Using Penelope To Assess the Correctness of NASA Ada Software: A Demonstration of Formal Methods as a Counterpart to Testing

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Abstract

Life-critical applications warrant a higher level of software reliability than has yet been achieved. Since it is not certain that traditional methods alone can provide the required ultra-reliability, new methods should be examined as supplements or replacements. This paper describes a mathematical counterpart to the traditional process of empirical testing.

ORA's Penelope verification system is demonstrated as a tool for evaluating the correctness of Ada software. Grady Booch's Ada calendar utility package, obtained through NASA, was specified in the Larch/Ada language. Formal verification in the Penelope environment established that many of the package's subprograms met their specifications. In other subprograms, failed attempts at verification revealed several errors that had escaped detection by testing.

Keywords

Life-critical software, ultra-reliability, formal methods, formal specification, formal verification, safety
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Preface

This report provides computer science professionals with a demonstration of Penelope, ORA's program verification system for producing highly reliable Ada components. The reader familiar with the Ada language will find the document self-explanatory. No prior knowledge is required of program verification in general or Penelope in particular; the basic concepts of program verification are explained before they are applied.

From this document, the reader should obtain a basic understanding of the capabilities and methods of the Penelope system when used as a counterpart to testing. The reader should also see that evaluating completed software is only one of many possible applications of program verification. The reader who wishes to explore the possibilities is directed to the suggestions for further reading.
Summary

Ultra-reliable software for life-critical aerospace applications is NASA’s goal. Specifically, the FAA proposes a probability of $10^{-9}$ of catastrophic failure during one service hour. Conventional software development methods have not by themselves produced ultra-reliable software. Several fly-by-wire systems now in service have failed catastrophically. Improvements to conventional methods need to be investigated. Promising alternative approaches deserve examination as well. Formal verification applies the power and precision of mathematics to the development of life-critical software, in such a way that software can be unambiguously specified and conclusively proved to meet its specifications.

ORA has developed Penelope, a computerized system for formally verifying Ada software. This report demonstrates Penelope’s capabilities.

NASA provided ORA with Grady Booch’s CalendarUtilities, a commercially released utility package, suitable for navigational uses. The package features several convenient representations of time and date and manipulations of them. ORA formally specified CalendarUtilities using the Larch/Ada mathematical specification language. ORA formally verified CalendarUtilities using the Penelope verification environment.

Formal specification provided an unambiguous description of every subprogram in the package. Informal analysis then uncovered dubious software and three outright errors. Formal verification determined the status of eleven representative subprograms. Successful proofs demonstrated nine subprograms to be correct. In two subprograms, failed attempts at verifications revealed additional errors in human blind spots.

Penelope is an effective, prototype tool which holds promise for producing ultra-reliable Ada software. As ORA continues development, Penelope will become even more effective.
1 Introduction

As the complexity of life-critical computer applications increases and the reliance placed upon these applications grows, software developers will have to attain higher levels of reliability than have been possible to date. Since it cannot be foreseen whether today's software practices will scale up to meet the challenge, alternative approaches need to be examined. One promising approach is the use of formal verification to prove mathematically that software is correct. This paper demonstrates that the formal approach is practical for the evaluation of existing software.

1.1 The Challenge: Ultra-Reliability

Nowhere are computerized life-critical systems more pervasive than in aerospace. Today, there are aircraft that cannot be controlled without computer assistance. In the future, there will be vehicles flown completely by computer. It is imperative that their software be correct.

The Federal Aviation Authority [4] has proposed a very ambitious standard for flight safety: a probability of $10^{-9}$ of catastrophic failure during a one-hour flight. Meeting this standard would effectively eliminate risk from flight. The probability of a fatal failure during 1000 years' worth of consecutive independent one-hour missions would be less than one percent.

Can the FAA's goal be achieved? The proposed ultra-reliability is several orders of magnitude from what has ever been attained for aircraft with purely human control. Computerized assistance, at the least, will be required if the FAA's goal is to be met. Ultra-reliable software will be needed for life-critical applications, but it is not at all clear that conventional software development methods alone are capable of its production.

1.2 The Conventional Approach

For a system to behave reliably, its developers must know what constitutes correct behavior: a specification is necessary. Traditional English-language specifications of the intended behavior of the software suffer from the imprecision and ambiguity inherent in natural language. Consequently, misunderstandings and resultant errors are common. Ultra-reliability has never been attained for software specified by traditional means.

But suppose that developers could attain ultra-reliability by some modification of traditional methods. How would they convince an impartial skeptic that they had done so? The faith of the developers in their product is not sufficient. Certification is not a matter of faith, but of demonstration.

---

1By specification in this report, we mean a description of what the software does. If we intend the Ada Reference Manual's sense of specification, we use the phrase Ada specification.
Conventional demonstrations of reliability depend heavily on empirical testing, a costly and time-consuming process that is never fully completed. Testing can conclusively demonstrate the existence of a particular error, but cannot demonstrate the general absence of all errors. Prolonged testing of software of any real complexity will continually reveal flaws for as long as tests are carried out. Error-free software is approached, at best, only asymptotically by testing.

The conclusions from testing about reliability are therefore drawn in terms of probability. Techniques are available that enable extrapolation from relatively short tests to probabilistic predictions of relatively long intervals of failure-free operation; however, these techniques do not scale up gracefully to encompass intervals of thousands of years. An alternative to empirical testing is the formal approach.

### 1.3 The Formal Approach

By applying mathematics to the specification and demonstration of correctness of software, great advances in reliability are possible. The use of a formal specification language brings the clarity and precision of mathematical logic to the description of the software's intended behavior. Formal specifications provide the user and the implementer with an unambiguous means of communication.

Formal verification is a mathematical counterpart to empirical testing. The verifier proves mathematically that software meets its specifications in all cases, rather than testing particular cases. Where testing is specific, verification is general. The tester removes flaws from software one by one. The verifier develops software free from flaws.

A leader in formal methods, the ORA Corporation has developed the Penelope [8, 14, 16] verification system for specifying and verifying Ada software. Using Penelope, computer science professionals can ensure that software is of the highest reliability. This paper demonstrates how.

### 1.4 Demonstrating the Formal Approach with Penelope

NASA Goddard Space Flight Center and NASA Lewis Research Center furnished ORA with samples of Ada software. From these samples, we chose a demonstration case: Grady Booch's Calendar.Utilities, a commercially available software package. We formally specified the subprograms of the package in the Larch/Ada language, then formally evaluated the correctness of the software using the Penelope editor. We verified that many of the subprograms are correct, but also uncovered errors in the software during both the specification and verification efforts.

---

2 In practice, in correcting one error, the developer risks introducing others.

3 Copyright Grady Booch, part of the Ada Booch components 1984-1992.
1.5 Structure of the Document

1.4.1 The Evaluated Software

CalendarUtilities is an extension of the basic Calendar package built into Ada, and employs Calendar, along with several other packages, by means of with clauses. The data types of CalendarUtilities provide several natural representations for time and date, including string representations. The subprograms of the package convert from one representation of time to another, extract specific information (such as day of the week) from a time value, and perform arithmetic on time values. CalendarUtilities encapsulates a rich set of manipulations of dates between 1901 and 2099.

1.4.2 The Specification

We used the Larch/Ada specification language to state fully and precisely the intended behavior of each of the subprograms in the package. On the basis of the specifications, we informally examined and evaluated the software. We detected outright errors, dubious features, and hidden assumptions.

1.4.3 The Verification

In the second phase, we selected subprograms from the package to evaluate within the Penelope Ada verification environment. We proved several subprograms to be correct; we showed others to be incorrect. We confirmed some errors we had detected earlier, during the specification phase, and detected other errors. The nature of the newly found errors was telling: they had evaded earlier detection. Penelope uncovered these errors because the formal approach is rigorous and mathematical.

1.5 Structure of the Document

Section 2 is a self-contained overview of program verification in the Penelope system; the overview is provided for readers with no prior exposure to formal methods. Before discussing the demonstration of Penelope in detail, we describe the subject of the demonstration. Section 3 explains the software that was evaluated, the package CalendarUtilities. In Section 4 we demonstrate formal specification and verification in Penelope. We draw our conclusions in Section 5.

Appendix A describes related work. Appendix B is the glossary for this paper. Appendix C contains the original text of the package CalendarUtilities. For convenient reference, Appendix D contains the text of the built-in Ada language Calendar package as it appears in the Ada Reference Manual. Finally, Appendix E contains the full Ada and Larch/Ada text of the software, specification, and verification performed with Penelope.
2  Overview of the Penelope System

2.1 Basics of Formal Specification and Verification

Every software developer reasons about program semantics. When writing software, the developer considers, usually on a very informal level, what constitutes correct behavior and how to make the software behave correctly. Sometimes, however, developers reason semi-formally about the behavior of software through thought experiments in which programs are "executed" with paper and pencil.

Consider the familiar three-step swap of x and y:

```plaintext
x := y;
y := t;
```

The following symbolic execution shows that the software does indeed interchange the values of the variables x and y. The intermediate values between execution steps reveal the action of the software.

```plaintext
x := x_init  y := y_init
t := x;
  x := x_init  y := y_init  t := x_init
x := y;
  x := y_init  y := y_init  t := x_init
y := t;
  x := y_init  y := x_init  t := x_init
```

A formal verifier reasons much the same way, but does so at the level of mathematical rigor, working within a mathematical model of computation for the computer language.

In the first step of formal specification and verification, the verifier uses the mathematical language of the model to describe the intended semantics of the software (what the software should do). This description is the formal specification. Next, the verifier analyzes the software within the model to derive the actual semantics (what the software actually does); this analysis is the first step of the formal verification. In the final step of the verification, the verifier uses formal mathematical proofs to show that the actual semantics are the intended semantics; that is, that the software does what the software developer intended. We elaborate on each of these steps in the following subsections.

2.1.1 Formal Specification

Formal specifications of software are written in a formal language having a precisely defined syntax and semantics. The principal benefits of formal speci-
Basics of Formal Specification and Verification

Formal specifications are the following:

- Formal specifications explicitly state all underlying assumptions.
- Formal specifications can be stated at a high level of abstraction.
- Formal specifications provide unambiguous descriptions.
- Formal proofs of correctness are possible.
- Formal specification and the subsequent formal verification allow enhanced confidence for critical systems.

The fundamental notion of program semantics is that of change of state; that is, the alteration of data. To specify a program formally is to describe mathematically how it transforms one state into another. We describe the states of a transformation by means of assertions, mathematical statements about those states.

We assume that a program is called in an initial state, performs a set of instructions, and terminates. Executing the program transforms an initial system state into a final state: program variables that hold certain values in the initial state may acquire new values in the final state, information in external storage is changed through I/O, and so on. We could completely describe the semantics of terminating programs by giving an exhaustive list of all possible pairs of initial system states and the final states into which the software transforms them.

An exhaustive description of program semantics would be similar to the complete description of a mathematical function by the list of all ordered pairs \((x, f(x))\) of its arguments and values. The complete listing is fully adequate, but a formula for \(f(x)\) is vastly preferable. For most purposes, the advantages of the formula \(f(x) = x^2\) over the list \((1, 1), (2, 4), (3, 9), (4, 16), (5, 25), \ldots\) are obvious.

