory generated by the equality axioms  $E_1$  and  $E_2$  plus

$$S_1 : S(e)$$

$$S_2 : \square x \square y (C(x) \square S(y) \rightarrow S(x.y))$$

$$S_3 : \square x (C(x) \rightarrow x.e = x)$$

We can check to see whether some sentences are in the theory. As a first example we take

$$\square x (C(x) \rightarrow S(x)) \tag{1}$$

First, assume that

$$C(a) \tag{2}$$

then, from S2 we have

$$C(a) \sqcap S(e) \rightarrow S(a.e) \quad (3)$$

with  $x$  in S2 as  $a$  and  $y$  as  $e$ . Then, from (2) and S1 we have

$$C(a) \sqcap S(e)$$

and this, together with (3) gives

$$S(a.e) \quad (4)$$

Then, S3, with  $x$  as  $a$  gives

$$C(a) \rightarrow a.e = a$$

and this together with (2) again gives

$$a.e = a$$

and this further, by properties of identity together with (4) gives

$$S(a)$$

Then, since  $a$  was arbitrary, we have the sentence (1) as required. So, we have shown (informally of course) that

$$S1, S2, S3, E1, E2 \vdash (1)$$

which is just to say that (1) is in the theory  $\text{Th}(\{S1, S2, S3, E1, E2\})$  since we also have, by the soundness theorem

$$S1, S2, S3, E1, E2 \vDash (1)$$

The tableau that proves this is given in figure 6.3.

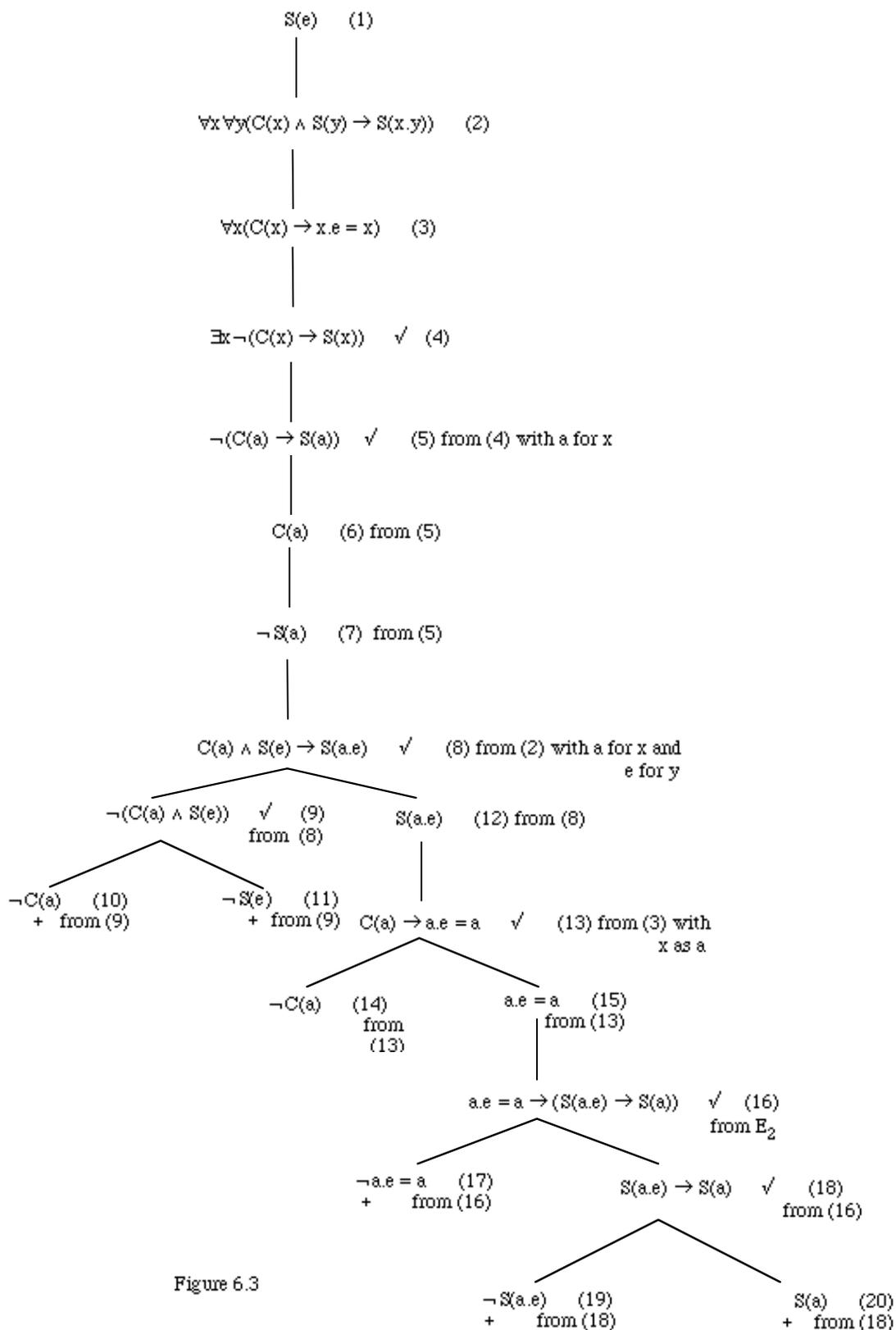


Figure 6.3

#### 6.2.4. Another example

Consider the theory given by the equality axioms  $E_1$  and  $E_2$  together with

$$St_1 : \forall x \forall y (f(g(x,y))=x)$$

$$St_2 : N(e) \wedge \forall y (\neg e = y \leftrightarrow \neg N(y))$$

$$St_3 : \forall x \forall y (\neg N(g(x,y)))$$

We will call this set of sentences  $St$ . Then, as usual, of all the possible interpretations of the non-logical symbols  $N$ ,  $e$ ,  $f$ ,  $g$  and  $=$ , only a certain sub-class of them form models of  $St$ . Therefore, only a subset of all possible sentences in the language are in the theory determined by these models, i.e. only a subset of all possible sentences are theorems.

Clearly, we only talk in a non-trivial way if our sentences 'pick out' a subset of all possible relations that hold in the world. If the only sentences that we could utter were all valid sentences then, since they would be, by definition, true in all interpretations, we would not be saying anything interesting about particular interpretations.

Thinking back to chapters two and three, we used the word 'axiom' in defining formal deductive systems. There the axioms were all valid. How can it be, considering what has just been said, that the formal deductive system is saying anything interesting? Well, the point is that those axioms are only valid under our underlying assumption that all statements are either true or false. Without that assumption those axioms are no longer necessarily valid. To put it another way, by framing the definitions so that those axioms are valid we are selecting interpretations in which all sentences are either true or false as a framework for our logic. So, the axioms are telling us something after all.

Going back to  $St$ , let us fix our interpretation of the non-logical symbols as one which is a model for  $St_1$ ,  $St_2$ ,  $St_3$ ,  $E_1$  and  $E_2$ , and call the model  $M$ . Now consider the sentence

$$\neg N(g(a,g(b,e)))$$

Is this true or false in  $M$ ? We can take axiom  $St_3$  above and substitute  $a$  for  $x$  and  $g(b,e)$  for  $y$  to get the required sentence. Therefore, since this is an instance of  $St_3$

(using a version of P5 from chapter three, section 3.2) we have established that the sentence is a theorem. You may have already noticed that  $St$  is an approximation to a theory of stacks (a stack is a data structure that can only be modified in a "last in, first out" manner; you can only access the last item to have been added to it).

**Exercise 6.3** Give similar arguments to decide whether or not the following are theorems of the theory  $St$ .

a)  $\neg e = g(a,e)$

b)  $f(f(g(a,e))) = a$

c)  $\exists x(N(x) \rightarrow x=e)$

### 6.2.5. Induction

Many proofs in mathematics and computer science require the principle of mathematical induction. This is almost invariably the case with recursively defined programs and data structures. To illustrate the formulation of induction in a logical theory we return to the theory of strings that was given in section 6.2.3 and extend it with further axioms for another function symbol '@' whose intended interpretation is concatenation of strings. (In fact the symbol '@' is the same as the one used to denote concatenation in the SML system).

We are going to prove by induction that '@' is associative, but before doing so, because there are minor complications in the theory of strings to do with having more than one sort of object, namely both characters and strings, we start by looking at how induction would be formulated in a simpler and more familiar setting.

If you were constructing a theory of non-negative integers you would have a predicate symbol such as  $I$  whose denotation is the integers, and axioms such as

$$I(0)$$

$$\exists x (I(x) \rightarrow I(s(x)))$$

where the intended denotation of the name '0' is the number zero, and that of the function symbol 's' is the successor function over the integers, i.e. the function that takes an integer and adds unity to it. So, for example,  $s(s(0))$  denotes the number two.

In this theory the principle of induction would be formulated as the schema

$$(\mathcal{F}[0] \wedge \forall x (\mathcal{F}[x] \rightarrow \mathcal{F}[s(x)])) \rightarrow \forall x \mathcal{F}[x]$$

where  $\mathcal{F}[x]$  is any sentence containing  $x$  as a free variable. In the same way as we did for equality, we need a schema for the induction axiom rather than a sentence because we want to leave open the possibility of using the principle for any statement about the domain (sentence in the formal language).

Now if we were to extend our theory of the integers with additional function symbols and axioms intended to formalize, say, the addition function, then we could use the induction schema given above to derive, for example, a sentence whose denotation is the associativity of addition.

In the theory of strings the role of the successor function is played by the denotation of the '!' function that extends a string by adding a single character to it. Recall that if  $a$  denotes  $\square$ ,  $b$  denotes  $\square$ ,  $c$  denotes  $\square$  and so on, then  $b.(c.e)$  denotes the string  $\square\square$  and  $a.(b.(c.e))$  denotes the string  $\square\square\square$ . The corresponding induction principle is an example of what is called structural induction - instead of arguing by induction over the integers we operate, in this case over strings, in general over formulas, trees, indeed anything whose structure can be given the appropriate recursive definition. In fact, many of the meta-theorems proved earlier in the book have employed structural induction, but in the observer's rather than the object language.

For the theory of strings the appropriate induction schema is

$$(\mathcal{F}[e] \wedge \forall x (S(x) \rightarrow (\mathcal{F}[x] \rightarrow \forall u (C(u) \rightarrow \mathcal{F}[u.x]))) \rightarrow \forall x (S(x) \rightarrow \mathcal{F}[x])$$

This looks more complicated than it is. It says that if the sentence  $F$  is true of the empty string and if, for all strings  $x$ ,  $F$  is true of  $x$  implies that  $F$  is true of  $u.x$  for any character  $u$ , then  $F$  is true of all strings. Because we have two sorts of object in the universe we need the  $S(x)$  and  $C(u)$  to ensure that the universal quantifiers can only range over the appropriate type. (There are 'many-sorted' logics in which this can be done more neatly but to discuss them would take us too far afield).

The additional axioms for '@' (written, like the function symbol '!' that we already have, in infix mode) are

$$S_4 : \forall x (S(x) \rightarrow e@x=x)$$

$$S_5 : \forall x \forall y \forall z (C(x) \wedge S(y) \wedge S(z) \rightarrow (x.y)@z = x.(y@z))$$

If the term  $a.(b.e)$  denotes the string  $\square\square$  and  $b.(c.e)$  denotes the string  $\square\square$  then the denotation of the term  $(a.(b.e))@(b.(c.e))$  is the string  $\square\square\square\square$ . It is clear from one's intuition of the domain that  $@$  is associative, in other words  $(t_1@t_2)@t_3$  denotes the same string as  $t_1@(t_2@t_3)$  whatever strings the terms  $t_1$ ,  $t_2$  and  $t_3$  denote. To prove this we take  $\mathcal{F}[x]$  in the induction schema as

$$\square y\square z ( S(y)\square S(z) \rightarrow (x@y)@z = x@(y@z) ) \quad (\mathcal{F}[x])$$

We are also going to need some theorems from the theory of equality. We have already shown

$$\square x\square y ( x=y \rightarrow y=x ) \quad (\text{Symmetry of } =)$$

Using suitable instances of  $E_2$  it is also straightforward to show

$$\square x\square y\square z ( x=y \rightarrow (y=z \rightarrow x=z) ) \quad (\text{Transitivity of } =)$$

and, for any terms  $t, t', t_1, \dots, t_n$  and function symbol  $f$ , that

$$t=t' \rightarrow f(t_1, \dots, t, \dots, t_n) = f(t_1, \dots, t', \dots, t_n) \quad (\text{Substitution in terms})$$

Now we take, as the inductive hypothesis,  $\mathcal{F}[q]$  for some string  $q$ , so we have  $S(q)$  and

$$\square y\square z ( (q@y)@z = q@(y@z) )$$

Then by  $\square$  elimination, and assuming  $S(r)$  and  $S(s)$ , we have

$$(q@r)@s = q@(r@s) \quad (1)$$

Now by  $S_5$ , and the rule for substitution in terms, if  $p$  is such that  $C(p)$  holds

$$((p.q)@r)@s = (p.(q@r))@s \quad (2)$$

and again by  $S_5$

$$(p.(q@r))@s = p.((q@r)@s) \quad (3)$$

From (1),  $E_1$ , and the rule for substitution in terms, we have

$$p.((q@r)@s) = p.(q@(r@s)) \quad (4)$$

From  $S_5$  and the rule for symmetry of  $=$  we have

$$p.(q@(r@s)) = (p.q)@(r@s) \quad (5)$$

So by several applications of the transitivity of  $=$  we have, from (2),(3),(4),(5),

$$((p.q)@r)@s = (p.q)@(r@s)$$

Discharging  $S(r)$  and  $S(s)$ , and using  $\square$  introduction and the definition of  $\mathcal{F}[x]$ , we have  $\mathcal{F}[p.q]$ , and discharging  $C(p)$  and using  $\square$  introduction we have

$$\square u ( C(u) \rightarrow \mathcal{F}[u.q] )$$

Discharging the inductive hypothesis  $\mathcal{F}[q]$  we have

$$\mathcal{F}[q] \rightarrow \square u ( C(u) \rightarrow \mathcal{F}[u.q] )$$

and discharging  $S(q)$  and using  $\square$  introduction we have

$$\square x ( S(x) \rightarrow (\mathcal{F}[x] \rightarrow \square u ( C(u) \rightarrow \mathcal{F}[u.x] ))) \quad (6)$$

Now from  $S_1$  and  $S_4$  we have both

$$e@q = q \quad (7)$$

and

$$e@(q@r) = (q@r) \quad (8)$$

and so, from (7) and (8), and the symmetry and transitivity of  $=$ , we have

$$(e@q)@r = e@(q@r)$$

But  $q$  and  $r$  are arbitrary strings, so discharging  $S(q)$  and  $S(r)$  and using  $\square$  introduction, we have

$$\square y \square z ( S(y) \square S(z) \rightarrow (e@y)@z = e@(y@z) )$$

But this is  $\mathcal{F}[e]$ , and so with (6) and the principle of induction we have  $\square x \mathcal{F}[x]$ , i.e.

$$\square x \square y \square z ( (x@y)@z = x@(y@z) )$$

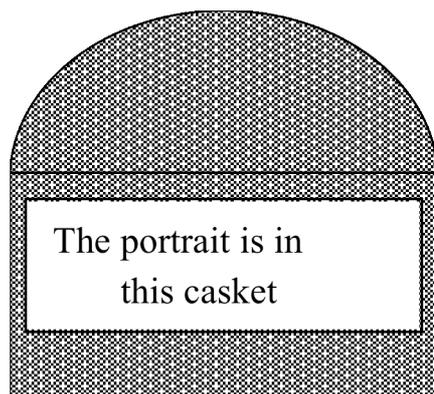
which is the associativity of '@' that we set out to derive.

This use of structural induction is typical of many proofs about abstract data structures that are carried out in computer science and similar theories can be constructed for lists and trees. Manna and Waldinger (1985) give numerous examples.

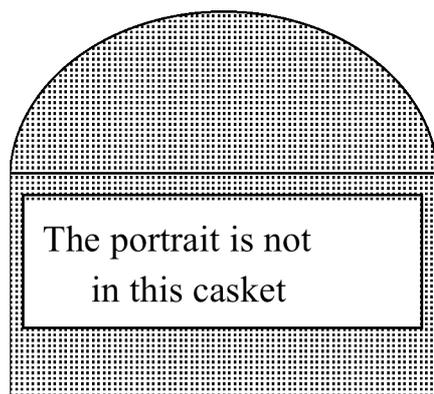
#### 6.2.6. A puzzling example

Raymond Smullyan is a well-known logician, but aside from his "serious" work he has also produced a number of more popular books about logic that are unique in that they illustrate quite difficult topics (up to and including Gödel's theorem for example) by means of stories and puzzles. We borrow one of his puzzles now to illustrate some points about theories involving equality and also to show that the application of formal deductive systems is not just confined to reasoning in mathematics or computer science.

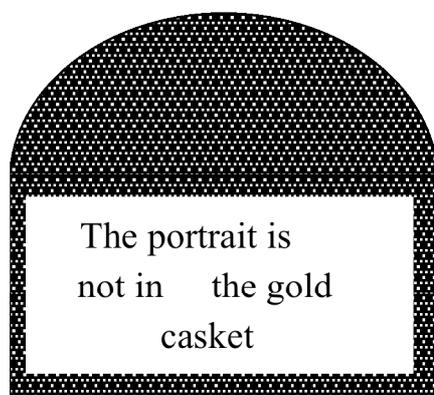
The story goes as follows. In the Merchant of Venice the character Portia had three caskets, one made of gold, one of silver and one of lead. Concealed inside one of them was her portrait. Prospective suitors were tested by being asked which casket the portrait was in. Inscribed on the top of each casket was a statement they might find useful in making their choice. At most one of the statements is true. For example:



Gold casket



Silver casket



Lead casket

It is quite easy to solve this conundrum by logical but informal reasoning. You should do it now as an exercise. To do it mechanically, either by hand or by computer, is another matter. As usual we have to set up an appropriate formal language. In this case we have three constant symbols, a, b and c say, which in the intended interpretation will denote the gold, silver and lead caskets respectively, and

two predicate symbols T and P. T(x) will be satisfied if the statement written on the casket that x denotes is true, P(x) will be satisfied if the portrait is in the casket that x denotes. There are many such puzzles that can be constructed, but they all have one thing in common; there is only one copy of the portrait and it is in one of the caskets. So the basic theory for all these puzzles will contain a sentence that says this in the casket interpretation. There are several ways to do it. Since we know there are only three objects in the domain we can do it without quantifiers by writing

$$C_1: (P(a) \sqcap \neg P(b) \sqcap \neg P(c)) \quad (\neg P(a) \sqcap P(b) \sqcap \neg P(c)) \quad (\neg P(a) \sqcap \neg P(b) \sqcap P(c))$$

or even without predicates by writing P(a), P(b) and P(c) as propositional letters A, B and C.

Using quantifiers has the advantage that our theory will cope with any number of caskets, but it does require some care with the theory of equality. First we solve the puzzle, then we return to consider how to use quantifiers and the theory of equality.

The condition that at most one of the inscriptions on the caskets is true can be expressed similarly by

$$C_2: (T(a) \sqcap \neg T(b) \sqcap \neg T(c)) \quad (\neg T(a) \sqcap T(b) \sqcap \neg T(c)) \\ (\neg T(a) \sqcap \neg T(b) \sqcap T(c)) \quad (\neg T(a) \sqcap \neg T(b) \sqcap \neg T(c))$$

and the inscriptions themselves by

$$C_3: T(a) \leftrightarrow P(a)$$

$$C_4: T(b) \leftrightarrow \neg P(b)$$

$$C_5: T(c) \leftrightarrow \neg P(a)$$

Now we don't know the answer to the puzzle so we don't know exactly what we are trying to prove but we do know that it will be either P(a), P(b) or P(c). We shall opt to use the tableau method - appropriately, since Smullyan (1968) has given a particularly clear exposition of it. When the tableau is completed we shall see what is required to close it. In fact it is a straightforward exercise in the use of the  $\sqcap$ ,  $\sqcup$  and  $\leftrightarrow$  rules that we leave to the reader. All branches except one close. The open branch contains  $\neg P(a)$ , P(b),  $\neg P(c)$ , showing that the silver casket is the one containing the portrait, because if we had known this at the start we would have added  $\neg P(b)$  to the initial set of sentences  $C_1, \dots, C_5$  and the tableau would have closed.

If we had decided to use quantifiers to express the two conditions that the portrait is in precisely one of the boxes and no more than one of the inscriptions is true then there are several ways to say these things in the formal language. There is, however, no way to do it without using equality. Perhaps the simplest is to use the sentence

$$\exists x \exists y (\neg(x=y) \wedge T(x) \wedge T(y))$$

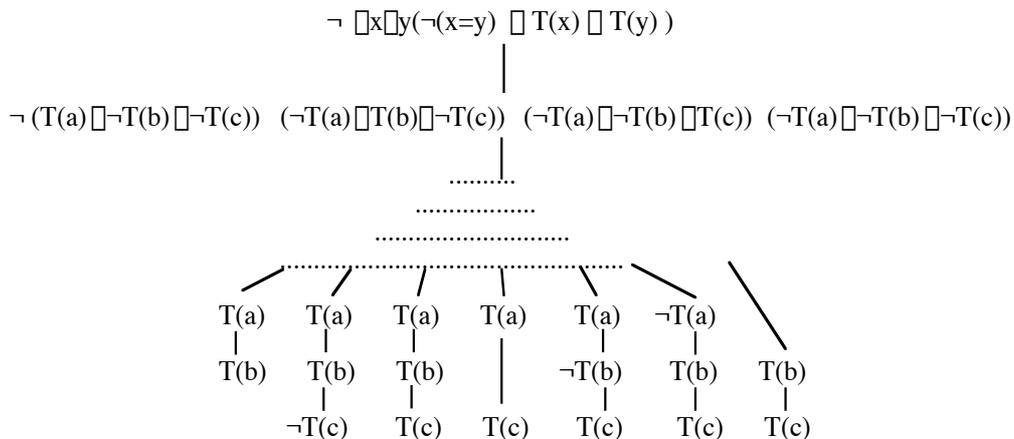
which says that at least two objects in the domain possess property T. We can then negate this to give the condition that no more than one of the inscriptions is true.

$$C'_2: \neg \exists x \exists y (\neg(x=y) \wedge T(x) \wedge T(y))$$

The condition that the portrait is in precisely one of the boxes is similar, but with the additional condition that says it is in at least one of the boxes,

$$C'_1: \neg \exists x \exists y (\neg(x=y) \wedge P(x) \wedge P(y)) \wedge \exists z P(z)$$

Showing that this formulation is equivalent to the one without quantifiers is instructive because it demonstrates some of the points that arise in working with theories that contain the theory of equality. We show that  $C'_2$  entails  $C_2$ . Negating  $C_2$  and applying the tableau rules gives  $3^4 = 81$  branches of which all but seven close or are duplicated. The seven distinct open branches contain (reading them vertically) the formulas shown below. Note that they enumerate all possible countermodels to  $C_2$ , i.e. those in which two or more of the statements on the caskets are true.

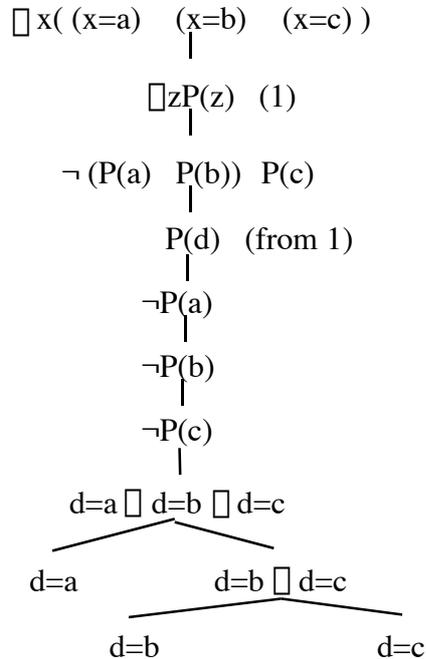




However  $\exists zP(z)$  does not entail  $P(a) \wedge P(b) \wedge P(c)$  unless we add an extra condition that says there are no objects other than a,b and c in the domain. The appropriate condition to add is

$$\forall x( (x=a) \vee (x=b) \vee (x=c) )$$

This is known as the Closed World Assumption (CWA). Together with the assumption that distinct names denote distinct objects in the domain, it is of particular importance in deductive databases and Artificial Intelligence where one of the aims is to write logically-based programs that, for example, will enable a computer-controlled robot to prove simple theorems about its environment . With the CWA we can get the equivalence we need as shown below.



and now we can close all these branches by using sentence  $E_2$  from the theory of equality, which gives for example  $(d=a) \rightarrow (P(d) \rightarrow P(a))$ , which when expanded closes the left-hand branch. The others are similar.

### 6.3. Gödel and the limits of formalization

Because so many good accounts are available elsewhere we have chosen not to describe the classical logical theories of arithmetic and the foundations of set theory. A theory of arithmetic (more precisely - a theory whose standard interpretation is the integers and the usual arithmetic operators and predicates over

them) can be generated from the theory of equality, six axioms for the arithmetic constants and operators and an induction schema. If Hilbert's assumption had been correct (see the end of chapter three) then all the truths of arithmetic could in principle have been established by the methods of the current chapter. However in 1931 Gödel showed that, for a certain sentence  $G$ , neither  $G$  nor  $\neg G$  can be proved within the formal system for arithmetic.

The method Gödel used was to show that formulas and proofs could be coded as numbers (Gödel numbers), so that statements in the observer's language about the existence of proofs in the formal system can be expressed as statements about numbers within the system itself. The formula  $G$  is a rather unusual one, in that it can be interpreted as asserting its own unprovability. Nevertheless its denotation can clearly be recognized as true, which means that there are truths of arithmetic that cannot be proved or disproved within the formal system for arithmetic.

## Summary

- A *theory* is a set of sentences all of which are true in a class of interpretations. A theory can be specified by giving the *axioms* from which all the other sentences in the theory can be deduced by one of the systems of deduction for predicate calculus. The soundness of the deduction system guarantees that, if the axioms are true in the intended class of interpretations, then all the sentences of the theory are true in those interpretations. Theories provide the means by which logic is actually used to formalize or automate reasoning in other domains such as mathematics, computer science and artificial intelligence.

- Theories of *ordering* and *equality* are often required as part of other theories. Axiomatizations are given for both these theories and some theorems are deduced from them. With such commonly used theories we often relax the rules of the logical language slightly, allowing infix predicate symbols to make formulas easier to read.

- Strings and stacks are examples of *abstract data structures*. Axiomatizations are given in this chapter and some theorems of these theories are deduced.

- Many proofs in mathematics and computer science use the principle of mathematical induction. This can be formalized by including in the theory an *induction schema*. An appropriate induction schema is given for the theory of strings and used to prove the associativity of string concatenation.

- Most theories have to include the theory of equality (identity) and, particularly in applications of logic in artificial intelligence, often require further axioms of identity stating, for example, that different names denote different objects, and the Closed World Assumption which says that no objects exist other than those named. We illustrate these aspects of automating practical reasoning by using logic to solve a well-known type of puzzle.

Furthermore Gödel showed that no formal system for arithmetic that is consistent can be complete. It might be thought that all one needs to do is to add all the truths of arithmetic that cannot be proved within the system as extra axioms. The catch here is that the set of Gödel numbers of the sentences that are true in arithmetic is not effectively computable, so once again we have come up against one of the fundamental limits to computation. All this meant that Hilbert's programme for the formalization of mathematics could never be realized in its entirety, although it must be said that the attempt to do so had led to several of the most significant discoveries in the history of mathematics.

# CHAPTER SEVEN

---

## Logic Programming

### 7.1. Introduction

#### 7.1.1. Background

We have already seen how logic can be used to reason about the objects or data structures that computer programs manipulate and we mentioned in the introduction that another use for logical notation in computer science is as a specification language. Given a problem to be solved or task to be carried out, what constitutes a solution is specified in some more or less formal notation. A method or algorithm for producing the required output is then invented and coded as a sequence of instructions that can be executed to produce an output that satisfies the specification. A necessary supplementary activity is proving, possibly using some of the methods we have already discussed, that the output satisfies the specification.

The idea behind logic programming is that, having written down down a specification of what constitutes a solution to a problem in some logical language, the execution mechanism or operational semantics is then given by a system of deduction for this language. Not only are the steps of inventing and coding an effective algorithm saved but, since a provably sound deduction mechanism is used, showing additionally that the output satisfies the specification is unnecessary.

Potentially many formulations of logic programming are possible, depending on the logic and deduction mechanism used. A common mistake is to confuse logic programming with programming in Prolog, which is just one particular (and impure) logic programming system. For readers with the background to make sense of the remark Prolog bears much the same relationship to logic programming as Lisp does to

the lambda calculus. However, while the core of Lisp is a complete implementation of the lambda calculus, the purely logical core of Prolog implements only a subset of the full predicate calculus and is supplemented, in the systems used in practice, by non-classical negation and other meta-logical constructions. There is no theoretical reason why the idea of using logic as a programming language should not be extended to the full predicate calculus but, at the present state of development, implementations are not efficient enough to be attractive for most programming tasks. With its non-logical extensions Prolog has the full power of any other language and yet is sufficiently close to the ideal of programming in logic to have generated an explosion of interest in the possibilities. As we described at the end of chapter three, Church and Turing showed that logic and the lambda calculus have equivalent computing power in the sense that the same set of functions is computable in both formalisms. This does not address the possibility that *formulating* algorithms may be more efficiently carried out in one formalism than the other. In chapter three we also briefly mentioned the notion of one formalism being of higher-order than another, and the lambda calculus is of higher-order than predicate calculus in just this sense. Whether this makes programming systems based on the lambda calculus better in any theoretical or practical sense than those based on logic programming is still a matter of current debate.

Prolog was developed around 1972 by Colmerauer and his group in Marseilles as a tool for processing natural language. Kowalski, who had some contact with the group, realized that there are two ways of looking at a Prolog program. You can either understand it procedurally, as you would a programming language such as Pascal, or you can read it as a set of sentences in (a subset of) predicate calculus. Of course it is not just logic programming languages that have this characteristic. Functional languages such as SML, can also be seen, partly at least, as executable specifications. As we have indicated, there is some controversy among computer scientists over whether programming with functions is more or less effective than programming with relations. The arguments centre round notions such as higher-order functions, i.e. functions which take other functions as arguments or return other functions as results, and logical variables, i.e. variables in the sense that we have been using them in logic rather than in the way that they are used in languages like Pascal. For the straightforward tasks in this book there is very little to choose between the two systems.

### 7.1.2. Definite Clauses

In this book we look at only one variety of logic programming, a subset of predicate calculus called definite clause programs. In order to make the analogy with programming as close as possible it is customary to change the logical notation slightly and introduce a new way of writing formulas and some new terminology.

#### Definition 7.1

A definite clause is a formula either of the form  $P \leftarrow$  or of the form  $P \leftarrow Q_1, Q_2, \dots, Q_n$ , for  $n > 0$ , where  $P$  and the  $Q_i$  are atomic formulas of predicate calculus, i.e. of the form  $S(t_1, \dots, t_k)$  where  $S$  is a predicate symbol and the  $t_i$  are terms. In both cases  $P$  is said to be the head of the clause (we will draw an analogy between this and a procedure heading in, say, Pascal) and  $Q_1, Q_2, \dots, Q_n$  is the body of the clause.

#### Definition 7.2

A definite clause program is a sequence of definite clauses.

For example

$$\begin{aligned} P(x) &\leftarrow Q(x,y), R(y) \\ Q(a,b) &\leftarrow \\ R(b) &\leftarrow \end{aligned}$$

is a definite clause program.

Logically speaking, the definite clause  $P \leftarrow Q_1, Q_2, \dots, Q_n$  is to be read as "P if  $Q_1$  and  $Q_2$  and ... and  $Q_n$ ", and semantically is exactly the same as the predicate calculus formula  $Q_1 \wedge Q_2 \wedge \dots \wedge Q_n \rightarrow P$ . The meaning of  $P \leftarrow$ , a definite clause with null body, is that  $P$  holds unconditionally, i.e. simply  $P$ ; the meaning of  $\leftarrow P$  is that there are no circumstances in which  $P$  holds, i.e.  $\neg P$ ; while the meaning of  $\leftarrow$  by itself is  $\square$ .

If  $P$  and the  $Q_i$  contain variables, then the meaning of  $P \leftarrow Q_1, Q_2, \dots, Q_n$  is the same as  $\square x_1 \dots \square x_j \square y_1 \dots \square y_k (Q_1 \wedge Q_2 \wedge \dots \wedge Q_n \rightarrow P)$  where  $x_1 \dots x_j$  are the variable symbols in  $P$  and  $y_1 \dots y_k$  are the variable symbols that occur in the  $Q_i$  but not in  $P$ . For example  $P(x) \leftarrow Q(x,y), R(y)$  means  $\square x \square y (Q(x,y) \wedge R(y) \rightarrow P(x))$ .

A set of definite clauses is like a set of procedure definitions; to use the procedures we have to execute a procedure call. To execute a definite clause program we add to it a goal, which is a formula of the form  $\leftarrow G_1, G_2, \dots, G_n$ . Logically what we are doing is to show that  $G_1 \wedge G_2 \wedge \dots \wedge G_n$  follows from the program. As in the

tableau method the proof is by refutation, but the inference mechanism is different. We use a new rule called resolution.

Before going into the details of what resolution is we explore a bit further the connection with programming by looking again at one of the examples from chapter six. There we discussed a theory of strings, the language for which contained two function symbols, one being the '.' which denotes the 'cons' function that takes a character and a string as arguments and adjoins them. The other function symbol '@' denoted concatenation of strings. We shall use concatenation as an example of programming with definite clauses. To do this we have to rewrite it as a relation over strings and, as is customary in programming, we give it a mnemonic symbol. The distinction between characters and strings that was preserved in section 6.2.8 can be omitted (and in fact we then get a slightly more general theory of sequences (lists) in which the elements of sequences can be general terms, including sequences). The axioms  $S_4$  and  $S_5$  from section 6.2.5 then become

$$\begin{aligned} & \exists v \text{Concat}(e,v,v) \\ & \exists w \exists x \exists y \exists z (\text{Concat}(x,y,z) \rightarrow \text{Concat}(w.x,y.w.z)) \end{aligned}$$

In the standard interpretation these sentences are easily seen to be true. The first asserts that the result of concatenating any sequence  $v$  on to the empty sequence is  $v$ . The second asserts that if the result of concatenating  $y$  on to  $x$  is  $z$  then the result of concatenating  $y$  on to the sequence whose first element (head) is  $w$  and whose remainder (tail) is  $x$ , is a sequence whose head is  $w$  and whose tail is  $z$ .

