

# Declarative program development in Prolog with GUPU

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**Abstract.** We present GUPU, a side-effect free environment specialized for programming courses. It seamlessly guides and supports students during all phases of program development, covering specification, implementation, and program debugging. GUPU features several innovations in this area. The specification phase is supported by reference implementations augmented with diagnostic facilities. During implementation, immediate feedback from test cases and from visualization tools helps the programmer's program understanding. A set of slicing techniques narrows down programming errors. The whole process is guided by a marking system.

## Introduction

Teaching logic programming has specific opportunities different from traditional languages. In particular, the declarative notions can be liberated from theoretical confines and be applied to actual program development. Our approach is centered around the programming course environment GUPU used for introductory Prolog programming courses since 1992 at TU Wien and other universities. The language used by GUPU is the monotone pure subset of Prolog which also contains the many constraint extensions offered by SICStus Prolog.

In this article, we focus on the program development process supported by GUPU. To illustrate this process, we will develop the predicate `alldifferent/1` describing a list of pairwise different elements.

The actual programming effort is divided into two stages which both are equipped with appropriate diagnosing facilities. The first stage (Sect. 1) is devoted to specifying a predicate by example. Cases are stated where the predicate should succeed, fail, terminate, or not terminate. In the second stage (Sect. 2), the actual predicate is implemented and immediately tested against the previously stated example cases. The whole development process is guided by a marking system that highlights missing items and computes an interval percentage of the fulfillment of an exercise.

## 1 Specification by example

Writing test cases prior to actual coding is good practice also in other programming languages. It has reached broader attention with the rise of the extreme

programming movement [1]. The major advantage generally appreciated is increased development speed due to the following reasons. Test cases are an unambiguous (albeit incomplete) specification. They influence system design, making it better testable. They provide immediate feedback during coding, which is most important in our context. And finally, they constitute a solid starting point for documentation and maintenance.

In the context of logic programming, there are several further aspects in favor of this approach. Test cases focus the attention on the meaning of the predicate avoiding procedural details. In particular, recursive predicates are a constant source of misunderstandings for students, because they confuse the notion of termination condition in imperative languages with Prolog's more complex mechanisms. While there is only a single notion of termination in procedural languages, Prolog has two: Existential and universal termination. By writing tests prior to coding, the student's attention remains focused on the use of a predicate. With logic variables, test cases are more expressive than in imperative languages. We can use these variables existentially (in positive queries) as well as universally (in negative queries).

In our attempt to develop `alldifferent/1` describing a list of pairwise different elements, we start by writing the following two assertions. The first is a positive assertion. It ensures that there must be at least a single solution for `alldifferent/1`. The second is a negative one which insists that the given goal is not the case. Here, `alldifferent/1` should not be true for a list with its two elements being equal. Both tests cannot be expressed in traditional languages.

```
← alldifferent(Xs).
≠ alldifferent([X,X]).
```

**@! Definition of `alldifferent/1` missing in above assertions**

We write test cases directly into the program text. Upon saving, GUPU inserts feedback *into* that text. Above, GUPU added the line starting with `@` to remind us that we have not yet defined `alldifferent/1`.

Taking all of the aforementioned advantages into account, this methodology appears preferable to the traditional "code then test" approach. Still, students prefer to write code prior to testing. It seems that the biggest obstacle is a lack of motivation. Test cases as such do not provide any immediate feedback when they are written. Why should one write tests when they might be incorrect? Such incorrect tests would be misleading in the later development. For this reason GUPU tests assertions for validity.

## 1.1 Reference implementation

All test cases provided by the student are tested against a reference implementation which is realized with otherwise inaccessible predicates. It is considered to be correct for those cases where the reference predicate fails finitely or succeeds unconditionally. In all other cases (exceptions, non-termination, pending constraints), the reference implementation is incomplete and therefore unspecified as discussed in the sequel.

Cases detected as incompatible with the reference implementation are highlighted immediately. In this manner, it is possible to “test the tests” without any predicate yet defined by the student. Errors due to the reference implementation start with `!=` to distinguish them from other errors.