Likewise, a symbolic way to relate possible initial states to possible final states is vastly preferable to a mere listing of pairs of states. The symbolism most often used in the theory of formal verification to relate initial states, software, and final states is the Floyd-Hoare triple [12], a kind of assertion. The triple

\[
\{\text{precondition}\} \ S \ \{\text{postcondition}\}
\]

symbolically states that the software \(S\) transforms the system from an initial state in which the assertion \(\text{precondition}\) holds to one in which the assertion \(\text{postcondition}\) holds.

In this notation, the swap example above is described by:

\[
\{x = x_{\text{init}} \ \text{AND} \ y = y_{\text{init}}\} \ S \ \{x = y_{\text{init}} \ \text{AND} \ y = x_{\text{init}}\}
\]

\(^4\text{We are specifically excluding programs that are intended to run indefinitely, such as operating systems, I/O repeaters, and so on.}\)
The triple asserts that $S$, the software that performs the swap, transforms any given initial state in which $x = x_{init}$ and $y = y_{init}$ into a final state in which $x = y_{init}$ and $y = x_{init}$. The triple above is a specification for the swap $S$.

Floyd-Hoare triples have the same advantages for specifying program semantics that formulas have for defining functions. Instead of listing all possible behaviors separately, we can describe the entire collection of permissible behaviors symbolically.

### 2.1.2 Formal Verification

Having made a specification of the intended semantics in terms of pre- and postconditions,

\[
\{\text{precondition}\} S \{\text{postcondition}\}
\]

the verifier mathematically analyzes the software for correctness. Analyzing for correctness is the process of formally determining whether $S$ is, in fact, a state changer that brings about \text{postcondition} whenever \text{precondition} is initially true. The two parts to this process are predicate transformation and proofs.

**Predicate Transformation**  The first part of formal verification is a kind of symbolic execution known as *predicate transformation*.\(^5\) Similar to paper-and-pencil execution in reverse, predicate transformation works from \text{postcondition}, the stated goal of the software, back to the essence of what must be true before $S$ is executed. Predicate transformation calculates the *weakest precondition*, i.e., the most general (hence, weakest in the logical sense) precondition that is certain to be transformed by $S$ into \text{postcondition}.\(^6\) The notation for the weakest precondition is

\[
\text{wp}(S, \text{postcondition})
\]

The weakest precondition is the precondition in the Floyd-Hoare triple that describes the actual semantics of $S$:

\[
\{\text{wp}(S, \text{postcondition})\} S \{\text{postcondition}\}
\]

Any state satisfying $\text{wp}(S, \text{postcondition})$ will be transformed by the action of $S$ into a state satisfying \text{postcondition}. By calculating the weakest precondition, the verifier derives the actual semantics of the software within the mathematical model.

Let us return to the example of the three-step swap $S$ as specified above. Reading from the bottom up, here are the intermediate and ultimate results of predicate transformation of \text{postcondition} through $S$. As a careful reading

\(^5\)In mathematical parlance, the precondition and postcondition are *predicates* on the states.

\(^6\)The expert in formal methods will note that, as Larch/Ada specifications are *partial correctness* specifications, we are actually interested in the "weakest liberal precondition"; and, in addition, our predicate transformers compute an approximation to the weakest liberal precondition. For the purposes of this discussion, these distinctions can be ignored.
shows, at each intermediate step, predicate transformation has calculated what must be true if the remaining code is to establish \textit{postcondition}.

\[
\begin{align*}
t &= y_{init} \land x = z_{init} & \text{\textit{wp}}(S, \text{postcondition}) \\
x &= y_{init} \land t = z_{init} & (2) \\
y &= y_{init} \land t = z_{init} & (1) \\
y &= t & \text{\textit{postcondition}}
\end{align*}
\]

**Formal Proof** The second part of formal verification is the demonstration that the calculated actual semantics agree with the specified intended semantics.

When the specified precondition logically implies the calculated weakest precondition, the semantics do agree. The specified precondition will be true in every initial state allowed by the specification. From the logical implication, it follows that the weakest precondition will also hold in every initial state allowed by the specification. From the definition of weakest precondition, it follows that \( S \) brings about the postcondition in the final state, as desired. Thus the actual behavior is the intended behavior.

The formula relating the specified and weakest preconditions is the \textit{verification condition} or \textit{VC}:

\[
\text{precondition} \rightarrow \text{wp}(S, \text{postcondition})
\]

Proving the verification condition verifies the software.

To illustrate, we show the VC of the three-step swap above:

\[
(x = x_{init} \land y = y_{init}) \rightarrow (y = y_{init} \land x = z_{init})
\]

Since the conclusion of the VC differs from the hypothesis only by rearrangement, the VC is easy to prove. The software is formally verifiable.

### 2.1.3 Summary

- The specified precondition and postcondition describe the intended behavior of the software.
- Predicate transformation is symbolic execution for the purpose of determining the actual semantics of the software.
- The logical formula connecting the actual semantics and the intended semantics is the verification condition (VC).
- Proving the VC shows that the software's actual semantics are the intended semantics.
2 OVERVIEW OF THE PENEOLE SYSTEM

2.2 Formal Specification in Larch/Ada

We have described, in general, formal specification using Floyd-Hoare triples. This section outlines formal specification using the Larch/Ada language. Larch/Ada consists partly of an adaptation of the Floyd-Hoare notation, and partly of a means for defining mathematical vocabulary. Its written form is designed to be readable by the Penelope verification environment. In this section, we show a Larch/Ada specification as it looks in Penelope.

2.2.1 Mathematics and Programming

There are both mathematical and programming expressions in a Floyd-Hoare triple. In a triple

\{precondition\} S \{postcondition\}

the statement S is written in a programming language (in this case Ada), while the precondition and postcondition are written in the specification language (in this case Larch/Ada).

Although some programming languages are mathematically oriented, they are not purely mathematical. The essential difference is that programming languages are executable while mathematical language is descriptive.

Consider for example the Ada operation + and the mathematical operation +. The ada expression x + y invokes a computation that may return a value, but may also raise a numeric exception if the arguments are too large. The mathematical expression \( z + y \), on the other hand, is completely descriptive: it simply denotes the sum of the values of the variables. The Ada expression is an instruction; the mathematical expression is a description.

In Larch/Ada, as in all specification languages in the Larch [10] family, the distinction between the two languages is carefully maintained. Larch/Ada cleanly separates mathematical and programming concerns. Mathematics is done in a language in which terms have their ordinary mathematical meanings. Programming is done in Ada, where expressions have their ordinary computational effects.

2.2.2 The Two-Tiered Approach

Larch/Ada, following the the Larch paradigm, has two major divisions or tiers: one for pure mathematics, one for an interface between mathematics and programming. The mathematical tier defines the mathematical vocabulary used in the specification. The interface tier specifies the behavior of programs.

The Mathematical Tier In the mathematical tier we employ the Larch Shared Language, common to the entire Larch family, to group together declarations of kinds of mathematical objects, declarations of functions, and definitions of objects and functions into collections called traits. In a trait, we first
2.2 Formal Specification in Larch/Ada

declare sorts—collections of abstract mathematical objects. There are sorts of integers, of lists, of stacks, of queues, of trees, and so on. We next declare the functions that operate on the sorts. Examples of functions from the sort of stacks are push, pop, top, and so on. We then define the functions mathematically with axioms and lemmas. An example is the axiom on stacks, \( \text{pop(push(element, } \text{S})) = \text{element} \).

The Interface Tier In the interface tier, we use the Larch/Ada interface language to describe the correspondence between the mathematical and programming realms. Part of the correspondence is built into Larch/Ada. Ada types are based on the Larch sorts modeling them. That is, Ada objects of a given type take their values in the corresponding Larch sort. For instance, Ada type integer is based on the mathematical integers of Larch sort Int. The set of all possible values of the type form a subset of the sort. The possible values of Ada type integer range from minint to maxint within sort Int, which is infinite.

Two-Tiered Specification Building on this foundation, we specify the software. There are special idioms for specifying the values of objects, for specifying the conditions that must hold when a program is called, for specifying what will be true upon normal exit, and for specifying the circumstances under which exceptions will be propagated and the consequences of doing so.

An example of the interplay of the two tiers is shown below in the Larch/Ada specification of fact, an Ada function to compute factorials. In Penelope, Larch/Ada appears as Ada commentary, set off with "--I". The specification below shows a Larch trait, the Ada function, and the pre- and postconditions of the triple after the function.

```
TRAIT T IS
| INTRODUCES
| factorial: Int-> Int;
| AXIOMS: FORALL [m:Int]
| f0: factorial(0) = 1;
| fplus: (m > 0) -> (factorial(m) = m*factorial(m-1));
| END AXIOMS;
| LEMMAS:
| END LEMMAS;

FUNCTION fact(n : IN integer) RETURN integer;
| WHERE
| IN (n>=0);
| RETURN factorial(n);
```
OVERVIEW OF THE PENELLOPE SYSTEM

--| END WHERE;

Trait T, appearing before the Ada function, introduces the mathematical factorial function, then defines it through axioms \( f_0 \) and \( f_{\text{plus}} \).

Note that because we use the ASCII character set for machine-readable Larch/Ada, our mathematical language looks somewhat like a programming language. There is no possibility for confusion, however, if the reader bears in mind that the "--|" marker precedes mathematical notation.

The vocabulary newly defined in trait T is used in the Larch/Ada interface, between "WHERE" and "END WHERE".

The \( \text{IN} \) annotation gives the precondition of fact: the value of the argument n must be non-negative.

The \( \text{RETURN} \) annotation gives the postcondition: the value returned by the function must be \( \text{factorial}(n) \).

Note: While Larch/Ada has idioms for side-effects on globals, and for termination by propagating exceptions, those idioms do not appear here. Their absence means that fact must have no side effects and must not terminate exceptionally.\(^7\)

2.2.3 Summary

- Larch/Ada cleanly separates mathematical and programming concerns.
- The Larch/Ada mathematical tier provides the mathematical vocabulary for the interface tier.
- The Larch/Ada interface tier makes explicit connections between mathematics and programming, specifying program behavior in mathematical terms.

\(^7\)This statement is almost correct as it stands. Please see the discussion of correctness in Section 4.4.1.
2.3 Formal Verification in Penelope

We have described, in general, formal verification using predicate transformation and proofs of VCs. This section outlines formal verification using the Penelope system. In this section, we show how we use Penelope to evaluate a piece of software.

2.3.1 Computer-Assisted Verification

Penelope is an environment for verifying Ada programs. From Ada input and Larch/Ada specifications, Penelope automatically performs the predicate transformations, calculating the pre- and postconditions and producing verification conditions. The verifier then uses Penelope’s built-in proof editor to prove the VCs.

The entire process is interactive and incremental. Any user of a spreadsheet will find Penelope’s approach familiar. The verifier edits the software, the specifications, or the proofs. Each change is propagated throughout the file by predicate transformation. Viewing the recalculated results, the verifier makes another change. The process continues until the verifier has proved all the VCs. The final product is verified, legal Ada code.

2.3.2 Larch/Ada in Penelope

As we mentioned in the last section, Larch/Ada appears in a Penelope file as Ada commentary, set off by the special mark “--!”. Likewise, displayed preconditions, VCs, and proofs are Ada commentary. Thus the output of Penelope will always be a legal Ada program and verified output will be a correct Ada program.

2.3.3 Evaluating Existing Software

Proving Correctness When we use Penelope to verify an existing Ada program, we must add our Larch/Ada specifications to the Ada program. As we do so, Penelope interactively computes and displays the VCs that we must prove. When we have proved them, we have formally proved that the software meets its specification.