In programming, this fact about sequences is used as the justification for function definitions such as

```
def concat(x,y) =
  if x=emptystring then y
  else cons(head(x),concat(tail(x),y))
endef
```

and this definition might be used by executing an instruction such as

```
print(concat("ab","c"))
```

resulting in the answer "abc" being output. The equivalent logic program consists of the two definite clauses

$$\begin{aligned} \text{Concat}(e,v,v) &\leftarrow \\ \text{Concat}(w.x,y,w.z) &\leftarrow \text{Concat}(x,y,z) \end{aligned}$$

and these would be used by adding the goal

$$\leftarrow \text{Concat}(a.(b.e),c.e,z)$$

resulting in the answer  $z = a.(b.(c.e))$  being output. To see exactly how this happens we now have to say what the resolution rule of inference is.

### 7.1.3. Propositional Resolution

Definite clause programs are only a subset of all predicate calculus formulas and we will only consider the simplified form of resolution that applies to definite clauses. We explain it first for the propositional case. The rule is

$$\begin{array}{l} \text{from} \\ \text{and} \\ \\ \text{deduce} \end{array} \quad \frac{\begin{array}{l} P \leftarrow Q_1, Q_2, \dots, Q_m \\ \leftarrow P, R_1, R_2, \dots, R_n \end{array}}{\leftarrow Q_1, Q_2, \dots, Q_m, R_1, R_2, \dots, R_n}$$

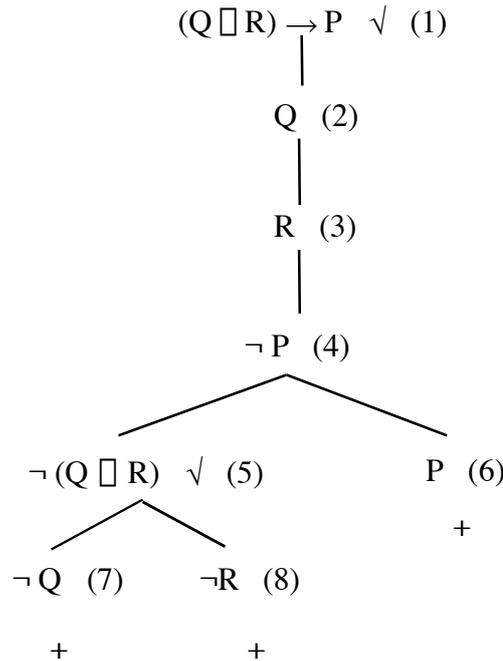
It can be shown that if both the formulas above the line (the resolvents) are satisfiable then the formula below the line is satisfiable. So, if we can derive  $\leftarrow$  from a definite clause program and a goal, then the program and the goal are together unsatisfiable. This means that the program entails the negation of the goal, i.e. entails the formula to the right of the  $\leftarrow$  in the goal. The basic idea is the same as the tableau method, but the inference rule used is, superficially at least, entirely different. Here is an example (the numbers are not part of the program they are there for explanation).

Program	1.	$P \leftarrow Q, R$
	2.	$Q \leftarrow$
	3.	$R \leftarrow$
Goal	4.	$\leftarrow P$
Resolution using 4 and 1	5.	$\leftarrow Q, R$

Resolution using 5 and 2                      6.                      ← R  
 Resolution using 6 and 3                      ←

We have shown that formulas 1 to 4 are unsatisfiable and hence that 1, 2 and 3 entail P, as of course is obvious from their logical meaning.

We can compare this with the tableau for the same initial sentences, i.e.  $(Q \sqcap R) \rightarrow P, Q, R$  and  $\neg P$ . The tableau we get, as you should check, is



Here (1) gives (5) and (6) and (5) gives (7) and (8). The connection with the resolution proof is made clearer if we note that (4) and (6), which came from (1), contradict. Then (7), which came from (5), contradicts (2). Finally (8), which also came from (5), contradicts (3). The same links between contradictory sentences, and the sentences that they came from, can be seen in the resolution proof. In fact, this similarity can be made even more precise, which makes resolution and tableaux look like variants of the same logical idea, which of course is exactly what they are.

For predicate calculus the resolution rule is essentially the same, but the presence of variables introduces the additional possibility of creating resolvents by making substitutions. Essentially what we do is to make atoms the same by suitable variable substitutions. To say this more precisely we will, at this point, have to go into considerable detail before we can return to logic programming. However the ideas involved are fundamental not just to logic programming, or even to the more general

subject of theorem-proving in full predicate calculus, but also to other areas of computer science such as functional programming and term rewriting. So a substantial digression at this point is worthwhile.

## 7.2. Substitution and Unification

### 7.2.1. Substitution

#### Definition 7.3

A substitution is a function from variable symbols to terms in which all but a finite number of variable symbols are mapped into themselves. Substitutions therefore can be presented as a finite set of variable/term pairs  $\{v_1/t_1, \dots, v_n/t_n\}$  in which the  $v_i$  are distinct variable symbols and no  $t_i$  is the same as the corresponding  $v_i$ . A pair  $v_i/t_i$  is called a binding for  $v_i$ . In computer science a substitution is often called a set of variable bindings or an environment.

A substitution  $\sigma$  can be extended to a function  $\sigma^*$  from terms to terms in which a term  $t$  is mapped into the term obtained from  $t$  and  $\sigma$  by, for every  $v_i/t_i$  pair in  $\sigma$  such that  $v_i$  occurs in  $t$ , simultaneously replacing all such  $v_i$  in  $t$  by the corresponding  $t_i$ . By a mild abuse of notation the image of  $t$  under  $\sigma^*$  is written  $t\sigma$  (rather than  $t\sigma^*$ ) and  $t\sigma$  is said to be an instance of  $t$ . Note that we say "simultaneously replacing" because some  $t_j$ , or even  $t_i$  itself, may contain  $v_i$  and this occurrence is not to be subject to further replacement. This notion of a single set of simultaneous replacements can be specified more formally but only by going into some mathematical detail. For our purpose the computer programs given below make the definition completely precise. The following examples should make it intuitively clear as well.

Suppose the formal language has constants  $a$  and  $b$ , variable symbols  $x$ ,  $y$  and  $z$ , and function symbols  $f$  and  $g$ . If  $t$  is the term  $f(x, g(y), b)$  and  $\sigma$  is  $\{x/a, y/x\}$ , then  $t\sigma$  is  $f(a, g(x), b)$ . If  $t$  is the term  $f(x, y, z)$  and  $\sigma$  is  $\{x/y, y/z, z/x\}$ , then  $t\sigma$  is  $f(y, z, x)$ .

Substitutions often have to be applied one after the other, which means we need the following definition.

#### Definition 7.4

If  $\sigma$  and  $\tau$  are substitutions then the composition  $\sigma\tau$  of  $\sigma$  and  $\tau$  satisfies  $(t\sigma)\tau = t(\sigma\tau)$  for any term  $t$ .

Let  $\sigma$  be the substitution  $\{x_1/s_1, \dots, x_m/s_m\}$  and  $\tau$  be the substitution  $\{y_1/t_1, \dots, y_n/t_n\}$ . Since function symbols and constants are unchanged by substitution we need only consider variable symbols. Let  $X = \{x_1, \dots, x_m\}$  and  $Y = \{y_1, \dots, y_n\}$  and let  $z$  be any variable. There are three cases to consider. Suppose  $z = x_i$  in  $X$ . Then  $(z\sigma)\tau = (x_i\sigma)\tau = s_i\tau$  so, if  $(z\sigma)\tau = z(\sigma\tau)$ , we must have  $x_i/s_i\tau$  in  $\sigma\tau$ . If  $z$  is also  $y_j$  in  $Y$  we must omit  $y_j/t_j$  from  $\sigma\tau$ . If  $z$  is not in  $X$  but is  $y_j$  in  $Y$  then, remembering that  $\sigma$  implicitly contains  $z/z$ , we have  $(z\sigma)\tau = z\tau = y_j\tau = t_j$  so we must have  $y_j/t_j$  in  $\sigma\tau$ .

So  $\sigma\tau$  is the substitution  $\{x_1/s_1\tau, \dots, x_m/s_m\tau, y_1/t_1, \dots, y_n/t_n\}$  in which pairs  $x_i/s_i\tau$  for which  $x_i = s_i\tau$  and pairs  $y_j/t_j$  for which  $y_j = x_i$  for some  $i$  have been deleted. For example, if  $\sigma$  is  $\{x/g(y), y/z\}$  and  $\tau$  is  $\{x/a, y/b, z/y\}$  then  $\sigma\tau$  is  $\{x/g(b), z/y\}$ .

Note that, if  $\rho$  is another substitution, then by the result above we have  $z((\sigma\tau)\rho) = (z(\sigma\tau))\rho = ((z\sigma)\tau)\rho = (z\sigma)(\tau\rho) = z(\sigma(\tau\rho))$ . Since this holds for any variable,  $(\sigma\tau)\rho = \sigma(\tau\rho)$  and so composition of substitutions is associative. Furthermore the null substitution  $\{\}$  is a left and right identity and so substitutions form a monoid under composition.

The following Prolog predicates define the function  $\sigma^*$  introduced above (and the SML versions are given in appendix two).

```
apply_subst(Subst, Term, NewTerm) :- Term = .. [Symbol | Args],
    (Args = [], !, (member(Symbol/NewTerm, Subst), !; NewTerm = Term);
    do_args(Subst, Args, NewArgs), NewTerm = .. [Symbol | NewArgs]).
do_args(_, [], []).
do_args(Subst, [FirstArg | RestofArgs], [NewArg | RestofNew]) :-
    apply_subst(Subst, FirstArg, NewArg),
    do_args(Subst, RestofArgs, RestofNew).
```

and the following define composition of substitutions.

```
composition([Var/Term | Sub1], Sub2, Sub12) :- composition(Sub1, Sub2, S),
    delete_pair(Var, S, Sub), apply_subst(Sub2, Term, NewTerm),
    (Var = NewTerm, !, Sub12 = Sub; Sub12 = [Var/NewTerm | Sub]).
composition([], Sub, Sub).
delete_pair(_, [], []).
delete_pair(X, [V/T | Y], Z) :- X = V, !, Z = Y; delete_pair(X, Y, U), Z = [V/T | U].
```

**Exercise 7.1**

a) Say which of the following are valid substitutions, and say why:

i)  $\{x/y, y/x\}$

ii)  $\{x/x, y/x\}$

iii)  $\{x/y, x/z\}$

iv)  $\{x/f(x,y), y/g(z)\}$

v)  $\{x/a, y/x\}$

vi)  $\{z/a, b/c\}$

b) Apply the substitution  $\{x/f(y,a), y/b, z/g(c)\}$  to each of the following terms:

i)  $f(x,y,z)$

ii)  $f(a,b,c)$

iii)  $h(x,x)$

iv)  $f(g(h(x),v),g(x,y),g(z,f(x,y,u)))$

c) Calculate the compositions  $\sigma\tau$  and  $\tau\sigma$  where  $\sigma$  and  $\tau$  are, respectively:

i)  $\{x/y, y/x\}$  and  $\{x/f(y), z/a\}$

ii)  $\{x/a, y/z, z/f(x,y,a)\}$  and  $\{x/b, z/g(x)\}$

iii)  $\{x/z, z/y\}$  and  $\{z/x, y/z\}$

## 7.2.2. Unification

### Definition 7.5

A unifier of two expressions  $F$  and  $G$  is a substitution  $\sigma$  that makes  $F\sigma = G\sigma$ .

A single pair of expressions may have no unifier or several. For example  $f(x,y)$  and  $f(x,a)$  not only have  $\{y/a\}$  as a unifier, but also  $\{x/a, y/a\}$ .

### Definition 7.6

Let  $\Sigma$  be the set of all unifiers of  $F$  and  $G$ . A substitution  $\sigma \in \Sigma$  having the property that  $\sigma\tau = \tau$  for any  $\tau \in \Sigma$  is called a most general unifier (mgu) of  $F$  and  $G$ .

It is by no means obvious that such a substitution exists: our proof that it does will be constructive. If such a substitution exists the proof will actually construct the substitution. We give a method that is guaranteed either to find the mgu of two expressions or to tell us that it does not exist, in which case  $\Sigma = \{\}$ .

We construct a finite sequence of triples  $\langle F_0, G_0, \sigma_0 \rangle, \dots, \langle F_n, G_n, \sigma_n \rangle$  such that  $F_0 = F$ ,  $G_0 = G$ ,  $\sigma_0 = \{\}$ ,  $F_n = G_n$  and  $\sigma_n = \sigma$ , an mgu of  $F$  and  $G$ , where

$$\begin{aligned} F_{i+1} &= F_i\sigma_i \\ G_{i+1} &= G_i\sigma_i \\ \sigma_{i+1} &= \sigma_i\sigma_i \end{aligned}$$

and  $\sigma_i$  is  $\{v_i/t_i\}$  where  $v_i$  is a variable symbol in  $F_i$  or  $G_i$  and  $t_i$  is a term in which  $v_i$  does not occur. This last condition is the crucial one that will ensure the algorithm terminates. If there are  $n$  distinct variable symbols in  $F$  and  $G$  taken together then, since we are eliminating one variable at each step, the sequence will contain  $n$  elements. The next step is to show how to construct the  $\sigma_i$ .

Given two expressions  $F = f(F_1, \dots, F_m)$  and  $G = g(G_1, \dots, G_n)$  we define a set  $d(F, G)$  called the difference-set of  $F$  and  $G$  as follows. If  $F = G$  then  $d(F, G) = \{\}$ , if  $F \neq G$  but  $f = g$  and  $m = n$  then  $d(F, G) = d(F_1, G_1) \cup \dots \cup d(F_n, G_n)$ , if  $f \neq g$  or  $m \neq n$  then  $d(F, G) = \{F:G\}$ .

A difference-set  $D$  is reducible if, for every pair  $U:V \in D$ , at least one of  $U$  and  $V$  is a variable symbol, and neither  $U$  occurs in  $V$  nor  $V$  occurs in  $U$ .

A reducing substitution for a difference-set  $D$  is a substitution  $\{v/t\}$  derived from any member  $U:V$  of  $D$  as follows: if  $U$  is a variable symbol then let  $v = U$  and  $t$

$= V$ ; if  $V$  is the variable (one of them must be) then let  $v = V$  and  $t = U$ . Note that a reducible difference-set  $D$  may become irreducible as a result of applying a reducing substitution  $\square$  to  $F$  and  $G$ . For example if  $F = f(g(x),x)$  and  $G = f(y,f(y))$  then  $d(F,G) = \{y:g(x),x:f(y)\}$ . A reducing substitution is  $\{y/g(x)\}$  and  $d(F\square,G\square) = \{x:f(g(x))\}$  which is irreducible. Note that choosing the other substitution doesn't help: we still get the irreducible set  $\{y:g(f(y))\}$ . It can be shown that unification is linear, in the sense that, if two expressions are unifiable, any choice of reducing substitutions will unify them (though possibly giving mgus that are variants - the variable symbols may be permuted), while if they are not unifiable then no choice of reducing substitution will unify them. This simplifies the programming. To unify two expressions we construct, notionally at least, the triples of the sequence defined above, generating at each step the difference-set  $d(F_i,G_i)$ . If  $d(F_i,G_i)$  is irreducible then  $F$  and  $G$  are not unifiable. If  $d(F_i,G_i)$  is reducible then every element is a reducing substitution and we can take  $\square_i$  as any one of them.

For example to unify  $f(x,g(a,y))$  and  $f(a,g(x,z))$  we can construct the sequence as set out in the following table.

$i$	$F_i$	$G_i$	$d(F_i,G_i)$	$\square_i$
0	$f(x,g(a,y))$	$f(a,g(x,z))$	$\{x:a,y:z\}$	$\{\}$
1	$f(x,g(a,z))$	$f(a,g(x,z))$	$\{x:a\}$	$\{y/z\}$
2	$f\{a,g(a,z)\}$	$f(a,g(a,z))$	$\{\}$	$\{x/a,y/z\}$

Here is another example, this time with terms  $f(g(x),g(y))$  and  $f(y,g(x))$ , which are not unifiable. Note that  $d(F_1,G_1)$  is not reducible because the pair  $x:g(x)$  violates the condition that the variable that in one element of the pair shall not occur in the other.

$i$	$F_i$	$G_i$	$d(F_i,G_i)$	$\square_i$
0	$f(g(x),g(y))$	$f(y,g(x))$	$\{y:g(x),y:x\}$	$\{\}$
1	$f(g(x),g(g(x)))$	$f(g(x),g(x))$	$\{x:g(x)\}$	$\{y/g(x)\}$

We have seen that termination is guaranteed but have not yet shown that we get the right answer on termination. A detailed proof of this is too long to give in full here but we will sketch the basic idea, which involves induction on the sequence of triples defined above. We show that for all unifiers  $\square$  of  $F$  and  $G$ ,  $\square = \square_i\square$  for all  $i$ ,  $0 \leq$

$i \leq n$ . Clearly this is true for  $i = 0$  because  $\square_0 = \{\}$ , and if it is true for  $i = n$  we have shown that  $\square_n = \square$  is an mgu of  $F$  and  $G$ . Whatever choice we make for  $\square_i$  from  $d(F_i, G_i)$  it has the form  $U:V$  where we can suppose  $U$  is a variable not occurring in  $V$ . It is then fairly straightforward to show that  $\square_i \square = \square$  for all unifiers  $\square$  of  $F$  and  $G$ . So  $\square = \square_i \square = \square_i(\square_i \square) = (\square_{i+1} \square)$  and hence  $\square_n = \square$  is an mgu by the definition of mgu. It is also clear that, if the sequence terminates with non-empty difference-set, then  $F$  and  $G$  are not unifiable, because, if they were, there would be a reducing substitution.

### Exercise 7.2

- a) Find the difference sets for each of the following pairs of terms:
- i)  $f(a,b,c)$  and  $f(x,y,z)$
  - ii)  $f(a,b)$  and  $g(a,b)$
  - iii)  $f(f(a,b),g(c))$  and  $f(f(g(a),g(b)),g(c))$
  - iv)  $f(x,f(x,z))$  and  $f(g(x),f(x,y))$
- b) For each of the sets that you calculated in a) above, say whether or not they are reducible and why.
- c) Calculate, where they exist, the most general unifiers for each of the pairs of terms in a) above. If no most general unifier exists, say why not.
- d) Under what circumstances is it true, for substitutions  $\square$  and  $\square'$  that  $\square \square' = \square \square'$ ?

#### 7.2.3. Some background on unification and resolution

The unification method just described, although theoretically transparent, contains a lot of redundancy in the representation and manipulation of the expressions and substitutions. For example, not only is it unnecessary to explicitly calculate  $F_i$  and  $G_i$  at each stage but the substitutions can be stored in product form rather than carrying out explicit composition. In practice much faster but less transparent algorithms are used. For more mathematical detail by far the best treatment (rigorous but very readable) of unification and resolution, and indeed of many of the basic ideas of logic, is the book *Logic, Form and Function* by Robinson (1979). Robinson, basing his work on that of Herbrand and Prawitz, developed resolution in 1965 as the basis of automatic theorem proving. In the ten years from 1965 to 1975 there were

numerous refinements, and it was believed at the time that theorem-provers could be constructed that would be applicable to a wide variety of problems in mathematics and artificial intelligence. This early optimism has turned out to be somewhat premature and it is now considered doubtful that one single uniform procedure will ever be effective for all problems. Nevertheless resolution is still the basis for one important subclass of automatic theorem-proving, namely logic programming, which brings us back to the main subject matter of this chapter.

## 7.3. Resolution

### 7.3.1. First-order definite clauses

The resolution rule for formulas containing variables is an elaboration, using unification, of that for the propositional case.

$$\begin{array}{l}
 \text{from} \\
 \text{and} \\
 \\
 \text{deduce}
 \end{array}
 \frac{
 \begin{array}{l}
 P \leftarrow Q_1, Q_2, \dots, Q_m \\
 \leftarrow P^*, R_1, R_2, \dots, R_n
 \end{array}
 }{
 \leftarrow Q_1\sigma, Q_2\sigma, \dots, Q_m\sigma, R_1\sigma, R_2\sigma, \dots, R_n\sigma
 }$$

where  $\sigma$  is a most general unifier of  $P$  and  $P^*$ , and the set of variable symbols occurring in  $P \leftarrow Q_1, Q_2, \dots, Q_m$  is disjoint from the set of those occurring in  $\leftarrow P^*, R_1, R_2, \dots, R_n$ . If these sets are not already disjoint then they can be made so by renaming. Recall that all the variables are quantified, though we do not write the quantifier, and so they are just placeholders, and as long as we rename them uniformly, so that whenever a certain variable appears we always replace it by the same new variable, the meaning of the formula is unchanged.

Here is an example of the more general resolution rule in use:

$$\frac{
 \begin{array}{l}
 P(x, f(x)) \leftarrow Q(x, y), R(y) \\
 \leftarrow P(a, z), R(z)
 \end{array}
 }{
 \leftarrow Q(a, y), R(y), R(f(a))
 }$$

Now that we have a resolution rule that handles variables we can complete the concatenate example and show how answer substitutions are calculated. The definite clause program was

1.  $\text{Concat}(e, v, v) \leftarrow$
2.  $\text{Concat}(w.x, y, w.z) \leftarrow \text{Concat}(x, y, z)$

where we have numbered the program clauses for reference in explanation. To use the program to compute the result of concatenating the single element  $c$  on to the sequence with elements  $a$  and  $b$  we add the goal

3.  $\leftarrow \text{Concat}(a.(b.e), c.e, z)$

resolving 3 and 2 with  $\{w / a, x / b.e, y / c.e, z / a.z_1\}$ , where we have renamed the ' $z$ ' in 2 to be ' $z_1$ ' to make sure that the rule can be properly applied, we get

4.  $\leftarrow \text{Concat}(b.e, c.e, z_1)$

resolving 4 and 2 with  $\{w / b, x / e, y / c.e, z_1 / b.z_2\}$ , where again the ' $z$ ' in 2 is renamed, this time to be ' $z_2$ ', we get

5.  $\leftarrow \text{Concat}(e, c.e, z_2)$

resolving 5 and 1 with  $\{v / c.e, z_2 / c.e\}$  we get

6.  $\leftarrow$

Tracing back through the substitutions:  $z_2$  is  $c.e$ ,  $z_1$  is  $b.(c.e)$ ,  $z$  is  $a.(b.(c.e))$  as we would expect.

Again, we can form a tableau proof for this. In fact, exactly the proof above can be produced by the tableau method when extended beyond the method that we talked about in chapter four, i.e. if we add the idea of unification to guide the choice of substitutions for universally quantified variables. We shall not actually present these extensions to the tableau method, but the tableau that the extended method produces can be seen as one where many unproductive instances of universally quantified sentences, as produced by the universal rule in the basic method that we are using, can be ignored. The tableau below has had such economies made in it:



Reverse(e,e) ←  
 Reverse(w.x,z) ← Reverse(x,y), Concat(y,w.e, z)

use resolution to show that the following are logical consequences of the program. Calculate the answer substitution where relevant.

a) Reverse(a.(b.e), b.(a.e))

b) Reverse(a.(b.e), z)

- b) Give corresponding tableau proofs for each of the above resolution proofs. As before, you should use the substitutions that the resolution proofs generate to guide your tableau proofs so as to make them as small as possible.

## 7.4. Least Herbrand models and a declarative semantics for definite clause programs

### 7.4.1. Herbrand interpretations

Up to now in our discussion of logic programming we have concentrated on demonstrating how the program and negated goal can be shown unsatisfiable using the resolution rule of inference, and how the answer substitution emerges from the composition of substitutions made in unification. This is an essentially operational description. In the terminology of computer science we have given an operational semantics for definite clause programs. Yet in chapter three we showed how meaning can be given to the sentences of a language via the notion of interpretation. Can we not do the same for logic programs?

The answer is that of course we can, since logic programs are just formulas in a subset of predicate calculus. However, interpretations involve a universe of objects external to the language, whereas programmers would usually be unwilling to imagine their programs tied to a particular application. They tend to think of their programs as manipulating abstract objects such as numbers and sequences and being applicable to any problem whose data fits these abstractions. The analogy for logic programming would lead us to describe the meaning of such a program as relations over the terms that are involved in it. This raises an apparent problem since in chapter

three we were very insistent that the elements of the formal language and the elements of the domain were to be thought of as distinct.

We can bring language and interpretation closer together via the notion of Herbrand interpretations. Given a logic program  $P$  we can identify the set of all ground terms (terms not containing occurrences of variable symbols) that can be formed from the names and function symbols of  $P$ . For the language with constant symbols  $a$  and  $b$ , binary function symbol  $f$  and unary function symbol  $g$ , for example, this set is

$$\{a, b, f(a,a), f(a,b), f(b,a), f(b,b), g(a), g(b), f(g(a),b), f(g(g(b))), g(a), \dots\}$$

Clearly the set is enumerably infinite if there are any function symbols or infinitely many names.

We now construct an interpretation whose universe has an element corresponding to each element of this set. We may as well give them similar names, for example  $\{\underline{a}, \underline{b}, \underline{f(a,a)}, \dots\}$ . This set is called the Herbrand universe for the program  $P$ . In practice, if we are careful to avoid confusion with terms of the language, we can omit the typographic distinction embodied in our underlining and just say that the Herbrand Universe consists of the ground terms themselves

We now define the Herbrand base for  $P$  as the set of all ground atoms, i.e. atomic formulas all of whose arguments are ground, that can be formed from the predicate symbols occurring in  $P$  and the Herbrand universe for  $P$ .

A Herbrand interpretation for  $P$  is then a subset of the Herbrand base, the elements of the subset being the ground atoms that are satisfied in the interpretation.

A Herbrand model for  $P$  is a Herbrand interpretation that makes all the clauses of  $P$  true. For example, if  $P$  is the program

$$\begin{aligned} p(a) &\leftarrow \\ q(b) &\leftarrow \\ r(c) &\leftarrow \\ p(x) &\leftarrow q(x) \\ r(y) &\leftarrow p(y) \end{aligned}$$

then the Herbrand universe is  $\{a,b,c\}$ , and the Herbrand base is

$$\{p(a), p(b), p(c), q(a), q(b), q(c), r(a), r(b), r(c)\}$$

A Herbrand model for P is  $\{p(a), p(b), q(a), q(b), r(a), r(b), r(c)\}$ .

The interpretation  $\{p(a), p(b), q(a), q(b), r(a), r(c)\}$  would not be a Herbrand model for P (why not?).

Now what meaning can we attach to P? What can we say that the program P denotes? One possible answer is that the meaning of P is given by a Herbrand model for P. But which one? Some models are larger than strictly necessary to satisfy the program, as in the example above. The intersection of all Herbrand models for P is clearly also a Herbrand model for P and no Herbrand model can be smaller. We call this the least Herbrand model for P, and denote it by  $M_P$ . It can be shown that  $M_P$  is precisely the set of ground atoms that are the logical consequences of P, the set of ground goals that succeed by resolution with the clauses of P.

In complicated cases the least Herbrand model will not be obvious from inspection, but there is a recursive method of calculating it. Let the function  $f_P$ , which maps Herbrand interpretations into Herbrand interpretations, be defined as follows

$$f_P(H) = H \cup \{B \mid B \leftarrow B_1, \dots, B_n \text{ is a ground instance} \\ \text{of a clause in P and } \{B_1, \dots, B_n\} \subseteq H\}$$

Then the least Herbrand model is the least fixed point of  $f_P$ , i.e. the smallest solution of the equation  $f_P(H) = H$ . For finite models this can be calculated by setting  $H_{n+1} = f_P(H_n)$ , where  $H_0 = \{\}$ , and finding the smallest  $n$  for which  $H_{n+1} = H_n$ . For the program P above, we have

$$\begin{aligned} H_1 &= f_P(\{\}) = \{p(a), q(b), r(c)\} \\ H_2 &= f_P(H_1) = \{p(a), q(b), r(c), p(b), r(a)\} \\ H_3 &= f_P(H_2) = \{p(a), q(b), r(c), p(b), r(a), r(b)\} \\ H_4 &= f_P(H_3) = \{p(a), q(b), r(c), p(b), r(a), r(b)\} \end{aligned}$$

So the least Herbrand model for P is given by  $H_4$  and it is obvious that this is the complete set of goals that would succeed, given P. It seems reasonable to view the least Herbrand model of a logic program as canonical, in this sense, and to say that that is what the meaning of the logic program is.

### 7.4.2. General clauses and theorem-proving

Herbrand interpretations have a significance that extends beyond definite clause programs. One can define a clause more generally as a universally quantified finite disjunction of literals. Literals are atomic formulas or their negations. The clauses that can appear in definite clause programs, or their goals, are special cases. Using the equivalence

$$(Q_1 \wedge Q_2 \wedge \dots \wedge Q_n \rightarrow P) \leftrightarrow (\neg Q_1 \vee \neg Q_2 \vee \dots \vee \neg Q_n \vee P)$$

it can be seen that definite clauses have precisely one unnegated literal and goals have none. (Clauses with at most one unnegated literal are called Horn clauses).

It can be shown that any sentence  $S$  of classical predicate calculus can be transformed into a set of clauses  $C_S$  such that if  $S$  is satisfiable then  $C_S$  has a Herbrand model. This means that if  $C_S$  can be shown by resolution to have no Herbrand model then  $S$  is unsatisfiable. Resolution therefore has application wider than logic programming, in that, like the tableau method, it can be used to test the validity of any sentence in predicate calculus. Robinson's (1979) book is the definitive reference.

**Exercise 7.4** Show that the sentence

$$P(a) \wedge \forall x(\neg P(x))$$

has a model but does not have a Herbrand model.

## Summary

- The idea behind logic programming is that the program is a specification, in a logical language, of what constitutes a solution to the problem, and the computational mechanism (operational semantics) is then provided by a system of deduction for that language.

- The logic programs in this chapter are *definite clause programs*. A definite clause is a universally quantified disjunction of one or more literals, exactly one of

which is unnegated. Definite clauses can be compared with procedure definitions in a procedural language. Definite clause programs are executed by adding a *goal*, a clause in which there are no unnegated literals.

- The system of deduction in this form of logic programming is *resolution*. Like the tableau method resolution works by refutation. Unlike the tableau method it requires the set of input sentences to be in a special form—a universally quantified conjunction of disjunctions—known as *clause form*. The resolution rule of inference sanctions the derivation, from a set of clauses, of an enlarged set having the property that, if the original set is satisfiable, so is the enlarged set. If falsity in the shape of the empty clause can be derived the original set is unsatisfiable and the entailment from which they were constructed is therefore valid.

- Resolution in the predicate calculus involves *unification*. Unification is the process of finding substitutions that make two terms containing free variables identical. A *substitution* is a function from variable symbols to terms and can be represented as a set of variable bindings. Algorithms are given for *composition* of substitutions and for finding the *most general unifier* (mgu) of two terms. The mgu is unique up to permutation of variable names.

- *Herbrand interpretations* can be used to give a semantics for logic programs. A Herbrand interpretation is based on the set of all ground atoms that can be constructed from the names, function symbols and predicate symbols in the program. The *least Herbrand model* of a program can be calculated as the least fixed point of a certain function that maps Herbrand interpretations into Herbrand interpretations.

- Any predicate calculus sentence can be transformed into a set of clauses such that if the original sentence is satisfiable, the corresponding clauses have a Herbrand model. On this case for some sentences resolution may not terminate. If the clauses can be shown by resolution to have no Herbrand model then the original sentence is unsatisfiable. So, like the tableau method, resolution can be used to test, by refutation, the validity of any entailment in predicate calculus.

# CHAPTER EIGHT

---

## Non-Standard Logics

### 8.1. Introduction

In this chapter we will look at other systems which formalize reasoning. We pre-empted this discussion a little when we introduced intuitionistic logic in chapter five, and we will return to this later. The other systems that we present here will be different from the logics, apart from intuitionistic logic, that we have seen so far, which we call classical logics, in that other sorts of valid reasoning will be treated. By other sorts of reasoning we mean both extensions to the sorts of arguments that we have looked at before and arguments based on different fundamental assumptions.

### 8.2. Necessity and Possibility

So far, we have only formalized reasoning in which relations have a truth-value timelessly. That is, when we say " $x$  is red" we do not refer to when it is red or for how long it is red or how I know that it is red. However, we often need to reason in situations where states of affairs change over time (especially in computing). Two important time or state dependent qualities of relations tell us whether a relation is necessarily true, i.e. true at all times or in all situations, or whether a relation is possibly true, i.e. there is at least one moment or state when or where the relation holds.

Whether a relation is necessary or possible is itself a proposition on the predicate, i.e. has a truth-value, which expresses something about the mood or manner or mode of the predicate. This leads to the name modal logic for a system of reasoning in which the ideas of necessity and possibility occur.

### 8.2.1. Possible Worlds

To begin to formalize such a logic we need to extend our semantics. Consider the sentence "the sky is blue". Clearly we have (by common experience) that "the sky is necessarily blue" is false (sunsets?) and "the sky is possibly blue" is true. So, there are situations or possible worlds in which "the sky is blue" is true, and some in which it is false.

By possible worlds we mean not only actually occurring worlds but any logically possible situation, i.e. one in which no contradictions arise. So, any imagined world counts as a possible world, as long as it is not logically impossible, i.e. contradictory. Thus, possibility is not the same as conceivability, it is a more general notion, and not all possible worlds are actual either. For instance, "London buses are black" is true in some imaginable world. The possibility is not ruled out just because it is not actually the case. In the future of our actual world (in which London buses are red) someone might decide to re-paint them. However, a proposition like "the sky is blue and the sky is not blue" cannot be true in any world since it is a contradiction.

For example consider the sentence " $0=1$ ", where we assume that all the terms in the sentence have their usual meanings. We ask whether there is a possible world in which this sentence is true. To see how to decide this question imagine the proposition "there are two objects on the table" in the case where there are two objects on the table at which you might be sitting. Then, if we also accept the truth of the sentence " $0=1$ " and since  $2+0=2+0$  it follows that  $2+0=2+1$  and hence  $2 = 3$ . So, the proposition "there are not two objects on the table" is true in exactly the same circumstances as the proposition "there are two objects on the table". Clearly, these are contradictory.

