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An investigation of design and execution alternatives for the Committed Choice Non-Deterministic Logic languages

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Abstract

The general area of developing, applying and studying new and parallel models of computation is motivated by a need to overcome the limits of current Von Neumann based architectures. A key area of research in understanding how new technology can be applied to AI problem solving is through using logic languages. Logic programming languages provide a procedural interpretation for sentences of first order logic, mainly using a class of sentence called Horn clauses. Horn clauses are open to a wide variety of parallel evaluation models, giving possible speed-ups and alternative parallel models of execution.

The research in this thesis is concerned with investigating one class of parallel logic language known as Committed Choice Non-Deterministic languages. The investigation considers the inherent parallel behaviour of AI programs implemented in the CCND languages and the effect of various alternatives open to language implementors and designers. This is achieved by considering how various AI programming techniques map to alternative language designs and the behaviour of these AI programs on alternative implementations of these languages.

The aim of this work is to investigate how AI programming techniques are affected (qualitatively and quantitatively) by particular language features. The qualitative evaluation is a consideration of how AI programs can be mapped to the various CCND languages. The applications considered are general search algorithms (which focuses on the committed choice nature of the languages); chart parsing (which focuses on the differences between **safe** and **unsafe** languages); and meta-level inference (which focuses on the difference between **deep** and **flat** languages). The quantitative evaluation considers the inherent parallel behaviour of the resulting programs and the effect of possible implementation alternatives on this inherent behaviour. To carry out this quantitative evaluation we have implemented a system which improves on the current interpreter based evaluation systems. The new system has an improved model of execution and allows several

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Chapter 1

Introduction

Artificial Intelligence (AI) by its nature is a multi-disciplined field bringing together subject areas such as Philosophy; Natural Language; Vision; Robotics; Logic; Computer Science; Engineering and Physics. The main tool of the Artificial Intelligence researcher has been the digital computer, enabling theory to be put into practice.

Currently most digital computers are based on the Von Neumann architecture; a single central processing unit with a small amount of memory and a large amount of separate memory (which holds the data and the program). The limits of such computers are widely recognised: the speed of a signal in a wire; the physical limits of integration; heat dissipation and memory accessing.

The development of new architectures with several processing and memory units and new models of computation promises to alleviate some of these limitations. There are two clear implications for Artificial Intelligence: increased execution speed and more natural decomposition of applications. An improvement in execution speed results in models and applications being tested that would not have been feasible on previous generations of computers, *e.g.* the use of AI in embedded real-time systems, which are time critical. More natural decomposition may be possible as many problems are parallel rather than sequential and so are better thought of in terms of a parallel rather than a sequential framework. For

example, being able to parse a string and build a semantic structure as well as refer to a world model in an incremental fashion requires control over how these parts execute and interlink. Implementing such a model in a sequential framework requires the programmer to consider how to mimic the parallel execution and control required. This adds an additional level of conceptual complexity to the problem when realising the solution as a program.

A key area of research in understanding how this new technology can be applied to AI problem solving is through using logic languages. The Japanese Fifth Generation Computer Systems (FGCS) project uses logic programming as the link between information processing and parallel architectures [Uchida 82]. Logic programming languages provide a procedural interpretation for sentences of first order logic, mainly using a class of sentence called Horn clauses. The first and most widely used of the family of Horn clause based languages is Prolog [Clocksin & Mellish 81], [Sterling & Shapiro 86]. Prolog currently provides a sequential means of evaluating Horn clause based programs. This sequential search efficiently realised in a stack based implementation [Warren 83] gives in excess of 100,000 Logical inferences per second (Lips). However, Horn clauses are open to a wide variety of parallel evaluation models, giving possible speed-ups and alternative parallel models of execution.

The research in this thesis is concerned with investigating one class of parallel logic language known as Committed Choice Non-Deterministic (CCND) languages. The investigation considers the inherent parallel behaviour of AI programs implemented in the CCND languages and the effect of various alternatives open to language implementors and designers. This is achieved by considering how various AI programming techniques map to alternative language designs and the behaviour of these AI programs on alternative implementations of these languages.

The aim of this work is to evaluate some of the design and execution alternatives open in the development of these languages, in the light of AI requirements. While choices have been made as to the direction that the languages should take,

the choices to date appear to be motivated by implementation or historical reasoning rather than a rational study of how the alternatives will affect the use of these languages and realisable parallelism. This work is a study of alternative language designs and execution models.

1.1 Thesis outline

The thesis is structured into three main parts:

- In **part 1** we provide a review of the field of parallel logic programming.
- In **part 2** we develop an evaluation system for the CCND languages.
- In **part 3** we evaluate three distinct classes of AI program.

The chapter structure is as follows:

Chapter 2 serves as an introduction to sequential and parallel logic programming, in particular the CCND languages, introducing basic concepts and technology. The chapter also considers how the languages are modelled by interpretation and how these interpretation systems can be instrumented.

Chapter 3 considers how the inherent parallelism available in the evaluation of programs implemented in the CCND languages can be measured. The chapter initially highlights the limitations of current evaluation systems and then incrementally develops an improved model for obtaining measures of the inherent parallelism.

Chapter 4 considers some of the alternatives open to language implementors. We also propose some new evaluation parameters that reflect the expected behaviour of programs in the alternative models of execution. Finally, we develop a profiling tool, which is described by considering some simple programs.

Chapter 5 is the first of the evaluation chapters. In this chapter we consider the behaviour of the various techniques for offering exhaustive search in the CCND languages, namely: Continuation based compilation; Stream based compilation; and Layered Streams. The techniques considered have been evaluated before and so we are able to compare our new evaluation with this previous evaluation.

Chapter 6 evaluates how shared data structures can be supported in the CCND languages. The main feature being investigated here is the differences between using **safe** and **unsafe** languages. The question of how shared data structures are supported in the CCND languages is an important one for AI. Several current AI paradigms which require several different forms of expertise, like blackboard systems, require a common communication medium which each expert can see and update. The various CCND languages require different programming techniques to support shared data structures, so this evaluation also serves to highlight and compare the differing language features. We use a well known natural language processing technique known as **chart parsing** as an application which makes use of shared data.

Chapter 7 focuses on another variation in the possible styles of CCND language being proposed, namely: the difference in using **deep** and **flat** languages. The first style of language appears to be more expressive, or at least more high level, whilst the second, a subset of the first, is more likely to be efficiently implemented. One solution to this problem is to develop algorithms using the complete languages and then translate them to the executable subset. However, there are several alternative translations that can be employed. We use a program, known as PRESS - PRolog Equation Solving System, which naturally maps to the full CCND languages to evaluate and compare the behaviour of programs implemented using the complete language and the alternative translations to the more efficiently implementable subset.

Finally, in chapter 8 we draw some conclusions on our work, comment on the research assumptions and highlight some areas of future work.

Part I

Committed Choice
Non-Deterministic languages

Preface

This part of the thesis is a review of the field. The review consists of one chapter with three main focuses:

- to show how logic can be used as a programming language and how programs specified in logic are open to both sequential and parallel evaluation models;

- to introduce a class of parallel logic programming language, known as Committed Choice Non-Deterministic languages, which we intend to evaluate in this thesis; and

- to consider the implementations of these languages for evaluation purposes, in particular via interpretation, as this is the method employed in the evaluation system we develop.

Chapter 2

The Languages

2.1 Overview

This chapter is a review of the field of parallel logic programming. The review aims to show how logic can be used as a programming language; how logic programs can be evaluated in a sequential or parallel fashion; the parallel computation model employed for the Committed Choice Non-Deterministic (CCND) languages (the class of language evaluated in this thesis); the execution of these CCND languages via interpretation (as this is the technique employed in our evaluation system).

Section 2.2 considers how logic can be used as a programming language and how such logic programs are open to a sequential evaluation model.

Section 2.3 considers several parallel execution models that can be employed in the evaluation of logic based programs.

Section 2.4 introduces the three main CCND languages, namely **Concurrent Prolog**, **Parlog** and **Guarded Horn Clauses.**

Section 2.5 presents two general classifications of the language features of these CCND languages. The classifications are used in our evaluation of how various AI programming techniques map to these languages.

Section 2.6 reviews current implementations of these languages, in particular the execution of these languages using interpreters which is how we implement our evaluation system.

2.2 Logic as a programming language

Logic provides a language of formal description. The earliest logic was **syllogistic logic** which was the main tool of philosophers and logicians up to the nineteenth century. The limitations of syllogistic logic were addressed by the advent of **propositional logic**, followed by a more general logic known as **predicate logic**. The automated proofs of problems stated in both **propositional logic** and **predicate logic** have been of considerable interest. Consideration of efficient automated proof procedures has resulted in a subset of **predicate logic** known as **Horn clauses** being adopted as one of the main logic languages for automated proofs. The automated proof of a logical specification allows us to consider logic as a programming language.

2.2.1 Syntax of Horn clauses

A **Horn clause** program is a finite set of clauses of the form:

$$H \text{ :- } B_1, \ldots, B_n \qquad (n \geq 0)$$

H is known as the **clause head** and $B_1, \ldots, B_n$ is known as the **clause body**.

The clause head is an **atom** of the form:

$$R(a_1, \ldots, a_k) \qquad (k \geq 0)$$

R is the **relation,** or **predicate, name** and $a_1, \ldots, a_k$ are the arguments. The relation is said to be of **arity** k. Each of the elements of the clause body, $B_1, \ldots, B_n$ are **literals**. These literals are either atoms or negated atoms, of the form:

$$\neg R(a_1, \ldots, a_k) \qquad (k \geq 0)$$

Each argument is either a **variable**, a **constant** or a **structure**; these are collectively known as **terms**. The convention used in this thesis is that variables will be unquoted alphanumerics beginning with an upper-case letter, *e.g.* `X`, `Foo` and `BaZ12`. Structures are of the form:

$$F(t_1, \ldots, t_i) \qquad (i \geq 1)$$

where F is known as the **functor** and $t_1, \ldots, t_i$ are known as the arguments, which are also terms, *e.g.* `foo(a,b,c)`, `baz12(X,Y)` and `foo(a,baz12(X,Y))`. Constants are either numbers, alphanumerics beginning with a lower-case letter or a term containing no variables.

Lists are one of the most common types of structure used in Horn clause programs. Lists have a reserved functor, namely ".", *e.g.* `.(a,.(b,.(c,nil)))` is a three element list. For convenience, lists also have a more readable syntax. This syntax is based around a list being viewed as the first element of the list (the head), say `h`, and the rest of the list (the tail), say `t`. So a list could be denoted as `[h|t]`. Using this syntax the above list becomes `[1|[2|[3|[]]]]`. This is still further simplified to `[1,2,3]`.

A general query in a Horn clauses language has the following form:

$$:\text{-}\ C_1, C_2, \ldots, Cn$$

each of the C_i is called a goal.

2.2.2 Semantics of Horn clauses

2.2.2.1 Declarative semantics

A Horn clause program has a declarative reading based on each of its clauses. Each clause:

$$H \text{ :- } B_1, \ldots, B_n$$

is read as:

H is true if B_1 and B_2 and ...and B_n are all true.

```
ancestor(X,Y) :- child(X,Y).
ancestor(X,Y) :- child(X,Z),ancestor(Z,Y).

child(abraham, isaac).
child(abraham, ishmael).
child(isaac, esau).
child(isaac, jacob).
```

Figure 2–1: Ancestor relation specified in Horn clauses

For example consider the Horn clause program in *Figure 2–1*. This program has the following declarative reading:

`X` is an ancestor of `Y` if `X` has a child `Y`.

`X` is an ancestor of `Y` if `X` has a child `Z` and `Z` is an ancestor of `Y`.

abraham has a child isaac.

abraham has a child ishmael.

isaac has a child esau.

isaac has a child jacob.

2.2.2.2 Operational semantics

The declarative semantics of Horn clauses do not consider the meaning of a program for a given inference system. This operational, or procedural, meaning of the program is the set of queries that are provable given the program and the inference scheme.

2.2.3 Prolog

In this section we consider a sequential logic programming language known as Prolog. This language is used later in this thesis to simulate the execution behaviour of the CCND languages.

In Prolog, Horn clauses are evaluated using a process known as resolution; a resolution step can be informally described as a process by which a given goal is reduced, via a Horn clause, to a conjunction of goals that must be satisfied. In this process, variables in the Horn clause may be instantiated, for the evaluation to proceed, known as unification. In Prolog these reduction steps occur in a sequential manner, namely a conjunction of body goals is evaluated left-to-right, with the search for a reduction path taking place from top-to-bottom (in a textual sense).

Prolog provides a **backtracking** mechanism which ensures consistency of results. If it is not possible to reduce the current goal using any of the clauses in the system, then the system will backtrack, undo the last reduction step, and try the next possible solution path.

This control structure is basically a depth-first search of the AND/OR tree. Prolog's backtracking means that the search for a solution will try the clauses (possible reduction paths) until all the instantiations are consistent. For example consider a Prolog interpreter evaluating the following query based on the Horn clause program in *Figure 2–1*:

```
:- ancestor(abraham, jacob)
```

- The evaluation reduces to `child(abraham, jacob)`; using the first clause for ancestor in *Figure 2–1*.
- The evaluation of `child(abraham, jacob)` fails and causes **backtracking**.
- On backtracking `ancestor(abraham, jacob)` is reduced to (using the second clause for ancestor in *Figure 2–1*) `child(abraham, Z), ancestor(Z, jacob)`.

- Prolog evaluates the goals in a left-to-right order, first `child(abraham, Z)` and then `ancestor(Z, jacob)`.

- The `child(abraham, Z)` goal can be reduced (using the 1st clause for `child`) to **true**. In the process `Z` is instantiated to `isaac`.

- The second goal `ancestor(isaac, jacob)` is now attempted. This goal is true.

- So, `ancestor(abraham, jacob)` is true.

2.3 Parallelism in logic programming

Horn clauses are open to many forms of evaluation, in that there are many ways that the statements making up a logical system can be applied to proving a query. Often several resolution steps can be applied in parallel. There are four main approaches to parallel application of Horn clause statements to proving a query:

- All-solutions AND-parallelism;

- OR-parallelism;

- Restricted AND-parallelism; and

- Streamed AND-parallelism.

2.3.1 All-solutions AND-parallelism

All-solutions AND-parallelism involves the parallel evaluation of a conjunction of goals, hence the use of the phrase **AND-parallelism**. However, the conjunction is being solved for all possible solutions (that is all the alternative bindings),

hence the use of the phrase **All-solutions**. This has resulted in the term **All-solutions AND-parallelism**. It is intended that all solutions to the query should be obtained in about the same time as it takes to obtain one solution. There are two main ways this parallelism could be implemented. This is illustrated by considering the Horn clause system in *Figure 2–2*.

```
smelly_flower(X) :- flower(X), has_scent(X).

flower(rose).
flower(tulip).
flower(carnation).
has_scent(rose).
has_scent(tulip).
has_scent(carnation).
```

Figure 2–2: A simple Horn clause program

To obtain all the solutions to the goal `smelly_flower(X)`, we could evaluate the program as follows:

- Start a `flower(X)` evaluation process, which searches for all the solutions to this goal. As soon as a value for X is found, start evaluating the particular `has_scent(X)` goal. This could be done in two ways. The first is a pipeline-like evaluation, *e.g.* while `flower(X)` is evaluating another instantiation for `X`, `has_scent(X)` is checking the current instantiation value for `X`. The second is by generating all the possible `X`'s for `flower(X)` as fast as possible and spawning a different `has_scent(X)` evaluation for each `X`.

- Another approach would be for each goal in the conjunction to compute a complete set of solutions and then to join these solution sets to obtain the overall solutions. Although this method allows for a great deal of parallelism (in that each goal is evaluated independently) it does have its drawbacks;

letting each of the goals in the conjunction produce a complete set of solutions without control may lead to a large amount of space being used for intermediate results. Depending on the type of problem the intersection could result in a small set of solutions.

2.3.2 OR-parallelism

If we again consider the example Horn clause system in *Figure 2–2*, then the following query:

```
:- flower(X).
```

would be true if `X` was `tulip` OR `rose` OR `carnation`. These solutions are the **OR-solutions** to the query posed.

Basically **OR-parallelism** is the search for a solution via each of the clauses (OR-alternatives) for a given predicate in parallel. Using this form of parallelism will lead to a more complete search than that of Prolog as all the OR-branches can be investigated in parallel. In Prolog if we have a clause in the search tree that never terminates then the OR-branches that are to be searched after this branch will never be tried. Another point to note is that because we are dealing with the parallel search of clauses the evaluation of the clauses will be independent and hence fairly easy to implement.

2.3.3 Restricted AND-parallelism

The general parallel evaluation of a conjunction of goals may be complex, as the goals may share variables. These variables must have consistent bindings and so the evaluation of these goals cannot be totally independent. However, in **Restricted AND-parallelism** only goals which do not share variables are evaluated in parallel. This restriction makes this form of parallelism fairly easy

to implement. An example of this is the parallel search of two lists, each search looking for a different element; this system is specified in *Figure 2–3.*

```
on_lists(Item1, List1, Item2, List2) :-
    on(Item1, List1), on(Item2, List2).

on(Item,[Item|Rest]).
on(Item,[Head|Tail]) :- Item \== Head, on(Item, Tail).
```

Figure 2–3: Searching down two lists in parallel

A query to this program should specify two elements and two lists, *e.g.* the goal `on_lists(a,[1,2,3,a,5],b,[1,2,b])`. The goal is reduced by clause (1) to two list searches which are totally independent and hence can be evaluated in parallel.

This form of parallelism has different implications for execution performance to the forms of parallelism considered so far. The **All-solutions AND-parallelism** and **OR-parallelism** both rely on there being several possible solution paths, *don't know non-determinism*, which can be investigated in parallel hence resulting in a speed-up. **Restricted AND-parallelism** evaluates the various independent AND-branches of the computation tree in parallel and so would also give a speed-up in deterministic programs.

2.3.4 Streamed AND-parallelism

The forms of parallelism considered so far allow parallelism to be realised without the programmer having to worry about communication and synchronisation between parallel processes which are exploring the search space. This is because either they are restricted to not allow communication as in **Restricted AND-parallelism**, or they are involved in parallel evaluation of independent branches of the AND/OR-tree, as in **All-solutions AND-parallelism** and **OR-parallelism.**

In **Streamed AND-parallelism** we have a conjunction of goals to evaluate, hence the **AND-parallelism.** These goals share variables which can act as a means of communications between goals. If the evaluation of one goal binds a variable, the evaluation of the other goals that share the newly bound variable can use the binding. By incrementally binding a shared variable (*i.e.* binding it to a structure containing a message and a new shared variable), processes can view shared variables as communication streams, hence the term **Streamed AND-parallelism.**

This form of parallelism can be realised in producer/consumer programs. The producer goal incrementally binds some shared variable, the consumer goal is evaluated in parallel with this producer and incrementally consumes the bindings. This is evident in the case where a list is being produced using a recursive procedure and this list can be consumed incrementally using a recursive procedure; on each recursion the consumer processes the next element on the list. *Figure 2–4* is a example of a producer/consumer Horn clause program which can exploit **Streamed AND-parallelism.**

```
producer(Current, List) :-
    List = [Current|Rest],
    Next is Current + 1,
    producer(Next, Rest).

consumer([Head|Rest]) :- process(Head), consumer(Rest).

process(Item) :- write(Item).

    :- producer(1, List),consumer(List).
```

Figure 2–4: An example of **Streamed AND-parallelism**

The producer builds up a list of integers. Starting with 1 this list is built-up incrementally by a perpetual producer process. The consumer takes the first integer

from the list, processes it and consumes the rest of the list. The consumer given in *Figure 2–4* simply writes the next integer to the screen. Note that the expected behaviour of this consumer is that it should not reduce until the shared variable is instantiated to a list, that is its evaluation should be suspended until it can reduce with the required operational effect. Similarly, the `process/1` goal should suspend until the head of the list is instantiated to give the required behaviour. So in offering this form of parallelism, issues of communication, synchronisation and suspension must be considered.

The issue of insuring consistent binding in a model of AND-parallelism and shared variables can be addressed in two ways. Either all the goals are evaluated in parallel and parallel backtracking takes place if bindings become inconsistent or only one goal can bind a shared variable (the producer) and the other goals that share this variable are required to suspend until they can be evaluated without binding the variable. The first approach is a fully parallel evaluation of the AND-OR tree, while the second approach forms the basis of the CCND languages.

Streamed AND-parallelism may become **Restricted AND-parallelism** if the shared variables become fully bound; making the goals independent.

2.3.5 Implicit/Explicit parallel languages

Implicit parallel languages attempt to offer the forms of parallelism previously discussed without the programmer being aware of the parallel execution. The idea is to speed up the execution of current Prolog programs (for instance) by using parallel evaluation. However, the parallel evaluation of Prolog programs may be limited in the degree of parallelism that can be obtained, in that these programs may rely on the (sequential) operational semantics of the Prolog interpreter. Another problem is that **Streamed AND-parallelism** may be difficult to exploit as current sequential logic programs do not obviously exploit such a model of computation. So, parallelism is restricted to **All-solutions AND-parallelism**, **Restricted AND-parallelism** and **OR-parallelism**. Of these forms of paral-

lelism, **OR-parallelism** looks the most promising evaluation model for obtaining a speed-up. **All-solutions AND-parallelism** only applies if an exhaustive search is required. **Restricted AND-parallelism** can only be used if the conjunctive goals are independent.

In explicit parallel languages the programmer has to address the issue of controlling the parallel evaluation, *e.g.* the parallel search of clauses and the synchronisation of the **Streamed AND-parallelism**. The justification for this language design is that the programmer usually knows the forms of parallelism that exist in the problem domain, and hence is best able to implement the parallelism explicitly. Also, by adding **Streamed AND-parallelism** to the current procedural interpretation of Horn clauses, it may be possible to implement algorithms that cannot currently be implemented in Prolog.

This explicit control of parallelism can be achieved in two ways. Firstly, by the addition of parallel search operators to Prolog which indicate those parts of the computation that will be unaffected by a parallel operational model. Secondly, by the addition of a controlling semantics to restrict a fully parallel evaluation of the AND/OR-tree for the purposes of control and synchronisation. This second approach can be seen as the basis of the Committed Choice Non-Deterministic logic languages. These languages derive their name from the use of a commitment operator (similar to Dijkstra's guarded command [Dijkstra 75]) which is used to control the parallel evaluation of the OR-alternatives while allowing the exploitation of **Streamed AND-parallelism**. The major variation between the CCND languages lies in their means of synchronisation of bindings of shared variables.

2.4 Committed Choice Non-Deterministic languages

2.4.1 Syntax of guarded horn clauses

A Committed Choice Non-Deterministic (CCND) program is a finite set of guarded horn clauses of the form:

$$R(a_1, \ldots, a_k) \text{ :- } G_1, \ldots, G_n : B_1, \ldots, B_m \qquad (n, m \geq 0)$$

The different CCND languages adopt various names for the various components of the guarded horn clause. We use the following terminology for all the languages:

- $R(a_1, \ldots, a_k)$ is a head goal;
- R is its functor, or predicate name;
- **k** is the number of arguments (referred to as the predicate arity);
- $G_1, \ldots, G_n$ form the guarded goals;
- ":" is known as the commit operator;
- $B_1, \ldots, B_m$ are known as the body goals.

where the Gs and Bs are literals.

The **commit operator** generalises and cleans the **cut** of sequential Prolog; the **cut** is used to control and reduce the search of OR-branches in Prolog. The **commit operator** forms the means of pruning OR-branches in a parallel search.

A general query in the CCND languages has the following form:

$$\text{:- } C_1, C_2, \ldots, Cn$$

2.4.2 Semantics of guarded horn clauses

2.4.2.1 Declarative semantics

A guarded horn clause program has a similar declarative reading to Horn clause based programs (see section 2.2.2).

Each clause:

$$H \text{ :- } G_1, \ldots, G_n : B_1, \ldots, B_m$$

is read as:

H is true if G_1 and ...and G_n and B_1 and ...and B_m are all true.

2.4.2.2 Operational semantics

As with Horn clauses the declarative semantics of guarded horn clauses does not consider the meaning of a program for a given inference system. This operational, or procedural, meaning of the program is the set of goals that are provable given the program and the inference scheme.

In the CCND model the general feature of the evaluation of a conjunction of goals is as follows. A given goal in the conjunction **Ci** is evaluated by unifying the goal with the clauses in the system. Those clauses whose heads successfully unify are now possible solution paths for this goal. The guarded goals for the possible solution paths are then evaluated, this evaluation can take place in parallel. The first guarded system to terminate successfully causes the evaluation committing to the body goals of the given clause. These body goals are essentially added to the original conjunction for evaluation. This is known as a *reduction*. On commitment to a given clause the other OR-guard evaluations can be discarded.

In the CCND languages concurrency is achieved by reducing several goals in parallel; **Streamed AND-parallelism**. The issue of insuring consistent bindings of shared variables is addressed by only allowing a variable to be bound once. This

requires some means of indicating that some goals should not be allowed to bind shared variables while others may. This requirement can be achieved in two ways:

- the evaluation of some goal which should not bind a variable can only be instigated when the given variable becomes bound;
- the evaluation of goals that should not bind a variable can be suspended when they require the given variable to be bound.

The CCND languages adopt the second approach of suspending evaluations on undesired bindings. The CCND languages differ in their means of specifying and insuring which goals can be evaluated and which should suspend.

The following sub-sections consider the three main CCND languages, **Concurrent Prolog**, **Parlog** and **Guarded Horn Clauses**. This is followed by an example evaluation which highlights the difference in the synchronisation models they employ.

2.4.3 Concurrent Prolog (CP)

2.4.3.1 History and background

Concurrent Prolog (CP), proposed by Shapiro [Shapiro 83], was initially designed to offer both **Streamed AND-parallelism** and some **OR-parallelism** (in the evaluation of the guarded goals). Due to implementation problems [Ueda 85a] several restricted versions of the language have been proposed.

- Flat Concurrent Prolog, FCP, [Mierowsky *et al* 85], here guarded goals are restricted to system predicates.
- Safe Concurrent Prolog, SCP, [Codish 85], Codish introduces output annotations into Concurrent Prolog. A clause is safe if all output instantiations are made through variables declared as output.

- Dual Concurrent Prolog, DCP, [Levy 86b] Levy also introduces output annotation into Concurrent Prolog. The resulting language is claimed to be a simple extension of Guarded Horn Clauses, [Ueda 85b] which is complementary or **Dual** to Concurrent Prolog.

2.4.3.2 Basic concept

In Concurrent Prolog, communication is achieved by shared variables and synchronisation by declaring certain occurrences of these shared variables as **read only**. The evaluation of a goal will suspend if it attempts to bind a **read only** variable. Any instantiation made during the evaluation of the guarded goals is made in a local binding environment which is unified with the global environment at the time of trying to commit to a given clause.

2.4.3.3 Syntax of CP

Concurrent Prolog adds two syntactic constructs to that of the guarded horn clause.

- The **read only** annotation of variables, "?". Any occurrence of a variable in a clause can be read only annotated.

- The "otherwise" guarded goal.

2.4.3.4 Operational semantics of CP

The synchronisation mechanism for instantiating shared variables in a conjunction takes place through the **read only** annotation of variables. Any evaluation that tries to instantiate a read only variable must suspend evaluation until the unification can take place without causing the given instantiation. The issue of several guards instantiating a global variable is addressed by making local copies of the

instantiations to the global environment. Once a guard terminates successfully, several operations take place as follows:

- Local copies of instantiations are unified with those in the calling process, *i.e.* passing back instantiations made in the guard.
- If the unification is successful the other parallel guards for this evaluation are terminated, or ignored.
- The calling process is reduced to the body goals of the clause that was committed to.

The guarded goals for a given clause can be evaluated in AND-parallel and once commitment takes place the body goals can also be reduced in AND-parallel.

There is one remaining semantic addition to the language called the **otherwise** goal. This goal can appear as the first goal in the guard of a CP clause. The operational semantics for clauses are that predicates with an **otherwise** goal in their guard will not be evaluated until all the other clauses for this predicate have failed.

2.4.4 Parlog

2.4.4.1 History and background

Parlog [Gregory 85], [Gregory 87] is a descendant of the Relational Language [Clark & Gregory 81]. The major difference between PARLOG and the Relational Language is that the mode constraints are relaxed in the former, to allow **weak arguments**. A weak argument of a goal is one in which an input argument contains variables which may be instantiated by evaluation of the goal; hence allowing a form of two way communication (**back communication**).

2.4.4.2 Basic concepts

Synchronisation is achieved by declaring the inputs and outputs to every clause in the system. A goal can only attempt to be reduced by a clause if the arguments declared as input can be unified with the head of the clause without causing any instantiations in the goal being evaluated and if the output arguments are not instantiated. If head unification attempts to cause any instantiations of input arguments that clause evaluation is suspended.

2.4.4.3 Syntax of Parlog

Parlog adds three types of syntactic constructs to guarded horn clauses.

- Mode declarations take the form:

```
mode A(m1,.....mk).
```

  where **A** is the predicate name and each of the mi's of the mode is either **?**, or **^**, optionally preceded by an identifier, which has no semantic significance.

- OR-parallel operators which separate the clauses for a given relation. These can be either a "." or ";", *e.g. Figure 2–5.*

```
clause(1);
clause(2).
clause(3);
clause(4).
```

Figure 2–5: Possible use of the "." and ";" operators in Parlog

- AND-parallel operators which separate the goals in a conjunction, these can be "," or "&" as follows:

`(C1,C2) OR (C1 & C2)`

where `C1` and `C2` are both conjunctions of goals.

2.4.4.4 Operational semantics of Parlog

The mode declarations serve to synchronise the binding of shared variables in Parlog. A "?" in the mode declaration means that this argument of a goal cannot be instantiated on head unification or guard evaluation of a possible clause. If the head unification would result in an output instantiation the evaluation of the particular clause is suspended. "^ " in the mode declaration specifies the output arguments from the predicate, which will be output unified when a given clause is committed to.

Note that the input restriction means that there is no need for local guard environments. Guard evaluations suspend if they require an output instantiation to be made. The mode declarations can be used by the compiler to translate programs into a form with explicit unification and suspension tests, known as kernel Parlog [Gregory 87].

The operators "." and ";" which separate clauses for a given predicate serve to control the OR-parallel search:

- Clauses separated by the "." can be tried in parallel.
- Clauses separated by ";" are evaluated sequentially, *i.e.* the clause after the ";" can only be tried if the one before fails.

If we consider the example in *Figure 2–5*, the clauses are tried as follows: clause(1) is evaluated, if it fails clause(2) and clause(3) are evaluated in parallel. If the first three clauses fail, clause(4) is tried.

The "," and the "&" separators for conjunctive goals serve to control the degree of parallelism in the evaluation of the conjunction:

- `(C1 , C2)` means that `C1` and `C2` would be evaluated in parallel.

- `(C1 & C2)` means that `C2` is to be evaluated only when `C1` has successfully terminated.

2.4.5 Guarded Horn Clauses (GHC)

2.4.5.1 History and background

Guarded Horn Clauses (GHC), was intended to form the basis of a Kernel Language for the Japanese Fifth Generation Parallel Inference Machines. GHC was proposed by Kazunori Ueda in 1985 [Ueda 85b]. A restricted version of GHC has been proposed based on the AND-parallel subset of the language and with the restriction of system goals in the guard. This is known as Flat Guarded Horn Clauses (FGHC).

2.4.5.2 Basic concepts

GHC adopts a unique approach to the problem of offering **Streamed AND-parallelism**. In GHC synchronisation is achieved by giving special significance to the semantics of the commit operator. The basic idea is that no output instantiations can occur until the evaluation has committed to a given clause. If the system tries to instantiate a variable in the goal being executed before commitment, the evaluation suspends. By adopting this form of synchronisation, the part of the clause before the **commit operator** just forms a test for input instantiation.

2.4.5.3 Syntax of GHC

GHC adds one new syntactic constructs to guarded horn clauses, the "**otherwise**" guarded goal.

2.4.5.4 Operational semantics of GHC

GHC adopts only one synchronisation rule for **Streamed AND-parallelism**, that is no instantiations may be passed to the calling goal in the **passive part** of the clauses - the head unification and the guarded evaluation. So output instantiations can only occur after commitment to a given OR-branch. There is one remaining semantic addition to the language, the **otherwise** goal. This construct has been borrowed from CP and has the same purpose and operational semantics as in CP.

2.4.6 An example of a CCND program, and its evaluation

In this section we consider a simple example program, quick-sort, to highlight the different suspension mechanisms proposed for the CCND languages. This example was first commented on for CP in [Shapiro 1983]. *Figures 2–6*, *2–7* and *2–8* respectively provide the CP, Parlog and GHC versions of the quick-sort program.

If we query the system with the goal *X*`quicksort([2,1,3],N)`, (*X* - is "c" for CP goals; "p" for Parlog goals; and "g" for GHC goals) this goal can reduce itself with clause (1) as follows:

```
Xquicksort([2,1,3],X) :- Xqsort([2,1,3],X-[]).
```

X`qsort([2,1,3],X-[])` in turn has two possible clauses to match against, but can only unify itself with the head of clause (1), resulting in the reduction:

```
Xqsort([2,1,3],X-[]) :-
    Xpartition([1,3],2,Y,Z),
    Xqsort(Y,X-[2|W]),
    Xqsort(Z,W-[]).
```

```
(1) cquicksort(Unsorted, Sorted) :-
        cqsort(Unsorted, Sorted-[]).

(1) cqsort([X|Unsorted], Sorted-Rest) :-
        cpartition(Unsorted?, X, Smaller, Larger),
        cqsort(Smaller?, Sorted-[X|SortedTemp]),
        cqsort(Larger?, SortedTemp-Rest).
(2) cqsort([], Rest-Rest).

(1) cpartition([X|Xs], A, Smaller, [X|Larger]) :-
        A < X
        :
        cpartition(Xs?, A, Smaller, Larger).
(2) cpartition([X|Xs], A, [X|Smaller], Larger) :-
        A >= X
        :
        cpartition(Xs?, A, Smaller, Larger).

(3) cpartition([],_,[],[]).
```

(each clause is numbered for reference purposes)

Figure 2–6: Quick-sort program in Concurrent Prolog

The system now contains processes for three goals. In the case of CP the three new goals will be read-only annotated as follows:

```
cpartition([1,3]?,2,Y,Z),
cqsort(Y?,X-[2|W]),
cqsort(Z?,W-[]).
```

The two Xqsort processes suspend, because:

CP their evaluation by any clause would result in the binding of a read only variable;

Parlog their input arguments are not yet instantiated and would be bound during their reduction;

```
    mode pquicksort(?,^),pqsort(?,^),ppartition(?,?,^,^).

(1) pquicksort(Unsorted, Sorted) :-
        pqsort(Unsorted,Sorted-[]).

(1) pqsort([X|Unsorted], Sorted-Rest) :-
        ppartition(Unsorted, X, Smaller, Larger),
        pqsort(Smaller, Sorted-[X|SortedTemp]),
        pqsort(Larger, SortedTemp-Rest).

(2) pqsort([], Sorted-Rest) :- Sorted = Rest.

(1) ppartition([X|Xs], A, Smaller, [X|Larger]) :-
        A < X
        :
        ppartition(Xs, A, Smaller, Larger).

(2) ppartition([X|Xs], A, [X|Smaller], Larger) :-
        A >= X
        :
        ppartition(Xs, A, Smaller, Larger).

(3) ppartition([],_,[],[]).
```

(each clause is numbered for reference purposes)

Figure 2–7: Quick-sort program in Parlog

GHC the passive part of the two clauses that these goals could be reduced by would instantiate the goal arguments.

The Xpartition goal can be reduced:

CP the goal has its read only term bound to `[1,3]` so it evaluation can proceed;

Parlog the goal has all its input instantiated, so its evaluation can proceed;

GHC the goal can be unified with the head of both clause (1) and clause (2), without instantiating goal variables, so its evaluation can proceed.

```
(1) gquicksort(Unsorted, Sort      -
        gqsort(Unsorted, Sorted-[]).

(1) gqsort([Pivot|Unsorted], Sorted-Rest) :-
        gpartition(Unsorted, Pivot, Smaller, Larger),
        gqsort(Smaller, Sorted-[Pivot|Sorted1]),
        gqsort(Larger, Sorted1-Rest).
(2) gqsort([], Rest0-Rest1) :-
        Rest0 = Rest1.

(1) gpartition([Value|List], Pivot, Smaller, BigOut) :-
        Pivot < Value :
        BigOut = [Value|Larger],
        gpartition(List, Pivot, Smaller, Larger).
(2) gpartition([Value|List], Pivot, LessOut, Larger) :-
        Pivot >= Value :
        LessOut = [Value|Smaller],
        gpartition(List, Pivot, Smaller, Larger).
(3) gpartition([], Pivot, Smaller, Larger) :-
        Smaller = [], Larger = [].
```

(each clause is numbered for reference purposes)

Figure 2–8: Quick-sort program in GHC

Its head matches both clause (1) and clause (2), and so invokes two subsystems for the two guards; only the second guard, (`2 >= 1`) succeeds and so clause (2) is used to reduce Xpartition:

CP

```
cpartition([1,3]?,2,[1,X],Y) :- ppartition([3]?,2,X,Y).
```

Parlog

```
ppartition([1,3],2,[1,X],Y) :- ppartition([3],2,X,Y).
```

GHC

```
gpartition([1,3],2,X,Y) :-
    X = [1|X1],
    gpartition([3],2,X1,Y).
```

As a result of this reduction, the read only argument of the first suspended Xqsort goal has become instantiated to `[1|X]`, so it can proceed:

CP

```
cqsort([1|X]?,Y-[2|Z]) :-
    cpartition(X?,1,V,W),
    cqsort(V?,Y-[1|Z1]),
    cqsort(W?,Z1-[2|Z]).
```

Parlog

```
pqsort([1|X],Y-[2|Z]) :-
    ppartition(X,1,V,W),
    pqsort(V,Y-[1|Z1]),
    pqsort(W,Z1-[2|Z]).
```

GHC

```
gqsort([1|X1],Y-[2|Z]) :-
    gpartition(X1,1,V,W),
    gqsort(V,Y-[1|Z1]),
    gqsort(W,Z1-[2|Z]).
```

However, these three new processes suspend (the fact that qsort could be run at all is because of the message-passing, which is facilitated by shared variables). The only process that can proceed is X`partition([3]?,2,X,Y)`, which is reduced to:

CP

```
cpartition([3]?,2,X,[3|W]) :- cpartition([]?,2,X,W).
```

Parlog

```
ppartition([3],2,X,[3|W]) :- ppartition([],2,X,W).
```

GHC

```
gpartition([3],2,X,Y) :- Y=[3|W], gpartition([],2,X,W).
```

As a result of this reduction, the first argument of the second X`qsort` goal becomes instantiated, so its evaluation can proceed:

CP

```
cqsort([3|X]?,Y-[]) :-
    cpartition(X?,3,U,V),
    cqsort(U?,Y-[3|Y1]),
    cqsort(V?,Y1-[]).
```

Parlog

```
pqsort([3|X],Y-[]) :-
    ppartition(X,3,U,V),
    pqsort(U,Y-[3|Y1]),
    pqsort(V,Y1-[]).
```

GHC

```
gqsort([3|X],Y-[]) :-
    gpartition(X,3,U,V),
    gqsort(U,Y-[3|Y1]),
    gqsort(V,Y1-[]).
```

All the remaining reductions use unit clauses, and occur as:

CP their read only variables become bound;

```
cpartition([]?,2,[],[]) :- true
cpartition([]?,1,[],[]) :- true
cqsort([]?,[1|X]-[1|X]) :- true
cqsort([]?,[2|X]-[2|X]) :- true
cpartition([]?,3,[],[]) :- true
cqsort([]?,[3|X]-[3|X]) :- true
cqsort([]?,[]-[]) :- true
```

Parlog their input arguments become instantiated;

```
ppartition([],2,[],[]) :- true
ppartition([],1,[],[]) :- true
pqsort([],[1|X]-[1|X]) :- true
pqsort([],[2|X]-[2|X]) :- true
ppartition([],3,[],[]) :- true
pqsort([],[3|X]-[3|X]) :- true
pqsort([],[]-[]) :- true
```

GHC their input arguments become instantiated.

```
gpartition([],2,X,Y) :- X=[], Y=[].
gpartition([],1,X,Y) :- X=[], Y=[].
gqsort([], X1-X2) :- X1 = X2.  (X2 = [1|X])
gqsort([], X1-X2) :- X1 = X2.  (X2 = [2|X])
gpartition([],3,X,Y) :- :  X=[], Y=[].
gqsort([], X1-X2) :- X1 = X2.  (X2 = [3|X])
gqsort([], X1-X2) :- X1 = X2.  (X2 = [])
```

The computation terminates with `X = [1,2,3]`.

2.5 Classifications

Although the CCND languages and their subsets adopt different synchronisation mechanisms the languages possess some similar features. Algorithms and programming techniques that make use of a given feature of a language will be portable to other languages with similar features. In our evaluation of the CCND languages for AI (part 3 of this thesis) we consider how some well known AI programming paradigms map to languages with different features. We then examine the execution behaviour of programs which make use of the different language features.

Two main groupings of the language features are widely recognised, these are detailed below. The AI applications considered later in this thesis highlight the differences between the languages in these two groups.

2.5.1 Safe/Unsafe

A clause is defined to be **safe** if and only if for any goal the evaluation of the head unification and guarded goals never instantiate a variable appearing in the goal to a non-variable term [Clark & Gregory 84]. This definition has been expanded by [Takeuchi & Furukawa 86] as follows:

- for any goal the evaluation of the head and guarded goals never instantiate a variable appearing in the goal to a non-variable;
- each clause in the program is **safe**;
- as a result, any program written in the language is **safe**;

The design of Parlog is supposed to exclude any programs which would violate the safety condition. It is proposed that the legality of programs could be checked at compile time. However, current attempts at performing this analysis exclude

possible legal programs [Gregory 87]. GHC is a **safe** language, in fact the suspension rule of GHC is based on guard safety. If a clause requires a goal variable to be instantiated in the guard the evaluation of that clause suspends. Concurrent Prolog is **unsafe**; goal variables are allowed to be instantiated by the evaluation of the guard. On commitment these bindings are unified with the global copies of the variables. The use of local environments results in difficulties in implementing Concurrent Prolog [Ueda 85a].

2.5.2 Deep/Flat

A program which only has system goals in the guards is said to be **flat** [Mierowsky *et al* 85] [Foster & Taylor 87]. This results in a simple language which still offers **Streamed AND-parallelism**; as the guarded evaluations are simple. This reduces the complexity of implementing the languages. Moreover, it should be possible to compile the full language into its **flat** subset. [Gregory 87] discusses how OR-parallel evaluation can be compiled to AND-parallel evaluation by using a *controlled metacall.* [Codish 85] provides a source to source transformation technique which does not require the introduction of a new language primitive.

2.6 Implementations

The development of the CCND languages has taken the following path. Firstly interpreters were implemented in Prolog [Shapiro 83], [Pinto 86]. These were followed by compilers where the target language was Prolog [Gregory 84], [Ueda & Chikayama 85]. Subsequently, compilers were produced where the target language was an abstract machine, which is emulated by a 'C' program [Foster *et al* 86]. Enough is now generally understood about the operational semantics of the languages to be able to consider implementation on a parallel architecture [Crammond 88]. Although interpreters allow the synchronisation mecha-

nism in **Streamed AND-parallelism** to be tested and the operational semantics of the language to be studied, they provide slow execution speed. Compiling to Prolog offers some speed up giving better performance, while still allowing for quick development time and testing of the evaluation model. Writing a compiler to 'C' allows for the unification and synchronisation primitives to be tested for implementability and gives even further improved performance.

2.6.1 Interpreters

One of the strengths of logic programming languages is the ability to implement **interpreters**[1] easily. This is in the main due to the equivalence of program and data in a logic programming framework. *Figure 2–9* is a simple interpreter for Prolog in Prolog[2].

```
solve(true).
solve((A,B)) :- solve(A), solve(B).
solve(A) :- clause(A,B), solve(B).
```

Figure 2–9: An interpreter for Prolog in Prolog

A declarative reading of this program is:

- The goal `true` is solved.
- To solve a conjunction `(A,B)` solve `A` and solve `B`.

---

[1]A interpreter treats other programs as data.

[2]Interpreters for a language in the same language are sometimes referred to as meta-circular interpreters.

- To solve a goal, pick a clause[3] from the program (whose head unifies with the goal) and solve the body goals of this clause.

The correct Prolog behaviour of this interpreter is due to the procedural (operational) reading of this interpreter. The behaviour of this interpreter using the Prolog model of evaluation is:

- if a goal is `true` then it is solved;
- to solve a conjunction `(A,B)` first solve the left most goal `A` and then solve the other goals `B`;
- to solve a goal, pick the first clause (textually) from the program (whose head unifies with the goal) and then solve the body goals of this clause;
- if the evaluation of the body goals fails then `clause/2` will select the next possible clause (textually) from the program.

2.6.1.1 Enhanced interpreters

Interpreters can be used to offer different models of execution, add functionality to the language, and provide information about program evaluation. Such interpreters are often referred to as **enhanced interpreters** [Safra & Shapiro 87]. In this section we consider three enhanced interpreters. The first and second shows how interpreters can be instrumented to collect information about program execution. The third shows how interpreters can be used to offer alternative models of execution. We consider these three systems as they provide suitable background

---

[3]The `clause/2` call is required to manipulate the program as data. Such calls are known as metacalls.

examples to interpreters and to some of the techniques employed in the implementation of our evaluation interpreter for the CCND languages (part 2 of this thesis).

For example, *Figure 2–10* is an enhanced interpreter which records the number of resolution steps performed in the evaluation of a goal.

```
solve(Query,Count) :-
    solve(Query,0,Count).

solve(true,C,C).
solve((A,B),Cin,Cout) :-
    solve(A,Cin,Cnext),
    solve(B,Cnext,Cout).
solve(Goal,Cin,Cout) :-
    Cnext is Cin +1,
    clause(Goal,Body),
    solve(Body,Cnext,Cout).
```

Figure 2–10: An interpreter for counting resolutions in Prolog

The number of resolution steps recorded by this interpreter reflects the number of procedure calls along the solution path; that is resolution steps performed in branches of the search which lead to failure are not recorded.

To count the total number of procedure calls performed in the evaluation of a goal requires a more complex interpreter. The main feature of such an interpreter is that it should not fail when a goal evaluation fails, as this will lead to backtracking and loss of the reduction count for the failed branch. Instead the interpreter should carry a **status** flag which indicates the success or failure of a given goal evaluation. On each procedure call the interpreter increments a counter. If a goal evaluation succeeds the interpreter returns the current counter value and sets the status flag to **success**. If a goal evaluation fails the interpreter returns the current counter value and sets the status flag to **fail**. The interpreter should try each of the clauses

```
solve(true,succeeded,R,R).
solve((A,B),ConjStatus,R0,R) :- !,
    solve(A,Status,R0,R1),
    (   Status=succeeded,
        solve(B,ConjStatus,R1,R)
    ;
        Status=failed,
        ConjStatus=failed,
        R=R1
    ).
solve(Goal,Status,R0,R) :-
    copy(Goal,GoalCopy),
    bagof((GoalCopy:-Body),clause(GoalCopy,Body),BodyList),
    R1 is R0+1, !,
    solve_bodygoals(Goal,BodyList,R1,R,Status).
solve(_,failed,R,R).

solve_bodygoals(_,[],R,R,failed).
solve_bodygoals(Goal,[(Head:-Body)|More],R0,R,GoalStatus) :-
    solve(Body,Status,R0,R1),
    (   Status=succeeded,
        Head=Goal,
        GoalStatus=succeeded,
        R=R1
    ;
        Status=failed,
        solve_bodygoals(Goal,More,R1,R,GoalStatus)
    ).

copy(Original, Copy) :-
    bagof(Original, true, [Copy]).
```

Figure 2–11: An interpreter for counting procedure calls in Prolog

for a given goal (top-down) until one results in a solution. As the interpreter has a count of the procedure calls performed in the failed branches, it can aggregate them to give the total number of procedure calls performed in the evaluation of a goal. Such an interpreter is given in *Figure 2–11.*

```
solve([]).
solve([true|Rest]) :-
    solve(Rest).
solve([Goal|Rest]) :-
    clause(Goal,Body),
    addtolist(Rest,Body,NewGoals),
    solve(NewGoals).

addtolist([H|T],Goals,[H|R]) :-
    addtolist(T,Goals,R).
addtolist([],(A,B),[A|R]) :-
    addtolist([],B,R).
addtolist([],Goal,[Goal]) :- Goal \= (A,B).
```

Figure 2–12: An interpreter for breadth-first evaluation of Horn clauses

The two enhanced interpreters considered so far have both provided information about the evaluation. We now consider a interpreter which provides a different model of execution. *Figure 2–12* shows an interpreter which evaluates the conjunction of goals breadth-first; that is, all the goals are reduced to their body goals, then those body goals are evaluated. As each goal is reduced the body goals are added to a continuation [4]. The breadth-first nature of the interpreter is achieved by adding the body goals to the end of the continuation.