Detecting Errors When we cannot prove program VCs, it may be because the software does not meet its specification or because we simply have not thought of the correct approach to the proof.

However, when the software is incorrect, we can usually find out by examining the proofs. Having located an error this way, we may confirm it with a special-purpose test run of the software. Penelope augments testing, rather than replacing it. Formal verification can demonstrate correctness; testing can demonstrate incorrectness.
Below, we show how we used Penelope to evaluate two versions of the Ada procedure `swap`: one correct, one incorrect. Both versions have the same specification:

```ada
PROCEDURE swap(x, y : IN OUT integer)
   --! WHERE
   --!      OUT ((x=IN y) AND (y=IN x));
   --! END WHERE;

   If we had wanted to restrict the initial state, we would have explicitly specified the precondition with an IN annotation. Not giving one implicitly specifies a precondition of TRUE. Since TRUE holds in any state, we are allowing any initial state for `swap`.

   With the Larch/Ada OUT annotation, we are specifying that the final value of x is the initial value of y, and vice versa.

   It is trivial to verify the correct version. The completed proof of the VC follows the specification, set off by the marker "--!". The computed precondition of the procedure body is also set off this way.

   --! Verification status: Verified

PROCEDURE good_swap(x, y : IN OUT integer)
   --! WHERE
   --!      OUT ((x=IN y) AND (y=IN x));
   --! END WHERE;
   --! VC Status: proved
   --! BY synthesis of TRUE
   --! []

   IS
      t : integer;

BEGIN
   --! PRECONDITION = ((y=IN y) AND (x=IN x));
   t := x;
   x := y;
   y := t;
END swap;
```

After we entered our specification, Penelope calculated the precondition of the procedure body, and from the precondition, Penelope calculated the VC. Since \( x = \text{IN} x \) in the initial state (and likewise for \( y \)) Penelope was able to simplify the VC to TRUE before displaying it for proof. We proved the trivial VC immediately. Since the proof is completed, Penelope does not display the VC.

We may locate the error in the incorrect version by inspecting the VC:
2.3 Formal Verification in Penelope

```ada
--! Verification status: Not verified
PROCEDURE bad_swap(x, y : IN OUT integer)
  --| WHERE
  --| OUT ((x=IN y) AND (y=IN x));
  --| END WHERE;
  --! VC Status: ** not proved **
  --! >> (x=y)
  --! <proof>
  --! []

IS
  t : integer;
BEGIN
  --! PRECONDITION = ((x=IN y) AND (x=IN x));
  t:=x;
  y:=t;
  x:=y;
END swap;
```

Having no assumptions about \( x \) and \( y \) in general, we could not prove the VC. Looking at the code, we saw that the equation \( x = y \) arises from the incorrect order of the assignments. The program will always set \( x \) and \( y \) to the same value: namely, \( \text{IN} \ x \).

2.3.4 Summary

- The user of Penelope enters Ada software and Larch/Ada specifications.
- Penelope computes preconditions and VCs.
- The user edits proofs of the VCs. Penelope checks the proofs for correctness.
- When all VCs are proved, the Ada software is verified.
- Unprovable VCs are evidence of errors.
3 Test-Case Software

So that we could demonstrate formal specification and verification in Penelope on actual software, rather than artificial examples, NASA furnished ORA with a commercially obtained copy of Grady Booch's Calendar.Utilities package. This package provides several convenient ways to represent and manipulate times and dates between the years 1901 and 2099 A.D., going considerably beyond what is built into the Ada language. The full Ada text of Calendar.Utilities appears in Appendix C. Here, we describe the package conceptually.

3.1 Data Types

Dates and times are expressed in units of years, months, days, hours, minutes, seconds and milliseconds.

A date can be expressed two ways. The first is by giving the year, the month, and the day of the month. The second is by giving the year and the day within the year. Both (1991, February, 2) and (1991, 33) express the same date.

The expressions of date and time are represented by three kinds of data type: numeric, enumerated, and string.

3.1.1 Numeric Representations

There are two explicit numeric representations of date and time, and one implicit representation of date.

- **Type Time**
  
  This record type represents a date and time by year, month, day, hour, minute, second, and millisecond.

- **Type Interval**
  
  This record type represents passage of time in units of days, hours, minutes, seconds, and milliseconds.

- **Year and Day (Implicit)**

  Several functions of the package have the_year and the_year_day in their argument lists to represent the date.

3.1.2 Enumerated Representations

Names of the months and days of the week are represented by enumeration types.
3.2 Operations

* Type Month Name
  (January, February, March, April, May, June, July, August, September, October, November, December)

* Type Day Name
  (Monday, Tuesday, Wednesday, Thursday, Friday, Saturday, Sunday)

Note that the week is unconventionally listed from Monday instead of its first day, Sunday. This unconventionality can lead to confusion in reading the code of the package unless it is kept in mind.

3.1.3 String Representations

Dates and times represented by strings can each have two formats.

* Date
  - Full (US standard)
    Example: "March 2, 1991"
  - Month-Day-Year
    Example: "03/02/91"

* Time
  - Full (hours, minutes, seconds, milliseconds, am/pm)
    Example: "01:23:45:67 pm"
  - Military (24 hour clock)
    Example: "13:23:45:67"

3.2 Operations

There are two categories of operations on data types: extractors of information and converters between representations. We give informal, English descriptions of the operations here. We formally specify them in Section 4.2.2.

When two or more functions share a name, we briefly indicate in a parenthetical comment what kind of argument each function takes.

3.2.1 Extracting Information

* Is Leap Year
  This Boolean function tells whether a given year is a leap year.

* Days In (Year)
  This function calculates the number of days in a given year.
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- **Days_In (Month)**
  This function calculates the number of days in a given month.

- **Day_Of (Year, Day)**
  This function calculates the day of the week of a given year-day pair.

- **Day_of (Time)**
  This function calculates the day of the week of a date and time given in the representation of type *Time*.

- **Period_of**
  This function tells whether a given date/time is a.m. or p.m.

### 3.2.2 Converting Between Representations

- **Month_of (Month Number)**
  This function converts the representation of months from numeric to enumerated.

- **Month_of (Month Name)**
  This function converts the representation of months from enumerated to numerical.

- **Time_of (Year, Day)**
  This function converts dates from the year-day representation to the *Time* representation.

- **Time_of (Time)**
  This function converts time from the *Calendar.Utilities.Time* representation to the built-in Ada *Calendar.Time* representation.

- **Time_of (Calendar.Time)**
  This function converts time from the built-in Ada *Calendar.Time* representation to the *Time* representation.

- **Date_Image_of**
  This function converts dates from the *Time* representation to a string representation.

- **Value_of (Date/Time Strings)**
  This function converts date and time from a string representation to the *Time* representation.
3.2 Operations

- **Duration_Of**
  This function converts time from the `Interval` representation to the built-in Ada `Duration` representation.

- **Interval_Of**
  This function converts time from the built-in `Duration` representation to the `Interval` representation.

- **Image_Of**
  This function converts time from the `Interval` representation to a string representation.

- **Value_Of** (Interval String)
  This function converts time from a string representation to an `Interval` representation.
4 A Demonstration of the Penelope System

This section describes our formal verification of the Calendar_Utilities package using Penelope. First, we present an overview of the demonstration. Next, we describe the specifics of the formal specification. Last, we give a complete account of the formal verification.

4.1 Overview of the Demonstration

During the first phase of this project, we developed Larch/Ada specifications for every subprogram in the Calendar_Utilities package. These specifications provided the context for informal mathematical discussion of the correctness of the subprograms. We noted in the interim report that most of the subprograms appeared to be correct, but that three subprograms were suspect.

In the second phase of this project, we used the Penelope Ada verification environment to investigate correctness formally. Our intention was to give a full, mathematically sound treatment of as much of the Ada code as was feasible with the resources available. We largely accomplished our intentions, but we must state some reservations. We found that, even on a Sun SPARCstation, a verification of the entire package at one time was beyond the current capabilities of Penelope.

The bookkeeping information for each individual verification was kept in the buffer at all times, seriously slowing the editor. The upcoming version of Penelope solves this problem, supporting libraries of verified components. After we verify a function, we will be able to store its verified text in a library and eliminate the bulk of its text from the buffer. Any time we need information about the function, we will retrieve it from the library.

We were also hampered by Penelope's incomplete support for strings. Penelope supports only unconstrained arrays and does not have string literals. We acknowledged both limitations and narrowed our scope to those subprograms in the package that do not involve strings. Six subprograms of twenty involve strings; of the remaining fourteen, we treated eleven in complete detail.

To perform the verification, we needed to expand both the Ada and the Larch/Ada text beyond what we presented in the interim report. These expansions were in three categories: additional specified Ada code required for a complete verification; additional theoretical facts; and additions and modifications to the Ada code necessary to circumvent limitations of Penelope.

The specification required enlargement. There are several dependencies in Calendar_Utilities involving many calls to subprograms in other packages. To represent formally the effect of these calls within Penelope, we needed to specify the called subprograms. For each package upon which Calendar_Utilities
depends, we needed an (Ada) package specification, fully specified in Larch/Ada.

We also had to enlarge the mathematical theory under which we verified Calendar.Utilities. Our specification included several facts of arithmetic that are not built into Penelope and had to be explicitly stated in the traits. Among these traits are certain facts about modular arithmetic, rational numbers, etc.

The last expansion included additions and modifications to the Ada code. Most of the modifications to the verified Ada code were slight. One example is the translation of FOR loops into WHILE loops. Penelope will support FOR loops in the next release. Another example involves type conversion. Because Penelope does not currently support type conversion, we wrote special-purpose Ada functions whose annotated effect is to convert objects of one type into objects of another. The major modification was our treatment of the fixed-point type duration as a rational number type, constructed as a record. The reasons for this modification are described below in Section 4.4.1.

The formal treatment of Calendar.Utilities was the largest undertaking yet for Penelope: 2938 lines\(^{10}\) of code, annotation, and verification, of which 441 lines were Ada code. Both the specification and verification phases of the project have demonstrated their value in assuring correctness and detecting errors in actual Ada programs.

---

\(^{10}\) before reformatting for this report
4.2 Specification

In Section 2, we described the general aspects of formal specification and the Larch/Ada language. In this section, we discuss Larch/Ada traits further, and we present detailed specifications of the Calendar_Utilities subprograms.

4.2.1 Mathematical Preliminaries

The specification of a program is written in the context of a logical theory defined by a single main trait, in which all of the mathematical vocabulary is introduced and defined. In a modular fashion, the main trait is built up from smaller component traits. Any trait may include another trait as a component, using a facility much like the Ada with facility for library unit dependencies. In this section, we describe the various component traits used for the specification.

Component traits comprise two classes: a class of traits that the system implicitly generates in response to the Ada text, and a class of traits that the user explicitly constructs.

System-Generated Traits  Just as an Ada program runs within the environment of the package standard, the main Larch trait implicitly includes (as though with an include statement) a standard trait that defines Ada's built-in data types. The standard trait defines the following: the integer sort Int and its associated operations (+, *, etc.); the enumeration sort AdaBool with its literals (TRUE, FALSE) and its operations (AND, OR, NOT, etc.); and other basic sorts, objects, and operations. Ada type integer is based on Larch sort Int, boolean is based on AdaBool, and so on. This standard trait essentially gives the theory governing Ada package standard.