We continue with the specification of `alldifferent/1`, by adding further positive and negative assertions. In the cases below GUPU disagrees and offers help.

```
← alldifferent([a,b,c,d,c]).
```

**!= Should be negative. Details with DO on the arrow**

```
≠ alldifferent([X,Y|_]).
```

**!= Should be positive. Details with DO on the arrow**

## 1.2 Diagnosis of incorrect assertions

A more elaborate explanation on why an assertion is incorrect is obtained on demand as proposed by the message “DO on the arrow” above. According to the kind of assertion the following steps are taken. In case of an incorrect negative assertion, a more specific query is produced if possible. For incorrect positive assertions, a generalized query is given. In this manner, GUPU provides a detailed diagnosis without showing the actual code of the reference implementation. Moreover, further assertions are offered that will improve test coverage during coding.

*Explaining incorrect negative assertions.* If the reference implementation succeeds in a negative assertion, a more specific goal is obtained using an answer substitution of the reference implementation. All free variables are grounded with new constants `any1`, `any2`, ...

Below, an answer substitution completed the end of the list with `[]`, and the variables `X` and `Y` have been grounded to constants. GUPU temporarily inserts the specialized assertion into the program text. By removing the leading `@`-signs, the assertion can be added easily to the program.

```
≠ alldifferent([X,Y|_]).
```

**@@ % != Should be a positive assertion.**

**@@ % Also this more specific query should be true.**

**@@ ← X = any0, Y = any1, alldifferent([X,Y]).**

*Explaining incorrect positive assertions.* If the reference implementation fails for a positive assertion, GUPU tries to determine a generalized goal that fails as well. Generalized goals are obtained by rewriting the goal (or a conjunction of goals) up to a fixpoint with the following rules.

**R1:** Replace a goal (in a conjunction) by `true`.

**R2:** Replace a subterm of a goal’s argument by a fresh variable `_`.

**R3:** Replace two or more identical subterms by a new shared variable.

**R4:** Replace two non-unifiable subterms by new variables `V1`, `V2` and add the goal `dif(V1, V2)`.

**R5:** Replace a goal by a set of other goals that are known to be implied.

```

← alldifferent([a,b,c,d,c]).
@@ % != Should be a negative assertion
@@ % @ Generalized negative assertion: — using R1,R2
@@ ≠ alldifferent([_,_,c,_,c]).
@@ % @ Further generalization: — using R1-R4
@@ ≠ alldifferent([_,_,V0,_,V0]).
@@ % @ Further generalization: — using R1-R5
@@ ≠ alldifferent([V0,_,V0|_]).

```

In our experience it is helpful to use several stages of generalizations. Explanations that are easier to compute are presented first. In the first stage, R1 and R2 are used, and the generalization is displayed immediately. In the next stage, R1-R4 may incur a significant amount of computation. In particular, R4 is often expensive if the number of non-unifiable subterms is large. Note that the obtained generalized goals are not necessarily optimal because of the incompleteness of the reference implementation. In the above example, the first generalization is sub-optimal. The optimum for R1 and R2 is  $\neq$  `alldifferent`([\_,\_,c,\_,c|\_]). However, our reference implementation loops in this case. In the last generalization, R5 applied “`alldifferent`([\_|Xs])  $\implies$  `alldifferent`(Xs).” twice. This permitted R1 to remove constant `[]` at the end of the list.

### 1.3 Incomplete reference implementations

For most simple predicates, our reference implementation is capable of determining the truth of all simple assertions. There are, however, several situations where no feedback is provided.

- The reference implementation takes too long, although most reference predicates take care of many situations and are therefore more complex than the student’s code.
- The predicate itself is under-specified. Many under-specified predicates, however, still allow for partial assertion testing.

The former situation has been illustrated previously with `alldifferent`([\_,\_,c,\_,c|\_]). For the latter, consider a family database, the usual introductory example. While the particular persons occurring in `child_of/2` and `ancestor_of/2` are not fixed, there still remain many constraints imposed on them.