---

[4] A list of goals that are to be solved upon successful reduction of this goal.

2.6.1.2 Interpreters for the CCND languages

When Shapiro first proposed Concurrent Prolog [Shapiro 83] [Shapiro 87a] he also presented a interpreter in Prolog for the new language. The interpreter maintains a queue (continuation) of Concurrent Prolog goals and a status flag.

To solve a query, the interpreter schedules the goals in the queue which also contains a cycle marker (used to indicate when all the goals have been attempted), and sets a status flag to `deadlock`. It then operates on each of the goals in the queue, dequeueing a goal, reducing it, and scheduling the body goals (according to the scheduling policy). If a goal reduction suspends, or fails to be reduced, the goal is placed at the end of the queue. The top level of the interpreter has the following procedural reading:

- If the queue only contains a cycle marker, then the interpreter terminates successfully.
- If each goal in the queue has been attempted and the status flag is `deadlock`, then the interpreter fails.
- If each goal in the queue has been attempted and the status flag is `nodeadlock`, then re-enqueue the cycle marker, set the status flag to `deadlock` and continue solving the remaining goals.
- If the dequeued goal is a system call, evaluate it and then solve the remaining goals in the queue.
- To reduce a Concurrent Prolog goal, the interpreter sequentially picks a guarded clause whose head unifies with the goal (according to Concurrent Prolog's unification algorithm). It then attempts to solve the guarded goals for this clause (by recursively calling itself). If the interpreter finds a clause (by backtracking) which satisfies such requirements, then the body goals for the clause are scheduled for evaluation.

The scheduling policy used in the interpreter for the goals is breadth-first, that is the body goals are scheduled at the back-end of the goal queue. However, because the guarded goals are evaluated by recursively calling the interpreter, the evaluation of the OR-goals is not breadth-first. The guarded clause selection, which involves using Concurrent Prolog's read-only unification, is given in [Shapiro 83].

Shapiro also proposed three profiling parameters, **cycles, reductions** and **suspensions**, which provide information about the evaluation.

- Cycles

  The cycles parameter attempts to measure the length of the breadth-first execution. A cycle corresponds to attempting to reduce all the goals in the system once in parallel.

- Reductions

  This parameter aims to give a measure of the work involved in solving a query. The parameter attempts to measure the number of inference steps performed by the system. In [Shapiro 83] an inference step is considered to be a commitment to a clause.

- Suspensions

  This parameter attempts to count the number of suspended evaluations in the evaluation of a query. The number of suspensions is however dependent on when suspended evaluations are rescheduled. When an evaluation suspends in Shapiro's interpreter it is immediately rescheduled for evaluation; this is known as **busy waiting**. This rescheduled evaluation may resuspend and so will count as two or more suspensions.

The **cycles, reductions** and **suspensions** have become the standard parameters used when comparing applications and programming techniques [Okumura & Matsumoto 87], [Sterling & Codish 87].

2.6.2 Abstract machine emulators

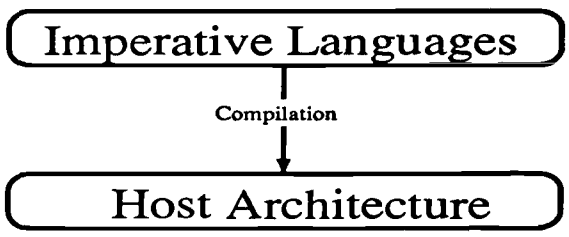


Figure 2–13: Execution of imperative languages

Compiling source language programs to the host machine proves to be a suitable way of executing many imperative languages. However, these languages are in a sense close to the "von-Neumann" target machine, this is not surprising given that their development has been based on such architectures. The same cannot be said of logic languages [Fagin *et al* 85]. One solution is to specify an abstract host machine which is more suited to the declarative language (logic language).

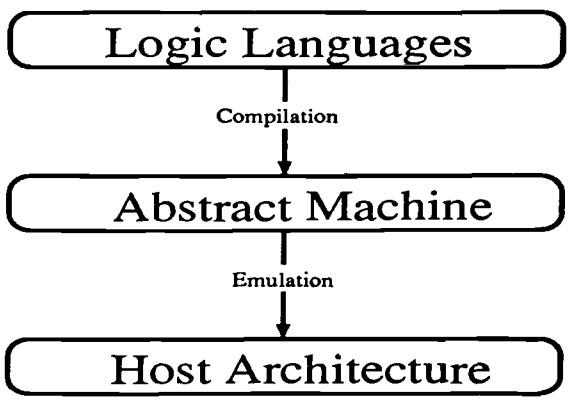


Figure 2–14: Execution of logic languages

The abstract machine can then be emulated by interpretation (see *Figures 2–13 and 2–14*). This results in a speed advantage over pure interpretation in that

much of the run-time overheads of unification and flow of control can be compiled away. Over pure compilation it results in a space advantage, in that the abstract machine is more closely tailored to the logic language and so a more (direct) efficient mapping exists.

A number of abstract machines have been proposed for logic languages, the most well known being [Warren 77a] [Warren 77b] [Warren 83] who proposed an abstract machine for Prolog. This notion of abstract machine emulation has also been applied to concurrent/parallel logic languages, the many different types of parallelism (see section 2.3) giving rise to a whole host of different abstract machines [Foster *et al* 86] [Houri & Shapiro 87] [Kimura & Chikayama 87] [Shapiro 87b] [Warren 87] [Crammond 88].

2.6.3 Multi-processor implementations

The Concurrent Logic Languages are amenable to parallel execution; in fact, this has been one of the driving forces in their development. The work on multi-processor realisations of these languages is split into two main areas.

- The first area of work is on the implementation of these languages on shared memory multi-processors, like the Sequent Symmetry^{TM}, [DeGroot 84] [Crammond 85] [Hausman *et al* 87] [Warren 87] [Westphal *et al* 87] [Crammond 88] [Sato & Goto 88]. With shared memory implementation, global binding schemes can be implemented directly, *i.e.* each processor manipulates the same data areas.

- The second area of work is on the implementation of these languages on distributed memory multi-processors, like the Intel iPSC Hypercube^{TM}, [Ali 86] [Conery 87] [Taylor *et al* 87]. With a distributed memory implementation either data areas are stored on one processor, or distributed binding and unification schemes are required. This makes distributed implementations more complex.

2.7 Summary

In this chapter the following have been presented and discussed:

- How logic can be used as a programming language, in particular via Horn clauses and the sequential evaluation model of Prolog.

- The various forms of parallel evaluation of programs specified in Horn clauses, namely OR-parallelism, Restricted AND-parallelism, All-Solutions AND-parallelism and Streamed AND-parallelism.

- The Committed Choice Non-Deterministic (CCND) model of execution. The synchronisation mechanisms for the three main CCND languages, Concurrent Prolog, Parlog and Guarded Horn Clauses, are highlighted using an example sort program.

- The CCND languages are then classified in two ways: **safe/unsafe** and **deep/flat**. In the evaluation of the CCND languages for AI (part 3 of this thesis) we consider how some well known AI programming paradigms map to languages with different features.

- Finally we review current implementations of these languages, in particular the modelling of the execution of these languages by enhanced interpreters.

Part II

An evaluation system

Preface

In this part of the thesis we develop our evaluation system for the CCND languages. The system developed aims to measure the inherent parallelism available in the execution of programs implemented in the CCND languages and the effects of alternative implementation possibilities on this inherent behaviour.

The first chapter in this part, chapter 3 has three main focuses:

- the limitations of current evaluation systems;
- the requirements of an improved model of execution on which we can collect information about the inherent behaviour of programs; and
- the incremental design and development of an interpreter which provides the basis of our new evaluation system.

The second chapter in this part, chapter 4 also has three main focuses:

- the possible implementation alternatives open to language implementors, which form the basis of a set of evaluation parameters;
- how we collect these evaluation parameters; and
- the theoretical behaviour of some example programs and the behaviour indicated using our evaluation system and proposed evaluation parameters.

Chapter 3

Interpreters for evaluation

3.1 Overview

This chapter considers the inherent parallelism available in the evaluation of programs implemented in the CCND languages. A measure of the inherent parallelism has several uses: it gives a theoretical measure of parallelism against which particular implementations can be gauged; and it provides information for programmers on the relative merits of various programming techniques.

For typical Computer Science application areas, such as matrix multiplication, it is often possible to obtain theoretical measures for the inherent parallelism. However, for AI type problems the parallelism depends on several factors, such as data structures (knowledge representation), inference mechanisms and irregular search spaces. The irregular nature of AI problems makes a theoretical measure of parallelism difficult. Another approach to obtaining measures of inherent parallelism for both regular and irregular problems is to simulate the given computation on an infinite processor model. The simulated processor utilisation then gives a measure of the inherent parallelism.

It is this second approach we adopt in this work. To obtain a measure of the inherent parallelism available in program execution we adopt a breadth-first

execution model assuming an unlimited number of processors. The evaluation system developed is used in the following chapters to consider some of the execution alternatives open to language implementors.

Section 3.2 considers some current evaluation systems for the CCND languages. The focus is on interpretation systems as these are generally used when evaluating and comparing programming techniques and applications.

Section 3.3 considers the current parameters that are collected during program execution and discusses their limitations as a way of measuring inherent parallelism.

Section 3.4 considers the requirements of an execution system which will allow us to more accurately obtain a measure of the inherent parallelism.

In section 3.5 we give an overview of the idealisations we assume in our execution model.

Finally, in section 3.6 we incrementally develop an interpreter which offers an improved AND/OR-parallel evaluation model which allows us to measure the inherent parallelism available in the execution of a program more accurately.

3.2 Current evaluation systems

The first implementations of the CCND languages consisted of interpreters on top of Prolog [Shapiro 83] [Gregory 84] [Tanaka *et al* 86] [Pinto 86], these were instrumented to record simple parameters, namely **cycles, suspensions** and **reductions** (see section 2.6.1.2). To measure the inherent parallelism of programs these interpreters use a breadth-first evaluation model. Subsequently, compilers to Prolog were produced. The compiled code could also include mechanisms for collecting **cycles, suspensions** and **reductions** [Gregory 84] [Ueda & Chikayama 85] [Saraswat 87a]. These compilers to Prolog could be viewed as partial evaluators of the original interpreters [Safra & Shapiro 87]. More recently, these languages

have been implemented via abstract machine emulators realised in 'C' (see section 2.6.2) [Foster *et al* 86] [Levy 86a] [Chikayama & Kimura 87], giving a speed-up over the original interpreters and compilers. However, for efficiency reasons these systems tend not to be instrumented, as in [Foster *et al* 86]. So, the evaluation of programming techniques and applications tends to be carried out on interpreters [Sterling & Codish 87] [Okumura & Matsumoto 87]. Although these interpreters claim to execute the object code (CCND program) breadth-first (see section 2.6.1.2), hence collecting information about inherent parallelism, the actual evaluation models used make several approximations, as follows:

- the AND-parallel goals are represented as a list of goals to be evaluated;
- as each goal is reduced, the resulting body goals are added to the goal list and any appropriate bindings are made;
- variable bindings are produced in the order that the goals are evaluated;
- guarded goals are evaluated as a single reduction which incur no cycle overheads;
- the interpreters make no distinction between suspension and failure of guarded goals;
- the interpreters model OR-parallelism by backtracking through alternative clauses;
- the first textual clause in a predicate whose guarded goals succeed is committed to.

```
solve(Goal) :-
        schedule(Goal,[],QueueTemp),
        append(QueueTemp,[cycle],Queue),
        solve(Queue,deadlock).

solve([cycle],_) :- !.
solve([cycle|_],deadlock) :- !,fail.
solve([cycle|Rest],nodeadlock) :-
        append(Rest,[cycle],NextQueue),!,
        solve(NextQueue,deadlock).
solve([Goal|Rest],_) :-
        system(Goal),!,Goal,
        solve(Rest,nodeadlock).
solve([Goal|Rest],_) :-
        get_modes(Goal,Functor,Arity,GoalArgs,Modes),
        functor(ClauseHead,Functor,Arity),
        clause(ClauseHead,(Guard:Body)),
        ClauseHead =.. [Functor|HeadArgs],
        verify_modes(Modes,GoalArgs,HeadArgs),
        solve(Guard),!,
        schedule(Body,Rest,NewQueue),
        solve(NewQueue,nodeadlock).
solve([Goal|Rest],DeadlockFlag) :-
        schedule(suspended(Goal),Rest,NewQueue),
        solve(NewQueue,DeadlockFlag).

schedule(true,Queue,Queue) :- !.
schedule(suspended(Goal),CurrentQueue,NewQueue) :-,!,
        append(CurrentQueue,[Goal],NewQueue).
schedule((A,B),Queue,NewQueue) :- !,
        schedule(A,Queue,TempQueue),
        schedule(B,TempQueue,NewQueue).
schedule(Goal,CurrentQueue,NewQueue) :-
        append(CurrentQueue,[Goal],NewQueue).
```

Figure 3–1: A basic Parlog interpreter in Prolog

```
get_modes(Goal,Functor,Arity,GoalArgs,Modes) :-
        functor(Goal,Functor,Arity),
        functor(Copy,Functor,Arity),
        par_mode(Copy),
        Goal =..[Functor|GoalArgs],
        Copy =..[Functor|Modes].

verify_modes([],[],[]) :- !.
verify_modes(['?'|Modes],[GArg|GArgs],[HArg|HArgs]) :- !,
        '<='(HArg,GArg),
        verify_modes(Modes,GArgs,HArgs).
verify_modes(['^'|Modes],[GArg|GArgs],[HArg|HArgs]) :-
        ':='(GArg,HArg),
        verify_modes(Modes,GArgs,HArgs).

% '<='/2 ONE WAY UNIFICATION PRIMITIVE
'<='(X,Y) :-
        var(X), !, X=Y.
'<='(_,Y) :-
        var(Y), !, fail.
'<='([X|Xs],[Y|Ys]) :- !,
        '<='(X,Y), '<='(Xs,Ys).
'<='(X,Y) :-
        atomic(X), !, X=Y.
'<='(X,Y) :-
        X=..[F|Xs], Y=..[F|Ys], '<='(Xs,Ys).

% ':='/2 ASSIGNMENT UNIFICATION PRIMITIVE
':='(X,Y) :-
        var(X),X=Y.
```

Figure 3–2: Mode based unification for PARLOG in Prolog

3.3 Current measurements and their limitations

Shapiro proposed three parameters, **cycles**, **suspensions** and **reductions** (see section 2.6.1.2) when he first proposed Concurrent Prolog [Shapiro 83]. These parameters are usually quoted when evaluating applications and programming techniques for CCND languages [Sterling & Codish 87], [Okumura & Matsumoto 87]. This thesis uses Parlog as a typical CCND language. *Figures 3–1* and *3–2* provide a basic breadth-first Parlog interpreter (based on Shapiro's basic Concurrent Prolog interpreter, given in [Shapiro 83]). Later in this section we incrementally enhance this basic Parlog interpreter to provide a system which can be used to obtain improved measures of the inherent parallelism. In this section we highlight the limitations of the current parameters collected by interpretation. In the following section we consider requirements for a system which evaluates CCND programs in a breadth-first manner assuming an unlimited number of processors. These requirements are then implemented for one of the CCND languages, Parlog; although they are equally valid for the other CCND languages.

3.3.1 Cycles

The **cycles** [Shapiro 83] parameter attempts to measure the depth of the breadth-first execution tree. A cycle corresponds to reducing all the goals in the system once in parallel. So if we consider the simple member check program and query in *Figure 3–3*, the query takes *three* cycles to reduce, as it recurses *three* times on its single body goal.

In the early interpreters [Shapiro 83] [Pinto 86], the evaluation of guarded goals was carried out by a call to a top-level of the interpreter and for simplicity took *zero* cycles to evaluate. So the cycle count can only claim to measure

```
mode member(?,?).
member(Element,[Head|Tail]) :-
    Element == Head
    :
    true.
member(Element,[Head|Tail]) :-
    Element \== Head
    :
    member(Element,Tail).

:- member(foo,[baz,baz1,foo,baz2]).
```

Figure 3–3: Member check in Parlog

the depth of the evaluation tree when evaluating **flat** code [Mierowsky *et al* 85], [Foster & Taylor 87]. Moreover, in the case of **deep** guards, any goals suspended awaiting the evaluation of a guard will only suspend for one cycle and not the number of cycles it takes for the **deep** guard to be evaluated. This distorts the breadth-first evaluation tree, reducing the cycle count.

```
mode foo(?),bas(^ ),bas1(?,^ )
foo(b).
bas(a).
bas1(a,b).

:- foo(X), bas1(Y,X), bas(Y).
```

Figure 3–4: Simple example program for suspensions

Another limitation is that the goal list in the interpreters is processed in a left-to-right order, any bindings made in the evaluation of goals taking place immediately. So, these bindings will be available to any remaining goals in the goal list. This will allow goals that require these bindings to reduce in the current cycle. Hence the evaluation is dependent on goal order.

If we consider the program in *Figure 3–4*, then by changing the order of the query to be:

```
:- bas(Y),bas1(Y,X),foo(X).
```

the existing interpreters will give a cycle count of *one*, whereas the previous query *(Figure 3–4)* resulted in a cycle count of *three*. Previously the goal evaluation order resulted in the goals `foo(X)` and `bas1(Y,X)` suspending in the first cycle and the goal `foo(X)` suspending in the second cycle. However, now the goal evaluation order and the order in which the bindings are produced are the same. So, all the goals are able to reduce to `true` in one cycle. In an AND-parallel evaluation, the cycle count should be *three*, as follows: in the evaluation of the first cycle both `foo(X)` and `bas1(Y,X)` will suspend; in the second cycle `foo(X)` will suspend and in the last cycle all the goals will evaluate to `true`.

3.3.2 Reductions

This parameter attempts to measure the reductions performed by the system in solving a query, which indicates the number of parallel goal evaluations that can take place. For the example query in *Figure 3–3*, the number of reductions measured by Shapiro's interpreter is *three*; where each commitment counts as a reduction. The evaluation of system calls, supported by calls to the underlying Prolog, are not counted as reductions. However, these system calls do contribute to the overall work done in evaluating programs. By ignoring their contribution the comparison of programming techniques which make use of system primitives is meaningless or at best misleading. If we also consider the successful system calls as reductions, then the evaluation will now perform *six* reductions (*three* more because of system guards) [1].

---

[1]It may be the case that some system calls like == should not be counted as a reduction as they are simple, and could be compiled to be part of the head unification. However,

Another limitation is that current interpreters try evaluating the alternatives for a given predicate top-down, committing to the first clause whose guarded goals succeed. So reductions can only be counted for the clauses that have been attempted. Hence the reduction count depends on the order of the clauses. In a parallel OR-evaluation model the set of guarded goals for the clauses whose head unified successfully should be evaluated in parallel, the evaluation committing to the first clause whose guard succeeds.

Finally if a goal fails, then in the current interpreters it is rescheduled and may be re-attempted (the failed goal will be re-evaluated if the computation goes on for further cycles before the whole computation deadlocks). The re-evaluation of failed goals may introduce erroneous statistics into the reduction count (that is if reductions are performed in a **deep** guard evaluation before failure, these reductions will be repeated when the goal is re-evaluated).

3.3.3 Suspensions

This parameter attempts to count the number of suspended evaluations in the evaluation of a query. The number of suspensions may be dependent on when suspended evaluations are rescheduled. When an evaluation suspends in the existing interpreters they are immediately rescheduled for evaluation; this is known as **busy** waiting. For example, the query in *Figure 3–4* will undergo *three* reductions in *three* cycles, and incur *three* suspensions, assuming that the interpreter is evaluating the query breadth-first. However, a **non-busy** waiting strategy could have been used [2]. Using an ideal **non-busy** waiting strategy each suspended

---

as a general principle system calls should be counted as reductions as they contribute to the overall work done.

[2]The suspended goals could be hooked (or tagged) to the variables that they are suspended on so that they can be reactivated when sufficient variables become instantiated.

goal will be suspended once. So, the example query in *Figure 3–4* will incur *two* suspensions.

Another point to note is that current interpreters process the goals from left-to-right, allowing any bindings that result to be made available to the remaining goals to be processed in the current cycle. This may allow a goal to reduce in the current cycle which would suspend if the goals were evaluated in a different order.

Finally, as failed goals are rescheduled they may introduce erroneous statistics into the suspension count as failed goals will add to the suspension counts.

3.4 Requirements of an improved model

Many of the limitations and inaccuracies of the statistics generated by current interpreter implementations are due to the execution mechanisms employed to model these languages. The collection of more meaningful statistics requires the development of an improved implementation. Such an implementation would have to exhibit the following features:

- The implementation must distinguish between suspension and failure of an evaluation of a goal. Goal evaluations can either:
  - succeed;
  - suspend; or
  - fail.
- The implementation must more accurately measure the depth of the evaluation tree:
  - the depth of the evaluation tree must account for the use of **deep** guards;

- the depth of the evaluation tree should not be dependent on goal or clause order;
- the depth of the tree should account for *producer-consumer* type algorithms. That is, a *consumer* should suspend for as many cycles as it takes the *producer* to generate the message. This is particularly relevant in the case of **deep** guarded *producers*, where *consumer* processes should suspend for the duration of the *producers* guard evaluation.

- The implementation should model parallel AND-parallelism:
  - each of the goals in the conjunction should appear to be evaluated in parallel;
  - each AND-parallel goal should be reduced once in each cycle. The reduction may take place in the guarded evaluation in the case of **deep** guards;
  - the simulated reduction of each goal in a given cycle should be independent of the actual order in which the goals are processed.

- The implementation should model parallel OR-parallelism:
  - each of the clauses that a goal could use to reduce should appear to be explored in parallel;
  - in a parallel evaluation a goal should commit to the first clause whose guard successfully terminates;
  - the evaluation of a goal suspends if no committable clause exists and at least one clause evaluation suspends (not suspend or fail as in current interpreters).

In the following subsection we consider the idealisations made in the design of our improved execution model. Then taking each of the requirements above we incrementally develop an improved interpreter. The interpreter developed aims

to provide a fully parallel model of program execution with which we can collect meaningful statistics. Using an interpreter allows us to collect coarse grained information like number of commitments or size of suspension queues. These coarse parameters are similar to the coarse grained parameters, like logical inferences [Wilk 83], collected for sequential logic programming languages (Prolog) and to the currently accepted evaluation parameters used for the CCND languages [Shapiro 83] [Sterling & Codish 87] [Okumura & Matsumoto 87]. However, it does not easily allow us to measure fine detail like the cost of the commitment operation.

The dynamic cost of various operations and the reference characteristics of CCND languages would require the instrumentation of a suitable and representative abstract machine, like [Crammond 88] for Parlog. The emulator for such an abstract machine can then be used to collect information about data and instruction referencing, in the same vein as [Tick 87]. This approach was not feasible for this work because there was no representative abstract machine for the entire class of CCND languages available for instrumentation.

3.5 Idealisations in our improved model

3.5.1 AND-parallel idealisations

In Shapiro's interpreter the goal list is processed in a left-to-right order, any bindings made in the evaluation of goals take place immediately. So, these bindings will be available to any remaining goals in the goal list. Hence the evaluation is dependent on goal order.

A fully accurate model would be able to determine exactly when a goal makes a binding, how long it would take for this binding to reach another goal and whether this would be in time for the goal to use it. Such a model would be heavily implementation dependent and its results would not transfer easily to

other implementations. Clearly the inherent parallelism should not be dependent on goal order. Instead we make the assumption that, in a cycle, a goal can only use bindings available to it at the start of the cycle. Such a model may not display all the parallelism that could be achieved in a given implementation, but at least it gives a measure which is not dependent on how the goals are ordered.

3.5.2 Guard evaluation idealisations

Shapiro's model assumed, that in a cycle, a goal can be head unified with the clauses in the system, the guarded goals could be evaluated, and the body goals committed to. This model assumed that guard evaluations take *zero* cycles, so no contribution of the guard evaluations are seen in the overall depth measure of the evaluation. Shapiro's depth measure (**cycles** count) only records the depth of the commitments of the goals at the top-level of the AND/OR-tree. Only in the case where all guards are all **flat** does this measure give an indication the depth of the evaluation tree.

We propose two alternative models for incorporating the effect of the guard evaluation into the overall evaluation. The first assumes that in a cycle, a goal can be head unified with a clause and the guarded goal evaluation instigated. The body goals will be committed to at a depth of `1+(the depth of the guarded evaluation)`. Note that this model assumes that guarded system goals (**flat** guards) will evaluate in 1 cycle. The second assumes that in a cycle, a goal can be head unified with a clause and either the guarded evaluation instigated or a system guard evaluated. Commitment to the body goals occurs at `1+(the depth of the guarded evaluation)` for **deep** guards and in the next cycle for **flat** guards. Note that this model assumes that system goals incur no cycle costs.

We adopt the second model as this model has a similar notion of depth to the previous implementations when executing **flat** guarded programs.

It should be noted that most cycle based models for obtaining a measure of the depth of the evaluation tree will be prone to giving distorted results, in that they will tend to associate fixed costs with the various components of the evaluation, like head unification, system call evaluation and commitment. Although an elaborate model of cost could be developed, these costs would tend to be implementation dependent. Moreover, such a model is unlikely to give a radically different view of the general features of the evaluation compared with a fixed cost model.

3.5.3 OR-parallel idealisations

The model of inherent OR-parallelism requires the evaluation to commit to the clause whose first guard successfully terminates. In our system the duration of a guard evaluation is approximated by the depth of its evaluation tree. So the evaluation should commit to the guard with the shallowest evaluation tree.

3.5.4 System call idealisations

The evaluation of system calls contributes to the overall work done in the evaluation of a goal. We assume the evaluation of a system call counts as a reduction. It may be the case that some system calls like == should not be counted as a reduction as they are simple, and could be compiled to be part of the head unification. As a general principle system calls should be counted as reductions as they contribute to the overall work done.

In suspending the evaluation of a system call we assume it behaves like a goal with one clause. Later in this thesis (section 4.2.2), we consider alternative suspension mechanisms and this idealisation will reflect the fact that there should be no performance difference in which suspension mechanism is employed for such calls.

3.6 Development of our improved model

We could implement the required improved execution model by an abstract machine emulated in 'C' (see section 2.6.2). The abstract machine could then be instrumented to dump, rather than dynamically collect information (as this will reduce the speed of the system) about program evaluation. Alternatively, we could implement an improved interpreter which could either dynamically collect statistics like the previous evaluation interpreters or dump information about the program evaluation as in the 'C' emulator. We have chosen to implement an improved interpreter which will then be used to dump profiling data about the program execution. This dump data is post analysed. Adopting a interpreter rather than a 'C' based emulator allows us to rapidly prototype our system [Sterling & Beer 86], however the trade-off is that our system executes orders (at least 2) of magnitude slower than a comparable 'C' version.

In this section we take each of the requirements for an improved evaluation system given in section 3.4 and incrementally design and develop an improved interpreter.

3.6.1 Suspension/Failure

Providing a interpreter which can distinguish between suspension and failure requires several improvements to the basic interpreter, given in *Figure 3–1.* The basic interpreter returned only two states `nodeadlock` or `deadlock/failed` indicated by the interpreter succeeding or failing. To indicate three possible termination states, `nodeadlock`, `deadlock` or `failed`, requires an additional argument which indicates the final state of the computation. This results in a two argument (top-level) interpreter, as given in *Figure 3–5.*

```
solve(Goal,StatusOut) :-
    schedule(Goal,[],QueueTemp),
    append(QueueTemp,[cycle],Queue),
    solve(Queue,deadlock,StatusOut).
```

Figure 3–5: Two argument call for a suspend/fail Parlog interpreter

The next stage is for each of the clauses in the original interpreter, *Figure 3–1*, to support this extra argument. The resulting interpreter is given in *Figure 3–6*. This interpreter has the following procedural reading:

- If the goal list only contains a cycle marker, the evaluation has terminated successfully, so set the output status flag to `nodeadlock`.

- If each goal in the goal list has been attempted and the current status flag is `deadlock`, then set the output status flag to `deadlock`.

- If each goal in the goal list has been attempted and the status flag is `nodeadlock`, then re-enqueue the cycle marker, set the status flag to `deadlock` and pass the output status flag onto the next cycle of the solver.

- If the dequeued goal is a system call and can be evaluated (that is if the goal is sufficiently bound to allow it to be evaluated), evaluate it using Prolog's built in metacall (`call/1`). If the evaluation fails then the output status flag is set to `failed`; if the evaluation succeeds then continue evaluating the goal list; and if the goal is not sufficiently bound to be evaluated suspend the goal and then continue evaluating the goal list.

Checking if a goal is sufficiently bound can be simply achieved by a call such as:

```
eval(_ is Y) :- numbervars(Y,1,1).
```

```
solve([cycle],_,nodeadlock) :- !.
solve([cycle|_],deadlock,deadlock) :- !.
solve([cycle|Rest],nodeadlock,StatusOut) :- !,
    append(Rest,[cycle],NextQueue),
    solve(NextQueue,deadlock,StatusOut).
solve([Goal|Rest],StatusIn,StatusOut) :-
    system(Goal),
    (eval(Goal) ->
         (call(Goal) -> solve(Rest,nondeadlock,StatusOut) ;
         StatusOut = fail) ;
    schedule(suspend(Goal),Rest,NextQueue),
    solve(NextQueue,StatusIn,StatusOut)).
solve([Goal|Rest],StatusIn,StatusOut) :-
    get_modes(Goal,Functor,Arity,GoalArgs,Modes),
    functor(ClauseHead,Functor,Arity),
    bagof(
         (StatusGuard, (ClauseHead :- (Guard:Body))),
         Functor^HeadArgs^GoalArgs^StatusHU^
         (
         clause(ClauseHead,(Guard:Body)),
         ClauseHead =.. [Functor|HeadArgs],
         verify_modes(Modes,GoalArgs,HeadArgs,StatusHU),
         (StatusHU == nodeadlock ->
              solve(Guard,StatusGuard) ;
              StatusGuard = StatusHU)),
         GuardInfo),
     (pick_commitment(GuardInfo,(Goal :- (Guard:CommitBody))) ->
         schedule(CommitBody,Rest,NewQueue),!,
         solve(NewQueue,nodeadlock,StatusOut);
     suspended(GuardInfo) ->
         schedule(suspended(Goal),Rest,NewQueue),!,
         solve(NewQueue,StatusIn,StatusOut);
     StatusOut = failed).
```

Figure 3–6: A suspend/fail Parlog interpreter in Prolog

```
verify_modes([],[],[],nodeadlock) :- !.
verify_modes(['?'|Modes],[GArg|GArgs],[HArg|HArgs],Status) :- !,
        '<='(HArg,GArg,StatusTemp),
     (StatusTemp == nodeadlock ->
            verify_modes(Modes,GArgs,HArgs,Status) ;
        Status = StatusTemp),!.
verify_modes(['^'|Modes],[GArg|GArgs],[HArg|HArgs],Status) :- !,
        ':='(GArg,HArg,StatusTemp),
        (StatusTemp == nodeadlock ->
             verify_modes(Modes,GArgs,HArgs,Status) ;
         Status = StatusTemp).

% '<='/2 ONE WAY UNIFICATION PRIMITIVE
'<='(X,Y,nodeadlock) :-
        var(X), !, X=Y.
'<='(_,Y,deadlock) :-
        var(Y), !.
'<='([X|Xs],[Y|Ys],Status) :- !,
        '<='(X,Y,Status1), '<='(Xs,Ys,Status2),
        (Status1==nodeadlock,Status2 ==nodeadlock ->
                Status = nodeadlock ;
        (Status1 == failed;Status2==failed) ->
                Status = failed ;
        Status = deadlock).
'<='(X,Y,Status) :-
        atomic(X),!,
        (X=Y -> Status = nodeadlock ; Status = failed).
'<='(X,Y,Status) :-
        X=..[F|Xs], Y=..[F|Ys], '<='(Xs,Ys,Status).
'<='(_,_,failed).

% ':='/2 ASSIGNMENT UNIFICATION PRIMITIVE
':='(X,Y,nodeadlock) :-
        var(X), X=Y,!.
':='(_,_,failed).
```

Figure 3–7: Mode based unification for suspend/fail PARLOG interpreter

which indicates that the `is/2` system call can be evaluated if its second argument contains no variables.

Before considering the procedural interpretation of the clause that processes Parlog goals we should consider some of the required extensions and how they may be achieved. The `reduction/suspension/failure` of a Parlog process requires several extensions.

- The head unification of a goal with some clause head may **suspend**, **succeed** or `fail`. This requires an extension to the mode based unification given in *Figure 3–2*, which is used by the basic interpreter. The new mode based unification should indicate the state of the unification; again this is achieved using an additional argument. The resulting mode based unification is given in *Figure 3–7*.

- Suspending a goal evaluation requires that no clause is committable and at least one clause evaluation suspends. Failing a goal evaluation requires that no clause is committable and no clause has suspended. These requirements mean that each clause has to be attempted and the status of each guard evaluation collected. This is achieved using a Prolog `bagof/3` metacall. Once a set of clause evaluation statuses are known, picking a committable clause, or testing if the goal evaluation has suspended, or testing if the goal evaluation has failed is a relatively simple task. The code for picking a committable clause or testing if the goal evaluation suspends is given in *Figure 3–8*.

Now we can consider the procedural interpretation of the clause used to reduce a Parlog process.

- Firstly, obtain the mode declarations for the dequeued Parlog goal. Secondly, for each clause (using a `bagof/3`) head unify the goal and the clause head. If the unification succeeds then evaluate the guard. The state of each clause

```
pick_commitment([(nodeadlock,Clause)|_],Clause) :- !.
pick_commitment([_|Rest],Clause) :-
    pick_commitment(Rest,Clause).

suspended(GuardInfo) :-
    member((deadlock,_),GuardInfo).
```

Figure 3–8: Simple clause selection for suspend/fail PARLOG interpreter

evaluation is collected. Finally, if there is a committable clause, schedule its body goals for evaluation; if no committable clause exists and a clause evaluation suspends then suspend the goal evaluation; otherwise the goal evaluation failed so set the output status flag to `failed`.

3.6.2 Depth (cycles)

In a parallel computation the length of the evaluation provides an important measure; comparing the execution time for a parallel evaluation with the execution time on a single processor indicates the degree of parallelism. For logic based programs the depth of the search tree can give a measure of the duration of the computation. However, some points should be noted:

- If the search tree is explored sequentially, as in Prolog, the duration of the computation will not depend on the depth of the search tree but on the length of those branches in the tree which are explored.

- If an OR-parallel evaluation strategy is used, the duration of the evaluation involves summing the expected duration of each of the goals (which will be tried sequentially); that is the depths of the goals evaluation.

- For the CCND languages, where the search space is explored partly in OR-parallel and partly in AND-parallel, the duration of the computation is more

complex to calculate as some goals in the evaluation may not be explored for several cycles (corresponding to the possibility of some goals suspending).

Shapiro proposed the **cycle** depth measure described in section 2.6.1.2 for the evaluation. However, the depth measured by his Concurrent Prolog interpreter (see section 2.6.1.2) did not include the depth of the guard evaluations (see section 3.3.1). The mechanism used in Shapiro's CP interpreter [Shapiro 83] provides the basis of our cycle counter (depth measure). Shapiro's interpreter included a counter in the cycle marker. On each new cycle this counter is incremented. The first stage of our cycle counter is to introduce this mechanism into our basic interpreter, given in *Figure 3–1*. The resulting interpreter has two arguments, the goal and its evaluation depth. *Figure 3–9* is the top-level call of this cycle counting interpreter.

```
solve(Goal,StatusOut) :-
    schedule(Goal,[],QueueTemp),
    append(QueueTemp,[cycle(1)],Queue),
    solve(Queue,deadlock,StatusOut).
```

Figure 3–9: Two argument top-level cycle counting Parlog interpreter

The second stage, incrementing the cycle counter each cycle, requires modifying the third clause of our interpreter (*Figure 3–6*), as follows:

```
solve([cycle(CurrentCycle)|Rest],nodeadlock,StatusOut) :- !,
    NextCycle is CurrentCycle +1,
    append(Rest,[cycle(NextCycle)],NextQueue),
    solve(NextQueue,deadlock,StatusOut).
```

However, Shapiro's mechanism does not provide a means of including the cycles incurred in the guard evaluation in the overall cycle measure. To incorporate the cycles incurred in the guard evaluation requires some mechanism by which

```
solve(Goal,StatusOut,DepthOut) :-
    schedule(Goal,[],QueueTemp),
    append(QueueTemp,[cycle(1)],Queue),
    solve(Queue,deadlock,StatusOut,DepthOut).

solve([cycle(Depth)],_,nodeadlock,Depth) :- !.
solve([cycle(Depth)|_],deadlock,deadlock,Depth) :- !.
solve([cycle(Depth)|Rest],nodeadlock,StatusOut,DepthOut) :- !,
    DepthNext is Depth + 1,
    append(Rest,[cycle(DepthNext)],NextQueue),
    solve(NextQueue,deadlock,StatusOut,DepthOut).
solve([Goal|Rest],StatusIn,StatusOut,DepthOut) :-
    system(Goal),
    (eval(Goal) ->
         (call(Goal) -> solve(Rest,nondeadlock,StatusOut,DepthOut);
        StatusOut = fail) ;
    schedule(suspend(Goal),Rest,NextQueue),
    solve(NextQueue,StatusIn,StatusOut,DepthOut)).
solve([Goal|Rest],StatusIn,StatusOut,DepthOut) :-
    get_modes(Goal,Functor,Arity,GoalArgs,Modes),
    functor(ClauseHead,Functor,Arity),
    bagof(
         (StatusGuard, GuardDepth,(ClauseHead :- (Guard:Body))),
         Functor^HeadArgs^GoalArgs^StatusHU^
        (
        clause(ClauseHead,(Guard:Body)),
        ClauseHead =.. [Functor|HeadArgs],
        verify_modes(Modes,GoalArgs,HeadArgs,StatusHU),
        (StatusHU == nodeadlock ->
             solve(Guard,StatusGuard,DepthGuard) ;
             StatusGuard = StatusHU)),
        GuardInfo),
    (pick_commitment(GuardInfo, CommitDepth,
                                (Goal :- (Guard:CommitBody))) ->
         schedule(CommitBody,Rest,NewQueue),!,
         solve(NewQueue,nodeadlock,StatusOut,DepthOut);
     suspended(GuardInfo,SuspendDepth) ->
         schedule(suspended(Goal),Rest,NewQueue),!,
    suspended(GuardInfo,SuspendDepth) ->
        schedule(suspended(Goal),Rest,NewQueue),!,
        solve(NewQueue,StatusIn,StatusOut,DepthOut);
    StatusOut = failed).
```

Figure 3–10: Three argument call for Parlog in Prolog

the depth of a guard evaluation is returned. This is achieved by having a three argument call. The first argument is the goal conjunction to be evaluated, the second argument is the final status of the evaluation and the third is the depth of the evaluation. *Figure 3–10* provides such a three argument interpreter.

We can now develop a mechanism by which the cycles incurred in the guard evaluation can contribute to the overall cycle (depth) measure. The actual mechanism developed forms the means by which we also model inherent AND-parallelism, and is covered in the next section.

3.6.3 AND-parallelism

As stated earlier (see section 3.3.1) current interpreters evaluate the process queue left-to-right and any bindings made by the evaluation of goals in the queue take place immediately. So these bindings will be available to any remaining goals in the goal list. This will allow goals that require these bindings to reduce in the current cycle. Hence the evaluation is dependent on goal order. We make the assumption that, in a cycle, a goal can only use bindings available to it at the start of the cycle (see section 3.5).

To offer such a model requires the addition of a binding list in which the bindings produced are maintained until the appropriate cycle. In the case of **deep** guards this mechanism can also be employed to account for the cycles performed in the guard evaluation. As well as having a binding list we maintain a commit list, this commit list contains a set of 'body goal'/'depth counter' pairs. The depth counter indicates when the body goals would have been committed to if the guard evaluation took place in parallel with other body goal evaluations. We have combined both the lists (bindings and goals) into one list. The new list contains `wtc/3`-(wait to commit) structures. Such a structure contains a relative depth counter (the depth of the guard evaluation), the goal that was evaluated and the clause that is to be committed to. The output bindings are made by unifying the goal and the head of the committed clause when the appropriate cycle is reached[3].

Implementing this functionality in our interpreter requires an additional argument, a wait to commit list, in the main loop of our interpreter. The resulting

---

[3]When carrying out the guard evaluation a copy of the goal is used to select the committable clause, hence the bindings that result are maintained in the committed clause and only exported when the goal and the clause head are unified. Using this mechanism the binding list becomes semi-implicit, in that no real binding list need be maintained. This method is suitable for **safe** languages, like Parlog.

```
solve([cycle(Depth)],[],_,nodeadlock,Depth) :- !.
solve([cycle(Depth)|_],[],deadlock,deadlock,Depth) :- !.
solve([cycle(Depth)|Rest],WCL,_,StatusOut,DepthOut) :-
    do_a_wait_update(WCL,Commits,WCLnext),
    DepthNext is Depth + 1,
    append(Rest,Commits,TempQueue),
    append(TempQueue,[cycle(DepthNext)],NextQueue),
    solve(NextQueue,WCLnext,deadlock,StatusOut,DepthOut).
solve([Goal|Rest],WCL,StatusIn,StatusOut,DepthOut) :-
    system(Goal),
    (eval(Goal) ->
         (copy(Goal,GoalCopy),
         call(GoalCopy) ->
              append([wtc(1,Goal,GoalCopy)],WCL,WCLnxt),
              solve(Rest,WCLnxt,nondeadlock,StatusOut,DepthOut) ;
         StatusOut = fail) ;
    schedule(suspend(Goal),Rest,NextQueue),
    solve(NextQueue,WCL,StatusIn,StatusOut,DepthOut)).
solve([Goal|Rest],WCL,StatusIn,StatusOut,DepthOut) :-
    get_modes(Goal,Functor,Arity,GoalArgs,Modes),
    functor(ClauseHead,Functor,Arity),
    bagof(
         (StatusGuard, GuardDepth,(ClauseHead :- (Guard:Body))),
         Functor^HeadArgs^GoalArgs^StatusHU^
         (
         clause(ClauseHead,(Guard:Body)),
         ClauseHead =.. [Functor|HeadArgs],
         verify_modes(Modes,GoalArgs,HeadArgs,StatusHU),
         (StatusHU == nodeadlock ->
              solve(Guard,StatusGuard,DepthGuard) ;
              StatusGuard = StatusHU)),
         GuardInfo),
    (pick_commitment(GuardInfo, CommitDepth,(Head:-(Guard:Body))) ->
         append([wtc(CommitDepth,Goal,(Head:-(Guard:Body)))],WCL,WCLnxt),
         solve(Rest,WCLnxt,nodeadlock,StatusOut,DepthOut);
     suspended(GuardInfo,SuspendDepth) ->
         schedule(suspended(Goal),Rest,NewQueue),!,
         solve(NewQueue,WCL,StatusIn,StatusOut,DepthOut);
     StatusOut = failed).
```

Figure 3–11: Parlog interpreter with a bindings and commitments queue

interpreter is given in *Figure 3–11.* The processing of the wait to commit list is given in *Figure 3–12.*

```
do_a_wait_update([],[],[]).
do_a_wait_update([wtc(1,Goal,(Goal:-(_:Body)))|Rest],Commits,
            WCLOut) :-!,
    do_a_wait_update(Rest,CommitsRest,WCLOut),
    schedule(Body,CommitsRest,Commits).
do_a_wait_update([wtc(1,Goal,Goal)|Rest],Commits,WCLOut) :-!,
    do_a_wait_update(Rest,Commits,WCLOut).
do_a_wait_update([wtc(D,G,C)|Rest],Commits,
            [wtc(Dnext,G,C)|WCLOut]) :-
    Dnext is D - 1,
    do_a_wait_update(Rest,Commits,WCLOut).
```

Figure 3–12: Binding/commitments processing for Parlog interpreter

3.6.4 OR-parallelism

The model of inherent OR-parallelism requires the evaluation to commit to the clause whose first guard successfully terminates. In our idealisation this will be the guard with the shallowest evaluation depth (see section 3.5). This enhancement can be simply incorporated in `pick_commitment/3`. The sequential `pick_commitment/3`, given in *Figure 3–8*, recurses down the `(guard state, guarddepth, clause)` list produced by evaluating each of the guarded goals in `bagof/3`, returning the first committable clause.

The `pick_commitment/3` of *Figure 3–13* picks the clause with the shallowest guard evaluation as the committable clause. This is achieved by comparing the depth of the first committable clause with the depth of the committable clause chosen from the remainder of the `(guard state, guarddepth, clause)` list.

```
pick_commitment([(nodeadlock,Depth,Clause)],Depth,Clause).
pick_commitment([Head|Tail],Clause_out,Depth_out) :-
    Head = (nondeadlock,Depth_H,Clause_H),
    !,
    (pick_commitment(Tail,Depth_T,Clause_T) ->
        (Depth_T > Depth_H ->
            Clause_out = Clause_H,
            Depth_out = Depth_H ;
        true ->
            Clause_out = Clause_T,
            Depth_out = Depth_T) ;
    Clause_out = Clause_H,
    Depth_out = Depth_H).
pick_commitment([_|Tail],Depth,Clause) :-
    pick_commitment(Tail,Depth,Clause).
```

Figure 3–13: Modelling parallel clause selection in a interpreter

3.6.5 Features of our improved model

The features of our interpreter are as follows:

- both AND and OR-parallelism are modelled;
- each of the guarded goals for a given predicate are tried and relevant statistics collected;
- the statistics from the evaluation of the guarded goal are used to pick the solution path (currently this is the shallowest successful guard, *i.e.* the first guard that would have succeeded in a breadth-first execution);
- the goals that form the goal list each undergo one reduction in a cycle; any bindings made as the goal list is processed occur only when all the goals have been attempted;
- the evaluation of a system goal which makes a call to the underlying Prolog system is counted as one reduction;
- bindings made using calls to the underlying Prolog system are made only when all the goals have been attempted;
- the interpreter makes a distinction between suspension and failure;
- although guard evaluations are carried out to completion in one go, the commitment of a goal to a given clause is prevented for the number of cycles the guard took to evaluate; and
- the suspension of all the guarded goals causes suspension of the goal being evaluated.

3.7 Summary

In this chapter the following have been presented and discussed:

- Why a measure of the inherent parallelism is useful.
- How we can obtain a measure of the inherent parallelism by simulating the execution of the evaluation on an unlimited number of processors.
- The current models of execution and what they provide in terms of evaluation metrics.
- The currently quoted metrics (**cycles, reductions** and **suspensions**) and their limitations.
- The requirements of an improved model of execution, which would be used to collect information about the inherent parallelism.
- The idealisations we assume in our execution model.
- The incremental design and implementation of an improved interpreter which forms the basis of our new evaluation system.

Chapter 4

New evaluation parameters and example evaluations

4.1 Overview

The current interpreters used for evaluation are limited in two respects:

- their model of breadth-first execution of these languages contains several major deviations from a fully parallel execution;
- the evaluation parameters used (**cycles**, **reductions** and **suspensions**) give no indication of various alternatives open to the language implementors.

In chapter 3, we considered limitations in the execution model provided by the current interpreters and then developed a new interpreter which allows us to obtain improved measures of the inherent parallelism in a program.

In this chapter we consider the second limitation of the current evaluation systems; the parameters collected. Current parameters give no indication as to how the program would have behaved under alternative models of execution. For example, on commitment to one clause the other guard evaluations could be terminated or ignored.