In addition to the standard trait, the system implicitly generates other traits to provide the abstract data sorts on which Ada's constructed types are based, together with the theory of those sorts. For example, if a user declares the Ada type

\[
\text{TYPE color IS (red, amber, green);}\]

the system implicitly generates a Larch/Ada trait and implicitly includes the trait in the main trait for the Ada program. This trait makes available a new enumerated sort on which to base color, together with the theory that makes it the proper enumerated sort.

In general, when a type \( T \) occurs in a program, Penelope creates the sort on which \( T \) is based. The mathematical operations on the sort use similar syntax to Ada operations on \( T \), and so can be understood with little difficulty.

The Penelope system generates an internal name for each sort it creates. For example, the internal name for the sort on which the enumeration type color is based, is essentially a listing of all its enumeration literals

\[(\text{red, amber, green})\]
4.2 Specification

Since such internal names can become unwieldy, we have added notational extensions to Larch by which the user may introduce more convenient names for these sorts. A full description of implicitly generated traits and our notational extensions to Larch is given in ORA Technical Report TR 89-34 [7].

**User-Constructed Traits** The user can construct traits to gain additional expressiveness or convenience. For example, in specifying Calendar.Utilities, we constructed traits to introduce new sorts, to give convenient names to existing sorts, to define conversion factors between time units, and to define various auxiliary functions from one time representation to another.

Traits contain both axioms and lemmas. The axioms express the theory in the form best suited to mathematical exposition. The lemmas encapsulate essential facts of the theory in a form best suited to proving VCs. In constructing our traits, we tried to write the axioms and lemmas in a style that appeals directly to people's usual understanding of the calendar. For example, when specifying the predicate is_leap_year, our aim was to provide a more straightforward notion of a leap year than the code for that function can provide and a more clearly stated specification than dense mathematics would provide.

**Current Limitations of Traits in Penelope** While the mathematical theory underlying Penelope is mature and adequate for formal verification, Penelope itself is still being developed. Consequently, we had two limitations on traits as input.

The first limitation is Penelope's syntax for traits. The Penelope syntax for traits is an extract of and somewhat different from the syntax in the Larch manual, although most of the differences are minor, reflecting the embedding of traits as commentary in Ada code.

The other limitation involves sortchecking of the logical language. Penelope's sortchecking is still being developed. The present sortchecking is too lenient, which means that the user must perform some of the sortchecking manually, exercising care not to present certain kinds of ill-sorted terms to Penelope. Only record terms concerned us directly in verifying Calendar.Utilities.

Currently, Penelope has only one record sort, AnyRecordSort, and treats all record fields as naming components of this most general record sort. Since Ada record types are based on Larch/Ada record sorts, the user must never employ the same field name in two distinct record types, for otherwise, there would be an invalid overloading of the corresponding Larch record field name. We respected this limitation in defining record types.

Penelope effectively turns off sortchecking when treating record components, assigning them the most general sort AnySort, thus discarding information about their actual sorts. Consequently, sortchecking finds apparent ambiguities in perfectly unambiguous record terms. If a function g is overloaded, there may be no way for Penelope to determine the proper sort of g(R.f)
For instance, in Calendar_Utilities, we have the sort fixnum representing rational numbers. We overload multiplication, so that Penelope has both these signatures in its symbol table:

"*" : Int, Int → Int
"*" : Int, fixnum → fixnum

As a result, Penelope treats the following equation as ambiguous:

\[(i\cdot m).\text{numer} = i\cdot(m.\text{numer})\]

The term on the left of the equation may have any sort, so the target sort of the second \(\cdot\) might be either Int or fixnum. The sort of \(m.\text{numer}\) can be either Int or fixnum. Thus, Penelope cannot determine which signature to use.

To direct the sortchecker in these cases, we remove the apparent ambiguity, employing identity functions from given sorts to themselves. Applying an identity function informs the sortchecker of the sort of the argument term while preserving the term's mathematical value. We can unambiguously write the formula as follows:

\[(i\cdot m).\text{numer} = \text{Int}_\text{id}(i\cdot(m.\text{numer}))\]

Now, the only choice of signature for \(\cdot\) is the first signature

"*" : Int, Int → Int

Summary of the Traits  The full text of the Penelope verification output for Calendar_Utilities given in Appendix E begins with six traits that we wrote in order to carry out the verification. Here is a brief summary of each trait.

- Trait Z
  Many, but not all, facts of arithmetic are built into Penelope. Trait Z contains additional facts about division and modular arithmetic. This trait also has an explicit identity function on the integers, which is useful for removing ambiguities during sortchecking.

- Trait fixed_point
  The theory of fixed point numbers is not yet built into Penelope. We use this trait to provide needed facts.

- Trait sort_names
  In this trait, we give all of the names of sorts that we later use to define the vocabulary of the Larch/Ada specification. The Ada types of Calendar_Utilities are based on the sorts of this trait. Some sorts have a "good" predicate that asserts that a given value within the sort is a
legitimate representation of a date and time. The "_tic_" functions represent the values of Ada attributes. The trait also defines miscellaneous arithmetic and sort-forcing functions.

We introduce the enumeration sort _century_ in order to provide the vocabulary to document that the Ada function _Value Of_ provided in package _Calendar Utilities_ is correct only for argument dates in the twentieth century:

```plaintext
SORT century IS (twentieth, twentyfirst)
```

Without _century_ terms, we would be unable to express mathematically that "02/27/55" might refer equally well to 1955 or 2055.

We also assign names, or aliases, to the sort _Int_. Penelope permits one or more aliases for a sort, which may be used to make the mathematics clearer and Penelope easier to use. Aliases are especially useful for clarity when several Ada types are based on the same mathematical sort.

In the mathematical tier of this trait, we define the integers only once. All integer types and subtypes are based on the single infinite sort _Int_. Each type determines a subset of _Int_, over which its values range.

Hence the years, months, etc., of _Calendar Utilities_ are all based on the sort _Int_. To declare the signatures of our mathematical functions clearly, it is helpful to use the following aliases:

```plaintext
SORT years IS Int
SORT months IS Int
SORT month_days IS Int
SORT year_days IS Int
SORT absolute_days IS Int
SORT hours IS Int
SORT minutes IS Int
SORT seconds IS Int
SORT milliseconds IS Int
```

This signature declaration from trait _time representations_

```plaintext
day_of_year: years, months, month_days -> year_days
```

shows clearly what the values in the arguments mean, whereas

```plaintext
day_of_year: Int, Int, Int -> Int
```

would be unenlightening.

There are many other aliases of this clarifying nature in _sort names_. Separate from them is the alias
catu ALIASES Int

We will use this alias later when we introduce a very short, but unspecified, unit of time, the catu (Calendar Atomic Time Unit). Catus relate the abstract time values from the implementation of Calendar.time to the time values of Calendar.Utilities.time.

The abstract sort Calendar.time.sort may have a smaller granularity than the millisecond: we do not know. By choosing to work with the small but unspecified catu, we do not have to know. We require of the catu only that it be positive and of sufficiently small granularity to represent faithfully times expressed in either setting. We treat it as an unspecified positive integer constant in the remainder of the specification.

- Trait conversion_factors
  
  This trait defines the functions for converting from hours to seconds, days to milliseconds, etc.

- Trait time_representations
  
  This trait encapsulates the theory of the individual time representations. We concentrate on extracting information from time values of the sort Time.sort on which the type Time of Calendar.Utilities is based. For instance, we find the number of days in a given month in a given year through the function days_in_month.

  We also define predicates that indicate whether formal time values represent possible times: good_year, good_month, good_month_day, and so on. We use these predicates to define the predicate good_time on an entire Time.sort value

  (the_year => 1990,  
  the_month => 2,  
  the_day => 29,  
  the_hour => 12,  
  the_minute => 34,  
  the_second => 56,  
  the_millisecond => 789)

  Since there is no February 29, 1990, this formal record value t does not represent an actual time. Accordingly,

  \text{good\_time}(t) = false

  We can use these predicates to document that a given Ada subprogram will behave correctly only when its arguments represent possible dates and times.
4.2 Specification

- Trait time_representation_conversions
  This trait encapsulates the theory of converting from one time representation to another.

4.2.2 Detailed Specifications

Here we present and discuss the Larch/Ada specification of every subprogram in the package Calendar_Utilities obtained from NASA. The mathematics used in the specification is found in the traits discussed above in Section 4.2.1. The disambiguating comments after overloaded function names are the same as in Section 3.

The style of each specification is much the same as every other. After reading the first few, as well as the specification of time_of (Time), the reader may wish to proceed to the general discussion of the specifications in Section 4.3. The specification of time_of (Time) deserves attention because it is the first in which the Ada type to Larch sort correspondence is discussed in full depth.

Function is_leap_year

FUNCTION is_leap_year(the_year : IN year) RETURN boolean;
--| WHERE
--|  IN (good_year(the_year));
--|  RETURN is_leap_year(the_year);
--| END WHERE;

This function calculates whether or not the given year is a leap year. The IN annotation uses the predicate good_year to restrict the value of the argument the_year to the acceptable interval [1901, 2099]. The RETURN annotation specifies that the returned boolean has value true if and only if the_year is a leap year, using the predicate is_leap_year to do so.

Note from the absence of global annotations that this function must have no side effects. Similarly, since there are no propagation annotations, this function must not terminate by propagating an exception.

Function days_in (Year)

FUNCTION days_in(the_year : IN year) RETURN year_day;
--| WHERE
--|  IN good_year(the_year);
--|  RETURN days_in_year(the_year);
--| END WHERE;

This function calculates the number of days in a given year. The IN annotation restricts the value of the argument the_year to the acceptable interval [1901, 2099]. The RETURN annotation specifies that function computes the number of days in the year. There are to be no side effects or propagated exceptions.
Function `days_in (Month)`

```ada
FUNCTION days_in(the_month : IN month; the_year : IN year) RETURN day;
--| WHERE
--|   good_month(the_month);
--|   good_year(the_year);
--| RETURN days_in_month(the_month, the_year);
--| END WHERE;
```

This function calculates the number of days in a given month. The year must also be given because of February and leap years. The first `IN` condition constrains the value of `the_month` to lie in the interval `[1, 12]`. The second `IN` annotation restricts the value of the argument `the_year` to the acceptable interval `[1901, 2099]`. The `RETURN` annotation specifies that the number of days in the month is to be computed. There are to be no side effects or propagated exceptions.

Function `month_of (Month Number)`

```ada
FUNCTION month_of(the_month : IN month) RETURN month_name;
--| WHERE
--|   good_month(the_month);
--| RETURN month_name_sort_tic_val((the_month-1));
--| END WHERE;
```

This function converts numerical months to the corresponding months within the enumeration type (January, February, ..., December). The `IN` annotation restricts the numerical month to the interval `[1, 12]`. The `RETURN` annotation specifies the enumeration value corresponding to the numerical month.

The language of this specification requires some explanation. First, the Larch/Ada function `month_name_sort_tic_val` represents the values of the Ada attribute function `month_name'val`

The name of the Larch/Ada function is intended to suggest that it takes values in sort `month_name_sort` on which Ada type `month_name` is based. The "tic" is used to represent the tic (apostrophe), which is not acceptable as part of Larch/Ada function names. The definition of `month_name_sort_tic_val` is given in trait `sort_names`, found in Appendix E.

Second, months of the calendar are numbered from 1, while Ada's enumeration types are numbered from 0. In Ada, `pos(January)` has value 0, not 1. Subtracting 1 from `The_Month` is the necessary adjustment.