This contradiction came about by using true facts of arithmetic together with the sentence " $0=1$ ". The only way out of this contradiction, then, is to deny that this sentence is true in the world and, by a similar argument, in any possible world, since no possible world can be contradictory and the inclusion of the sentence " $0=1$ " as true in any world gives rise to contradiction.

**Exercise 8.1** In the following exercises, all the terms that appear should be understood with their usual meanings. For each sentence, say whether or not there is a possible world in which it can be true:

- a) Mount Snowdon is higher than Mount Everest.

- b)  $2+2 \neq 4$ .
- c) A yard is shorter than a metre, a metre is shorter than a chain and a chain is shorter than a yard.
- d) I believe that there is a greatest natural number.
- e) I know that there is a greatest natural number.

### 8.2.2. Contingency

A sentence or proposition which can be either true or false, depending on the situation it is evaluated in, is called contingent. Any proposition which has the same truth-value no matter what situation it is evaluated in is called non-contingent. For example, "the sky is blue" is contingent since, for example, on Mars it is pink, i.e. the sentence is false, whereas on Earth the sentence can be true. On the other hand 'all yellow things are coloured' is true no matter what situation or possible world it is in, i.e. it is non-contingent.

**Exercise 8.2** In each of the following, say whether the sentence is contingent or non-contingent. If you think that it is non-contingent, say whether it is true or false.

- a) All uncles are males
- b) All males are uncles
- c) All black birds are black
- d) All blackbirds are black
- e) No toadstools are poisonous
- f) All coloured things are red

### 8.3. Possible world semantics

This idea of possible worlds or situations has been taken up and used as one basis for a formalization of modal logic. We shall use this basis too. However, unlike

classical logic, formalizations and proof systems for modal logics (among others) are still a matter of research and our presentation is by no means the only one or universally agreed to be the correct one (whatever that means).

We use an extension of the language of classical (propositional) logic, so we have  $\Box$ ,  $\Diamond$ , etc.

If we know that  $A$  is necessarily true then we are saying that whatever worlds we can 'get to' or 'imagine' in some way—we shall say access—then  $A$  is true in each of them. So, since we know that "anything red is necessarily coloured" we are saying that in any world that we can access from our world "anything red is coloured" is true.

Similarly, since "possibly the sky is blue" is true we are saying that there is at least one world that we can access from our world in which "the sky is blue" is true.

## 8.4. Frames, interpretations and models

We wish to formalize the ideas above. We have a set of possible worlds  $P$  and a relation, the accessibility relation  $R$ , which tells us which worlds are accessible from which others. (You may also, though rarely, see the term reachability, instead of accessibility). So, if  $W$  and  $V$  are possible worlds, i.e.  $W, V \in P$ , then  $R(W, V)$  means that  $V$  is accessible from  $W$ . The exact definition of any particular  $R$  will determine what 'sort' of accessibility we mean, as we will see later. Thus, non-accessible worlds are in some way irrelevant to us in the current world.

### Definition 8.1

If  $P$  is a set of possible worlds and  $R$  is an accessibility relation then  $\langle P, R \rangle$  is a frame (of reference).

### Definition 8.2

Let  $\langle P, R \rangle$  be a frame. An interpretation in  $\langle P, R \rangle$  is a function  $\nu$  such that

$$\nu : P \times L \rightarrow \{\text{true}, \text{false}\}$$

where  $L$  is a set of propositional letters.

So, an interpretation tells us whether a given proposition (from  $L$ ) is true in a possible world (from  $P$ ). Note how this extends our definition previously because now we need to take into account the world in which the sentence is being considered as well as the sentence itself.

For example: let  $P = \{\text{today}, \text{tomorrow}\}$  and  $L = \{P_1, P_2\}$ . Then let  $\nu(\text{today}, P_1) = \text{true}$

$$v(\text{tomorrow}, P_1) = \text{false}$$

$$v(\text{today}, P_2) = \text{false}$$

$$v(\text{tomorrow}, P_2) = \text{true}$$

and let the accessibility relation over  $P$  be reflexive and transitive then, informally, you might now see that, as far as "today" is concerned, "possibly  $P_1$ " and "possibly  $P_2$ " are true while "necessarily  $P_1$ " and "necessarily  $P_2$ " are false. What we have to do is to formalize this notion, which we now do.

#### 8.4.1. Extending the language

We extend our alphabet and language with two new symbols.  $\Diamond$  (diamond) means 'possibly' and  $\Box$  (box) means 'necessarily'. Then, if  $\mathcal{S}$  is any sentence, so are  $\Diamond \mathcal{S}$  and  $\Box \mathcal{S}$ . So, in our example we have  $\Diamond P_1$ ,  $\Diamond P_2$ ,  $\neg \Box P_1$  and  $\neg \Box P_2$ .

#### Definition 8.3

For a frame  $\langle P, R \rangle$ , we write  $W \Vdash_v \mathcal{S}$  iff  $\mathcal{S}$  is true in the interpretation  $v$  at world  $W \in P$ , i.e.  $W \Vdash_v \mathcal{S}$  iff  $v(W, \mathcal{S}) = \text{true}$  for some  $v$ . When  $v$  is clear from the context that we are in we drop it. We read ' $W \Vdash \mathcal{S}$ ' as ' $W$  forces  $\mathcal{S}$ '.

#### Definition 8.4

If  $v$  is an interpretation in the frame  $\langle P, R \rangle$  of a set of sentences  $S$  at any world  $W \in P$  then, given the above definition, we have the following for any  $\mathcal{S}, \mathcal{T} \in S$ :

$$m_1) W \Vdash (\mathcal{S} \wedge \mathcal{T}) \text{ iff } W \Vdash \mathcal{S} \text{ and } W \Vdash \mathcal{T}$$

$$m_2) W \Vdash (\mathcal{S} \vee \mathcal{T}) \text{ iff } W \Vdash \mathcal{S} \text{ or } W \Vdash \mathcal{T}, \text{ or both}$$

$$m_3) W \Vdash (\mathcal{S} \rightarrow \mathcal{T}) \text{ iff not } W \Vdash \mathcal{S} \text{ or } W \Vdash \mathcal{T}, \text{ or both}$$

$$m_4) W \Vdash \neg \mathcal{S} \text{ iff not } W \Vdash \mathcal{S}$$

$$m_5) W \Vdash \Box \mathcal{S} \text{ iff for all } V \in P \text{ such that } R(W, V) \text{ we have } V \Vdash \mathcal{S}$$

$$m_6) W \Vdash \Diamond \mathcal{S} \text{ iff there is a } V \in P \text{ such that } R(W, V) \text{ and } V \Vdash \mathcal{S}.$$

#### Example 8.1

Going back to our previous example, we can illustrate these definitions. We will take  $P$  and  $L$  as before and re-define  $R$  to be the equivalence relation,

$$\{(\text{today}, \text{tomorrow}), (\text{tomorrow}, \text{today}), (\text{today}, \text{today}), (\text{tomorrow}, \text{tomorrow})\}$$

We have

$$\text{today} \Vdash P_1$$

$$\text{tomorrow} \Vdash P_2$$

$$\text{today} \Vdash \neg P_2$$

tomorrow  $\models \neg P_1$

Since it is not the case that for all  $U \Box P$  such that  $R(W,U)$  we have  $U \models P_1$  (because tomorrow  $\Box P$ ,  $R(\text{today}, \text{tomorrow})$  and not tomorrow  $\models P_1$ ) it follows that not today  $\models \Box P_1$ . Similarly, we can show that

not today  $\models \Box P_2$

not tomorrow  $\models \Box P_1$

not tomorrow  $\models \Box P_2$

However, since today  $\Box P$ ,  $R(\text{today}, \text{today})$  and today  $\models P_1$  we have today  $\models \Diamond P_1$ .

Also, since today  $\Box P$ ,  $R(\text{tomorrow}, \text{today})$  and today  $\models P_1$ , we have tomorrow  $\models \Diamond P_1$ .

Similarly

today  $\models \Diamond P_2$

tomorrow  $\models \Diamond P_2$

We can illustrate these facts by using a diagram, a possible-worlds diagram, which is essentially a labeled, directed graph. The nodes are intended to be possible worlds, so they are labeled with their names. Also, at each node we write the propositions which are true there. The arcs are arrows which show which worlds (nodes) are directly accessible from which others. Therefore, the above example will be as shown in figure 8.1. There we see that the accessibility relation is reflexive, transitive and symmetric.

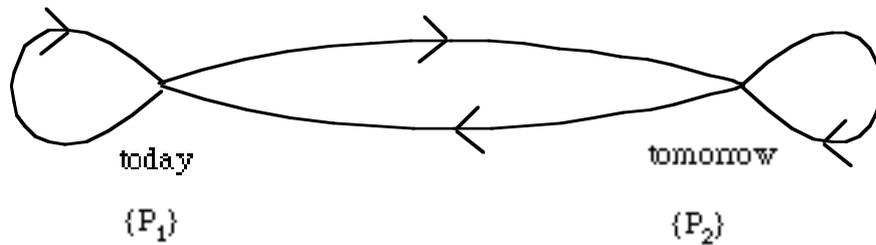


Figure 8.1

### Example 8.2

As another example consider the frame  $\langle P, R \rangle$  given by

$P = \{W_1, W_2\}$

$R = \{(W_1, W_2), (W_1, W_1), (W_2, W_2)\}$

Consider the sentence  $A \rightarrow \Box \Diamond A$  in the interpretation  $v$  given by

$v(W_1, A) = \text{true}$

$v(W_2, A) = \text{false}$

Then,  $W_1 \models A$ . Now, what about  $W_1 \models \Box \Diamond A$ ? Is it true that for all  $U \Box P$  such that  $R(W_1, U)$  that  $U \models \Diamond A$ ? i.e. is it true that  $W_1 \models \Diamond A$  and  $W_2 \models \Diamond A$ ? i.e. is it true that

- (1) there is a  $U \Box P$  such that  $R(W_1, U)$  and  $U \models A$  and
- (2) there is a  $U \Box P$  such that  $R(W_2, U)$  and  $U \models A$ ?

Well, (1) has the answer yes since  $W_1 \Box P$ ,  $R(W_1, W_1)$  and  $W_1 \models A$ . However, (2) has the answer no, This is because although  $W_1 \Box P$  and  $W_1 \models A$ , it is not true that  $R(W_2, W_1)$ . And, although  $W_2 \Box P$  and  $R(W_2, W_2)$ , it is not true that  $W_2 \models A$ .

So, we finally have that not  $W_1 \models \Box \Diamond A$ , so not  $W_1 \models A \rightarrow \Box \Diamond A$ . Figure 8.2 shows the possible-worlds diagram that describes this.

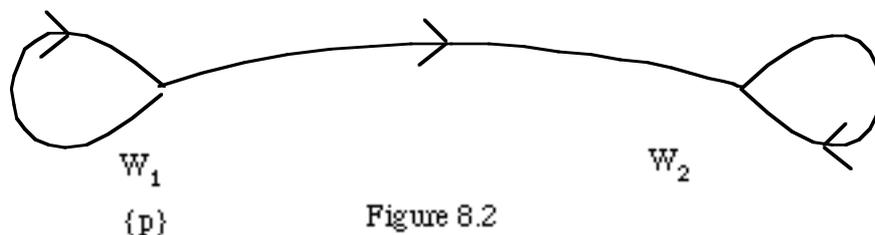


Figure 8.2

### Definition 8.5

Let  $F = \langle P, R \rangle$  be a frame, with  $P$  a set of possible worlds and  $R$  an accessibility relation, and let  $v$  be an interpretation in  $F$ . Also, let  $S$  be a sentence. Then  $v$  is a model of  $S$  in  $F$  iff  $v(W, S) = \text{true}$  for all  $W \Box P$ .  $S$  is satisfied by  $v$  iff  $v(W, S) = \text{true}$  for some  $W \Box P$ . So,  $S$  is satisfiable iff there is an interpretation in  $F$  such that  $v(W, S) = \text{true}$  for some  $W \Box P$ .  $S$  is true in  $v$  in  $F$  iff  $v$  in  $F$  is a model of  $S$ .  $S$  is valid in  $F$  iff all interpretations in  $F$  are models of  $S$ , i.e.  $S$  is true in all interpretations in  $F$ .

Going back to the example above,  $A \rightarrow \Box \Diamond A$  is not valid in  $\langle P, R \rangle$  since we have given an interpretation in  $\langle P, R \rangle$  which is not a model, i.e. we have an interpretation in which the sentence is not true for all possible worlds in  $P$ .

### Exercise 8.3

- a) Draw the possible-worlds diagrams, as exemplified above, for the following frames:

$$\text{i) } Pa = \{W_1, W_2, W_3\}, Ra = \{(W_1, W_1), (W_2, W_2), (W_3, W_3)\}$$

$$\text{ii) } Pb = \{W_1, W_2, W_3\}, Rb = \{(W_1, W_2), (W_2, W_1), (W_3, W_3)\}$$

$$\text{iii) } Pc = \{W_1, W_2\}, Rc = \{(W_1, W_2), (W_2, W_1), (W_1, W_1), (W_2, W_2)\}$$

$$\text{iv) } Pd = \text{set of natural numbers}, Rd = \text{the less-than relation over Pd}$$

b) Draw the possible-worlds diagram for frames given by the following:

$$\text{i) } P = \{W_1, W_2\}, R \text{ is an equivalence relation over } P.$$

ii) with  $P$  and  $R$  as in i), but a different frame.

## 8.5. Truth-functionality and modal logic

When we say that a logic is truth-functional we mean, essentially and as you should recall, that its semantics can be given by truth-tables. Putting this another way, it means that the meaning of a sentence can be calculated from the meanings of its sub-sentences. However, modal logics do not have this property. Thus, they are non-truth-functional, as we shall see. This means that we cannot use the simple ideas of truth-tables to give the meanings of such logics, so the (relatively) complicated methods introduced above must be used.

For example, the operator  $\Diamond$  is not truth-functional (unlike  $\neg$  which is) because the truth-value of  $\Diamond A$  does not depend only on the truth-value of  $A$ . If  $A$  is true, then clearly  $\Diamond A$  is true too. However, if  $A$  is false the answer to the question must be "it depends...". When pressed further we might say "it depends on the situation". Exactly! The truth-value of  $\Diamond A$  depends not only on the truth-value of  $A$  but also on the situation, i.e. on the frame in which the question is asked.

If we try to fill in its truth-table we get

$\Diamond$	
t	t
f	?

where '?' stands for "it depends...".

Another way of seeing that there is no truth-table for  $\Diamond$  is to consider the fact that  $\Diamond$  is a unary operator and write down all the truth-tables, since there are only four. However, two of them are 'used' in the sense that one of them is the truth-table

for  $\neg$  and another is just the identity function (which  $\diamond$  and  $\square$  certainly are not). The other two give 't' for all possibilities and 'f' for all possibilities. Clearly, these will not do either. So, there are not enough truth-tables to give one each to  $\diamond$  and  $\square$ .

A further way of exploring this problem is to introduce more than two truth-values, e.g. true, false and undefined. This idea was worked on extensively by many people. A major example is the three-valued logic of Lukasiewicz.

## 8.6. Systems of modal logic

Obviously, as the frame varies, even for a fixed language, the behaviour of the logic will change, i.e. we will have different logics. It turns out that certain simple ways of axiomatizing the logics, which we have not looked at for modal logics, correspond to certain simple and familiar properties of the accessibility relation. A series of such axiomatizations were studied in the past by Lewis (Lewis and Langford, 1932) and the elements of the series were named S1, S2, ..., i.e. system 1, system 2, .... They were generated by taking some initial set of axioms and adding new axioms to get new logics with particular properties. We shall be looking at S4 in the next section. In S4 the accessibility relation is reflexive and transitive. The system after S4, that is S5, is such that its accessibility relation is an equivalence relation, i.e. it is reflexive, transitive and symmetric. Though we shall say no more about these systems other than S4, it is remarkable that they can be characterized in such simple terms.

## 8.7. A tableau system for S4

### 8.7.1. Introduction

We have chosen to use the possible worlds idea (originally due to Kripke (1963)) to present a semantics for modal logics. One component of such a semantics is the accessibility relation. The choice of this relation, and in particular its properties, reflects just what sort of reasoning we are doing. For instance, if the relation is not symmetric then we cannot be reasoning about a system in which "going back to where we have been" is possible, i.e. if I pass from world W to world V then I cannot pass from V back to W, in general. From now on we will concentrate on a logic whose accessibility relation is reflexive and transitive. This is the logic S4 as mentioned in the previous section. Our goal here is to develop a tableau system which, as before, will give us a mechanical way to test the validity (in S4) of sentences in our language. We will use the possible worlds interpretation to do this.

First, remember that the basic idea behind tableaux is to explore all possible ways in which a sentence or set of sentences can be satisfiable. If we ask the right question, we can thus devise a system which allows us to decide whether a sentence is valid. By valid here we mean valid in any S4 logic, i.e. we specialize the definition above to

**Definition 8.6**

A sentence  $\mathcal{S}$  is S4-valid iff  $\mathcal{S}$  is true in all interpretations in any frame  $\langle P, R \rangle$  where  $R$  is reflexive and transitive. We write this as

$$\vDash_{S4} \mathcal{S}$$

We shall say just 'valid' in the future and write just

$$\vDash \mathcal{S}$$

Thus, above we showed that it is not the case that

$$\vDash (A \rightarrow \Box \Diamond A)$$

i.e.  $A \rightarrow \Box \Diamond A$  is not S4-valid.

This definition also extends to sets of sentences in the usual way.

**8.7.2. Testing validity**

Now, we want to devise a way to answer questions like "is it the case that  $\vDash \mathcal{S}$ ?" As before in the classical case, what we do is to try to find all possible ways in which  $\neg \mathcal{S}$  is (S4-)satisfiable. If no such way exists then we conclude that  $\vDash \mathcal{S}$ . It turns out that the rules for non-modal operators (i.e. those other than  $\Box$  and  $\Diamond$ ) are much as before. We need new rules to deal with modal sentences. (We are essentially presenting Kripke's original work as extensively developed by Fitting (Fitting, 1983).) Consider the case for a sentence of the form  $\Box \mathcal{S}$ . How can we express (in our tableau style) all possible ways in which this can be true? Well, it says that  $\mathcal{S}$  is necessarily true, i.e. that  $\mathcal{S}$  is true in all worlds accessible from our current one. So, if we were to move to a representative accessible world,  $\mathcal{S}$  would be true there.

Now, what about  $\Diamond \mathcal{S}$ ? We can express the truth of this in all possible ways by thinking of moving to an arbitrary accessible world in which  $\mathcal{S}$  is true and which includes just what must be there. Putting this another way, in moving to this other world we need to delete all information that does not have to be there, i.e. all non-necessary information. So, in moving between worlds we should delete all sentences

not of the form  $\Box T$  or  $\neg\Diamond T$ , since no sentences other than these *has* to be true in every accessible world.

The reason why this is correct is that if our sentence  $\neg S$  is not satisfiable in this 'minimal' accessible world, then it is certainly not satisfiable in any world which has more things true in it. So if, when we need to change worlds, we always change to one which only has in it the things which must be true, and our test sentence is unsatisfiable in an arbitrary such world, then it must be unsatisfiable in any accessible worlds (since these will have either the same things true in them or more things true in them, but never less, by definition).

We will give the extra rules needed and then give some more justification. Written in the pictorial way, as previously, we have four more rules:

### Definition 8.7

The non-deleting modal rules can be pictured as (where  $S$  is any sentence)

$$\begin{array}{cc} \Box S & \neg\Diamond S \\ S & \neg S \end{array}$$

and the deleting modal rules can be pictured as

$$\begin{array}{cc} \Diamond S & \neg\Box S \\ S & \neg S \end{array}$$

BUT in these two cases delete from the paths that have just been extended all sentences except those of the form  $\Box R$  and  $\neg\Diamond R$

### Example 8.3

Consider

$$\vDash A \rightarrow \Box\Diamond A$$

the tableau for which is in figure 8.3. As usual, we start with the initial sentence which is the negation of the one whose validity we are testing, i.e we start with the initial sentence  $\neg(A \rightarrow \Box\Diamond A)$ . Here, (2) and (3) came from (1) by the usual rule for  $\neg\rightarrow$ . Then, (4) came from (3) by the rule for  $\neg\Box$ , which also caused the crossing out of sentences (1), (2) and (3), since none of them are of the form which we have to save, i.e. none of them have to be true in the 'minimal' accessible world. Finally (5) came from (4) by the rule for  $\neg\Diamond$ .

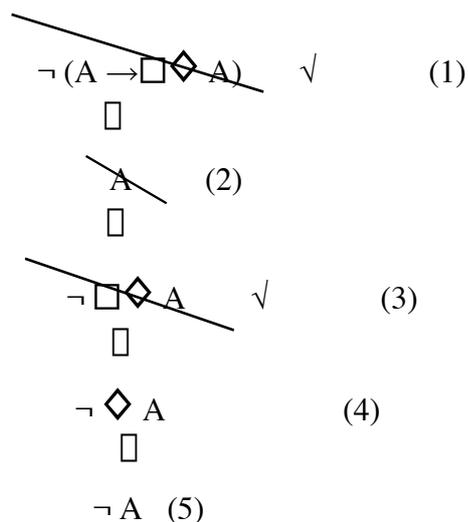


Figure 8.3

The tableau does not close here because the sentences true in the current world, i.e. those not crossed out, are not contradictory. Since the tableau is complete but not closed, we say that, having elaborated the tableau in all possible true ways there is one which is not contradictory, namely the one in which there is a world in which  $\neg A$  is true. If you look at the way we dealt with this example before you will see that this is exactly the frame we used.

#### Example 8.4

As another example consider

$$\vDash (\Box \neg A \leftrightarrow \neg \Diamond A)$$

Informally, we can see that this says that if  $A$  is necessarily false then it is not possible that it is true, and vice versa. The tableau method gives the tableau shown in figure 8.4.

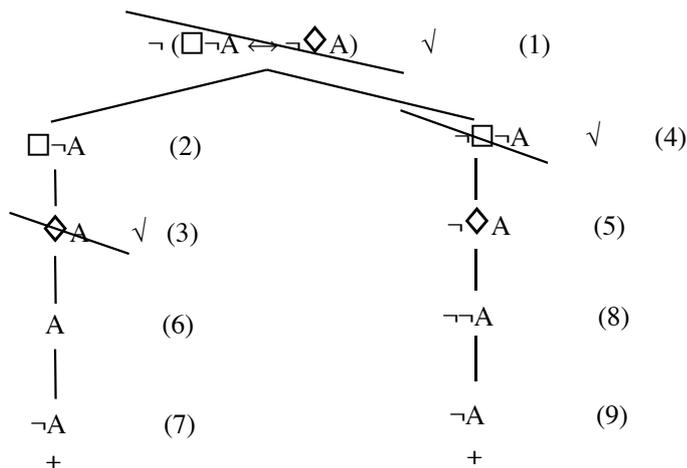


Figure 8.4

Here (1) is as usual the negation of the sentence whose validity is being tested. (2), (3), (4) and (5) come from the rule for  $\neg\leftrightarrow$ . Then, (6) comes from (3) by the rule for  $\Diamond$ , which also causes (1) and (3) to be deleted. Then (7) comes from (2) by the  $\Box$ -rule. This path then closes because it contains both  $A$  and  $\neg A$ . (8) comes from (4) by  $\neg\neg$  and (9) comes from (5) by  $\neg\neg$ . This path then closes too since  $\neg A$  and  $\neg\neg A$  are contradictory.

8.7.4. Cycles and backtracking

With these new rules for modal operators, we need to take care about when we use them. In fact, they must only be used after all possible sentences with non-modal operators (i.e. the connectives) at the top-most level have been used. The following example shows that we get wrong results otherwise. We know that

$$\{\Diamond A \rightarrow A, \Diamond A\} \vDash A$$

since this is just an instance of  $\{S \rightarrow T, S\} \vDash T$ , but if we do not take note of the point above we might get the tableau shown in figure 8.5, which does not close.

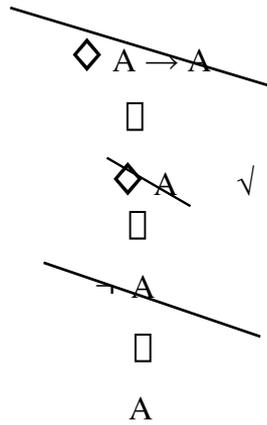


Figure 8.5

A further complication arises when two (or more) sentences of the form  $\diamond S$  occur on the same path. Consider the tableau for the valid sentence

$$\neg \Box \neg (\Box A \quad \Box \neg \Box A)$$

as given in figure 8.6.

In constructing this tableau we chose sentences 1 and 1' to be elaborated at each choice point, i.e. when we first had to choose between 1 and 2 and then between 1' and 2'. When we reach the state shown in the figure we can stop building the tableau because it is clear that we have reached a cycle, i.e. if we keep making the same choices then the path will never be finished and so never closes. Hence, we would conclude that the initial sentence is satisfiable, i.e. that  $\neg \Box \neg (\Box A \quad \Box \neg \Box A)$  is invalid. But, we know that this is not the case, so we need to do something to stop this wrong conclusion being reached.

The problem is that we have not explored all possible ways in which the initial sentence, and its sub-sentences, can be elaborated. For instance, we have at no point chosen sentence 2 as the one to be used. One way of making sure that all possibilities are eventually tried is to remember where a choice is made and use backtracking.

So, if we detect a cycle then we backtrack to the previous choice point, make a different choice, if possible, and carry on. If no other choice was possible, i.e. all the others have been tried, then we backtrack to an even earlier choice point and make another choice if possible. If all choices have been made and they lead to non-closing paths then, and only then, can we conclude that the initial sentence is invalid.

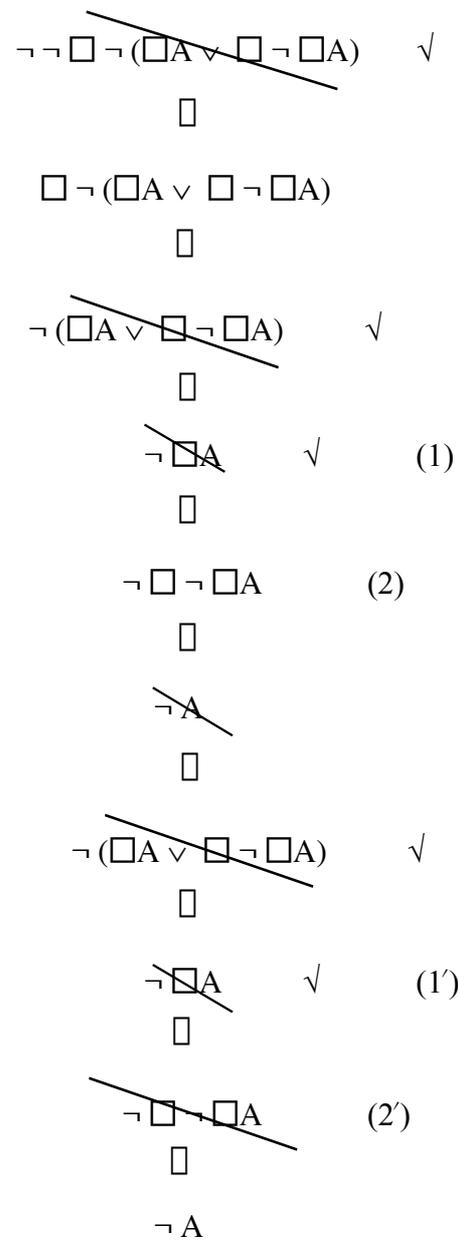


Figure 8.6

Going back to the example we would backtrack to the last choice point, i.e. where we chose 1', and this time choose 2'. As you can see in figure 8.7 the path does close now because the starred sentences are contradictory. As you can check for

yourself, an even shorter proof could have been obtained by choosing sentence 2 at the first choice point.

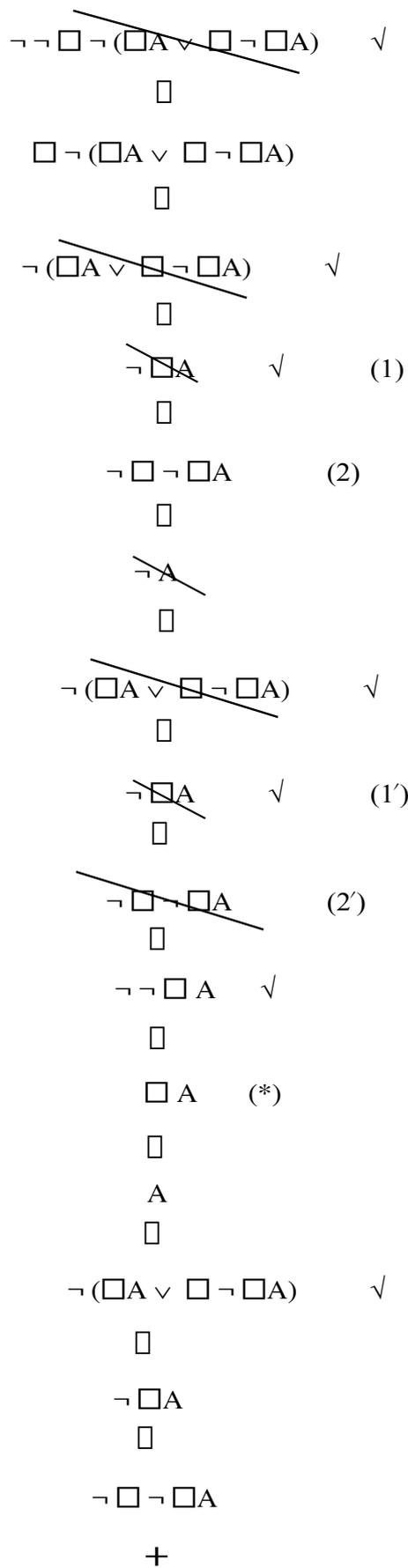


Figure 8.7

Having taken all these points into consideration we can write down an algorithm for constructing tableaux as we did in the classical case. This algorithm will be an easy adaptation of the original one, as you can see.

```

begin
  repeat
    changes := false
    close each path that contains a sentence
    and its negation
    if all paths are closed
    then deliver "S4-valid"
    else
      if a connective rule can be applied
        to a sentence
      then
        changes := true
        apply the appropriate rule
        mark the sentence as used
      else
        if a non-deleting modal rule
          can be used
        then
          apply the rule
          changes := true
        else
          apply a deleting modal rule
          mark the sentence as used
          remember this as a choice point
          do the necessary deletions
          changes := true
      if a cycle is detected
      then
        backtrack to last choice point
        changes := true
    until changes is false
    deliver "not S4-valid"
end

```

Note here that the non-deleting modal rules do not lead to the sentence being marked as used. This is so since if a sentence is of the non-deleting sort, i.e. either  $\Box S$  or  $\neg\Diamond S$ , then either  $S$  or  $\neg S$  is true in all possible worlds (respectively), including any minimal ones we might move to, so they should be available for elaboration in all those worlds. This is rather similar to the case for the universal quantifier in classical logic.

Once again we can show, though we won't here, that this algorithm is sound and complete.

#### Exercise 8.4

a) Use the tableau method for S4 to decide the validity of the following sentences:

i)  $\Box A \rightarrow A$

ii)  $A \rightarrow \Box A$

iii)  $\Diamond(A \Box B) \rightarrow (\Diamond A \Box \Diamond B)$

iv)  $\Diamond A \rightarrow A$

v)  $\Box(A \Box \neg A)$

vi)  $\Box(A \Box \neg A)$

vii)  $\Box(\Box A \Box \neg\Diamond A)$

viii)  $\Diamond\Diamond A$

b) Check your answers to i), ii), iv), v) and viii) above by using the definitions of the semantics of the modal operators as given in section 8.4.

### 8.8. One use for modal logic in programming

In this section we will briefly illustrate how modal logic has been used to get some grasp on the problem of expressing properties of programs (as you would want to if you are going to reason about their correctness etc.) This example is one among many given by Zohar Manna and Amir Pnueli in (Manna and Pnueli, 1981).

First, we need to set the scene. We will consider sequential computation as described by a language which manipulates states. A state will be a pair  $(\square, \underline{v})$  where  $\square$  is the current location and  $\underline{v}$  is a vector of current identifier values, i.e. an environment. Each statement of the program will be linked with the next by a location. So, for instance, we can write

```

        y1 := 2
□0 : print(y1)
□1 : y1 := y1 + 1
□2 : y2 := 2
□3 : if (y2)2 > y1 then goto □0
□4 : if (y1 mod y2) = 0 then goto □1
□5 : y2 := y2 + 1
□6 : goto □3

```

which we call PR. The  $y$ s are identifiers, so their values are what are stored in  $\underline{e}$  (in order, i.e. value of  $y_1$ , value of  $y_2$  etc.), and the  $\square$ s are locations. Therefore, an example of a state is  $(\square_1, \langle 2, 2 \rangle)$

Then, our set of possible worlds will be a set of such states and the accessibility relation holds between two states  $S = (\square_i, \underline{v})$  and  $T = (\square_k, \underline{w})$  iff there is a statement, whose location is  $\square_i$ , which being executed in state  $S$  results in state  $T$ . So in our example  $(\square_4, \langle 3, 2 \rangle)$  is related to  $(\square_5, \langle 3, 2 \rangle)$  and this state is in turn related to  $(\square_6, \langle 3, 3 \rangle)$  etc.

We also define a useful predicate 'at  $\square$ ' which is true iff in the current state the current location is  $\square$ .

Now, the program PR prints an infinite sequence of successive prime numbers 2 3 5 7 11 13 17 19 .... If we have a predicate 'prime(x)' which is true iff  $x$  is a prime number then using our knowledge of modal logic we can make statements about the program. For instance, part of the statement that the program is correct is

$$\models \square(\text{at } \square_0 \rightarrow \text{prime}(y_1)) \quad (1)$$

i.e. it is necessarily the case that if we are in a state whose current location is  $\square_0$  then the value of the first current identifier is a prime number. We might paraphrase this as 'nothing but primes are printed'. But there is much more to be said before we have stated that PR prints the required sequence. For instance, the sequence 3 17 2 5 19

... also satisfies (1). The property that every prime number is printed could be expressed by

$$\models \Box u[(\text{at } \Box_0 \Box y_1 = 2 \Box \text{prime}(u)) \rightarrow \Diamond(\text{at } \Box_0 \Box y_1 = u)] \quad (2)$$

i.e. if we are ever in the state where the current location is  $\Box_0$  and  $y_1$  is 2 (which we are at the start of an execution of PR) and  $u$  is any prime number then there is at least one state in which we are at  $\Box_0$  and  $y_1$  is  $u$  (which means that  $u$  will be printed).