Section 4.2 considers some possible execution alternatives open to language implementors. This provides the basis for a set of parameters which can be used to indicate the relative merits of these alternatives. These are presented in Section 4.3.

In section 4.4 we present a tool developed to profile the various proposed parameters over time (cycles). Later in this thesis we use this profiling tool to consider the execution behaviour of several AI programs.

Section 4.5 presents measurements of our parameters for one CCND language, Parlog. An evaluation using these parameters is given for a small set of simple example programs and the results analysed. The nature of these examples allows us to consider the theoretical behaviour of these programs compared with the behaviour predicted by our evaluation system.

Finally, section 4.6 considers some of the limitations of our evaluation system.

4.2 Basis for new parameters

Apart from having inaccuracies in measuring the inherent parallel behaviour of programs introduced through limitations in the execution model, the parameters proposed by Shapiro (**cycles**, **suspensions** and **reductions**) do not give any indication of the effects that alternative implementation models may have had.

Currently the models of execution being adopted for the CCND languages are settling down to a subset of the possible models. For example, the languages are being restricted to **flat** guards or only allowing the clauses to be investigated sequentially. In general the subset being adopted as standard is being governed by implementation issues rather than application requirements. This work aims to present an applications viewpoint of the possible direction that the CCND implementors may take. To this end we have considered how applications would

behave on various alternative executions and hence provide some applications rationale for the implementation alternatives.

The execution alternatives considered are relevant to the complete CCND language rather than any given subset and represent extremes in the implementation options, for instance the alternatives for scheduling are **busy** and **non-busy** waiting. Our results for **busy waiting**, an implementation option which many think is not appropriate, indicates that for Layered Streams this could be a suitable implementation option (see section 5). In the following subsections we consider some of these alternatives. The new parameters we propose aim to provide information about the relative merits of these different alternatives.

4.2.1 Pruning OR-branches

The parallel evaluation of a goal invokes several guarded systems, one for each clause that the goal successfully head unifies with. The evaluation commits to the first clause whose guarded system successfully terminates. On commitment, the other guarded systems invoked by the goal evaluation can be terminated or ignored. Terminating the alternative clauses (**pruning**) requires the system to stop the computation being carried out in the alternative branches. This may prevent these branches carrying out needless computation. However, if the guarded goals for a given predicate are balanced, that is evaluated in the same time, then **pruning** the OR-search will not prevent any computation in the alternative guards. Ignoring the other alternative clauses (**non-pruning**) when a goal commits, requires the system to disregard any commitment requests from the other alternatives should their guarded systems also terminate successfully. This assumes that guard evaluations terminate and certainly do not diverge. This may save some computation (in sending a terminate message to the other guard evaluation) if the guards are balanced or in cases where only one clause can be committed to.

Even if **pruning** the clauses reduces some theoretical computation it may be worth attempting only if the amount of work saved is comparable to the expected

overheads of terminating the other clause evaluations. This will depend on the architecture and implementation.

Pruning clauses is likely to be most beneficial for programming techniques and applications that employ an uneven guarded computation. Such programs in the main will employ **deep** guards [Gregory 87]. However, it should be noted that even **flat** guards may benefit from **pruning**. This will occur when some of the **(flat)** guards have data dependencies which result in them taking longer to evaluate than other guards, or if some guards make use of costly system predicates while others do not. However, most programs with **flat** guards are likely to have an even guard evaluation.

4.2.2 Suspension mechanisms

A goal evaluation suspends if there is no committable clause and at least one of the guard evaluations or head unifications suspends. Suspending the evaluation can be achieved in several ways, the two extremes being **goal** suspension and **clause** suspension. **Goal** suspension involves suspending the parent goal of a computation when each of the clauses it could reduce by suspend. Note that this parent goal may actually be the guarded goal of some other evaluation.

Alternatively each of the clauses (guarded computations and head unifications) could be suspended, which is known as **clause** suspension. Here the current state of each clause evaluation is saved. As there may be recursive guard evaluations invoked, **clause** suspension may result in a tree of suspended evaluations, representing the guard call structure. The trade-off between these two extremes is basically a space-time consideration. Suspending a goal requires less space than suspending the evaluation of each of the clauses. However, if some computation is performed in the evaluation of the guarded goals before the evaluation suspends then this computation will be lost, and repeated, if the goal is suspended.

In our system we treat system calls as goals with one clause. This is because we assume the two suspension mechanism alternatives should not portray a difference for system calls (see section 3.5).

4.2.3 Scheduling policy

Another choice is how and when suspended evaluations are re-scheduled. When an evaluation suspends it could be tagged to the variables which are required and unbound and re-scheduled when they become bound, this is known as **non-busy** waiting. It should be noted that some predicates, like `merge/3`, only suspend on one variable whereas others, like `equals/2`, require both arguments to be bound. The other extreme would be to immediately reschedule the suspended evaluation, known as **busy** waiting.

Employing a **non-busy** waiting suspension mechanism is appropriate if suspended evaluations remain suspended for several cycles, for example in generating primes numbers by sifting [Gregory 87] most of the filter processes will be suspended most of the time. Employing a **busy** waiting suspension mechanism is appropriate if suspended goals are only likely to be suspended for a short period, as with Layered Streams [Okumura & Matsumoto 87] (see chapter 5).

4.3 Proposed profiling parameters

The profiling parameters we propose aim to reflect the effect of the various options available in **pruning** OR-branches, alternative suspension mechanisms and alternative scheduling polices. The basic parameters are still suspensions and reductions. However, these are given for the various combinations of the execution alternatives considered. Two additional parameters are also considered, the **depth of the evaluation** and the **minimum reductions.** So the basic top-level parameters put forward are suspensions and reductions using:

- **busy** waiting, **non-pruning** and **goal** suspension;
- **busy** waiting, **non-pruning** and **clause** suspension;
- **busy** waiting, **pruning** and **goal** suspension;
- **busy** waiting, **pruning** and **clause** suspension;
- **non-busy** waiting, **non-pruning** and **goal** suspension;
- **non-busy** waiting, **non-pruning** and **clause** suspension;
- **non-busy** waiting, **pruning** and **goal** suspension; and
- **non-busy** waiting, **pruning** and **clause** suspension.

```
mode on_either(?,?,?,^).
on_either(Element,List1,List2,Output) :-
    member(Element,List1)
    :
    Output = List1.
on_either(Element,List1,List2,Output) :-
    member(Element,List2)
    :
    Output = List2.


mode member(?,?).
member(E,[H|T]) :-
    E == H : true.
member(E,[H|T]) :-
    E \== H : member(E,T).


:-  on_either(a,[1,2,3,a,b],[1,2,a,b],Output),
    on_either(b,Output,[1|Output],Output1).
```

Figure 4–1: Parallel member test in Parlog

Table 4–1 gives predicted results for our new parameters for the query in *Figure 4–1*. We now discuss the **reductions** and **suspensions** obtained for two of the

execution models with reference to this query, (a full description of all 8 models of execution is given in appendix A). We also consider the two additional parameters.

Execution Model	Cycles	Reductions	Suspensions
Original model *Section 3.2*	3	11	1
Busy waiting, Non-Pruning, Goal suspension	10	40	6
Busy waiting, Non-Pruning, Clause suspension	10	36	14
Busy waiting, Pruning, Goal suspension	10	38	6
Busy waiting, Pruning, Clause suspension	10	34	14
Non-busy waiting, Non-Pruning, Goal suspension	10	38	3
Non-busy waiting, Non-Pruning, Clause suspension	10	36	4
Non-busy waiting, Pruning, Goal suspension	10	34	3
Non-busy waiting, Pruning, Clause suspension	10	34	4

Table 4–1: Predicted results for example query

4.3.1 Busy waiting, non-pruning, goal suspension

Here the execution model is: suspended evaluations are immediately rescheduled for evaluation; on commitment to one clause the other clauses are not terminated; and the suspension of an evaluation involves suspending the parent goal.

We now consider the evaluation of the two query goals given in *Figure 4–1*:

goal 1: This goal (`on_either(a,[1,2,3,a,b],[1,2,a,b],Output)`) evaluation results in two sets of guarded systems, `member(a,[1,2,3,a,b])` and `member(a,[1,2,a,b])`. The first of these will require 8 reductions to reduce to `true`; that is the guard test takes 1 reduction for each element and the commitment another [1]. Similarly the second (guard) `member(a,[1,2,a,b])` goal requires 6 reductions.

As this execution model uses **non-pruning** both these guards will be evaluated fully. So, the total number of reductions performed in the evaluation

[1]This is because we count system calls as reductions (see section 3.5).

of this goal is 16 (8 in evaluating the first guard, 6 in the second guard, 1 for the commitment to the body goals and finally 1 for the output unification).

The total number of cycles that this evaluation takes is 4. That is the evaluation commits to the second, `on_either/4`, clause after 3 cycles and it takes 1 cycle to carry out the output unification. So the binding made to the shared variable "`Output`" will be seen by the other AND-parallel goals in cycle 5.

goal 2: The second goal (`on_either(b,Output,[1|Output],Output1)`) evaluation results in two sets of guarded goals, `member(b,Output)` and `member(b,[1|Output])`. The first of these could be evaluated via two clauses, however these both suspend on head unification. As we are using **goal** suspension the evaluation of the first guarded goal suspends. The second (guard) is able to perform 2 reductions (the guard test and the commitment to `member(b,Output)`). The resulting goal could be evaluated via two clauses but both of these suspend on head unification. This results in the suspension of the second guarded goal. Now both sets of guarded goals have suspended the evaluation of the second query goal suspends, giving a total of 3 goal suspensions and 2 reductions, the second query goal suspends after 2 cycles.

Using **busy** waiting this top-level goal will be retried in cycle 3. In cycle 3 the variable "`Output`" will still be unbound, so the rescheduled evaluation will perform the same 2 reductions and then suspend again. The goal will next be tried in cycle 5.

In cycle 5 the shared variable "`Output`" will be bound, so the second query goal becomes `on_either(b,[1,2,a,b],[1,1,2,a,b],Output1)`. This goal invokes two guarded systems, `member(b,[1,2,a,b])` and `member(b,[1,1,2,a,b])`. The first of these will require 8 reductions to reduce to `true`. Similarly the second guard requires 10 reductions.

As the execution uses **non-pruning** both these guards will be evaluated fully. Hence the final attempt at evaluating this goal results in 20 reductions (8 in the first guard, 10 in the second, 1 for the commitment to the body goals and finally 1 for the output unification). The total number of cycles that this evaluation takes is 5. That is the evaluation commits to the first clause after 4 cycles and it takes 1 cycle to carry out the output unification.

So, the evaluation of the query using this execution model takes: 10 cycles; 40 reductions (16 for the first goal, 4 for the second goal before suspension, and 20 for the final evaluation of the second goal); and 6 goal suspensions (1 suspension for the first guarded goal, `member(b,L)`, 1 suspension for the second guarded goal, `member(b,[1|L])` and 1 suspension for the query goal, these suspensions occur twice because of the busy waiting).

4.3.2 Non-busy waiting, pruning, clause suspension

Here the execution model is: suspended evaluations are tagged to the variables which must be bound before the evaluation can proceed; on commitment to one clause the other clauses are not terminated; and the suspension of an evaluation involves suspending the clauses.

We now consider the evaluation of the two query goals given in *Figure 4-1*:

goal 1: The evaluation of the first goal of the query will invoke two guarded systems, `member(a,[1,2,3,a,b])` and `member(a,[1,2,a,b])`. The first of these requires 8 reductions to reduce to true, and evaluates in 4 cycles. The second (guarded) goal requires 6 reductions and evaluates in 3 cycles.

This execution model uses **pruning**, so on commitment to the second clause the system will be able to prevent 2 reductions being performed[2] in the

[2]That is two reductions at best, ie. assuming that **pruning** can happen immediately.

evaluation of the first guard. Hence the total number of reductions performed in the evaluation of this goal is 14 (6 in the first guard (when it is pruned), 6 in the second guard (when it commits), 1 for the commitment to the body goals and finally 1 for the output unification). The binding of the variable "`Output`" will be available to the other goals in cycle 5.

goal 2: The second goal will invoke two guarded systems, `member(b,Output)` and `member(b,[1|Output])`. The first (guard) could be evaluated via two clauses. However, both evaluations suspend on head unification. These suspended clause evaluations are tagged to the variable "`Output`". The second (guard) is able to perform 2 reductions (the guard test and the commitment to `member(b,Output)`). This resulting goal could be evaluated via two clauses but again both evaluations suspend on head unification. The two suspended clause evaluations are again tagged to variable "`Output`".

In cycle 5 the shared variable "`Output`" will be bound, so the 4 suspended clause evaluations will now be evaluated. These will reduce to true in 16 reductions. Hence the total number of reductions performed in the evaluation of this goal is 20 (8 in the first guard, 10 in the second (2 before the suspensions and 8 after the suspensions), 1 for the commitment to the body goal and finally 1 for the output unification). No **pruning** can take place, although the guards are different depths the evaluation of the deeper guard (via second clause) is able to perform some evaluation while the first guard is suspended.

So the evaluation of the query using this execution model takes: 10 cycles; 34 reductions (14 for the first goal and 20 for the second goal); and 4 suspensions.

4.3.3 Depth of evaluation

A measure of the average expected processor utilisation is a useful quantity in selecting appropriate architectures or in estimating expected performance improve-

ments. This quantity can be estimated by the average number of reductions that can be performed in parallel. While we have measures for the total numbers of reductions we require a measure of the duration of the computation.

Such a measure was available in previous interpreters, the **cycle** parameter. However this parameter was erroneous in several respects (see section 3.3.1). The improvements in our interpreter (see section 3.6.5) result in our system providing a more accurate measure of this **cycle** parameter.

4.3.4 Minimum reductions

The evaluation of CCND programs contains a mix of AND-parallel evaluations and OR-parallel evaluations. It would be useful to have a break-down of the overall parallelism in terms of AND-parallelism and OR-parallelism, as this may affect the design of abstract machines and implementations of the languages.

The AND-parallelism can be estimated by comparing the reductions performed in only those clauses that are committed to with the cycle parameter. The OR-parallelism can be estimated by comparing the overall parallelism with the AND-parallelism.

OR-parallelism $\simeq$ Average parallelism / AND-parallelism

Average parallelism = Total reductions / Depth (cycles)

AND-parallelism $\simeq$ Minimum reductions / Depth (cycles)

$\rightsquigarrow$ OR-parallelism $\simeq$ Total reductions / Minimum reductions

---

The total number of reductions may differ for the different evaluation models, this results in several different measures for the OR-parallelism. If **goal** suspension is used then rescheduled goals may result in **deep** guards being retried and so increase the OR-parallelism. To obtain a measure of the minimum reductions required we count the reductions in only the guards that are committed to.

To obtain a measure of the OR-parallelism we need to have a measure of reductions performed in only those guards that are committed to. For the example program and query in *Figure 4–1* this is *sixteen* reductions: *six* reductions to evaluate the guard of the on_either goal; *one* reduction to commit to the assign/2 system goal; *one* reduction to evaluate the assign/2 goal and *eight* reductions to evaluate the member/2 test. Comparing this value to the various reduction parameters gives a measure of the degree of OR-parallelism, as given in *Table 4–2.*

Evaluation Model	Reductions	OR-Parallelism
Busy waiting, Non-Pruning, Goal Suspension	40	2.5
Busy waiting, Non-Pruning, Clause Suspension	36	2.25
Busy waiting, Pruning, Goal Suspension	38	2.375
Busy waiting, Pruning, Clause Suspension	34	2.125
Non-busy waiting, Non-Pruning, Goal Suspension	38	2.375
Non-busy waiting, Non-Pruning, Clause Suspension	36	2.25
Non-busy waiting, Pruning, Goal Suspension	34	2.125
Non-busy waiting, Pruning, Clause Suspension	34	2.125

Table 4–2: Example of degree of OR-parallelism

4.4 Profile tool

As mentioned earlier, see section 3.6, our new interpreter provides information about the execution by creating a dump-data file. This dump file contains tokens which allows us to build a parallel picture of the execution under a range of alternative models of execution. For example, the tokens indicate when the interpreter starts to evaluate a goal and the final outcome (suspension, failure or commitment); when the interpreter starts evaluating a guarded evaluation; the suspension of an evaluation and if the evaluation had suspended before.

The tokens in this dump file are used by our post analysis to extract the parameters we put forward. The main features of this post analysis are:

- The profiler maintains a cycle by cycle aggregate of each of the proposed profile parameters. This provides us with a break down of the various profiling parameters which can be used to give a dynamic picture of the execution. Moreover this mechanism also provides the means by which we are able to collect **pruned/non-pruned, busy/non-busy** and **goal/clause** data.

- Profiling the guard data also maintains a cycle by cycle aggregate of each of the parameters as collected in the guard evaluation.

- On completing the profiling of some guard data the next token indicates that the parent goal either commits, suspends or fails.

  - If the goal commits, the clause number and depth of the commitment are also returned. This provides information which is used to *prune* those profiling parameters which adopt a **pruned** execution model. The *pruned* guard cycle by cycle profile is then combined (spliced) into its parents cycle by cycle profile. Next, an additional reduction representing this commitment is added to each of the reduction parameters at the depth at which the guarded evaluation committed. Finally, the **minimum reduction** parameter from the guard evaluation is added to the parents **minimum reduction** parameter, which is then incremented by one (to reflect the commitment).

  - If the goal evaluation suspends for the first time the suspension parameters of the guarded goal evaluations are spliced into the parents profile. An additional suspension is also added to all the **goal** suspension parameters at the depth at which the guard suspended.

  - If the goal evaluation re-suspends (**non-busy** waiting) the busy suspension parameters of the guarded goal evaluations are spliced into the parents profile. An additional suspension is also added to the **busy waiting goal** suspension parameters, at the depth at which the guarded evaluation suspended.

– Head unifications only contribute to the **clause** suspension parameters.

The data produced by our analysis system gives a cycle by cycle break down of the various proposed parameters. We have also implemented a **profile tool** which executes under SUNVIEW^{TM}. This tool allows us to see any, or several, profiling parameters in graphical form. The tool also provides information on the totals of the various parameters. The tool is best used in an interactive mode. However as technical reports do not facilitate this usage we have included, where appropriate, screendumps of this tool executing.

The dump file could be used to collect several other parameters. For example, we count system calls as reductions, which we use as a measure of parallelism. However the dump file contains different tokens for commitments and system call evaluations and so different measures for the parallelism could be obtained. Similarly, our current analysis assumes that **pruning** takes place immediately. However the dump file could be processed differently, allowing some number of cycles before **pruning** is applied. This would reflect the possible delay in committing to a clause and being able to terminate the evaluation of the other clauses.

Figure 4–2 contains an example screendump of our tool. The tool shows plots of the number of reductions and suspensions (y-axis) in each cycle (x-axis). Such plots can be given for any combination of **suspension mechanism**, **scheduling strategy** and **pruning option**. The options selected are indicated by the toggle buttons on the right hand side. The tool also presents information on the total number of reductions and suspensions using a given execution model. These are presented next to the toggle buttons for each option. Finally, the tool also contains some more general information, like: the goal that was evaluated; the elapsed time of the evaluation; and the minimum number of reductions required to evaluate the goal, assuming the existence of an oracle to pick the correct clause.

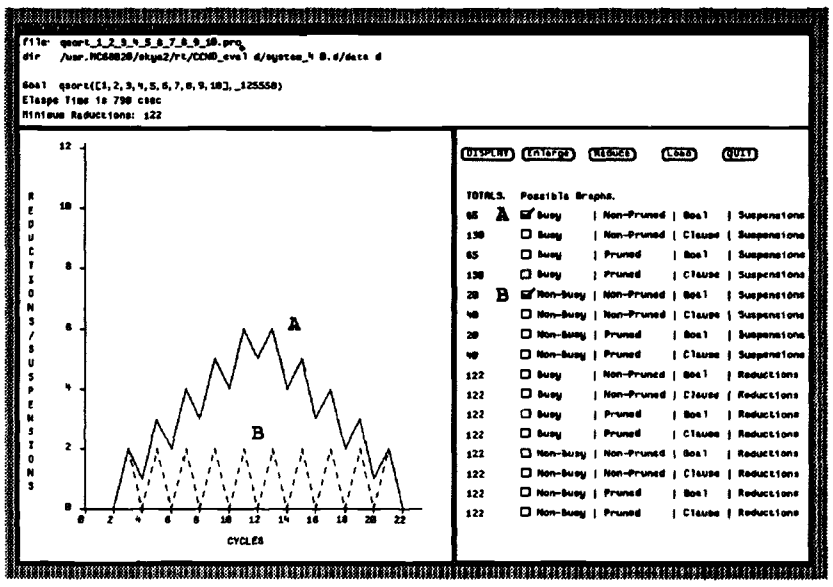


Figure 4–2: An example of an interactive profile tool to analyse program execution

4.5 Example executions and measurements

In this section we consider the behaviour of some simple example programs. This serves two purposes:

- considering simple programs allows us to determine the theoretical behaviour of these programs and compare it to the behaviour observed using our profile tool;

- these example programs hopefully will introduce the reader to the information provided by the profile tool.

4.5.1 List member check

This example program highlights how system calls are handled in our system. Consider the program in *Figure 3–3* with the following query:

```
:- member(a,[1,2,3,4,5,6,a,7,8])
```

Firstly, note that the evaluation of this goal will not result in any suspensions. Secondly, as the guards are system calls, **pruning** the guards will not save any reductions.

The schematic representation of the evaluation of this query on our Parlog version of Shapiro's interpreter is given in *Figure 4–3* (the -> indicates a reduction, while the indentations indicate cycles). This evaluation records *7 reductions* in *7 cycles* and *0 suspensions.*

```
member(a,[1,2,3,4,5,6,a,7,8])
->member(a,[2,3,4,5,6,a,7,8])
  ->member(a,[3,4,5,6,a,7,8])
    ->member(a,[4,5,6,a,7,8])
      ->member(a,[5,6,a,7,8])
        ->member(a,[6,a,7,8])
          -> member(a,[a,7,8])
             ->true
```

Figure 4–3: Schematic of `member/2` evaluation on the original Parlog interpreter

Figure 4–4 gives a schematic representation of the evaluation of this query on our new system. This system records the evaluation as taking *14 reductions* in *7 cycles* and *0 suspensions.*

For this example, both the original model and our new model appear valid. As the guards are **flat** both systems record the evaluation depth as 7 cycles. Also each guard only contains one system call, so the 7 reductions recorded by the

```
member(a,[1,2,3,4,5,6,a,7,8])
a == 1
a \== 1 ->
->member(a,[2,3,4,5,6,a,7,8])
  a == 2
  a \== 2 ->
  ->member(a,[3,4,5,6,a,7,8])
    a == 3
    a \== 3 ->
    ->member(a,[4,5,6,a,7,8])
      a == 4
      a \== 4 ->
      ->member(a,[5,6,a,7,8])
        a == 5
        a \== 5 ->
        ->member(a,[6,a,7,8])
          a == 6
          a \== 6 ->
          -> member(a,[a,7,8])
             a == a ->
             a \== a
             ->true
```

Figure 4–4: Schematic of `member/2` evaluation on our new system

original interpreter are as valid as the 14 reductions recorded by our new system[3]. However, it should be noted that if the guarded goals contained several system calls then the original model would appear more erroneous. *Figure 4–5* contains a reduction profile of the evaluation performed by our system.

[3]Although the meaning of a reduction differs for the two systems

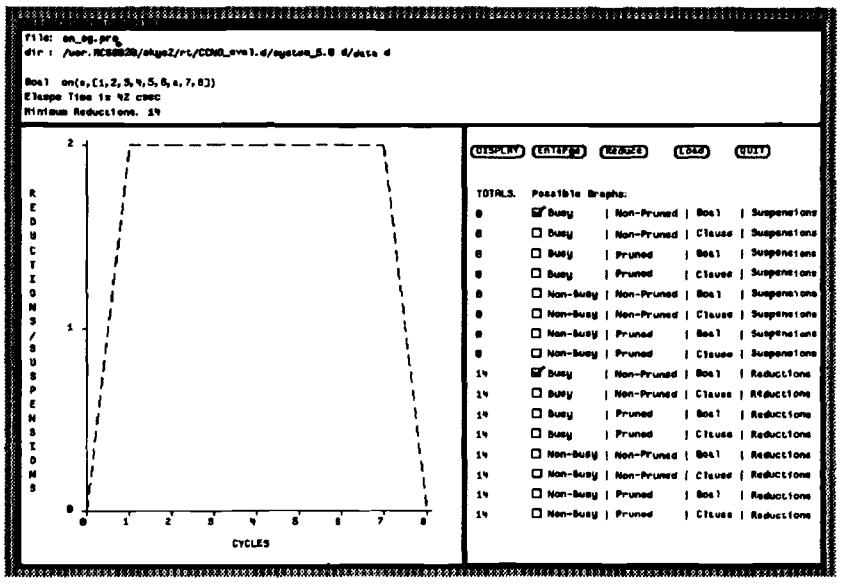


Figure 4–5: List member check **reductions**

4.5.2 Parallel list member checks

In this example we consider how **deep** guards are handled in our system. Consider the program in *Figure 4–1* with the following query:

```
on_either(a,[1,2,3,4,5,6,7,8,9,a],[1,a],L)
```

The program checks to see if a given a term is on either of two lists. The two lists are searched in parallel in the guards of two clauses. The first list that is found to contain the given term is returned. Firstly, note that the evaluation of the above query will not result in any suspensions. Secondly, as the guards are **deep** and uneven, **pruning** the guards should save some reductions.

Figure 4–6 gives a schematic representation of the evaluation of the query on our Parlog version of Shapiro's interpreter (the branches of the tree indicate reductions while the depth indicates cycles). The evaluation commits to the first

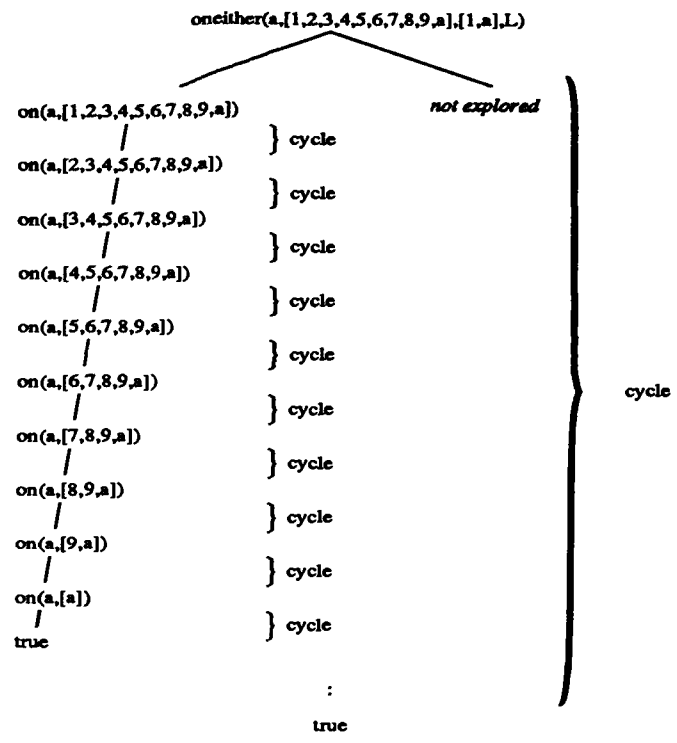


Figure 4–6: Schematic of `oneither/4` evaluation on the original Parlog interpreter

clause (as it is the first clause tried) and incurs 10 reductions in 1 cycle and 0 suspensions. This does not reflect the nature of the computation, in that the guard evaluation takes 10 cycles and yet the overall evaluation only takes 1 cycle.

Figure 4–7 gives a schematic representation of the evaluation of this query on our new system (the branches of the tree indicate reductions while the depth indicates cycles). Using the new interpreter the evaluation commits to the second clause whose guard succeeds in two cycles. So the evaluation commits to the second clause, in cycle 3, and the evaluation of the first clause can be **pruned** from cycle 3 onward (the pruned part of the first guard evaluation is indicated by the shading).

Figure 4–8 contains a profile of the evaluation performed by our system. This profile graphically indicates the advantages of pruning in this computation. It is

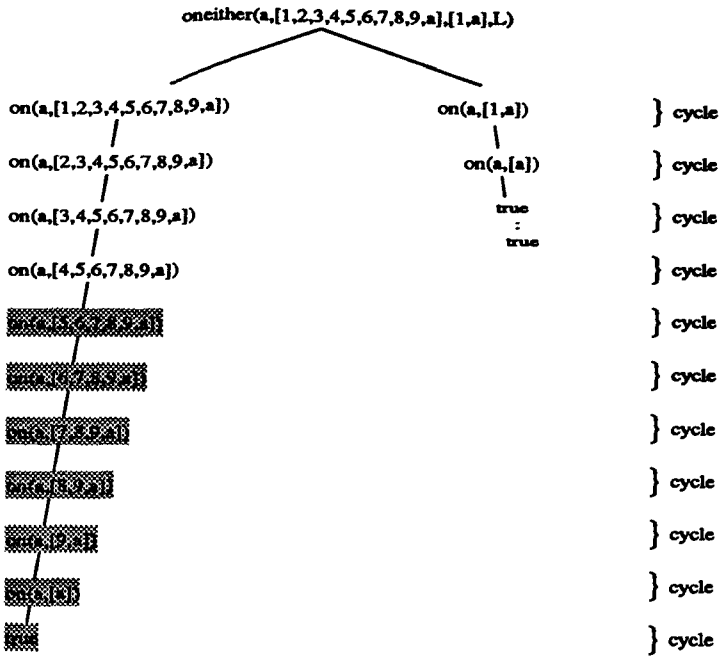


Figure 4–7: Schematic of `oneither/4` evaluation on our new system

also worth noting the depth of the overall evaluation (number of cycles) incorporates the depth of the guard evaluation.

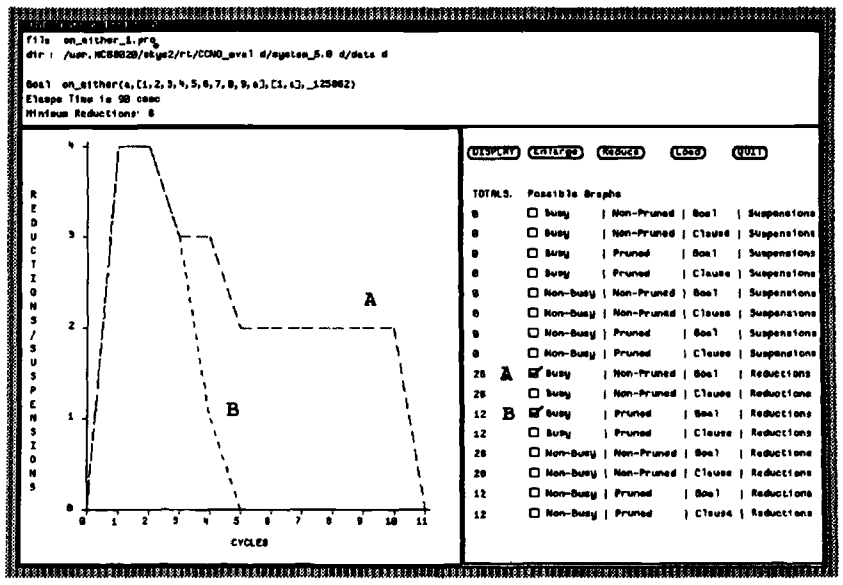


Figure 4–8: Parallel list member check (**pruned** and **non-pruned** reductions)

4.5.3 Quick-sort

This example highlights the various differences in the various suspension parameters and how regular and irregular queries result in differing dynamic features of the computation. The program being used is quick-sorting a list (see *Figure 2–7*). This program was used in section 2.4.6, to highlight the difference in the suspension mechanisms employed by the various CCND languages.

Firstly, we consider how this program behaves if the list to be sorted is already ordered. We then consider how this program behaves if the input list is unordered.

4.5.3.1 Quick-sort of an ordered list

Consider the program in *Figure 2–7* with the following query:

```
quicksort([1,2,3,4,5,6,7,8,9,10],L)
```

The regular nature of the data for this query allows us to reason about its evaluation. Basically, `quicksort([1,2,3,4,5,6,7,8,9,10],L)` will be reduced to the initial `qsort/2` goal. This goal is then reduced to a `partition/4` and two new `qsort/2` goals. The `partition/4` goal will partition the input list (based on the current first element; the *pivot*) into two output lists. One output list contains elements greater than the *pivot* the other elements less than the *pivot*. As the input list is already ordered the `partition/4` goal will only add elements to one of the output lists. The two `qsort` processes will initially suspend awaiting the output lists from the `partition/4` to be generated. In the following cycle one of the `qsort` goals will be able to reduce, as the `partition/4` process constructs the output lists. The reduction of this `qsort` goal will again result in a `partition/4` process and two `qsort/2` processes. The other `qsort/2` process remains suspended until the entire list has been partitioned, *i.e.* until the `partition/4` processes complete.

These processes will behave as before: the `partition/4` process will only add elements to one of its output lists, the two `qsort` processes will initially suspend, one of which will be able to reduce in the following cycle.

This computation results in the following `partition/4` processes being spawned:

```
partition([2,3,4,5,6,7,8,9,10],1,Smaller,Larger)
partition([3,4,5,6,7,8,9,10],2,Smaller,Larger)
partition([4,5,6,7,8,9,10],3,Smaller,Larger)
partition([5,6,7,8,9,10],4,Smaller,Larger)
partition([6,7,8,9,10],5,Smaller,Larger)
partition([7,8,9,10],6,Smaller,Larger)
partition([8,9,10],7,Smaller,Larger)
partition([9,10],8,Smaller,Larger)
partition([10],9,Smaller,Larger)
partition([],10,Smaller,Larger)
```

Note that `Smaller` *and* `Larger` *represent different variables in each process above.*

The processes will be spawned in cycles 2,4,6,8,10,12,14,16,18,20 respectively. The duration of the processes will be 9,8,7,6,5,4,3,2,1 cycles respectively. So these `partition/4` processes will terminate in cycles 11,12,13,14,15,16,17,18,19,20,21. After cycle 11 there will be one less suspended process each cycle (a `qsort/2` process) until cycle 21.

This effect has to be combined with the spawning pattern of the `qsort/2` goals, *i.e.* initially 2 suspensions, of which 1 reduces in the next cycle. So the overall goal suspension pattern is that initially in every other cycle there will be two new suspensions, one of which is able to reduce in the following cycle. After cycle 11 the pattern will be inverted. In every other cycle there will be one new suspension followed by two of the suspended goals being re-scheduled and reducing.

We now consider profiles of this execution obtained on our new system, see *Figures 4–9*, *4–10* and *4–11*.

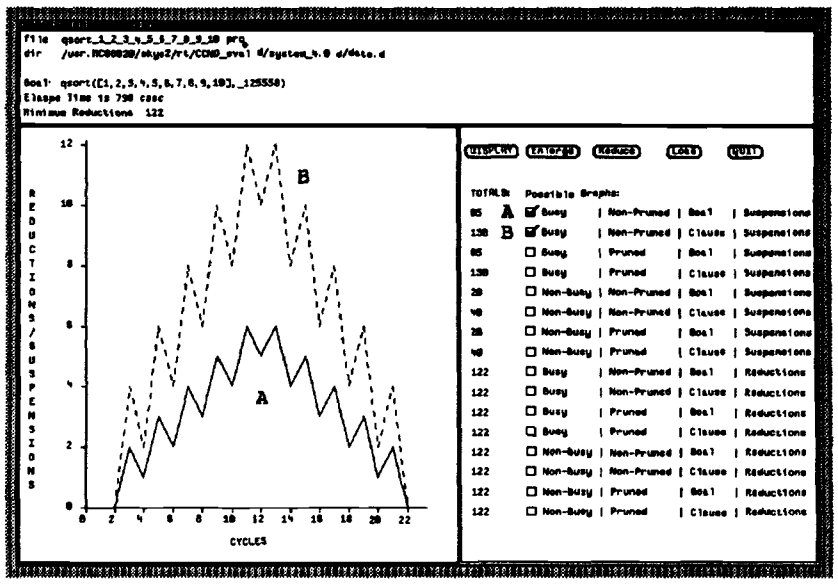


Figure 4–9: Quick-sorting an ordered list (**goal** and **clause** suspensions)

Figure 4–9 gives profiles for **goal** and **clause** suspensions using **busy** waiting and **non-pruning**. Using **busy** waiting gives us a measure of the total number of processes suspended. Note that the **goal** suspension profile (the lower graph) is as predicted, that is the total number of suspended processes will initially increase in a step wise manner (steps of +2, -1) and from cycle 11 onwards will reduce in a step wise manner (steps of +1,- 2).

Moreover comparing the **goal** and **clause** suspension profiles indicates the number of clauses that each suspended evaluation could be reduced by in the dynamic program [4]. This gives a ratio of exactly 2 **clause** suspensions for every

---

[4]There is a difference between counting the number of clauses for each predicate statically, and the dynamic nature of the program, as some predicates may be used more often than others, hence weighting the results. Of course comparing suspensions for **goal** and **clause** suspension mechanisms only provides the dynamic information for

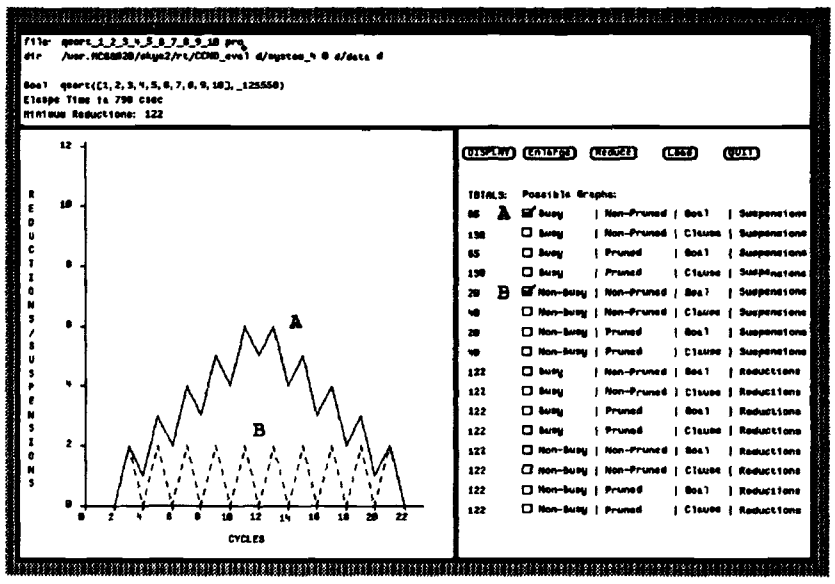


Figure 4–10: Quick-sorting an ordered list (**busy** and **non-busy** suspensions)

goal suspension. This is also confirmed by our analysis, in that the only processes to be suspended are `qsort/2` which could be evaluated via two clauses.

Figure 4–10 gives profiles for **goal** suspension using **busy** and **non-busy** scheduling strategies. **Busy** waiting (the upper graph) gives a measure of the total number of suspended processes while **non-busy** gives a measure of the new suspended processes in each cycle. The profiles fit the analysis of this execution. In every other cycle there will be two new suspended goals one of which will reduce in the next cycle.

---

suspended evaluations and not the whole evaluation. This comparison still provides useful information about the space-time considerations for the suspension mechanism. Suspending the **clauses** may save head unifications and possibly some reductions (for **deep** guard examples) but requires more space in that there may be several clause states to suspend rather than a single goal state.

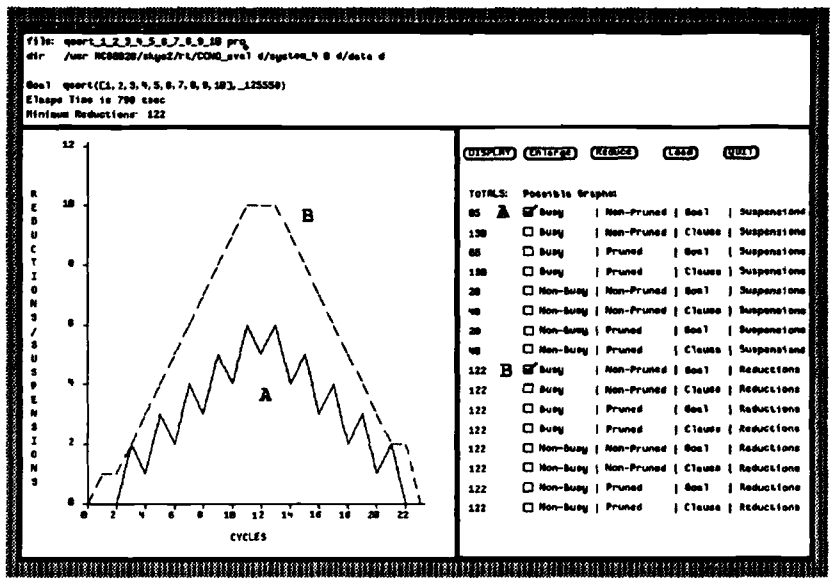


Figure 4–11: Quick-sorting an ordered list (**reductions** and **suspensions**)

Finally we give a profile of the reductions in *Figure 4–11.* The number of reductions increases by 1 each cycle, as new `partition/4` processes are spawned and reduced. After cycle 11 the `partition/4` goals begin to succeed (terminate) and the processes begin to collapse. At the peak there will be 10 `partition/4` and 1 `qsort` process reducing in parallel.

4.5.3.2 Quick-sort of an unordered list

We now turn our attention to the behaviour of quicksort on an unordered list. Consider the program in *Figure 2–7* with the following query:

```
quicksort([4,6,2,9,5,5,1,10,3,7],L)
```

The irregular nature of the data for this query makes reasoning about its evaluation difficult. However some global features can be predicted, namely:

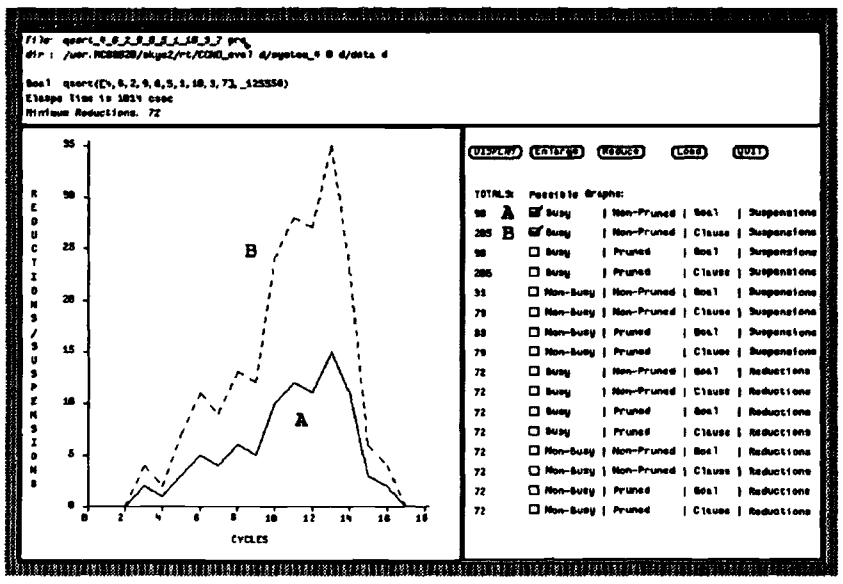


Figure 4–12: Quick-sorting an unordered list (**goal** and **clause** suspensions)

- The unordered query will result in the `partition/4` process adding elements to both output lists. This will result in both the `qsort/2` processes reducing before the `partition/4` processes have terminated. Compared with the ordered list example this should show an increase in the average number of reductions and reduce the total length of the computation.

- As the `partition/4` processes add elements to both output lists the `qsort/2` goals may reduce to three suspended processes, *i.e.* the newly spawned `partition/4` goal may suspend because no further elements have been added to its input list. This will be indicated by the ratio between **goal** and **clause** suspensions increasing, as the `partition/4` processes can be evaluated via 3 clauses, whereas the `qsort/2` processes can be evaluated by 2 clauses.

- In both the ordered list example and the unordered list example there will be 10 `partition/4` processes spawned (one for each element of the input list). In the ordered example each `partition/4` process will partition the

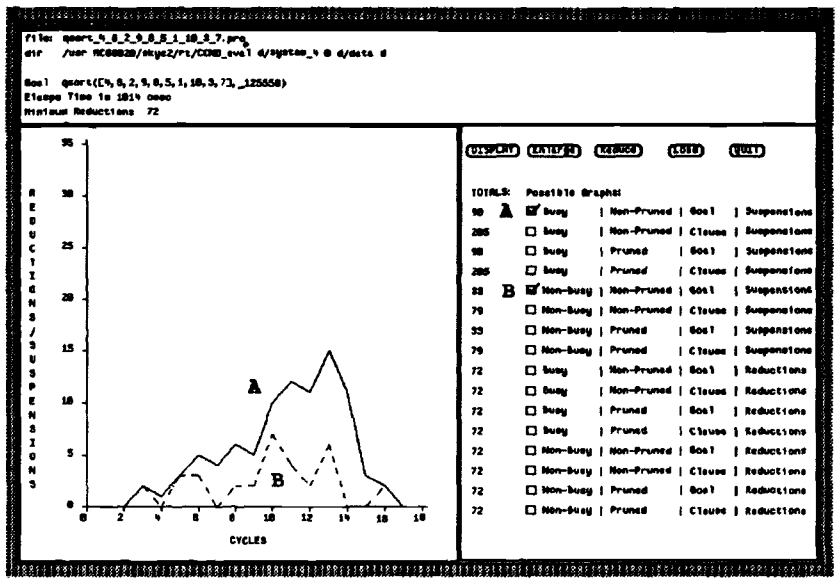


Figure 4–13: Quick-sorting an unordered list (**busy** and **non-busy** suspensions)

remainder of the input list, *i.e.* the partition process with a *pivot* of 3 will have to partition the remainder of the input list, namely `[4,5,6,7,8,9,10]`. For the unordered example each `partition/4` process will only have to partition a subset of the remaining input list because the remaining input list will be partitioned into two lists. So there will be less reductions performed in the sorting of the unordered list example.

We now compare the data collected using our new profiling system with the theoretical evaluation given above. *Figure 4–12* gives profiles for **goal** and **clause** suspensions using **busy** waiting and **non-pruning**. The first point to note is that the ratio of **goal** to **clause** suspensions changes from 1:2 for the ordered example, to 90:205 for the unordered example. From this we can conclude that some `partition/4` processes suspend. Furthermore, we can see that the overall length of the computation has been reduced from 23 cycles (for qsorting an ordered list) to 18 cycles for this example.

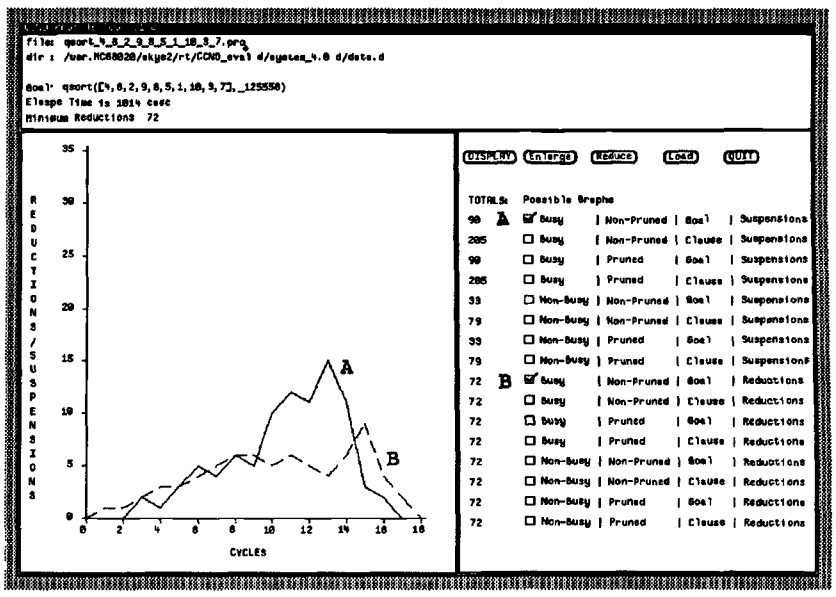


Figure 4–14: Quick-sorting an unordered list (**reductions** and **suspensions**)

Figure 4–13 gives profiles for **goal** suspensions using **busy** and **non-busy** scheduling strategies. Firstly, we can see that the duration of suspended processes is more complex to predict. Secondly, we see that the ratio of **busy** to **non-busy** suspensions is 90:33 for this query, whereas it was 65:20 for the ordered list example. This indicates that the suspended goals remain suspended for less time in the unordered example, which is intuitively the case.