There are to be no side effects or propagated exceptions.
4.2 Specification

Function month_of (Month Name)

\[
\text{FUNCTION month_of} (\text{the\_month} : \text{IN month\_name}) \text{ RETURN month;}
\]

-\[\text{-WHERE}
\]
-\[\text{-RETURN (month\_name\_sort\_tic\_pos(\text{the\_month} +1)};\]
-\[\text{-END WHERE;}\]

Months in the enumeration type (January, February, ..., December) are converted to the corresponding numerical months. The RETURN annotation specifies the enumeration value corresponding to the numerical month.

The language of this specification requires some explanation. The Larch/Ada function \text{month\_name\_sort\_tic\_pos} represents the values taken by the Ada attribute function \text{month\_name'pos}. Subtracting 1 from \text{The\_Month} is necessary to adjust from the 0-based numbering of Ada enumeration types to the ordinary 1-based numbering of months. For more information, please read the exposition of the preceding Ada function.

There are to be no side effects or propagated exceptions.

Function day_of (Year, Day)

\[
\text{FUNCTION day\_of} (\text{the\_year} : \text{IN year;}}
\text{the\_day} : \text{IN year\_day}) \text{ RETURN day\_name;}
\]

-\[\text{-WHERE}
\]
-\[\text{-IN good\_year\_and\_day(\text{the\_year, the\_day});}
\]
-\[\text{-RETURN day\_name\_of(\text{the\_year, the\_day});}\]
-\[\text{-END WHERE;}\]

This function calculates the day of the week for a given date. The \text{IN} annotation specifies that the year and day together constitute a valid date. The \text{RETURN} annotation specifies that the proper day of the week is calculated. There are to be no side effects or propagated exceptions.

Function day_of (Time)

\[
\text{FUNCTION day\_of} (\text{the\_time} : \text{IN time}) \text{ RETURN year\_day;}
\]

-\[\text{-WHERE}
\]
-\[\text{-IN good\_time(\text{the\_time});}
\]
-\[\text{-RETURN day\_of\_year(\text{the\_time.\_year,}}
\text{the\_time.\_month, the\_time.\_day);}\]
-\[\text{-END WHERE;}\]

This function differs from the previous \text{day\_of} function only in the representation of the given date. The \text{IN} annotation specifies that \text{the\_time} is a good representation of a date and time. The \text{RETURN} annotation specifies that the proper day of the week is calculated. There are to be no side effects or propagated exceptions.
Function time_of (Year, Day)

FUNCTION time_of(the_year : IN year;
       the_day : IN year_day) RETURN time;
--| WHERE
--|  IN good_year_and_day(the_year, the_day);
--|  RETURN t SUCH THAT (
      t.the_year=the_year
      AND
      t.the_month=month_of(the_year, the_day)
      AND
      t.the_day=day_of_month(the_year, the_day)
      AND
      t.the_hour=0
      AND
      t.the_minute=0
      AND
      t.the_second=0
      AND
      t.the_millisecond=0);
--| END WHERE;

This function converts the date from representation by a Year-Day pair to
time representation. The IN annotation specifies that the Year-Day pair must
actually represent a date. The RETURN annotation specifies that the returned
time value will represent the same date, at the instant it begins. There are to
be no side effects or propagated exceptions.

Function period_of

FUNCTION period_of(the_time : IN time) RETURN period;
--| WHERE
--|  IN good_time(the_time);
--|  RETURN (IF (the_time.the_hour<12) THEN am ELSE pm);
--| END WHERE;

This function computes whether a given time of day is before noon or not.
The IN annotation specifies that the_time is a good representation of a date
and time. The RETURN annotation specifies that am is to be returned for times
before noon, and that pm is to be returned for times from noon onward. There
are to be no side effects or propagated exceptions.

Function time_of (Time)

FUNCTION time_of(the_time : IN time) RETURN calendar.time;
4.2 Specification

```
-- | WHERE
-- |   IN good_time(the_time);
-- |   RETURN time_to_cal_time(the_time);
-- | END WHERE;
```

This function converts time representations to calendar.time representations of time and date. Before we discuss its annotations, recall that the value of the Ada variable the_time is in Larch sort time_sort since that is the sort on which the Ada type time is based.

The IN annotation specifies that the_time is a good representation of a date and time. The value of the_time belongs to Larch sort time_sort. Applying the mathematical function time_to_cal_time to this value yields the corresponding equivalent value in the sort calendar.time_sort. The RETURN annotation specifies that this equivalent value is the value returned by the Ada function.

There are to be no side effects or propagated exceptions.

Function time_of (Calendar.Time)

```
FUNCTION time_of(the_time : IN calendar.time) RETURN time;
-- | WHERE
-- |   RETURN cal_time_to_time(the_time);
-- | END WHERE;
```

This function differs from the previous time_of function basically in that the representations of time are reversed: the conversion proceeds in the opposite direction. The IN annotation is implicitly TRUE: all calendar.time values are valid. The RETURN annotation specifies that value returned is the equivalent, in the time representation, of the original value, which is in the calendar.time representation. There are to be no side effects or propagated exceptions.

Function time_image_of

```
function time_image_of (the_time : in time;
                       time_form : in time_format)
return string;
-- | WHERE
-- |   IN good_time(the_time);
-- |   RETURN time_to_time_string(the_time, time_form);
-- | END WHERE;
```

This function extracts the time of day from the given time representation and converts it to a string representation in the given format. The IN annotation specifies that the_time is a good representation of a date and time. The RETURN annotation specifies that the returned string represents the input time in the chosen time string format. There are to be no side effects or propagated exceptions.
Function date_image_of

function date_image_of (the_time : in time;
                        date_form : in date_format)

    return string;

--| WHERE
--|   IN good_time(the_time);
--|   RETURN time_to_date_string(the_time, date_form);
--| END WHERE;

This function differs from the above in that it converts the extracted date, not time, to the chosen string representation. The IN annotation specifies that the_time is a good representation of a date and time. The RETURN annotation specifies that the returned string represents the input date in the chosen date string format. There are to be no side effects or propagated exceptions.

Function value_of (Date/Time Strings)

function value_of (the_date : in string;
                    the_time : in string;
                    date_form : in date_format;
                    time_form : in time_format)

    return time;

--| WHERE
--|   RETURN strings_to_time( the_date,
--|                          the_time,
--|                          date_form,
--|                          time_form,
--|                          twentieth
--|);
--| RAISE lexical_error <=>
--|   (NOT well_formed_date_string(the_date, date_form))
--| OR
--|   (NOT well_formed_time_string(the_time, time_form));
--| END WHERE;

This function converts date and time from string representation to time representation. The absence of an IN annotation indicates that any input is acceptable. The RETURN annotation specifies that the returned time value is to be equivalent to the representation of time and date in the given input formats. Notice that we have explicitly documented that the code treats every two-digit year as belonging to the twentieth century. The RAISE annotation specifies that the function will raise lexical_error if and only if the string input is invalid. There are to be no side effects.
4.2 Specification

Function duration_of

FUNCTION duration_of(the_interval : IN interval)
    RETURN builtin.duration;
--| WHERE
--| RETURN interval_to_duration(the_interval);
--| RETURN result SUCH THAT good_duration(result);
--| END WHERE;

This function converts time in interval representation to time in duration representation. The absence of an IN annotation indicates that any input is acceptable. The first RETURN annotation specifies that the returned duration value is to be equivalent to the given interval value. The second RETURN annotation is a convenience for verification. Without it, every time that duration_of is invoked, the user is likely to have to prove the predicate good_duration of the returned value. With it, the user need only prove the predicate once, within the verification of duration_of itself. Thereafter, the predicate will automatically apply to the returned result, and need not be reproved. There are to be no side effects or propagated exceptions.

Function interval_of

FUNCTION interval_of(the_duration : IN builtin.duration) RETURN interval;
--| WHERE
--| RETURN duration_to_interval(the_duration);
--| END WHERE;

This function is the inverse of the preceding function. No IN conditions need to be placed on the_duration, since all duration values are valid. The RETURN annotation specifies that the returned value is the interval equivalent of the input value. There are to be no side effects or propagated exceptions.

Function image_of (the_interval : in interval) return string;
--| WHERE
--| RETURN interval_to_string(the_interval);
--| END WHERE;

This function returns the string representation of the time in interval form. There is no IN annotation because all interval values are valid. The RETURN annotation specifies that the returned value is the string equivalent of the interval input. There are to be no side effects or propagated exceptions.

Function value_of (Interval String)
function value_of (the_interval : in string) return interval;
  --| WHERE
  --| RETURN string_to_interval(the_interval);
  --| RAISE lexical_error <>
  --| NOT well_formed_interval_string(the_interval);
  --| END WHERE;

This function converts time intervals in string representation to time intervals in interval representation. All inputs are acceptable: there is no explicit IN annotation. The RETURN annotation specifies that the returned interval value is to be the equivalent of the input string interval value. There are to be no side effects or propagated exceptions.
4.3 Discussion of the Specification

In this section, we first explain our approach for formally specifying existing software. We then describe the problems with the Calendar.Utilities package that were revealed when we specified the package.

4.3.1 Formally Specifying and Verifying Existing Software

Ideally, we formally specify software before it is written, and write the software in tandem with verifying it. Formal methods are best applied to a program when it is under development. In practice, however, we often specify and verify existing software, that is, software written previously, independently of us. Although verifying existing software applies only part of the strength of formal methods, we still can uncover problems with software.

When verifying existing software without an original specification, we cannot absolutely know what the software was meant to do. We make assumptions in writing the specification and we document those assumptions. We then verify the software with respect to our specifications.

In the case of the Calendar.Utilities package, we used the following approach to specify the software. First, for reasonable inputs, we specify that the output be what people would expect. For example, a reasonable input for a date could be March 2, 1991, and people would expect a conversion of that date to be 03/02/91 (in terms of the string representation formats in the program). Second, we specified that the input must be reasonable. The functions we were given accept unreasonable inputs without complaint. For example, the function

\begin{verbatim}
function Time_Of (The_Time : in Time) return Calendar.Time;
\end{verbatim}

as written accepts impossible dates (e.g., March 31) and returns invalid values for type Calendar.Time without raising an exception. If the invalid values are then passed as arguments to operations of package Calendar, an exception will be raised.

We used restrictive IN annotations to show that the Time_Of can be trusted only on certain inputs.

We verify the software with respect to our assumptions and specifications. The demonstrated correctness of a program assures that the program satisfies our mathematical statement of its behavior; a formally based judgement of incorrectness assures that the program does not satisfy our description of its intended behavior.

4.3.2 Discussion of the Software

For most of the Calendar.Utilities subprograms, the Larch/Ada specifications document the clearly intended design of the software. Informal inspection assured us that the design was well implemented. However, the entire package was not problem-free. We found and documented subprograms that do not
guard against unsafe arguments, that is, arguments that lead to unexpected results. Of greater concern, we also found dubious features and outright errors in the software.

**Software with No Apparent Problems** Functions such as `IsLeapYear` presented no difficulties. The IN annotation is practically trivial: the year lies in the intended range. There are no RAISE annotations. We informally determined that this function will behave as intended for all permissible inputs.

**Software with Minor Problems** We found that some functions, such as `DayOf` (Time) and `TimeOf`, do not guard against unsafe arguments. We therefore specify, for example, that the `Time` value passed to `DayOf` must not represent such impossible dates as September 31. The IN annotation defines the acceptable input values.