This still does not mean that the primes (all of which will be printed) are printed in order. To get that we need to have

$$\models \Box u[(\text{at } \Box_1 \Box y_1 = u) \rightarrow \Box(\text{at } \Box_0 \rightarrow y_1 > u)]$$

This simple example does, hopefully, show that we can use a modal logic to state (and then prove) properties of programs. In this simple case the only apparent benefit seems to be that precise statements can be made relatively easily readable. You should contrast this with trying to express the above purely in first-order logic, i.e. with the sequentiality explicitly mentioned. However, the real power of using this logic becomes apparent if we consider describing computations involving several programs which run simultaneously and interacting with one another. As an example, we might express what is known as the 'liveness' of a program, i.e. the property that the program never 'gets stuck' (perhaps waiting for a communicating program to give it some input) indefinitely as

$$\models \text{at } \Box \rightarrow \Diamond \neg \text{at } \Box$$

i.e. if the program is at a particular location then there is an accessible state in which it has moved from that location. Many other such important properties can be so expressed.

## 8.9. Tableaux for Intuitionistic Logic

Computationally, the assumption that, for any proposition  $S$ ,  $S \rightarrow \neg S$  is valid leads to problems. For example consider the program:

```
select
  S : print "hello"
```

```

    ¬S : print "hello"
endselect

```

This can be shown to be equal to the program

```

print "hello"

```

using the rule

```

if P=Q then
  select ... Ci : P ... Cj : Q ... endselect
= select ... Ci  Cj : P endselect

```

as follows:

```

select
  S : print "hello"
  ¬S : print "hello"
endselect
= select S  ¬S : print "hello" endselect
= select true : print "hello" endselect
= print "hello"

```

However, if  $S$  is a proposition whose truth-value is not known, for instance if  $S$  is "there are an infinite number of twin primes", then the original program, when executed, gets no further than the test. Thus, the proof above must be wrong when compared with the execution.

Considerations like this may lead us to think about logics where the assumption that, for any  $S$ ,  $S \vee \neg S$  is valid is not made.

We first looked at such a logic in chapter five where we gave a natural deduction system for it. We will now give a tableau system too, but first we recap a little.

Intuitionistic logic rejects this basic assumption of classical logic that every sentence is either true or false, regardless of whether or not we know which it is. Intuitionistic logic requires that if we say something is true (false) then we have shown that it is true (false) by, for instance, constructing a proof or disproof. So,

given an arbitrary sentence, we cannot say it is true or false since in general we will have shown neither.

A slogan of intuitionistic logic is "provability equals truth"; that is, speaking intuitionistically, if you say a sentence is true then you mean the sentence has been proved. Thus, to say a sentence is either true or false is to mean that it has either been proved or disproved, but this is clearly not true of every sentence. So, while classically  $S \vee \neg S$  (where  $S$  is any sentence) is a tautology, intuitionistically it certainly is not. Thus, we reject the so-called "Law of the Excluded Middle". We shall have more to say on all of this in the next chapter.

We next want to develop a tableau procedure for deciding the truth of a sentence under its intuitionistic meaning. It turns out that we can already do this by using the procedure above for S4. What we do is to model intuitionistic reasoning within a certain modal logic, and S4 turns out to be the one that works.

First of all, recall that an S4-logic is one in which the accessibility relation is reflexive and transitive. Now, if we consider states of knowledge to be our possible worlds then these clearly have a reflexive and transitive relation between them. That is, once in a given state of knowledge we assume that all the knowledge in that state is accessible to us (where by 'us' we mean 'ourselves as working mathematicians, scientists etc.'). Also, if state of knowledge A leads to state of knowledge B, and B leads to state of knowledge C then C is accessible from A too. This, we feel, is a reasonable model for the development of knowledge.

Now, the model becomes complete if we follow a certain translation. If  $S$  is an atomic sentence that is intuitionistically true, then it is classically provable. Furthermore, if it is provable in state of knowledge A then it is provable in all states of knowledge accessible from A (i.e. 'in the future' if we think of the accessibility as allowing access between a state and its future). That is, we assume that something once known is not 'not known'. If we formalize this we have that

A makes  $S$  intuitionistically true iff for any state of knowledge B accessible from A, B allows us to classically prove  $S$

Now, if you look back to the definition of  $\Box$  you will see that the following is the case

A  $\vDash_{S4} \Box S$  iff for all possible worlds B such that B is accessible from A we have that B  $\vDash_{S4} S$ .

Since, 'allows us to classically prove' can be summed up as ' $\vDash_{S4}$ ' and since our possible worlds are states of knowledge we have

A makes  $S$  intuitionistically true iff for all possible worlds B accessible from A we have  $B \vDash_{S4} S$

and further

A makes  $S$  intuitionistically true iff  $A \vDash_{S4} \Box S$

which we write, finally, as

$A \vDash_I S$  iff  $A \vDash_{S4} \Box S$

Therefore, we can test the intuitionistic validity of  $S$  by testing the S4-validity of  $\Box S$ . In general we have to extend this to other than just the atomic sentences. We have the following translation function T:

$T(S) = \Box S$ , for  $S$  atomic.

$T(S \Box T) = \Box(T(S) \Box T(T))$

$T(S \dashv T) = \Box(T(S) \dashv T(T))$

$T(S \rightarrow T) = \Box(T(S) \rightarrow T(T))$

$T(S \leftrightarrow T) = \Box(T(S) \leftrightarrow T(T))$

$T(\neg S) = \Box \neg T(S)$

which, for example, formalizes the idea that  $S \Box T$  is intuitionistically true if it is provable that  $S$  is intuitionistically true and  $T$  is intuitionistically true. So, if we have  $A \Box B$ , where A and B are atomic, then we have that  $A \Box B$  is intuitionistically true iff A is provable and B is provable, as we should have expected. Also we have that  $S \dashv T$  is intuitionistically true iff  $S$  is intuitionistically true or  $T$  is intuitionistically true (which makes it clear that we should not expect  $S \dashv \neg S$  in general). The last clause says that  $\neg S$  is true is read as  $\Box \neg \Box S$ , i.e (approximately) it is provable that  $S$  is not provable. The other translations can be read similarly.

We then have the property

$\vDash_I S$  iff  $\vDash_{S4} T(S)$

for  $\mathcal{S}$  and  $\mathcal{T}$  any sentences.

Thus, to test the validity of a sentence intuitionistically we first translate it using  $T$  and then test the validity of the resulting sentence by using the procedure for S4.

For example, the sentence  $A \rightarrow \neg A$  gives

$$T(A \rightarrow \neg A) =$$

$$\Box(T(A) \rightarrow T(\neg A)) =$$

$$\Box(\Box A \rightarrow \Box \neg T(A)) =$$

$$\Box(\Box A \rightarrow \Box \neg \Box A)$$

Then, the S4 procedure will show that this sentence is not valid, as we did in section seven of this chapter, and hence  $A \rightarrow \neg A$  is not valid intuitionistically.

**Exercise 8.5**

a) Decide on the classical and intuitionistic validity of each of the following sentences:

i)  $A \rightarrow \neg A$

ii)  $\neg \neg A \rightarrow A$

iii)  $A \rightarrow \neg \neg A$

b) We can extend the translation function  $T$  above to cope with the quantifiers as well.  $T$  is extended so that as well as the rules above we have:

$$T(\Box x \mathcal{S}) = \Box x \Box T(\mathcal{S})$$

$$T(\Box x \mathcal{S}) = \Box x \Box T(\mathcal{S})$$

using this, decide on the classical and intuitionistic validity of:

i)  $\Box x A(x) \rightarrow \Box x A(x)$

ii)  $\neg \Box x \neg A(x) \rightarrow \Box x A(x)$

## Summary

- Predicate calculus can only formalize types of reasoning in which sentences are true or false timelessly whereas in computer science, particularly, we often want to formalize systems in which propositions are true in some situations and false in others (such propositions are called *contingent*). To do this we introduce into the language two new *modalities*.,  $\Diamond S$  which is read 'possibly  $S$ ' and whose intended interpretation is that  $\Diamond S$  is true if  $S$  is true in *some* possible situation, and  $\Box S$  which is read 'necessarily  $S$ ' and is true if  $S$  is true in *all* possible situations.

- These extensions to the language are given a semantics by introducing the notion of a *frame*. A frame consists of a set of *possible worlds* together with a relation of *accessibility* between worlds. Propositions may be true in some worlds and false in others. If  $S$  is a sentence then  $\Box S$  is true in a particular world if  $S$  is true in *all* worlds accessible from that world, and  $\Diamond S$  is true if  $S$  is true in *some* world accessible from it. Thus modal logic is not truth-functional. The truth-value of a formula such as  $\Box S$  or  $\Diamond S$  cannot be calculated from the truth-value of  $S$  at that world alone. The truth-value of the other logical connectives, however, depends only on their value at the world in which it is calculated, and so they are truth-functional and have the same meaning as in predicate calculus.

- A model in modal logic consists of a frame and an interpretation which specifies which atomic formulas are *forced* (i.e. true) in each possible world. A formula is satisfiable if there is an interpretation and a world in which it is forced. The validity of a formula can be disproved by displaying a counter-model in the form of a *possible-worlds diagram*, showing the frame as a directed graph together with the propositions that are forced at each world (node of the graph).

- Many systems of modal logic can be defined, depending on the properties of the accessibility relation. For example the modal logic called S4 is the system in which the accessibility relation is reflexive and transitive. All such systems however have the tautologies of propositional logic together with some basic equivalences such as  $\Diamond S \leftrightarrow \neg \Box \neg S$ . For different accessibility relations in the semantics there are corresponding proof systems. We show how a tableau system can be defined for S4.

- Modal logic can be used to give a semantics for intuitionistic logic, the logic that is obtained by dropping the Contradiction rule from the natural deduction

system for predicate calculus. We saw in chapter five that a simple extension of the truth-table idea to many linearly-ordered truth-values is not sufficient. However, a possible-worlds semantics can be given for intuitionistic logic. The appropriate accessibility relation is reflexive and transitive and we show how the tableau system for S4 can be adapted to yield a proof procedure. A sentence  $\mathcal{S}$  is intuitionistically valid iff  $\Box \mathcal{S}$  is valid in S4.

# CHAPTER NINE

---

## Further Study

### 9.1. Introduction

This chapter is intended as an appetizer for further study. Having worked through the book the reader will hopefully be in a position to go on to more advanced work: to look at logics with more sophisticated bases; to look further, and more sceptically, at the philosophical basis for much that we have presented here; to see how logics have been developed for talking about, and making progress towards solutions for, many problems in computer science.

We will, in what follows, do no more than briefly mention some problems and further work based on them, and direct the reader to some reasonably accessible texts that will allow further study. By no means do we claim to present a complete bibliography, merely one that will allow the reader to move onto the next stage in each area.

### 9.2. Connection method

#### 9.2.1. *Basic ideas*

The connection method was introduced by Bibel (1987) as an efficient method for deciding validity in predicate logic. It turns out that it has very close connections with the tableau method that we looked at in chapter four, and can be seen, especially in its later developments, as a very efficient way of implementing tableau systems. Indeed, this has been demonstrated best by Wallen (1987) not only for classical logics but non-standard ones too.

We shall give here just the first few steps towards the full connection method. It is rather complicated to describe as the logical and algorithmic aspects that give it its efficiency tend to be rather intertwined.

Consider the usual first example of a predicate logic argument

$$A1: \exists x(\text{Man}(x) \rightarrow \text{Mortal}(x))$$

$$A2: \text{Man}(\text{Socrates})$$

$$TH: \text{Mortal}(\text{Socrates})$$

As we know, we can express this argument as

$$(\exists x(\text{Man}(x) \rightarrow \text{Mortal}(x)) \wedge \text{Man}(\text{Socrates})) \rightarrow \text{Mortal}(\text{Socrates}) \tag{1}$$

If we then replace  $\rightarrow$  by its expression in terms of  $\wedge$  and  $\neg$  we get

$$\begin{aligned} & \neg[\exists x(\text{Man}(x) \rightarrow \text{Mortal}(x)) \wedge \text{Man}(\text{Socrates})] \wedge \text{Mortal}(\text{Socrates}) \\ \leftrightarrow & \neg[\exists x(\neg\text{Man}(x) \wedge \text{Mortal}(x)) \wedge \text{Man}(\text{Socrates})] \wedge \text{Mortal}(\text{Socrates}) \\ \leftrightarrow & \exists x(\text{Man}(x) \wedge \neg\text{Mortal}(x)) \wedge \text{Man}(\text{Socrates}) \wedge \text{Mortal}(\text{Socrates}) \end{aligned} \tag{2}$$

The next step is to write (1) in the form of a matrix. This is a two dimensional representation of any sentence that is in the form of a disjunction of conjuncts, the disjunctive normal form, like (1) above. So the matrix here is

$$\begin{array}{cccc} \exists & \text{Man}(x) & & \\ & & \wedge & \text{Man}(\text{Socrates}) \quad \text{Mortal}(\text{Socrates}) \\ \exists & \text{Mortal}(x) & & \end{array}$$

and by convention variables, like x here, are existentially quantified. The above is said to be a matrix consisting of a set of clauses, which are in disjunction, and each clause consists of a set of literals, which are in conjunction. If we cross the matrix from left to right, visiting one literal from each clause, we form a path.

A pair of literals with the same predicate symbol, where one of the literals is negated, is called a connection. A set of connections is called spanning if each path through a matrix contains a connection from the set.

In the matrix above there are two paths

$$\{ \text{Man}(x), \neg\text{Man}(\text{Socrates}), \text{Mortal}(\text{Socrates}) \} \quad (\text{p1})$$

$$\{ \neg\text{Mortal}(x), \neg\text{Man}(\text{Socrates}), \text{Mortal}(\text{Socrates}) \} \quad (\text{p2})$$

and two connections

$$\{ \text{Man}(x), \neg\text{Man}(\text{Socrates}) \} \quad (\text{c1})$$

$$\{ \neg\text{Mortal}(x), \text{Mortal}(\text{Socrates}) \} \quad (\text{c2})$$

Since each of p1 and p2 contains one of c1 or c2, i.e.  $c1 \not\subseteq p1$  and  $c2 \not\subseteq p2$ , then by definition  $\{c1, c2\}$  is a spanning set of connections for the matrix.

It can be shown that a sentence is valid iff each element of a spanning set of connections for the matrix form of S can be made into a complementary pair of literals, i.e. the literals have the same predicate letter, one negated, and the same arguments.

In the case above c1 and c2 can each be made complementary by the substitution of Socrates for x. Therefore, we conclude that the original sentence (1) is valid.

It is illuminating to compare this with the tableau proof:

$$\begin{array}{c}
 \exists x(\text{Man}(x) \wedge \neg \text{Mortal}(x)) \quad (1) \\
 | \\
 \text{Man}(\text{Socrates}) \quad (2) \\
 | \\
 \neg\text{Mortal}(\text{Socrates}) \quad (3) \\
 | \\
 \text{Man}(\text{Socrates}) \wedge \neg \text{Mortal}(\text{Socrates}) \quad (4) \\
 \swarrow \quad \searrow \\
 \neg\text{Man}(\text{Socrates}) \quad (5) \qquad \text{Mortal}(\text{Socrates}) \quad (6) \\
 + \qquad \qquad \qquad + \\
 \text{using (2) and (5)} \qquad \text{using (3) and (6)}
 \end{array}$$

Note that we have made the same substitution and, essentially, the same connections, shown here by contradictions. We can think of this set of contradictions as spanning since they close every path of the tableau. Note, further, that by listing the atomic sentences of all paths on the tableau we regain all of the paths through the matrix.

### 9.2.2. Generating spanning sets

Consider the matrix shown below:

	0	1	2	3	4
□L	□L	□M	K	L□	□
□					□
□K	M			M□	□

We have added a grid to this matrix to make the naming of (positions of) literals easier in what follows. This matrix has eight paths:

{00, 01, 02, 03, 04}	p1
{00, 01, 02, 03, 14}	p2
{00, 11, 02, 03, 04}	p3
{00, 11, 02, 03, 14}	p4
{10, 01, 02, 03, 04}	p5
{10, 01, 02, 03, 14}	p6
{10, 11, 02, 03, 04}	p7
{10, 11, 02, 03, 14}	p8

The task is to find a spanning set of connections, i.e. a connection for each path.

We choose a clause, say 0, and a literal within it, say 00. We then look for a complementary literal in some other clause, say 1, so we find the literal 01. After making this connection we can form three disjoint sets of paths:

- a) those containing the connection {00,01} - these need no more work
- b) those still to be worked on which contain 00
- c) those still to be worked on which do not contain 00

so here we have

- a) {p1,p2}
- b) {p3,p4}
- c) {p5,p6,p7,p8}

Next we put set c aside, perhaps on a stack in an implementation of this procedure, and look at set b. With b we now repeat the procedure above. We choose a clause, say 1, and a literal not yet in a connection (here there is only one, namely 11). Then, we search the other clauses to form a connection with 11. Say we find 02. Then, we partition the set b, as before, into three disjoint sub-sets:

- ba) {p3,p4}

bb) {}

bc) {}

Clearly, this sub-problem is solved since there are no clauses in the "still to be connected" sets. So, we go back to our stack of sets containing paths yet to have connections found for them and work on them. Here, we work on set c. This gives

ca) {p5,p6,p7,p8}

cb) {}

cc) {}

by choosing the connection {10,03}. Now, since there are no more problems stacked the whole problem is solved and we have our spanning set. Hence, the initial matrix represents a valid sentence.

There is, of course, much more to say about the connection method. In particular we have not mentioned here how we deal with first-order sentences. Having generated spanning sets using the above mechanism we would need to find substitutions that make the literals in the sets complementary. This involves the use of unification and also some mechanism for respecting the restrictions that govern universal and existential quantifiers. We have also not said anything about the algorithms developed by Bibel for efficiently implementing the method. However, all these questions really take us too far into the research area of automated reasoning and so too far outside the scope of the current text. To treat the method properly would take a whole textbook, as Bibel indeed does (Bibel, 1987), so we prefer to leave the topic here and let readers follow up if they wish.

## 9.3. LCF

### 9.3.1. Introduction

The name "LCF" (which stands for Logic for Computable Functions) nowadays covers more than one system. The one that we shall look at here, which is the original one, is more properly called "Edinburgh LCF". It grew out of work that was started at Stanford University in California, USA. It is essentially a computer program that acts as a proof-checker for a logic of computable functions.

The interactive nature of this system means that instead of a problem being stated and then given to the program to work on until it gets an answer (or, more usually, until it runs out of storage or the user runs out of patience), the idea of a proof-checker (as opposed to a theorem-prover) is that the user issues commands to build proofs step by step in an interactive manner. So, a step might be, "apply modus ponens to theorems A and B". The program will check that the premises A and B are

of the right form for this step to be correct and then go on to produce the conclusion. (Our SML program for proof checking does just this, though not interactively.)

In the case of Edinburgh LCF the way of issuing commands has been embodied in a language that has an expressive functional subset. This language is ML, for Meta Language, and is the pre-cursor to the language SML that we have been using in this book.

Using a language with the expressiveness of ML means that not only can proof rules be encoded but also rules for composing proof rules together. This feature is a very important one.

The form of proof used in LCF is that of natural deduction. Each rule of inference in the logic is expressed as an ML function which has as result a value of the ML abstract type `thm`, i.e. a theorem. There are also functions which work on the syntax of the language to break up sentences and build new ones, rather in the manner of our functions like `free_for`, `free_in`, `instance_of` etc.

### 9.3.2. An example proof

As an example of how the system is used we will re-express a proof given above in chapter five. This theorem to be proved is

$$\vdash p \rightarrow (q \rightarrow (p \sqcap q))$$

and, adapting the proof from chapter five we have the following proof:

$$\begin{array}{c}
 \frac{}{\{p\} \vdash p} \text{ ASSUME} \qquad \frac{}{\{q\} \vdash q} \text{ ASSUME} \\
 \hline
 \{p, q\} \vdash p \sqcap q \qquad \text{ CONJ} \\
 \hline
 \{p\} \vdash q \rightarrow (p \sqcap q) \qquad \text{ DISCH} \\
 \hline
 \vdash p \rightarrow (q \rightarrow (p \sqcap q)) \qquad \text{ DISCH}
 \end{array}$$

Having discovered a proof like the above, we now need to use the LCF system to check that it is in fact a correct proof. As we said before, the rules of the logic are implemented as ML functions. These functions check that the premises given to each application of a rule really do meet the requirements given in the rule definition.

Further, the only way of getting values of type `thm`, i.e. theorems in the implementation is as the result of the functions which implement the rules. Hence, if something is of type `thm` then it really is a theorem. So, if we can show that at each stage of the proof above the statements are in `thm` then we know that the proof is correct, i.e. we will successfully have checked it.

The first rule we need to use is

```
ASSUME : form -> thm
```

where the formula  $w$  is mapped to  $\{w\} \vdash w$ . So, if we are sitting with the system waiting in readiness for us to interact with it, we type

```
let a1 = ASSUME "p" ;;
let a2 = ASSUME "q" ;;
```

and get the response

```
val a1 = ["p"] ]- "p" : thm
val a2 = ["q"] ]- "q" : thm
```

(where `]-` is the turnstile). Then we use the function

```
CONJ: (thm x thm) -> thm
```

which takes a theorem of the form  $A_1 \vdash w_1$  and one of the form  $A_2 \vdash w_2$  and returns  $A_1 \cup A_2 \vdash w_1 \sqcap w_2$  so here we type

```
let a3 = CONJ(a1, a2) ;;
```

which gives

```
val a3 = ["p", "q"] ]- "p & q" : thm
```

Then we use

```
DISCH: form -> thm -> thm
```

where  $w$  and  $A \vdash w'$  are mapped to  $A' \vdash w \rightarrow w'$  where  $A'$  is  $A$  with all occurrences of  $w$  deleted. So here we type

```
let a4 = DISCH "q" a3;;
```

to get

```
val a4 = ["p"] ]- "q imp (p & q)" : thm
```

and finally

```
let a5 = DISCH "p" a4;;
```

to get

```
val a5 = ]- "p imp (q imp (p & q))" : thm
```

as required. So, our proof has been checked and found correct. If we had actually made a mistake in any of the above steps then the system would have informed us of this and disallowed the step. That is, a step is only allowed if the rule is being used correctly. Any misuses are reported and the user has to adapt the alleged proof so that all its steps are correct uses of the rules.

### 9.3.3. *Tactics*

Having seen how the system might be used on a very simple example where the user decides at each step which rule to use, we now go on to look at a way in which we can begin to make the system do more work for us. This will depend on using the expressiveness of ML to program some more or less general purpose problem-solving strategies.

One common way of constructing proofs in a natural deduction style (though it is not of course restricted to this style) is as described in the natural deduction chapter above, i.e. we use the rules of inference in a backward sense. That is, given the correct goal, we find a rule whose conclusion can be made to match the goal and hence, by reading off the associated premises, find some sub-goals which are simpler

to prove than the original goal. We keep on using this basic strategy until all the sub-goals reduce to axioms or to sentences that we have proved previously.

For example, we can try to prove

$$\vdash (p \sqcap q) \rightarrow (q \sqcap p) \quad (1)$$

First we look for a rule whose conclusion matches the sentence. In general there will be many matches, so a searching mechanism will be required to make sure that we try all possibilities. In this case it turns out that two rules are applicable; the rule **ASSUME** or the rule **DISCH** as given above.

Clearly **ASSUME** gets us nowhere with our current goal so we use **DISCH**. We match with (1) so that

$$\begin{aligned} (p \sqcap q) &\text{ is } w \\ (q \sqcap p) &\text{ is } w' \\ \{\} &\text{ is } A \\ \{\} &\text{ is } A' \end{aligned}$$

and end up with the sub-goal, i.e. the instantiated premise of **DISCH**, being

$$(p \sqcap q) \vdash (q \sqcap p) \quad (2)$$

We also need to record, for use later, the reason why this is a legitimate step. In this case it is because of the rule **DISCH**. Now, we do the same with sub-goal (2). The only rule that matches is **CONJ** which means we now have the sub-goals

$$(p \sqcap q) \vdash q \quad (3a)$$

$$(p \sqcap q) \vdash p \quad (3b)$$

and we record **CONJ** as the reason for these sub-goals. Tackling (3a) first, the only rule which matches it is

**SEL2**:  $\text{thm} \rightarrow \text{thm}$

takes a theorem of the form  $A \vdash w_1 \sqcap w_2$  and returns  $A \vdash w_2$

to give the goal

$$(p \sqcap q) \vdash (p \sqcap q) \tag{4a}$$

with the reason **SEL2**. Similarly, (3b) needs **SEL1**

**SEL1**:  $t \text{ hm } \rightarrow t \text{ hm}$  takes a theorem of the form  $A \vdash w_1 \sqcap w_2$  and returns  $A \vdash w_1$

to give

$$(p \sqcap q) \vdash (p \sqcap q) \tag{4b}$$

with reason **SEL1**. Then (4a) and (4b) can be satisfied by **ASSUME** applied to  $(p \sqcap q)$ , and leading to no further sub-goals.

Now, we can put the all the validations together to get

$$\text{DISCH} (\text{CONJ} (\text{SEL2} (\text{ASSUME} (p \& q) ) , \text{SEL1} (\text{ASSUME} (p \& q) ) ) ) \tag{5}$$

which can be thought of a linear way of describing what, in chapter five, would have been more conventionally written as

$$\frac{\frac{\frac{}{(p \sqcap q) \vdash (p \sqcap q)}{\text{ASSUME}}}{\text{SEL2}}}{(p \sqcap q) \vdash q} \quad \frac{\frac{\frac{}{(p \sqcap q) \vdash (p \sqcap q)}{\text{ASSUME}}}{\text{SEL1}}}{(p \sqcap q) \vdash p} \text{CONJ}}{\frac{(p \sqcap q) \vdash (q \sqcap p)}{\text{DISCH}} \vdash (p \sqcap q) \rightarrow (q \sqcap p)}$$

The task of mapping a goal to a list of sub-goals and a validation is carried out by what, in LCF parlance, are called tactics. (Here we are going to present a simplified version of the full LCF idea. It will however convey the main points about use of tactics.) . A validation is some action which makes a tactic T valid. This means that,

if  $g$  and  $g_1, \dots, g_n$  are goals and  $v$  is a validation and  $T(g) = ([g_1, \dots, g_n], v)$  then,

if  $v_1, \dots, v_n$  achieve  $g_1, \dots, g_n$  respectively then  $v(v_1, \dots, v_n)$  achieves  $g$ , which rule we call  $V$ .

By looking at the example above, together with the descriptions of the rules, we can assemble the following tactics, sub-goal lists and validations:

<b>DISCH</b> $\tau$ <b>ac</b>	where $(A', w \rightarrow w')$ is mapped to $([(A \cup \{w\}, w'), \Box x.(\text{DISCH } w \ x)])$
<b>CONJ</b> $\tau$ <b>ac</b>	where $(A_1 \cup \Box_2, w_1 \Box w_2)$ is mapped to $([(A_1, w_1), (A_2, w_2)], \Box(x, y). \text{CONJ}(x, y))$
<b>SEL1</b> $\tau$ <b>ac</b>	where $(A, w_1) \ w_2$ are mapped to $([(A, w_1 \Box w_2)], \Box x.(\text{SEL1 } x))$
<b>SEL2</b> $\tau$ <b>ac</b>	where $(A, w_2)$ and $w_1$ are mapped to $([(A, w_1 \Box w_2)], \Box x.(\text{SEL2 } x))$
<b>ASSUME</b> $\tau$ <b>ac</b>	where $(\{w\}, w)$ is mapped to $([], \text{ASSUME } w)$

and note that this last tactic is a special case since it produces no sub-goals.

Now we can re-trace our steps in the construction of the proof above. First, at step one, we apply **DISCH** $\tau$ **ac** to " $(p \ \& \ q) \ \text{imp} \ (q \ \& \ p)$ " which gives us

$$([( (p \ \& \ q), (q \ \& \ p) )], \Box x.(\text{DISCH } (p \ \& \ q) \ x))$$

(and here we have left out some of the quotes and brackets to make the text a little easier to read.) Then we begin on the sub-goal list, which in this case means dealing with just one sub-goal. We use **CONJ** $\tau$ **ac** to get, at step two,

$$([( (p \ \& \ q), q ), ( (p \ \& \ q), p ) ], \Box(x, y). \text{CONJ}(x, y))$$

and then **SEL2** $\tau$ **ac** on the first sub-goal and **SEL1** $\tau$ **ac** on the second to get, at steps three and four

$$([( (p \ \& \ q), (p \ \& \ q) )], \Box x.(\text{SEL2 } x)) \ ([ ( (p \ \& \ q), (p \ \& \ q) ) ], \Box x.(\text{SEL1 } x))$$

and each of these is solved with  $\text{ASSUME}t_{ac}$ , at steps five and six, to give, for both cases

$$([], \text{ASSUME } (p \ \& \ q))$$

which has no sub-goals, so we are finished. Now we just need to collect up the validations in each case and use the rule V for achieving goals. So, to achieve the two sub-goals resulting from steps three and four we apply  $\text{ASSUME } (p \ \& \ q)$  to what achieves the sub-goals at steps five and six, but since the list is empty in each case, i.e. there are no sub-goals, we apply it to nothing. Then, to achieve the first sub-goal at step two we apply  $\Box x.(\text{SEL2 } x)$  to  $\text{ASSUME } (p \ \& \ q)$  (according to rule V) and to achieve the second sub-goal at step two we apply  $\Box x.(\text{SEL1 } x)$  to  $\text{ASSUME } (p \ \& \ q)$ . To achieve the sub-goal at step one we apply  $\Box(x,y).\text{CONJ}(x,y)$  to  $(\Box x.(\text{SEL2 } x) \text{ASSUME } (p \ \& \ q), \Box x.(\text{SEL1 } x) \text{ASSUME } (p \ \& \ q))$ . Finally, to get the original goal we apply  $\Box x.(\text{DISCH } (p \ \& \ q) \ x)$  to  $(\Box(x,y).\text{CONJ}(x,y) (\Box x.(\text{SEL2 } x) \text{ASSUME } (p \ \& \ q), \Box x.(\text{SEL1 } x) \text{ASSUME } (p \ \& \ q)))$  to get

$$\Box x.(\text{DISCH } (p \ \& \ q) \ x) (\Box(x,y).\text{CONJ}(x,y) (\Box x.(\text{SEL2 } x) \text{ASSUME } (p \ \& \ q), \Box x.(\text{SEL1 } x) \text{ASSUME } (p \ \& \ q)))$$

which simplifies, by the rules of the  $\Box$ -calculus, to the expression (5) above.

So, we can see that by having tactics, which are essentially the rules of inference backwards with extra mechanism for book-keeping purposes, we can formalize the idea of working backwards from goal to simpler and simpler sub-goals. The next stage, which we will not go into, allows these tactics to be combined together, by functions called *tacticals*, by operators to form more and more complex tactics to get nearer and nearer to aim of making more and more of the proof construction process automatic, at least in fairly uniform and simple cases.

We will leave our presentation of LCF here, but fuller details can be found in Gordon et al. (1979).

## 9.4. Temporal and dynamic logics

### 9.4.1. Temporal logic

One particularly important use for the ideas of modal logics are logics where the modalities are related to the time at which or for which statements are true or

false. We looked briefly at an approximation to this idea when we showed an example of using modal logics to describe computations in chapter eight. There the possible worlds were states in a computation and the accessibility relation related worlds which were linked by the execution of a program statement. This can be taken further and instead of states in the computation being linked by program statements we can think of moments in time linked by the passage of time. Under this more general presentation the accessibility relation relates states that are temporally earlier with states that are temporally later. Finally, this idea can then be used to model any system where there is a temporal relation between states.

Let us set up a simple temporal logic, as we call logics which reason about time (and they are also called "tense logics" by other authors). We follow the pattern set when we talked about modal logics, so first we need a frame. We let  $P$  be a set of possible worlds and  $R$  be an accessibility relation, but this time, to remind ourselves that we are dealing with an "earlier-later than" relation we shall write  $R$  as  $<$ . As suggested by the use of this symbol, we shall make  $<$  transitive. We shall also make  $<$  connected. This means that no time that we can get to is isolated from past or future times. These two conditions mean that the sort of time we shall look at is the usual linear one that is used in everyday reasoning (though it does break down once we start to think of relativistic effects). The conditions can be formalized as

$$\begin{aligned} < \text{ is connected: } & \exists t \exists t' (t < t' \quad t = t' \quad t' < t) \\ < \text{ is transitive: } & \exists t \exists t' ((t < t' \wedge t' < t'') \rightarrow t < t'') \end{aligned}$$

Now, following our pattern for modal logics we can introduce the counterpart to  $\Box$  and  $\Diamond$ . Following our previous use of the notation we will write

$$t \models S$$

to mean that  $S$  is true at time  $t$ .