Finally, we give a profile of the reductions in *Figure 4–14* (the dashed curve). Comparing the total reductions performed for the ordered list (122 reductions) and the unordered list (72 reductions) we see that, as predicted, there is a marked decrease in the required number of reductions.

4.5.4 Iso-tree

This example highlights how recursive **deep** guards (user defined guarded goals which in turn have user defined guarded goals) are handled in our system. The example used is to test if two binary trees are isomorphic. Trees are isomorphic if:

- either both trees are empty;
- or if they have the same root node and both left and right subtrees are isomorphic;
- or if they have the same root node and the left subtree of one is isomorphic with the right subtree of the other and vice-versa.

This algorithm can be realised in the CCND languages using **deep** guards. The resulting program is given in *Figure 4–15.*

```
mode isomorphic(?, ?).

isomorphic(terminal, terminal).
isomorphic(tree(Node, Ltree1, Rtree1),
        tree(Node, Ltree2, Rtree2)) :-
    isomorphic(Ltree1, Ltree2),
    isomorphic(Rtree1, Rtree2)
    :
    true.
isomorphic(tree(Node, Ltree1, Rtree1),
        tree(Node, Ltree2, Rtree2)) :-
    isomorphic(Ltree1, Rtree2),
    isomorphic(Rtree1, Ltree2)
    :
    true.
```

Figure 4–15: Isomorphism algorithm expressed in a CCND language (Parlog)

If we evaluate this program for the three pairs of trees given in *Figure 4–16* the resulting reduction profiles are given in *Figures 4–17, 4–18* and *4–19.*

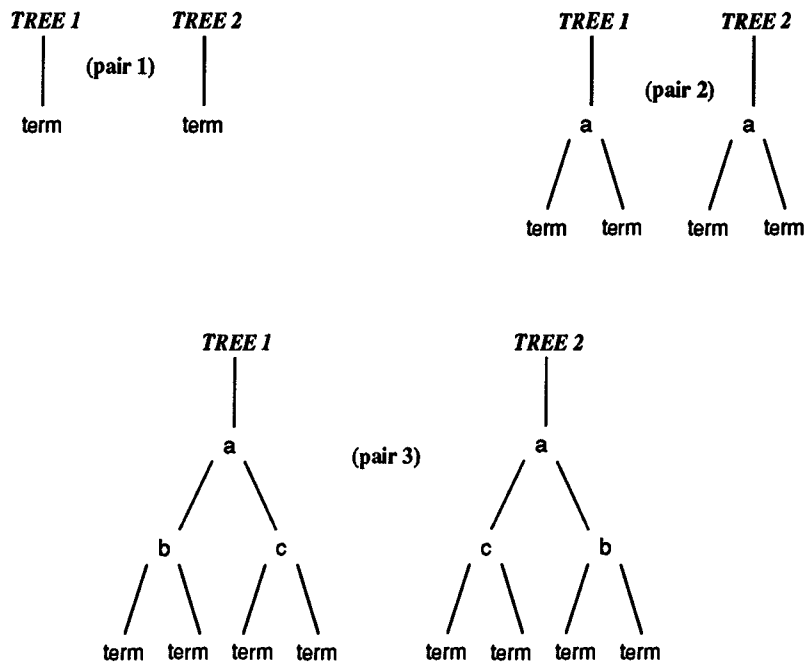


Figure 4–16: Iso-tree examples

As mentioned in section 3.6.2 our model of evaluation assumes that in a cycle a goal can be unified with the head of the clauses in the system and either the guarded evaluation instigated, or system guards evaluated. The body goal is committed to at a depth of `1+(the depth of the guarded evaluation)` and in the next cycle for system guards.

If we now consider the first example, that is two empty trees. This will evaluate in 1 cycle and incur 1 reduction. The profile for this evaluation is given in *Figure 4–17.*

The second example considers a guarded goal whose depth is 1 cycle. In our model this will result in the four guard evaluations, which are all:

```
isomorphic(term,term)
```

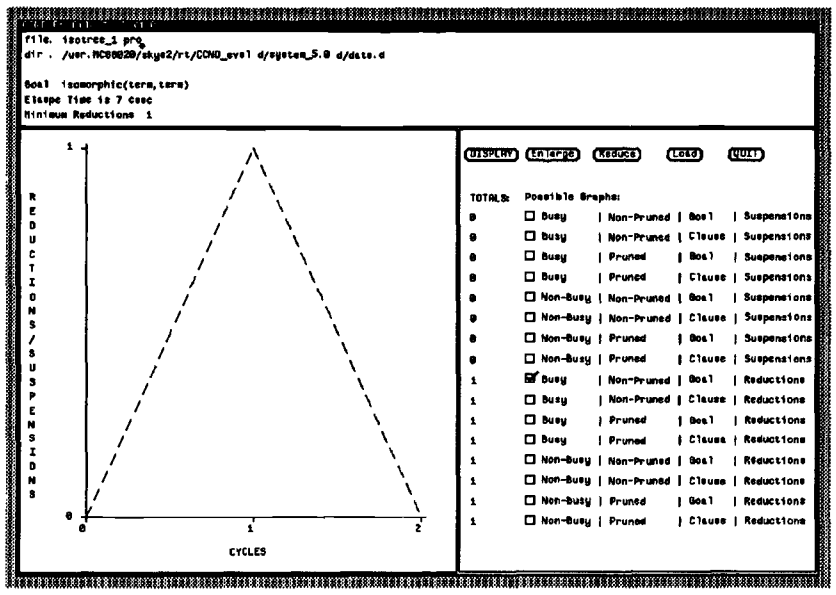


Figure 4–17: Iso-tree evaluation example 1 (**reductions**)

These will reduce to true in 1 cycle and incur 4 reductions. In the next cycle (cycle 2) the original query goal will commit to `true`. *Figure 4–18* gives a reduction profile for this evaluation.

The third example considers guarded goals which in turn have guarded goals. The query is:

```
:- isomorphic(tree(a,tree(b,term,term),tree(c,term,term)).
              tree(a,tree(c,term,term),tree(b,term,term))).
```

The evaluation results in two sets of guarded goals, namely:

1. `isomorphic(tree(b,term,term),tree(c,term,term))`,
   `isomorphic(tree(c,term,term),tree(b,term,term))`; and

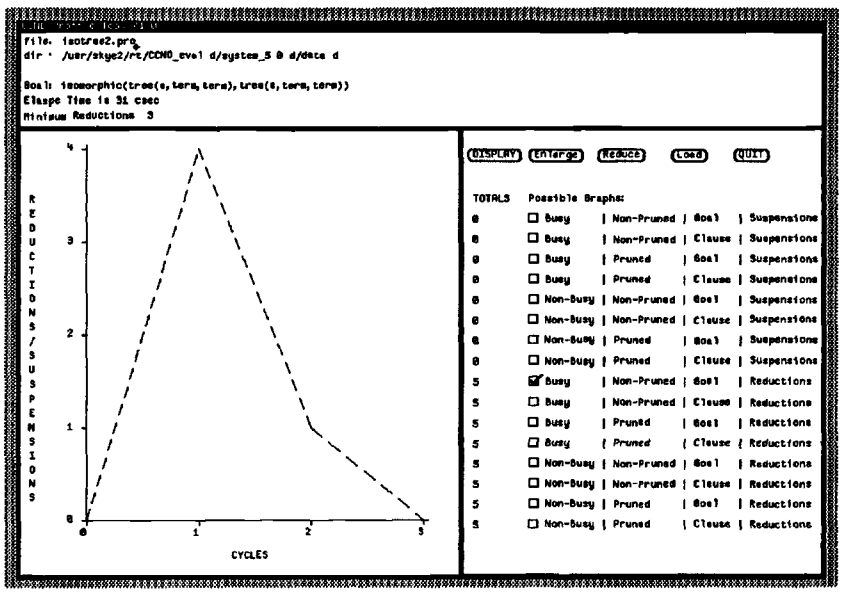


Figure 4–18: Iso-tree evaluation example 2 (**reductions**)

2. `isomorphic(tree(b,term,term),tree(b,term,term)),`
   `isomorphic(tree(c,term,term),tree(c,term,term)).`

The first guarded system fails. The second guarded system has two goals, each of which has the same profile as example 2 above. Using our system the resulting profile for this example is obtained by composing the profiles for the two guarded systems and one additional reduction in cycle 3 when the top-level goal commits. *Figure 4–19* gives a profile for this evaluation.

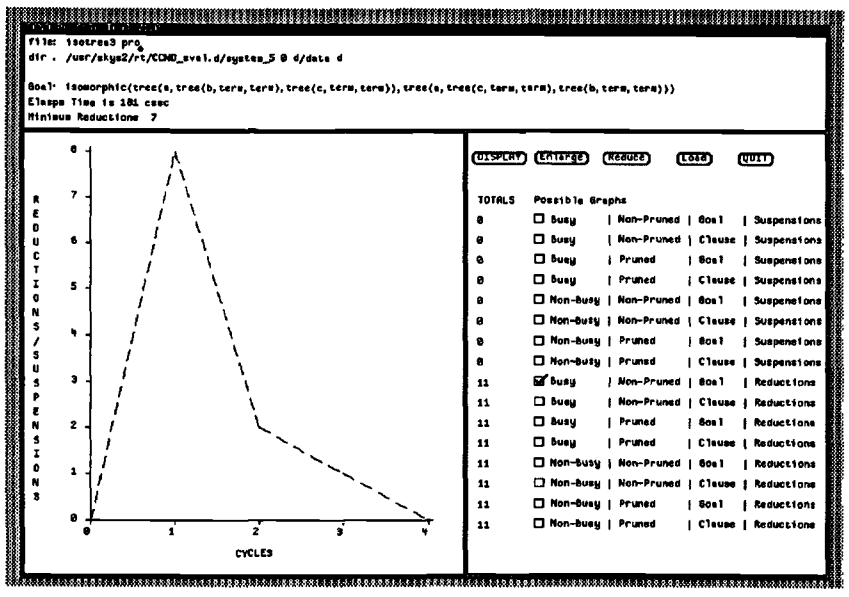


Figure 4–19: Iso-tree evaluation example 3 (**reductions**)

4.5.5 Prime number generation by sifting

```
primes :-
    integers(2,I), sift(I,J).

mode integers(?,^ ).
integers(N,[N|I]) :-
    N1 is N+1,integers(N1,I).

mode sift(?,^ ).
sift([],[]).
sift([P|I],[P|R1]) :-
    filter(I,P,R), sift(R,R1).

mode filter(?,?,^ ).
filter([],_,[]).
filter([N|I],P,R) :-
    0 =:= N mod P
    :
    filter(I,P,R).
filter([N|I],P,[N|R]) :-
    0 =\= N mod P
    :
    filter(I,P,R ).
```

Figure 4–20: Prime number generation by sifting

This example illustrates how our model for AND-parallelism gives a more realistic indication of the depth of the computation. The program used generates prime numbers by sifting a stream of integers [Ueda 86a]. The algorithm involves generating a pipeline of filter processes one for each integer that is unfiltered (new prime) by the previous set of filters, the combined effect of these filters is to sift the stream of integers (see *Figure 4–20*). Each unsifted integer is a prime number. As each prime number is produced it results in a filter process being spawned; each filter process removes multiples of itself from the remainder of the stream. So the algorithm involves generating a pipeline of filter processes one for each integer

that is unfiltered (new prime) by the previous set of filter processes. We consider the generation of *primes up to 50* and *primes up to 100.*

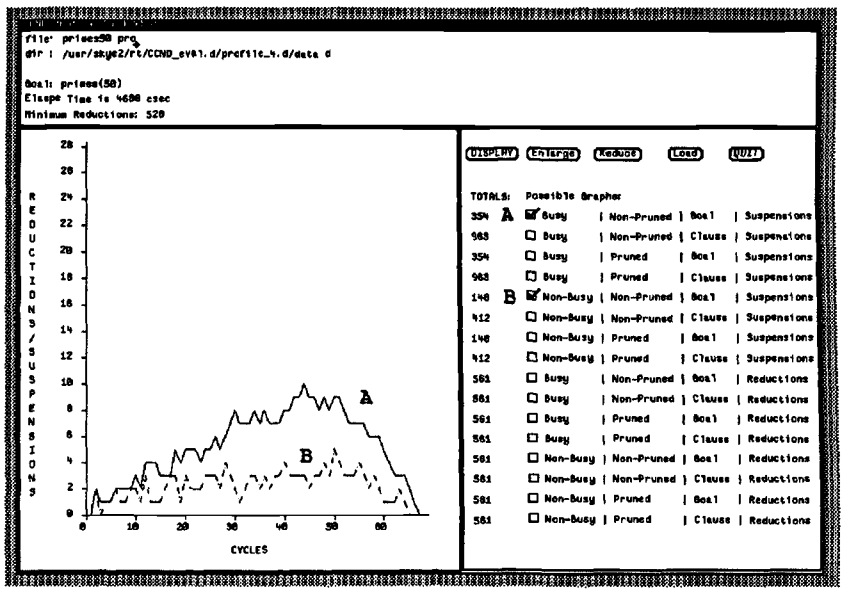


Figure 4–21: Prime numbers up to 50 (**busy** and **non-busy** suspensions)

The prime number generation by sifting example gives a good indication of how the execution model affects the collection of meaningful statistics. The technique involves generating a stream of integers, say *fifty*, these integers being generated in *fifty* cycles. This stream of integers then under-goes a sifting stage, this will require further cycles. Consider the number 47. This will be generated in the *forty-seventh* cycle. This integer will then be filtered by filter processes representing the following prime numbers: 2;3;5;7;11;13;17;19;23;29;31;37;41;43. This takes at least *fourteen* cycles, one for each filter process.

Now let us look at the statistics that were previously given for this example program (see *Table 4–3*) obtained on our Parlog version of Shapiro's CP interpreter. The cycle count is only *fifty*, this is because the goals in the process queue are evaluated in a left-to-right fashion. Any bindings made in reducing a goal

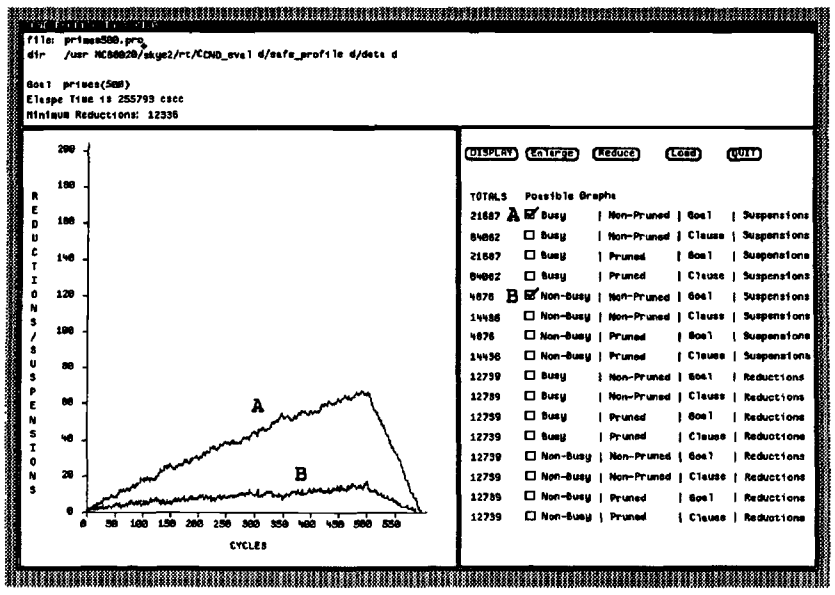


Figure 4–22: Prime numbers up to 500 (**busy** and **non-busy** suspensions)

occur immediately. So an integer that is produced in a given cycle is able to propagate through the filter processes in the same cycle (the filter processes in the queue are set-up in a left to right fashion). Our system gives 67 cycles to produce the first 50 prime numbers (see *Table 4–5*). *Fifty* of these cycles can be attributed to producing the 50 integers, *fifteen* of these can be attributed to propagating the last integer through the *fifteen* filter processes and the remaining *two* are due to spawning the first filter process and terminating the output of these integers. The effect of accounting for the propagation of the integers through the filter processes results in the number of suspended goals being higher. Other points that arise are:

- There is no difference between the various new reduction counts (see *Table 4–4*) for this program. The similarity in the reduction counts using **goal** and **clause** suspensions indicate either there are no suspensions or that the

Program		Cycles	Reductions	Suspensions
on	- List member check	7	7	0
oneither	- Parallel list member check	1	10	10
qsort1	- Qsorting an ordered list	12	77	45
qsort2	- Qsorting an unordered list	12	52	70
isotree1	- Iso-tree example 1	1	1	0
isotree2	- Iso-tree example 2	1	3	0
isotree3	- Iso-tree example 3	1	7	0
primes50	- Primes up to 50	50	249	321
primes100	- Primes up to 100	100	587	1151

Table 4–3: Summary of previous measurements for example programs

		Reductions							
	Minimum Required	Busy Waiting				Non-Busy Waiting			
		Non-Pruned		Pruned		Non-Pruned		Pruned	
Program	Reductions	Goal	Clause	Goal	Clause	Goal	Clause	Goal	Clause
on	14	14	14	14	14	14	14	14	14
oneither	6	26	26	12	12	26	26	12	12
qsort1	122	122	122	122	122	122	122	122	122
qsort2	72	72	72	72	72	72	72	72	72
isotree1	1	1	1	1	1	1	1	1	1
isotree2	5	5	5	5	5	5	5	5	5
isotree3	11	11	11	11	11	11	11	11	11
primes50	528	561	561	561	561	561	561	561	561
primes100	1244	1317	1317	1317	1317	1317	1317	1317	1317

Table 4–4: Summary of new reduction parameters for example programs

evaluations suspend on head unification. However, as some suspensions occur (see *Table 4–5*) these suspensions must be on head unification.

- The similarity in the reduction and suspension counts using **pruned** and **non-pruned** evaluation models indicate that either guards are even in their computation or that only one could ever be picked as a solution path. If we also consider the minimum reductions (see *Table 4–4*) then the actual reductions performed are similar to the minimum possible reductions. This implies that only one clause in general succeeds as a solution path.

Suspensions									
		Busy Waiting				**Non-Busy** Waiting			
		Non-Pruned		**Pruned**		**Non-Pruned**		**Pruned**	
Program	Cycles	Goal	Clause	Goal	Clause	Goal	Clause	Goal	Clause
on	7	0	0	0	0	0	0	0	0
oneither	4	0	0	0	0	0	0	0	0
qsort1	22	65	130	65	130	20	40	20	40
qsort2	17	90	205	90	205	33	79	33	79
isotree1	1	0	0	0	0	0	0	0	0
isotree2	2	0	0	0	0	0	0	0	0
isotree3	3	0	0	0	0	0	0	0	0
primes50	67	354	963	354	963	148	412	148	412
primes100	127	1204	3413	1204	3413	388	1112	388	1112

Table 4–5: Summary of new suspension parameters for example programs

- The difference between suspension counts using **goal** and **clause** suspension highlights the number of clauses that each clause could be reduced by in the dynamic program. The ratio for this program is about 1:3 (354:963 for prime numbers up to 50 and 3412:1204 for prime numbers up to 100).

- The difference between suspension counts using **busy** waiting and **non-busy** waiting scheduling policies indicates the benefit of tagging suspended executions to variables (see section 4.2.3). It also suggests how long suspended evaluations remain suspended. If we compare **busy** and **non-busy** suspensions for prime numbers up to 50, the ratio is about 5:2 (354:148) for **goal** suspension. For prime numbers up to 100, the ratio is about 3:1 (1204:388). So, on average the number of cycles that a process is suspended is about 3. However, for large examples the results imply that this ratio will increase. This is because a pipeline of filter processes is being spawned as each new prime number is generated. This pipeline will be more active for the earlier primes rather than the later ones. For example, the filter process for the prime number 2 , will never be suspended, it will either be removing an integer from the stream or passing it on to the next filter process. This result is highlighted graphically in *Figures 4–21* and *4–22*, in that the ratio between

two suspension graphs for **busy** *(the large plot)* and **non-busy** *(the smaller plot)* suspensions increases with the number of primes being produced.

4.6 Limitations of the new measurements

The limitations of our new system can be classified in two ways. Those associated with modelling the execution and the collection of our proposed parameters, and those associated with information we do not collect. The second class of limitation forms the basis of future possible evaluation systems, these are discussed in the section on future work at the end of this thesis. Here we focus on the first class of limitation - those with our evaluation model and the collection of our new parameters:

- Firstly, we adopt a fixed cost model (see section 3.6.2). In this model the various components of the evaluation, like head unification, have been assigned fixed costs (in terms of cycles). However, the cost of the given operation may depend on several factors, such as its complexity. It would be better to adopt a functional cost model, where the cost of an operation is calculated based on its complexity. Such a model would however require the costs of the various operations to be accurately quantified. The resulting cost model would be difficult to construct without reference to an actual implementation.

- Secondly, we make the assumption that, in a cycle, a goal can only use bindings available to it at the start of the cycle. This is an improvement over the current interpreters, in modelling the inherent parallelism. Current interpreters process the goals in a given order, allowing bindings to be made immediately and so possibly allowing subsequent goals that require these bindings to reduce in the current cycle. This problem is compounded if **deep** guards are employed. A fully accurate model would be able to determine exactly when a goal makes a binding, how long it would take for this binding

to reach another goal and whether this would be in time for the goal to use it in the current cycle. Such a model would be heavily implementation dependent and its results would not transfer easily to other implementations. Clearly the inherent parallelism should not be dependent on goal order. Our model may not display all the parallelism that could be achieved in a given implementation, but at least it gives a measure which is not dependent on how the goals are ordered.

- Finally, in our interpreter, if an evaluation suspends, the top-level goal being evaluated is suspended. Unlike previous interpreters the suspension record contains information (counters) about the duration of the guard evaluation before the evaluation suspended. Although each goal record in the goal list is processed each cycle the additional counters indicate whether this goal would have been evaluated in a given execution model. Whilst this is an improvement over the previous evaluation systems our new parameters may be in error for certain classes of program.

  Two related problems arise:

  - There may be a problem in **busy** clause suspension profiles. Only the bindings that are available at the beginning of a cycle are used in the evaluation of a goal. However, if the guard has a **deep** consumer then this guard may suspend, whereas in a parallel implementation the bindings may become available as the **deep** guard is being evaluated.
  - There may be a problem in **pruning** consumer guards. If a **clause** suspension model is employed and the different consumer guards have different data dependencies then it may be possible for one guard to be processed further than another, before suspending. So, the depth to which these guards will be evaluated may differ if **clause** suspension is employed (as one guard can be processed while the other suspends). Our interpreter actually employs goal suspensions, while some information like the depth of the previous evaluation before suspension is

stored in the suspension record. The depth to which each of the various guards was previously evaluated to is not stored and so this information is lost. If **pruning** is employed then for such evaluation models the results may be in error, as the evaluation depth may be in error.

The class of program affected by these two problems have consumer goals in the guard (**deep** consumer guards) which suspend and the guard evaluations suspend at different depths. An example of such a program and query is given in *Figure 4–1.*

Execution Model	Cycles	Reductions	Suspensions
Original model *Section 3.2*	3	11	1
Busy waiting, Non-Pruning, Goal Suspension	10	40	6
Busy waiting, Non-Pruning, Clause Suspension	10	36	16
Busy waiting, Pruning, Goal Suspension	10	36	6
Busy waiting, Pruning, Clause Suspension	10	32	16
Non-busy waiting, Non-Pruning, Goal Suspension	10	38	3
Non-busy waiting, Non-Pruning, Clause Suspension	10	36	4
Non-busy waiting, Pruning, Goal Suspension	10	34	3
Non-busy waiting, Pruning, Clause Suspension	10	32	4

Table 4–6: Results collected for example query

The query has two goals. The second goal is a **deep** guarded consumer and the first goal is a producer. *Table 4–1* gives a summary of the predicted results of the evaluation of this query. *Table 4–6* gives a summary of the results obtained by our evaluation system. As expected our results are slightly in error for the suspension parameters using **busy** waiting and **clause** suspension and also for reductions using **pruning**.

4.7 Summary

In this chapter the following have been presented and discussed:

- The basis of the new profiling parameters we propose.
- A detailed example execution which highlights the various new parameters.
- How the new parameters are collected by post analysis of a dump file and an example of a graphical tool developed for viewing profiles of the various new parameters.
- The use of this graphical tool to analyse the execution of several example programs. These highlight several features of both the interpreter and our proposed metrics.
- The limitations of our evaluation system.

Part III

Example AI programs and their evaluation

Preface

In this part of the thesis we evaluate the execution behaviour of AI applications/programming techniques realised on the CCND languages. The selection of the application areas was motivated by two requirements:

- The applications should represent some common AI programming techniques or paradigms.

- The possible realisations (mappings) should highlight the use of particular language features. The evaluation of the resulting programs then allows us to compare the dynamic behaviour of the use of these features in our AI applications.

This part of the thesis consists of three chapters, each focusing on a different AI application and CCND language feature:

- Chapter 5 considers how AI search based algorithms can be mapped to the committed choice feature of the CCND languages. The qualitative evaluation highlights the need for some techniques for translating general search programs into all-solutions search programs. Three techniques for translating search programs on to the CCND computation model are then discussed, namely Continuation based compilation; Stream based compilation; and Layered Streams. We then evaluate three all-solutions versions (obtained using each of the translation techniques) of the n-queens problem.

- Chapter 6 considers how multiple writers to shared data structures can be supported in the CCND languages. The main feature being investigated here is the difference between using **safe** and **unsafe** languages. Support for shared data areas appears to be a important consideration for AI programming. Several current AI applications/programming paradigms use a shared

area to allow independent experts to co-operate in the solving of a problem *e.g.* blackboard type problem solvers and chart parsers. We consider how chart parsing maps to **safe** and **unsafe** languages and to a language with additional primitives to support shared streams. The three resulting chart parsers are then evaluated.

- Chapter 7 considers how an AI programming technique known as meta-level inference maps to the CCND languages. The language feature being investigated here is the difference between using **deep** and **flat** languages. Meta-level inference attempts to control the search at one level of the problem space (the object-level) by providing some general control rules (the meta-level) to guide the search over the object level search. The application evaluated is known as PRESS. We consider how the meta-level of PRESS maps to **deep** guards and to **flat** guards using two techniques in supporting the meta-level. The three resulting PRESS systems are then evaluated.

Chapter 5

Search - committed choice

5.1 Overview

This chapter considers how AI search based algorithms can be mapped to the committed choice feature of the CCND languages. Axioms specified in Horn clauses can be viewed as a program if there is some theorem prover which can apply the axioms to solving a query. The selection of which axioms to apply to solving a given goal highlights several types of choice point (*don't care*; *don't know*; and *generate and test*) that exists in the search space for the theorem prover. The scope and applicability of a logic programming language is determined by how it supports/caters for these various choice points.

This chapter first considers how various forms of non-determinism (*don't care*; *don't know*; and *generate and test*) can be realised in the CCND framework. This analysis highlights a class of search algorithms which cannot be supported directly (mapped) on the CCND computational model. We then consider various techniques for offering exhaustive search in the CCND languages. The techniques considered are Continuation based compilation, Stream based compilation and Layered Streams.

These exhaustive search techniques have been evaluated and compared before in [Okumura & Matsumoto 87]. The main program used in their comparison was *n-queens*; in particular *4-queens*, *6-queens* and *8-queens*. We re-evaluate the *4-queens* and *6-queens* examples for each of the programming techniques on our new evaluation system.

Section 5.2 considers various issues related to how the CCND languages can model search algorithms.

In sections 5.3, 5.4 and 5.5 we consider in detail the use of the various All-solutions programming techniques.

Section 5.6 summarises the previous analysis [Okumura & Matsumoto 87] of these techniques.

Section 5.7 gives our analysis of these programming techniques.

Finally, in section 5.8 we give a synopsis of our results.

5.2 Search

5.2.1 *Don't care* non-determinism

Don't care non-determinism is where choice of any evaluation path will lead to a solution. Take for example the merge predicate (the unordered combination of two lists) in *Figure 5–1.*

CCND realisation

In the CCND execution model the first clause that can commit does commit, so the evaluation of the `merge/3` predicate given in *Figure 5–1* will produce an unordered combination of the two input lists. The other feature is that the lists can be thought of as streams, so this process serves to merge the two streams

```
merge([],L,L).
merge(L,[],L).
merge([H|T],L,[H|Y]) :- merge(T,L,Y).
merge(L,[H|T],[H|Y]) :- merge(T,L,Y).
```

Figure 5–1: Unordered combination of two lists in Horn clauses

into one (hence the name merge), *i.e.* the evaluation of the merge goal suspends waiting for either one of its input arguments to be instantiated to a list (an input on a stream), when either argument becomes instantiated (a message) it is added as the head of the output list (the output stream) and the tail forms the new list (rest of the input stream) to be merged.

The CCND languages provide a good approximation to this form of non-determinism. However, the fairness of the merge will depend on the actual implementation.

5.2.2 *Don't know* non-determinism

Don't know non-determinism is where there is a choice of possible solution paths. However, at this choice point it is not known which path will lead to a solution. (Here we restrict ourselves to choice points in which no instantiations need to be made, we treat the other cases in the next section on "*Generate and test* non-determinism").

A typical example of such a search is testing if two binary trees are isomorphic. Basically two trees are isomorphic if:

- either both trees are empty;
- or, if they have the same root node and both left and right subtrees are isomorphic;

- or if they have the same root node and the left subtree of one is isomorphic with the right subtree of the other and vice-versa.

```
isomorphic(terminal, terminal).
isomorphic(tree(Node, Ltree1, Rtree1),
        tree(Node, Ltree2, Rtree2)) :-
    isomorphic(Ltree1, Ltree2),
    isomorphic(Rtree1, Rtree2).
isomorphic(tree(Node, Ltree1, Rtree1),
        tree(Node, Ltree2, Rtree2)) :-
    isomorphic(Ltree1, Rtree2),
    isomorphic(Rtree1, Ltree2).
```

Figure 5–2: Isomorphic tree program expressed in Horn clauses

These three statements can be represented by Horn clauses as in *Figure 5–2*. Each node in the tree is either labelled a terminal, for a node whose parent is a leaf node, or has two subtrees. If we use this Horn clause definition to test if two binary trees are isomorphic, then we cannot pre-determine which of the last two clauses will be used to prove the isomorphism.

CCND realisation

In the CCND execution model a goal is unified with the heads of the clauses in the system. Those clauses that successfully unify are possible OR-alternative solution paths. The guarded goals for these solution paths are then evaluated in parallel. The first such guarded system to succeed is committed to and its body goals are added to the goals to be solved.

The algorithm for testing if two trees are isomorphic requires an OR-choice to be made. To insure that the correct solution path is committed to, the OR-search has to be resolved within the guard. So the Horn clause algorithm in *Figure 5–2*,

would be transformed into a CCND language by making use of **deep guards** (see section 2.5.2) as shown in *Figure 5–3*.

```
mode isomorphic(?, ?).

isomorphic(terminal, terminal).
isomorphic(tree(Node, Ltree1, Rtree1),
        tree(Node, Ltree2, Rtree2)) :-
    isomorphic(Ltree1, Ltree2),
    isomorphic(Rtree1, Rtree2)
    :
    true.
isomorphic(tree(Node, Ltree1, Rtree1),
        tree(Node, Ltree2, Rtree2)) :-
    isomorphic(Ltree1, Rtree2),
    isomorphic(Rtree1, Ltree2)
    :
    true.
```

Figure 5–3: Isomorphism algorithm expressed in a CCND language (Parlog)

So the CCND computation model is able to support this form of non-determinism.

5.2.3 *Generate and test* non-determinism

Another type of non-deterministic construction exploited in logic programming algorithms is known as *generate and test*. Here one process generates a possible solution to a problem and another process places certain test conditions upon the solution. The non-determinism lies at the point where the possible solution is generated, as it cannot be predetermined whether the possible solution will pass the test stage.

Figure 5–4 gives a simple *generate and test* algorithm in Horn clauses. The `male_height/2` is a search on a database which returns (`Person`, `Height`) pairs.

```
male_and_tall(Person) :-
    male_height(Person, Height),
    tall(Height).

tall(Height) :-
    Height >=180.

male_height(john, 150).
male_height(jack, 175).
male_height(jim , 190).
```

Figure 5–4: *Generate and test* algorithm expressed in Horn clauses

The `tall/1` predicate verifies that this person is tall. However, at the point when the `Person` and `Height` pairs are generated it cannot be determined if the tall test will succeed.

CCND realisation

In CCND languages, this sort of non-determinism is not so easily modelled. The basic problem is that the generate goal has to commit to a given clause in order to generate a possible solution (make an instantiation) for testing. However, the generate goal may commit to the wrong solution, and with CCND languages, once the evaluation has committed to a given solution path, all others paths are ignored. Consider trying to directly map the *generate and test* algorithm in *Figure 5–4* into a CCND language, as in *Figure 5–5.*

If we pose the query:

```
:- male_and_tall(X).
```

then depending on which `male_height/2` clause is committed to, the evaluation will either fail or return the instantiation:

```
X = jim.
```

```
mode male_and_tall(?).

male_and_tall(Tall) :-
    male_height(Person, Height),
    tall(Height)
    :
    assign(Tall,Person).

mode male_height(?, ?).

male_height(john, 150).
male_height(jack, 175).
male_height(jim , 190).

mode tall(^ ).

tall(Height) :-
    Height >= 180
    :
    true.
```

Figure 5–5: *Generate and test* algorithm nearly implemented in Parlog

The problem is that the evaluation has to commit to a given `male_height/2` clause before any instantiations for `X` and `Height` can be passed back to the `tall/1` goal. Once the evaluation commits, the evaluation cannot backtrack to obtain another possible instantiation as in Prolog.

5.2.4 Summary

The CCND languages are based on *don't care* non-determinism. *Don't know* non-determinism can be realised using **deep** guards; *i.e.* placing the relevant OR-search within the guarded goals. However, *generate and test* non-determinism cannot be directly mapped to the CCND model. The problem is that to generate a

solution the evaluation has to commit to a given solution path. Once the evaluation has committed, alternative bindings cannot be generated.

In [Trehan & Wilk 87] we consider various automated and manual methods for offering full search in the CCND languages. The automatic methods are only suitable for a restricted set of Horn clause programs. The basic restrictions are that each predicate must be input and output moded and the input arguments must be instantiated when a goal is to be evaluated and its output arguments must be fully instantiated when the goal has been evaluated. This prevents the use of **Streamed And-Parallelism** in the algorithm.

Three manual methods for addressing the *generate and test* problem have been considered: restructuring the knowledge; selected use of **all-solutions** parallelism; and Layered Streams. The first involves generating a set of possible solutions. This is achieved by altering the data to insure that all possible solutions can be generated by a deterministic search. The second involves using an **all-solutions** search mechanism at the *generate* choice points, to return a set of possible bindings. The last provides a programming style suitable for solutions that are generated incrementally and bottom-up, for example constructing sentences from words. Here, the test goal is placed inside the generate goal.

In the following sub-sections we consider three of the techniques for translating Horn clause programs into all-solutions search programs in more detail. The techniques are applied to a simple search program for the 4-queens problem, (given in *Figure 5–6*). Two of the techniques, Continuation based compilation and Stream based compilation allow Horn clause programs to be automatically translated into an all-solutions CCND program. The third technique is suitable for problems in which the solution can be generated in an incremental and bottom-up manner.

```
queen(Q) :- q([1,2,3,4],[],Q).

q([],SoFar,SoFar).
q([H|T],SoFar,Q) :-
        sel([H|T],Picked,Rest),
        insqueen(SoFar,Picked,Rest,Q).

sel([X|Y],X,Y).
sel([X|Y],U,[X|V]) :-
        sel(Y,U,V).

insqueen(SoFar,Picked,Rest,Q) :-
        check(SoFar,Picked,1),
        q(Rest,[Picked|SoFar],Q).

check([],_,_).
check([Queen|Rest],Pos,Diag) :-
        Queen =\= Pos + Diag,
        Queen =\= Pos - Diag,
        NextDiag = Diag + 1,
        check(Rest,Pos,NextDiag).
```

Figure 5–6: 4-queens problem in Horn clauses

5.3 Continuation based compilation

The Continuation based compilation approach [Ueda 86b],[Ueda 87] involves unpacking the search via the use of a continuation. The continuation provides a record of the remaining goals to be evaluated after the evaluation of the current goal. The compiled code is open to "Restricted AND-parallel" evaluation.

This technique is applicable to a restricted set of Horn clause programs. The restriction is that every goal appearing in the program must be moded (inputs and output arguments to predicates fixed). Input arguments must be fully instantiated when a goal is to be evaluated. Output arguments must be fully instantiated when the goal has been successfully evaluated.

The first stage in the compilation is to I/0 mode each clause, for example *Figure 5–7* gives the modes for `sel/3` clauses in *Figure 5–6.*

```
        +   - -
sel([X|Y],X,Y).
        +   -   -           + - -
sel([X|Y],U,[X|V]) :- sel(Y,U,V).

( + : input,  - : output)
```

Figure 5–7: Mode analysis of `sel/2`

The next stage is to move all the output instantiations from the head to dummy output goals. The resulting code is known as **normal form** (see *Figure 5–8*).

```
sel([X|Y],X,Y).
sel([X|Y],Z,Y) :- sel(Y,U,V), /*L1*/ Z=U,Y=[X|V]
```

Figure 5–8: Normal form of `sel/2`

Note also that a continuation marker `L1` is included in the code.

The last stage is to transform the two clauses into two AND-parallel goals. The clauses are renamed and carry a continuation and difference list pair to collect solutions. The resulting code is given in *Figure 5–9.*

```
s(L,Cont,S0,S2) :- s1(L,Cont,S0,S1), s2(L,Cont,S1,S2).

s1([H|T],Cont,S0,S1) :- conts(Cont,H,T,S0,S1).
s1([],Cont,S0,S1) :- S0 = S1.

s2([H|T],Cont,S0,S1) :- s(T,'L1'(Cont,H),S0,S1).
s2([],Cont,S0,S1) :- S0 = S1.

conts('L1'(Cont,H),L,T2,S0,S1) :- conts(Cont,L,[H|T],S0,S1).
conts('L0',H,T,S0,S1) :- S0 = [(H,T)|S1].
```

Figure 5–9: `sel/2` - translated using Continuation based compilation

If we evaluate the following query:

```
:- s([1,2,3,4],'L0',S,[]).
```

`S` will be bound to: `[(1,[2,3,4]),(2,[1,3,4]),(3,[1,2,4]),(4,[1,2,3])]`.

Applying this technique to the entire 4-queens program given in *Figure 5–6* results in the **All-solutions** 4-queens program given in *Figure 5–10.*

```
mode 'CB4_queens'(^).
'CB4_queens'(Q) :-
        true : 'sweeper$q1'([1,2,3,4],[],'L1',Q,[]).

mode 'sweeper$q1'(?,?,?,^,?).
'sweeper$q1'([H|T],R,Cont,Rs0,Rs1) :-
        true : 'sweeper$sel'([H|T],'L2'(Cont,R),'L2',Rs0,Rs1).
'sweeper$q1'([],R,Cont,Rs0,Rs1) :-
        true : Rs0 = [R|Rs1].

mode 'sweeper$sel'(?,?,?,^,?).
'sweeper$sel'(HT,Cont,Conts,Rs0,Rs2) :-
        true : 'sel/3#1'(HT,Cont,Conts,Rs0,Rs1),
               'sel/3#2'(HT,Cont,Conts,Rs1,Rs2).

mode 'sel/3#1'(?,?,?,^,?).
'sel/3#1'([A|L],'L2'(Cont,R),Conts,Rs0,Rs1) :-
        true : 'sweeper$check1'(R,A,1,'L2b'(Cont,R,A,L,Conts),Rs0,Rs1).
'sel/3#1'([],Cont,Conts,Rs0,Rs1) :-
        true : Rs0 = Rs1.

mode 'sel/3#2'(?,?,?,^,?).
'sel/3#2'([H|T],Cont,Conts,Rs0,Rs1) :-
        true : 'sweeper$sel'(T,Cont,'L5'(Conts,H),Rs0,Rs1).
'sel/3#2'([],Cont,Conts,Rs0,Rs1) :-
        true : Rs0 = Rs1.

mode 'sweeper$check1'(?,?,?,?,^,?).
'sweeper$check1'([H|T],U,N,Cont,Rs0,Rs1) :-
        H =\= U+N, H=\=U-N, N1 is N+1 :
        'sweeper$check1'(T,U,N1,Cont,Rs0,Rs1).
'sweeper$check1'([H|T],U,N,Cont,Rs0,Rs1) :-
        H is U+N : Rs0 = Rs1.
'sweeper$check1'([H|T],U,N,Cont,Rs0,Rs1) :-
        H is U-N : Rs0 = Rs1.
'sweeper$check1'([],U,N,'L2b'(Cont,R,A,L,Conts),Rs0,Rs1) :-
        true : b(Conts,'L3'(Cont,R,A),L,Rs0,Rs1).

mode  b(?,?,?,^,?).
b('L5'(Conts,A),Cont,T,Rs0,Rs1) :-
        true : b(Conts,Cont,[A|T],Rs0,Rs1).
b('L2','L3'(Conts,R,A),L,Rs0,Rs1) :-
        true : 'sweeper$q1'(L,[A|R],Cont,Rs0,Rs1).
```

Figure 5–10: 4-queens implemented using Continuation based compilation

5.4 Stream based compilation

The Stream based compilation approach [Tamaki 87] involves viewing the execution of a predicate as a function that maps a stream of variable bindings to a stream of variable bindings. Each set of bindings on the input stream results in several sets of bindings on the output stream. This method places the same restrictions on the set of Horn clause programs that can be compiled as the **Continuation based method**. These restrictions result in the compiler being able to determine the sets of bindings that should be passed from one goal to the next. This information is used to compile the original Horn clause code into committed choice code.

An additional problem is how output streams are composed. Consider the example clause, given in [Tamaki 87]:

```
p(X,Y : Z,V) :- q(X : Z,W), r(Y,Z,W : V).
```

where inputs and outputs are delimited by colons. The output stream for `p` is not simply a composition of output streams for `q` and `r` as the elements need to be synchronised to insure outputs are only combined for matching inputs. This problem is resolved by using interfaces which distribute and combine tuples on the various I/O streams.

We now consider how `sel/2` given in *Figure 5–6* is translated using Stream based compilation, the resulting program is given in *Figure 5–11*. `sel/2` is translated to `s/3` whose first argument is the input argument to `sel/2` and second and third arguments are a difference list pair used to collect the solutions. The first clause of `s/3` is the ground case for `sel/3`: if there are no elements to select from then return `[]` as the solution. The second clause: places a solution, the one that would have been generated by the first clause of `sel/2`, on the output stream; makes the recursive call, as given by the second clause of `sel/2`; and then

```
s([],S0,S1) :-
        S0 = S1.
s([H|T],S0,S2) :-
        S0 = [(H,T)|S1],
        s(T,UV,[]),
        i(H,UV,S1,S2).

i(X,[(U,V)|UVs],S0,S2) :-
        i(X,UVs,S1,S2),
        S0 = [(U,[X|V])|S1].
i(X,[],S0,S1) :- S0 = S1.
```

Figure 5–11: `sel/2` - translated using Stream based compilation

combines the solution of the recursive call with the input argument to give the remainder of the solution stream. The composing interface is given by `i/4`.

If we execute the following goal:

```
:- s([1,2,3,4],S,[]).
```

S will be bound to: `[(1,[2,3,4]),(2,[1,3,4]),(3,[1,2,4]),(4,[1,2,3])]`.

Applying this technique to the entire 4-queens program given in *Figure 5–6* results in the All-solutions 4-queens program given in *Figure 5–12*.

```
mode 'SB4_queens'(^).
'SB4_queens'(Q) :- true : 'Qq'([1,2,3,4],[],Q,[]).

mode 'Qq'(?,?,^,?).
'Qq'([],Y,Z0,Z1) :- true    : Z0 = [Y|Z1].
'Qq'(X,Y,Z0,Z1)  :- X \= [] :
        'Qsel'(X,UVs,[]), 'Iq21'(Y,UVs,Z0,Z1).

mode 'Qsel'(?,^,?).
'Qsel'([],Z0,Z1) :-    true : Z0 = Z1.
'Qsel'([X|Y],Z0,Z2) :- true : Z0 = [(X,Y)|Z1],
        'Qsel'(Y,UVs,[]),
        'Isel21'(X,UVs,Z1,Z2).

mode 'Iq21'(?,?,^,?).
'Iq21'(Y,[(U,V)|UVs],Z0,Z2) :-
        true : 'Qcheck'(Y,U,1,YY),
               'Iq22'(V,[U|Y],YY,Z0,Z1),
               'Iq21'(Y,UVs,Z1,Z2).
'Iq21'(_,[],Z0,Z1) :- true : Z0 = Z1.

mode 'Iq22'(?,?,?,^,?).
'Iq22'(V,List,ok,Z0,Z1) :- true : 'Qq'(V,List,Z0,Z1).
'Iq22'(_,_,ng,Z0,Z1) :-    true : Z0 = Z1.

mode 'Isel21'(?,?,^,?).
'Isel21'(X,[(U,V)|UVs],Z0,Z2) :-
        true : Z0 = [(U,[X|V])|Z1], 'Isel21'(X,UVs,Z1,Z2).
'Isel21'(_,[],Z0,Z1) :- true : Z0 = Z1.

mode 'Qcheck'(?,?,?,^).
'Qcheck'([Q|R],P,N,Res) :-
        Q =\= P+N, Q =\= P-N : M is N+1, 'Qcheck'(R,P,M,Res).
'Qcheck'([Q|R],P,N,Res) :- Q is P+N : Res = ng.
'Qcheck'([Q|R],P,N,Res) :- Q is P-N : Res = ng.
'Qcheck'([],_,_,Res) :- true : Res = ok.
```

Figure 5–12: 4-queens implemented using Stream based compilation

5.5 Layered Streams

The Layered Streams approach [Okumura & Matsumoto 87] is a programming paradigm for implementing search problems in the CCND languages. Using Layered Streams, solutions are generated in an incremental and bottom-up manner. This gives rise to partial solutions (on each incrementation) which can be tested, and so incorrect partial solutions can be eliminated before being fully generated. The other feature of this programming technique is that the partial solutions are represented in a layered data structure. This data structure provides the means by which each further generation of the possible solutions can share the previous bottom-up solutions. This allows for an efficient testing mechanism.

Figure 5–13 gives a Layered Streams solution to the 4-queens problem. Using Layered Streams queens can be added to the board incrementally, on each incrementation the new partial board solutions can be tested. The representation of the board is a layered data structure which combines together the bottom-up generated partial solutions. The top-level call `'LS4_queens'(Q4)` spawns four `queen/2` processes, which are connected by streams. Each `queen/2` process places another queen on to the board and tests (or rather filters) out the previous bottom-up partial solutions that are incompatible with this new queen.