- c1 No child has three parents.
- c2 A parent is an ancestor of its children.
- c3 The ancestor relation is irreflexive.
- c4 The ancestor relation is transitive.

We give here the actual reference implementation of `child_of/2` and `ancestor_of/2` implemented in CHR [4], a high-level language to write constraint systems with simplification ( $\Leftrightarrow$ ) and propagation rules ( $\implies$ ). The definition provides two predicates that can be executed together with regular predicates of the

reference implementation. This reference implementation cannot succeed unconditionally because of the pending constraints imposed by CHR. Therefore, it can only falsify positive assertions.

```

% Reference implementation in CHR
← use_module(library(chr)).
option(already_in_store, on). % prevents infinite loops

c1 @ child_of(C,P1), child_of(C,P2), child_of(C,P3) ⇔
    true & P1 \= P2, P2 \= P3, P1 \= P3 | false.
c2 @ child_of(A,B) ⇒ ancestor_of(B,A).
c3 @ ancestor_of(A,A) ⇔ false.
c4 @ ancestor_of(A,B), ancestor_of(B,C) ⇒ ancestor_of(A,C).

← child_of(A,B), child_of(B,C), A = C.
!= Should be negative.
← alldifferent([P1,P2,P3]), child_of(C,P1), child_of(C,P2), child_of(C,P3).
!= Should be negative.

```

#### 1.4 Termination

Termination properties and in particular non-termination properties are often considered unrelated to the *declarative* meaning of a program. It is perceived that ideally a program should always terminate. We note that non-termination is often closely related to completeness. In fact, a query *must not* terminate if the intended meaning can only be expressed with an infinite number of answer substitutions. Notice that this observation is completely independent of Prolog's actual execution mechanism! No matter how sophisticated an execution mechanism may be, its termination property is constrained by the size of the generated answer. If this answer must be infinite, non-termination is inevitable. For this reason, cases of non-termination that are due to necessarily infinite sets of answer substitutions can be safely stated in advance. On the other hand, cases of termination always depend on the particular predicate definition as well as on Prolog's execution mechanism.

The most interesting cases of termination are those where actual solutions are found. Termination is therefore expressed with two assertions: A positive assertion to ensure a solution:  $\leftarrow$  Goal. A negative one to ensure universal termination under Prolog's simplistic left-to-right selection rule:  $\not\leftarrow$  Goal, false. In our particular case of `alldifferent/1`, we can state that `alldifferent(Xs)` must not terminate, because there are infinitely many lists as solutions. With the negative infinite assertion  $\not\leftarrow$  Goal, false. we state that Goal must not terminate universally.

```

← alldifferent(Xs).
 $\not\leftarrow$  alldifferent(Xs), false.

```

When the length of the list is bounded (at most) a single answer substitution for `alldifferent/1` is possible. Therefore, the predicate could terminate if defined appropriately. In the example below, the ideal answer is `dif(A,B)`.

```

← Xs = [A,B], alldifferent(Xs).
 $\not\leftarrow$  Xs = [A,B], alldifferent(Xs), false.

```

## 1.5 Summary

In the first stage of realizing a predicate, only test cases are given. The idea is to start from the most general goal and refine the meaning of the predicate by adding further cases. To streamline this process, their correctness is ensured with the help of an internal reference implementation. It provides immediate feedback and detailed diagnosis in the form of further test cases that can be added to the program. Without any actual predicate code written, the learner is put into the situation of formulating and reading queries generated by the system. Note that in this first stage most errors remain local in each query. The marking system provides overall guidance by demanding various forms of assertions. E.g., a ground positive assertion, non-termination annotations, etc.

## 2 Predicate definition

Armed with validated test cases obtained in the first stage, we are now ready to implement `alldifferent/1`. Inconsistencies between the student's test cases and implementation, are highlighted immediately. Answer substitutions are tested with the reference implementation, as shown in the central column of the following table. Explanations based on slicing locate an error. We continue our example by defining the predicate with an error in the underlined part.

```

alldifferent([]).                nonmember_of(_X, []).
alldifferent([X|Xs]) ←         nonmember_of(X, [E|Es]) ←
    nonmember_of(Xs, X),       dif(X, E),
    alldifferent(Xs).          nonmember_of(X, Es).
← X = any1, Y = any2, alldifferent([X,Y]).
! Unexpected failure. Explanation with DO on the arrow.
← Xs = [-,-], alldifferent(Xs).
!= The first solution is incorrect. Explanation with DO on the arrow.
≠ Xs = [-,-], alldifferent(Xs), false.
! Universal non-termination. Explanation with DO on the arrow.