Contrast this with function `ValueOf` (Date/Time Strings), which does guard against unsafe values by raising exceptions. We document what these unsafe arguments are with the RAISE annotation. The IN annotation can be the trivial condition TRUE, because `ValueOf` can be called with any input.

**Problematic Software** We begin by describing some shortcomings in the software that we found in the process of performing the specification. Related to the above-mentioned numerical representations of impossible dates, there is unfaithful extraction of information represented in strings.

In the function `ValueOf` (Date/Time Strings), which takes a string and returns a `Time` record, the year from “02/27/55” becomes 1955. This assumption that all two-digit year dates represent years in the twentieth century is dubious, particularly for software written so near the end of the century. The software should have a century parameter to allow the user to select the century for the date. (We have such an argument in our specification function, but its role is purely documentary, not restrictive. The software, not merely the specification, needs to take centuries into account.)

We found this dubious feature while attempting to define an inverse to the original mathematical record-to-string conversion: the inverse did not exist because century information was being thrown away. We therefore defined the sort century to carry the necessary information.

After completing the specification, we systematically compared the software with the description of what it should do, though this comparison was of course informal. We marked a number of problems in the software for closer examination, the most salient three are listed below. We tested these problems before the verification phase and determined that two of the problems were indeed errors, while the third was a dubious feature of the software.

We had one difficulty with testing that requires explanation. Of the library units that Calendar Utilities depends upon, several were available to us only in
incomplete form and were not compilable. To run our test cases after we identified potential errors, we removed sections of the software and wrote a handful of lines so that the necessary units would compile. None of our alterations affected the software in CalendarUtilities undergoing formal analysis.

First Problem In the body of CalendarUtilities, Value_Of (Date/Time Strings) contains the following lines of software (some of the initial lines are omitted).

```plaintext
function Value_Of (The_Date : in String;
          The_Time : in String;
          Date_Form : in Date_Format := Full;
          Time_Form : in Time_Format := Full)
return Time is
  Result : Time;
  Left_Index : Positive;
  Right_Index : Positive;
begin
-- ...

  case Time_Form is
  when Full =>
    Right_Index :=
      StringUtilities.Location_Of
        (The_Character => Blank,
         In_The_String =>
           The_Time(Left_Index .. The_Time'Last)
        );

    Result.The_Millisecond :=
      Millisecond(NaturalUtilities.Value_Of
                           (The_Time
                           -- (1)***
                             (Left_Index .. (Right_Index - 1)));

    Left_Index := Right_Index + 1;
    if Period'Value(The_Time
                  (Left_Index .. The_Time'Last)) = PM then
      if Result.The_Hour /= Noon then
        Result.The_Hour :=
          Result.The_Hour + Noon;
      end if;
    end if;

  when Military =>
    Result.The_Millisecond :=
      Millisecond(NaturalUtilities.Value_Of
                           (The_Time
                           -- (1)***
                             (Left_Index .. (Right_Index - 1)));

    Left_Index := Right_Index + 1;
    if Period'Value(The_Time
                  (Left_Index .. The_Time'Last)) = PM then
      if Result.The_Hour /= Noon then
        Result.The_Hour :=
          Result.The_Hour + Noon;
      end if;
    end if;
```
-- (2)***

value_of((the_time(left_index .. the_time(last)));

end case;
return result;
exception
when constraint_error =>
raise lexical_error;
end value_of;

value_of takes two string representations of time (e.g., "FEBRUARY 27, 1955" and "01:21:06:30 PM") and extracts the corresponding numerical components to build a record representation. The assignments indicated by (1) and (2) in the code above take hundredths of a second (the "30" from the second string above) and insert the millisecond component into the record. There is no multiplication by 10, so the milliseconds in our example are recorded as 30, instead of 300. Re-conversion back to a string, using the correct function time_image_of (employing the expected division by 10) produces the different string "01:21:06:03 PM".

Second Problem In the body of package CalendarUtilities, the function duration_of (which immediately follows value_of) is as follows.

function duration_of (the_interval : in interval)
return duration is
begin
return ( duration(integer(the_interval.elapsed_days) * seconds_per_day) +
duration(integer(the_interval.elapsed_hours) * seconds_per_hour) +
duration(integer(the_interval.elapsed_minutes) * seconds_per_minute) +
duration(the_interval.elapsed_seconds) +
-- (1)***
duration(the_interval.elapsed_milliseconds / 1000));
end duration_of;

This function takes a record representation of time and returns a numerical fixed-point representation. In line (1), an integral number of milliseconds is intended to be converted into a fractional number of seconds. Thus 276 milliseconds should convert to 0.276 seconds. The conversion to fixed-point type duration occurs, however, after integer division. Millisecond values are between 0 and 999 and hence will always produce 0 when divided by 1000. Thus, duration_of wrongly converts any interval record into a whole number of seconds.
Third Problem  Consider again the function Value_Of (Date/Time Strings).

```ada
function Value_Of (The_Date : in String;
The_Time : in String;
Date_Form : in Date_Format := Full;
Time_Form : in Time_Format := Full)
return Time is
    Result : Time;
    Left_Index : Positive;
    Right_Index : Positive;
begin
    case Date_Form is
    when Full =>
        ...
        when Month_Day_Year =>
            ...
            -- (1)***
            Result.The_Day := Day(Natural_Utilities.Value_Of
            (The_Date (Left_Index .. (Right_Index - 1))));
            ...
            end case;
    ...
    end Value_Of;
```

In line (1), which occurs in the first case statement of the software, the day of the month is selected from the date string. Thus if the string is “FEBRUARY 27, 1955”, we wish to select the “27” and then convert it to the integer value of 27. An Ada slice is taken, using

```
(Left_Index .. (Right_Index - 1))
```

In our example, the Ada ‘first and ‘last values of the slice are 10 and 11, respectively. This fairly arbitrary slice is then passed to the separate package Natural_Utilities for conversion to a numerical value. A better approach might be to “normalize” the slice to one whose range was 1..2, rendering the software robust across differing implementations of the Natural_Utilities package. In fact, the package Natural_Utilities that came with the software was written assuming that strings began at position 1, and an exception was raised when we ran Value_Of on this example.
4.4 Verification

In Section 2.3, we described formal verification in Penelope in general terms. In this section, we will describe the verification of CalendarUtilities in detail.

First, we place qualifications on our results. Second, we comment briefly on the subprograms that we fully verified. Third, we discuss the errors we detected. Finally, we summarize the results.

4.4.1 Qualifications of the Results

When we state that software has been verified as correct using Penelope, we must consider three qualifications. First, we are working within Penelope's program semantics, which do not model all the possible behaviors of an Ada program. An Ada program correct in the Penelope semantics may still have certain unacceptable behaviors. Second, correctness is verified with respect to a specification that may not exactly reflect the developer's intention. Third, the correctness is verified for a modified version of the CalendarUtilities code. Because Penelope is still being developed, we had to modify the code to be in the subset of Ada that Penelope currently supports. Some modifications were major changes to the code, and others were minor changes to accommodate the limitations of Penelope.

Correctness Within Penelope’s Program Semantics  Our notion of correctness is termed partial correctness. Partial correctness means that a program is correct if whenever it is started in a state that satisfies all of its initial conditions and the program also halts, it halts in a state that satisfies all of its final conditions. The program may, however, fail to halt. A program that loops forever will be correct by our semantics.

Fortunately, failure to halt is not a concern in this effort, since the only iteration constructs in the verified code are FOR loops, which have been transformed into equivalent WHILE loops. The upper bounds have predefined maximum values. There are no recursively defined routines.

Secondly, our notion of correctness excludes the possibility of numeric overflow or storage error. The formal basis of Penelope deliberately omits them. Penelope verification is predicated upon programs not raising those exceptions.

For a fuller description and discussion of the meaning of a complete Penelope verification, see Guaspari [9].

Specifications  The software is proved to meet specifications that we supplied. If our specifications are not the proper ones, the verification of the software is irrelevant. For the verification to be relevant, we must reflect the intent of the developer.

We must also define the logical theory correctly. If the vocabulary from the theory does not have its intended meaning, or worse yet, if the theory is
4.4 Verification

self-contradictory, the verification is suspect. Furthermore, the asserted lemmas may not actually follow from the axioms. Currently, the only safeguard against these defects is the expertise of the verifier. Efforts are underway to provide automated assistance to users of Penelope in constructing theories.

Major Changes to the Code There are four types representing time in package Calendar.Utilities. There is the private type Time from the package Standard.Calendar, the record type Time of the package Calendar.Utilities, the record type Interval of the package Calendar.Utilities, and the built-in fixed-point type Duration. The first three types presented no problems, but we had to make major changes to the code to treat the last type.

The Ada Reference Manual does not specify a concrete implementation for the private type Time, nor does the concrete type matter so long as we are able to represent values of types year_number, month_number, day_number and day_duration as objects of type time in a manner that respects the operations. We must be able to convert to type time, add, subtract, compare and subsequently convert back to the correct values by means of the functions in the package. Beyond this, the particulars of type time are irrelevant.

We used integer as the concrete type for Time: it satisfies all the necessary conditions. We conceive of time as integer multiples of a fundamental unit, the catu (calendar atomic time unit), of which all of our other time units are integer multiples. The traits describe the theory for converting between all our discrete representations of time, all based on the catu.

Everything would be completely straightforward if it were not for the fixed-point type duration. ORA has addressed the theory of real number types [11], and real number verification will be melded with Penelope in Penelope/Ariel, schedule for release in 1992. In the meantime, we must give some treatment of the fixed-point type Duration.

We changed the Ada declaration of Duration to be a record type pairing numerator and denominator; we based all fixed-point numbers and operations on the rational numbers under addition and multiplication. In doing so, we assumed that the error inherent in rounding, addition, assignment, and so on is too small to affect the basic correctness of our results.

Because fixed point operations in Ada are not exact, while our rational operators are, a critic could reasonably argue that our verification should be performed again in Penelope/Ariel, which supports real number types. We feel, however, that our treatment of fixed-point types was sufficient for us to certify the correctness of some subprograms and to detect the incorrectness of others. The differences between rational and fixed-point operations should be negligible. We would expect no surprises under subsequent re-verification.

Accommodating Limitations of Penelope To accommodate the limitations of our current editor, we made minor changes to the code and performed
some tasks manually. The changes we made to the code were innocuous. These changes included translating the Ada text to lower case, using the fully qualified forms of several names, converting from one type to another with function calls instead of with explicit type conversions, translating FOR loops to equivalent WHILE loops. In addition, we altered the form of certain procedure calls in order to satisfy Penelope's conservative restrictions against potential aliasing.

We removed the declarations of exceptions because Penelope does not yet support their Ada declarations; they are, however, implicitly declared by mention in Larch/Ada. Finally, we changed named parameter associations to positional parameter associations. None of these changes affected the Ada semantics.

We overcame other limitations by doing manually what Penelope does not yet do automatically. We explicitly coded range constraint checks. We type-checked Ada expressions by hand. We simulated Larch/Ada attribute functions by functions we defined ourselves. We simulated Larch/Ada aggregates similarly. All of this work was performed in accordance with our mathematical theory of verification.

The details of these changes and manual tasks are described below.

- Restriction to lower case

Ada identifiers and reserved words are case-independent (RM 2.3[3], RM 2.9[4]). The Ada object obj may be denoted by "OBJ", "Obj", "obj", etc. The Ada programmer is free to use any mixture of case desired for object identifiers.