The use of the layered data structure and testing of partial solutions is highlighted by considering the streams which connect the four `queen/2` processes. The first stream `Q1` will be bound to:

```
[1*begin,2*begin,3*begin,4*begin]
```

This stream represents the position of the final queen whilst no other queens are in place (as the solution is being generated bottom-up); the final queen can (for now) be placed anywhere.

```
mode 'LS4_queens'(?).
'LS4_queens'(Q4) :-
        true
        :
        queen(begin,Q1),
        queen(Q1,Q2),
        queen(Q2,Q3),
        queen(Q3,Q4).

mode queen(?,^).
queen(In,Out) :-
        true
        :
        filter(In,1,1,Out1),
        filter(In,2,1,Out2),
        filter(In,3,1,Out3),
        filter(In,4,1,Out4),
        Out = [1*Out1,2*Out2,3*Out3,4*Out4].

mode filter(?,?,?,^).
filter(begin,_,_,Out) :-
        true : Out = begin.
filter([],_,_,Out) :-
        true : Out = [].
filter([I*_ | Ins],I,D,Out) :-
        true : filter(Ins,I,D,Out).
filter([J*_ | Ins],I,D,Out) :-
        D =:= I - J :
        filter(Ins,I,D,Out).
filter([J*_ | Ins],I,D,Out) :-
        D =:= J - I :
        filter(Ins,I,D,Out).
filter([J*In1 | Ins],I,D,Out) :-
        J \= I, D =\= I - J, D =\= J - I :
        D1 is D + 1,
        filter(In1,I,D1,Out1),
        filter(Ins,I,D,Outs),
        Out = [J*Out1 | Outs].
```

Figure 5–13: 4-queens implemented using Layered Streams

The second stream Q2 will be bound to:

```
[1*[3*begin,4*begin],
 2*[4*begin],
 3*[1*begin],
 4*[1*begin,2*begin]]
```

This represents that the last two queens can be in the following positions: the second from last queen on position 1 and the last queen on position 3 or 4; the second from last queen on position 2 and the last queen on position 4; the second from last queen on position 3 and the last queen on position 1; the second from last queen on position 4 and the last queen on position 1 or 2. This is obtained from the partial solution for the last queen being filtered to remove incompatible solutions with the previous queen position. Moreover this layered data structure means that once a queen position is found to be incompatible with a bottom-up generated partial solution all the sub-board positions are removed in one operation.

The third stream Q3 will be bound to:

```
[1*[3*[],4*[2*begin]],
 2*[4*[1*begin]],
 3*[1*[4*begin]],
 4*[1*[3*begin],2*[]]]
```

Finally the fourth stream Q4 will be bound to the complete solution:

```
[1*[3*[],4*[2*[]]],
 2*[4*[1*[3*begin]]],
 3*[1*[4*[2*begin]]],
 4*[1*[3*[]],2*[]]]
```

This data structure has the following interpretation:

- The first queen can be placed on position 1. The second queen can be placed on position 3 or 4. If the second queen is placed on position 3 then no further queens can be added. If the second queen is placed on position 4 then the only place the next queen can be added is position 2. However, no further queens can be added after this third queen.

- The first queen can be placed on position 2. The only place for the second queen is position 4. Similarly the third and fourth queens can only be placed in positions 1 and 3 respectively. This is a complete solution.

- The first queen can be placed on position 3. The only place for the second queen is position 1. Similarly the third and fourth queens can only be placed in positions 4 and 2 respectively. This is a complete solution.

- The first queen can be placed on position 4. The second queen can be placed on position 1 and 2. If the second queen is placed on position 1 then the only place the next queen can be added is position 3. However, no further queens can be added after this third queen. If the second queen is placed on position 2 then no further queens can be added.

5.6 Previous analysis

Program		Cycles	Reductions	Suspensions
CB4Q	(Continuation based 4-queens)	38	241	0
SB4Q	(Stream Based 4-queens)	35	252	155
LS4Q	(Layered Streams 4-queens)	11	119	17
CB6Q	(Continuation based 6-queens)	81	2932	0
SB6Q	(Stream Based 6-queens)	70	3161	2146
LS6Q	(Layered Streams 6-queens)	18	1297	306

Table 5–1: Summary of previous measurements for All-solutions programs

We have reconstructed the previous analysis of the example programs on our Parlog version of Shapiro's interpreter (see *Figure 3–1*). The results are given in *Table 5–1*. These results agree with those obtained in the earlier analysis of this work [Okumura & Matsumoto 87].

The conclusions drawn in [Okumura & Matsumoto 87] were based on results replicated in *Table 5–1*. From these results it appears that using a technique like Layered Streams is particularly good for reducing the amount of computation- 119 reductions as compared to 241 reductions for Continuation based compilation and 252 reductions for Stream based compilation. Also the degree of parallelism (or rather average parallelism-*reductions/cycle*) is better for Layered Streams- 10.8 (119/11) compared to 6.3 (241/38) for Continuation based compilation and 6.6 (252/35) for Stream based compilation. The last point to note is that both Layered Streams and Stream based compilation require the systems to support suspended processes whereas Continuation based compilation does not [1].

---

[1]The resulting program for Continuation based compilation is hence open to "Restricted AND-parallel" evaluation [DeGroot 84].

5.7 Results and new analysis

Reductions									
	Minimum Required	Busy Waiting				Non-Busy Waiting			
		Non-Pruned		Pruned		Non-Pruned		Pruned	
Program	Reductions	Goal	Clause	Goal	Clause	Goal	Clause	Goal	Clause
CB4Q	365	373	373	373	373	373	373	373	373
SB4Q	511	519	519	519	519	519	519	519	519
LS4Q	325	355	352	355	352	355	352	355	352
CB6Q	5382	5484	5484	5484	5484	5484	5484	5484	5484
SB6Q	7177	7279	7279	7279	7279	7279	7279	7279	7279
LS6Q	4303	4653	4555	4653	4555	4653	4555	4653	4555

Table 5–2: Summary of reduction parameters for All-solutions programs

Suspensions									
		Busy Waiting				Non-Busy Waiting			
		Non-Pruned		Pruned		Non-Pruned		Pruned	
Program	Cycles	Goal	Clause	Goal	Clause	Goal	Clause	Goal	Clause
CB4Q	38	0	0	0	0	0	0	0	0
SB4Q	49	338	628	338	628	175	302	175	302
LS4Q	13	69	266	69	266	46	158	46	158
CB6Q	81	0	0	0	0	0	0	0	0
SB6Q	104	6316	10028	6316	10028	3736	4868	3736	4868
LS6Q	23	1265	3812	1265	3812	902	2614	902	2614

Table 5–3: Summary of suspension parameters for All-solutions programs

The results obtained by our system are summarised in *Tables 5–2* and *5–3*. In addition some information is given pictorially in *Figures 5–14,5–15* and *5–17*. We first compare our data to the previous statistics collected and then compare the various programming techniques using our new results.

- The previous interpreters employed **goal** suspension and **busy** waiting; system calls were not counted in the reduction measure (see section 3.3). The previous reduction counter is closest to our new reduction counter using **busy** waiting and **goal** suspension. *Table 5–4* compares the previous reduction counts with our new reduction counts.

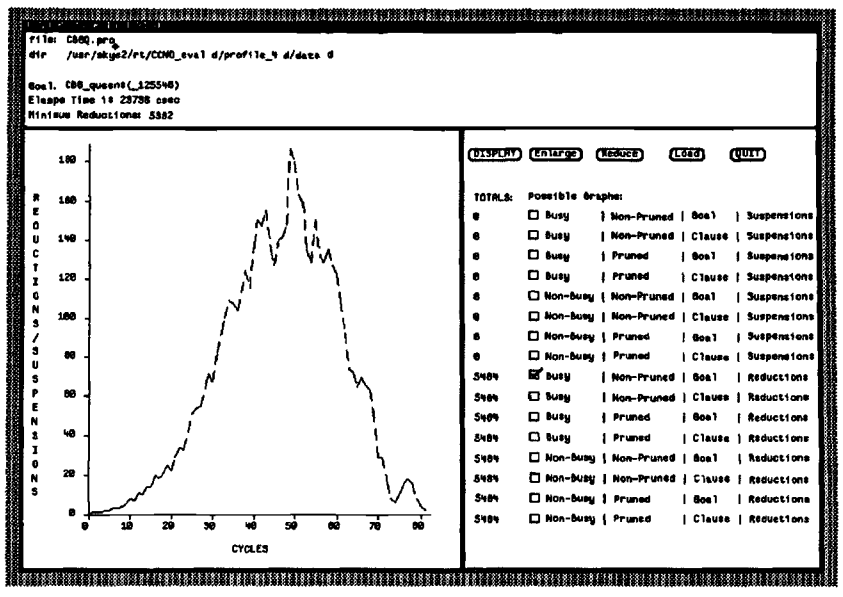
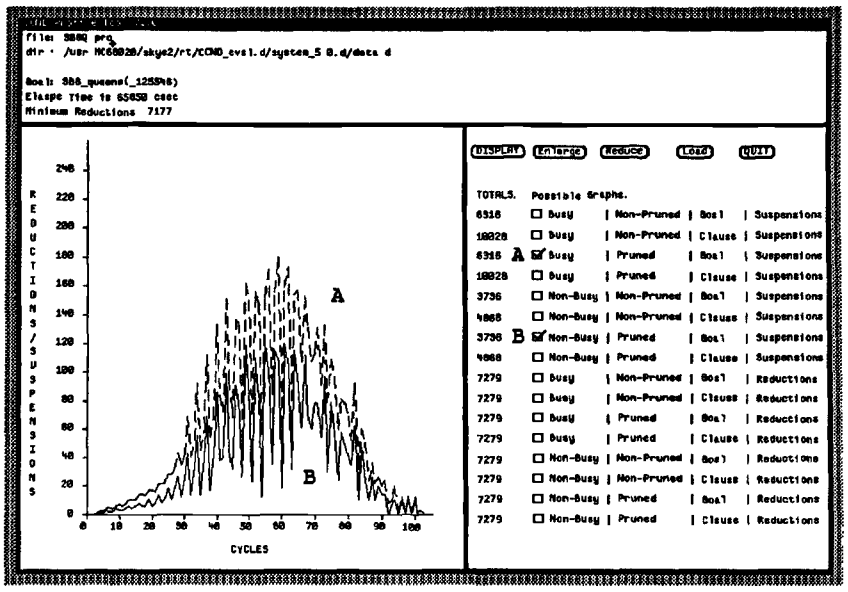


Figure 5–14: Profile of 6-queens using Continuation based compilation

Our new reduction count is consistently higher than the previous count. The difference between the two sets of results can be attributed to system calls which we count in the reduction parameter. The next point to consider is why Stream based compilation has a larger increase in reductions than Continuation based compilation and why Layered Streams has the highest increase in reductions. Stream based compilation requires predicate inter-

Comparison of previous and new reduction measures				
Program	Previous	New **Busy-Goal**	Difference	% Difference
CB4Q	241	373	132	55
CB6Q	2932	5484	2552	87
SB4Q	252	519	267	106
SB6Q	3161	7279	4148	131
LS4Q	119	355	236	198
LS6Q	1297	4653	3356	259

Table 5–4: Comparison of previous and new reduction measures

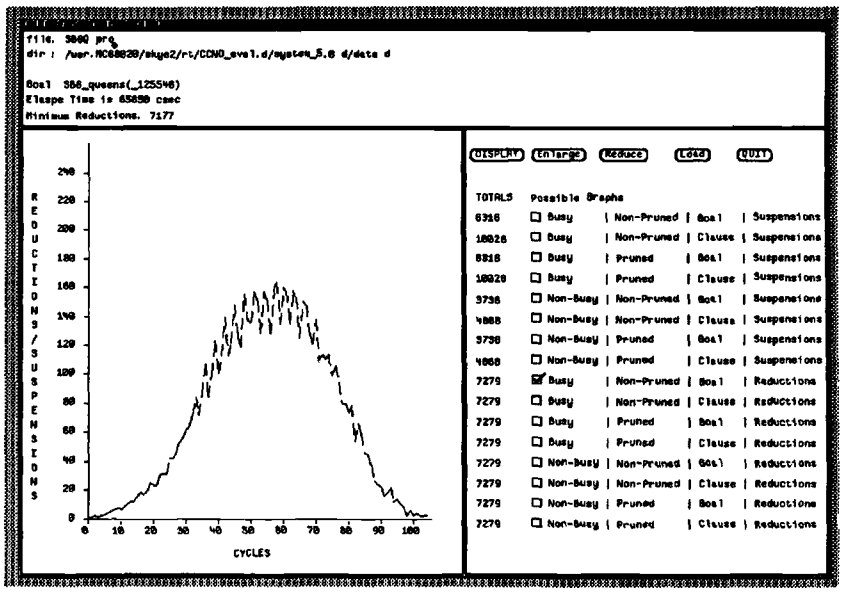


(**busy** and **non-busy** suspensions)

Figure 5–15: Profile of 6-queens using Stream based compilation

faces (see section 5.4) to distribute and combine tuples on the various I/O streams. This results in an extra reduction to construct each partial solution. The increase for Layered Streams is because this technique involves the filtering of partial solutions which are generated in a bottom-up fashion. The solution is constructed using a layered data structure, the deepest layer being the first incrementation of the solution. Each layer in this data structure is generated eagerly, that is before the previous layer has been fully constructed. The construction of the deeper layer is a process of filtering the layered data structure generated so far with respect to the current layer. This may of course result in no solutions.

The result is incomplete solutions which are eagerly generated and continually filtered. In our system we count system calls that are applied to the filtering of each partial/incomplete solution, so our results show a higher increase in the reductions for this particular technique. In fact for larger problems the continual filtering of incomplete solutions may result in more



(reductions)

Figure 5–16: Profile of 6-queens using Stream based compilation

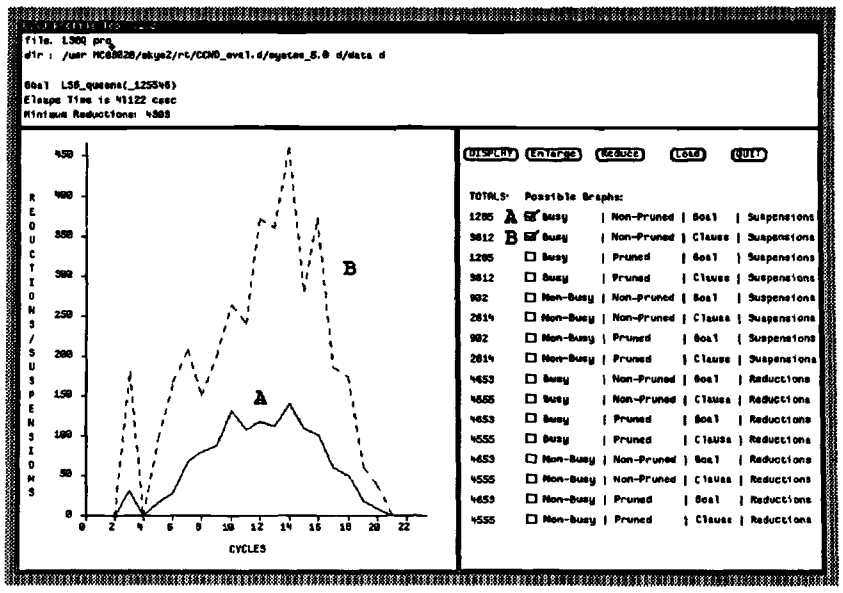
reductions being performed in a Layered streams even if we do not count system calls as reductions.

This is further highlighted by comparing the data for 4-queens and 6-queens. The 6-queens example generates more incomplete solutions which are continually filtered. As we count the system calls in this filtering process our statistics will show a larger increase in reductions.

- previous interpreters employed **goal** suspension and **busy** waiting. Moreover some failed evaluations would be recorded as suspensions (see section 3.3).

The previous suspension counter is closest to our new suspension counter using **busy** waiting and **goal** suspension. *Table 5–5* compares the previous suspension counts with our new suspension counts.

Our new suspension count is consistently higher than the previous. This is because we model the inherent AND-parallelism (see sections 3.3.3 and 3.4) and because we count the suspension of system calls.



(**goal** and **clause** suspensions)

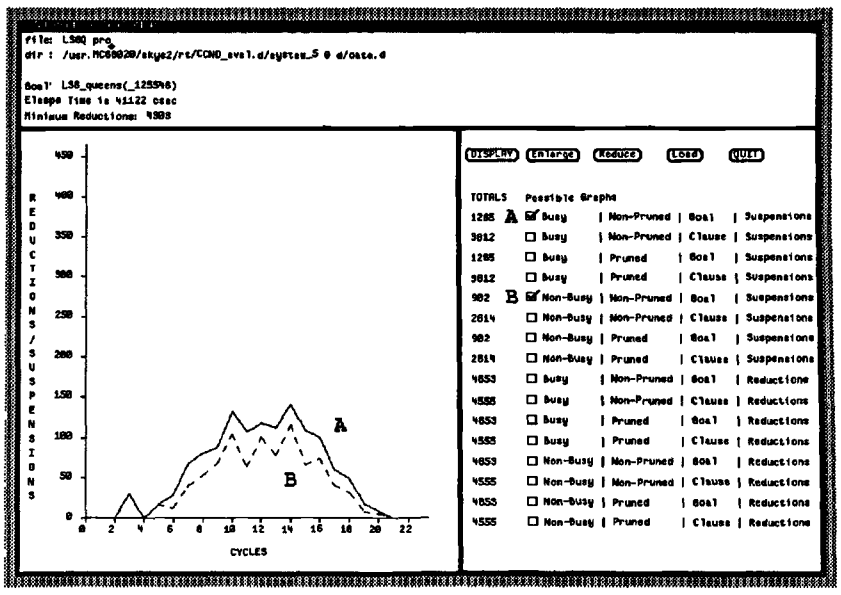
Figure 5–17: Profile of 6-queens using Layered Streams

- *Table 5–6* compares the degree of parallelism *(reductions/cycles)* obtained using our system and the previous system.

  Our results give higher measures for the average degree of parallelism. This is because our system records the work done by system calls.

Comparing previous and new suspension measures				
Program	Previous	New **Busy-Goal**	Difference	% Difference
SB4Q	155	338	183	118
SB6Q	2146	6316	4170	194
LS4Q	17	69	52	306
LS6Q	306	1265	959	313

Table 5–5: Comparing previous and new suspension measures



(**busy** and **non-busy** suspensions)

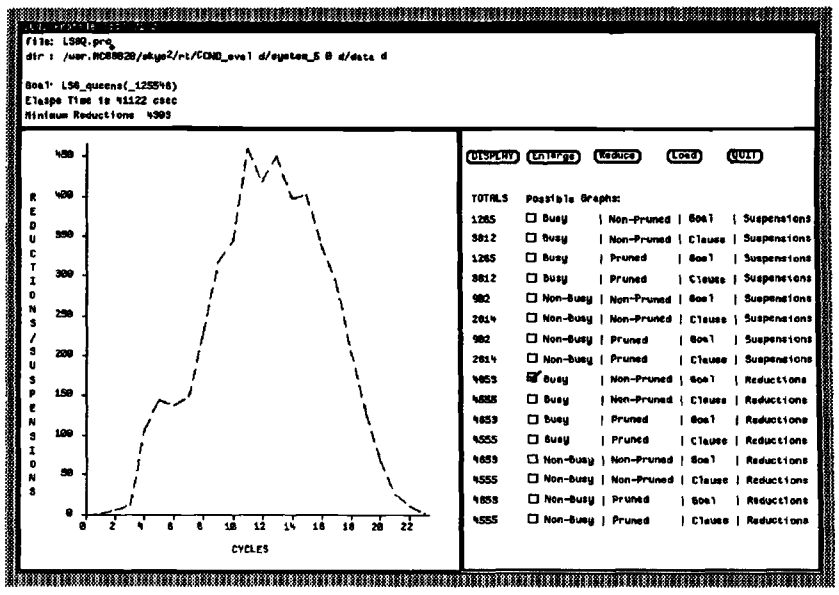
Figure 5–18: Profile of 6-queens using Layered Streams

We now carry out an analysis of the programming techniques using our new results.

- There is no difference between the various reduction counts (see *Table 5–2*) for Continuation based compilation. The same is true of the reduction counts for Stream based compilation. The similarity in the reduction counts using **goal** and **clause** suspensions indicates either there are no suspensions, or that the evaluation suspends on head unification before any reductions

Comparing previous and new measures for average parallelism						
	Previous			New **Busy-Goal**		
program	Reductions	Cycles	Parallelism	Reductions	Cycles	Parallelism
CB4Q	241	38	6.34	373	38	9.82
CB6Q	2932	81	36.2	5484	81	67.70
SB4Q	252	35	7.20	519	49	10.59
SB6Q	3161	70	45.16	7279	104	69.99
LS4Q	119	11	10.82	355	13	27.31
LS6Q	1297	18	72.10	4653	23	202.30

Table 5–6: Comparing previous and new measures for average parallelism



(reductions)

Figure 5–19: Profile of 6-queens using Layered Streams

in the guard take place. From *Table 5–3*, we see that Continuation based compilation results in no suspensions. So, **goal** and **clause** reductions will be the same. For Stream based compilation suspensions occur; these must occur on head unification.

- There is a small difference between the **goal** and **clause** reduction counts for Layered Streams (see *Table 5–2*). This is because the last clause in the `filter/4` predicate given in *Figure 5–13*, can suspend after doing one reduction. This reduction will be repeated if **goal** suspension is used.

- The similarity in the reduction and suspension counts using **pruned** and **non-pruned** evaluations (see *Tables 5–2* and *5–3*) indicates that either guards are balanced in their computation (this includes the guards being **flat**) or that the clause committed to has the deepest guard evaluation. In this case the code is known to be **flat**.

- Comparing the minimum reductions to the actual reductions gives a measure of the OR-parallelism (see section 4.3.4). *Table 5–7* summarises the degree of OR-parallelism for the various All-solutions programs.

Program	Reductions	Minimum Reductions	OR-parallelism
CB4Q	373	365	1.021
CB6Q	5484	5382	1.018
SB4Q	519	511	1.015
SB6Q	7279	7177	1.014
LS4Q	355	325	1.092
LS6Q	4653	4303	1.081

Table 5–7: Degree of OR-parallelism for All-solutions programs

The All-solutions programming techniques result in code with minimal OR-parallelism. This is not surprising as the compilation techniques involve translating OR-parallel search into AND-parallelism.

- As we give a cycle by cycle profile of our evaluation parameters we are able to see the maximum number of reductions and suspensions in a cycle using a given execution model. *Table 5–8* is a summary of the maximum number of reductions that can be performed in a given cycle; some of this information is given graphically in *Figures 5–14, 5–16* and *5–19*.

Program	Max reductions	Cycle number
CB4Q	22	25
CB4Q	187	49
SB4Q	25	30
SB6Q	164	58
LS4Q	49	7
LS6Q	461	11

Table 5–8: Maximum reductions in a given cycle for All-solutions programs

Table 5–9 is a summary of the maximum number of suspensions that can occur in a given cycle. This information provides an indication of the maximum size of the various suspension queues that will be needed for the different

suspension mechanisms and scheduling policies, given by the **busy** waiting suspension parameters. It also indicates the maximum number of suspensions that will occur in a cycle, given by the **non-busy** waiting suspension parameters.

Maximum number of suspensions in a given cycle								
	Busy Waiting				Non-Busy Waiting			
	Goal		Clause		Goal		Clause	
Program	Max	Cycle	Max	Cycle	Max	Cycle	Max	Cycle
SB4Q	23	31	34	31	13	31	16	28
SB6Q	180	59	258	59	120	61	166	55
LS4Q	16	8	72	3	14	8	72	3
LS6Q	141	14	460	14	115	14	364	14

Table 5–9: Maximum suspensions in a given cycle for All-solutions Programs

- The difference between suspensions using **goal** and **clause** suspension mechanisms highlights the number of clauses that each goal could be reduced by in the dynamic program (see section 4.5.3.1). *Table 5–10* is a summary of the ratio of **clause** to **goal** suspensions for Stream based compilation and Layered Streams, using **busy** and **non-busy** waiting.

	Busy Waiting			Non-Busy Waiting		
Program	Goal	Clause	Ratio	Goal	Clause	Ratio
SB4Q	338	628	1.875	175	302	1.725
SB6Q	6316	10028	1.587	3736	4868	1.302
LS4Q	69	266	3.855	46	158	3.434
LS6Q	1265	3812	3.013	902	2614	2.898

Table 5–10: **Goal/Clause** suspension ratios for All-solutions programs

Consider the results for Stream based compilation and the program given in *Figure 5–12*. Most of the predicates in the program have two clauses which can suspend for each goal. However, the last predicate `'Qcheck'/4` will result in four clause suspensions for each goal if its first input is not bound and four clause suspensions and five goal suspensions if its first input is partially bound; the first element on the list is unbound. This is because

system calls are treated as goals with one clause. The ratios for **clause** to **goal** suspensions shown in *Table 5–10* indicate that the `'Qcheck'/4` does suspend with its first argument bound, as the ratios for **SB4Q** and **SB6Q** are less than two. Furthermore, the difference in the ratio for **busy** and **non-busy** waiting indicates that a larger number of two clause predicates suspend for more than one cycle.

Now consider the results for Layered Streams (the program given in *Figure 5–13*). This program quickly reduces to a large number of `filter/4` goals. If the first argument to such a goal is unbound then there will be six clause suspensions for each goal. However, if the first argument is bound and the evaluation suspends there will be 6 **clause** suspensions (`D=:=I-J`; `D=:=J-I`; `J\=I`; `D=\=I-J`; `D=\=J-I`; and one head unification) and six **goal** suspensions (`D=:=I-J`; `D=:=J-I`; `J\=I`; `D=\=I-J`; `D=\=J-I`; and the top-level `filter/4` goal). The ratios of **goal** to **clause** suspensions indicate that more `filter/4` evaluations suspend due the first argument being unbound rather than on the suspensions of the guard evaluations. This is because this programming technique generates the next stage of the layered data structure (see section 5.5) before filtering the bottom-up solutions that make up the lower layers. This allows subsequent `filter/4` processes to start evaluating even if their evaluation is short lived.

- The difference between **busy** waiting and **non-busy** waiting suspensions indicates the benefit of tagging suspended executions to variables (see *section 4.2.2*). It also indicates how long suspended executions remain suspended. *Table 5–11* summarises the ratios of **busy** and **non-busy** waiting suspensions for Stream based compilation and Layered Streams, using **goal** and **clause** suspensions.

  For both Stream based compilation and Layered Streams the ratio is higher for **clause** suspensions. This occurs because when a goal can commit, some clauses may still suspend.

Program	Goal Suspension			Clause Suspension		
	Busy	Non-busy	Ratio	Busy	Non-busy	Ratio
SB4Q	338	175	1.93	628	302	2.08
SB6Q	6316	3736	1.69	10028	4868	2.06
LS4Q	69	46	1.50	266	158	1.68
LS6Q	1265	902	1.40	3812	2614	1.46

Table 5–11: Busy/Non-busy suspension ratios for All-solutions programs

The ratio of **busy** to **non-busy** waiting suspensions for Stream based compilation is 2:1. So, on average, each suspended goal remains suspended for about 2 cycles. This conclusion is highlighted in *Figure 5–15*, in that the **non-busy** suspension graph *(solid line)* gives the new suspensions that occur each cycle and the **busy** suspension graph *(dashed line)* gives all the suspensions that occur each cycle. As both graphs have the same shape and scale about 2:1, suspended processes only remain suspended for two cycles

The same comparison for Layered Streams, **busy** and **non-busy** suspensions, gives a ratio of about 3:2 indicating that most suspended goals only suspend for 1 cycle. Again this result is confirmed graphically in *Figure 5–18*, **busy** suspensions are given by the *solid line* and **non-busy** suspensions are given by the *dashed line*. The ratio between the two graphs is about 3:2.

5.8 Synopsis of analysis

In this section we consolidate some of the results given in our analysis.

- The previous results for the **All-solutions** programming techniques indicate that Layered Streams achieves the best results:

  Cycles: Layered Streams requires about 1/4 of the cycles of Continuation based compilation and about 1/3 the cycles of Stream based compilation.

  Reductions: Layered Streams requires half as many reductions as Continuation based compilation or Stream based compilation.

  Suspensions: Layered Streams incurs only about 1/8 of the suspensions incurred by Stream based compilation. Continuation based compilation incurs no suspensions.

- Our new results give a slightly different picture:

  Cycles: In terms of cycles, our new results are similar to the previous cycle measures for Layered Streams and Continuation based compilation. The cycles parameter indicates the duration of the computation, so if all the parallelism could be exploited Layered Streams would indeed be the best.
  The results for Stream based compilation have increased. The increase in cycles is due to our model of AND-parallelism, we assume only bindings available at the start of a given cycle are available for each of the goal evaluations and not those that are generated during the processing of each goal. This causes some goals to suspend for additional cycles and so increases the cycle count.

Viewed another way, the processing of goals in the previous interpreters gave rise to goal data dependencies being satisfied as the goals were processed. This reduced the measured depth of the evaluation tree.

Reductions: In terms of reductions, our new results are higher for each of the **All-solutions** techniques. Although Layered Streams has a larger increase in reductions than either of the other All-solutions programming techniques we see that it is still the most parallel programming technique (see *Table 5–6*). However, if the chosen architecture cannot support all of the realisable parallelism then other factors like the overall amount of work become important considerations; that is the total number of reductions. In which case Layered Streams and Continuation based compilation would appear comparable.

Suspensions: In terms of suspensions, our new results are higher than the previous suspension counts. This is because our model of AND-parallelism does not allow goals to reduce on bindings generated in the same cycle as their evaluation and because we count the suspension of system calls as suspensions.

The suspension statistics for Layered Streams (see *Table 5–11*) indicate that on average suspended evaluations suspend for about 1.5 cycles. Given that there will be overheads in using **non-busy** suspensions (tagging suspended computations) it may be the case that a **busy** suspension mechanism is suitable for applications employing this search technique.

- None of these techniques make use of OR-parallelism (see *Table 5–7*). This is not surprising as the compilation techniques involve translating OR-parallel search into AND-parallelism.

5.9 Summary

In this chapter the following have been presented and discussed:

- How the CCND languages support various forms of non-deterministic search.
- Several methods, automatic and manual, for addressing the limitations of mapping *generate and test* non-determinism on to the CCND computation model. The particular example program used was n-queens, which has been evaluated using the previous evaluation system by [Okumura & Matsumoto 87].
- Our re-evaluation of the n-queens example for 4-queens and 6-queens, using our basic Parlog interpreter, confirm the previous evaluation was carried out on a similar system.
- The results from the evaluation of the 4-queens and 6-queens on our new evaluation system. The results differ in several respects to those obtained on our basic Parlog interpreter. Our new analysis and results highlight how our new evaluation gives a better picture of the program behaviour and the relative merits of the various programming techniques. In particular, it shows that Layered Streams is not as good as was previously supposed.
- A consolidation of the results obtained using our system.

Chapter 6

Shared data structures - safe/unsafe

6.1 Overview

Support for shared data areas appears to be an important consideration for AI programming. Several current AI applications/programming paradigms use a shared area to allow independent experts/problem solvers to cooperate in the solving of a problem, *e.g.* blackboard type problem solvers [Hayes-Roth 85] [Hayes-Roth 88] [Corkill *et al* 88] and chart parsers [Earley 70], [Kay 73]. These systems could be parallelised by having the problem solvers working in parallel.

It has been noted by several researchers [Shapiro 87c] that only CP derivatives, like Flat Concurrent Prolog (FCP) [Mierowsky *et al* 85] can directly support several processes with write access to shared data structures. By directly we mean that the language provides the relevant synchronisation primitives to allow multiple writers. Such languages are known as **unsafe** (see section 2.5.1). Parlog and GHC cannot directly support such shared data structures, they are known as **safe** (see section 2.5.1). Shared data areas can be indirectly supported in **safe** languages by a manager process which maintains the shared data structure, the writer processes send update requests to this manager. The two particular appli-

cations/programming paradigms mentioned above have been reconstructed (parallelised) for Parlog (a **safe** language) in [Davison 87] and [Trehan & Wilk 88].

This chapter considers how multiple writers to shared data structures and streams can be supported in the CCND languages. Initially two types of CCND language are considered, **safe** and **unsafe**. We then consider a third language in which streams and multiple writers are supported by system primitives. The three language types, **unsafe**, **safe** and **safe+system streams** are examined by considering how they support a shared binary tree with multiple writers. We go on to consider how an Artificial Intelligence application which requires a shared data structure, a chart parser, maps onto the various languages. Three resulting chart parsers are described and then evaluated.

Section 6.2 considers how shared data structures are supported by the various features of the CCND languages.

In section 6.3 we consider how shared data structures can be supported in the three styles of language, **unsafe**, **safe** and **safe+system streams**.

Section 6.4 provides an overview of chart parsing.

Section 6.5 describes the chart parsers developed for comparing the three styles of language.

In section 6.6 we evaluate the execution of these chart parsers.

Finally, in section 6.7 we give a synopsis of our results.

6.2 Shared Data

The CCND languages provide an elegant means of inter-process communication. Communication is achieved though a variable which is shared between the processes that wish to communicate. If one process binds the variable another process can consume the binding. These languages easily support *one-to-many* communication. That is one process binds a shared variable, which is shared by several other consumer processes each of which consumes the binding. By incrementally binding a shared variable, that is binding it to a structure containing a message and a new variable, processes can use shared variables as communication streams. The most common data structure used for this stream communication is a list, the tail of which is incrementally bound to a message and a new variable.

It has been noted by several researchers [Shapiro 87c] that only CP derivatives, like Flat Concurrent Prolog (FCP) [Mierowsky *et al* 85] can directly support *many-to-one* communication on a single variable. By directly we mean that the language provides the relevant synchronisation primitives to allow multiple writers. In the CP family of languages this is supported by allowing process evaluations to make bindings to variables within a local environment, the guard. On commitment the system tries to unify the local bindings with the binding environment of the parent process. This requires the commitment stage to be atomic [Saraswat 87b], that is all bindings that would result by unifying local and parent environments should be made in one step or not at all. Such languages are known as **unsafe**, as the local bindings that are made are speculative until commitment has taken place.

Parlog and GHC do not allow bindings of global variables to be made in the guard. They are known as **safe** languages, so they avoid the problems associated

with supporting atomic commitment [1]. As a consequence they cannot directly support multiple writers. However, one important case of multiple writers, multiple writers to a stream, can be modelled by the use of **merge/3** processes (see *Figure 6–1*).

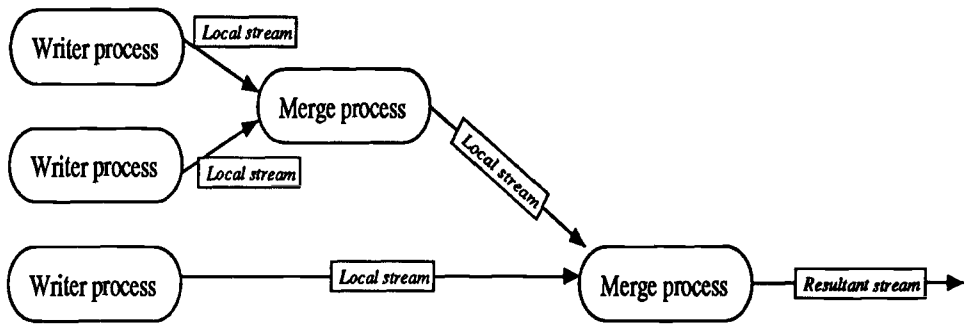


Figure 6–1: Use of merge processes to support multiple writers to a stream

These *merge* processes serve as interconnections between several *writer* processes. Each *writer* that wishes to update some shared stream binds a local stream. The local streams for each *writer* are then merged together to form the final shared stream.

This use of *merge* processes to connect together communication streams between processes is one of the commonest ways to achieve *many-to-one* stream communication, even when using a Concurrent Prolog derivative, which could use its multiple writers capabilities directly. Hence the use and implementation of *merge*

---

[1]Experiments comparing Flat Parlog and Flat Concurrent Prolog, **safe** and **unsafe** languages, indicate that allowing unsafe bindings requires a more complex abstract machine. On a single processor architecture, where atomic unification is less costly than on a multiple processor, Flat Parlog executes 5 to 15% faster than Flat Concurrent Prolog [Foster & Taylor 87].

```
merge([],L,L).
merge(L,[],L).
merge([H|T],L,[H|R]) :- merge(T,L,R).
merge(L,[H|T],[H|R]) :- merge(T,L,R).
```

Figure 6–2: Predicate to merge two streams into one

operations has received much attention [Ueda & Chikayama 84] [Kusalik 84] [Shapiro & Mierowsky 87] [Shapiro & Safra 87] [Saraswat 87c] [Gregory 87].

The general use of multiple writers to any structure, not just a stream, can be supported by creating a process which manages the structure. Multiple processes that wish to write to the structure make write requests to this manager process. The write requests from the writer processes are merged together to form a request stream. This technique has been used in several applications which require multiple writers to a shared resource [Davison 87] [Trehan & Wilk 88].

6.3 Support for Shared Data Structures

In this section we indicate how general shared resources can be manipulated in three styles of language, **unsafe**, **safe** and **safe+system streams**. The example we use is that of a shared ordered binary tree to store integers. For a given node in the tree, nodes in the left subtree contain integers which are smaller than the integer labelling this node, and the nodes in the right subtree contain integers which are greater than the integer labelling this node. Terminal nodes are variables. The example programs in this section have not been annotated with specific synchronisation primitives or mode declarations; we assume the generic features of the particular language systems when executing a given program. For example, **unsafe** languages allow global variables to be bound in the guard while in **safe** languages attempting to bind in the guard results in a suspension.

6.3.1 Unsafe

The **unsafe** predicate in *Figure 6–3* allows several processes to add integers to a shared binary tree. The predicate takes an integer and an ordered binary tree. The integer either already exists in the tree or should be added to the tree. The first two clauses traverse the binary tree comparing the integer to be added to the current node value and hence traversing either the left or right subtree. The last clause has a dual purpose. If the second argument (the binary tree) is instantiated, the clause serves as a test whether the integer to be added already exists in the tree. If the second argument is uninstantiated the clause serves to make an **unsafe** binding of the terminal node, currently a variable, in the binary tree. On committing to this clause the local and global binding environments will be atomically unified.

```
add_binary_tree(Element,tree(Value,Left,Right)) :-
    Element < Value
    :
    add_binary_tree(Element,Left).
add_binary_tree(Element,tree(Value,Left,Right)) :-
    Element > Value
    :
    add_binary_tree(Element,Right).
add_binary_tree(Element,tree(Element,_,_)).
```

Figure 6–3: An unsafe predicate to add an element to an ordered binary tree

Consider the behaviour of two processes which make additions, *4* and *3*, to a shared binary tree, namely `tree(7,L,R)`:

```
add_binary_tree(4,tree(7,L,R)),add_binary_tree(3,tree(7,L,R)).
```

Both processes will traverse the binary tree to the left subtree `L`, resulting in two goals `add_binary_tree(4,L)` and `add_binary_tree(3,L)`. Now consider the evaluation of these goals. The evaluation of both goals via the first two clauses will

suspend, as the guard evaluations `Value > 3`, `Value < 3`, `Value > 4` and `Value < 4` suspend. Both will hence make speculative bindings of the parent variable `L` via the last clause; the first binding `L` to `tree(4,_,_)`; the second binding `L` to `tree(3,_,_)`. The system will then on commitment try to make both local bindings global. However, using atomic commitment one of the processes will succeed and the other will fail. Say the second process succeeds, hence `L` will be bound to `tree(3,_,_)`. Now the two suspended clauses for the first process can be rescheduled for evaluation as `Value` is now bound to 3. This will result in the evaluation committing to the second clause, as `4 > 3`. Finally, this process will bind the right subtree of the newly created node to `tree(4,_,_)`. So, the final state of the shared binary tree is:

```
tree(7,tree(3,_,tree(4,_,_)),_)
```

6.3.2 Safe

In a **safe** language the binary tree addition predicate in *Figure 6–3* would suspend. **Safe** languages do not permit the binding of global variables in the guard. In the case where the last clause is used to add an element to a binary tree, rather than test to see if an element already exists, the evaluation of the third clause would suspend awaiting the second argument to be bound. The programmer could, of course, transfer the output binding of the global variable to the body of the clause. However, if the binding is transferred to the body, two processes could try to bind the same variable to different terms. In this case one of the processes would fail.

The manipulation of a global data structure, like a global binary tree, by several writer processes would have to be supported by a manager process, (perpetual process [Shapiro & Takeuchi 83]). This manager is the only process which can write to the shared data structure, hence resolving the problem of binding conflicts that occurs with several processes writing to a shared resource. The processes that

```
manager_binary_tree([add(X)|Rest],continue,BinaryTree) :-
    add_binary_tree(Element,Flag,BinaryTree),
    manager_binary_tree(Rest,Flag,BinaryTree).

add_binary_tree(Element,Flag,tree(Value,Left,Right)) :-
    Element < Value
    :
    add_binary_tree(Element,Flag,Left).
add_binary_tree(Element,Flag,tree(Value,Left,Right)) :-
    Element > Value
    :
    add_binary_tree(Element,Flag,Right).
add_binary_tree(Element,Flag,BinaryTree) :-
    var(BinaryTree)
    :
    bind(tree(Element,_,_),BinaryTree,continue,Flag).

bind(TreeIn,TreeOut,FlagIn,FlagOut) :-
    TreeOut = TreeIn,
    flagger(TreeOut,FlagOut,FlagIn).

flagger(TreeOut,FlagOut,FlagIn) :-
    data(TreeOut)
    :
    FlagOut = FlagIn.
```

Figure 6–4: Manager process for a binary tree

wish to update the shared data structure send requests to this manager process. The requests from each of the writer processes are merged together to form a single request stream to the manager process.

Figure 6–4 shows the code for a perpetual process that manages a binary tree. The process consumes a stream of requests, in this case requests for additions. For each request the manager invokes a process to add the element to a binary tree. Once the addition, or confirmation, has taken place the manager processes the next request. The addition and the recursive call to the manager have been se-

quentialised using a short circuit technique [Hirsch *et al* 87]. The writer processes that wish to make additions to this data structure would send requests to the manager, which in turn would make the updates. So, requests from write processes would have to be collected together into a single request stream. The commonest way of collecting the requests together is via merge processes (see *Figure 6–2*). Consider two processes that generate streams of integers which are to be added to a shared binary tree (see *Figure 6–5*). The request streams from the two processes are merged together and the *resultant stream* is consumed by a manager process for the binary tree, as in the query in *Figure 6–5*.

```
random(Seed,Requests) :-
    generate(Seed,Number,NewSeed),
    Requests = [Number|NewRequests],
    random(NewSeed,NewRequests).

:-  random(1,Ra),random(2,Rb),merge(Ra,Rb,Requests),
    manager_binary_tree(Requests,continue,BinaryTree).
```

(`merge/3` *and* `manager_binary_tree/3` *are defined in Figures 6–2 and 6–4)*

Figure 6–5: A perpetual process which generates a stream of random integers

For large numbers of writer processes the problems associated with how to interconnect the writer processes, allowing each fair access to the resource, has been the attention of considerable research [Kusalik 84] [Ueda & Chikayama 84] [Gregory 87] [Shapiro & Mierowsky 87] [Shapiro & Safra 87] [Saraswat 87c]. Two main issues arise when one is faced with an interconnection of merge processes. Ensuring that a given request stream is not starved indefinitely and that the delay in propagating a request to the final stream is small.

6.3.3 Safe+System Streams

In the **safe** languages merge processes are the commonest way to support *many-to-one* communication. Moreover the general manipulation of a shared data structures by multiple writers can be supported by using merge processes to combine streams of write requests and manager processes to maintain the shared data structure. The general feature of both these uses of streams is to combine requests from many sources to one final stream, the *resultant stream.*

Consider another view of this *resultant stream*, that is a list with a tail variable to be instantiated. This view of the *resultant stream* was employed in [Saraswat 87c] to mimic merging several streams together in constant time. Basically, processes that wish to write to the *resultant stream* could use the multiple writers capabilities of **unsafe** languages. Each writer would have a copy of the stream, additions to the stream taking place by a writer recursing down the stream until it finds the tail variable which is then instantiated to a list containing the required message and a new tail variable. For efficiency the writer could keep a copy of the new tail variable for future additions. This technique would require n process reductions, where n is the number of new elements that have been added to the stream since the last addition. However, this approach is not applicable to **safe** languages, as they do not support multiple writers.

The use of streams generally requires the use of merge processes to combine these streams. While the use of merge processes is logically clear with respect to the CCND computation model they may add heavy overheads in terms of creating and managing large numbers of processes. This may degrade system performance.

An alternative option is for the system to support the use of streams more directly [Itoh *et al* 87]. [Itoh *et al* 87] propose several stream manipulation primitives for GHC, for creating a system supported stream, adding an element to a stream, removing an element from a stream and merging streams. The most interesting of these primitives is the merge operation. The merge primitive introduces an indirect stream pointer cell which is shared by every producer and points to the

```
random(Seed,Resultant_handle) :-
    generate(Seed,Number,NewSeed),
    add_to_stream(Resultant_handle,Number),
    random(NewSeed,Resultant_handle).

:-  make_stream(resultant,Requests),
    random(1,resultant),random(2,resultant),
    manager_binary_tree(Requests,continue,BinaryTree).
```

the above query assumes `add_to_stream/2` *will suspend if the stream handle has not been identified, ie.* `make_stream(resultant,Requests)` *has not been evaluated.*

Figure 6–6: A perpetual process which uses proposed stream primitives

current tail of the *resultant stream.* The addition of elements to a merged stream now have to be atomic actions, that is if two processes wish to add elements to a merged stream only one process at a time is permitted to update the shared pointer to the tail of the *resultant stream.* This requires the shared pointer to have a locking mechanism which introduces two forms of overhead:

- the locking of a given variable may be a costly operation. However most parallel architectures provide such locks (semaphores) and so the overheads should not be too high; and

- while one process is adding an element to a merged stream another process will have to wait. This is not likely to be a significant overhead compared with the merge process alternative. If two processes wish to add elements to a merged stream using merge processes one message will be added to the *resultant stream* and then the other; this will take two process reductions. While using system streams one process will be locked out while the other process make its addition.

The results of [Itoh *et al* 87] show a significant improvement when using their proposed primitives. This clearly indicates that the cost of manipulating streams in the system is less than when under programmer control.

We consider similar extensions to our system, the basis for these extensions being that the system could provide special primitives for multiple writers to a *resultant stream*. The extended language we identify as **safe+system streams**. This requires the system to know when a given stream, or variable, is a *resultant stream*. The system can then keep track of the end of this stream via a pointer to the tail variable. Additions to this stream would be supported by the system which would automatically update the pointer. The additions to this *resultant stream* would have to be atomic actions. The consumption of a *resultant stream* by any process would proceed as normal, as it is still a stream.

Two primitives are introduced to support our notion of a *resultant stream*. The first `make_stream(STREAM_ID,STREAM)` identifies a stream as a *resultant stream*. The second `add_to_stream(STREAM_ID,Element)` directly adds an element to this *resultant stream*. An additional primitive to close a resultant stream could also be provided. Using these primitives the example predicate in *Figure 6–5*, is transformed into *Figure 6–6*. A point to note is that the clarity of the program with respects to the CCND computation model has been somewhat lost. This is because the use of system streams means that streams are addressed by some global name rather than as a local logical variable so predicates are not declarative. Future systems may be able to recognise the use of streams in predicates and automatically support their use by system streams.

Our analysis of programs which use system streams compared with the two other language types, **unsafe** and **safe**, indicates that while programs may be less declarative if system streams are used the advantages in performance and system predictability make this language extension an important addition for future systems (see section 6.7).

6.4 Chart Parsing: an overview

In this section we present an overview of an Artificial Intelligence programming technique known as chart parsing [Earley 70] [Kay 73]. The basis of chart parsing is that duplicate attempts at parses of sub-phrases of a sentence, should be prevented. Redundant parses occur because natural language is often ambiguous (at least locally) and hence alternative parsing options must be frequently tried. These alternative options may have common parts and it is wasteful to duplicate these sub-parses. We now consider a sequential chart parsing algorithm and a parallel extension.

6.4.1 Sequential chart parsing

Sequential chart parsing is achieved by keeping a record of all parses undertaken in an Active Edge Table (AET), and a record of all sub-strings found, in the Well Formed Sub-string Table (WFST). The AET and the WFST form the *chart*. Ongoing parses are referred to as *active edges* and complete sub-strings are referred to as *inactive edges*:

- An example of the contents of an active edge is:
  - searching for a Noun Phrase (NP);
  - using the grammar rule a NP is a Determiner (Det), Noun (N);
  - so far a Det has been found;
  - the initial words being parsed are: "the man saw the woman";
  - the remaining words to be parsed are: "man saw the woman".
- An example of the contents of an inactive edge is:
  - searching for a Noun Phrase (NP);

- using the grammar rule NP is a Det,N;
- we have found the Det and the N;
- the initial words being parsed are: "the man saw the woman";
- the remaining words to be parsed are: "saw the woman".