There are usually taken to be four temporal modalities and these are as follows, where  $S$  is any statement:

- $F S$     there is a future time when  $S$  will be true
- $G S$     at all future times  $S$  will be true
- $P S$     there is a past time when  $S$  was true
- $H S$     at all past times  $S$  was true

These can be formalized as:

$t \models_{\mathcal{V}} FS$	iff	there is a $t'$ such that $t < t'$ and $t' \models_{\mathcal{V}} S$
$t \models_{\mathcal{V}} GS$	iff	for all $t'$ , if $t < t'$ then $t' \models_{\mathcal{V}} S$
$t \models_{\mathcal{V}} PS$	iff	there is a $t'$ such that $t' < t$ and $t' \models_{\mathcal{V}} S$
$t \models_{\mathcal{V}} HS$	iff	for all $t'$ , if $t' < t$ then $t' \models_{\mathcal{V}} S$

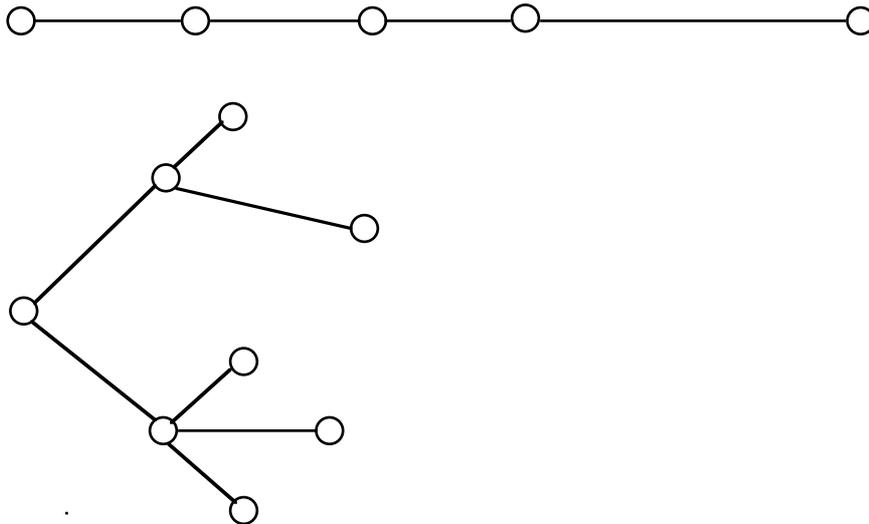
with the definitions for the non-temporal operators as before. These definitions give, analogous to the case with  $\Box$  and  $\Diamond$ ,

$$\neg FS \leftrightarrow G\neg S$$

$$\neg PS \leftrightarrow H\neg S$$

It turns out that for this system there is also a tableau method which can be used to decide validity, just as in the modal and classical cases.

This, of course, is just the beginning of the story. We can go on to ask whether time is discrete, i.e. broken into indivisible moments, or continuous, in which case, like the real line, there is always a moment of time between any two moments. Also, we can model the idea that the future is not linear, as we have it here, but branching, in the sense that, even though, a given observer passes through a sequence of moments, the future might be a branching structure of possibilities through which an individual traces a single, linear path. The difference can be suggested by comparing the diagrams below, for linear and branching time respectively:



We have here only looked at a tiny fragment of the huge and varied philosophical and mathematical literature on temporal logics. For further study we refer the reader to Rescher and Urquhart (1971). For work on temporal logics directly related to programming Manna and Pnueli (1981) is a good starting point.

#### 9.4.2. Dynamic logic

This is another example of an extension of the basic ideas of modal logic. If we take  $P$ , the set of possible worlds, to be possible states of a computation then the accessibility relation  $R$  will relate a state  $s$  to a state  $t$ . However, we want the fact that states are related, because execution of a program causes transition from one to the next to be reflected in the accessibility relation. The dynamic logic way of doing this is to index the relation with the program. So, if  $s$  and  $t$  are states of a computation and we get from  $s$  to  $t$  by executing the program  $\alpha$  then we should have that  $(s,t) \in R(\alpha)$ . That is, the relation  $R$  changes depending on what program we are currently dealing with. This is clearly an extension of the idea of accessibility relation that we saw previously.

Now we want to see how this change is reflected at the level of propositions. Recall the definition of  $\Box$ :

$$s \models \Box S \text{ iff for all } t \in P \text{ such that } (s,t) \in R, t \models S$$

Since the relation  $R$  will now depend upon the program  $\alpha$  we make the necessity operator depend upon it too. If the frame and valuation (as before) are understood then we write  $s \models [\alpha]S$  to mean that whenever the program  $\alpha$  is executed

starting in state  $s$ , then proposition  $S$  is true under the valuation in the state that obtains after the execution. Formally we have

$$s \models [\Box]S \text{ iff for all } t \models P \text{ such that } (s,t) \in R(\Box), t \models S \tag{1}$$

and we also have, as you might expect,

$$s \models \langle \Box \rangle S \text{ iff there exists a } t \text{ such that } (s,t) \in R(\Box) \text{ and } t \models S \tag{2}$$

that is  $s \models \langle \Box \rangle S$  means that if  $\Box$  is executed in state  $S$  then there is a state that the computation will be in where  $S$  obtains. As before, a sentence is valid in a frame iff it is true for all valuations in the frame and a sentence is valid iff it is valid in all frames.

The language of propositions, with the extension of indexing the modalities, is just as usual. The language of programs is usually based, using the initial work in Pratt (1976), on the following primitives:

do $\Box$ then do $\Box$	$\Box; \Box$
do either $\Box$ or $\Box$	$\Box \cup \Box$
do $\Box$ a finite number of times	$\Box^*$
evaluate the proposition $S$ , if it is true	
then carry on with the evaluation,	$S?$
otherwise fail	

The meaning of these programs is given in an obvious way. So, for instance, we have

$$\text{if } (s,t) \in R(\Box) \text{ and } (t,r) \in R(\Box) \text{ then } (s,r) \in R(\Box; \Box), \text{ for any } s,r,t \in P.$$

Using these program forms we can introduce more expressive statements by definition. For example we have

while $S$ do $\Box$	is defined to be	$(S?; \Box)^*; \neg S?$
if $S$ then $\Box$ else $\Box$	is defined to be	$(S?; \Box) \cup (\neg S?; \Box)$

Using this simple propositional language we can make statements about the correctness of algorithms. For instance, the statement

$$(n \geq 0) \rightarrow [x, y := n, 1; \text{while } x > 0 \text{ do } (y := y * x; x := x - 1)] (y = n!)$$

is true if, whenever we start in a state where  $n \geq 0$  (where a state is a tuple of variable values) and then execute the program, the final state will be one where  $y = n!$ , i.e. the statement says that the program correctly calculates the factorial function of  $n$ .

We can, more abstractly, also make statements about relations between programs. So, for instance, if  $S$  is any statement then if we can prove

$$\langle \Box \rangle S \leftrightarrow \langle \Box \rangle S$$

then we can conclude that the programs  $\Box$  and  $\Box$  are equivalent, that is they give the same result when started in the same state.

We can also prove derived properties of programs that can serve to make proofs easier. For instance, under the intended interpretation, it is clear that we would expect that if

$$\models S \rightarrow [\Box] \mathcal{T} \text{ and } \models \mathcal{T} \rightarrow [\Box] \mathcal{R}$$

then

$$\models S \rightarrow [\Box; \Box] \mathcal{R}$$

and we can show this as follows. By assumption, for any frame  $\langle P, R \rangle$  and any valuation in that frame we have, for any  $s \in P$ ,  $s \models S \rightarrow [\Box] \mathcal{T}$ , i.e. if  $s \models S$  then  $s \models [\Box] \mathcal{T}$ . So, for all  $t \in P$  such that  $(s, t) \in R(\Box)$ ,  $t \models \mathcal{T}$ . Similarly, again by assumption, we have that if, for any  $t \in P$ ,  $t \models \mathcal{T}$ , then for all  $r \in P$  such that  $(t, r) \in R(\Box)$ ,  $r \models \mathcal{R}$ . So, putting this together, we have that if  $s \models S$  then for all  $t \in P$  such that  $(s, t) \in R(\Box)$  and for all  $r \in P$  such that  $(t, r) \in R(\Box)$ ,  $r \models \mathcal{R}$ . By definition, this means that if  $s \models S$  then, for all  $s, r \in P$  such that  $(s, r) \in R(\Box; \Box)$ ,  $r \models \mathcal{R}$ . And this means that if  $s \models S$  then  $s \models [\Box; \Box] \mathcal{R}$ . This, finally, gives us the desired conclusion.

Here we have only given an idea of the expressiveness of dynamic logic and have given very little in the way of formal semantics. Its expressiveness can be extended by allowing the statements to be first-order and then as well as quantifying over, say, numbers we can quantify over programs themselves. The formal semantics that we gave for modal logics can be extended to include a formal semantics for programs too. This in turn leads to an extension of the tableau system to provide algorithmic means for decision procedures and semi-decision procedures as before.

However, we will leave this huge subject here since, again, we would need to write a whole book to do it justice.

## 9.5. Intuitionistic logic

### 9.5.1. Introduction

Intuitionistic logic was developed because mathematicians working at the turn of the century thought that the foundations of their subject were not secure. The basis for these thoughts came with problems in set theory like the Cantor paradox. This can be briefly described as follows. If  $A$  is a set then the size of the set is given by its cardinal number  $\bar{A}$ , which is the set of all sets which have the same number of elements as  $A$  (or more precisely whose elements can be put into a one-one correspondence with those of  $A$ ). Let  $\bar{A} \leq \bar{B}$ , for two sets  $A$  and  $B$ , mean that  $A$  has the same cardinality as a sub-set of  $B$ . Then, by a result of Cantor's, for any set  $A$  and its powerset  $P(A)$  we have  $\bar{A} < \overline{\overline{P(A)}}$ . Now, let  $U$  be the set of all sets, i.e. the universal set. Then, by definition  $P(U) \subseteq U$  so  $\overline{\overline{P(U)}} \leq \bar{U}$ . But, by Cantor's result we have  $\bar{U} < \overline{\overline{P(U)}}$ , which gives a contradiction. This is Cantor's paradox.

Frege and Hilbert, who thought that mathematics lacked proper foundations, set about trying to provide them.

Frege thought that the foundations should be built by basing everything on logic, as he considered this to be a more fundamental subject. Hilbert thought that mathematics should be built by setting up, say, arithmetic by using completely agreed upon and clear axioms and then using only completely clear "metamathematical" arguments to construct all of the rest. Both these projects failed. Frege's ideas, as we said before, failed to form the foundations based on purely logical grounds because of the contradictions found by Russell. Hilbert's program, as it was called, failed because of the incompleteness theorems of Gödel. Brouwer started a third movement that tried to provide a proper foundation, and this movement is usually called intuitionism.

If you are working as an intuitionist then you want all of your mathematics to be constructive. Put simply, this means that you do your mathematics without use of the so-called law (or principle) of the excluded middle and without the use of non-constructive existence proofs.

The law of the excluded middle states that for any statement  $S$ , either  $S$  is true or  $\neg S$  is true. This is the fundamental assumption that we introduced when starting with classical logic. The general form of a non-constructive existence proof is one where we seek to prove  $\exists x.S(x)$  by proving  $\neg \forall x.\neg S(x)$

As an example of the sort of proof that mathematicians do not want to give up, due to its elegance and simplicity and which uses the law of the excluded middle, we have the following time-honoured first example:

**Theorem**

There exist solutions of  $x^y = z$  with  $x$  and  $y$  irrational and  $z$  rational.

**Proof**

$\sqrt{2}$  is irrational. Also,  $\sqrt{2}^{\sqrt{2}}$  is either rational or irrational. If  $\sqrt{2}^{\sqrt{2}}$  is rational then put  $x = \sqrt{2}$  and  $y = \sqrt{2}$ , then  $z$  is rational. If  $\sqrt{2}^{\sqrt{2}}$  is irrational then put  $x = \sqrt{2}^{\sqrt{2}}$  and  $y = \sqrt{2}$ , then  $z = \left(\sqrt{2}^{\sqrt{2}}\right)^{\sqrt{2}} = \sqrt{2}^2 = 2$  is rational.

Constructively the problem with this is that, having "proved" the theorem is true, we still do not know how to actually give examples of the numbers  $x$ ,  $y$  and  $z$ . This is rather unsatisfactory and certainly not constructive.

### 9.5.2. Brouwer's criticism

Brouwer said that mathematics was essentially something that people carried out in their minds. He saw mathematics as the activity of building mental models and finding relationships between them. Formalism, under his reading, is not a part of mathematics itself; however, since we like to communicate our mathematics to other people we need to express it in some precise language, hence the formalisms that have been developed.

Brouwer also saw as basic the idea of a unit and the idea of putting units together, from which we get the basic notion of counting and so the natural numbers. This analysis also immediately yields the idea of mathematical induction. This is in contrast to Frege's development of the natural numbers from purely logical principles.

However Brouwer rejected the idea of the law of the excluded middle and the validity of non-constructive existence proofs. He believed that the problem that was at the root of the set theoretic paradoxes was that classical logic was generalized from the logic that is behind finite sets. This is what mathematics essentially dealt with until the work of Cantor, Dedekind and others, who introduced the idea of infinite sets as completed objects. It then seems as though people eventually forgot or ignored this development from the finite and used this actually rather restricted logic on sets in general. This misuse was what gave rise to the paradoxes.

### 9.5.3. Formalization of intuitionistic mathematics

The first formal system for the logical part of intuitionistic mathematics was presented in 1930 by Heyting. (A more readable, to a non-German reader, presentation is in (Heyting, 1956)). He gave an interpretation of the connectives which forms the basis of the system that we shall talk about below. The interpretation is as follows:

$S \wedge T$  can be asserted iff both  $S$  and  $T$  can be asserted.

$S \vee T$  can be asserted iff at least one of  $S$  and  $T$  can be asserted.

$\neg S$  can be asserted iff we have a method which, supposing we have constructed a proof of  $S$ , would when applied to the proof for  $S$  lead to a contradiction.

$S \rightarrow T$  can be asserted iff we have a method which when applied to a proof for  $S$  will give a proof for  $T$ .

$(\forall x)S(x)$ , with  $x$  ranging over  $\mathcal{T}$ , can be asserted iff we have a method which, for any element  $a$  from  $\mathcal{T}$ , gives a method for constructing a proof of  $S(a)$ .

$(\exists x)S(x)$  can be asserted iff we can construct an element  $a$  and a proof of  $S(a)$ .

Logical schemas, i.e. formulae with sentence variables, can be asserted iff we have a method which by specialization gives a method for constructing a proof for the formula with any propositions substituted for the variables. For example, we have  $S \rightarrow S$  since the "identity method" trivially can be specialized to provide a proof of this formula with any proposition in place of  $S$ .

We can see how this explanation shows that the excluded middle,  $S \vee \neg S$ , is not valid. If it were valid then it would give a general method to solve any problem. That is, for any proposition  $S$  the general method would specialize to give either a proof of  $S$  or a proof of  $\neg S$ . Since such a general method does not exist, the law is not valid.

Heyting actually gave his logic as a formal system. It consisted of ten axioms together with the usual rules of deduction, i.e. modus ponens and instantiation.

### 9.5.4. The link between proofs and programs

The connection between intuitionistic mathematics and programming comes via the propositions-as-types principle. This, as its name suggests, says that propositions and types (in the logical and programming senses respectively) are equivalent. In this section we go on to look at how the ideas above have more recently been brought together.

Basically, we use Heyting's definitions of the logical constants, so we have things like (where  $\mathcal{P}$  maps propositions to their proofs)

$$\mathcal{P}(S \sqcap T) = \{(a,b) \mid a \sqcap \mathcal{P}(S) \text{ and } b \sqcap \mathcal{P}(T)\} = \mathcal{P}(S) \times \mathcal{P}(T)$$

$$\mathcal{P}(S \sqcup T) = \{i(a) \mid a \sqcap \mathcal{P}(S)\} \sqcup \{j(b) \mid b \sqcap \mathcal{P}(T)\} = \mathcal{P}(S) + \mathcal{P}(T)$$

$$\mathcal{P}(S \rightarrow T) = \{\lambda x.b \mid \text{if } a \sqcap \mathcal{P}(S) \text{ then } b(a) \sqcap \mathcal{P}(T)\} = \mathcal{P}(S) \rightarrow \mathcal{P}(T)$$

and so on. We see here that the witnesses to the truth of a proposition are made explicit and shown as terms, like (a,b) as the proof of  $S \sqcap T$ , which we write

$$(a,b) : S \sqcap T$$

When we read this as a type we have

$$(a,b) : S \times T$$

just as in SML. So, the third term in each of the lines above, i.e.  $\mathcal{P}(S) \times \mathcal{P}(T)$  etc., uses an interpretation that we would expect to see if we remember that we are looking for a link between propositions and types. Thus, we see that the above semantics introduces all our favourite data-type constructors like  $\times$ ,  $+$ , function space etc.

The quantifiers, when thinking of propositions as types, are modelled by the operators  $\sqcap$  and  $\Sigma$ , universal and existential respectively. These operators can be thought of as acting like quantifiers ranging over some type, i.e. instead of saying "For all x,  $\mathcal{T}(x)$ " we say "For all x in  $S$ ,  $\mathcal{T}(x)$ ". Extending the definitions above we get (and following Heyting again):

$$\mathcal{P}(\sqcap x \sqcap S)\mathcal{T}(x) = \{\lambda x.b(x) \mid \text{if } a \sqcap \mathcal{P}(S) \text{ then } b(a) \sqcap \mathcal{P}(\mathcal{T}(a))\} = \sqcap(\mathcal{P}(S), \mathcal{P}(T))$$

$$\mathcal{P}(\Sigma x \sqcap S)\mathcal{T}(x) = \{(a,b(a)) \mid a \sqcap \mathcal{P}(S) \text{ and } b(a) \sqcap \mathcal{P}(\mathcal{T}(a))\} = \Sigma(\mathcal{P}(S), \mathcal{P}(T))$$

The final gloss we add is to interpret propositions not only as types but also as specifications. The reason that we can do this is that the type language is so rich, far richer than with SML for instance. As we shall see this means that we now have a single language in which to specify and construct programs.



and we can see how this fits with the definition that Heyting gave to  $\rightarrow$ ; if  $a$  is a proof witness of  $S$  then applying  $\lambda((x)x)$  to  $a$  gives  $a$  back, which is a proof witness of  $S$ , so  $\lambda((x)x)$  is properly a proof witness of  $S \rightarrow S$ . We see here a simple example of a proof witness being a program, i.e.  $\lambda((x)x)$  is the program for the identity function.

The inputs and outputs, so to speak, of the rules are known as judgements. So, above  $(x)x(x) : S [x : S]$  and  $\lambda((x)x) : S \rightarrow S$  are judgements. The first, since it depends upon another judgement, is called a hypothetical judgement. There are four readings of the judgement form  $a : S$  which are:

- i)  $a$  is a proof witness of proposition  $A$
- ii)  $a$  is an object of type  $A$
- iii)  $a$  is an element of the set  $A$
- iv)  $a$  is a program that satisfies  $A$  (as a specification).

The first two express the idea of propositions-as-types. The third one can be seen as a reading of the first if we consider that, thought of as a set, the elements of a proposition are its proofs. The final reading is a more suggestive version of the second made possible because of the computational nature of proofs and the very expressive types.

Apart from logical rules such as these we also have the natural numbers as a basic type. If we think of the type  $\mathbb{N}$  to be "logically" the predicate "there is a natural number" then we usually have

$$N(0) \quad \frac{N(x)}{\lambda N(\text{succ}(x))}$$

which we have in the formal system as

$$0 : \mathbb{N} \quad \frac{x \in \mathbb{N}}{\text{succ}(x) \in \mathbb{N}}$$

We also have mathematical induction:

$$[P(0) \wedge (\forall k)(P(k) \rightarrow P(\text{succ}(k)))] \rightarrow (\forall x)P(x)$$

which becomes

$$\frac{n \in \mathbb{N} \rightarrow \text{rec}(0, d, e) \in \mathbb{N} \rightarrow \text{rec}(\text{succ}(a), d, e) \in \mathbb{N}, \text{rec}(a, d, e) \in \mathbb{N}}{\text{rec}(n, d, e) \in \mathbb{N}}$$

Here  $\text{rec}(n, d, e)$  is an example of a non-canonical expression, i.e. an expression which can be evaluated or converted into a simpler (more canonical) form. In this case, as you would expect with "rec" denoting primitive recursion, we have (with  $\gg$  denoting "converts to")

$$\begin{aligned} \text{rec}(0, d, e) &\gg d \\ \text{rec}(\text{succ}(a), d, e) &\gg e(a, \text{rec}(a, d, e)) \end{aligned}$$

For example, if we put  $d \equiv 0$  and  $e \equiv (x, y)\text{succ}(y)$  then we have

$$\text{rec}(0, d, e) \gg d \equiv 0$$

and

$$\begin{aligned} \text{rec}(\text{succ}(0), d, e) &\gg \\ (x, y)\text{succ}(y)(0, \text{rec}(0, d, e)) &\equiv \\ \text{succ}(\text{rec}(0, d, e)) &\gg \\ \text{succ}(d) &\equiv \\ \text{succ}(0) & \end{aligned}$$

In fact we can show that  $(n, m)\text{rec}(n, m, (x, y)\text{succ}(y))$  behaves like addition.

### 9.5.6. Algorithm development - A sorting example

The formal system very briefly introduced above was developed by Martin-Löf (1985) and is called, variously, ITT, for Intuitionistic Type Theory, or CST, for Constructive Set Theory. Algorithm development in ITT consists of writing a specification (which will look like what may be viewed as a typed predicate calculus sentence) for a task and then, considering the specification as a type, demonstrating that the type is non-empty. If the demonstration is successful then an object of the appropriate type (equally a program that satisfies the specification, equally a proof that the statement of the, as we are reading it, typed predicate calculus sentence is true) will have been constructed.

In the course of proving the sentence it will probably, for all but the most trivial cases, be necessary to have many theorems about the objects that are mentioned. Some of these theorems will be about basic objects and will, hence, already be available since basic objects are defined by stating some of their properties (specifically, how to construct them and how to prove two objects equal).

For derived objects, i.e. objects which are not basic, the fact that they exist means that we have some sentences which describe some of their properties. Indeed, the activity of programming in ITT must be viewed as the construction of a hierarchy of objects, each with various theorems describing them, such that more complex derived objects are built from simpler ones.

So, when we start to develop an algorithm, we must assume that we are working in an environment where various properties of various objects are known, either by being basic properties or because, at some previous time, we have demonstrated that various derived objects have these properties.

The first task is to write down the specification for the program to be developed. In English we might express the specification of an algorithm to sort lists of natural numbers as

"write a program which, for any list  $x$  of natural numbers, gives a list  $l$  of natural numbers such that  $l$  is a permutation of  $x$  and  $l$  is ordered".

In ITT we would say that we must prove that the type

$$\square (\text{List}(\mathbb{N}), (x) \Sigma (\text{List}(\mathbb{N}), (l) (\text{Perm}(x, l) \square \text{Ordered}(l)))) \quad (1)$$

is not empty, and we do that by constructing an object of that type. This object will then be, under the alternative reading, a program which satisfies the specification. It turns out, as you may have guessed, that since this construction process is to be carried out entirely within this formal system it is a long and complicated process. There are many research level projects currently being carried out whose aim is to transfer more and more of the burden of these formal constructions onto programming systems so as to allow a programmer more freedom to think and provide the inspiration needed to make the constructions possible. For this reason, i.e. that the constructions are hard and also, in all their detail, unpleasant to look at, we shall only go as far as presenting the development of a type, or specification, for a sorting algorithm and the first simple steps in the construction of a program.

Before we can carry on with our construction, we must know what Perm and Ordered are. Ordered should be provable of a list  $x$  if either  $x$  is nil or  $x$  is a singleton or its first two elements are in order and its tail is ordered, which we write (using  $\equiv$  for definitional equality)

$$\text{Ordered} \equiv (l) \text{listrec}(l, \text{True}, (x, y, z) \text{listrec}(y, \text{True}, (x', y', z') ((x \leq x' =_{\mathbb{B}} \text{true}) \square z)))$$

To see how the English and the definition match up first note that we have

$$\text{listrec}(\text{nil}, a, (x, y, z)c(x, y, z)) = a$$

and

$$\text{listrec}(b.l, a, (x, y, z)c(x, y, z)) = c(b, l, \text{listrec}(l, a, (x, y, z)c(x, y, z)))$$

where  $.$  is infix cons.

The type True has only one element, i.e.

$$\text{True} \equiv \{\text{it}\}$$

and is trivially non-empty since the property that defines it is

$$\text{it} : \text{True}$$

i.e. the sentence True is trivially always provable. Thus, in the definition of Ordered above we are stating that Ordered(nil) is simply the type True and thus

$$\text{it} : \text{Ordered}(\text{nil})$$

so Ordered(nil) is true.

By repeatedly applying the listrec we have

$$\text{Ordered}(\text{nil}) = \text{True}$$

$$\text{Ordered}(a.\text{nil}) = \text{True}$$

$$\text{Ordered}(a.(b.c)) = (a \leq b) =_{\mathbf{B}} \text{true} \square \text{Ordered}(b.c)$$

where the type B (for Boolean) is another enumerated type such that

$$\mathbf{B} \equiv \{\text{false}, \text{true}\}$$

Similarly, we define Perm by

$$\text{Perm} \equiv (a, b)(\text{listrec}(a, \text{True}, (x, y, z)(\text{occurrencesof}(x, a) =_{\mathbf{N}} \text{occurrencesof}(x, b) \square z) \square \text{len}(a) =_{\mathbf{N}} \text{len}(b)))$$

As with our previous natural deduction derivations from chapter six, a good, overall strategy is to work in a goal directed fashion, bottom-up. So, given that (1) needs to appear at the root of a derivation we need to find a rule which has a judgement of the form

$$e : \Box(A, B)$$

as its conclusion. Such a rule is called  $\Box$ -intro and has the form

$$\frac{b(x) \Box \Box(x) \Box \Box(A)}{\Box((x)b) \Box \Box(A, B)}$$

so our first step is to write the root of the derivation as, where  $b$  is to be discovered as the derivation proceeds,

$$\frac{b(x) \Box \Box(\text{List}(N), (l)(\text{Perm}(x, l) \Box \text{Ordered}(l))) \Box \Box \Box \text{List}(N)}{\Box((x)b) \Box \Box(\text{List}(N), (x) \Box (\text{List}(N), (l)(\text{Perm}(x, l) \Box \text{Ordered}(l))))}$$

Now we have reached the stage where the construction starts to get very detailed and difficult and the reader should note that this section forms the basis of the more detailed introduction in Reeves (1989). As we said before, we have to leave the development here and allow the interested reader to follow the references given earlier on their own.

## Summary

- We have seen four methods of deciding validity in predicate calculus, namely axiom systems, semantic tableaux, natural deduction (or sequent calculus) and resolution. All these methods are logically equivalent but they differ substantially when viewed as algorithms for practical implementation. 'State of the art' at the time of writing (i.e. 1990) is the *connection method* which can be viewed as an efficient development of the tableau method that avoids explicit and wasteful duplication of sub-formulas and branches. (Added in 2003: there has been a great upsurge in interest in tableaux methods too over the last ten years, which is very heartening.)

- The basic reason why fully automatic theorem-proving is currently too slow to be practical is that it is difficult, in a fully automatic uniform procedure that doesn't know the meaning of the formulas it is manipulating, to control the size of the search space. Currently the most successful systems for using logic to reason about programs are *interactive*. Both partners do the part they are good at. The machine does the book-keeping and checks that the rules are correctly applied; the person interacting with it chooses what to do next on the basis of understanding and experience of the domain. The LCF system described in this chapter goes further than this. Based on natural deduction, it not only does the basic book-keeping when rules are applied but also allows general-purpose proof techniques, such as working backwards, to be used, and simple strategies to be combined together into more complex ones.

- One important application of modal logic is in *temporal reasoning*. For example, in reasoning about the execution of concurrent programs, the possible worlds are different states of a computation at different points in time and the accessibility relation represents the ordering of time points. The modalities are used to *tense* statements, for example  $F S$  is true if  $S$  is true at some future time.

- Another application of the ideas of modal logic in computer science is *dynamic logic*. Here the possible worlds are different states of a computation and the accessibility relation represents the program which determines, for each state, the state that succeeds it. The  $\Box$  of modal logic now depends on the program  $\square$  and is written  $[\square]$ .  $[\square] S$  is true in state  $s$  if  $S$  is true in the state that results when  $\square$  is executed in state  $s$ . Dynamic logic is expressive enough to represent many programming constructions such as 'if...then...else'.

- Intuitionistic logic arose out of the constructivist movement in mathematics which rejected non-constructive existence proofs or those based on the law of the excluded middle. Recently a connection between intuitionistic mathematics and programming has come out of the observation that propositions and types (in the programming sense) are equivalent. Algorithm development in this formal system, which is based on natural deduction, consists of writing a specification in logical notation and then, considering this as a type, proving that it is non-empty. Because the underlying logic is constructive the proof, if it can be carried out, must embody the explicit construction of an object of the appropriate type.

# APPENDIX A

---

## Introductions to Standard ML and Prolog

### A.1. Introduction

In this appendix we will describe and present programs in Standard ML and Prolog for the various algorithms introduced in the body of the book and for those asked for in answers to exercises.

We begin with a brief run through the basic features of SML and Prolog, so that the reader who is fairly familiar with these languages may understand the programs that we present. For those of our readers who are not familiar with either of these languages we would recommend the texts by Wikström (1987) and Bratko (1987) as excellent introductions to SML and Prolog respectively.

### A.2. Standard ML

#### A.2.1. *Simple values*

A program in Standard ML (hereafter SML) is a sequence of declarations which are always read from top to bottom and left to right. Each declaration refers to and updates a value environment, which is a function which maps names to values. The simplest form that such a declaration can take is to associate a name with a basic value, like an integer:

```
val n = 2;
```

This declaration associates the name `n` with the value of 2, the association being recorded in the environment. When this declaration is presented to the SML implementation it not only updates the environment but its type is also calculated, printed and added to a type environment, which maps names to types. So, having checked that the above declaration is well-formed, i.e. conforms to the grammar of SML, the implementation prints some type information; in this case we have

```
val n = 2 : int
```

which tells us that `n` is associated with the value of 2 in the value environment and the type of '`n`' is '`int`', i.e. `n` is associated with the type '`int`' in the type environment.

There is a particular form of declaration which looks as though it should be called something like 'expression'. For example

```
2;
```

is of this form. In fact any input of this form is treated by SML as a declaration of the hidden name '`it`'. This name is a standard one that exists in every environment and any input like the one above is taken to be an abbreviation of the declaration

```
val it = 2;
```

or more generally

```
val it = EXP
```

where `EXP` is any SML expression.

### A.2.2. Function values

As well as simple values of the types of `int`, `string`, `bool` and so on we have values of function type. For instance, we can define a successor function `s` by

```
fun s(x) = x+1;
```

Again, the environment is updated so that the name `s` is associated with a value; in this case the value is the function which adds one to its single argument. Given the above declaration the interpreter will return

```
val s = fn : int -> int
```

i.e. that `s` is a function of type integer to integer, as we would expect. Note that instead of writing out the value of `s` the interpreter writes just `fn`.

The language SML is known as a strict language. This means that the arguments to any function are evaluated before the body of the function is executed. This means, for instance, that if one of the arguments is undefined then the whole function is undefined *whether or not the argument is used in the body of the function*. To see the difference consider the function `s` again and imagine applying it the expression `1 div 0`. As we would hope, the evaluation of the expression `s (1 div 0)` fails, but this would have happened even in a language that was not strict. However, now consider applying the function defined by

```
fun t x = 2;
```

to `1 div 0`. In SML the expression `t(1 div 0)` is also undefined, even though the argument is unused in the body of `t`, proving that SML is strict. In a non-strict language, where the arguments to a function are evaluated only if they are needed in its body, the expression would have evaluated to 2.

While we are talking about the notion of an expression being undefined we should say something about how this is handled in SML. If you try to evaluate `1 div 0` then you will get the message

```
Failure: div
```

from the interpreter, which means, as we expected, that the evaluation of the function `div` for this pair of arguments has failed. In the jargon on SML we say that an exception has been raised. As a first approximation to how this system works we can assume that if we are evaluating an expression and an exception is raised then the evaluation fails and the exception is passed to the enclosing expression. If the enclosing expression cannot do anything with the exception then it is passed to the next enclosing expression and so on. Eventually the exception will reach the outer level and at this point the interpreter forms the message that we have just seen above.

In SML we do not have to rely just on exceptions from system defined functions; the user can define exceptions too. For instance we may want to fail in the evaluation of a function if the value that is given as its argument is, in some way, too big. We would first declare the exception, say `large`, and then raise it at the appropriate point in the function

```
exception large;  
fun test n = if n > 10000 then raise large else n div 5;
```

which would give values like

```
test 6;  
1 : int  
test 12000;  
Failure: large
```

In fact exceptions can be used in far more sensitive ways than the simple one shown here, but this is something we must leave the reader to learn from the recommended books.

This simple example of the definition of `s` also shows an important feature of SML, namely that of type inference. This is the mechanism by which the interpreter, in the example above, was able to calculate the type of the function `s`. The reasoning was as follows: assume the type of `x` is unconstrained. Then, we see that `x` is involved in an addition and one of the values in the addition is `1` which has type `int`. Therefore, for the expression to type correctly the other value in the addition must have the type `int` too. Since `int` is one of the types that `x` can have, because its type is unconstrained, we can consistently type the whole expression to give the answer as above.

These definitions using `fun` can also be recursive, so that the declaration

```
fun t x = if x > 0 then t (x-1) else 1;
```

would result in the environment being updated so that `t` was associated with the function of one argument that always has value one.

SML has a way of writing such a function which can be thought of as SML's way of writing  $\lambda$ -expressions which some of our readers may have come across. Where we might write  $\lambda x. \lambda y. x+y$  ordinarily we can write

```
fn x => fn y => x+y
```

in SML. So, if we write the declaration

```
val f = fn x => fn y => x+y;
```

then `f` has the value denoted by  $\lambda x. \lambda y. x+y$  and so is, of course, equivalent in meaning to writing

```
fun f x y = x+y;
```

and our function `t` above can also be defined by

```
val t = fn x => 1;
```

Functions are treated as 'first-class citizens' in SML. That is, they, like any other type of value, can be taken as argument and given as result by functions. So, it makes perfect sense to have the declarations

```
fun s x = x+1;
fun twice f y = f(f(y));
```

The interpreter will write

```
val s = fn : int -> int
val twice = fn : ('a -> 'a) -> 'a -> 'a
```

which means that the environment is updated so that `s` refers to the successor function and `twice` refers to a function which takes a unary function of any type `'a` (where `'a` can be thought of as a type variable, i.e. an expression that can stand for any type) and a value of type `'a` and returns the result, also of type `'a`, of applying the function `twice` to the argument in the obvious way. This example also introduces

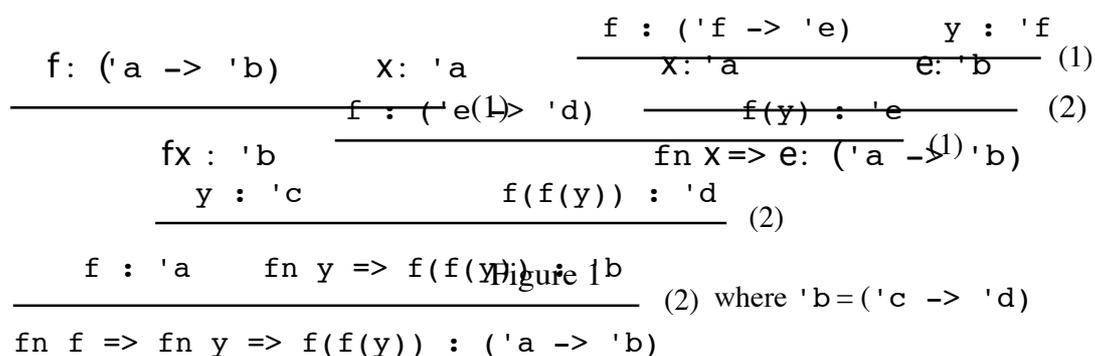


Figure 2

the idea of polymorphic types, i.e. types which contain variables and, hence, can themselves stand for a range of types. So, since `s` has type `int -> int`, it can properly have `twice` applied to it, because the type of `s` and the type of the first argument of `twice` can be unified, i.e. there is a substitution of the type variable 'a that makes it the same as the type of `s`. The result of making the declaration

```
twice s;
```

is to associate `it` with the function which when applied to `x` has `s(s(x))` as value, i.e. the same value as the value of `fn x => s(s(x))`, and to write

```
fn : int -> int
```

i.e. to give the type of `twice s`.