```

### 2.1 Slicing

Slicing [11] is a technique to facilitate the understanding of a program. It is therefore of particular interest for program debugging. The basic idea of slicing is to narrow down the relevant part of a program text. For the declarative properties insufficiency (unexpected failure) and incorrectness (unexpected success), two different slicers have been realized. A further slicer was realized to explain universal non-termination [7]. They all highlight fragments of the program where an error has to reside. As long as the programmer does not modify the displayed fragment, the error persists.

- a) For unexpected failures, generalized program fragments are produced that still fail. The program is generalized by deleting some goals, indicated with a \*-sign. To remove the error, the slice must be generalized.

E.g., a rule  $p \leftarrow q, r.$  is generalized to  $p \leftarrow * \bar{q}, r.$

- b) In case of unexpected success, still succeeding specialized fragments are obtained by inserting some goals `false/0` that effectively remove program clauses. In order to remove the error, the programmer has to specialize the remaining program fragment.
- c) For universal non-termination, slicing determines still non-terminating specialized fragments. The inserted `false/0`-goals hide all subsequent goals in a clause. If `false/0` is inserted as the first goal, the clause is completely eliminated. The remaining program fragment has to be modified in order to remove non-termination. The constraint based algorithm is found in [7].

E.g., `p ← p, q.` is specialized to `p ← p, false,  $\bar{q}$ .`

GUPU generates the following slices on demand (“DO on the arrow”).

|                                                                                                                                                                                                                                                                                                                        |                                                                                                                                                                                                                                                                                                      |                                                                                                                                                                                                                                                                                                                                            |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <pre>← X = any1, Y = any2,   alldifferent([X,Y]). ! Unexpected failure.</pre>                                                                                                                                                                                                                                          | <pre>← Xs = [-,-], alldifferent(Xs). @@ % Xs = [[],[ ]]. % Incorrect! @@ % Generalization @@ ≠ alldifferent([[],[ ]]). @@ % Further generalization @@ ≠ alldifferent([V0,V0 _]).</pre>                                                                                                               | <pre>≠ Xs = [-,-], alldifferent(Xs),   false. ! Universal non-termination</pre>                                                                                                                                                                                                                                                            |
| <p>—— Explanation, ad a) ——</p>                                                                                                                                                                                                                                                                                        | <p>—— Explanation, ad b) ——</p>                                                                                                                                                                                                                                                                      | <p>—— Explanation, ad c) ——</p>                                                                                                                                                                                                                                                                                                            |
| <p>Generalized fragment fails.</p> <pre>← X = any1, Y = any2,   alldifferent([X,Y]). alldifferent([ ]). alldifferent([X Xs]) ←   nonmember_of(Xs, X),   * <del>alldifferent(Xs).</del></pre> <pre>nonmember_of(X, [ ]). nonmember_of(X, [E Es]) ←   * <del>diff(X, E).</del>   * <del>nonmember_of(X, Es).</del></pre> | <p>Specialized fragment succeeds.</p> <pre>≠ alldifferent([V0,V0 _]). alldifferent([ ]). alldifferent([X Xs]) ←   nonmember_of(Xs, X),   alldifferent(Xs).</pre> <pre>nonmember_of(X, [ ]). <del>nonmember_of(X, [E Es]) ← false;</del> <del>diff(X, E);</del> <del>nonmember_of(X, Es);</del></pre> | <p>Fragment does not terminate.</p> <pre>≠ Xs = [-,-], alldifferent(Xs),   false. <del>alldifferent([ ]) ← false;</del> alldifferent([X Xs]) ←   nonmember_of(Xs, X), false,   <del>alldifferent(Xs).</del></pre> <pre><del>nonmember_of(X, [ ]) ← false;</del> nonmember_of(X, [E Es]) ←   dif(X, E),   nonmember_of(X, Es), false.</pre> |