The AET is used by the parser to ensure that no repeat parsing attempts are undertaken. The WFST is used by the parser to share the results of successful sub-parses. The data structure used to represent the chart may be anything that allows the parser to refer to it and update it, e.g. a database or partially instantiated list.

The parser picks an active edge from the AET. The parser may further the evaluation of the active edge using information in the WFST. Active edges and inactive edges are combined under the *fundamental rule* [Thompson & Ritchie 84]. The resulting edges may be active (which will be added to the AET) or inactive (which will be added to the WFST). Possible new active edges are also generated using the grammar and an activation strategy. A bottom-up strategy constructs possible new active edges based on the WFST (*inactive edges*). A top-down strategy constructs possible new active edges based on the AET (*active edges*). Active edges that are new are added to the AET. New active edges are those that do not already exist in the AET. A description of sequential chart parsing, and an implementation, can be found in [Thompson & Ritchie 84].

6.4.2 Parallel chart parser

There are many ways of adding parallel extensions to sequential chart parsers. The parallelism occurs at a number of conceptual levels within a chart parser. Here, we consider several processes which pick different active edges from the AET, process them in parallel, and update the chart by adding any new active edges to the AET and any sub-strings to the WFST. This approach requires that testing for a new active edge and its addition to the AET be an atomic step. Without an atomic

step another process might add the proposed edge after the test and before the update. Usually, this type of extension is supported by an atomic test and set operation in the programming language. This approach is similar to that taken in several chart parsers, for example [Grishman & Chitrao 88].

6.5 Parallel Chart Parsers for the CCND languages

In this section we focus on how the AET table of a parallel chart parser could be implemented in the various languages.

6.5.1 Unsafe Chart Parser

In an **unsafe** language the shared data structure, the chart, can be directly supported. Given some possible new active edges the parser compares these proposed new edges against the AET. Those edges that do not exist on the AET are added to the AET. The predicate in *Figure 6–7* supports an AET which is a stream. The edges to be added are compared against each of the edges in the AET. If the head of the AET and the edge to be added are the same the addition process succeeds (not adding the edge to the AET). If the head of the AET and the edge to be added are different the process recurses on the rest (tail) of the AET. If the AET is a variable then this variable (tail) is bound, in the guard, to the new edge and a new tail variable.

If the activation strategy is top-down, the process generating the possible new active edges will consume the AET. For each active edge in the AET, the process will examine the grammar to see if there are any grammar rules which can be applied to further the evaluation of this edge. For each grammar rule a new possible active edge is generated. Those active edges that are new are added to

```
add_new_additions(AET,[]).
add_new_additions(AET,[H|T]) :-
    add_if_new(AET,H),
    add_new_additions(AET,T).

add_if_new([AET_H|AET_T],Edge) :-
    testedges(Edge,AET_H)
    :
    true.
add_if_new([AET_H|AET_T],Edge) :-
    not(testedges(Edge,AET_H))
    :
    add_if_new(AET_T,Edge).
add_if_new(AET,Edge) :-
    var(AET),
    AET=[Edge|_]
    :
    true.
```

Figure 6–7: Unsafe predicate to support an AET based on a stream

the AET using the predicate in *Figure 6–7*. This activation processing of each new active edge on the AET can take place in parallel (see *Figure 6–8*).

```
chart_adder_td([Edge|AET_rest],AET) :-
    chart_adder_td(AET_rest,AET),
    grammar_activation_td(Edge,Grammar_rules),
    grammar_forker_td(Edge,Grammar_rules,Additions),
    add_new_additions(AET,Additions).
```

Figure 6–8: Top-down activation process for an unsafe language

Note that the predicate in *Figure 6–8* has two arguments. The first argument is the AET consumed by this process and used to generate new possible active edges. The second argument is the complete AET, used by `add_new_additions/2` to insure that no duplicate edges are added to the AET.

6.5.2 Safe Chart Parser

In a **safe** language the shared data structure, the chart, can only be supported by a manager process and writer processes which make requests for updates. The manager process for a chart has to insure that no two update requests will lead to duplicate active edge requests in the chart. The basic mechanism employed by our manager is "sifting" which is a generalisation of a prime number generator program [Ueda 86a]. Prime numbers are generated by sifting a stream of integers. Each unsifted integer is a prime number. As each prime number is produced it results in a filter process being spawned; each filter process removes multiples of itself from the remainder of the stream. Hence the sifting is achieved by a set of filter processes.

In the chart parser, a stream of sub-parse requests is generated with reference to the current state of the parse. This stream contains possible new entries for the AET. Before any of these requests are added to the AET the stream undergoes a sifting stage. This stage removes requests for sub-parses that have already been undertaken. The sifting is achieved by a set of filter processes that are spawned as a result of requests for a new sub-parse. *Figure 6–9* presents a sifter predicate for a chart parser.

So, a set of filter processes, one for each new active edge request, dynamically sifts possible additions to the AET. Any new sub-parses can of course be processed concurrently with other requests. This technique for chart parsing is covered more fully in [Trehan & Wilk 88].

Using a top-down activation strategy the activation process which will generate new possible active edges is based on the AET. For each applicable grammar rule a new possible active edge is generated. This stream of possible new active edges will then be sifted using the predicate in *Figure 6–9*. The activation processing for each new active edge can take place in parallel, the resulting request streams generated being merged together (see *Figure 6–10*).

```
sifter([Request | Rest], [Request | Rest_out]) :-
    filter(Rest,Request,Rest_tmp),
    sifter(Rest_tmp,Rest_out).
sifter([],[]).

filter([Request|Rest],Edge,Rest_filtered) :-
    testedges(Edge,Request)
    :
    filter(Rest,Edge,Rest_filtered).
filter([Request|Rest],Edge,Filtered) :-
    not(testedges(Edge,Request))
    :
    Filtered = [Request|Rest_filtered],
    filter(Rest,Edge,Rest_filtered).
```

Figure 6–9: Safe predicate to support a manager for an AET based on a stream

The first argument of the activation process in *Figure 6–10* is consumed by this process, and used to generate new possible active edges. The second argument is used to send the stream of activation requests to the **sifter/2** process defined in *Figure 6–9*. Note that the second argument of the recursive consumer call and the grammar rule activation that take place by this call are merged together.

```
chart_adder_td([Edge|AET_rest],AET_out) :-
    chart_adder_td(AET_rest,AETa_out),
    grammar_activation_td(Edge,Grammar_rules),
    grammar_forker_td(Edge,Grammar_rules,AETb_out),
    merge(AETa_out,AETb_out,AET_out).
```

Figure 6–10: Top-down activation process for a safe language

6.5.3 Safe+System Streams Chart Parser

In our **safe+system streams** language the shared data structure, the chart, must be supported by a manager process. Writer processes make update requests to this manager. However, unlike pure **safe** languages, these requests need not make explicit use of merge processes. Instead the writer processes could make use of the support for system streams outlined earlier. The manager process for the chart, the process that insures no duplicate edges are added, is the same as for a **safe** language (see *Figure 6–9*).

For a top-down activation strategy the activation process will consume the AET. For each applicable grammar rule a new possible active edge is generated. These possible new active edges will be added to a stream of unfiltered requests using the built in goal `add_to_stream/2`. The resulting activation object is given in *Figure 6–11.*

```
chart_adder_td([Edge|AET_rest]) :-
    chart_adder_td(AET_rest),
    grammar_activation_td(Edge,Grammar_rules),
    grammar_forker_td(Edge,Grammar_rules).

grammar_forker_td([Edge,_,_,_,WordsLeft],Grammar_rules):-
    forks(Grammar_rules,WordsLeft).

forks([],_).
forks([['-->'(Edge,FindList)] | Rest],Words) :-
    add_to_stream(aet_ugas,[Edge,FindList,FindList,Words,Words]),
    forks(Rest,S0)
```

The resultant stream has a handle `aet_ugas`.

Figure 6–11: Top-down activation process making use of **system streams**

6.6 Results and analysis

As these parsers have not been analysed before and the *safe+system streams* example cannot run on previous interpreters we do not carry out a comparative analysis of our new system with the previous systems. To execute the three styles of language on one system, Parlog, we have added some extensions to our evaluation system.

- **unsafe** predicates are declared by program annotation. The interpreter delays the processing of any goals to be evaluated by such a predicate within a cycle until all the **safe** goals have been processed. The **unsafe** goals are then evaluated as in the previous interpreters (see section 2.6.1.2) which handle the evaluation of **unsafe** predicates [2].

- The two *stream* manipulation system calls are also supported by extensions to our system. Any *stream* calls are only processed at the end of a cycle. The interpreter maintains a record of the streams declared as *resultant stream* and is hence able to add elements to these streams as if they were atomic actions.

---

[2] **Unsafe** predicates are allowed to bind the input variables in the guard. In Shapiro's original interpreter [Shapiro 83] these predicates did not cause any implementation difficulties as bindings were generated as the goals were processed. As this processing was sequential there were no problems associated with supporting atomic commitment required for **unsafe** bindings. In our system we have attempted to model parallel AND-parallelism and to this end we have developed a model in which goal order does not affect the overall computation; by allowing only bindings available at the beginning of a cycle to be used by the goals (see section 3.6.3). To execute **unsafe** predicates we relax this restriction but require that such predicates are evaluated at the end of a cycle and only possess **flat** guards

We evaluate the various chart parsers using both top-down and bottom-up activation strategy. Profiles of the execution of the various chart parsers are given in *Figures 6–12, 6–13, 6–14, 6–15, 6–16, 6–17, 6–18, 6–19, 6–20, 6–21, 6–22,* and *6–23.* The results are also summarised in *Tables 6–1* and *6–2.*

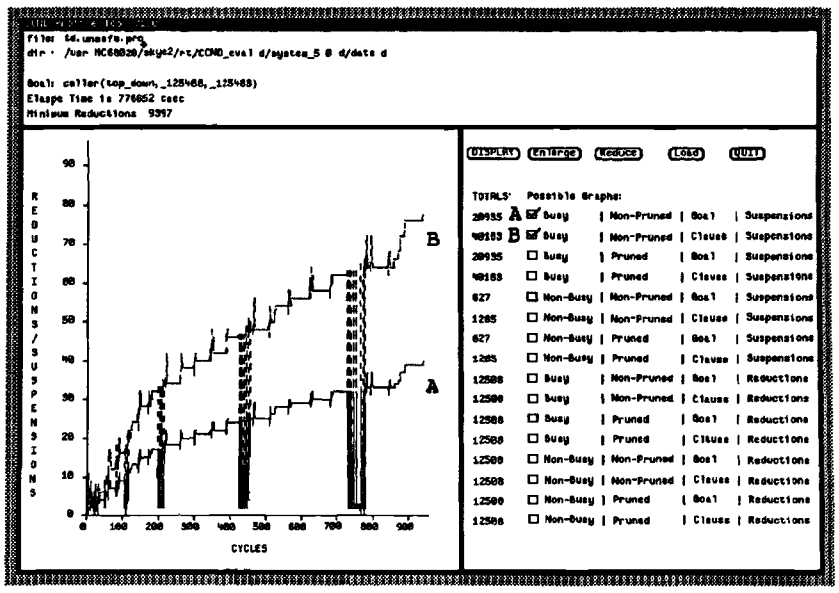
Chart Parser	Cycles	Minimum Required Reductions	Actual Reductions
Unsafe, top-down activation (UTD)	943	9397	12508
Safe, top-down activation (STD)	951	8863	11554
Safe+system streams top-down (S+SSTD)	632	7840	10531
Unsafe, bottom-up activation (UBU)	526	12565	16538
Safe, bottom-up activation (SBU)	591	12611	16220
Safe+system streams bottom-up (S+SSBU)	385	10708	14317

For a given chart parser the results for the various reduction parameters are the same (see Figures 6–12, 6–15 and 6–18*) hence only one value is given for the reductions, namely the* **Actual Reductions.**

Table 6–1: Summary of reduction parameters for the various chart parsers

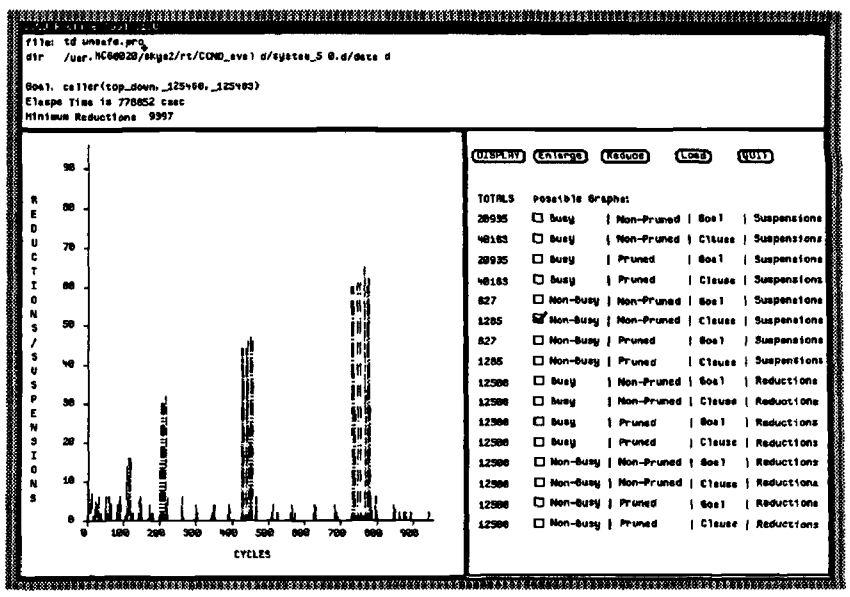
	Suspensions							
	Busy waiting				Non-busy waiting			
	Non-Pruned		Pruned		Non-Pruned		Pruned	
Chart Parsers	Goal	Clause	Goal	Clause	Goal	Clause	Goal	Clause
UTD	20935	40163	20935	40163	627	1285	627	1285
STD	81096	255585	81096	255585	1962	6148	1962	6148
S+SSTD	21179	43081	21179	43801	777	1645	777	1645
UBU	14218	27607	14218	27607	1094	2219	1094	2219
SBU	67704	218602	67704	218602	3192	10398	3192	10398
S+SSBU	14895	30291	14895	30291	1110	2334	1110	2334

Table 6–2: Summary of suspension parameters for the various chart parsers



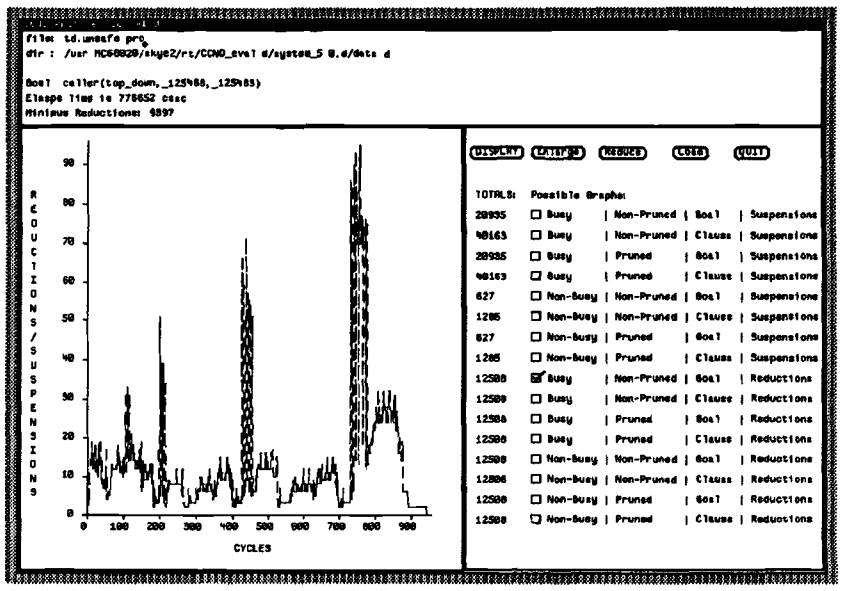
(**busy** waiting-**goal** and **clause** suspensions)

Figure 6–12: Profile of a top-down **unsafe** chart parser



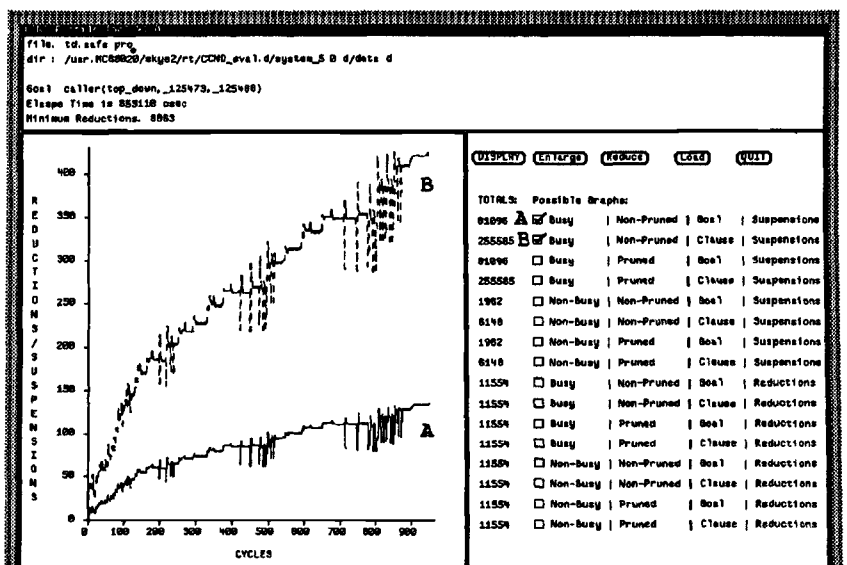
(**non-busy** waiting-**clause** suspensions)

Figure 6–13: Profile of a top-down **unsafe** chart parser



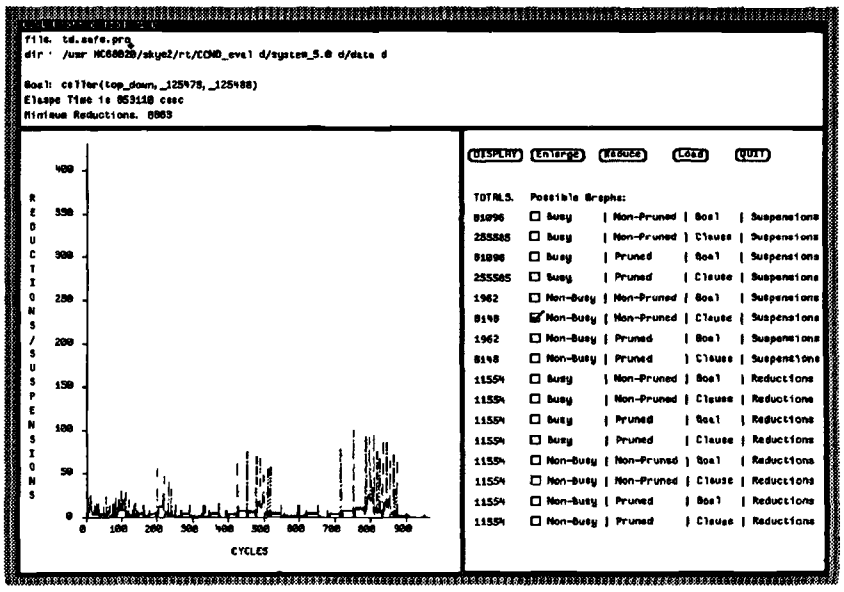
(reductions)

Figure 6–14: Profile of a top-down **unsafe** chart parser



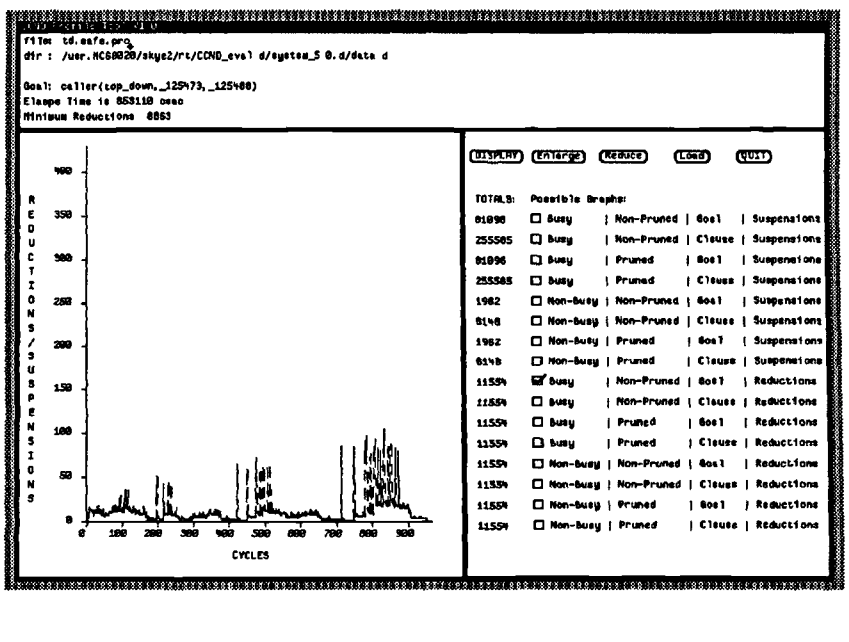
(**busy** waiting-**goal** and **clause** suspensions)

Figure 6–15: Profile of a top-down **safe** chart parser



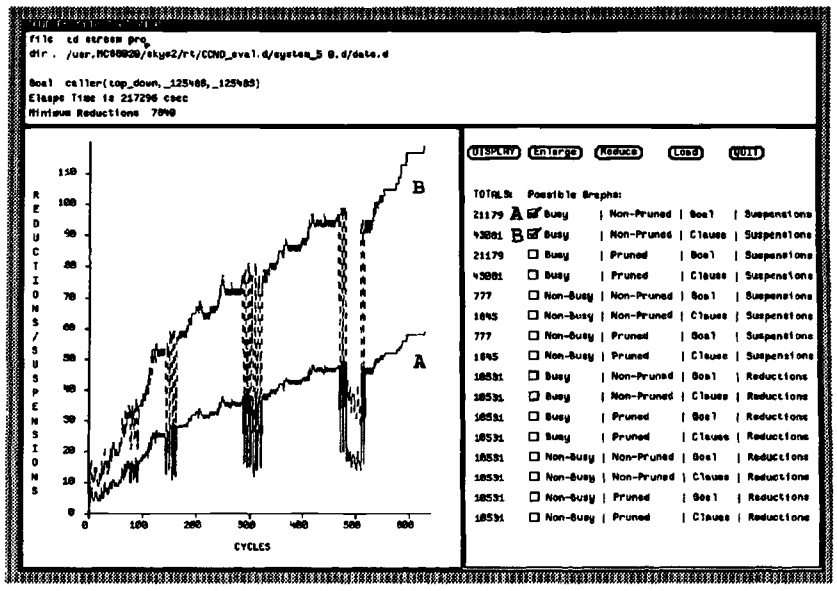
(**non-busy** waiting-**clause** suspensions)

Figure 6–16: Profile of a top-down **safe** chart parser



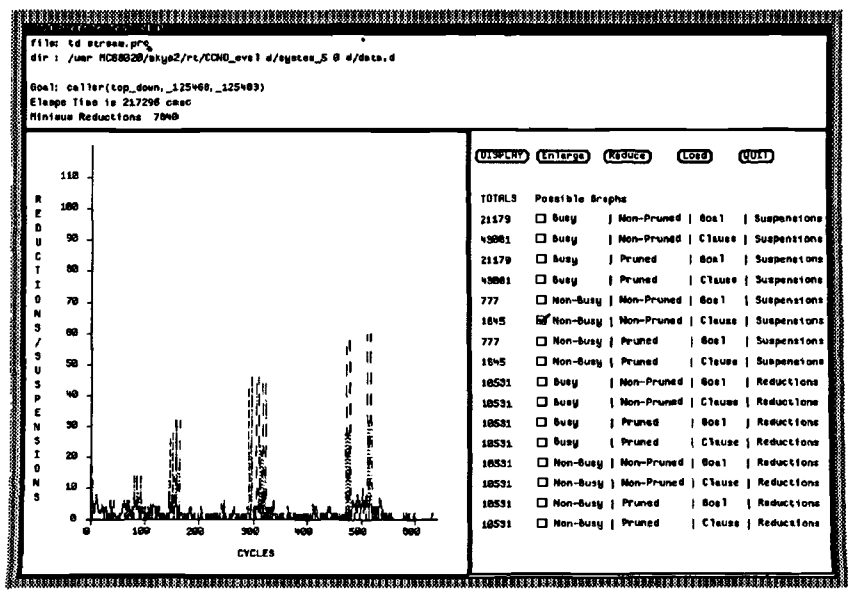
(**reductions**)

Figure 6–17: Profile of a top-down **safe** chart parser



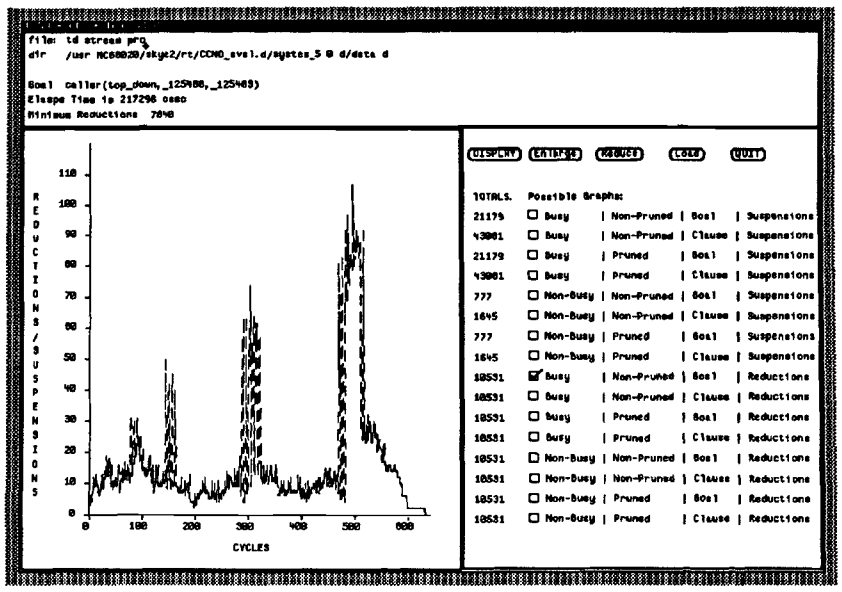
(**busy** waiting-**goal** and **clause** suspensions)

Figure 6–18: Profile of a top-down **safe+system streams** chart parser



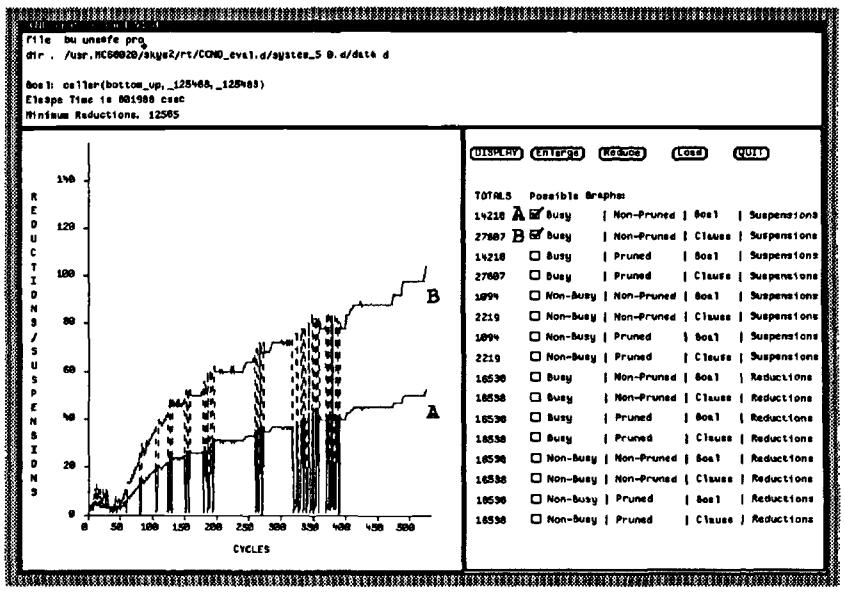
(**non-busy** waiting-**clause** suspensions)

Figure 6–19: Profile of a top-down **safe+system streams** chart parser



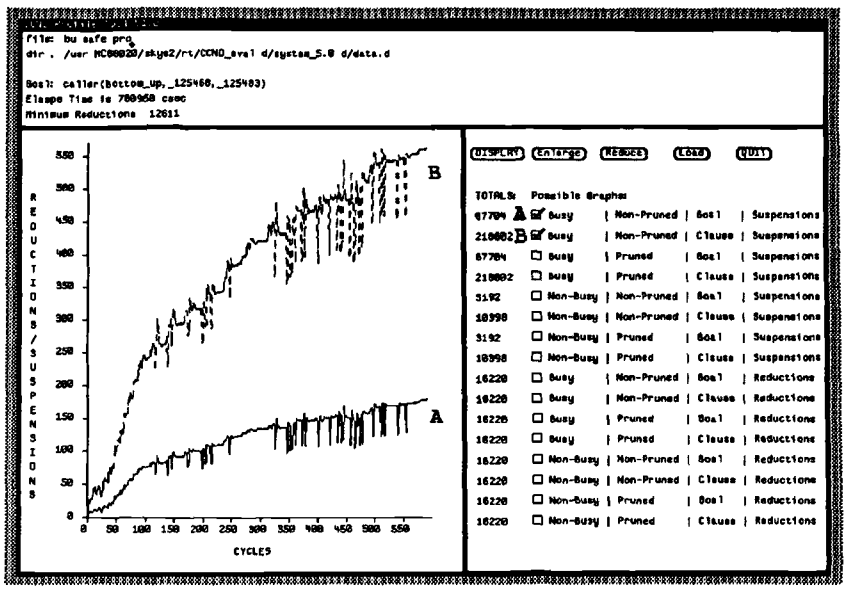
(reductions)

Figure 6–20: Profile of a top-down **safe+system streams** chart parser



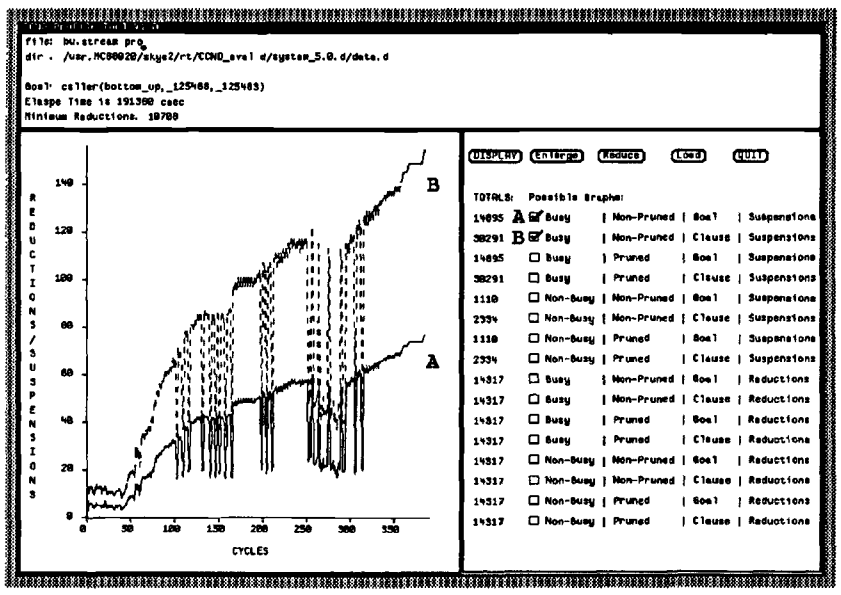
(**goal** and **clause** suspensions)

Figure 6–21: Profile of a bottom-up **unsafe** chart parser



(**goal** and **clause** suspensions)

Figure 6–22: Profile of a bottom-up **safe** chart parser



(**goal** and **clause** suspensions)

Figure 6–23: Profile of a bottom-up **safe+system streams** chart parser

First we consider some general points raised by these profiles:

- There is no difference between the various reduction counts for the **unsafe** chart parsers (see *Figure 6–14*). The same is also true of the **safe** and **safe+system streams** parsers (see *Figures 6–17 and 6–20*). The similarity in the reduction counts, using **goal** and **clause** suspensions, indicates either there are no suspensions or that the evaluation suspends on head unification before any reductions in the guard take place. As there are suspensions for each of these chart parsers the suspensions must occur on head unification.

- The similarity in the suspension counts using **pruned** and **non-pruned** evaluations indicates that either guards are even in their computation (this includes the guards being **flat**) or that only one clause could ever be picked as a solution path.

- Comparing the minimum reductions to the actual reductions gives a measure of the OR-parallelism (see section 4.3.4). *Table 6–3* summarises the degree of OR-parallelism for the various chart parsers and activation strategies.

Chart Parser	Actual Reductions	Minimum Reductions	OR-parallelism
UTD	12508	9397	1.33
STD	11554	8863	1.30
S+SSTD	10531	7840	1.34
UBU	16538	12565	1.32
SBU	16220	12611	1.29
S+SSBU	14317	10708	1.34

Table 6–3: Degree of OR-parallelism for the various chart parsers

The various chart parser do not exhibit much OR-parallelism. This is because the perpetual process view of Parlog which was employed in the design of these chart parsers gives rise to predicates with simple guards. The most complex guards in the systems check if two edges combine or if two edges

will result in the same activations. Also chart parsing computes all-solutions, essentially replacing OR-parallelism by AND-parallelism.

- Our profiles allow us to obtain an indication of the maximum number of reductions and suspensions in a cycle. *Table 6–4* summarises the maximum number of reductions that can be performed in a given cycle, some of this information is given graphically in *Figures 6–13, 6–16* and *6–19.*

Program	Max reductions	Cycle number
UTD	95	757
STD	105	834
S+SSTD	107	497
UBU	154	374
SBU	145	458
S+SSBU	152	280

Table 6–4: Maximum reductions in a given cycle for the various chart parsers

Whilst we see that the maximum number of reductions is high, the profiles, *Figures 6–13, 6–16 and 6–19* show that these maxima are very narrow peaks. This indicates that the maximum reductions in a cycle should not be taken as a strong indication of the possible number of exploitable processes [3]. The main feature to note is the maximum parallelism occurs sooner for the bottom-up activation strategy, indicating that activation model is more parallel at the start.

- *Table 6–5* summarises the maximum number of suspensions that can occur in a given cycle. Because of the nature of these chart parsing algorithms

[3]It can be argued that the average number of reductions over the whole computation is the only measure that reflects realistic processor requirements. However, some computation may exhibit large amounts of parallelism for several cycles but still have a low average utilisation. In these cases some weight should be given to the maximum possible processor utilisation.

(ie. they terminate by deadlocking), the maximum number of suspended processes will occur in the last cycle. However, the maximum number of new suspensions in a given cycle will occur some time during the computation. This is confirmed pictorially in *Figures 6–12, 6–13, 6–15, 6–16, 6–18,* and *6–19.*

Maximum number of suspensions in a given cycle								
	Busy waiting				Non-busy waiting			
	Goal		Clause		Goal		Clause	
Program	Max	Cycle	Max	Cycle	Max	Cycle	Max	Cycle
UTD	40	943	78	930	33	766	65	766
STD	136	951	424	938	42	751	100	751
S+SSTD	59	632	119	632	30	512	60	512
UBU	53	526	104	526	40	378	80	378
SBU	180	591	564	591	57	459	142	459
S+SSBU	77	385	155	385	44	315	88	315

Table 6–5: Maximum suspensions in a given cycle for the various chart parsers

We now compare the three chart parsers.

- The difference between suspensions using **goal** and **clause** suspension mechanisms highlights the number of clauses that each goal could be reduced by in the dynamic program (see section 4.5.3.1). *Table 6–6* summarises the ratio of **clause** to **goal** for the various chart parsers using **busy** and **non-busy** waiting scheduling.

	Busy waiting			Non-busy waiting		
Program	Goal	Clause	Ratio	Goal	Clause	Ratio
UTD	20935	40163	1.9	627	1285	2.0
STD	81096	255585	3.2	1962	6148	3.1
S+SSTD	21179	43081	2.0	777	1645	2.1
UBU	14218	27607	1.9	1094	2219	2.0
SBU	67704	218602	3.2	3192	10398	3.3
S+SSBU	14895	30291	2.0	1110	2334	2.1

Table 6–6: **Clause/Goal** suspension ratios for the various chart parsers

The similarity in **busy** and **non-busy** waiting ratios indicates that the different predicates (differing in number of clauses) suspend for similar numbers of cycles. The similarity in the ratios for top-down and bottom-up activations indicates either that all the goals that suspend have similar numbers of clauses or that the program's behaviour is independent of activation model. In the various chart parsers most predicates have two clauses.

The ratio of suspensions using **clause** and **goal** suspension mechanisms is largest for the **safe** chart parsers. This is due to `merge/3` processes. In the main these merge processes are suspended. Since each merge goal can reduce via four clauses this increases the average suspension count.

- The **(non-busy)** suspension parameter records the number of new suspended processes that occur in each cycle. For the **safe** chart parser the number of new goals suspended is 1962 (see *Table 6-2*) for the **unsafe** chart parser the number is 627 and for the **safe+system streams** chart parser the number is 777.

In the **unsafe** chart parser the main processes that suspend are those for active edges. Updates to the shared data structure are achieved by directly accessing the *chart*. In the **safe+system streams** chart parser there will be suspended processes for active edges and some filter processes, which sift the request stream. Messages are placed on the request stream using system primitives. In the **safe** chart parser there will be suspended processes for active edges, filter processes and a network of merge processes to combine local request streams from each active edge process. For each active edge

their are two associated merge processes [4]. This indicates that generally both the filter processes and the network of merge processes are suspended.

Program	Goal Suspension			Clause Suspension		
	Busy	Non-busy	Ratio	Busy	Non-busy	Ratio
UTD	20935	627	33.4	40163	1285	31.2
STD	81096	1962	41.3	255585	6148	41.6
S+SSTD	21179	777	27.3	43081	1645	26.2
UBU	14218	1094	13.0	27607	2219	12.4
SBU	67704	3192	21.2	218602	10398	21.0
S+SSBU	14895	1110	13.4	30291	2334	13.0

Table 6–7: Busy/Non-busy suspension ratios for the various chart parsers

- The comparison of **busy** and **non-busy** suspensions (total suspensions with new suspensions) indicates the benefit of tagging suspended executions to variables (see section 4.2.2). *Table 6–7* summarises the ratios of **busy** and **non-busy** waiting suspensions for the various chart parsers using **goal** and **clause suspension** mechanisms.

  In chart parsing the generation of inactive edges can be delayed in two ways: Firstly, delays in the creation of new active edges and their addition to the AET, which construct the inactive edges. Secondly, in the addition of newly formed inactive edges being added to the WFST (see section 6.5). The interaction and effect of the alternative delays result in the behaviour of the chart parsers being complex [5]. From the results we can deduce:

---

[4]Merge processes are created by the active edge spawner, this process spawns one active edge and two merge processes. That is the AET and WFST streams from the spawned active edge are merged with AET and WFST streams from any active edge processes that will be generated in the future.

[5]In the **unsafe** chart parser additions to the WFST take place using an unsafe predicate which recurses down the WFST until it reaches the unbound tail which it then

- the delay is less for the bottom-up activation model rather than top-down. This is because the bottom-up activation is more parallel;
- the delay is greatest for the **safe** chart parser. Comparing **unsafe** and **safe** chart parsers, the additional delay is because the **safe** chart parser has to first combine possible requests and then *sift* the resultant request stream while the **unsafe** chart parser combines these operations. Comparing **safe+system streams** and **safe** chart parsers, the additional delay is because the **safe** chart parser added elements to the *resultant stream* by merging streams, whilst the **safe+system streams** uses system primitives;
- using top-down activation the **safe+system stream** chart parser has smaller delays than the **unsafe** chart parser. However using a bottom-up activation model the delays are comparable. For the **unsafe** chart parser the delay in adding elements to the WFST will be proportional to the number of elements that have to be recursed over to find the tail of the WFST. If a top-down activation model is used, the active edge processes which will combine sub-parses together will be generated first. These active edge processes will form inactive edges near the end of the parse and so have to recurse over most of the WFST in order to

---

binds to the new inactive edge. Additions to the AET take place by a similar means however the new edge is also compared with each current element of the AET.

In the **safe** chart parser additions to the WFST take place using a network of merge processes which combine streams from the various active edge processes onto the *resultant* WFST. Additions to the AET undergo a two stage process. Firstly, the possible additions are combined using a network of merge processes. The *resultant stream* is *sifted* to remove any edges that would result in duplicate activations.

In the **safe+system streams** chart parser additions to the WFST take place using a system primitive (see section 6.3.3). Additions to the AET are firstly added to a *resultant stream* using a system primitive, the *resultant stream* is then *sifted.*

add these edges to the WFST. If a bottom-up activation model is used the active edge processes which will combine sub-parses together will be generated towards the end of the parse. These active edge processes are given the tail of the WFST stream when they are created, so they will only need to recurse over a subset of the WFST in order to add an edge. So, for the **unsafe** chart parser, the delays in adding elements to the WFST will be larger for top-down activations. The delay in adding elements to the WFST in the **safe+system streams** chart parser will be constant, as the additions are supported using system primitives.

- *Table 6–8* summarises the degree of parallelism *(reductions/cycle)* for the various chart parsers.

Average parallelism for the various chart parsers			
Program	Reductions	Cycles	Parallelism
UTD	12508	943	13.3
STD	11554	951	12.1
S+SSTD	10531	632	16.7
UBU	16538	526	31.4
SBU	16220	591	27.4
S+SSBU	14317	385	37.2

Table 6–8: Average parallelism for the various chart parsers

For the grammar used in our chart parsers a bottom-up activation model is about twice as parallel as a top-down one the bottom-up activation model requires more reductions to be performed. This is because of using a bottom-up activation model, which results in some phrases being constructed that cannot be used. Using a top-down model results only in searches for phrases which can be combined.

6.7 Synopsis of analysis

In this section we consolidate some of the results given in our analysis.

- The various chart parsers do not exhibit much OR-parallelism. This is because the chart parsers are constructed as a collection of simple processes which receive messages and based on these messages, send further messages. The computation involved in processing incoming messages is simple, so the guards are not too complex and hence there is little OR-parallelism.

- The maximum number of suspended processes occur at the end of the computation for all of the chart parsers, as they deadlock, although the maximum number of new suspensions occur somewhere during the computation.

- It was expected that the **unsafe** chart parser would be significantly better than the **safe** chart parser, because of the differences in the support for shared data structures. The actual results give the following conclusions:

  Reductions: In terms of reductions, the **safe** and **unsafe** systems are very similar. The combining of request streams using a network of merge processes and the filtering of the *resultant stream*, requires a similar number of reductions to recursing down the shared chart comparing the possible new edge with the existing edges and eventually adding the new edge to the tail of the shared data structure.

  Suspensions: In terms of suspensions, the **unsafe** chart parser only has one type of suspended process: that representing the active edge searches. The **safe** chart parser has three types of suspended processes: those representing the active edge searches; those representing the network of merge processes; and those representing the pipeline of filter processes. This is reflected in the results, in that there are about 4 times as many suspensions for the **safe** chart parser as for the **unsafe** chart parser.

Cycles: In terms of cycles, the **unsafe** chart parser was marginally better than the **safe** chart parser. Both chart parsers have the same activation model and search space so the difference between the cycle counts is due to different delays in making additions to the shared chart.

In the **unsafe** chart parser additions to the chart involve finding the tail of the shared data structure, while in the **safe** chart parser additions to the chart involve first merging streams of requests together and then filtering the request stream.

If a top-down activation model is used, the active edge processes which combine sub-parses together will be generated first. These active edge processes will form inactive edges near the end of the parse. For the **unsafe** chart parser this will involve recursing over most of the WFST in order to add these edges to the WFST, whilst for the **safe** chart parser the additions will involve the traversal of only a few merge processes (as the active edge processes were generated early on in the parse). This is a complex feature of the parsers which results in the actual difference in cycles not being as high as first expected.

So the **unsafe** chart parser appears marginally better than the **safe** chart parser. However, this margin is based mostly on the difference in suspended processes. In an actual implementation if an efficient suspension mechanism can be employed and the cost of atomic unification to support the **unsafe** chart parser is accounted for, this margin may swing to the benefit of the **safe** system.

- The merge networks which connect together streams onto one single *resultant stream* are mostly suspended. This is indicated by considering **goal** and **clause** suspensions using **busy** and **non-busy** waiting.

- We now turn our attention to the **safe+system streams** chart parser. This system proves to be better than either the **unsafe** or **safe** chart parser.

Reductions: In terms of reductions, the **safe+system streams** preforms about 10 % fewer reductions than either of the other two parsers. Compared with the **unsafe** chart parser the difference occurs in processing over the shared data structure to find the unbound tail. Compared with the **safe** chart parser the difference occurs in supporting a network of merge processes.

Suspensions: In terms of suspensions, the **safe+system streams** parser has more suspensions than the **unsafe** parser. These are due to the pipeline of filter processes. Compared with the **safe** chart parser the **safe+system streams** chart parsers has about 1/4 of the suspensions using **busy** waiting and about 1/3 of the suspensions using **non-busy** waiting. This is due to the **safe+system streams** parser not supporting a network of (mostly suspended) merge processes.

Cycles: In terms of cycles, the **safe+system streams** shows about a 30% reduction in the overall cycle count. This is due to the additions to the *resultant stream* being supported by the system and so the delays associated with the merge network are avoided in the case of the **safe** chart parser. Compared with the **unsafe** chart parser the **safe+system streams** parser gains because processing over the shared data structure to find the unbound tail can be avoided.

- Finally, the **safe+system streams** chart parser exhibits the most parallelism. This is because of improved accessing to the shared data structures. Supporting streams in the system results in fewer reductions being performed in data management and also fewer cycles for the overall computation.

6.8 Summary

In this chapter the following have been presented and discussed:

- How all the CCND languages easily and directly support *one-to-many* communication by single writers to a shared variable.
- Why only **unsafe** CCND languages are able to directly support *many-to-one* communication.
- How shared data structures can be supported in the other, **safe**, CCND languages; by merging requests for updates to a manager process.
- Possible stream manipulation extensions to **safe** languages which support the combining of several streams onto one *resultant stream.* The extended language is known as **safe+system streams**.
- How an AI application, a chart parser, maps onto the three different languages: **unsafe**; **safe**; and **safe+system streams**.
- The evaluation of the three resulting chart parsers using our profiling system developed in Chapter 3. The results indicate that:
  - there are significant overheads introduced by networks of merge processes, in the **safe** languages;
  - the **unsafe** languages also introduce some delays in supporting shared streams, in that the tail of the shared stream has to be found;
  - in terms of suspension overheads, available parallelism and total number of cycles required the **safe+system streams** chart parser is best, highlighting the benefits of supporting multiple writers to a stream by the system.

Chapter 7

Meta-level inference - deep/flat

7.1 Overview

This chapter considers how an AI programming technique known as meta-level inference maps to the CCND languages. Meta-level inference attempts to control the search at one level of the problem space (the object-level) by providing some general control rules (the meta-level) to guide the search over the object level search. The program evaluated is known as PRESS- **PR**olog **E**quation **S**olving **S**ystem, [Sterling *et al* 82]. PRESS was originally implemented in Prolog, this system was translated to Concurrent Prolog and FCP in [Sterling & Codish 85] resulting in CONPRESS and FCPPRESS respectively.

In [Trehan 86] we reconstruct this translation for Concurrent Prolog, Parlog and GHC, resulting in CONPRESS, PARPRESS and GHCPRESS. The translations were used to compare the synchronisation, expressiveness and programmability of the various CCND languages.

In this chapter we consider the behaviour of DeepPARPRESS (which employs **deep** guards) and two **flattened** versions known as FlatPARPRESS-term and FlatPARPRESS-nonterm. The **flat** programs are derived from DeepPARPRESS

using some of the techniques employed in **flattening** CONPRESS to FCPPRESS and some techniques covered in [Gregory 87].

The purpose of this chapter is to highlight improvements in our system as a basis for collecting information about the inherent parallelism of programs with **deep** guards; to provide an application which allows us to investigate the relationship between **deep** and **flat** guards; and to consider the effects of employing termination techniques for **flat** guarded programs.