Larch, however, is case sensitive [10]. The Larch/Ada terms "OBJ", "Obj", and "obj" are, thus, all distinct linguistic entities—only one of these terms can canonically represent the value of the Ada object. Early in the development of Penelope, we made the all-lower-case form canonical.

So as to maintain a clear relationship between Ada objects and the Larch terms that represent their values, we converted all the identifiers appearing in Calendar_Utilsities to lower case. This change did not affect the Ada semantics.

- Fully expanded expressions

Penelope does not yet support the USE context clause. When referring to types and objects of WITHed packages, it was necessary to write their fully expanded names. Thus, we needed to change the references to type year_number of package calendar to read "calendar.year_number". In the same vein, we declared and WITHed a package builtin so that we could refer to the built-in type duration.

- Constraints and ranges

Penelope does not yet support range constraints. The integer type definitions in the original code have therefore been transformed to declarations
of unconstrained new integer types. Larch/Ada predicates for the sorts corresponding to these types have been defined so that we can code range checking explicitly.

The names of these functions are the names of the corresponding types prefixed with "good". Their definitions are taken from the bounds of the range in the original Ada text of CalendarUtilities. We used them systematically in the specifications of programs that have formal parameters of the original range type, and as conditions on axioms and lemmas that have variables of the corresponding sort. Doing so ensured that range checking is always part of the correctness condition of the verified software.

For instance, the explicit Larch/Ada IN annotation

\[
\text{IN good_month(the_month);}
\]

takes the place of the implicit constraint check

\[1 \leq \text{the_month} \leq 12\]

for the Ada type Month.

- Derived types
Penelope does not yet fully support derived types in Ada. The type mark\footnote{See the Ada RM 3.3.2-2.3, 3.4} of a derived type is today treated as an alias for the parent type instead of as an isomorphic copy. This means that Penelope's typechecking of Ada is somewhat too lenient, as it does not guard against improperly mixing parent and derived types in an Ada expression. It was part of our task as verifiers to take such precautions manually.

- Type conversion
Type conversions are not yet supported by Penelope. Its typechecker does, however, support the restriction against using names of types as function names. Where explicit type conversions appear in the original Ada code, therefore, they are rejected by Penelope as illegal function calls. To overcome these limitations, we have replaced all explicit type conversions with calls to actual functions whose specified effect is to perform the desired type coercions.

The name of a coercion function follows this convention: the name of the target type has the suffix "ize". Thus a function that coerces to type integer is named "integer_ize"\footnote{Ada overloading permits as many identically-named functions as required, one for each type to be coerced. The typechecker determines which function is intended from the type of the argument.}. Since the coercion functions
are purely auxiliary, no bodies for them are given, only Ada specifications. Their Larch/Ada specifications provide the predicate transformers with all of the information that is required to perform the necessary type coercions.

That constrained types and ranges are not yet supported introduces further complications. There is currently no distinction in Penelope between the types integer, natural and positive; consequently, are all the same type: the conversion between them is apparent, not real. The "_ize" functions for the numeric types thus actually all take integer arguments and return integer results under another name.

We have these pseudo-conversions in the code for two reasons. First, we wish to change the text as little as possible. The change in going from natural(obj) to natural_ize(obj) is smaller than in going from natural(obj) to obj. Second, we express the constraints that must hold for the object as Larch/Ada II specifications on the "_ize" functions. Thus, we specify that the input value to natural_ize must be non-negative. In fact, we explicitly state all of the constraints on objects that Penelope will later infer from their types.

- Attribute functions

Penelope does not yet support the automatic generation of attribute functions, nor is the "tic" (i.e., the character ") notation for them acceptable syntax. We replaced each function of the form <type_mark>_"<attribute> in the original code by a function named <type_mark>_tic_<attribute>. We have added Ada specifications for these functions; the new Ada specifications are identical to those defined for the corresponding attribute functions. These pseudo-attribute functions have been annotated with Larch/Ada specifications that correctly describe the semantics of the attribute function by means of axioms that have been entered manually into the traits. The entire process is well defined and capable of automation.

- Aggregates

Penelope does not yet support aggregate expressions. We circumvented this limitation in each case by declaring a temporary object of the result type, assigning the appropriate values to its fields, and returning the object thus constructed.

Penelope will someday have aggregate-like constructs in Larch/Ada. Even without them, however, we have full expressiveness in Larch/Ada to name any (finite) array value. The array-update notation

\[ \text{Array[index => value]} \]

denotes the array having value value at index index and agreeing with Array at every other index. Repeated application of the array-update
notation can be used to denote an array having a chosen value at each index.

To suggest the aggregate-like notation that we will someday implement, we declared constant functions on array sorts and updated all of the components of these undetermined constants whenever we wished to name a particular array value. One example is the term denoting the array of days of the months in an ordinary year:

\[
\text{month\_days\_tic}[1=>31][2=>28][3=>31][4=>30]
\]
\[
[5=>31][6=>30][7=>31][8=>31]
\]
\[
[9=>30][10=>31][11=>30][12=>31]
\]

- **FOR loops**

FOR loops are not yet included in the subset of Ada for which Penelope has verification rules. FOR loops in the code have been replaced by WHILE loops whose test is that the index variable has reached the upper bound. The index variable is initialized to the lower bound by a preceding assignment statement and is incremented by an assignment statement at the end of the loop body.

- **Aliasing**

Penelope has very conservative checks against improper aliasing; these checks reject subprogram calls which would result in certain kinds of program errors\(^{13}\), but may also reject subprogram calls that are error-free. In particular, Penelope does not allow two components from the same record object to appear as actuals for out or in out formal parameters—for example, the call

\[
\text{calendar.split(result.the\_year, result.the\_month, result.the\_day)}
\]

To accommodate the checks, we rewrote the call slightly. The modified code calls calendar\_split with temporaries in place of the record components and assigns each of the temporaries to the corresponding component after the procedure call.

- **Exceptions**

The circumstances under which Constraint\_Error would be raised by the application of day\_name\_tic\_val are specified in the Larch/Ada annotation of that function.

\(^{13}\)Technically, certain kinds of erroneous executions and incorrect order dependences.
Penelope does not yet support Ada restrictions on declaration of exceptions. Instead, Penelope considers an exception to be implicitly introduced at its first occurrence in propagation annotations. We removed exception declarations to perform this verification. After this change, Penelope is, in effect, more lenient than Ada in the declaration of exceptions. We therefore ensured that we did not introduce new exceptions.

- Actual Parameter lists

Penelope does not yet support named parameter association. We changed occurrences in the original code to positional parameter association. This change affects only the convenience of the caller, not the correctness of the subprogram.

4.4.2 Results

Verified Functions We fully verified the functions IsLeapYear, DaysIn (both Month and Year versions), MonthOf (both Number and Name versions), DayOf (Time version), TimeOf (Year, Day version) and PeriodOf.

Detected Errors The function DurationOf contains a programming error that was detected first in the specification phase and is discussed in Section 4.3. In this verification phase, the error was highlighted by completing the proofs for all of the VCs of the program except for one, which can be seen to closely correspond to the incorrect expression.

The goal of the VC, paraphrased, says that the value held by an integer variable (TheInterval.ElapsedMilliseconds) is unchanged when it is successively divided, then multiplied by 1000 (using integer arithmetic):

\[
\text{the_interval.elapsed_milliseconds}/1000 \times 1000 = \text{the_interval.elapsed_milliseconds}
\]

A well-trained verifier may respond to this clearly unprovable goal by recognizing its relation to the RETURN condition of the specification and pinpointing the line of code with the offending expression.

Two further errors were actually discovered during the verification process. Both errors occur in the function DayOf (Year, Day). We detected them by realizing that we could not prove the VC generated for the loop invariant. The two remaining incomplete subproofs correspond to the two errors.

The function

\[
\text{Day_of(\text{the_year}: \text{year}; \text{the_day}: \text{year_day}) return day_name;}
\]

returns the name day of the week on which day number the.day falls in the year the.year. It proceeds by first executing a loop to determine the day of
4.4 Verification

the week on which the_year begins, and then shifting that day of the week by the_day (modulo 7). Each step contains an error.

The loop counter Index runs from year'first+1 to the_year, and each iteration of the loop should advance the day_name stored in result by either one day (if Index is not a leap year) or two days (if it is). The VC for the loop, however, is this:

(IF is_leap_year(the_year)
 THEN (good_day_name(day_name_sort_increment(result, 2))
 ->
 (day_name_sort_increment(result, 2)
 =
 day_name_of(index, 1)))
ELSE (good_day_name(day_name_sort_increment(result, 1))
 ->
 (day_name_sort_increment(result, 1)
 =
 day_name_of(index, 1)))

This is unprovable, because the IF assertion is branching, not on the value of index, but on the value of the_year. On checking the IF statement in the body of the loop, we find that it incorrectly tests the loop bound instead of the loop index; that is, IsLeapYear(The_Year), instead of IsLeapYear(Index).

The problem with the second step is that it attempts to calculate the shift as follows:

(Natural((the_day mod 7) - 1)
If the value of the_day mod 7 is zero, the type conversion to Natural will raise an exception. The shift should instead be calculated by

(Natural((the_day - 1) mod 7)

This error was discovered by considering the VC

0 < (the_day MOD 7)

AND

( good_day_name(
    day_name_sort_increment(result, (the_day MOD 7) - 1)
 )
->
( day_name_sort_increment(result, (the_day MOD 7) - 1)
 =
 day_name_of(the_year, the_day)
 )
)
The assertion $0 < (\text{the day MOD 7})$ is simply not true, and this directed us immediately to the mistaken calculation of the shift. (Note the origin of $0 < (\text{the day MOD 7})$: it is precisely what must hold in order to guarantee that the unwanted constraint error is not raised.)

The most intriguing thing about these last two errors is that they will not invariably lead to incorrect output from the function. Though we will not prove it here, the function will in fact return the correct value for the years 1984-87, as long as the value of the input parameter The.Day is not congruent to 0 mod 7. There is at least the possibility that the existence of a problem could go undetected through some moderately extensive, but unfortunately chosen, test cases.

Each of the errors described in this section is a local mistake and can be fixed with a small change to the program. The near-completeness of the corresponding VCs clearly shows that the resulting programs could then be fully verified.
4.4 Verification

4.4.3 Summary of Results

We specified all eighteen functions of the package Calendar_Utilsities using Larch/Ada. Of these, we selected thirteen for formal verification. We treated eleven of the thirteen completely.

Of the eleven we treated formally, we verified eight and detected errors in three others. Seven functions were not treated formally.

Our results are in the table below. When two functions share a common name, we comment on their arguments enough to distinguish them.

<table>
<thead>
<tr>
<th>Function</th>
<th>Comments</th>
<th>Verified</th>
<th>Incorrect</th>
<th>Not Treated</th>
</tr>
</thead>
<tbody>
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<td>Is_Leap_Year</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Days_In</td>
<td>(Year)</td>
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<td></td>
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<td>(Month Number)</td>
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<tr>
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<td>*</td>
</tr>
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<tr>
<td>Date_Image_Of</td>
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<tr>
<td>Value_Of</td>
<td>(Date/Time Strings)</td>
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<tr>
<td>Duration_Of</td>
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<td>Interval_Of</td>
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<tr>
<td>Image_Of</td>
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<tr>
<td>Value_Of</td>
<td>(Interval String)</td>
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</tbody>
</table>
5 Conclusions

This demonstration of the power and practicability of formal methods in Penelope was a success. Formal specification in Penelope was useful for analyzing the software, both informally and formally. Formal verification gave greater confidence in the correctness of most of the package. Where the software was incorrect, the errors detected by Penelope could have gone unnoticed in testing.