In the above example, two declarative errors and a procedural error yielded three different explanations. All explanations exposed some part of the program where an error must reside. Reasoning about errors can be further enhanced by combining the obtained explanations. Under the assumption that the error can be removed with a single modification of the program text, the error has to reside in the intersection of the three fragments. The intersection of all three fragments comprises only two lines of a total of eight lines — the head and first goal of `alldifferent/1`. This intersection is currently not generated by GUPU.

```
alldifferent([ ]);
alldifferent([X|Xs]) ←
  nonmember_of(Xs, X),
alldifferent(Xs);
nonmember_of(X, [ ]);
nonmember_of(X, [E|Es]) ←
diff(X, E);
nonmember_of(X, Es);
```

The advantages of using slicing in the context of a teaching environment are manifold. The students’ attention remains focused on the logic programs and not on auxiliary formalisms like traces. Reading program fragments proves to be a fruitful path toward program understanding. Simpler and smaller parts can be read and understood instead of the complete program. Further, the described techniques are equally used for monotone extensions of pure Prolog programs like constraints in the domain CLP(FD).

## 2.2 Beyond Prolog semantics

The truth of infinite queries cannot be tested with the help of Prolog's simplistic but often efficient execution mechanism. GUPU subjects infinite queries implicitly to an improved execution mechanism based on iterative deepening. In contrast to approaches that exclusively rely on iterative deepening [12], we can therefore obtain the best of both worlds: Prolog's efficiency and a sometimes more complete search. In the case of negative infinite queries, a simple loop checking prover is used. We are currently investigating to further integrate more sophisticated techniques.

|                                  |                               |
|----------------------------------|-------------------------------|
| nat(s(N)) ←                      | q ←                           |
| nat(N).                          | q.                            |
| nat(0).                          |                               |
| ⊄ nat(N).                        | ∞ q.                          |
| !++ Unexpected success. Remove / | !++ Unexpected failure. Add / |

## 2.3 Viewers

In a pure logic programming environment, the only way to see the result of a computation is via answer substitutions which often serves as an excuse to introduce impure features and side-effects. In GUPU, answer substitutions are visualized in a side-effect free manner with the help of viewers. Viewers provide an alternate visual representation of an answer substitution which helps to understand the investigated problem. To ensure that no side effects take place, viewers are only allowed in assertions of the form  $\leftarrow \textit{Viewer} \lll \textit{Goal}$ . When querying such an assertion, an answer substitution of *Goal* is displayed along with a separate window for the viewer. *Viewer* is one of the predefined viewers. Most complex viewers are based on the Postscript viewer which expects a string describing a Postscript document. In fact, many viewers have been implemented side-effect free within GUPU in student projects. We present two select viewers. Further viewers are discussed in [8].

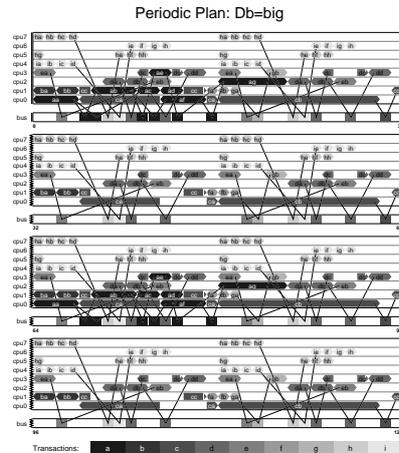
```
← postscript(Cs) <<< Cs = "0 0 100 100 rectfill".
@@ % Cs = "0 0 100 100 rectfill".
@@ %% One solution found.
```

*Repetitive Scheduling.* Within the context of fault-tolerant, distributed hard real-time systems, the need to calculate time-rigid schedules arises. Before system start up, a schedule meeting the time criteria of the application is calculated. The resulting table is executed at run time by the components of the system. This real-world application of CLP(FD) [3] has been integrated into GUPU. The viewer `repsched/1` displays one particular solution to this scheduling problem:

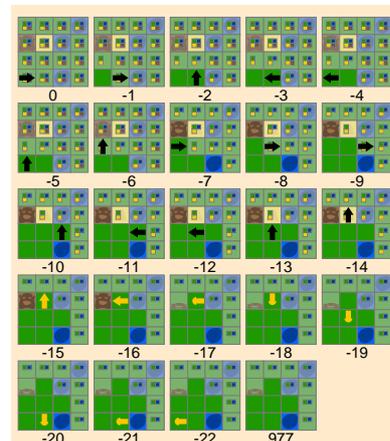
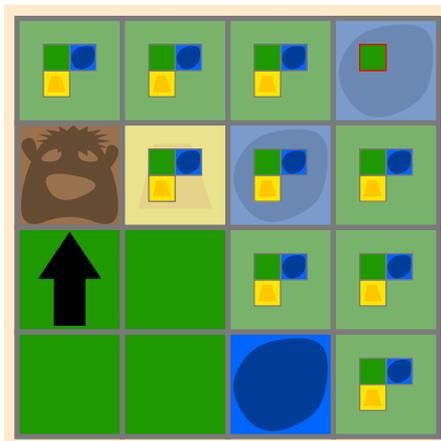
```
← repsched(DB-S) <<< DB = big, db_timerigidschedule(DB,S).
```

The modeled system consists of several processors and of one global interconnect (a bus). During design-time, every task is assigned to exactly one processor. All tasks are executed periodically and are fully preemptive. Tasks communicate and synchronize by sending messages. Internal messages are used for tasks on the same processor. All other messages are sent over the bus.

Solutions to the scheduling problem obey several constraints. All messages must be transmitted after the completion of the sending task and before starting the receiving task. The bus transfers at most one message at a time. Transactions (specific groups of tasks) have a guaranteed maximal response time (time from the start of the earliest task to the end of the last completing task). Tasks having a period smaller than the period of their transaction are replicated accordingly. Processors execute at most one task at a time.



*An agent environment.* Another critical issue apart from basic I/O concerns the side-effect free representation of logical agents. As an example, the wumpus cave has been realized, well known from introductory AI texts [10]. In this world the agent is supposed to find and rescue gold in a dark cave guarded by a beast and paved with other obstacles. Only by using rudimentary perception, the agent makes its way through the cave. The basic functionality of the agent is represented with two predicates. One for initialization of the agent's state `init(State)` and one to describe the agent's reaction upon a perception `percept_action_(Percept, Action, State0, State)`. In addition, the state of the agent's knowledge can be communicated via `maybe_obj_(Position, Object, State)` which should succeed if the agent believes at the current State that an Object may be located at Position.



The graphical representation shows the agent depicted as an arrow walking through the cave as well as the location of the objects invisible to the agent. The agent's belief is represented by the centered squares on each field. The agent may

believe that a field is free, a pit, contains gold, or is occupied by the wumpus. In the picture, the agent has discovered the wumpus, a pit, and some free fields. All other fields are believed to contain a free field, gold, or a pit. Inconsistencies between the agent's belief and reality are highlighted as depicted by the field in the upper right corner. While that field is a dangerous pit, the agent believes it to be safe. The left viewer only displays a single situation at a time, the other viewer presents the complete course through the cave at a glance, simplifying the comparison of different agents.

*Related Work.* Ushell [12] uses iterative deepening in introductory courses. GUPU resorts to better strategies only when Prolog takes too long. CIAOPP [5] provides a rich assertion language (types, modes, determinacy, cost, ...). It is much more expressive than GUPU's but also complex to learn. Prolog IV [9] has a very sophisticated assertion language which is particularly well suited for constraints. Approaches to teaching Prolog with programming techniques [2] highlight patterns otherwise invisible to the inexperienced. Advice is given on the programming technique and coding level [6]. GUPU provides guidance prior to any coding effort. We believe programming techniques might also be useful for GUPU.

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