As something of a digression we will present some rules for finding such types. These rules will be in a natural deduction style but with objects and their types in the place of propositions.

If we write `f : t` to mean the object `f` has type `t` then we have two rules as shown in figure 1. Now, we can use these rules to work out the value of `twice` in the following way. First, we remember that `twice` can also be defined by

```
val twice = fn f => fn y => f(f(y));
```

First, we do a piece of "rough working" where we leave types as unconstrained as possible but where the rules (1) and (2) are obeyed. Here 'a, 'b, 'c, 'd, 'e, 'f are type variables and the working is shown in figure 2.

To make this a proper derivation we need to make sure that we have the same type for all occurrences of  $f$  and all occurrences of  $y$ . For this to happen we need  $'a$  to match with  $'e \rightarrow 'd$  and with  $'f \rightarrow 'e$ .

This means that we have  $'d = 'e = 'f$ . Also we need  $'c$  to match with  $'f$ , so  $'c = 'f$ . This in turn means that  $'a = 'e \rightarrow 'e$  and  $'b = 'c \rightarrow 'd = 'e \rightarrow 'e$ . Then figure 3 shows a proper derivation of the type of `twice` which, up to a consistent renaming of type variables, is as we expected.

This use of polymorphic types does carry some overhead in the sense that the programmer has to be careful to disambiguate contexts when necessary otherwise type inference may not succeed. For instance if we made the declaration

```
fun g x = x*x;
```

then, since  $*$  is overloaded, this definition is ambiguous, for we cannot tell whether the operation to be carried out is, say, multiplication of `reals` or of `ints`, which are, of course, very different operations. (To see this consider the fact that in real multiplication there are extra rules about where the decimal point goes which integer multiplication does not have.) The interpreter will respond to this declaration with a message saying that it cannot decide on the type of the  $*$  and the declaration will fail. This problem can be overcome by the use of type tags which convey type information to the interpreter. For instance, we can disambiguate the attempted declaration above by writing

$$\begin{array}{c}
 \frac{f : ('e \rightarrow 'e) \quad y : 'e}{(1)} \\
 \frac{f : ('e \rightarrow 'e) \quad f(y) : 'e}{(1)} \\
 \frac{y : 'e \quad f(f(y)) : 'e}{(2)} \\
 \frac{f : ('e \rightarrow 'e) \quad \text{fn } y \Rightarrow f(f(y)) : ('e \rightarrow 'e)}{(2)} \\
 \text{fn } f \Rightarrow \text{fn } y \Rightarrow f(f(y)) : (('e \rightarrow 'e) \rightarrow 'e \rightarrow 'e)
 \end{array}$$

Figure 3

```
fun g (x:real) = x*x;
```

to get the response

```
fun g = _ : real -> real
```

as expected. We could have got the declaration to work by tagging the result type of the function, rather than its argument type, by writing

```
fun (g x):real = x*x;
```

or we could also have written

```
fun g x = (x:real)*x;
```

It is sometimes more usual to think of certain functions as being *infix*, that is written between their arguments. We can arrange for this in SML by using the `infix` directive, which tells the interpreter that the function named is going to be used in an infix fashion. We would write

```
infix plus;
fun x plus y :int = x+y;
2 plus 3;
```

to get the required effect.

### A.2.3. Datatypes

The next idea in SML that the reader needs to understand, to allow them to have some idea of the meaning of the SML programs given in this book, is that of datatype declarations.

We can think of a datatype declaration as describing a way of making a new type from a mixture of old types and, since they can be recursive, from the new type itself. For instance, if a term could be either a string or a term applied to a term we would write

```
datatype term = var of string | app of term*term;
```

and this would introduce two new values, called constructors, named `var` and `app` above, which take a string and a pair of terms, respectively, and give a term. So, if we have the string `"abc"` then it can be made into a term using the constructor `var` to get `var "abc"`. Then, having the term `var "abc"` we can make another term using `app` to get `app(var "abc", var "abc")`.

In the parser for propositional calculus, which we present completely later, we have the following datatype, which you should now be able to understand:

```
datatype SENT = Prop of string |
              Not of SENT |
              And of (SENT * SENT) |
              Or of (SENT * SENT) |
              Imp of (SENT * SENT) |
              Eq of (SENT * SENT);
```

Having constructors to form new types not only makes it easier to uniformly build up quite complicated types, but it allows the introduction of a technique which makes it easier to define functions which work on such types using the idea of matching. Imagine that we have the datatype `term` as introduced above and, for some reason, we wish to recover the components that go to make up the values of type `term`. We can do this by defining a function which systematically works through all the possible forms of values of type `term` and describes an operation for each such form. So, since we have two possible forms of values of type `term`, namely `var s` and `app(t1, t2)`, `s` is a string and `t1` and `t2` are of type `term`, we have two clauses in the function definition:

```
fun parts (var s) = [s]
  | parts (app(t1,t2)) = [parts t1, parts t2];
```

The first clause tells us that if the argument has the form `var s` then its parts are just the string `s` which it returns in a list. However, if the argument is in the form of an application involving `t1` and `t2` then the list of parts returned is calculated by finding, in turn, the parts of `t1` and `t2`. This form of definition at once makes it clear what to do with each form of `term` and allows us to see that we have looked at all possibilities, since we have two parts to the definition of `term` and two clauses in the function `parts`. To complete this idea we also need to know that a variable matches anything and a constant matches only itself.

This technique is used heavily in the programs in this book since we are mainly taking sentences or formulas or terms in logical languages and manipulating them, which means breaking them into their component parts and re-building these parts into other terms. The function `decide` given in chapter two is probably the simplest example of this sort of operation.

#### *A.2.4. Other forms of expression*

As well as the forms of expression and declaration that we have introduced so far there are others, most of which you probably expected to see and whose meaning is likely to be obvious to you. Probably the most common expression used is the `if-then-else` form. So, we would use it in definitions like

```
fun fact n = if n=0 then 1 else n*(fact (n-1));
```

Of course in this case we could have used the matching mechanism to define the same function as in

```
fun fact 0 = 1
  | fact n = n*(fact(n-1));
```

The choice between these two forms is largely one of style, but the latter can be useful with more complicated types to ensure that all possibilities of argument form have been taken into account, as we said before.

There is a restriction on the typing of the conditional expression, and that is that both "arms" of the conditional must have the same type. So the expression

```
if true then 1 else 2.0;
```

would not be allowed by the interpreter because the "true" arm gives a value of type `int` and the other arm a value of type `real`. Since these two types are mutually exclusive the expression has no type and is rejected.

We said above that SML is strict, but the conditional expressions and boolean expressions are an exception to this. So, when evaluating

```
if true then 1.0 else (1.0/0.0);
```

the interpreter gives the value 1.0 rather than an error, as it would if the expression were thought of as the "function" `if-then-else` being applied to the arguments `true`, `1.0` and `(1.0/0.0)`. So, the rule is that the boolean test is first evaluated and then the appropriate arm, the other arm being discarded. Also, boolean expressions are treated in a similar way so we should consider, for instance, the definition of the function `andalso` to be

```
infix andalso;
fun x andalso y = if x then y else false;
```

so the value of

```
false andalso ((1.0/0.0)= 0.0);
```

is `false` rather than undefined.

Remember that declarations are read from top to bottom and a name must be defined before it is used. This means that a definition that is mutually recursive, i.e. one in which, say, two functions are defined, each referring to the other, does not seem to be allowable. This is overcome by the use of the `and` construct for combining declarations. So, whereas

```
fun f x = if x=0 then 1 else g (x-1);
fun g x = if x=0 then 0 else f (x-1);
```

would lead to a message from the interpreter to the effect that `g` is undefined in the definition of `f`, we can make the declaration work by writing

```
fun f x = if x=0 then 1 else g (x-1)
and g x = if x=0 then 0 else f (x-1);
```

We use this construct a great deal in the programs in this book, especially for the parser, which contains many definitions that are mutually recursive.

A further addition to forms of expression is provided by the "let-in-end" form. This allows definitions to be made locally, which enhances the modularity of programs and can make them much more efficient. For instance, we might write

```

fun f y x z =
  if y = 2*(x div z) then 3*(x div z) else 0;

```

but the same effect, as far as the definition of `f` is concerned, would be produced by writing

```

fun f y x z = let val u = x div z in
  if y = 2*u
  then 3*u
  else 0
end;

```

Here, `u` is not defined either before or after the declaration of `f` and so reference to it is a mistake. The advantage is that `x div z` is computed only once, whereas originally it had to be computed twice. Clearly, with very much more complicated repeated computations, the use of this mechanism can save a lot of computing effort. Another reason for using this construct is for enhancing modularity, i.e. the property of programs that makes them separable into independent parts. This means that different programmers can work on the parts of a program without fear of creating mistakes or ambiguities. For instance, a programmer working on a part of a program might have used the name `x` to refer to some value and another programmer working on a different part might have used `x` to refer to something different, and the effect of combining these two parts might not be what was intended. So, this construct can be used to hide names that are purely local to particular declarations, especially when there is no need for them to be available anywhere else.

We can also use local declarations in other declarations by using the "local-in-end" form, as in

```

local fun (g x):int = x*x in
  fun f a b c = ((g a)*(g b)*(g c) div 2)
end;

```

or in

```

local val e = 2 div 3 in val y = e*e end;

```

which again can enhance modularity (and readability) and also improve efficiency.

### A.2.5. Lists

Lists form a pre-defined type in SML. Lists are formed by using the constructors `nil`, which is the empty list, and `::`, which is a function from elements and lists to lists, also known as "cons". Both these constructors are polymorphic, with the proviso that all the elements of a list must have the same type. For instance we can form lists of `ints` like

```
1::(2::(3::nil));
```

or of `strings` like

```
"a"::("b"::("c"::("d"::nil)));
```

or of lists of `bools` like

```
(true::nil)::((false::nil)::nil);
```

and these expression would be type as `int list`, `string list` and `(bool list) list` respectively. If you try evaluating these expressions using an SML interpreter you will find, however, that the value printed is not in the same form as given above. In fact, the responses will show the lists as

```
[1,2,3]
["a","b","c"]
[[true],[false]]
```

and this is because there is a shorthand way of writing lists which means that `nil` becomes `[]` and `e::nil` becomes `[e]` etc.

We can define functions over lists either by using the matching mechanism or by using the "if-then-else" expression. For instance, we can define the function which gives the length of a list over any type as

```
fun length(a::l) = if l=nil then 1 else 1+(length
l);
```

or as

```
fun length nil = 0
  | length (a::l) = 1+(length l);
```

or as

```
fun length (a::nil) = 1
  | length (a::l) = 1+(length l);
```

and each of these functions will have type

```
('a list) -> int
```

The question of which of these definitions is "best" is hard to answer but the second will pass the interpreter without comment whilst the first and third will provoke a message like

```
***Warning: Patterns in Match not exhaustive
```

which means that there is the possibility that the writer has not given a value of the function for all possible forms of the argument. The reason that the interpreter does not give this warning for the second declaration is that we should imagine the type `'a list` as defined by

```
infix ::;
datatype 'a list = nil | op :: of ('a * 'a list);
```

So as far as the interpreter is concerned there are two forms which define lists: either `nil` alone or an expression like `e1::e2`. As you can see the first and third declarations for `length` do not mention both of these forms and so the interpreter gives a warning just in case you did not mean to leave out some possible forms. In fact we can see that in the first and third examples the functions are not defined for lists which are `nil`, which may be a mistake.

Two functions that are very commonly applied to lists are `map` and `append`, denoted by `@` in SML. The idea of `map` is to encapsulate the operation of "doing the same thing to all elements of a list". For instance, we may have a list of `ints` and want to square them all. A function to do this, called `squarelist`, might be

```
fun squarelist nil = nil
```

```
| squarelist ((n:int)::l) = (n*n)::(squarelist l);
```

We can make this declaration look a bit more general by taking the squaring part and using a local declaration for it

```
local fun square (n:int) = n*n in
  fun squarelist nil = nil
    | squarelist (n::l) = (square n)::(squarelist l)
end;
```

Now consider a function that takes a list of booleans and negates each of them

```
local fun negate b = if b then false else true in
  fun negatelist nil = nil
    | negatelist (b::l) = (negate b)::(negatelist
l)
end;
```

If you compare these two definitions a pattern becomes clear. They are both of the form

```
local fun f x = <some expression> in
  fun g nil = nil
    | g (x::y) = (f x)::(g y)
end;
```

This is still not as general a form as is possible though. The auxiliary function *f* above is only used in the declaration of *g*, but if we make the auxiliary function an argument of *g* then *g* is more generally usable. So, we now have

```
fun g f nil = nil
  | g f (x::y) = (f x)::(g y);
```

and the two functions we had before can be defined by

```
fun squarelist l = g (fn (n:int)=>n*n) l;
```

```
fun negatelist l = g (fn b=>if b then false else true)
l;
```

Since this function that we have called `g` turns out to be so useful it is already defined within the SML interpreter and is the function called `map`. The other function is `@` which can be thought of as defined by

```
infix @;
fun nil @ m = m
  | (a::l) @ m = a::(l @ m);
```

and simply takes two lists, of the same base type, and joins the left one to the right one keeping the same order between the elements.

Armed with these basic functions you should now be able to understand the functions over lists used in the programs in this book, with more or less work. You will see that lists form a very adaptable type which can be used to imitate many different structures and, historically they were used to imitate tree structures. For instance, a binary tree might be imitated by a list of lists, each list denoting a path from the root through the tree. However, in SML we can use the datatype mechanism to represent trees much more directly, and since, via this method, we also have all the typechecking mechanism working for us we can have more confidence in our solutions.

A simple binary tree might be defined by

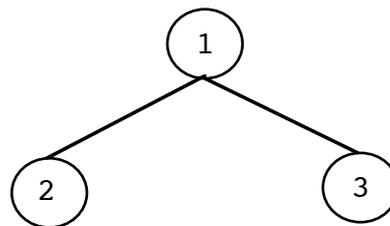
```
datatype bintree = null
  | node of (int * bintree * bintree);
```

which means that examples of values of type `bintree` might be

```
null
node(1,null,null)
node(1,node(2,null,null),node(3,null,null))
```

which might be displayed in two dimensions as

an empty tree



and so on for more complicated shapes of tree. Now we can write functions that manipulate the contents of nodes rather as we did with `map`, the function that manipulated the contents of lists, without changing their structure or shape. (This sort of function, a homomorphism, turns out to be a central notion throughout computer science and logic). A function to square the contents of each node might be `squarenodes` given by

```

fun squarenodes null = null
  | squarenodes (node(n,t1,t2)) =
    node(n*n, squarenodes t1, squarenodes t2);
  
```

and again we can see how the definition of the function follows exactly the structure of the tree. However, just as we did with lists, we can write a more abstract function which does an arbitrary operation, provided as an argument, to all nodes of a tree whilst preserving the tree structure. We call this `maptree` and it is defined by

```

fun maptree f null = null
  | maptree f (node(n,t1,t2)) =
    node(f n, maptree f t1, maptree f t2);
  
```

and using this our first function can be defined by

```

fun squarenodes t = maptree (fn n => n*n) t;
  
```

The other main activity that takes place when we traverse trees is to build new datatypes from their parts. For instance, we may wish to construct a list which contains all the values in the nodes of a value of type `bintree`. Again we need to write a function which takes into account all the possible forms of tree but this time instead of preserving the structure of the tree it produces values from the list datatype. A reasonable definition might be

```

fun getnodes null = []
  | getnodes (node(n,t1,t2)) =
      n::((getnodes t1)@(getnodes t2));

```

and when we apply it to each of the three trees given above we get the values `[]`, `[1]` and `[1,2,3]` respectively.

As a final level of abstraction we can introduce a function which can be specialized to either `maptree` or `getnodes`, even though `maptree` preserves the structure of the tree and `getnodes` constructs something almost completely new. We can do this first by exploiting the structure of the bintree and also by using, quite heavily, the facility with which SML deals with functional parameters. We construct a function which takes two arguments, one which describes the value of the function at values of the form `null` and the other which describes an action for the form `node(n,t1,t2)`. If these arguments are represented by `f` and `s` below then we know that the most information that can be passed to `s` are the three pieces of information that go to make up a node, namely the `int` value `n` and the two subtrees, values of type `bintree`. Since the information for a node which is `null` is fixed the `f` is a constant. Our definition for this most general function, which we name `bintreerec`, for bintree recursion, is

```

fun bintreerec f s null = f
  | bintreerec f s (node(n,t1,t2)) =
      s n (bintreerec f s t1) (bintreerec f s
t2);

```

and using this we can define both `maptree` and `getnodes` by abstracting the appropriate auxiliary function from their definitions which gives us

```

fun maptree g l =
  let val f = null
      fun s n t1 t2 = node(g n,t1,t2)
      in bintreerec f s l end;

```

and

```

fun getnodes l =
  let val f = []
      fun s n t1 t2 = n::(t1@t2)

```

```
in bintreerec f s l end;
```

The use of `bintreerec` gives us even more checks on the correctness of our definitions of functions over `bintrees` because, once `bintreerec` is properly defined, we have much more structure, which the typechecker can use, against which to judge the completeness of our subsequent definitions. This level of abstraction means that a few highly abstract definitions can be given and then specialized as needed to the more basic functions over a given datatype and this means that we, as programmers, have less to remember to check because the typechecker does much of the work for us. This, in turn, means that our programs are much less likely to be wrong and this is the great strength of languages such as SML.

We have introduced some of the main features of SML, but much more remains to be said and the textbooks referred to should be consulted for further details.

### A.3. Prolog

This brief introduction is not intended as a stand-alone course on Prolog programming. The aim is to give sufficient explanation of the language, and relevant programming techniques, for the programs in the text to be used and understood by a reader with some experience of a procedural or functional language such as Pascal, C, Lisp or Miranda. Good books that give a more complete explanation of Prolog and cover a much wider variety of programming tasks are Bratko (1986), Sterling and Shapiro (1986) and the original Clocksin and Mellish (1981).

Prolog is a practical programming language whose theoretical basis lies in the notion of logic programming, an introduction to which is given in chapter seven. Here we are concerned with the pragmatics of using Prolog to carry out calculations in which the objects manipulated are logical formulas. This section will not depend on having read chapter seven, but use of some basic logical terminology, as explained in chapters two and three, is unavoidable.

A Prolog program is a sequence of clauses, which play much the same role as function definitions in a functional language such as Lisp, Miranda and SML, or procedure definitions in Pascal and C. Clauses have a head and a body and are always terminated by a full stop. The head has the form of a logical atom, i.e. it consists of a predicate name followed by zero or more arguments which have the form of logical terms (see chapter three and below). The body is a sequence of zero or more atomic formulas separated by commas and terminated by a full stop. The head

and body are separated by the compound symbol ':' which is omitted if the body is null. The following is an example of a complete Prolog program.

```
p(X):- q(X,Y),r(Y).  
q(a,b).  
q(a,c).  
r(c).
```

Variables in Prolog are denoted by strings beginning with a capital letter or the underline symbol '\_'. All other strings not starting with a capital letter or the '\_' symbol are constants in various categories such as predicate names, data, operators, numbers. Prolog programs can be read in both a declarative (i.e. logical) and a procedural (i.e. operational) way. The declarative reading is ultimately more productive, but the operational reading can be helpful provided one remembers that Prolog 'procedures' are satisfied (by appropriate substitutions for their bound variables) rather than executed. So the first line of the program above can be compared with the definition of a function or procedure  $p$  with formal parameter  $X$ , the  $q(X, Y), r(Y)$  on the right of the ':' symbol being analogous to the statements in the body of the function or procedure. The predicates  $q$  and  $r$  are like procedures with no body and so are analogous to primitive instructions. Many Prolog texts call the first line, that defines  $p(X)$ , a rule and the remaining clauses facts because the latter are unconditionally satisfied.

Declaratively, the first line of the program is read as "For all terms that can be substituted for  $X$ ,  $p(X)$  is satisfied if there is a term that can be substituted for  $Y$  such that both  $q(X, Y)$  and  $r(Y)$  can be satisfied". The second line of the program says that  $q(a, b)$  is unconditionally satisfied. It can be seen that  $p(a)$  can be satisfied because there is a substitution for  $Y$ , namely  $c$ , that enables both  $q(a, Y)$  and  $r(Y)$  to be simultaneously satisfied. Although substituting  $b$  for  $Y$  satisfies  $q(a, Y)$  it doesn't satisfy  $r(Y)$  because there is no clause  $r(b)$  in the program. It should be noted that if, within a clause, a substitution is made for a particular instance of a variable symbol then the substitution is made throughout the clause. So, in first line of the program above, the two occurrences of the variable symbol  $X$  either have the same instantiation or are both uninstantiated, and the same applies to  $Y$ . However, a particular variable symbol denotes different variables in different clauses, in a similar way, for example, to the local variables or formal parameters of a procedure in

Pascal. There are no global variables in Prolog, although we see later that operator definitions can be given global scope.

A Prolog program is used by typing a goal in response to the interpreter's prompt. Following the procedural analogy this is the Prolog equivalent of a procedure call. For example

```
?- p(a).
```

The compound symbol `?-` is the system's prompt and the `p(a).` is input by the user and is a request for the system to check that the formula `p(a)` follows logically from the program clauses. The reply, that `p(a)` does follow logically from the program, is output simply by the system as 'yes'.

Operationally speaking the goal is matched against the heads of all program clauses starting at the top of the program until a match is found, in this case at the first line. The head of the first clause is `p(X)` and `X` is a variable so a substitution can be made for it to enable the match to succeed, in this case by substituting `a` for `X`. Then a similar matching process is carried out on the body of the clause, which is now `q(a, Y), r(Y)`, working from left to right. *Starting again from the top of the program* `q(a, Y)` is matched against the clause heads. It cannot match `p(X)` because the predicate symbol `q` is not the same as `p`. However it matches `q(a, b)` provided `Y` is instantiated to `b`. We now attempt to satisfy `r(b)` *starting again at the top of the program*. This time no match can be found for `r(b)` so we go back to `q(X, Y)` and see if this could be satisfied in a different way. This going back to try other possibilities for goals to be satisfied is called backtracking, and is one of the ways in which Prolog differs radically from other languages, including SML. The matching process for `q(a, Y)` resumes *from the point it previously got to* at `q(a, b)`. Another match is found, this time with `Y` instantiated to `c`, so now we try to satisfy `r(c)` *starting again at the top of the program*. This time the search succeeds, so the original goal `p(a)` succeeds and the system outputs `yes`.

The possibilities become more interesting when goals contain uninstantiated variables. The goal

```
?- p(Answer).
```

can be read as a request for a binding for the variable `Answer` that enables the formula `p(Answer)` to be satisfied. The resulting binding (the output from the

computation) is printed by the system as `Answer=a`. The variable name `Answer` has no particular significance, of course. We use it to emphasise that one is not restricted to the `X,Y,Z,...` of mathematical or logical notation. Any other string starting with a capital or '\_' could have been used.

Operationally the computation is very similar to that described above for `?- p(a)`. The goal `p(Answer)` is matched against the heads of all program clauses starting at the top of the program until a match is found, at the first line in this case. Uninstantiated variables always match and become, in effect, two aliases for the same variable. The body of the matching clause is now `q(Answer,Y), r(Y)` and an attempt is now made to satisfy this, working from left to right. Starting again from the top of the program `q(Answer,Y)` is matched against the clause heads. As before it matches `q(a,b)`, this time with `Answer` instantiated to `a` and `Y` to `b`. But `r(b)` fails and backtracking occurs in the same way as before. Eventually the original goal `p(Answer)` succeeds and the instantiation that enabled it to succeed, namely `Answer=a`, is output.

Chapter seven will show that a Prolog program (or at least most of it) is a formula in a subset of first-order logic, and the interpreter that executes it is a simple-minded theorem-prover. This means that Prolog programs can be understood and reasoned about at a logical level, as well as in the operational style exemplified above. The declarative (logical) reading of Prolog programs is the best one for constructing programs and convincing oneself of their correctness but, because the Prolog interpreter is not a complete theorem-prover for first-order logic, the operational understanding is also necessary for reasoning about completeness and efficiency. The perfect logic programming system has not yet been invented.

In comparison with languages such as Pascal or SML there is no equivalent notion of type in Prolog. The only data structure is the term. A term is either a constant, a variable, or a function symbol followed in brackets by one or more terms. The definition is as it is in chapter three or, less formally, like the notion of expression in mathematics. Prolog is essentially a system for doing calculations in a term algebra. There are several examples below that use terms but, as a simple example here, we can slightly elaborate the program above by replacing the clause `q(a,c)` by `q(f(a),c)`. The output that would then result from satisfying the goal

`?- p(Answer).`

would be  $\text{Answer} = f(a)$ . Note that no type declarations are required to say for example that  $f$  is a function symbol rather than a predicate symbol. The grammatical category of any given symbol in the program is inferred from its position in the program text. In this case  $f$  is a function symbol because a term is expected after the symbols  $q()$ . This is not the same as in logic where you have to say in advance what the function and predicate symbols are.

### *A.3.1. System predicates and unification*

All Prolog systems make available to the programmer a predefined set of predicates and one has to think of the user-defined program as being an extension of these. One of the most important is  $=$ , which can be thought of as being internally defined in every program by the single clause

$X = X.$

Thus with no user-defined program at all, you can input the goal

?-  $a = a.$

and get the output *yes* (because it matches  $X = X.$  with  $X$  as  $a$ ) or

?-  $a = b.$

and get the answer *no* because  $a = b.$  cannot match  $X = X.$  The goal

?-  $Y = a.$

results in the output  $Y = a$  because the goal  $Y = a$  is matched against  $X = X$  and succeeds with  $Y$  instantiated to  $X$  and  $X$  to  $a$ . A more interesting example is

?-  $f(g(Y), h(b)) = f(g(a), Z).$

which gives the output

$Y = a$

$Z = h(b)$

because these are the variable instantiations required to make the left and right hand sides the same, i.e. to make  $X=X$  succeed. This computation of the set of substitutions required to make two terms identical is known as unification and is discussed in more detail in chapter seven. A goal matches a program clause in Prolog if the predicate names are identical and the arguments can be unified pairwise. Note that unification is more general than the matching in functional languages such as SML because in Prolog variables can occur in both sides to be matched. One limitation, though, is that function or predicate symbols in Prolog cannot be variables. Variables stand for terms, not for symbols (remember that a constant is a term).

In this book we are using Prolog to do calculations in a term algebra, with expressions formed from constants, variables and function symbols, so we will now concentrate entirely on this type of application and briefly cover some of the necessary techniques. In particular we want to be able to represent logical formulas and terms, and to take them to pieces in order to examine and operate on their component parts. We also have to carry out calculations with sets and sequences of terms.

### A.3.2. Sets, sequences and lists

It is convenient to represent both sets and sequences as lists. Lists have to be represented in Prolog as terms since that is the only data type but, since manipulating lists is such a common requirement, all Prolog systems provide a special notation to make list programming easier and programs more readable. By convention a special constant `[]` is used to denote the empty list and a special function symbol, the dot `'.'` is used to denote an operator that may already be familiar as the *cons* function of Lisp, i.e. the function that takes a term `T` and a list `L` as arguments and returns the list whose first element is `T` and the rest of which, the so-called tail of the list, is `L`. Thus, by convention in Prolog, one thinks of the term `.(a,.(b,[],))` as denoting the list whose head is `a` and whose tail is the list consisting of the single element `b`. To make programs more readable the notation `[a,b]` is allowed for this but it should be emphasised that this is only for readability. There are no special "list processing facilities" or "list structures" in Prolog. The only data type is the term.

A basic operation in many computations is a test for set membership. Again we have to choose some way of representing sets by terms. One possibility is to represent sets as lists, and if we do this we can program set membership in Prolog as

```
member(X,[H|T]):- X=H.
member(X,[H|T]):- member(X,T).
```

This introduces some more notation.  $[H|T]$  is allowed as a more readable synonym for the term  $.(H,T)$ , i.e. the list whose head is  $H$  and whose tail is  $T$ . The declarative reading of the first clause is that "for all  $X, H$  and  $T$ ,  $X$  is a member of the list with head  $H$  and tail  $T$  if  $X$  and  $H$  are the same term". The second clause reads "for all  $X, H$  and  $T$ ,  $X$  is a member of the list with head  $H$  and tail  $T$  if  $X$  is a member of the list  $T$ ." Both these statements are mathematically correct statements about the member relation. We show now that they are also operationally effective when executed by the Prolog interpreter in the manner described above.

One way in which the `member` program could be used is by typing the goal

```
?- member(b,[a,b]).
```

which would get the answer `yes` as a result of the following sequence of operations. As before, the goal is matched against the sequence of program clauses starting at the top. The goal `member(b,[a,b])` doesn't match `member(X,[H|T])` because  $X$  gets instantiated to  $a$  and  $H$  to  $b$ , and  $a=b$  fails, so a match with the second clause is attempted. This succeeds with  $X$  instantiated to  $b$ ,  $H$  to  $a$  and  $Y$  to  $[b]$ , and the body of the clause is now executed in an environment containing these variable bindings. So `member(b,[b])` is matched against the sequence of program clauses *starting again at the top*. This time it matches with the first because  $X$  and  $H$  both get instantiated to  $b$  and so  $X=H$  succeeds and hence the original goal also succeeds.

Logically it is irrelevant, but as a point of programming style most Prolog programmers would prefer to write the two clauses above as

```
member(X,[X|_]).
member(X,[_|Y]):- member(X,Y).
```

where the `'_'` symbol is used to denote a variable whose binding is irrelevant. Note also how the  $X=H$  in the first clause is unnecessary because it can be incorporated by replacing  $H$  by  $X$  in the clause head. Another way to write the definition of `member` is

```
member(X,[Y|Z]):- X=Y; member(X,Z).
```

where the semicolon symbol ';' is read as a logical 'or'. The declarative reading is thus "For all X, X is a member of the list whose head is Y and whose tail is the list Z if, either X is the same as Y, or X is a member of Z". Logically and operationally all these definitions of member are identical. Neatness, readability and personal preference determine which style is used in practice.

Another basic relation on lists is concatenation, which often goes by the name of `append` in Prolog systems, and can be implemented by the following clauses

```
append([],Y,Y).
append([H|X],Y,[H|Z]):- append(X,Y,Z).
```

Once again these clauses correspond directly to the base case and induction step in proofs of statements about the `append` relation. As for `member`, there is more than one way to use `append`. For example

```
?-append([a,b],[c,d],[a,b,c,d]).
    yes
```

```
?- append([a,b],[b,c],Z).
    Z=[a,b,b,c]
```

As an exercise it is a good test of understanding to go, as we did for `member`, through the steps that the Prolog interpreter has to make in order to produce these responses. A full explanation of `append` is given in the recommended textbooks. It is worth noting here though that `append` can be used in a variety of other ways and many useful predicates can be defined neatly, if not always efficiently, in terms of it. For example

```
member(X,Y):- append(_,[X|_],Y).
```

which says that X is a member of Y if there is a list with head X which, when appended to some other list, gives Y. The second argument of `append` is not fully instantiated here, and this brings up another of the ways in which Prolog differs radically from functional languages. With functions there is a distinction between domain and range, whereas with relations no such distinction can be made between

the arguments. This has the consequence that many Prolog programs that can be used to compute the value of a function can also be used, unchanged, to compute its inverse. For example

```
?- append([a,b],Y,[a,b,c,d]).
```

```
Y=[c,d]
```

```
?- append(X,Y,[a,b,c,d]).
```

```
X=[ ]
```

```
Y=[a,b,c,d];
```

```
X=[a]
```

```
Y=[b,c,d];
```

```
etc.
```

This ability to use a deterministic program "backwards" to generate all solutions that satisfy a constraint is an extremely useful feature, but it is not a universal property of Prolog programs and examining its correctness often involves non-logical, operational reasoning.

If we are implementing set union rather than concatenation of lists then we have to remove duplicates. The `union` predicate can be defined with the clauses

```
union([],Y,Y).
```

```
union([H|X],Y,Z):- member(H,Y), union(X,Y,Z).
```

```
union([H|X],Y,[H|Z]):- not(member(H,Y)), union(X,Y,Z).
```

which again correspond to mathematically correct statements about a relation `union(X,Y,Z)` which is satisfied when the list represented by the term `Z` is the union of the lists represented by the terms `X` and `Y`. Note that we have carefully said "list" rather than "set" here. The definition given is adequate for *computing* the union of two sets, with a goal such as

```
?- union([a,b],[b,c],Z).
```

```
Z=[a,b,c]
```

```
yes
```

but a goal such as

```
?- union([a,b],[b,c],[c,b,a]).
```

would give the result `no`, which is right for lists but wrong for sets. There is nothing in the program to say that two lists that are permutations of each other represent the same set. One way to do this is given below. We leave the reader to work out how to use this in the `union` program.

```
same_set([H|U],V):- take_out(H,V,W),same_set(U,W).
same_set([],[]).
take_out(H,[H|T],T):-!.
take_out(X,[H|T],[H|U]):- take_out(X,T,U).
```

The usual close correspondence between recursion and mathematical induction is again evident in the `union` program. The induction is on the size of the list corresponding to the first argument. The base case is given by the first clause which says that the union of `Y` with the null list is `Y`. The second and third clauses deal with the two possible cases of the induction step. Taking an element `H` of the first list: either `H` is a member of `Y`, in which case the relation is satisfied if `Z` is the union of `Y` and the remainder of the first list `X`, or `H` is not a member of `Y`, in which case the union is a list containing both `H` and `Z` where `Z` is the union of `X` and `Y`.