In section 7.2 we give a short review of PRESS and consider how the meta-level of PRESS was originally represented in Prolog.

Section 7.3 considers the issues of translating PRESS to a CCND language which supports **deep** guards.

Section 7.4 considers the method employed in **flattening** CONPRESS to FCP-PRESS and how we have **flattened** PARPRESS.

In section 7.5 we present the programs and queries that we intend to evaluate.

Section 7.6 summarises the previous analysis [Sterling *et al* 82] of the execution of the Parallel PRESSes.

In section 7.7 we first compare our results with those obtained in the previous evaluation. We compare the behaviour of our three Parallel PRESSes.

Finally, in section 7.8 we give a synopsis of our results.

7.2 PRESS

PRESS attempts to capture a theory of solving mathematics equations in terms of axioms specified in Prolog. These axioms can then be executed to give an equation solving system. The axioms of PRESS represent a control level which embodies a meta-theory of solving mathematical equations. As such the top-level of PRESS is

termed the meta-level. The level of the search space that this meta-level controls is termed the object-level.

The meta-level of PRESS is defined as a set of axioms which have two parts. A *precondition* which determines the suitability of some method and the *method* itself. In the following sections we consider how the meta-level of PRESS was originally realised in Prolog. This is followed by considering how the meta-level of PRESS can be realised in the CCND languages. We focus on the use of **deep** guards to directly support the meta-level rules in CCND languages and how these deep guards can be **flattened**.

7.2.1 Prolog

The axioms that make up the meta-level of PRESS are easily represented in an executable form as Prolog clauses of the following form:

```
solve_equation(Equation,X,Solution) :-
    precondition(Equation,X), solution_method(Equation,X,Solution).
```

The subset of PRESS we consider has meta-rules (axioms) which cater for equations requiring the following types of solution methods:

- factorisation;
- isolation;
- polynomial; and
- homogenisation.

The meta-level axioms for PRESS are given in *Figure 7–1*. The main point to note is that the meta-level rules will be investigated sequentially, according to Prolog's evaluation model.

```
solve_equation(Equation, Unknown, Solution) :-
    factorisation_test(Equation, Unknown),
    factorisation_method(Equation, Unknown, Solution).

solve_equation(Equation, Unknown, Solution) :-
    isolation_test(Equation, Unknown),
    isolation_method(Equation, Unknown, Solution).

solve_equation(Equation, Unknown, Solution) :-
    polynomial_test(Equation, Unknown),
    polynomial_method(Equation, Unknown, Solution).

solve_equation(Equation, Unknown, Solution) :-
    homogenisation_test(Equation, Unknown),
    homogenisation_method(Equation, Unknown, Solution).
```

Figure 7–1: Meta-level of PRESS in Prolog

7.3 Using deep guards

Translating Prolog programs to a language which has **deep** guards is mostly a matter of translating code with *generate and test* type choice points (see section 5.2.3) to allow different alternative solutions to be generated and maintained (see sections 5.2). Exploring (or rather applying) the object-level of PRESS, the rewrite rules for mathematics, result in a search space with many *generate and test* choice points; each rewrite generates a new temporary equation, which may be a solution or may lead to a solution or may never result in a solution. However, the meta-level of PRESS embodies a theory for solving equations which serves to control the use of the object-level rewrites and hence guides the search over the object-level *generate and test* search. The translation of PRESS to CONPRESS [Sterling *et al* 82] serves to highlight the fact that PRESS does not actually have any *generate and test*

choice points; in that the translation essentially involves replacing Prolog's **cut** operator for Concurrent Prolog's (Parlog's and GHC's) **guard** operator.

Consider the meta-level axioms of PRESS. The structure of the meta-rules maps to the CCND languages in the following way. The tests for the suitability of various solution methods becomes the guarded goals and the solution methods become the body goals (which are committed to if the guards succeed), *i.e.* guarded horn clauses of the following form:

```
solve_equation(Equation,X,Solution) :-
    precondition(Equation,X) : solution_method(Equation,X,Solution).
```

Now the meta-rules can be evaluated in parallel, and the first rule to evaluate its guard completely is committed to. There are several points arising from this evaluation model:

- When the conditions are written the sequential evaluation of the conditions (as in Prolog) cannot be assumed, *i.e.* the conditionK cannot assume the negation of condition1 to conditionK-1 being true. The only reason for adopting knowledge of the control mechanism, like the negation of certain goals, is performance. By knowing certain goals will have been attempted, some computation may be prevented. In a parallel system, the evaluation of the conditions occurs in parallel, and hence this particular efficiency aspect is no longer such a major consideration for the programmer. Instead the conditions are made completely independent of textual order, *i.e.* they introduce whatever explicit tests are required in each condition, even if it means duplicating code.

- Each condition must be strict enough to ensure that the action will produce a solution because once a method is committed to there is no backtracking to find another possible solution method. In Prolog, backtracking allows the programmer to try another meta-rule, should the current one fail to

produce a solution. Even if the current condition succeeded, this could lead to all sorts of poor programming practice, like ignoring the real structure of a meta-rule. The effect of commitment could be introduced into a Prolog meta-rule by using the "cut operator".

Figure 7–2 gives the meta-rules for PRESS, for the CCND languages with **deep** guards.

```
mode solve_equation_meta(?,?,^).

solve_equation_meta(LHS=RHS,X,Soln) :-
        precond_factorial(LHS=RHS,X)
        :
        factorise(LHS,X,Factors1\[]),
        remove_duplicates(Factors1,Factors),
        solve_factors(Factors,X,Soln).
solve_equation_meta(LHS=RHS,X,Soln) :-
        precond_isolation(LHS=RHS,X)
        :
        position(X,LHS=RHS,[Side|Position]),
        maneuver_sides(Side,LHS=RHS,Equation1),
        isolate(Position,Equation1,Soln).
solve_equation_meta(LHS=RHS,X,Soln) :-
        precond_polynomial(LHS=RHS,X)
        :
        polynomial_normal_form(LHS-RHS,X,PolyForm),
        solve_polynomial_equation(PolyForm,X,Soln).
solve_equation_meta(LHS=RHS,X,Soln) :-
        precond_homog(LHS=RHS,X,Offenders)
        :
        homogenize(LHS=RHS,X,Offenders,Equation1,X1),
        solve_equation(Equation1,X1,Soln1),
        solve_equation(Soln1,X,Soln).
```

Figure 7–2: Meta-level of PRESS using **deep** guards

7.4 Using flat guards

The **flattening** of a **deep** guarded program essentially requires translating OR-parallelism into AND-parallelism. [Sterling & Codish 87] consider three techniques for translating **deep** guards into **flat** guards. We call these techniques:

- guard continuation-mutual exclusion semaphore;
- if-then-else; and
- rewriting.

The first of these techniques can only be used for **unsafe** languages. However it does have a **safe** analogue, given in [Gregory 87], which we term:

- Guard continuation-monitor goal.

We now consider each of these techniques in turn.

7.4.1 Guard continuation - mutual exclusion semaphore

The guard continuation technique makes use of FCP's **unsafe** features. The guarded goals for the various clauses are translated into an a conjunction of goals; one goal for each guard. Each goal contains an additional call argument known as a *mutual exclusion variable*. The conjunction also contains a continuation goal. The goals that represent meta-level preconditions are executed in parallel. On successful termination of one of the preconditions the given goal binds the *mutual exclusion variable* to the successful method. This variable is consumed by the continuation goal which commits to the selected solution method. The resulting meta-level is given in *Figure 7–3*. Note that this method requires each of the goals to succeed, even if the precondition that it is testing for fails.

```
mode solve_equation_meta(?,?,^).
solve_equation_meta(LHS=RHS,X,Soln) :-
        precond_factorial(LHS=RHS,X,Method),
        precond_isolation(LHS=RHS,X,Method),
        precond_polynomial(LHS=RHS,X,Method),
        precond_homog(LHS=RHS,X,HomoCont,Method),
        meta_level_cont(Method, HomoCont, LHS=RHS,X,Soln).

mode meta_level_cont(?,?,?,?,^).
meta_level_cont(factorisation,_,Lhs = _,X,Soln) :-
        factorise(Lhs,X,Factors1\[]),
        remove_duplicates(Factors1,Factors,_),
        solve_factors(Factors,X,Soln).
meta_level_cont(isolation,_,Equation,X,Soln) :-
        position(X,Equation,[Side|Position]),
        maneuver_sides(Side,Equation,Equation1),
        isolate(Position,Equation1,Soln).
meta_level_cont(polynomial,_,Lhs = Rhs,X,Soln) :-
        polynomial_normal_form(Lhs-Rhs,X,PolyForm),
        solve_polynomial_equation(PolyForm,X,Soln).
meta_level_cont(homogenization,Offenders,Equation,X,Soln) :-
        homogenize(Equation,X,Offenders,Equation1,X1),
        solve_equation(Equation1,X1,Soln1),
        solve_equation(Soln1,X,Soln).
```

Figure 7–3: Meta-level of PRESS using **flat** guards-*mutual exclusion variable*

The *mutual exclusion variable* can also be consumed by the other goals to allow them to be terminated early. This is achieved by treating the *mutual exclusion variable* not only as a selection semaphore for the meta-level but also as a termination broadcast message to the other goals exploring the preconditions.

This technique can be applied to **flattening** any **deep** guarded program at least for the **unsafe** languages, as they support the use of a single variable (the *mutual exclusion variable*) with several writers.

7.4.2 If-then-else

The second method given in [Sterling & Codish 87] is a much weaker technique than using a guard continuation. The technique relies on there being only one clause for a predicate with a **deep** guarded goal. This clause is translated into the default clause with the guarded goal returning a status, as in the guard continuation technique the status is used as an *if-then-else* selector. We highlight this technique by considering the predicate **parse/3** which collects a set of terms which do not parse as a polynomial or trigonometric in the unknown. *Figure 7–4* gives a deep guarded version of this predicate. The first 9 clauses provide various cases that test for allowable terms. The last clause adds a term which cannot be parsed to the output list. The only **deep** guard in this predicate is **free_of/2**.

```
mode parse(?,?,?).
parse(Term,Term,L\L).
parse(cos(Term),X,L1\L2) :-
        parse(Term,X,L1\L2).
parse(sin(Term),X,L1\L2) :-
        parse(Term,X,L1\L2).
parse(A+B,X,L1\L2) :-
        parse(A,X,L1\L3), parse(B,X,L3\L2).
parse(A*B,X,L1\L2) :-
        parse(A,X,L1\L3), parse(B,X,L3\L2).
parse(A-B,X,L1\L2) :-
        parse(A,X,L1\L3), parse(B,X,L3\L2).
parse(A=B,X,L1\L2) :-
        parse(A,X,L1\L3), parse(B,X,L3\L2).
parse(A^B,X,L) :-
        integer(B), B>1 : parse(A,X,L).
parse(A,X,Lout\L) :-
        free_of(X,A) : Lout = L;
parse(A,X,[A|L]\L).
```

Figure 7–4: parse/3 using deep guards

Figure 7–5 gives the **flattened** version of the last two clauses for this predicate. The **deep** guard and output clause have been combined into the default clause using an if-then-else construct; if the `free_of` fails, output the term, else output nothing.

```
mode parse(?,?,?).
parse(A,X,Lout\L) :-
        free_of(X,A,Flag),
        output_fail_flag(A,Flag,Lout\L).

mode output_fail_flag(?,?,^).
output_fail_flag(A,failed,[A|L]\L).
output_fail_flag(_,true,L\L).
```

Figure 7–5: Flattened clauses of **parse/3**

7.4.3 Rewriting

This technique basically involves rewriting the definition of certain **deep** guarded predicates. [Sterling & Codish 87] refer to this as a *specialisation* process. Consider the predicate `remove_duplicates` given in *Figure 7–6.*

The `member/2` guarded goal can be specialised for its use within `remove_duplicates` which gives rise to the the **flat** version given in *Figure 7–7.*

This particular predicate could have been **flattened** using either of the previous two techniques considered. However, the code generated by the previous two techniques would have been less efficient than rewriting (specialising) the member check with respect to its use in `remove_duplicates`.

```
mode remove_duplicates(?,^).
remove_duplicates(In,Out) :-
        remove_duplicates(In,[],Out\[]).

remove_duplicates([],[]).
remove_duplicates([X|Xs],Ys) :-
        member(X,Xs)
        :
        remove_duplicates(Xs,Ys);
remove_duplicates([X|Xs],[X|Ys]) :-
        remove_duplicates(Xs,Ys).
```

Figure 7–6: `remove_duplicates/2` using **deep** guards

7.4.4 Guard continuation - monitor goal

The guard continuation using a *mutual exclusion variable* given in section 7.4.1 makes use of FCP's **unsafe** features, in that the *mutual exclusion variable* can be bound by several goals and hence requires atomic unification (see chapter 5). However, this technique has an analogue which can be supported in **safe** languages. The technique given in [Gregory 87] for eliminating OR-parallel search can be seen as analogous to the guard continuation using a *mutual exclusion variable.* Both use a guard continuation to commit to a given set of body goals, the commitment being based on the evaluation of several AND-parallel goals which perform the guarded search.

The difference between the two techniques is that, using a *mutual exclusion variable*, each guard is translated into a goal with the same additional argument serving to flag the selected guard; as well as acting as a semaphore for excluding the selection of the other guards. In the **safe** languages the guards are translated into goals, each of which has a unique termination flag. Each of these termination flags is monitored by the guard continuation goal, which commits to a set of body goals as soon as one of the flags is bound to success. Hence we term this technique

```
mode remove_duplicates(?,^).
remove_duplicates(In,Out) :-
        remove_duplicates(In,[],Out\[]).

mode remove_duplicates(?,?,^).
remove_duplicates([],_,Out\Out).
remove_duplicates([X|Xs],Sofar,Out\Out1) :-
        remove_duplicates(X,Sofar,SofarNext,Out\Out2),
        remove_duplicates(Xs,SofarNext,Out2\Out1).

mode remove_duplicates(?,?,^,^).

remove_duplicates(X,[],[X],[X|Out]\Out).
remove_duplicates(X,[H|T],[H|T1],Out) :-
        X \= H
        :
        remove_duplicates(X,T,T1,Out).
remove_duplicates(X,[H|T],[H|T],Out\Out) :-
        X == H
        :
        true.
```

Figure 7–7: `remove_duplicates/2` using **flat** guards

guard continuation using a monitor goal. *Figure 7–8* gives the meta-level of PRESS using this technique.

Using a *mutual exclusion variable* also provided a means by which the other goals could be terminated early, once a selection has been found. This can also be achieved using a monitor goal. Basically it requires the monitor goal to set a terminate flag on committing to a given set of body goals. Note that this flag is only written to by the monitor goal and is consumed by each of the goals exploring meta-level preconditions. The resulting meta-level is given in *Figure 7–9*.

```
mode solve_equation_meta(?,?,^).

solve_equation_meta(LHS=RHS,X,Soln) :-
        precond_factorial(LHS=RHS,X,FactFlag),
        precond_isolation(LHS=RHS,X,IsoFlag),
        precond_polynomial(LHS=RHS,X,PolyFlag),
        precond_homog(LHS=RHS,X,HomoCont,HomoFlag),
        meta_level_cont(FactFlag,IsoFlag,PolyFlag,HomoFlag
                        HomoCont, LHS=RHS,X,Soln).

mode meta_level_cont(?,?,?,?,?,?,?,^).

meta_level_cont(true,_,_,_,_,Lhs = _,X,Soln) :-
        factorise(Lhs,X,Factors1\[]),
        remove_duplicates(Factors1,Factors,_),
        solve_factors(Factors,X,Soln).
meta_level_cont(_,true,_,_,_,Equation,X,Soln) :-
        position(X,Equation,[Side|Position]),
        maneuver_sides(Side,Equation,Equation1),
        isolate(Position,Equation1,Soln).
meta_level_cont(_,_,true,_,_,Lhs = Rhs,X,Soln) :-
        polynomial_normal_form(Lhs-Rhs,X,PolyForm),
        solve_polynomial_equation(PolyForm,X,Soln).
meta_level_cont(_,_,_,true,Offenders,Equation,X,Soln) :-
        homogenize(Equation,X,Offenders,Equation1,X1),
        solve_equation(Equation1,X1,Soln1),
        solve_equation(Soln1,X,Soln).
```

Figure 7–8: Meta-level of PRESS using **flat** guards-*monitor goal* (nonterminating)

```
mode solve_equation_meta(?,?,^).
solve_equation_meta(LHS=RHS,X,Soln) :-
        meta_factorial(LHS=RHS,X,FactFlag,MetaKill),
        meta_isolation(LHS=RHS,X,IsoFlag,MetaKill),
        meta_polynomial(LHS=RHS,X,PolyFlag,MetaKill),
        meta_homog(LHS=RHS,X,HomoCont,HomoFlag,MetaKill),
        meta_level_cont(FactFlag,IsoFlag,PolyFlag,HomoFlag,
                        MetaKill,HomoCont, LHS=RHS,X,Soln).

par_mode meta_level_cont(?,?,?,?,^,?,?,?,^).
meta_level_cont(true,_,_,_,_,_,Lhs = _,X,Soln) :-
        factorise(Lhs,X,Factors1\[]),
        remove_duplicates(Factors1,Factors,_),
        solve_factors(Factors,X,Soln).
meta_level_cont(_,true,_,_,_,_,Equation,X,Soln) :-
        position(X,Equation,[Side|Position]),
        maneuver_sides(Side,Equation,Equation1),
        isolate(Position,Equation1,Soln).
meta_level_cont(_,_,true,_,_,_,Lhs = Rhs,X,Soln) :-
        polynomial_normal_form(Lhs-Rhs,X,PolyForm),
        solve_polynomial_equation(PolyForm,X,Soln).
meta_level_cont(_,_,_,true,_,Offenders,Equation,X,Soln) :-
        homogenize(Equation,X,Offenders,Equation1,X1),
        solve_equation(Equation1,X1,Soln1),
        solve_equation(Soln1,X,Soln).
```

Figure 7–9: Meta-level of PRESS using **flat** guards-*monitor goal* (terminating)

7.5 Programs evaluated

There are several programs that we could evaluate:

- Parallel PRESS, making use of **deep** guards for both the meta-level axioms and the various auxiliary functions.

- Parallel PRESS, using **deep** guards only for the meta-level axioms (rules) and **flat** guards for the various auxiliary functions:

  - the **flat** code does not employ termination techniques;
  - the **flat** code does employ termination techniques.

- Parallel PRESS, using **flat** guards for the meta-level axioms and the various auxiliary functions. The **flat** code does not employ termination techniques.

- Parallel PRESS, using **flat** guards for the meta-level axioms and the various auxiliary functions. The **flat** code does employ termination techniques.

The subset of PRESS being considered allows the following type of equation to be solved (these examples were the ones evaluated in [Sterling & Codish 87]):

PRESS example 1 : $\cos(x) \times (1 - \sin(2 \times x)) = 0$

PRESS example 2 : $x^2 - 3 \times x + 2 = 0$

PRESS example 3 : $2^{2 \times x} - 5 \times 2^{x+1} + 16 = 0.$

We can evaluate all the Parallel PRESSes with all the queries. However this would lead to a large amount of data which may obscure the purpose of this particular evaluation: to highlight improvements in our system as a basis for collecting information about the inherent parallelism of programs; to provide an

application which allows us to investigate the relationship between **deep** and **flat** guards; and to consider the effects of employing termination techniques for **flat** guarded programs.

We have chosen to consider one aspect of PRESS and meta-level inference; how the execution of the meta-level differs using **deep** and **flat** guards, where the **flat** meta-levels may or may not employ termination techniques. The systems evaluated are:

DeepPARPRESS : Parallel PRESS implemented in Parlog, employing **deep** guards just for the meta-level axioms.

FlatPARPRESS-nonterm : Parallel PRESS implemented in Parlog, employing **flat** guards. On successful termination of one of the preconditions (to a meta-level axiom) the other preconditions are not terminated.

FlatPARPRESS-term : Parallel PRESS implemented in Parlog, employing **flat** guards. On successful termination of one of the preconditions (to a meta-level axiom) the other preconditions are terminated.

We evaluate these systems using the three example queries given above.

Using our basic Parlog interpreter (see *Figure 3–1*) we have reconstructed the previous evaluation of these systems. Our raw results differ from those given in [Sterling & Codish 87] due to using slightly different parallel implementations; we only employ **deep** guards for the meta-level. However, the conclusions that can be drawn from these results are the same as those drawn in [Sterling & Codish 87].

In the following sections we first briefly consider the conclusions that can be drawn from the results obtained using the basic Parlog interpreter. We then present the raw data obtained from our improved Parlog interpreter. The results from the two interpreters are then briefly compared. We finally analyse the data from our improved Parlog interpreter.

7.6 Previous analysis

Using deep guards			
Query	Cycles	Reductions	Suspensions
PRESS1	30	142	99
PRESS2	17	79	51
PRESS3	41	284	218

Using non-terminating flat guards			
Query	Cycles	Reductions	Suspensions
PRESS1	42	337	213
PRESS2	24	149	97
PRESS3	71	564	426

Using terminating flat guards			
Query	Cycles	Reductions	Suspensions
PRESS1	42	241	162
PRESS2	24	126	90
PRESS3	71	539	416

Table 7–1: Summary of our reconstructed previous measurements for Parallel PRESSes

The conclusions drawn in [Sterling & Codish 87] were based on results similar to those given in *Table 7–1*; in that if we perform the same analysis as in [Sterling & Codish 87] we can obtain the same conclusions. We feel that the previous analysis was confused and mis-leading in several respects:

- It is not known whether system calls were counted as Prolog reductions. They certainly do not count the system calls as reductions in their CP interpreter.

- There are open questions as to the correlation between Prolog reductions, CCND reductions and cycles. As the Prolog reductions occur sequentially the reduction count gives some measure of the duration of the computation; whilst the duration of the computation is given by the cycle count for the

CCND languages. But how long does a Prolog reduction take compared to a CCND cycle? Are they really the same?

- They do not count reductions in the failed guards (preconditions) of their CP code. Did they count reductions in the branches backtracked over in the Prolog code? If not, the comparison of CP cycles with Prolog reductions to measure parallel speed-up is incorrect.

We feel that from these results it can be noted that using termination techniques for the meta-level axioms specified in **flat** Parlog saves some computation for **PRESS1**. However the extent of this saving is not as noticeable for **PRESS2** and **PRESS3**.

The cycle counter for both **flat** implementations is the same for each example. So we can conclude that the evaluations of the preconditions all terminate before the selected solution method is applied.

The cycle count for **deep** guards is less than that given for the **flat** systems. This is because guard evaluations were assumed not to incur cycle overheads in the interpreter.

The number of reductions and suspensions recorded using **deep** guards is less than that recorded for the **flat** examples. This is because the clauses are evaluated sequentially, so using **deep** guards some meta-level preconditions may never be tried, whilst in the **flat** system, the meta-level axioms will all be attempted.

Finally the degree of parallelism (*reductions/cycle*) is about 5 for the **deep** guarded PARPRESS and **flat** guarded PARPRESS employing termination of the meta-level, and is about 7 for the **flat** guarded PARPRESS not employing termination of the meta-level.

7.7 Results and new analysis

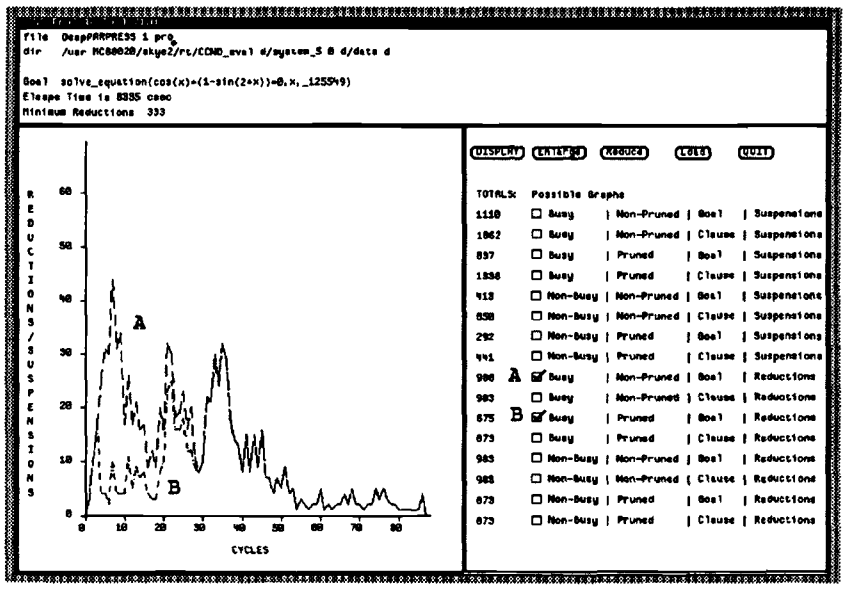
We first compare our data to the previous statistics collected and then compare the various programming technique using our results. The results obtained by our system are summarised in *Tables 7–2* and *7–3*. Also, some information is given pictorially in *Figures 7–10* to *7–18*

Reductions									
	Minimum Required	Busy waiting				Non-busy waiting			
		Non-Pruned		Pruned		Non-Pruned		Pruned	
Query	Reductions	Goal	Clause	Goal	Clause	Goal	Clause	Goal	Clause
Using deep guards									
PRESS1	333	988	983	675	673	983	983	673	673
PRESS2	159	435	433	339	339	433	433	339	339
PRESS3	631	1917	1657	1755	1498	1911	1657	1752	1498
Using non-terminating flat guards									
PRESS1	802	1032	1022	1032	1022	1022	1022	1022	1022
PRESS2	332	445	441	445	441	441	441	441	441
PRESS3	1289	1704	1694	1704	1694	1694	1694	1694	1694
Using terminating flat guards									
PRESS1	574	749	745	748	744	745	745	744	744
PRESS2	275	370	370	370	370	370	370	370	370
PRESS3	1187	1583	1579	1581	1577	1579	1579	1577	1577

Table 7–2: Summary of reduction parameters for Parallel PRESSes

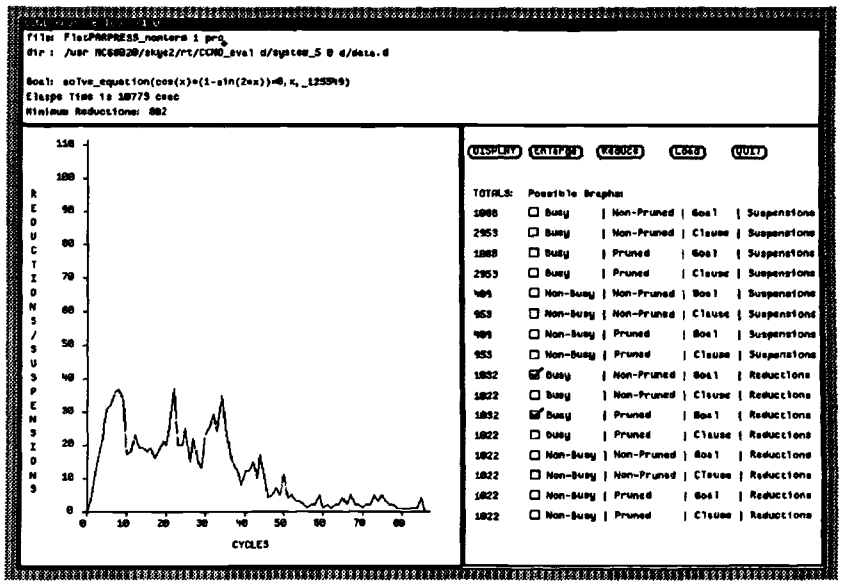
Suspensions									
		Busy waiting				Non-busy waiting			
		Non-Pruned		Pruned		Non-Pruned		Pruned	
Query	Cycles	Goal	Clause	Goal	Clause	Goal	Clause	Goal	Clause
Using deep guards									
PRESS1	87	1110	1862	837	1338	413	650	292	441
PRESS2	40	364	760	265	513	136	236	86	140
PRESS3	130	2031	4924	1853	4464	597	1017	575	968
Using non-terminating flat guards									
PRESS1	86	1088	2953	1088	2953	409	953	409	953
PRESS2	44	380	1172	380	1172	129	338	129	338
PRESS3	132	1736	5227	1736	5227	614	1509	614	1509
Using terminating flat guards									
PRESS1	86	816	2034	816	2034	286	643	286	643
PRESS2	44	302	892	302	892	86	231	86	231
PRESS3	132	1605	4730	1605	4730	546	1328	546	1328

Table 7–3: Summary of suspension parameters for Parallel PRESSes



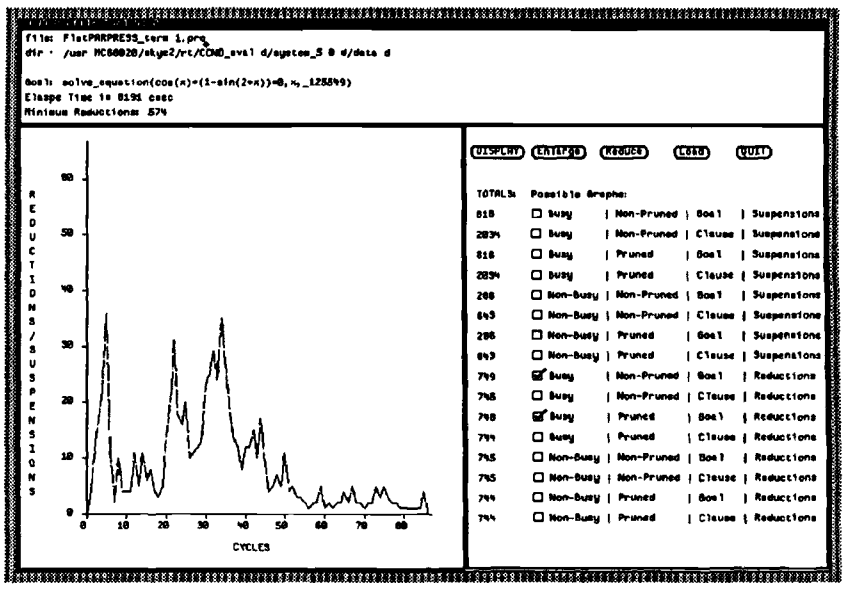
(**pruned** and **non-pruned** reductions)

Figure 7–10: Profile of PRESS1 using **deep** guards



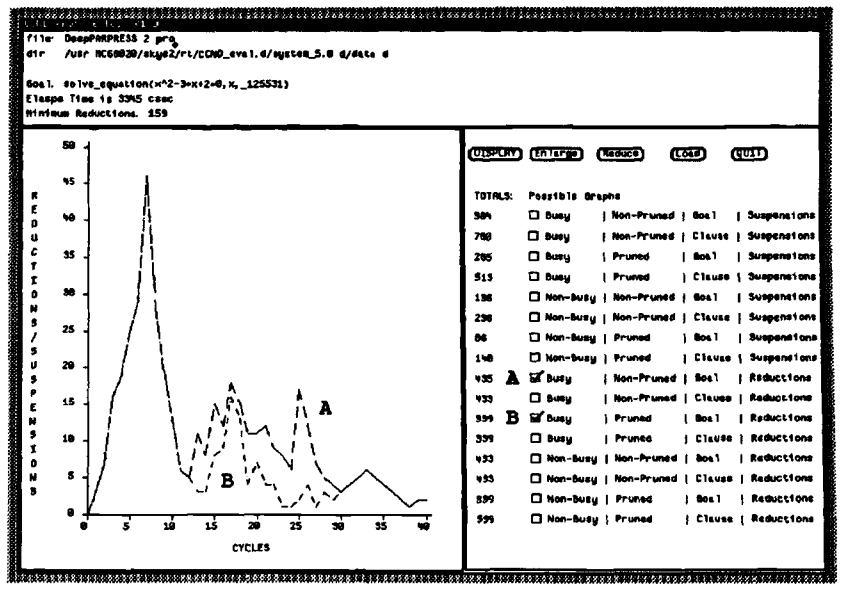
(**pruned** and **non-pruned** reductions)

Figure 7–11: Profile of PRESS1 using (non-terminating) **flat** guards



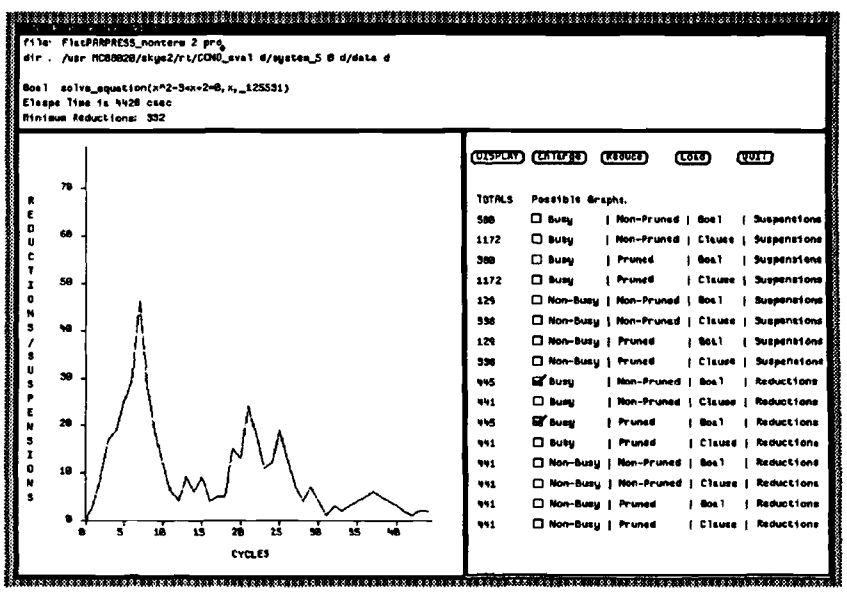
(**pruned** and **non-pruned** reductions)

Figure 7–12: Profile of PRESS1 using (terminating) **flat** guards



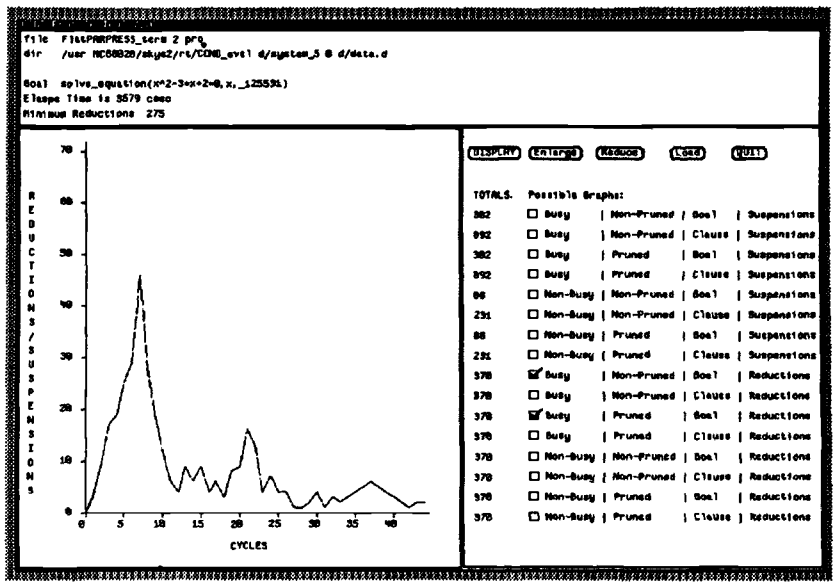
(**pruned** and **non-pruned** reductions)

Figure 7–13: Profile of PRESS2 using **deep** guards



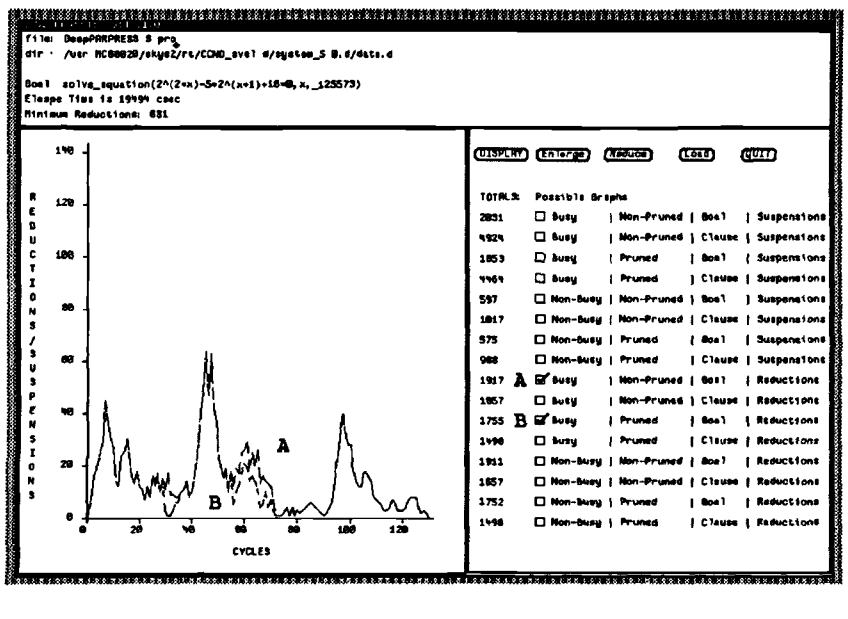
(**pruned** and **non-pruned** reductions)

Figure 7–14: Profile of PRESS2 using (non-terminating) **flat** guards



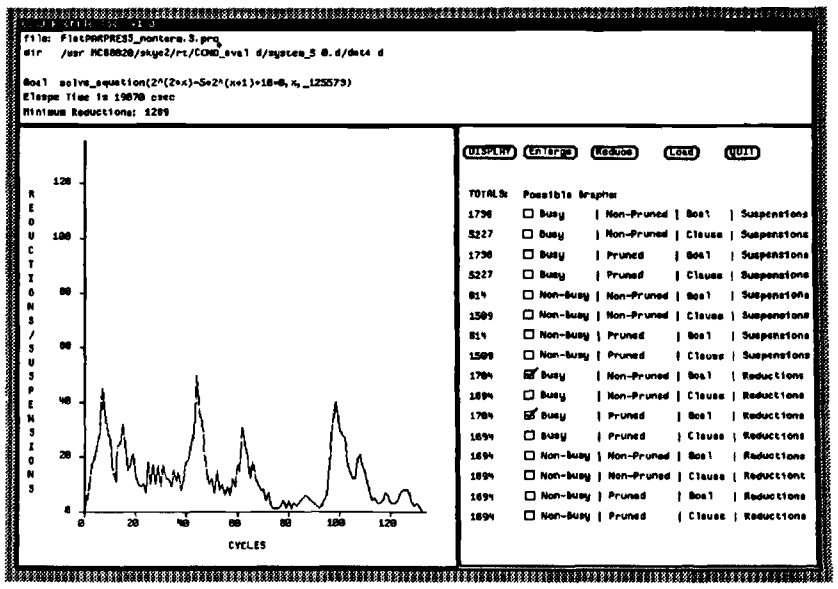
(**pruned** and **non-pruned** reductions)

Figure 7–15: Profile of PRESS2 using (terminating) **flat** guards



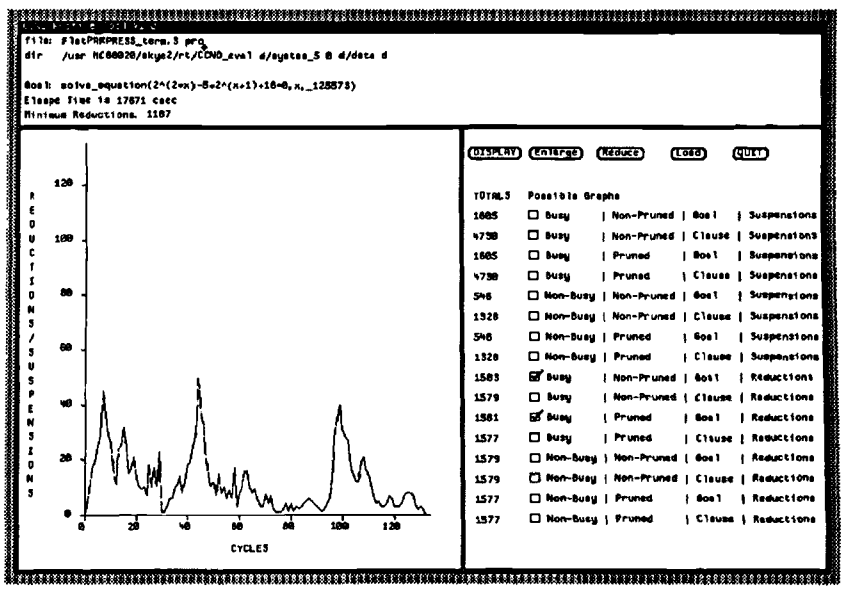
(**pruned** and **non-pruned** reductions)

Figure 7–16: Profile of PRESS3 using **deep** guards



(**pruned** and **non-pruned** reductions)

Figure 7–17: Profile of PRESS3 using (non-terminating) **flat** guards



(**pruned** and **non-pruned** reductions)

Figure 7–18: Profile of PRESS3 using (terminating) **flat** guards

- The previous interpreters employed **goal** suspension and **busy** waiting. The previous reduction counter is closest to our new reduction counter using **busy** waiting and **goal** suspension. *Table 7–4* compares the previous reduction counts with our new reduction counts.

Comparing previous and new reduction measures				
Query	Previous	New **Busy-Goal**	Difference	% Difference
Using deep guards				
PRESS1	142	988	846	596
PRESS2	79	435	356	451
PRESS3	284	1917	1633	575
Using non-terminating flat guards				
PRESS1	337	1032	695	306
PRESS2	140	445	305	318
PRESS3	564	1704	1140	302
Using terminating flat guards				
PRESS1	241	749	508	310
PRESS2	126	370	244	294
PRESS3	539	1583	1044	294

Table 7–4: Comparing previous and new reduction measures

Our new reduction count is higher than the previous count. Part of this difference can be attributed to system calls which are included as part of our reduction measures. The other effect, for **deep** guards, which compounds this difference is the modelling of OR-parallelism. The previous system attempts the clauses sequentially, committing to the first clause whose guard succeeds, whilst our system attempts each of the clauses and commits to the clauses with the shallowest guard evaluation. So the previous counter can only record reductions for those clauses attempted. Hence it may be the case that our new reduction counter is higher, especially if the clause committed to is textually near the top.

This view is substantiated by considering the actual percentage differences. For the **flat** PARPRESS the increase is a constant 300 %. For **deep** guards

the difference is greatest for **PRESS1** and **PRESS3** where the computation commits to the first-meta level axiom in solving the equation.

- The earlier interpreters counted only **goal** suspensions and used **busy** waiting, moreover some failed evaluations would be recorded as suspensions (see section 3.3). This previous counter is closest to our new suspension counters using **busy** waiting and **goal** suspension. *Table 7–5* compares the previous suspension counter with our new suspension counter.

Comparing previous and new suspension measures				
Query	Previous	New **Busy-Goal**	Difference	% Difference
Using deep guards				
PRESS1	99	1110	1011	1020
PRESS2	51	364	313	614
PRESS3	218	2031	1813	832
Using non-terminating flat guards				
PRESS1	213	1088	875	411
PRESS2	97	380	283	292
PRESS3	426	1736	1310	408
Using terminating flat guards				
PRESS1	162	816	654	404
PRESS2	90	302	212	336
PRESS3	416	1605	1189	386

Table 7–5: Comparing previous and new suspension measures

Our new suspension count is higher than the previous counter. There are several components to this increase. Firstly, we model parallel AND-parallelism (see sections 3.3.3 and 3.4), hence some AND-parallel goals suspend for additional cycles whilst bindings become available; either because **deep** guards are accounted for or because bindings are not generated as goals are processed. Secondly, we count the suspension of system calls. Finally, because we model parallel OR-parallelism, our suspension counter records the suspensions in each of the clauses not just the clauses attempted. This final point is reflected in the greatest increase in reductions occurring for the **PRESS1** and **PRESS3** examples using **deep** guards.

- *Table 7–6* compares the degree of parallelism *(reductions/cycles)* obtained using our system and the previous system. For this comparison we use our reduction parameter employing **goal** suspensions, **busy** waiting and **non-pruning**, as this is closest to the previous reduction counter.

Comparing previous and new measures for average parallelism						
	Previous			New **Busy-Goal**		
Query	Reductions	Cycles	Parallelism	Reductions	Cycles	Parallelism
Using deep guards						
PRESS1	99	30	3.3	988	87	11.4
PRESS2	51	17	3.0	435	40	10.9
PRESS3	218	41	5.1	1917	130	14.8
Using non-terminating flat guards						
PRESS1	213	42	5.1	1032	86	12.0
PRESS2	97	24	4.0	445	44	10.1
PRESS3	426	71	6.0	1704	132	12.9
Using terminating flat guards						
PRESS1	162	42	3.9	749	86	8.71
PRESS2	90	24	3.8	370	44	8.41
PRESS3	416	71	5.9	1583	132	12.0

Table 7–6: Comparing previous and new measures for average parallelism

There are two points to note from this comparison. Firstly, our results give higher measures for the average degree of parallelism. This is due to our system recording the work done in the evaluation of system calls. Secondly, comparing **deep** guards using **non-pruning** with non-terminating **flat** guards, we see that our results give more consistent figures for the average parallelism. This should be expected as the **flat** implementation is obtained by translating OR-parallelism into AND-parallelism. This is not true of the previous evaluation data.

We now carry out an analysis, based on our new results, of the various Parallel PARPRESS systems.

- For the **flat** PARPRESSes there is little or no difference in the reduction counts using **goal** and **clause** suspensions (see *Table 7–2*). As suspensions do occur, we can conclude that these take place on head unification before any reductions in the guard can be performed.

- For the **deep** PARPRESS we see that there is a noticeable difference (see *Table 7–2*) in reduction counts for the **PRESS3** example using **goal** and **clause** suspensions. To understand why there is a difference we must consider the evaluation of this example. The **PRESS3** example involves changing the unknown of the equation; the equation in the new unknown is solved and this solution is substituted back to give solutions to the original unknown. In **PRESS3** these three processes, change of unknown, solving for the new unknown and substituting back and solving, take place in parallel. The purpose in carrying out the three stages in parallel is that some precondition can fail on partially complete equations, so changing the unknown and solving the new equation may be more parallel. However, our results indicate that the preconditions perform some reductions and then suspend. So, if **goal** suspension is used these reductions will be repeated.

  Furthermore, the difference between **busy** and **non-busy** waiting indicates that these suspended meta-level preconditions only suspend once before they can be evaluated; the differences in reduction parameters, using the **busy** and **non-busy** waiting, is minimal.

- For the **flat** PARPRESSes there is little or no difference between the reduction and suspension parameters using **pruned** and **non-pruned** evaluations. On the other hand, for **DeepPARPRESS**, **pruning** saves some reductions and suspensions. This is because pruning **flat** guards can only be of limited benefit.

- If we now consider the benefit of **pruning DeepPARPRESS** we see that it differs for the various example queries. *Table 7–7* summarises the saving that can be obtained by **pruning deep** guards for **DeepPARPRESS**.

Comparing reductions pruned and non-pruned for DeepPARPRESS								
Busy waiting								
	Goal				Clause			
Query	non-pruned	pruned	saving	% saving	non-pruned	pruned	saving	% saving
PRESS1	988	675	313	32	983	673	310	32
PRESS2	435	339	96	22	433	339	94	22
PRESS3	1917	1755	162	8	1657	1498	159	3.5

(we only give this comparison for **busy** waiting because the reductions using **busy** and **non-busy** parameters are very similar).

Table 7–7: Comparing **pruned** and **non-pruned** reductions for DeepPARPRESS

Comparing **pruned** vs **non-pruned** reductions we note that **pruning** saves most reductions for the **PRESS1** query. This indicates that the successful precondition, when solving this query, succeeds much sooner than the other precondition takes to fail. The precondition to solving **PRESS1** is to check the equation is of the form $A \times B = 0$. For the **PRESS2** and **PRESS3** query the number of reductions saved is smaller. This indicates that the successful preconditions in solving these equations are more complex. In fact for **PRESS3**, **pruning** occurs twice, first in the precondition to solving the original equation (which is homogenisation) and again in solving the equation in a new unknown. These points are confirmed graphically in *Figures 7–10; 7–13;* and *7–16.*

Figure 7–10 shows that **pruning** can take place very quickly in solving **PRESS1**. *Figures 7–13* indicates that **pruning** for **PRESS2** occurs after some number of cycles. *Figure 7–16* shows that **pruning** occurs in two places in solving **PRESS3**.

- Our profiling parameters should reflect the benefit of **pruning** or **non-pruning** the computation. In terms of meta-level inference this reflects the amount of computation that will be saved in fully evaluating the preconditions once one succeeds. The two techniques employed in **flattening** PARPRESS also aim to highlight the benefit of terminating or not terminating the evaluation of the preconditions once one succeeds.

In fact our parameters using **pruning** for **DeepPARPRESS**, should be similar to the parameters for **FlatPARPRESS-term**, and our parameters using **non-pruning** for **DeepPARPRESS**, should be similar to the parameters for **FlatPARPRESS-nonterm**. *Table 7–8* compares the reduction parameters for **DeepPARPRESS** using **non-pruning** with **FlatPARPRESS-nonterm**. *Table 7–9* compares the reduction parameters for **DeepPARPRESS** using **pruning** with **FlatPARPRESS-term**. Both tables show a high correlation in the reduction counts for **deep** and **flat** systems.

Comparing reductions **DeepPARPRESS** non-pruning VS **FlatPARPRESS-nonterm**								
	Busy waiting				**Non-busy waiting**			
	Goal		**Clause**		**Goal**		**Clause**	
Query	deep	flat	deep	flat	deep	flat	deep	flat
PRESS1	988	1032	983	1022	983	1022	983	1022
PRESS2	435	445	433	441	433	441	433	441
PRESS3	1917	1704	1657	1694	1911	1694	1657	1694

Table 7–8: Comparing reductions: **deep** non-pruning and **flat**-nonterm

Table 7–10 compares the suspension parameters for **DeepPARPRESS** using **non-pruning** with **FlatPARPRESS-nonterm** and *Table 7–11* compares the suspension parameters for **DeepPARPRESS** using **pruning** with **FlatPARPRESS-term**.

Both tables show a high correlation in the suspension counts using **goal** suspensions. However, using **clause** suspension, the suspension count for **FlatPARPRESS-term** is always higher than the counter for **DeepPAR-**

Comparing reductions DeepPARPRESS pruning VS FlatPARPRESS-term								
	Busy waiting				Non-busy waiting			
	Goal		Clause		Goal		Clause	
Query	deep	flat	deep	flat	deep	flat	deep	flat
PRESS1	675	749	673	743	673	745	673	744
PRESS2	339	370	339	370	339	370	339	370
PRESS3	1755	1583	1498	1579	1752	1579	1498	1577

Table 7–9: Comparing reductions: **deep** pruning and **flat** terminating

Comparing suspensions DeepPARPRESS non-pruning VS FlatPARPRESS-nonterm								
	Busy waiting				Non-busy waiting			
	Goal		Clause		Goal		Clause	
Query	deep	flat	deep	flat	deep	flat	deep	flat
PRESS1	1110	1088	1862	2957	413	409	650	953
PRESS2	364	380	760	1172	136	126	236	338
PRESS3	2031	1736	4924	5227	597	614	1017	1509

Table 7–10: Comparing suspensions: **deep** non-pruning and **flat**-nonterm

PRESS. This is because each **flat** predicate called as part of the meta-level precondition requires one extra clause to support the possible termination message required for terminating the evaluation of the other preconditions[1].

[1]This need not be true of **FlatPARPRESS-nonterm** as it does not terminate the precondition evaluation. However, we use the same **flat** functions for both **FlatPARPRESSes** and only send the terminate message in **FlatPARPRESS-term**.

Comparing suspensions DeepPARPRESS pruning VS FlatPARPRESS-term								
	Busy waiting				Non-busy waiting			
	Goal		Clause		Goal		Clause	
Query	deep	flat	deep	flat	deep	flat	deep	flat
PRESS1	837	816	1338	2034	292	286	441	643
PRESS2	265	302	513	892	89	86	140	231
PRESS3	1853	1605	4464	4730	575	546	968	1328

Table 7–11: Comparing suspensions: **deep** pruning and **flat** terminating

- Comparing the minimum reductions to the actual reductions gives a measure of the OR-parallelism (see section 4.3.4). As we have already noted there is little or no difference in the reduction counts for either of the **FlatPARPRESSes** so we choose to use the reduction count using **non-busy** waiting, **non-pruned** guards and **clause** suspensions to obtain a measure for the OR-parallelism. For **DeepPARPRESS** we require two reduction parameters: **pruned** and **non-pruned**. *Table 7–12* summarises the degree of OR-parallelism for the various Parallel PRESSes.

OR-parallelism			
Query	Reductions	Minimum Reductions	OR-parallelism
DeepPARPRESS: non-pruned reduction			
PRESS1	333	988	2.97
PRESS2	159	435	2.74
PRESS3	631	1917	3.04
DeepPARPRESS: pruned reduction			
PRESS1	333	675	2.03
PRESS2	159	339	2.13
PRESS3	631	1755	2.78
FlatPARPRESS-nonterm			
PRESS1	802	1022	1.27
PRESS2	332	441	1.33
PRESS3	1289	1694	1.31
FlatPARPRESS-term			
PRESS1	574	745	1.30
PRESS2	275	370	1.35
PRESS3	1187	1579	1.33

Table 7–12: Degree of OR-parallelism for Parallel PRESSes

As expected **DeepPARPRESS** not using **non-pruning** exhibits the most OR-parallelism; as the OR-search is not terminated. This is closely followed by **DeepPARPRESS** using **pruning**. Both **FlatPARPRESS-term** and **FlatPARPRESS-nonterm** exhibit minimal OR-parallelism; this is not surprising as **flattening** involves translating OR-parallel search into AND-parallel search.

- As we give a cycle by cycle profile of our evaluation parameters we are able to see the maximum number of reductions and suspensions in a cycle using a given execution model. *Table 7–13* summarises the maximum number of reductions that can be performed in a given cycle, some of this information is given graphically in *Figures 7–10* to *7–18*. As with obtaining measures for OR-parallelism (see *Table 7–12*) we only use a subset of the reduction parameters: **FlatPARPRESSes** using **non-busy non-pruned** and **clause** suspensions; and for **DeepPARPRESS** we use two parameters, **pruned** and **non-pruned**.

Maximum number of reductions in a given cycle		
Query	Max reduction	Cycle number
DeepPARPRESS: non-pruned reduction		
PRESS1	44	7
PRESS2	46	7
PRESS3	64	45
DeepPARPRESS: pruned reduction		
PRESS1	33	35
PRESS2	46	7
PRESS3	64	45
FlatPARPRESS-nonterm		
PRESS1	37	8
PRESS2	46	7
PRESS3	50	44
FlatPARPRESS-term		
PRESS1	35	34
PRESS2	46	7
PRESS3	50	44

Table 7–13: Maximum reductions in a given cycle for Parallel PRESSes

There are two points to note from this table. Firstly, there is a difference in maximum number of reductions for the **PRESS1** example using **pruning** and **non-pruning**. If **pruning** is employed then some evaluation of the other preconditions can be prevented. Secondly, there is a strong correlation in the maxima for **DeepPARPRESS** using **non-pruning** and **FlatPARPRESS-nonterm** and **DeepPARPRESS** using **pruning** and

FlatPARPRESS-term. This agrees with the general comparison of reductions given in *Tables 7–8* and *7–9*.

- *Table 7–14* summarises the maximum number of suspensions that can occur in a given cycle. As with the reduction tables, *Table 7–8, 7–9* and *7–13*, we present **pruned** and **non-pruned** data for **DeepPARPRESS** and only **non-pruned** for the **FlatPARPRESSes**. This information provides an indication of the maximum size of the various suspension queues that will be needed for the different suspension mechanisms and scheduling policies, this is given by the **busy** waiting suspension parameters. It also indicates the maximum number of suspensions that will occur in a cycle. This is given by the **non-busy** waiting suspension parameters.

Maximum number of suspensions in a given cycle								
	Busy waiting				Non-busy waiting			
	Goal		Clause		Goal		Clause	
Query	Max	Cycle	Max	Cycle	Max	Cycle	Max	Cycle
DeepPARPRESS: non-pruned								
PRESS1	43	10	53	18	22	10	39	10
PRESS2	24	18	50	20	14	18	25	18
PRESS3	53	64	142	64	21	12	38	12
DeepPARPRESS: pruned								
PRESS1	28	44	49	44	18	42	28	42
PRESS2	24	8	37	8	13	6	20	6
PRESS3	47	46	135	47	21	12	38	12
FlatPARPRESS-nonterm								
PRESS1	41	11	110	11	24	11	53	11
PRESS2	29	24	78	24	17	24	36	24
PRESS3	39	15	134	15	21	12	49	12
FlatPARPRESS-term								
PRESS1	26	43	66	43	14	43	30	43
PRESS2	23	8	71	8	12	6	32	6
PRESS3	39	15	134	15	21	12	49	12

Table 7–14: Maximum suspensions in a given cycle for Parallel PRESSes

As with the maximum reductions, given in *Table 7–13*, this table shows a high correlation in maxima for **DeepPARPRESS** using **non-pruning** and

FlatPARPRESS-nonterm and **DeepPARPRESS** using **pruning** and **FlatPARPRESS-term**.

- The difference between suspensions using **goal** and **clause** suspension mechanisms highlights the number of clauses that each goal could be reduced by in the dynamic query (see section 4.5.3.1). *Table 7–15* summarises the ratio of **clause** to **goal** suspensions using **busy** and **non-busy** waiting scheduling for **DeepPARPRESS**, using **pruned** and **non-pruned** models and **FlatPARPRESS-nonterm** and **FlatPARPRESS-term**.

	Busy waiting			Non-busy waiting		
Query	Goal	Clause	Ratio	Goal	Clause	Ratio
DeepPARPRESS: non-pruned						
PRESS1	1110	1862	1.68	413	650	1.57
PRESS2	364	760	2.09	136	236	1.74
PRESS3	2031	4924	2.42	597	1017	1.70
DeepPARPRESS: pruned						
PRESS1	837	1338	1.60	292	441	1.51
PRESS2	265	513	1.94	86	140	1.63
PRESS3	1853	4464	2.41	575	968	1.68
FlatPARPRESS-nonterm						
PRESS1	1088	2953	2.71	409	953	2.33
PRESS2	380	1172	3.08	129	338	2.60
PRESS3	1736	5227	3.01	614	1509	2.45
FlatPARPRESS-term						
PRESS1	819	2034	2.48	286	643	2.24
PRESS2	302	892	2.95	86	231	2.68
PRESS3	1605	4730	2.95	546	1328	2.43

Table 7–15: Clause/Goal suspension ratios for Parallel PRESSes

The only point to note is that the **flattened** code incurs a high **clause** to **goal** suspension ratio. This is because additional clauses are required to support the termination of those goals in the conjunction, which are essentially performing the guarded search.

- The difference between **busy** waiting and **non-busy** waiting suspensions indicates the benefit of tagging suspended executions to variables (see *section*

4.2.2). It also indicates how long suspended executions remain suspended. *Table 7–16* summarises the ratios of **busy** and **non-busy** waiting suspension using **goal** and **clause** suspension mechanisms, for **DeepPARPRESS** using **pruned** and **non-pruned** models, **FlatPARPRESS-nonterm** and **FlatPARPRESS-term**.

Program	Goal suspension			Clause suspension		
	Busy	Non-busy	Ratio	Busy	Non-busy	Ratio
DeepPARPRESS: non-pruned						
PRESS1	1110	413	2.69	1862	650	2.86
PRESS2	364	136	2.68	760	236	3.22
PRESS3	2031	597	3.40	4924	1017	4.84
DeepPARPRESS: pruned						
PRESS1	837	292	2.87	1338	441	3.03
PRESS2	265	86	3.08	513	140	3.66
PRESS3	1853	575	3.22	4464	968	4.61
FlatPARPRESS-nonterm						
PRESS1	1088	409	2.66	2953	953	3.10
PRESS2	380	129	2.95	1172	338	3.47
PRESS3	1736	614	2.83	5227	1509	3.46
FlatPARPRESS-term						
PRESS1	819	286	2.86	2034	643	3.16
PRESS2	302	86	3.51	892	231	3.86
PRESS3	1605	546	2.94	4730	1328	3.56

Table 7–16: Busy/Non-busy suspension ratios for Parallel PRESSes

There are two points to note from this data. Firstly, for the **FlatPARPRESS** most processes suspend for about 3 cycles on average. Secondly, for **DeepPARPRESS**, **PRESS1** and **PRESS2** also result in evaluations suspending for about 3 cycles. However, for **PRESS3**, suspended **clause** evaluations suspend for about 4.75 cycles. It is difficult to reason about exactly what is happening in this final comparison. It is known that the **PRESS3** example has a **deep** guarded consumer process (the preconditions) which suspend. In such circumstances our system is known to give an exaggerated value for **clause** suspensions using **busy** waiting (see section 4.6).

7.8 Synopsis of analysis

In this section we consolidate some of the results given in our analysis.

- Our re-evaluation of the Parallel PRESS systems gives similar raw data to that given in [Sterling & Codish 87]. However, we feel that their analysis of this data is mis-leading and incomplete. We re-analyse the raw data, the basic **cycle**, **reductions** and **suspensions**. The evaluation is enhanced by the fact that we consider **flat** implementations which employ termination and do not employ termination of the meta-level precondition.

- We then present our new measurements and perform an in depth analysis of this data. Our new data indicates the benefits in using **pruning** if *deep* guards are employed.

- The data for the **DeepPARPRESS** evaluation strongly indicates the saving in both reductions and suspensions if the **flat** implementations employ termination techniques.

- The results also show that the overall parallelism remains unchanged for **deep** and **flat** implementations. Whilst the contribution of AND and OR-parallelism vary for the **deep** and **flat** implementations, the **flat** implementations have little or no OR-parallelism.

- It is worth noting that our model for including the contribution of **deep** guards into the overall evaluation appears reasonable, *e.g.* the overall cycle measures for the evaluations are similar for the various Parallel PRESS systems.

- Using **deep** guards is more natural for the meta-level of PRESS where preconditions for a given meta-rule become user defined guarded goals. In

flattening the meta-level of PRESS, or for that matter any code with **deep** guards, various alternatives techniques can be applied. The simplest and most basic is to translate each precondition, the guard, into an AND-goal. If the precondition succeeds a continuation flag is set and the solution method selected is committed to. An alternative and more complex translation is to generate **flat** code which employs early termination. The evaluation of the alternative meta-rule preconditions can be terminated as soon as one precondition succeeds rather than being fully evaluated. This enhancement is applicable if the amount of computation that can be prevented by early termination is significant. This is where there is a dilemma - how do we know how much computation can be saved if we do not translate the code to both terminating and non-terminating **flat** code?

The use of the profiletool in this context is very informative. Our results indicate that there is a very strong correlation between the results for the **deep** guarded version when executing without **pruning** and the **flat** guarded version not employing termination and the **deep** guarded version when executing with **pruning** and the **flat** guarded version employing termination. So, by first implementing the more natural **deep** guarded version and then using the profiletool we are able to select the most appropriate **flattening** technique.

7.9 Summary

In this chapter the following have been presented and discussed:

- PRESS - a PRolog Equation Solving System and how it provides a set of meta-level axioms for solving symbolic equation.
- How the meta-level axioms of PRESS can be realised in terms of Prolog clauses, known as meta-rules.

- How these meta-rules can be directly mapped into CCND languages which allow **deep** guards.

- How the **deep** guarded version of PRESS can be **flattened**. The resulting **flat** code can either terminate the evaluation of the other meta-rules should one rule succeed or allow all the rules to execute to completion.

- The re-evaluation of these Parallel PRESSes on both the basic evaluation system and our new system. The results indicate that:

  - our system provides a more accurate picture of the execution of the parallel PRESSes;
  - our system also allows us to consider the benefits of the various translation options between **deep** and **flat** code by analysing the behaviour of the **deep** implementation;
  - it is worth employing **pruning** in the implementation of the system to evaluate PRESS using **deep** guards; and
  - it is worth the programmer employing termination techniques in the mapping of the meta-level of PRESS to **flat** guards.

Chapter 8

Conclusions

8.1 Overall Contribution of the Thesis

In this thesis, the following contributions are made to the task of understanding and evaluating the execution behaviour of the CCND languages with regard to AI applications:

- We develop a model of execution which allows us to obtain measures for the inherent parallelism available in the evaluation of CCND programs.

- The evaluation system developed also allows us to observe the effects of varying several implementation parameters, such as the suspension mechanism, the scheduling of suspended evaluations and the pruning (termination) of competing guarded evaluations on commitment.

- We then focus on three aspects of these languages - how they support search, the benefits in using **safe** or **unsafe** languages and the benefits in using **deep** or **flat** guards. These reflect questions about how these languages should be used and implemented.

- We test these aspects of the languages by choosing AI type applications which we have implemented across the various language classifications. These various systems are evaluated and the results analysed.

- The study shows the significant improvement our evaluation system gives in terms of both measuring the inherent features of the algorithm and understanding the dynamic behaviour of the execution.

- Our analysis of AI applications highlights several interesting points relating to the behaviour of programs which make use of given language features. These points are summarised in the following sections.

8.1.1 Inherent parallelism

The CCND languages provide a model of computation which supports both limited OR-parallelism and concurrent goal evaluation. In this work we consider the inherent parallelism that is available in the evaluation of programs implemented in the CCND languages. A measure of the inherent parallelism provides a theoretical measure of the parallelism against which particular implementations can be gauged. Without a theoretical measure it is difficult to consider the actual performance improvements of various implementations. The inherent parallelism also provides information for programmers on the relative merits of various programming techniques regardless of the particular implementation. Finally a theoretical model of the parallel execution of these languages allows implementors of the languages to consider the possible benefits of alternative implementation issues like suspensions, pruning and scheduling.

To obtain a measure of the inherent parallelism available in program execution we adopt a breadth-first execution model on an unlimited number of processors. Previous systems used for evaluating and comparing programming techniques and applications suffer from two main limitations. The first is that the parameters quoted in the evaluations of a program do not reflect possible alternatives open

to language implementors, like scheduling policy. The second is that although these interpreters claimed to execute the object code (CCND program) breadth-first (hence allowing the inherent parallel features to be measured) the actual evaluation models used make several approximations. This results in misleading and distorted measurements.

In this work we have considered the measurements that should be collected to capture the nature of a CCND computation. The new system comprises two stages: an AND/OR-interpreter, which evaluates the program breadth-first producing a dump file and an analyser program which reconstructs a parallel view of the program execution. The statistics obtained are more accurate in two respects. The first is in the modelling of a parallel AND/OR execution, this allows us to measure the inherent parallel features of our algorithm. The second is in identifying the nature of the execution: **pruned** or **non-pruned** guard evaluations; **busy** or **non-busy** waiting; and **goal** or **clause** suspension.

8.1.2 Search - committed choice

The CCND languages are committed choice, as such they cannot be used to directly implement general search algorithms. To carry out search in these languages requires some means of translating the non-determinism in the search algorithm into a deterministic algorithm.

We evaluate three models for translating search algorithms into deterministic algorithms:

- Continuation based compilation;
- Stream based compilation; and
- Layered streams.

These three techniques were chosen because they had already been evaluated on an earlier evaluation system [Okumura & Matsumoto 87]. We revaluate the n-queens

example for 4-queens and 6-queens using our basic Parlog interpreter. The results obtained agree with the previous evaluations.

We then re-evaluate the 4-queens and 6-queens on our new evaluation system. The results given by our system differ in several respects to those obtained on our basic Parlog interpreter. Our analysis of the results highlights how our evaluation gives a picture of the program behaviour and the relative merits of the various programming techniques.

Previous results for the all-solutions programming techniques indicated that Layered Streams required only half the reductions that Continuation based compilation required. Also the results highlighted the greater increase in the available parallelism for large problems using Layered streams. This is due to solutions being generated bottom-up and hence large problems tend to have more parallelism if explored bottom-up.

Our re-evaluation gives a slightly different picture. Layered Streams does require less reductions than Continuation based compilation but the difference is only 5%. Layered streams also results in the continual exploration of incomplete solutions, ie. incomplete solutions are continually tested against each incrementation in the generation of the solution. For larger problems this over generation may result in more reductions being performed for Layered Streams. So, our results show that Layered Streams is not as good as was previously supposed. However, the overall number of cycles required for Layered Streams is considerably less than for either of the other two methods, so this technique is the most inherently parallel.

8.1.3 Shared data structures - safe/unsafe

The question of how shared data structures are supported in the CCND languages is an important one for AI. Several current AI paradigms which require several different forms of expertise, like blackboard systems, require a common communi-

cation medium which each expert can see and update. Also, parallelising existing sequential algorithms often results in several solvers performing similar tasks on different parts of the same data; this is particularly the case if the parallelisation involves replacing a sequential control mechanism like a scheduler for parallel functioning solvers, as in parallelising a chart parser.

Whilst all the CCND languages and their subsets allow several processes to read the same data structure; *one-to-many* communication, it has been noted by several researchers that only **unsafe** languages directly support *many-to-one* communication on a single variable; several writers to the same data. Whilst the **safe** languages cannot directly support *many-to-one* type communication, one important case of multiple writers, multiple writers to a stream, can be modelled by the use of merge processes. Each *writer* that wishes to update some shared stream, binds a local stream. The local streams for each *writer* are then merged together to form the final shared stream.

The general use of multiple writers to any structure, not just a stream, can be then indirectly supported by creating a process which manages the structure. Multiple processes that wish to write to the structure make write requests to this manager process. The write requests from the writer processes are merged together to form a request stream. This technique has been used in several applications which require multiple writers to a shared resource [Davison 87] [Trehan & Wilk 88]. The general feature of this use of streams is to combine requests from many sources to one final stream, which we call the *resultant stream.*

System extensions to support *resultant streams* have been considered by us and other researchers. If the system knows that a given variable, or list, is a *resultant stream* it can keep a pointer to its tail, which can be used to add elements to this stream in unit time. We consider two basic primitives: the first identifies a stream as a *resultant stream*; the second directly adds an element to this *resultant stream.* The stream addition primitive has to be atomic.

We have implemented several chart parsers using three styles of language: **safe**;

unsafe; and **safe+system streams** (where the *resultant stream* is supported by the system). The chart parsers allow several processes which pick different active edges from the AET (active edge table), process them in parallel, and update the chart (records of the active edges undertakes and the parses found) by adding any new active edges to the AET and any sub-strings to the WFST (parses found). The approach requires that testing if an active edge is new and its addition to the AET to be an atomic step. In an **unsafe** language the shared data structure, the chart, can be directly supported. In a **safe** language the shared data structure, the chart, can only be supported by a manager process and writer processes which make requests for updates. The basic mechanism employed by the manager is "sifting" which is a generalisation of a prime number generator program. In the **safe+system streams** language the shared data structure, the chart, must also be supported by a manager process. Writer processes make update requests to this manager. However, unlike in a pure **safe** language, these requests need not make explicit use of merge processes as streams are supported by the system.

Our evaluation of these chart parsers indicates that:

- there are significant overheads introduced by networks of merge processes, in the **safe** languages;

- the **unsafe** languages also introduce some delays in supporting shared data, in that the data structure has to be traversed to find the next free position, in the case of shared streams the unbound tail;

- the dynamic behaviour of the manipulation of shared data structures depends on which processes access the data, when they access the data and how often they access the data;

- in the chart parsers the dynamic considerations result in the difference, in terms of cycles, between **unsafe** and **safe** chart parsers not being as high as first expected;

- there are benefits from supporting multiple writers to a stream by the system, in terms of suspension overheads, available parallelism and total number of cycles required.

8.1.4 Meta-level inference - deep/flat

The question of whether guards should be **deep** (any user defined goals are allowed in the guards) or **flat** (only system calls are allowed in the guards), is interesting and controversial. **Deep** guards appear to be more expressive and **flat** guards more efficiently implemented. One proposal to get the best from both worlds is to write **deep** guarded code and then have this code translated to **flat** code which is executed. In the translation from **deep** to **flat** code there are several alternative models that can be employed. For example, should the **flattened** code be correct or should it also mimic possible efficiency options open to **deep** guarded evaluations, like that of **pruning** guarded evaluations on the commitment to one clause.

To compare **deep** guards with **flat** guards and the possible effects of mimicing **pruning** we consider the behaviour of a program implemented using several different flavours of language. The application considered is known as PRESS - a Prolog Equation Solving System. A subset of this system was initially translated to Concurrent Prolog and FCP in [Sterling & Codish 87] the resulting system being known as CONPRESS. We take their basic translation and reconstruct it for Parlog, which results in PARPRESS. The translation to Parlog is essentially the same as the translation to Concurrent Prolog. The translation of PARPRESS into **flat** code required us to adopt slightly different translation techniques [Gregory 87].

As a result we have several Parallel PRESS systems which we could have evaluated and we chose to consider one aspect of PRESS and meta-level inference. This is how the execution of the meta-level differs using **deep** and **flat** guards, where the **flat** meta-levels may or may not employ termination techniques. The systems evaluated are:

DeepPARPRESS - Parallel PRESS implemented in Parlog, employing **deep** guards just for the meta-level axioms;

FlatPARPRESS-nonterm - Parallel PRESS implemented in Parlog, employing **flat** guards. On successful termination of one of the preconditions (to a meta-level axiom) the other preconditions are not terminated.

FlatPARPRESS-term - Parallel PRESS implemented in Parlog, employing **flat** guards. On successful termination of one of the preconditions (to a meta-level axiom) the other preconditions are terminated.

Our new evaluation indicates the benefits in using **pruning** if **deep** guards are employed. Moreover, the data for the **DeepPARPRESS** evaluation strongly indicates the saving in both reductions and suspensions if the **flat** implementations employ termination techniques.

The results also show that the overall parallelism remains unchanged for **deep** and **flat** implementations. Whilst the contribution of AND and OR-parallelism varies for the **deep** and **flat** implementations, the **flat** implementations have little or no OR-parallelism.

Finally, it is worth noting that our model for including the contribution of **deep** guards into the overall evaluation appears reasonable, *e.g.* the overall cycle measures for the evaluations are similar for the various Parallel PRESS systems.

8.1.5 Summary of Contribution

In this section we summarise the contribution of this work. The main contribution of this work can be classed in two ways. Firstly in the approach. This work aims to present an applications viewpoint of the possible direction that the CCND implementors may take. To this end we have implemented an improved interpreter for collecting more meaningful information; proposed and collect an improved set of profiling parameters, which reflect the effect of alternative model of execution and

and developed several applications which allow us to compare language features. Secondly the actual results of our evaluations. The three different application areas and language features investigated in this work provide a large number of interesting points for both users of these languages as well as language implementors. The following points aim to provide some general messages that result from this work:

- Language design and execution models has been governed by implementation considerations. The resulting languages appear to have **flat** guards and adopt **non-busy** waiting scheduling policy. There is still some discussion on whether the languages should be **safe** or **unsafe**. Our work aims to place some applications rationale for the design of language features and their usage. Applications input is important because the classes of application that language implementors aim to support and the models of execution that they provide make not be those required by applications programmers.

  For example, the results for our evaluation of Layered Streams indicates that this programming technique could employ a **busy** waiting scheduling policy. **Busy** waiting scheduling policy is easier to implement than **non-busy** waiting. However, most implementations do not offer **busy** waiting scheduling as it is assumed not to be applicable for real programs.

- Other language features, or rather additions, being provided by implementors, like supporting streams in the system results in more efficient programs because the heavy overhead in maintaining and using merge processes is alleviated. Our results indicate that while the programs that use systems streams may be less declarative the programs tend to have more predictable behaviours. Because the exact structure of the merge network, for **safe** languages, or the manipulation of a shared data structure, for **unsafe** languages, is not an issue if additions to the shared streams are supported by the system. So, the behaviour of an application is not dependent on how the

worker processes are interconnected by merge processes, but rather on the global behaviour of the worker processes.

- Finally, we note the use of tools, like our profiletool, can provide a great deal of insight into the dynamic properties of an application program. Such insight is useful if a programmer intends to modify or improve their program. For example, **deep** guards are easier to use for certain algorithms. However, implementations are unlikely to offer such language features. This will require translating to **flat** code, or using **flat** guards in the first place. There are many alternative options in mimicking the partial search capabilities of **deep** guards in a **flat** system. For example, the benefits of using a technique which not only produce correct code but also allows the early termination may be limited. Our profiletool provides such information without having to translate to **flat** code.

8.2 Research assumptions

This work is limited to some extent by the idealisations made, a large number of which give directions for future work. These come in several classes:

- Those associated with the evaluation system.
- Those associated with the applications chosen.
- Those associated with our evaluations.
- Those associated with this general approach.

8.2.1 The evaluation system

We adopt a fixed cost model, that is the various components of the evaluation, like head unification, have been assigned fixed costs (in terms of cycles). However,

the actual costs of a given operation may depend on several factors, eg. the cost of a head unification will depend on the number of arguments and the complexity of these arguments. It would be better to adopt a functional cost model, where the cost of an operation is calculated based on its complexity.

We assume that, in a cycle, a goal can only use bindings available to it at the start of the cycle. This is an improvement over the previous interpreters, in modelling the inherent parallelism, a fully accurate model would be able to determine exactly when a goal makes a binding, how long it would take for this binding to reach another goal and whether this would be in time for the goal to use it in the current cycle.

Although we are able to vary several parameters in our evaluation system to reflect different implementation alternatives we do not consider the effects of a finite number of processors and the resulting scheduling issues like bounded depth first-search. Our focus from the start has been to provide measures of the inherent parallelism which we obtain by using an infinite processor model. Simulating the evaluation on a finite processor model would have been relatively straightforward for **flat** code, but is non-trivial for **deep** guarded evaluation.

There are several questions that our system is not designed to answer, for example the following questions relating to memory usage:

- the relative costs of the different suspension mechanisms (**goal** and **clause**);
- the overhead in creating tag suspension lists to support **non-busy** waiting;
- the different data types (temporary variables; streams, state holding, etc.) and their frequency of occurrence.

We are sure there are countless other limitations in this method of obtaining a measure of the inherent parallelism. However, we feel that there is a significant improvement in our evaluation system over the original and currently widely used evaluation systems.

8.2.2 The applications

In evaluating these languages for AI type processing we could only hope to open a "can of worms" rather than answer all the questions relating to the behaviour of AI programs and Concurrent Logic Languages. We have tried to motivate our choice of applications and programming technique to answer questions which relate to the design and possible implementation of these languages. However, such knowledge really comes not from one set of example programs but from the analysis of many programs which then allow the generic features to be distilled. We do not intend to, or attempt to, provide a list of possible extensions to our existing applications or propose other suitable applications which would either enhance or complicate the conclusions we draw in this thesis.

8.2.3 The evaluations

The evaluations performed using the raw data extracted by our system tend to be complex exercises. There are main two limitations we wish to note:

- We do not give a step by step guide to the analysis of raw data. In our evaluations we compare a given parameter with another to get a measure of a particular property of the execution. For example, **reductions** and **cycles** gives average parallelism. However, in some cases we perform an in depth comparison, eg. comparing all the **busy** waiting parameters with all the **non-busy** parameters and other times we do not, as we can see that there is no difference in the individual counters. The outcome is that although we are able to perform this analysis the skill has not been abstracted.

- Secondly, we only compare total figures for given parameters rather than the profile curves. It is possible to obtain measures of the correlation between two curves or the scaling factor that will produce the best coefficient of correlation. This is likely to be more conclusive than just comparing totals and would be more akin to the interactive use of the profiletool.

8.2.4 The approach

Finally, we should also question this approach to evaluating these languages and in particular the emphasis on AI applications and programming techniques. Several questions spring to mind:

- Are AI applications and programming techniques any different from conventional programs as far as the CCND languages are concerned? If not, then we could just analyse conventional programs, possibly even theoretically, and then apply the results to executing all programs. There is no fixed answer to this question, unless you have a vested interest in the outcome. We do however feel that the demands made on current computer architecture and languages by AI applications are a good indication that there are likely to be differences between executing a CCND language as a conventional programming language (*e.g.* for system programming) and as an AI language, (*e.g.* to support co-operating problem solvers).

- Does the inherent parallelism as measured by our system really provide any useful information about the execution of the programs on real multiprocessor architectures? Again this question is difficult to answer. The only justified statement we can make is that it appears to be an improvement over the previous systems being used to compare the executions of applications and programming techniques. We have carefully tried to mimic the execution of these languages on an infinite number of processors and we attempt to consider different implementation alternatives.

- Finally, the programs evaluated attempt to focus on given features of the languages, providing a means to consider the benefits of these feature for programmers and the possible implementation of these features for language implementors. It could be claimed that the approach taken does neither, as the programs were implemented to highlight the differences that we drew conclusions about. It may have been more appropriate to just implement

and evaluate programs and only then draw conclusions on the effects of the various features used in the programs and the resulting execution behaviour. The problem with this approach is that it is not scientific, as the search space of application areas is vast, and on drawing conclusions the classic "what if" questions arises; that is "what if I had implemented this program like this"?

8.3 Future work

There are many directions for future work that are either extensions of our work or should complement our work.

- The evaluation could be enhanced by adopting a functional, rather than fixed, cost model, although an elaborate model of cost would tend to be to be implementation dependent.

- Additional measures could be considered, for example memory usage for the various suspension mechanisms.

- The interpreter could be extended to consider the effects of a finite number of processors and the resulting scheduling issues.

- An extended evaluation tool could be implemented that performed the various alternative analysis of the raw data and helped spot particular patterns in the results.

- Finally, further applications could be considered. This would eventually allow more generic features of applications to be abstracted away from the specific results that can only be obtained for a small number of applications.

- The correlation of our results with measurements obtained from parallel implementations.

- The analysis of AI programs and languages is an important area if we are to better support AI applications in terms of hardware and software.

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Part IV

Appendices

Appendix A

Effect of alternative execution models

In this appendix we consider the alterntaive evaluations of the program and query in *figure 4–1*.

A.1 Busy waiting, non-pruning, goal suspension

Here the execution model is: suspended evaluations are immediately rescheduled for evaluation; on commitment to one clause the other OR-clauses are not terminated; and the suspension of an evaluation involves suspending the parent goal.

We now consider the evaluation of the two query goals given in *figure 4–1*:

goal 1: This goal (`on_either(a,[1,2,3,a,b],[1,2,a,b],Output)`) evaluation results in two sets of guarded systems, `member(a,[1,2,3,a,b])` and `member(a,[1,2,a,b])`. The first of these will require 8 reductions to reduce to `true`; that is the guard test takes 1 reduction for each element and the

commitment another [1]. Similarly the second (guard) `member(a,[1,2,a,b])` goal requires 6 reductions.

As this execution model uses **non-pruning** both these guards will be evaluated fully. So, the total number of reductions performed in the evaluation of this goal is 16 (8 in evaluating the first guard, 6 in the second guard, 1 for the commitment to the body goals and finally 1 for the output unification).

The total number of cycles that this evaluation takes is 4. That is the evaluation commits to the second, `on_either/4`, clause after 3 cycles and it takes 1 cycle to carry out the output unification. So the binding made to the shared variable "`Output`" will be seen by the other AND-parallel goals in cycle 5.

goal 2: The second goal (`on_either(b,Output,[1|Output],Output1)`) evaluation results in two sets of guarded goals, `member(b,Output)` and `member(b,[1|Output])`. The first of these could be evaluated via two clauses, however these both suspend on head unification. As we are using **goal** suspension the evaluation of the first guarded goal suspends. The second (guard) is able to perform 2 reductions (the guard test and the commitment to `member(b,Output)`). The resulting goal could be evaluated via two clauses but both of these suspend on head unification. This results in the suspension of the second guarded goal. Now both sets of guarded goals have suspended the evaluation of the second query goal suspends, giving a total of 3 goal suspensions and 2 reductions. The second query goal suspends after 2 cycles.

Using **busy** waiting this top-level goal will be retried in cycle 3. In cycle 3 the variable "`Output`" will still be unbound, so the rescheduled evaluation

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[1] This is because we count system calls as reductions, see section 3.5.

will perform the same 2 reductions and then suspend again. The goal will next be tried in cycle 5.

In cycle 5 the shared variable "`Output`" will be bound, so the second query goal becomes `on_either(b,[1,2,a,b],[1,1,2,a,b],Output1)`. This goal invokes two guarded systems, `member(b,[1,2,a,b])` and `member(b,[1,1,2,a,b])`. The first of these will require 8 reductions to reduce to `true`. Similarly the second guard requires 10 reductions.

As the execution uses **non-pruning** both these guards will be evaluated fully. Hence the final attempt at evaluating this goal results in 20 reductions (8 in the first guard, 10 in the second, 1 for the commitment to the body goals and finally 1 for the output unification). The total number of cycles that this evaluation takes is 5. That is the evaluation commits to the first OR-clause after 4 cycles and it takes 1 cycle to carry out the output unification.

So, the evaluation of the query using this execution model takes: 10 cycles; 40 reductions (16 for the first goal, 4 for the second goal before suspension, and 20 for the final evaluation of the second goal); 6 goal suspensions (1 suspension for the first guarded goal, `member(b,L)`, 1 suspension for the second guarded goal, `member(b,[1|L])`, and 1 suspension for the query goal, these suspensions occur twice because of the **busy** waiting).

A.2 Busy waiting, non-pruning, clause suspension

Here the execution model is: suspended evaluations are immediately rescheduled for evaluation; on commitment to one clause the other OR-clauses are not terminated; and the suspension of an evaluation involves suspending the clauses.

We now consider the evaluation of the two query goals given in *figure 4–1*:

goal 1: The evaluation of this goal will be as given in section A.1, as this goal evaluation incurs no suspensions and so an alternative suspension mechanism makes no difference.

goal 2: The evaluation of the second goal results in two guarded systems, `member(b,Output)` and `member(b,[1|Output])`. The first (guard) could be evaluated via two clauses. Both clause evaluations suspend on head unification. Using **clause** suspension and **busy** waiting these 2 suspended evaluations will be attempted every cycle until cycle 5, when the variable "`Output`" becomes bound; a total of 8 suspensions. The second (guard) is able to perform 2 reductions (the guard test and the commitment to `member(b,Output)`). The resulting goal could be evaluated via two clauses but again both evaluations suspend on head unification. These two suspended evaluations will also be tried every cycle until cycle 5, resulting in 6 suspensions.

In cycle 5 the shared variable "`Output`" will be bound, so the 4 suspended clause evaluations will now be evaluated. These will reduce to `true` in 16 reductions. Hence the total number of reductions performed in the evaluation of this goal is 20 (8 in the first guard, 10 in the second (2 before the suspension and 8 when the variable "`Output`" becomes bound), 1 for the commitment to the body goal and finally 1 for the output unification). The total number of cycles that this evaluation takes is 5.

So, the evaluation of the query using this execution model takes: 10 cycles; 36 reductions (16 for the first goal, and 20 for the second goal); 14 suspensions (8 for suspending the two clauses of the first guarded goal, 6 for suspending the two clauses of the second guarded goal).

Note: that 4 reductions can be prevented by using **clause** rather than **goal** suspension; although the suspension counts are the same the nature of the suspen-

sions are different. **Clause** suspension will incur some overheads in maintaining a suspension tree, *see section 4.2.2.*

A.3 Busy waiting, pruning, goal suspension

Here the execution model is: suspended evaluations are immediately rescheduled for evaluation; on commitment to one clause the other OR-clauses are terminated; and the suspension of an evaluation involves suspending the goal.

We now consider the evaluation of the two query goals given in *figure 4–1*:

goal 1: The evaluation of the first goal of the query will invoke two guarded systems `member(a,[1,2,3,a,b])` and `member(a,[1,2,a,b])`. The first of these requires 8 reductions to reduce to true, and evaluates in 4 cycles. The second (guarded) goal requires 6 reductions and evaluates in 3 cycles.

This execution model uses **pruning**, so on commitment to the second clause the system will be able to prevent 2 reductions being performed[2] in the evaluation of the first guard. Hence the total number of reductions performed in the evaluation of this goal is 14 (6 in the first guard (when it is pruned), 6 in the second guard (when it commits), 1 for the commitment to the body goals and finally 1 for the output unification). The binding of the variable "`Output`" will be available to the other goals in cycle 5.

goal 2: The evaluation of the second goal results in the same number of suspensions as the evaluation given in section A.1, as the **pruning** of OR-clauses will not prevent any suspensions and both use **busy** waiting and **goal** suspension.

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[2]That is two reductions at best, ie. assuming that **pruning** can happen immediately.

In cycle 5 the shared variable "`Output`" will be bound, so the suspended goal becomes `on_either(b,[1,2,a,b],[1,1,2,a,b],Output1)`. This goal results in two guarded systems, `member(b,[1,2,a,b])` and `member(b,[1,1,2,a,b])`. The first of these will require 8 reductions to reduce to true which takes 4 cycles. Similarly the second (guard) goal requires 10 reductions which take 5 cycles.

As this execution model uses **pruning**, 2 reductions will be prevented in the evaluation of the second guard. Hence the total number of reductions performed in the evaluation of this goal is 18 (8 in the first guard (to commit), 8 in the second (before it is pruned), 1 for the commitment to the body goals and finally 1 for the output unification).

So, the evaluation of the query using this execution model takes: 10 cycles; 38 reductions (16 for the first goal, 4 to suspend the second goal twice, and 18 for the second goal); and 6 suspensions.

A.4 Busy waiting, pruning, clause suspension

Here the execution model is: suspended evaluations are immediately rescheduled for evaluation; on commitment to one clause the other OR-clauses are terminated; and the suspension of an evaluation involves suspending the clauses.

We now consider the evaluation of the two query goals given in *figure 4–1*:

goal 1: The evaluation of the first goal of the query will be the same as in section A.3, as both execution models use **pruning** and the evaluation of this goal incurs no suspensions.

goal 2: This goal will have the same suspension count as the evaluation in section A.2, as **pruning** does not prevent any suspensions and both execution models use **busy** waiting with **clause** suspension.

In cycle 5 the shared variable "**Output**" will be bound, so the 4 suspended clause evaluations can now be evaluated. These evaluations reduce to **true** in 16 reductions; no reductions will be preventable by **pruning**. So, the total number of reductions performed in the evaluation of this goal is 20 (8 in the first guard, 10 in the second (2 before suspension and 8 after suspension), 1 for the commitment to the body goal and finally 1 for the output unification). The total number of cycles that this evaluation takes is 5. That is the evaluation commits to the first OR-clause after 4 cycles and it takes 1 cycle to carry out the output unification.

So, the evaluation of the query using this execution model takes: 10 cycles; 34 reductions (14 for the first goal, 2 to suspend the second goal, and 18 to evaluate the second goal); 14 suspensions.

A.5 Non-busy waiting, non-pruning, goal suspension

Here the execution model is: suspended evaluations are tagged to the variables which must be bound before the evaluation can proceed; on commitment to one clause the other OR-clauses are not terminated; and the suspension of an evaluation involves suspending the goal.

We now consider the evaluation of the two query goals given in *figure 4–1*:

goal 1: The evaluation of the first goal will be the same as in section A.1, as both execution models use **non-pruning** and the evaluation of this goal involves no suspensions.

goal 2: The evaluation of the second goal will initially be as in section A.1. However, once this top-level goal suspends it will not be rescheduled as in section

A.1 because we employ **non-busy** waiting. So this goal evaluation suspends awaiting the variable "`Output`" to be bound. The initial suspension requires 3 suspensions and 2 reductions.

In cycle 5 the shared variable "`Output`" will be bound. So the suspended evaluation becomes `on_either(b,[1,2,a,b],[1,1,2,a,b],Output1)`. This is now rescheduled and will be evaluated as in *section A.1*. The total number of reductions performed in the evaluation of this goal, after "`Output`" is bound, is 20 (8 in the first guard, 10 in the second, 1 for the commitment to the body goals and finally 1 for the output unification).

So, the evaluation of the query using this execution model takes: 10 cycles; 38 reductions (16 for the first goal, 2 in suspending the second goal, and 20 for evaluating the second goal); 3 goal suspensions.

A.6 Non-busy waiting, non-pruning, clause suspension

Here the execution model is: suspended evaluations are tagged to the variables which must be bound before the evaluation can proceed; on commitment to one clause the other OR-clauses are not terminated; and the suspension of an evaluation involves suspending the clauses.

We now consider the evaluation of the two query goals given in *figure 4–1*:

goal 1: The evaluation of the first goal will be the same as in section A.1.

goal 2: The second goal will invoke two guarded systems, `member(b,Output)` and `member(b,[1|Output])`. The first (guard) could be evaluated via two clauses. However, both evaluations suspend on head unification. These suspended clause evaluations are tagged to the variable "`Output`". The second

(guard) is able to perform 2 reductions (the guard test and the commitment to `member(b,Output)`). This resulting goal could be evaluated via two clauses but again both evaluations suspend on head unification. The two suspended clause evaluations are again tagged to variable "`Output`".

In cycle 5 the shared variable "`Output`" will be bound, so the 4 suspended clause evaluations will be rescheduled and evaluated. These will reduce to true in 16 reductions. Hence the total number of reductions performed in the evaluation of this goal is 20 (8 in the first guard, 10 in the second (2 before suspension and 8 after suspension), 1 for the commitment to the body goal and finally 1 for the output unification).

As this execution model uses **non-pruning** all the reductions and suspensions will be counted fully. Therefore the evaluation of the query using this execution model takes: 10 cycles; 36 reductions (16 for the first goal, and 20 for the second goal); 4 suspensions.

A.7 Non-busy waiting, pruning, goal suspension

Here the execution model is: suspended evaluations are tagged to the variables which must be bound before the evaluation can proceed; on commitment to one clause the other OR-clauses are terminated; and the suspension of an evaluation involves suspending the goal.

We now consider the evaluation of the two query goals given in *figure 4-1*:

goal 1: The evaluation of the first goal will be the same as in section A.3.

goal 2: The evaluation of the second goal will initially be as in section A.3. However, once this top-level goal suspends it will not be rescheduled as in section

A.3 because we employ **non-busy** waiting. So this goal evaluation suspends awaiting the variable "`Output`" to be bound. The initial suspension requires 3 suspensions and 2 reductions.

In cycle 5 the shared variable "`Output`" will be bound. So the suspended evaluation becomes `on_either(b,[1,2,a,b],[1,1,2,a,b],Output1)` this is rescheduled. As no further suspensions occur this will be evaluated as in *section A.3*. The total number of reductions performed in the evaluation of this goal, after "`Output`" is bound, is 18 (8 in the first guard (when it commits), 8 in the second guard (before it is pruned), 1 for the commitment to the body goals and finally 1 for the output unification).

So, the evaluation of the query using this execution model takes: 10 cycles; 34 reductions (14 for the first goal, 2 before suspending the second goal, and 18 for evaluating the second goal); 3 suspensions.

A.8 Non-busy waiting, pruning, clause suspension

Here the execution model is: suspended evaluations are tagged to the variables which must be bound before the evaluation can proceed; on commitment to one clause the other OR-clauses are not terminated; and the suspension of an evaluation involves suspending the clauses.

We now consider the evaluation of the two query goals given in *figure 4–1*:

goal 1: The evaluation of the first goal will be the same as in section A.3.

goal 2: The second goal will invoke two guarded systems, `member(b,Output)` and `member(b,[1|Output])`. The first (guard) could be evaluated via two

clauses. However, both evaluations suspend on head unification. These suspended clause evaluations are tagged to the variable "`Output`". The second (guard) is able to perform 2 reductions (the guard test and the commitment to `member(b,Output)`). This resulting goal could be evaluated via two clauses but again both evaluations suspend on head unification. The two suspended clause evaluations are again tagged to variable "`Output`".

In cycle 5 the shared variable "`Output`" will be bound, so the 4 suspended clause evaluations will now be evaluated. These will reduce to true in 16 reductions. Hence the total number of reductions performed in the evaluation of this goal is 20 (8 in the first guard, 10 in the second (2 before the suspensions and 8 after the suspensions), 1 for the commitment to the body goal and finally 1 for the output unification). No **pruning** can take place, although the guards are different depths the evaluation of the deeper guard (via second clause) is able to perform some evaluation while the first guard is suspended.

So the evaluation of the query using this execution model takes: 10 cycles; 34 reductions (14 for the first goal, and 20 for the second goal); 4 suspensions.