These are clearly mathematically correct statements. Readers should satisfy themselves that they are operationally effective by working out, in the same way as we did above for `member`, what happens when, for example, the goal `?- union([a,b],[b,c],Z)` is satisfied to give the answer substitution `Z=[a,b,c]`. Before you can do this we have to explain the system-defined predicate `not`. The goal `not(X)` is defined to succeed if the term that `X` is instantiated to fails when an attempt is made to satisfy it as a goal. So in this case to see, when some goal matches the third clause, whether `not(member(H,Y))` succeeds we have to see if `member(H,Y)` succeeds, taking account of what `H` and `Y` might at that point be instantiated to. If `member(H,Y)` succeeds then `not(member(H,Y))` fails, but if `member(H,Y)` fails then `not(member(H,Y))` succeeds. This definition of `not` is known as negation-as-failure and it will be seen, certainly after reading chapter three, that it is not the same, in general, as logical negation. Being unable to prove `P` in some system of deduction is not metalogically equivalent to being able to prove `¬P`.

The second and third clauses of the `union` program are mutually exclusive in the sense that a non-empty set must match one or the other and cannot match both. In the case where an attempted match with the second clause fails because `H` is not a member of `Y` a completely redundant repetition of the `member` computation is made

when the third clause is executed to show that `not (member (H, Y))` succeeds. One cannot simply leave out the `not (member (H, Y))` because the union program might be used in another program where backtracking forces the third clause to be tried after the second has succeeded, and this would be mathematically unsound. To get round this Prolog interpreters provide a system predicate denoted by the symbol '!' and pronounced 'cut'. The example above would be rewritten using cut as

```
union([],Y,Y).
union([H|X],Y,Z):- member(H,Y),!,union(X,Y,Z).
union([H|X],Y,[H|Z]):- union(X,Y,Z).
```

The cut predicate always succeeds and has the side-effect of removing all choices available up to that point on subsequent backtracking. So, in the example above, if the second clause of union is being tried, and `member (H, Y)` succeeds, then the cut succeeds and removes the possibility of backtracking to the third clause.

One sometimes sees use of the cut vilified as a dangerously operational, non-logical notion, but properly used it is perfectly safe and can make programs more concise as well as more efficient. A common construction, which arises in many of the examples in this book, is the Prolog equivalent of the if-then-else construction of other languages. The general form is

```
p:-q,!,r;s.
```

which says that `p` is satisfied either if `q` is satisfied and `r` is satisfied, or if `q` is not satisfied but `s` is satisfied (i.e. if `q` then `r` else `s`).

There are many other ways to use the cut to manipulate the operational behaviour of Prolog programs. Sterling and Shapiro give a discussion of the issues. From a pragmatic point of view if there is any doubt about the correctness of a construction involving 'cut' then it should not be used - there will always be a corresponding definition using 'not'. However one or other of the constructions is often unavoidable. There are good mathematical reasons why it is not possible to write clauses defining set intersection, for example, without using negation or some logically equivalent construction.

### A.3.3. Taking terms to pieces

System-defined predicates are provided for getting inside and manipulating terms. Of these the most useful for our purposes is one whose predicate symbol is `=..` pronounced 'univ' for historical reasons. Used without any user-defined program this has the following behaviour.

```
?- f(a,b)=..X.
    X=[f,a,b]

?- f(a,b)=..[f|Args].
    Args=[a,b]

?- Term=..[f,a,b].
    Term=f(a,b)

?- [a]=..Functor_and_Args.
    Functor_and_Args=[.,a,[]]
```

The last example in particular is a good test of understanding. Recall that lists are terms of arity two, whose function symbol is '!'. In general `T=..L` is satisfied if `L` is or can be instantiated to a list and `T` can be unified with the term whose function symbol is the head of `L` and whose sequence of arguments is the tail of `L`. We will see in the examples below, and in the main text, that, even though function symbols in Prolog terms have to be ground, we can use `=..` to write programs which operate on general terms. So this is a departure from strict first-order logic; one of the metalogical features of Prolog.

Other useful system predicates in the same category are `functor(T,F,N)` which unifies `F` and `N` with the function symbol and number of arguments, respectively, of the term to which `T` is instantiated, and `arg(I,T,X)` which, if `I` is instantiated to an integer `i`, unifies `X` with the  $i^{\text{th}}$  argument of the term to which `T` is (and must be) instantiated. Thus

```
?- functor([a],F,N).
    F=.
    N=2
```

```
?- arg(2,[a],X).
    X=[]
```

Finally, a pragmatic point, it is worth noting that most Prolog systems implement '=' in terms of `functor` and `arg` so the latter should be used if efficiency is at a premium.

#### A.3.4. Arithmetic

Even in algebraic computation we sometimes have to do some arithmetic. An arithmetic expression such as  $2+3$  is a term whose function symbol is `+` and whose arguments are `2` and `3`. By convention in mathematics the function symbol `+` is infix, i.e. written between its two arguments, and the same facility is provided in Prolog for function and predicate symbols to be defined as infix if required - we have already seen this in the case of the system predicates `=` and `=..`. If, for example, we give the interpreter the goal

```
?- 2+3=..X.
```

then we get the output `X=[+,2,3]`, showing that  $2+3$  is recognised by the system as a term whose function symbol is `+` and whose arguments are the constants `2` and `3`. Because  $2+3$  is just a term like `f(2,3)` the goal

```
?- X=2+3.
```

gives the, at first sight unexpected, answer `X=2+3`. This is because in first-order logic there is nothing to say that a term represents a function that may be applied to arguments to yield a value. It is perfectly feasible by purely logical means to define a predicate that can be used to evaluate an expression, but all Prolog systems in fact provide a system predicate `'is'` for this purpose. So

```
?- X is 2+3.
```

succeeds with `X` instantiated to the result of evaluating the right-hand side by the normal conventions of arithmetic, giving in this case the output `X=5`. It is important to understand the difference between `=` which succeeds if both sides can be unified

and 'is' which succeeds if the right-hand side can be evaluated arithmetically and then both sides unified. Again more detail is given in the recommended Prolog texts.

### A.3.5. User-defined operators

We have seen that the arithmetic operators can be used in the conventional infix form. We now go on to show that programmers can define their own function symbols as infix. To give an example, the goal

```
:- op(550,xfx,[->]).
```

succeeds and has the side effect of recording that the compound symbol '->' is an infix operator with precedence 550 and associativity of type 'xfx'. Precedence and associativity are used to disambiguate terms whose structure is not made explicit through the use of brackets. Again this is covered in full detail in the recommended books; here we just give a few examples.

The precise value of the precedence number is of no significance, it is only used as a convenient way to specify a linear ordering. The general rule is that the function symbol of highest precedence is the principal connective. So if we also include in the program

```
:- op(540,yfx,[/\]).
```

then we are saying that the string  $a/\backslash b \rightarrow c$  stands for the term  $(a/\backslash b) \rightarrow c$  rather than  $a/\backslash (b \rightarrow c)$ . The second argument of the `op` predicate, the associativity type, can be used to say, for example, that  $a-b-c$  stands for  $(a-b)-c$  rather than  $a-(b-c)$ , by including at the head of the program the goal

```
:- op(500,yfx,[-]).
```

although this would, in fact, be unnecessary since most Prolog systems already include standard definitions for the arithmetic operators. Note that these operator definitions have to be included as goals rather than definitions (`:-` is essentially the same as `?-`) because they have to be satisfied, and not just stored, in order to produce the required side-effect. For the same reason they must appear before the operators that they introduce are used. For present purposes we need these operator definitions in order to be able to use the conventional logical notation in our programs (see also

chapter two, section 2.1.2). For the examples in this book we have used the definitions

```
:-op(510, fx, [~]).
:-op(520, yfx, [/\]).
:-op(530, yfx, [\/]).
:-op(540, xfx, [->]).
:-op(550, xfx, [<->]).
:-op(560, xfx, [| -]).
```

for the logical connectives and the metalogical 'turnstile'  $\vdash$ , but other choices for the symbols would be perfectly valid. It cannot be emphasised too often that, to the Prolog interpreter, expressions involving these symbols are just terms, they have no logical significance.

### A.3.6. Some common patterns in manipulating terms

We conclude this brief introduction to Prolog by discussing two of the basic program schemas that arise in manipulating terms.

A common pattern of recursion is illustrated by the following program. A term  $S$  is a subterm of a term  $T$  either if it is identical to  $T$  or if it is a subterm of one of the arguments of  $T$ . In the latter case we use the `=..` system predicate to access the list of arguments of  $T$  and, if necessary, check  $S$  against each of them.

```
subterm(T,T).
subterm(S,T):- T=..[_|Args], sub(S,Args).
sub(S,[First|Rest]):- subterm(S,First); sub(S,Rest).
```

Note the use of the subsidiary predicate `sub` to process the list of arguments. It would be wrong to use `subterm(S,Args)` at the end of the second line because `subterm` expects a general term and not just a list as its second argument. Note also that here we don't need a base case for `sub` because we want it to fail if the second argument is the null list `[]`. Smaller points of style are the use of the anonymous variable `'_'` in the second line because the precise value of the function symbol doesn't matter here, and the use of the 'or' construction with `;` which seems neater here than having two clauses, one for the case where  $S$  is a subterm of the first argument, and the other for the recursive case.

Another frequently-occurring type of program is where we have a different case for each operator in some algebra. We could illustrate this with the logical connectives defined above but there are several such examples in the text. Suppose instead that we want to define predicates to evaluate expressions in an algebra of sets with two binary infix operators  $\setminus/$  and  $/\setminus$  denoting union and intersection and a unary prefixed operator  $\sim$  denoting complement with respect to some given universal set. The program, headed by the appropriate operator definitions, might be

```
:-op(500, fx, [~]).
:-op(510, xfx, [/]).
:-op(520, xfx, [\]).

set([]).
set([_|S]):- set(S).
universal_set([a,b,c,d]).

complement([],_,[]).
complement([H|T],X,Y):- complement(T,X,Z),
                        (member(H,X),!,Y=Z; Y=[H|Z]).

value(A\B,C):-value(A,U),value(B,V),union(U,V,C).
value(A/B,C):-value(A,U),value(B,V),intersection(U,V,C).
value( ~A,C):-value(A,B),universal_set(U),complement(U,B,C).
value(A,A):- set(A).
```

where `union` is given above and `intersection` (left as an exercise) is very similar to `union`.

The program would be used by typing goals of the form

```
?- X=[a,b],Y=[b,c],value(~((X/\~Y)\/(Y/\~X)),Z).
```

when the appropriate answer  $Z=[b,d]$  should be output.

Demands on space preclude any more examples, but there are plenty in the text. Some are more complicated, but all employ the basic ideas covered here. The aim of this brief introduction to algebraic manipulation in Prolog has been to prepare the ground for using and understanding them.

# APPENDIX B

---

## Programs in Standard ML and Prolog

### B.1. Programs in SML

#### *B.1.1. A parser for propositional logic*

```
(* The datatype that represents sentences of propositional logic
internally *)
```

```
datatype SENT = Null |
               Prop of string |
               Not of SENT |
               And of (SENT * SENT) |
               Or of (SENT * SENT) |
               Imp of (SENT * SENT) |
               Eq of (SENT * SENT);
```

```
(* Some useful functions *)
```

```
fun eq a (b:string) = (a=b);
fun fst (a,b) = a;
```

```
(* Variables are lowercase letters a to z *)
```

```
fun var h = "a" <= h andalso h <= "z";
```

```

fun andoper oper = (oper("&")) orelse (oper("v"));
fun impoper oper = (oper(">")) orelse (oper("="));

exception varerror;
fun makeVar (h, rest) = if var h
                        then (Var h, rest)
                        else raise varerror;

exception error;
fun rest P (head :: tail) = if P head
                            then tail
                            else raise error;

(* The parser from strings to SENT *)

fun constructsent str = auxconstructsent(constructterm str)
and auxconstructsent (l, nil) = (l, nil)
  | auxconstructsent (l, head :: tail) =
    if impoper head
    then let val (r, tail) = constructterm tail in
          auxconstructsent( if head = ">"
                           then (Imp(l,r), tail)
                           else (Eq(l,r), tail))
        end
    else (l, head :: tail)
and constructterm tail =
    auxconstructterm(constructfact tail)
and auxconstructterm (l, nil) = (l, nil)
  | auxconstructterm (l, head :: tail) =
    if andoper head
    then let val (r,tail) =
          constructfact tail in
          auxconstructsent(if head = "&"
                          then (And(l,r), tail)
                          else (Or(l,r), tail))
        end
    else (l, head :: tail)

```

```

        end
        else (l, head :: tail)
and constructfact nil = raise error
| constructfact (head :: tail) =
    if head = "~"
    then let val (t1, tail) =
            constructfact tail in
            auxconstructsent (Not(t1),tail)
        end
    else if head = "("
    then let val (t1,tail)=
            constructsent tail in
            if hd tail = ")"
            then (t1, rest (eq "))" ) tail)
            else raise error
        end
    else makeVar (head , tail);

```

(\* Packaging the parser to make it easily useable \*)

```

fun strip nil = nil
| strip S = if hd S = " "
            then strip (tl S)
            else (hd S) :: (strip (tl S));

```

```

fun make S = fst(constructsent (strip (explode S)));

```

(\* Unparsing, ready for printing \*)

```

fun printsent (Var v) = v
| printsent (And(left, right)) =
    "(" ^ printsent left ^ "&" ^ printsent right ^ ")"
| printsent (Not(rest)) =
    "(" ^ "~" ^ printsent rest ^ ")"
| printsent (Or(left, right)) =
    "(" ^ printsent left ^ "V" ^ printsent right ^ ")"

```

```

| printsent (Imp(left, right)) =
    "(" ^ printsent left ^ ">" ^ printsent right ^ ")"
| printsent (Eq(left, right)) =
    "(" ^ printsent left ^ "=" ^ printsent right ^ ")";

(* Finally, we parse some input and
    print it out if it is correct *)

val pr = printsent o make;

```

### *B.1.2. Extending the parser for predicate calculus*

```

datatype TERM = Var of string |
    Name of string |
    app of (string * TERM list) |
    empty;

datatype SENT = Null |
    Prop of string |
    Pred of (string * TERM list) |
    Not of SENT |
    And of (SENT * SENT) |
    Or of (SENT * SENT) |
    Imp of (SENT * SENT) |
    Eq of (SENT * SENT) |
    Forall of (TERM * SENT) |
    Exists of (TERM * SENT);

(* Some useful functions *)

fun eq a (b:string) = (a=b);
fun fst (a,b) = a;

(* Predicate letters are capitals from P to T *)
fun propored h = "M" <= h andalso h <= "T";
fun andoper oper = (oper("&")) orelse (oper="V");

```

```

fun improper oper = (oper=">") orelse (oper="=");

(* Names start with lower case letters from a to e... *)
fun name n = "a"<= n andalso n <= "e";
    (* ...and carry on with one or more digits *)
fun number n = "0"<= n andalso n <= "9";
    (* Variables are lower case letters from x to z *)
fun variable v = "x" <= v andalso v <= "z";
    (* Functions letters are lower case from f to h *)
fun function f = "f" <= f andalso f <= "h";
fun quantifier q = (q="A") orelse (q="E");

exception Var_error
and Name_error
and term_error1
and term_error2
and app_error1
and app_error2
and app_error3
and termlist_error0
and termlist_error1
and termlist_error2;

fun bldVar (v,nil) = raise Var_error
  | bldVar (v, h::t) = if number h
                      then bldVar(v ^ h,t)
                      else (Var v, h::t);

fun bldName (n,nil) = raise Name_error
  | bldName (n,h::t) = if number h
                      then bldName(n ^ h, t)
                      else (Name n,h::t);

fun bldterm nil = raise term_error1
  | bldterm (h::t) = if name h
                    then bldName (h,t)
                    else if variable h

```



```

                                (Pred(p,terms),rest)
                                end
                                else (Prop p,h::t);

exception  rest_error
and        fact_error0
and        fact_error1
and        quant_error0;

fun rest P (head :: tail) = if P head
                            then tail
                            else raise rest_error;

fun constructsent str = auxconstructsent(constructterm str)
and auxconstructsent (l, nil) = (l, nil)
  | auxconstructsent (l, head :: tail) =
    if improper head
    then let val (r, tail) =
           constructterm tail
        in auxconstructsent(
            if head = ">"
            then (Imp(l,r),tail)
            else (Eq(l,r),tail))
        else (l, head :: tail)
and constructterm tail = auxconstructterm(constructfact tail)
and auxconstructterm (l, nil) = (l, nil)
  | auxconstructterm (l, head :: tail) =
    if andoper head
    then let val (r,tail) =
           constructfact tail in
        auxconstructterm(
            if head = "&"
            then (And(l,r),tail)
            else (Or(l,r),tail))
        end
    else (l, head :: tail)

```

```

and constructfact nil = raise fact_error0
| constructfact (head :: tail) =
    if head = "~"
    then let val (t1, tail) =
            constructfact tail in
            auxconstructsent (Not(t1),tail)
        end
    else if head = "("
        then let val (t1, tail) =
                if hd tail = ")"
                then (t1, rest (eq "))" tail)
                else raise fact_error1
            end
            else if quantifier head
                then bldquant (head,tail)
                else makeProporPred (head,tail)
and bldquant (h,t)=
    let val (v,tail) =
            bldVar (hd t,tl t) in
        let val (S,tail') =
                constructfact tail in
            if h="A"
            then auxconstructsent(Forall(v,S),tail')
            else if h="E"
                then auxconstructsent
                else raise quant_error0
        end
    end;

fun strip nil = nil
| strip S = if hd S = " "
            then strip (tl S)
            else (hd S) :: (strip (tl S));

(* This is the final function that maps a string to a SENT *)

```

```

fun make S = fst(constructsent (strip (explode S)));

(* Auxiliary functions for printing terms, used in... *)

exception printterms_error0;
fun printterms nil = raise printterms_error0
  | printterms ((Name n)::t) = "(" ^ n ^ (printterms' t)
  | printterms ((Var v)::t) = "(" ^ v ^ (printterms' t)
  | printterms ((app(f,terms))::t) =
      "(" ^ f ^ (printterms terms)
and printterms' nil = ")"
  | printterms' ((Name n)::t) = "," ^ n ^ (printterms' t)
  | printterms' ((Var v)::t) = "," ^ v ^ (printterms' t)
  | printterms' ((app(f,terms))::t) =
      "," ^ f ^ (printterms terms) ^ (printterms' t);

(* ...this function, which takes SENTs and
      prints them as strings *)
fun printsent (Prop v) = v
  | printsent (And(left, right)) = "(" ^ printsent left ^ "&" ^ printsent right ^ ")"
  | printsent (Not(rest)) = "(" ^ "~" ^ printsent rest ^ ")"
  | printsent (Or(left, right)) =
      "(" ^ printsent left ^ "V" ^ printsent right ^ ")"
  | printsent (Imp(left, right)) =
      "(" ^ printsent left ^ ">" ^ printsent right ^ ")"
  | printsent (Eq(left, right)) = "(" ^ printsent left ^ "=" ^ printsent right ^ ")"
  | printsent (Pred(p,terms)) = p ^ printterms terms
  | printsent (Forall(Var v,S)) = "A" ^ v ^ "(" ^ printsent S ^ ")"
  | printsent (Exists(Var v,S)) = "E" ^ v ^ "(" ^ printsent S ^ " ";

```

### *B.1.3. Using truth-tables efficiently*

(\* Here is a collection of functions to use the truth-tables method for deciding validity of entailments. Instead of building the whole truth-table we check line by line because we can stop whenever to

conditions for validity are first broken, rather than going through all possibilities \*)

```

fun filter p nil = nil
  | filter p (x::xs) = if p x
                        then x :: filter p xs
                        else filter p xs;

fun mem nil a = false
  | mem (x::xs) a = a=x orelse mem xs a;

fun union(s,t) = s @ filter (not o mem s) t;

fun apply((s,v)::rest,S) =   if s=S
                              then v
                              else apply(rest,S);

exception finished;
fun switch' nil a = raise finished
  | switch' ((sent,true)::rest) a = a@((sent,false)::rest)
  | switch' ((sent,false)::rest) a = switch' rest ((sent,true)::a);
fun switch a = switch' a nil;

fun set_up (Var s) = [(s,true)]
  | set_up(Not s) = set_up(s)
  | set_up(And(s,t)) = union(set_up(s),set_up(t))
  | set_up(Or(s,t)) = union(set_up(s),set_up(t))
  | set_up(Imp(s,t)) = union(set_up(s),set_up(t))
  | set_up(Eq(s,t)) = union(set_up(s),set_up(t));

local fun valid' (s,valuation) =
        if (truthvalue valuation s)
        then output std_out "\nincorrect\n")
        else valid'(s,switch valuation) in
  fun valid sent = valid'(sent,set_up sent)
end;

```

```

fun transform(nil,goal) = Not(goal)
  | transform(x::nil,Null) = x
  | transform(x::xs,goal) = And(x,transform(xs,goal));

infix ttentails;

      (* Here is the main function.
        Given a list of assumptions ass and
        a conclusion conc we evaluate
            ass ttentails conc *)

fun ass ttentails conc =
  (valid(transform(ass,conc)))
  handle finished => output std_out "\ncorrect\n");

```

#### *B.1.4. Proofs using tableaux*

```

(* Here is a version of the tableau algorithm which shortens
    the amount of tableau traversal by keeping a
    note of all the sentences passed on the way
    from root to node.This makes testing
        for closure much quicker *)

type nodeinfo = {Closed : bool, Used : bool};
datatype Tableau = Leaf of (SENT * nodeinfo) |
                  Onenode of (SENT * nodeinfo * Tableau) |
                  Twonode of (SENT * nodeinfo * Tableau * Tableau);

fun Neg (Not(sent)) = sent | Neg sent = Not(sent);

infix mem;
fun a mem nil = false | a mem (x::xs) = a=x orelse a mem xs;

```

```

val initinfo = {Closed=false,Used=false};
fun initialise (nil,goal) = Leaf(Neg(goal),initinfo)
  | initialise (premise::nil,Null) = Leaf(premise,initinfo)
  | initialise (premise :: rest,goal) =
      Onenode(premise,initinfo,initialise (rest,goal));

fun alpha(And(s,t)) = true
  | alpha(Not(Imp(s,t))) =true
  | alpha(Not(Or(s,t))) = true
  | alpha(s) = false;

fun composite(Var s) = false
  | composite(Not(Var s))= false
  | composite(s) = true;

fun apply_rule (Imp(s,t)) = (Neg(s),t)
  | apply_rule (Eq(s,t)) = (And(s,t),And(Neg(s),Neg(t)))
  | apply_rule(And(s,t)) = (s,t)
  | apply_rule(Or(s,t)) = (s,t)
  | apply_rule(Not(Imp(s,t))) = (s,Neg(t))
  | apply_rule(Not(Eq(s,t))) = (And(Neg(s),t),And(s,Neg(t)))
  | apply_rule(Not(And(s,t))) = (Neg(s),Neg(t))
  | apply_rule(Not(Or(s,t)))= (Neg(s),Neg(t));

val useup = {Closed=false,Used=true};
val useable = (fn a => fn b:nodeinfo =>
                not(#Used(b)) andalso composite(a));

fun extend(Leaf(S,N),sent,path)=
    let fun test s ={Closed = Neg(s) mem path,Used = false} in
        if not(#Closed(N))
        then let val (f,s) = apply_rule(sent) in
            if alpha(sent)
            then Onenode(S,N,Onenode(f,test f,
                                     Leaf(s,test s)))
            else Twonode(S,N,next'(Leaf(f,test f),S::path),
                        next'(Leaf(s,test s),S::f::path))
        end
    end

```



```

                else make_tableau T'
            end;

infix entails;

fun asstlist entails goal =
    let val start_tableau = initialise(asstlist,goal) in
        let val final_tableau = make_tableau(start_tableau) in
            if closed(final_tableau)
            then output std_out "\ncorrect\n"
            else output std_out "\nincorrect\n"
        end
    end;
end;

```

### B.1.5. Terms, substitutions

```

(* Here we introduce some terms and
   show how we can do substitutions on them.
   We also show how composition of substitutions
   can be implemented *)

datatype term = app of string * term list |
              var of string |
              const of string |
              empty;

fun lookup(x,nil) = empty
  | lookup(x,(y,t)::rest) = if x=y
                          then t
                          else lookup(x,rest);

fun applySubst (Subst,(app(f,Args))) = app(f,(Sub (Subst,Args)))
  | applySubst (Subst, (var x)) =
    let val NewTerm = lookup(var x,Subst) in
        if NewTerm = empty
        then var x
        else NewTerm
    end
end

```

```

| applySubst (_, (const a)) = const a
| applySubst (_,empty) = empty
and Sub (_,nil) = nil
| Sub (Subst,FirstArg::RestofArgs) =
    applySubst (Subst,FirstArg) :: Sub (Subst,RestofArgs);

fun combine(S,nil) = S
| combine(Sub,(Var,_)::Rest) = let val S=combine(Sub,Rest) in
    if not(lookup(Var,Sub)=empty)
    then S
    else (Var,Var)::S
end;

fun compose(nil,_)=nil
| compose((Var,Term)::Rest,Sub2) =
    let val NewTerm = applySubst(Sub2,Term)
    and S = compose(Rest,Sub2) in
    if Var=NewTerm
    then S
    else (Var,NewTerm)::S
    end;

fun composition(Sub1,Sub2) = compose(combine(Sub1,Sub2),Sub2);

```

### *B.1.6. Program for semantic tableau method for predicate calculus*

```

fun lookup(x,nil) = empty
| lookup(x,(y,t)::rest) = if x=y then t else lookup(x,rest);

fun applySubst Subst (app(f,Args)) =
    app(f,map (applySubst Subst) Args)
| applySubst Subst (Var x) = let val NewTerm =
    lookup(Var x,Subst) in
    if NewTerm = empty
    then Var x
    else NewTerm
    end
| applySubst _ (Name a) = Name a

```

```

| applySubst _ empty = empty;

type nodeinfo = {Closed : bool, Used : bool};
datatype Tableau =
    Leaf of (SENT * nodeinfo)
  | Onenode of (SENT * nodeinfo * Tableau)
  | Twonode of (SENT * nodeinfo * Tableau * Tableau);

fun fst (a,b) = a;
fun snd (a,b) = b;

infix mem;
fun a mem nil = false | a mem (x::xs) = a=x orelse a mem xs;
infix -;
fun l1 - nil = l1
  | l1 - (h::t) = take(h,l1) - t
and take(h,nil) = nil
  | take(h,a::b) = if h = a then b else a::take(h,b);
fun anddist nil = true
  | anddist (h::t) = h andalso (anddist t);

fun flatten nil = nil
  | flatten (h::t) = h @ (flatten t);

fun filter nil = nil
  | filter (h::t) = if (h mem t) then filter t else h::(filter t);

val allnames = [Name "a",Name "b",Name "c",Name "d",Name "e",
                Name "a1",Name "a2", Name "a3"];

fun name (Name n) = true
  | name (app(f,l)) = anddist (map name l)
  | name s = false;

fun alpha(And(s,t)) = true

```

```

| alpha(Not(Imp(s,t))) = true
| alpha(Not(Or(s,t))) = true
| alpha(s) = false;

fun beta(Or(s,t)) = true
  | beta(Imp(s,t)) = true
  | beta(Not(And(s,t))) = true
  | beta(Eq(s,t)) = true
  | beta(Not(Eq(s,t))) = true
  | beta(s) = false;

fun gamma(Forall(v,s)) = true
  | gamma(Not(Exists(v,s))) = true
  | gamma(s) = false;

fun delta(Exists(v,s)) = true
  | delta(Not(Forall(v,s))) = true
  | delta(s) = false;

fun composite(Pred(p,t)) = false
  | composite(Not(Pred(p,t))) = false
  | composite (Prop p) = false
  | composite (Not(Prop p)) = false
  | composite(s) = true;

fun Neg (Not(sent)) = sent | Neg sent = Not(sent);

fun instance term (Forall(x,s)) = instance'(s,x,term)
  | instance term (Not(Exists(x,s))) = Neg(instance'(s,x,term))
  | instance term (Exists(x,s)) = instance'(s,x,term)
  | instance term (Not(Forall(x,s))) =Neg(instance'(s,x,term))

and instance'(And(s,t),x,newt) =
  And(instance'(s,x,newt),instance'(t,x,newt))
  | instance'(Or(s,t),x,newt) =
  Or(instance'(s,x,newt),instance'(t,x,newt))

```

```

| instance'(Imp(s,t),x,newt) =
    Imp(instance'(s,x,newt),instance'(t,x,newt))
| instance'(Eq(s,t),x,newt) =
    Eq(instance'(s,x,newt),instance'(t,x,newt))
| instance'(Not(s),x,newt) = Not(instance'(s,x,newt))
| instance'(Forall(Var y,s),x,newt) =
    if x = Var y
    then Forall(Var y,s)
    else Forall(Var y,instance'(s,x,newt))
| instance'(Exists(Var y,s),x,newt) =
    if x = Var y
    then Exists(Var y,s)
    else Exists(Var y, instance'(s,x,newt))
| instance'(Pred(p,terms),x,newt) =
    Pred(p,map (applySubst [(x,newt)]) terms)
| instance'(p,x,newt) = p;

fun apply_rule (Imp(s,t)) = (Neg(s),t)
| apply_rule (Eq(s,t)) = (And(s,t),And(Neg(s),Neg(t)))
| apply_rule(And(s,t)) = (s,t)
| apply_rule(Or(s,t)) = (s,t)
| apply_rule(Not(Imp(s,t))) = (s,Neg(t))
| apply_rule(Not(Eq(s,t))) = (And(Neg(s),t),And(s,Neg(t)))
| apply_rule(Not(And(s,t))) = (Neg(s),Neg(t))
| apply_rule(Not(Or(s,t))) = (Neg(s),Neg(t))
| apply_rule p = (Null,Null);

fun newname nl = if (allnames - nl) = nil
    then (Name "*")
    else hd(allnames - nl);

fun getnames (And(s,t)) = (getnames s) @ (getnames t)
| getnames (Or(s,t)) = (getnames s) @ (getnames t)
| getnames (Imp(s,t)) = (getnames s) @ (getnames t)
| getnames (Eq(s,t)) = (getnames s) @ (getnames t)
| getnames (Not(s)) = getnames s

```

```

| getnames (Forall(v,s)) = getnames s
| getnames (Exists(v,s)) = getnames s
| getnames (Pred(p,l)) = flatten (map getnames' l)
| getnames p = nil

and getnames' (Name n) = [Name n]
| getnames' (Var x) = nil
| getnames' (app(f,l)) = (if name(app(f,l))
                          then [app(f,l)]
                          else nil) @ (flatten (map getnames' l))
| getnames' empty = nil;

val initinfo = {Closed=false,Used=false};
fun initialise (nil,goal) = Leaf(Neg(goal),initinfo)
| initialise (premise::nil,Null) = Leaf(premise,initinfo)
| initialise (premise :: rest,goal) =
    Onenode(premise,initinfo,initialise (rest,goal));

infix oneof;
fun S oneof (Leaf(S',N)) = S=S'
| S oneof (Onenode(S',N,T)) = S=S' orelse (S oneof T);

fun initialclosed (Leaf(S,N)) = false
| initialclosed (Onenode(S,N,T)) = (Neg(S) oneof T) orelse
    (initialclosed T);

fun nameson path =
    filter(flatten(map (fn (a,b) => getnames a) path));

infix onpath;
fun S onpath path = ((S,{Closed=true,Used=true})mem path) orelse
    ((S,{Closed=true,Used=false}) mem path) orelse
    ((S,{Closed=false,Used=true}) mem path) orelse
    ((S,{Closed=false,Used=false}) mem path);

infix appears_unused_on;

```



```

                                agn(sent, test (S,N)
newsent (Null,initinfo)
path,sent,path,t)))
                                end
| agn(S,N,sent,path,nil) =
                                let val nn = instance (Name "a") sent in
                                  (print ("\nuniversal\n" ^ (printsent
                                  if sent appears_unused_on path
                                  then Onenode(S,N,Leaf(nn, test
                                  (S,N) nn (Null,initinfo) path))
                                  else Onenode(S,N,Onenode(nn, test
                                  (S,N) nn (Null,initinfo)
                                  end;

fun adddeltanode(S,N,sent,path) = adn(S,N,sent, nameson path,path)

and adn(S,N,sent,nl,path) =
  let val nn = instance (newname nl) sent in
    (print ("\nexistential\n" ^ (printsent nn)^ "\n");
    Onenode(S,N,Leaf(nn,test (S,N) nn (Null,initinfo) path)))
  end;

val useable = (fn a => fn b:nodeinfo => not(#Used(b)) andalso

datatype kinds = prop | univ | exis| ground;

fun kindof s = if alpha(s) orelse beta(s)
  then prop
  else if gamma(s)
    then univ
    else if delta(s)
      then exis
      else ground;

val useup = {Closed=false,Used=true};

```

```

fun extend(Leaf(S,N),sent,path) kind =
  if not(#Closed(N))
  then case kind of
    prop=>
      if alpha(sent)
      then let val (f,s) = apply_rule(sent) in
        (Onenode(S,N Onenode(f,test (S,N) f
          end
        else if beta(sent)
          then let val (f,s) = apply_rule(sent) in
            (Twonode(S,N,
              Leaf(f,test (S,N)
                f (Null,initinfo) path),
                Leaf(s,test (S,N)
                  s (Null,initinfo) path
                )),true)
            end
          else (Leaf(S,N),false)
        | univ=>
          if gamma(sent)
          then (addgammanodes(S,N,sent,(S,N)::path),true)
          else (Leaf(S,N),false)
        | exis=>
          if delta(sent)
          then (adddeltanode(S,N,sent,(S,N)::path),true)
          else (Leaf(S,N),false)
        | ground=> (Leaf(S,N),false)
      else (Leaf(S,N),false)
  | extend(Onenode(S,N,T),sent,path) kind =
    if not(#Closed(N))
    then let val (f,s) =
      extend(T,sent,(S,N)::path)
    kind in
      (Onenode(S,N,f),s)
    end
    else (Onenode(S,N,T),false)

```

```

| extend(Twocode(S,N,T1,T2),sent,path) kind =
    if not(#Closed(N))
    then let val (f1,s1) =
            extend(T1,sent,(S,N)::path) kind
            and (f2,s2) =
    extend(T2,sent,(S,N)::path) kind in
            (Twocode(S,N,f1,f2),s1 orelse s2)
    end
    else (Twocode(S,N,T1,T2),false)

and next' (Leaf(S,N),path) kind =
    if (useable S N) andalso (kindof S) = kind
    then extend(Leaf(S,useup),S,path) kind
    else (Leaf(S,N),false)

| next' (Onenode(S,N,T),path) kind =
    if (useable S N) andalso (kindof S) = kind
    then extend(Onenode(S,useup),S,path) kind
    else let val (f,s) =
            next'(T,(S,N)::path) kind in
            (Onenode(S,N,f),s)
    end

| next' (Twocode(S,N,T1,T2),path) kind =
    if (useable S N) andalso (kindof S) = kind
    then extend(Twocode(S,useup,T1,T2),S,path) kind
    else let val (f1,s1) =
            next'(T1,(S,N)::path) kind
            and (f2,s2) =
            next'(T2,(S,N)::path) kind in
            (Twocode(S,N,f1,f2),s1 orelse s2)
    end

and propnext T = next'(T,nil) prop
and univnext T = next'(T,nil) univ
and exisnext T = next'(T,nil) exis;

fun closed (Leaf(S,N)) = #Closed(N)

```

```

| closed (Onenode(S,N,T)) = #Closed(N) orelse closed T
| closed (Twonode(S,N,T1,T2)) = #Closed(N) orelse ((closed T1)

fun make_tableau T = let val (T',changes) = propnext T in
    if closed T'
    then T'
    else if changes
        then make_tableau T'
        else let val (T',changes) = exisnext T' in
            if closed T'
            then T'
            else if changes
                then make_tableau T'
                else let val (T',changes) =
                    univnext T' in
                    if closed T'
                    then T'
                    else if changes
                        then make_tableau T'
                        else T'
                    end
                end
            end
        end
    end
end;

infix entails;
fun asslist entails goal =
    let val start_tableau = initialise(map make asslist,make goal) in
        if initialclosed start_tableau
        then output std_out "\ncorrect\n"
        else let val final_tableau = make_tableau(start_tableau) in
            if closed(final_tableau)
            then output std_out "\ncorrect\n"
            else output std_out "\nincorrect\n"
        end
    end
end;

```

## B.2. Programs in Prolog

### B.2.1. Using truth-tables efficiently

```
:-op(510, fx, [~]).
```

```
:-op(520, xfy, [/ \]).
```

```
:-op(530, xfy, [ \ /]).
```

```
:-op(540, xfx, [->]).
```

```
:-op(550, xfx, [?]).
```

```
Assumptions?Goal:- transform(Assumptions,Goal,Formula),
                        setup(Formula,Valuation),
                        (generate(Valuation),
                         value(Formula,t,Valuation),
                         write('not valid'));
                        write('valid').
```

```
transform([],G,~G).
```

```
transform([H|T],G,H/\X):- transform(T,G,X).
```

```
setup(A,[A|_]):-atomic(A).
```

```
setup(~F,V):-setup(F,V).
```

```
setup(F,V):- F=..[_ ,A,B],setup(A,X),setup(B,Y),union(X,Y,V).
```

```
generate([]).
```

```
generate([[A,V]|T]):- (V=t;V=f),generate(T).
```

```
value( A,Z,V):- atomic(A),!,member([A,Z],V).
```

```
value( ~A,Z,V):- value(A,X,V), truth_table( ~X,Z).
```

```
value(A/\B,Z,V):- value(A,X,V),value(B,Y,V),truth_table(X/\Y,Z).
```

```
value(A\B,Z,V):- value(A,X,V),value(B,Y,V),truth_table(X\Y,Z).
```

```
value(A->B,Z,V):- value(A,X,V),value(B,Y,V),truth_table(X->Y,Z).
```

```
truth_table(t/\t,t):-!.
```

```
truth_table(_/\_,f).
```

```
truth_table(f\f,f):-!.
```

```
truth_table(_\/_ ,t).
truth_table(t->f,f):-!.
truth_table(_->_ ,t).
truth_table( ~t,f).
truth_table( ~f,t).

union([],Y,Y).
union([[A,_]|T],Y,Z):- member([A,_],Y),!,union(T,Y,Z).
union([[A,V]|T],Y,[[A,V]|Z]):-union(T,Y,Z).
member(X,[H|T]):- X=H;member(X,T).
```

## Solutions to Selected Exercises

---

2.2  
(b)

The sentences in the arguments in one have the following truth-values:

sentence	truth-value
A	f
B	t
C	t
D	t
E	f

	premise	conclusion	argument
a)	f	f	valid
b)	t	t	invalid
c)	t	f	invalid
d)	t	t	valid
e)	f	t	valid
f)	f	f	invalid
g)	f	t	invalid

This shows that an invalid argument can have

true premises and true conclusion.

true premises and false conclusion

false premises and true conclusion  
false premises and false conclusion

and that a valid argument can have

true premises and true conclusion  
false premises and true conclusion  
false premises and false conclusion.

(c)

No such argument can be constructed since a valid argument cannot have true premises and false conclusion. This is because an argument is valid iff the sentence which is "conjunction of its premises  $\rightarrow$  its conclusion" is a tautology. That this was so would contradict the fact that the premises were true and the the conclusion false.

### 2.3

(e)

We use the abbreviations:

A : The Eiffel Tower is in Australia

B : Australia is below the equator

C : The Eiffel Tower is in Paris

D : Paris is in France

E : France is in Australia

i)

$A \sqcap B$

$\sqcap A$

A	B	$A \sqcap B$	$(A \sqcap B) \rightarrow B$
t	t	t	t
t	f	f	t
f	t	f	t
f	f	f	t

The argument is valid since it is true under all valuations, i.e. lines of the truth-table.

ii)  
 $C \quad D$   
 $\neg C$

C	D	C	D	$(C \wedge D) \rightarrow C$
t	t	t	t	t
t	f	t	f	t
f	t	f	t	f
f	f	f	f	t

The argument is invalid since the third line makes the argument false, so it is not true under all valuations.

iii)  
 $A \quad B$   
 $\neg B$

same form of argument as ii), so it is invalid too.

iv)  
 $C \wedge D$   
 $\neg C$

same form of argument as i), so it is valid too.

v)  
 $A \wedge D$   
 $\neg D$

As  $A \wedge D$  is equivalent to  $D \wedge A$ , this is the same form of argument as i), so it is valid too.

vi)  
 $A \quad E$   
 $\neg A$

Same form of argument as iii), so it is valid too.

vii)

A E

 $\square$  C

A	E	A E	C	(A E) $\rightarrow$ C
t	t	t	t	t
t	t	t	f	f
t	f	t	t	t
t	f	t	f	f
f	t	t	t	t
f	t	t	f	f
f	f	f	t	t
f	f	f	f	t

Here, there are valuations, i.e. lines of the truth-table where the argument is false, so it is invalid.

**2.6**

(d)

```

fun truthvalue V Null = raise invalid_sentence
  | truthvalue V (Prop P) = apply(V,P)
  | truthvalue V (Not(S)) =
      if truthvalue V S = true
      then false else true
  | truthvalue V (And(S, T)) =
      if truthvalue V S andalso truthvalue V T = true
      then true else false
  | truthvalue V (Or(S, T)) =
      if truthvalue V S = true orelse truthvalue V T = true
      then true else false
  | truthvalue V (Imp(S, T)) =
      if truthvalue V S = true andalso truthvalue V T = false
      then false else true
  | truthvalue V (Eq(S, T)) =
      if truthvalue V S = truthvalue V T then true else false;

```

**2.7**

(c)

```

fun rhsimp(s,nil) = (false,Null)
  | rhsimp(s,(Imp(l,r))::t) = if s=r then (true,l) else rhsimp(s,t)
  | rhsimp(s,h::t) = rhsimp(s,t);

fun MP l s = let val (ok,left) = rhsimp(s,l) in

```

```

                ok andalso (left memberof l)
            end;

fun proof l = proof' nil l
and proof' l nil = true
  | proof' l (h::t) = (axiom h orelse MP l h) andalso
                      (proof' (l @ [h]) t);

```

## 3.2

(d)

```

infix free_for;
fun t free_for (x, And(S,T)) = (t free_for (x,S)) andalso
                               (t free_for (x,T))
  | t free_for (x, Or(S,T)) = (t free_for (x,S)) andalso
                              (t free_for (x,T))
  | t free_for (x, Imp(S,T)) = (t free_for (x,S)) andalso
                               (t free_for (x,T))
  | t free_for (x, Eq(S,T)) = (t free_for (x,S)) andalso
                              (t free_for (x,T))
  | t free_for (x, Not(S)) = (t free_for (x,S))
  | t free_for (x, Forall(v,S)) =
      not(x free_in (Forall(v,S)) andalso
          v occurs_in [t]) andalso (t free_for (x,S))
  | t free_for (x, Exists(v,S)) =
      not(x free_in (Exists(v,S)) andalso
          v occurs_in [t]) andalso (t free_for (x,S))
  | _ free_for _ = true;

```

(g)

We first new two auxiliary functions before we can give the definition of `forms_match`:

```

fun combine (b,t) (b',t') = let val b'' = (b andalso b') in
                            if t=t'
                              then (b'',t)
                              else if t=empty
                                    then (b'',t')
                                    else if t' = empty
                                          then (b'',t)
                                          else (false,empty)
                          end;

fun terms_match (x,nil) nil = (true,empty)
  | terms_match (x,(Name n)::tail) ((Name n')::tail') =
      if n=n'
        then (terms_match (x,tail) tail')
        else (false,empty)
  | terms_match (x, (Var v)::tail) (t::tail') =
      if x = Var v
        then (combine (terms_match (x,tail) tail') (true,t))
        else if t=Var v

```

```

        then (terms_match (x,tail) tail')
        else (false,empty)

| terms_match (x,(app(f,terms))::tail) ((app(f',terms'))::tail') =
    if f=f'
    then (terms_match (x,tail) tail')
    else (false, empty)
| terms_match _ _ = (false,empty);

fun forms_match (x,And(S,T)) (And(S',T')) =
    combine (forms_match(x,S) S') (forms_match(x,T) T')
| forms_match (x,Or(S,T)) (Or(S',T')) =
    combine (forms_match(x,S) S') (forms_match(x,T) T')
| forms_match (x,Imp(S,T)) (Imp(S',T')) =
    combine (forms_match(x,S) S') (forms_match(x,T) T')
| forms_match (x,Eq(S,T)) (Eq(S',T')) =
    combine (forms_match(x,S) S') (forms_match(x,T) T')
| forms_match (x,Not(S)) (Not(S')) = (forms_match (x,S) S')
| forms_match (x, Forall(v,S)) (Forall(v',S')) =
    if v=v'
    then (forms_match (x,S) S')
    else (false,empty)
| forms_match (x,Exists(v,S)) (Exists(v',S')) =
    if v=v'
    then (forms_match (x,S) S')
    else (false,empty)
| forms_match (x,Pred(p,terms)) (Pred(p',terms')) =
    if p=p'
    then (terms_match (x,terms) terms')
    else (false,empty)
| forms_match (x,Prop p) (Prop p') = (p=p',empty)
| forms_match _ _ = (false,empty);

```

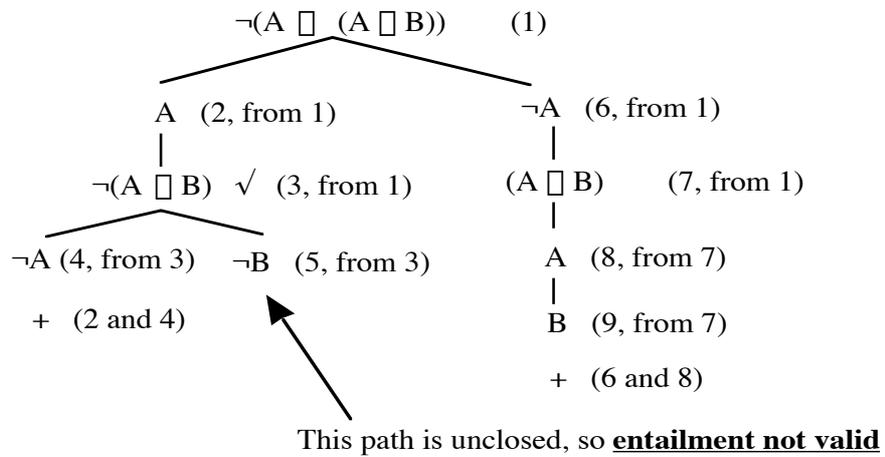
**(h)**

```

fun proof l = proof' nil l
and proof' l nil = true
| proof' l (h::t) = (axiom h orelse MP l h
                    orelse generalization l h) andalso
                    (proof' (l @ [h]) t);

```

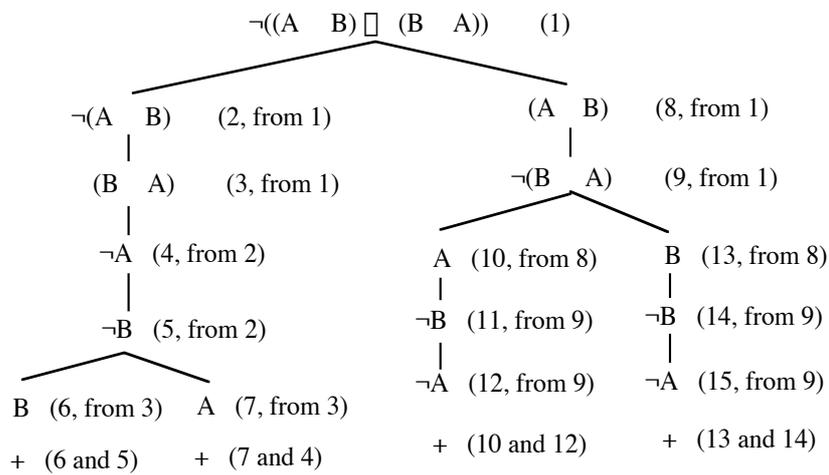
4.1  
(a)



A	B	$A \leftrightarrow B$	$A \leftrightarrow (A \leftrightarrow B)$
t	t	t	t
t	f	f	f
f	t	f	t
f	f	f	t

here is a line which is f  
so since we do not have  
true in all valuations, i.e.  
lines of the truth-table the  
**entailment is not valid**

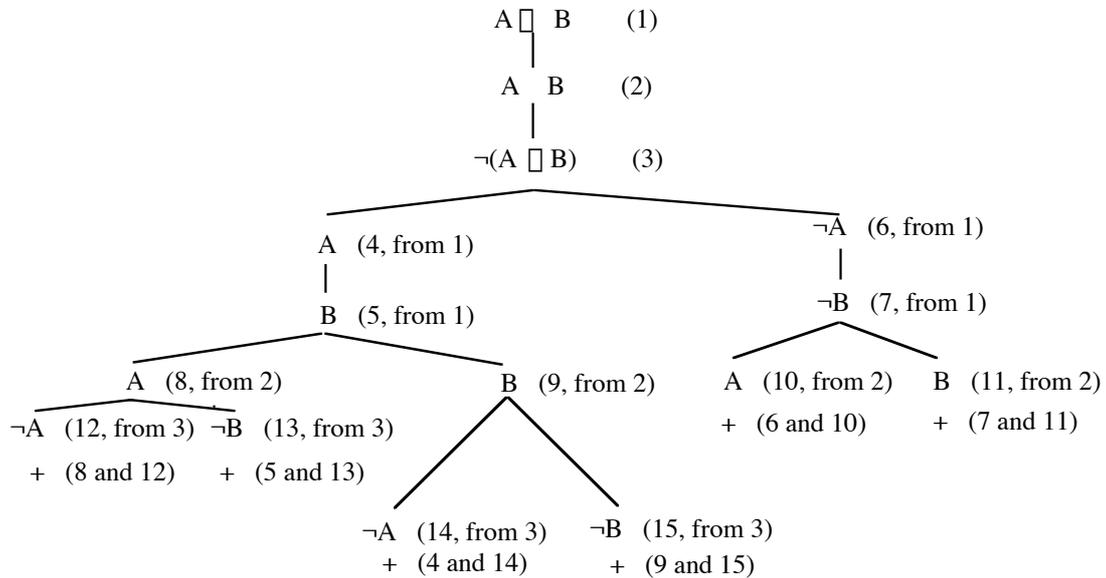
(b)



All paths are closed, so **entailment is valid**

A	B	A B	B A	$(A \rightarrow B) \rightarrow (B \rightarrow A)$	
t	t	t	t	t	the conclusion is true in all valuations and so the <b><u>entailment is valid</u></b>
t	f	t	t	t	
f	t	t	t	t	
f	f	f	f	t	

(c)



all paths closed, so **entailment is valid**

A	B	$A \leftrightarrow B$	A B	$A \Box B$	
t	t	t	t	t	this is the only line where both the premises are true, so as the conclusion is true here too the <b><u>entailment is valid</u></b>
t	f	f	t	f	
f	t	f	t	f	
f	f	t	f	f	

(d)

$$\begin{array}{l}
 A \quad (1) \\
 | \\
 \neg(A \supset B) \quad (2) \\
 | \\
 \neg A \quad (3, \text{ from } 2) \\
 | \\
 \neg B \quad (4, \text{ from } 2) \\
 + \quad (1 \text{ and } 3)
 \end{array}$$

all paths closed, so **entailment is valid**

A	B	A $\supset$ B
t	t	t
t	f	f
f	t	t
f	f	t

these first two lines are where the premise is true and the conclusion is true here too so the **entailment is valid**

(e)

$$\begin{array}{l}
 A \quad (1) \\
 | \\
 B \quad (2) \\
 | \\
 \neg(A \sqcap B) \quad (3) \\
 \swarrow \quad \searrow \\
 \neg A \quad (4, \text{ from } 3) \quad \neg B \quad (5, \text{ from } 3) \\
 + \quad (1 \text{ and } 4) \quad + \quad (2 \text{ and } 5)
 \end{array}$$

all paths closed, so **entailment is valid**

A	B	A $\sqcap$ B
t	t	t
t	f	f
f	t	f
f	f	f

this line is where the premises are both true and the conclusion is true here too, so the entailment is valid



A	B	C	A B	A (B $\supset$ C)	A $\supset$ C
t	t	t	t	t	t
t	t	f	t	t	f
t	f	t	t	t	t
t	f	f	t	t	f
f	t	t	t	t	f
f	t	f	t	f	f
f	f	t	f	f	f
f	f	f	f	f	f

The marked lines show that the entailment is not valid.

## 8.1

(a) There is a possible world in which this can be true.

(b) There is no possible world in which this is true. If it were true in some world then, since  $2+2 \neq 4$  then there is some number, say  $n$ , for which  $2+2=n$ . Then, if  $2+2 > n$ , by repeatedly subtracting 1 from either side we will eventually get to a stage where we have  $m=0$  where  $m$  is not 0. Then, by subtracting  $m-1$  1s from  $m$  we get  $1=0$  and the argument given in the text just before this exercise leads to a contradiction. A similar argument in the case where  $2+2 < n$  leads to a contradiction also. So, there is no possible world in which the sentence can be true.

(c) There is no possible world in which this can be true. In any one where it is we get a yard is shorter than a yard, which is contradictory.

(d) There is a possible world where this is true. For instance, one where I am ignorant of, or mistaken about, results on natural numbers.

(e) There is no possible world where this can be true since knowledge is simply the belief of facts, and it is not a fact that there is a greatest prime number.



# REFERENCES

---

- Bibel W. (1987). Automated Theorem-Proving. 2nd. revised edition. Braunschweig: Vieweg
- Boolos G. and Jeffrey R. (1980). Computability and Logic 2nd edn. Cambridge: Cambridge University Press
- Bornat R. (1987). Programming from First Principles Hemel Hempstead: Prentice-Hall International
- Bratko I. (1986). Prolog programming for artificial intelligence. Wokingham: Addison-Wesley
- Church A. (1936). A note on the Entscheidungsproblem. Journal of Symbolic Logic, 1,1,40-41,101-102
- Clocksin W.F. and Mellish C.S. (1981). Programming in Prolog. Springer-Verlag
- Fitting M. (1983). Proof methods in modal and intuitionistic logics. Reidel
- Gentzen G. (1934). Investigations into Logical Deduction. In (1969) The Collected papers of Gerhard Gentzen (M. Szabo ed.). North-Holland
- Gordon M.J., Milner R., Wadsworth C.P. (1979). Edinburgh LCF, Lecture notes in Computer Science 78. Berlin: Springer-Verlag
- Hamilton A. (1978). Logic for Mathematicians. Cambridge University Press
- Henson M. (1987). Elements of Functional Languages. Blackwell
- Heyting A. (1956). Intuitionism : an introduction. North-Holland
- Hilbert D. and Ackermann W. (1950). Principles of Mathematical Logic. New York: Chelsea Publishing Company (translation from (1938) Grundzüge der Theoretischen Logik. 2nd edn. Berlin: Springer-Verlag)

- Hodges W. (1977). Logic. Pelican Books
- Jeffreys R. (1967). Formal Logic: its Scope and Limits New York:McGraw-Hill Book Company
- Kripke S. (1963). Semantical analysis of modal logic I. Normal modal propositional calculi. Zeitschrift für Mathematische Logik und Grundlagen der Mathematik, **9**, 67-96
- Landin P.J.(1964). The mechanical evaluation of expressions. Computer Journal, **6** (4), 308-320
- Landin P.J. (1965) A correspondence between ALGOL 60 and Church's lambda-notation. Comm. ACM, **8**, 89-101,158-165
- Landin P.J. (1966) The next 700 programming languages. Comm. ACM, **9**(3), 157-166
- Lewis C.I. and Langford C.H. (1932). Symbolic Logic. New York: Dover
- Lloyd J.W. (1984). Foundations of Logic Programming. Springer-Verlag
- Manna Z. and Pnueli A. (1981). Verification of Concurrent Programs: the temporal framework. In Proc. International Summer School on Theoretic Foundations of Programming Methodology, Marktoberdorf, FRG, June 1981
- Manna Z. and Waldinger R. (1985) The Logical Basis for Computer Programming. Addison-Wesley
- Martin-Löf P. (1985). Constructive Mathematics and Computer Programming. In Mathematical Logic and Computer Programming (eds. Hoare C.A.R. and Shepherdson J.C.), Prentice-Hall
- McCarthy J. (1960). Recursive functions of symbolic expressions and their computation by machine, part 1. Comm. ACM, **3**(4), 184-195
- Mendelson, E. (1987). Introduction to Mathematical Logic, 3rd Edition. Wadsworth and Brooks
- Pratt V.R. (1976). Semantical considerations on Floyd-Hoare Logic. In Proc. 17th IEEE Symposium on the Foundations of Computer Science, 109-121
- Reeves S.V. (1989). Programming as Constructive Mathematics. In Proceedings of IMA Conference on Mathematical Structures for Software Engineering, Manchester, July 1988
- Reid C. (1970). Hilbert. Heidelberg: Springer-Verlag Berlin
- Rescher N. and Urquhart A. (1971). Temporal Logic. Wien: Springer-Verlag
- Robinson J.A. (1979). Logic: Form and Function. Edinburgh: University Press
- Scott D., Bostock D., Forbes G., Issacson D. and Sundholm G. (1981). Notes on the Formalization of Logic. Faculty of Philosophy, University of Oxford

- Smullyan R. (1984). What is the name of this book. Pelican
- Smullyan R. (1968). First-Order Logic. Berlin: Springer-Verlag
- Sterling L. and Shapiro E. (1986). The Art of Prolog. Cambridge: MIT Press
- Stoy J. (1977). Denotational semantics: the Scott-Strachey approach to Programming Languages. Cambridge: MIT press
- Turing A.M. (1936). On computable numbers, with an application to the Entscheidungsproblem. Proceedings of the London Mathematical Society, ser.2, **42**, 230-265
- Wikström Å. (1987). Functional programming using Standard ML. Hemel Hempstead: Prentice-Hall International
- Wallen L. (1987). Automated Proof Search in Non-Classical Logics: Efficient Matrix Proof methods for Modal and Intuitionistic Logics. PhD Thesis. University of Edinburgh



# INDEX

---

- $\neg$ , 9
- $\Box$ , 26
- $\Vdash$ , 171
- $\Box$ , 171
- $\Diamond$ , 171
- $\forall$ , 50
- $\exists$ , 50
- $\vdash$ , 40
- $\vdash_C$ , 119
- $\vdash_I$ , 119
- $\vDash$ , 28
- $\vDash_{S4}$ , 176
- $\Box$ , 9
- $\Box$ , 9
- $\Box$ , 9
- $\Box$ , 9
- $\leftarrow$ , 149
- $\Box$ , 110
- accessibility, 170, 175
- accessibility relation, 170
- Ackermann, 37
- adequacy, 42
- alphabet, 9, 33, 50
- arguments, 20
  - decidablity, 22
  - formal, 22
  - informal, 20
  - predicate logic, 49
- associativity, 26
- assumptions, 29
  - inconsistent, 31
- atomic, 34, 51
- axioms, 37
  - of a theory, 69
  - predicate, 60
  - propositional calculus, 38
- backtracking, 180
- binary tree, 72
- binding, 153
- Boole, 2
- bound, 51
- Brouwer, 120, 210, 211
- Cantor, 210
- cardinal number, 210
- Church, 66
- Church-Turing Thesis, 67
- classical assumption, 18
- classical logic, 23, 117, 121
- clause, 165
  - connection method, 194
  - goal, 149
  - Horn, 165
- closed world assumption, 144
- commutativity, 26
- complete
  - paths in tableaux, 83
- completeness
  - predicate, 61
  - propositional, 46
  - semantic tableaux, 89
  - tableaux, 80
- computable, 67
- conclusion, 29
- connected relation, 205
- connection, 194
- connection method, 193
  - clauses, 194
  - literals, 194

- matrix, 194
- path, 194
- connective symbols, 50
- connectives, 9, 22
  - associativity, 26
  - commutativity, 26
  - idempotence, 26
- consequence relation, 121
- consistent, 28
- constructive, 120, 210
- constructive set theory, 216
- contingent, 27, 169
- contradiction, 6, 26, 168
  - proof by, 100
- Cut Rule, 113, 114
- Cut theorem, 33
- cut-free, 114
- cycle
  - in an S4 tableau, 180
- decidability
  - predicate, 61
- decidable, 10, 22
- declarative sentence, 5
- deducible, 40
- deduction, 40
- deduction theorem
  - predicate, 61
  - propositional, 43
- definite clause, 149
  - body, 149
  - head, 149
- definite clause program, 149
- difference-set, 156
- disjunctive normal form, 194
- dynamic logic, 207
- effective, 67
- entailment
  - properties of, 31
- Entscheidungsproblem, 65
- environment, 153
- equality, 128
- equivalence relation, 175
- excluded middle, 26, 120, 188, 210
- extension, 53
- false
  - in an interpretation, 55
- first-order, 55
- forces, 171
- form, 20, 33
- formal deductive system
  - predicate, 60
  - propositional, 37
- formalism, 211
- formalization, 7
- formula, 51
- frame of reference, 170
- free for, 52
- Frege, 2, 37, 210
- functional completeness, 27
- generalization, 60
- Gentzen, 114, 120
- goal, 149
- Gödel, 145, 210
- grammar, 33, 50
- graph
  - directed, labelled, 172
- Hauptsatz, 114
- Herbrand base, 163
- Herbrand interpretations, 163
- Herbrand model, 163
- Herbrand universe, 163
- Heyting, 120
- higher-order, 148
- Hilbert, 37, 65, 145, 210
- Horn clause, 165
- idempotence, 26
- inconsistent, 28, 30
- index, 163
- induction, 135
- instance, 39, 153
- interpretation, 53, 68, 125
  - over a frame, 170
- intuitionism, 210
- intuitionistic, 120
  - S4 translation, 188
  - tableaux for, 186
- intuitionistic logic, 210
- intuitionistic type theory, 216
- ISWIM, 66
- Kripke, 120, 175
- $\lambda$ -calculus, 66
- Landin, 66
- language
  - predicate calculus, 50
  - propositional calculus, 33
- LCF, 102, 197
- lemma, 100
- Lisp, 66
- literal, 165
- literals
  - connection method, 194
- logic programming, 147
- logical equivalence, 25
- Lukasiewicz, 37, 175
- Martin-Löf, 216
- McCarthy, 66
- metalanguage, 3
- minimal

- possible world, 177
- ML, 198
- modal, 167
  - tableau rules
    - deleting, 177
    - non-deleting, 177
    - ordering, 179
- model, 37, 68, 125
  - Herbrand, 163
  - in a frame, 173
- model set, 82
- modus ponens, 38, 100
- monotonicity
  - of consequence relation, 122
- most general unifier, 156
- natural deduction
  - discharge an assumption, 100
  - Fitch boxes, 105
  - LCF, 198
  - negation, 102
  - proof strategy, 103
  - rules, 99
  - rules for predicate classical
    - predicate calculus, 100
- non-constructive existence, 210
- non-contingent, 169
- NOR, 27
- observer's language, 3
- occurrence
  - bound, 51
  - free, 51
- object language, 3
- overloaded, 53
- path, 73
- possible worlds, 168, 170
- possible-worlds diagram, 172
- predicate calculus
  - informal, 49
  - natural deduction, 100
- Prolog, 148
  - arithmetic, 251
  - backtracking, 241
  - body of clause, 239
  - clauses, 239
  - cut, 249
  - declarative reading, 240
  - goal, 241
  - head of clause, 239
  - if-then-else, 249
  - lists, 244
  - matching, 241
  - negation-as-failure, 248
  - procedural reading, 240
  - program, 239
  - system predicates, 243
  - term, 242
  - unification, 244
  - univ, 250
  - user-defined operators, 252
  - variable, 240
- Prolog programs
  - efficient truth\_tables, 279
  - semantic tableaux
    - propositional, 88
  - substitutions, 154
- proof
  - in a formal deductive system, 40
- proof-checker, 197
- propositional
  - sentence, 9
- propositional calculus
  - formal, 33
- propositional language, 34
- propositions, 5
  - internal structure, 49
- propositions-as-types, 212
- provability
  - intuitionistic, 188
- provable
  - by semantic tableau, 82
- quantifier
  - existential, 50
  - universal, 50
- quantifier symbols, 50
- reachability, 170
- recursive, 67
- reducible difference-set, 156
- reducing substitution, 156
- reductio ad absurdum, 100
- reflexivity
  - of consequence relation, 122
- resolution, 150
  - predicate, 159
  - propositional, 151
- resolvents, 151
- rules of deduction
  - propositional, 37
- Russell, 2, 210
- S4, 175
  - intuitionistic logic, 188
- S5, 175
- satisfiable, 55
- satisfy, 36, 54
  - modal, 173
- scope, 51
- SECD machine, 67
- semantic entailment, 28
- semantic tableaux, 71

- basis of the method, 72
- closing paths, 74
- completed, 83
- direct extension, 81
- entailment represented by, 73
- initial sentences, 73
- intuitionistic logic, 186
- invalid entailment, 76
- predicate
  - algorithm, 95
  - correctness, 96
- predicate calculus, 89
- propositional, 72
  - algorithm, 83
  - completeness, 80, 89
  - correctness, 89
  - Prolog program, 88
  - SML program, 84
  - soundness, 80
- relation to sequents, 116
- rules for quantifiers
  - formal, 93
  - informal, 91
- S4, 175
- splitting rules, 78
- semantics, 18
  - classical, 18
  - denotational, 19
  - operational, 18, 67
  - possible worlds, 169
- semi-decidable, 94
- sentence, 50
  - propositional, 34
- sequent, 110
- sequent calculus, 110
  - Cut Rule, 114
  - relation to tableaux, 116
- Sheffer stroke, 27, 37
- SML
  - conditional expression, 230
  - constructors, 229
  - datatypes, 228
  - declaration, 221
  - exception, 223
  - function value, 222
  - if-then-else, 230
  - infix, 228
  - i $\tau$ , 222
  - lists, 233
  - local definitions, 231
  - matching, 229
  - mutual recursion, 231
  - polymorphic types, 226
  - program, 221
  - raising and exception, 223
  - sentence, 52
  - strict language, 223
  - term, 52
  - type, 222
  - type environment, 222
  - type inference, 224
  - value environment, 221
  - $\lambda$ -expressions, 225
- SML programs
  - efficient truth-tables, 263
  - parser
    - predicate, 258
    - propositional, 255
  - propositional tableaux, 265
  - semantic tableaux
    - predicate, 269
    - propositional, 84
  - terms and substitutions, 268
- Smullyan, 139
- soundness
  - predicate, 61
  - propositional, 44
  - tableaux, 80
- spanning
  - set of connections, 194
- stacks
  - theory of, 135
- state
  - in a computation, 185
- Stone, 120
- Strachey, 66
- strings
  - theory of, 131
- sub-formula, 51
- substitution, 39, 153
  - composition of, 153
- symmetry
  - of equality, 129
- tactics, 202
- Tarski, 120
- tautology, 24, 28, 29, 37
- temporal logic, 204
- temporal modalities, 205
- term, 51
- theorem, 40
- theorems
  - of a theory, 69
- theory, 68, 125
  - axioms, 69
  - theorems, 69
- three-valued logic, 175
- transitivity
  - of consequence relation, 122

- of equality, 131
- translation
  - intuitionistic to S4, 188
- translation function, 189
- true
  - in a frame, 173
  - in an interpretation, 55
  - paths in tableaux, 81
- truth
  - intuitionistic, 188
- truth-functional, 23, 174
- truth-functors, 23
- truth-tables, 22
- truth-values, 23
- Turing, 66
- Turing machine, 66
- undecidable, 10, 61
- unifier, 156
- universe, 53, 68
  - Herbrand, 163
- unsatisfiable, 55
- valid, 24, 28, 55
  - for a tactic, 202
  - in a frame, 173
  - in S4, 176
- validation, 202
- valuation, 24, 28, 34, 76
- variable, 50