This verification effort was the first to use a non-built-in data type extensively in Penelope. Without the automatic simplification that is provided for the built-in types, we found ourselves spending far too much of our time manually applying simplification directives. Future directions for Penelope should include consideration of automatic simplification within user-supplied theories.

Library-based verification would have been greatly advantageous. Because of the sheer bulk of the Ada code within a single buffer, Penelope ran very slowly. This problem lends support to our conclusions, drawn before this demonstration, that library-based verification is a necessity and validates our efforts in that direction.

Penelope is a useful prototype today for developing correct software. As ORA continues to enhance Penelope, it will become a generally useful tool.
Appendix A: Related Work

The field of formal verification began with the work of Hoare [12, 13]. Dijkstra and Gries went on to develop and advocate a distinctive style of verification based on Hoare's ideas. A thorough basic introduction to Dijkstra-Gries style verification can be found in Gries [6]. The same material is covered more fully in Dijkstra [3].

A serious obstacle to performing Dijkstra-Gries style verification by hand is the crushing work of bookkeeping in verifying actual programs (as opposed to textbook exercises). Penelope [8] is an automated assistant that manages the details of predicate transformation and proof checking, freeing the user to perform the conceptual work of verification.

Other computerized verification systems include EHDM [2], Gypsy [5], ORA Ottawa's m-EVES [1], and SDVS [15].

The Larch [10] system of mathematical specification separates mathematical concerns from programming concerns. Significant research has investigated how best to specify programs in the Larch system [17].
<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Assertion</strong></td>
<td>A mathematical statement about a program state. To make an assertion is to claim that a certain predicate is true.</td>
</tr>
<tr>
<td><strong>Floyd-Hoare Triple</strong></td>
<td>The triple {initial} S {final} symbolizes that software S transforms state initial into state final. The Floyd-Hoare triple is basic to the mathematics of program semantics.</td>
</tr>
<tr>
<td><strong>Precondition</strong></td>
<td>A predicate that must hold on the program state before a statement executes if the statement is to bring about its intended effect.</td>
</tr>
<tr>
<td><strong>Predicate</strong></td>
<td>A logical formula such as (x &gt; 17); a mathematical expression that is either true or false when its variables are assigned values.</td>
</tr>
<tr>
<td><strong>Program Semantics</strong></td>
<td>Loosely speaking, the behavior of software. Program semantics treats the behavior of a program as its meaning.</td>
</tr>
<tr>
<td><strong>Sort</strong></td>
<td>The logical category of a mathematical object, analogous to a data type. The sort of the mathematical integers is Int.</td>
</tr>
<tr>
<td><strong>Specification</strong></td>
<td>A user-supplied predicate describing the conditions that are to hold at various points in the execution of a program.</td>
</tr>
</tbody>
</table>

- Input specifications describe the initial state of the program; that is, what must be true before the program executes.
- Output specifications describe the final state of the program. The circumstances of both normal and exceptional termination can be specified.
- In addition, there are specifications available to describe conditions at user-chosen points within the program body.
| Tier | One of the two levels of Larch/Ada specification. The interface tier is used to specify program behavior mathematically. The mathematical machinery for the specification is modularized into traits in the mathematical tier. |
| Trait | A Larch theory module. Traits encapsulate all of the apparatus of a logical theory: the sorts, function declarations, axiom, lemmas, and so on. An example is the trait for the theory of integer arithmetic given on p. 83 of *Larch in Five Easy Pieces* [10]: the sort introduced is Int, a familiar axiom is \( z < (z + 1) \). Note that traits can be built up from other traits, just as program modules can call other program modules. |
| Predicate Transformation | A process akin to symbolic execution of a program during which the precondition of each statement in a program is calculated. |
| VC | See Verification Condition. |
| Verification Condition | A formula that must be proved true for a program to be proved correct. Loosely speaking, the verification conditions of a program collectively assert that the statements of the program act together to transform the specified initial program state into one of the specified acceptable final states. Verification conditions are calculated from specifications and preconditions. |
Appendix C: Package Calendar_Utilities

This appendix shows the full Ada text of the Ada specification and the body of the package Calendar_Utilities. It differs only by reformatting from the text that NASA sent ORA.


C.1 Package Specification of Calendar_Utilities

with Calendar;
package Calendar_Utilities is

  type Year is new Calendar.Year_Number;
  type Month is range 1 .. 12;
  type Day is range 1 .. 31;
  type Hour is range 0 .. 23;
  type Minute is range 0 .. 59;
  type Second is range 0 .. 59;
  type Millisecond is range 0 .. 999;

  type Time is record
    The_Year: Year;
    The_Month: Month;
    The_Day: Day;
    The_Hour: Hour;
    The_Minute: Minute;
    The_Second: Second;
    The_Millisecond: Millisecond;
  end record;

  type Interval is record
    Elapsed_Days: Natural;
    Elapsed_Hours: Hour;
    Elapsed_Minutes: Minute;
    Elapsed_Seconds: Second;
    Elapsed_Milliseconds: Millisecond;
  end record;

  type Year_Day is range 1 .. 366;

  type Month_Name is (January, February, March,
    April, May, June,
July, August, September,
October, November, December);

type Day_Name is (Monday, Tuesday, Wednesday,
Thursday, Friday, Saturday, Sunday);

type Period is (AM, PM);

type Time_Format is (Full, -- 01:21:06:30 PM
    Military); -- 13:21:06:30

type Date_Format is (Full, -- FEBRUARY 27, 1965
    Month_Day_Year); -- 02/27/55

function Is_Leap_Year (The_Year : in Year)
    return Boolean;

function Days_In (The_Year : in Year)
    return Year_Day;

function Month_Of (The_Month : in Month;
    The_Year : in Year)
    return Month_Name;

function Day_Of (The_Year : in Year;
    The_Day : in Year_Day)
    return Day_Name;

function Time_Of (The_Year : in Year;
    The_Day : in Year_Day)
    return Time;

function Period_Of (The_Time : in Time)
    return Period;

function Date_Image_Of (The_Time : in Time;
    Date_Form in Date_Format := Full)
    return String;

function Value_Of (The_Date : in String;
    Time_Form in Time_Format := Full)
APPENDIX C

The_Time : in String;
Date_Form : in Date_Format := Full;
Time_Form : in Time_Format := Full)

return Time;

function Duration_Of (The_Interval : in Interval)
return Duration;
function Interval_Of (The_Duration : in Duration)
return Interval;
function Image_Of (The_Interval : in Interval)
return String;
function Value_Of (The_Interval : in String)
return Interval;

Lexical_Error : exception;
end Calendar_Utilities;

C.2 Package Body of Calendar_Utilities

with Integer_Utilities,
Fixed_Point_Utilities,
String_Utilities;
package body Calendar_Utilities is

type Month_Day is array(Month) of Day;

Century_Offset : constant := 1900;
Days_Per_Year : constant := 365;
Days_Per_Month : constant Month_Day := (1 => 31,
2 => 28,
3 => 31,
4 => 30,
5 => 31,
6 => 30,
7 => 31,
8 => 31,
9 => 30,
10 => 31,
11 => 30,
12 => 31);

First_Day : constant Day_Name := Tuesday;
Seconds_Per_Minute : constant := 60;
C.2 Package Body of Calendar_Utilsities

| Seconds_Per_Day | constant := \(60 \times \text{Seconds_Per_Minute}\); |
| Milliseconds_Per_Sekond | constant := \(24 \times \text{Seconds_Per_Hour}\); |
| Noon | constant Hour := 12; |
| Time_Separator | constant Character := ":"; |
| Date_Separator | constant Character := "/"; |
| Blank | constant Character := ":"; |
| Comma | constant Character := ","; |
| Zero | constant Character := "0"; |

package Natural_Utilsities is new Integer_Utilsities (Number => Natural);

package Duration_Utilsities is new Fixed_Point_Utilsities (Number => Duration);

function Image_Of (The_Number : in Natural) return String is begin
  if The_Number < 10 then
    return String_Utilsities.Replaced
      (The_Character => Blank,
       With_The_Character => Zero,
       In_The_String =>
         Natural_Utilsities.Image_Of(The_Number));
  else
    return String_Utilsities.Stripped_Leading
      (The_Character => Blank,
       From_The_String =>
         Natural_Utilsities.Image_Of(The_Number));
  end if;
end Image_Of;

function Is_Leap_Year (The_Year : in Year) return Boolean is begin
  if The_Year mod 100 = 0 then
    return (The_Year mod 400 = 0);
  else
    return (The_Year mod 4 = 0);
  end if;
end Is_Leap_Year;

function Days_In (The_Year : in Year) return Year_Day is begin
if Is_Leap_Year(The_Year) then
    return (Days_Per_Year + 1);
else
    return Days_Per_Year;
end if;
end Days_In;

function Days_In (The_Month : in Month;
                   The_Year : in Year) return Day is
begin
    if (The_Month = Month_Name'Pos(February) + 1) and then
        Is_Leap_Year(The_Year) then
        return (Days_Per_Month(Month_Name'Pos(February) + 1) + 1);
    else
        return Days_Per_Month(The_Month);
    end if;
end Days_In;

function Month_Of (The_Month : in Month) return Month_Name is
begin
    return Month_Name'Val(The_Month - 1);
end Month_Of;

function Month_Of (The_Month : in Month_Name) return Month is
begin
    return (Month_Name'Pos(The_Month) + 1);
end Month_Of;

function Day_Of (The_Year : in Year;
                 The_Day : in Year_Day) return Day_Name is
Result : Day_Name := First_Day;
procedure Increment(The_Day : in out Day_Name;
                    Offset : in Natural := 1) is
    --This moves you through day names by offset places.
    --Instead of using MOD, it uses exception when you pass
    --Sunday
begin
    The_Day := Day_Name'Val(Day_Name'Pos(The_Day) + Offset);
exception
    when Constraint_Error =>
        The_Day := Day_Name'Val(Day_Name'Pos(The_Day) + Offset - 7);
end Increment;
begin
  for Index in (Year'First + 1) .. The_Year loop
    if Is_Leap_Year(The_Year) then
      Increment(Result, Offset => 2);
    else
      Increment(Result);
    end if;
  end loop;
  --this uses 365/366 REM 7 and goes through the years,
  --then does days
  Increment(Result,
    Offset => Natural(((The_Day mod 7) - I)));
  return Result;
end Day_Of;

function Day_Of (The_Time : in Time) return Year_Day is
  Result : Natural := 0;
begin
  for Index in Month'First .. (The_Time.The_Month - 1) loop
    Result := Result + Natural(Days_In(Index, The_Time.The_Year));
  end loop;
  return Year_Day(Result + Natural(The_Time.The_Day));
end Day_Of;

function Time_Of (The_Year : in Year;
  The_Day : in Year_Day) return Time is
  Result : Year_Day := The_Day;
begin
  for Index in Month'First .. Month'Last loop
    if Result <= Year_Day(Days_In(Index, The_Year)) then
      return Time'(
        The_Year => The_Year,
        The_Month => Index,
        The_Day => Day(Result),
        The_Hour => Hour'First,
        The_Minute => Minute'First,
        The_Second => Second'First,
        The_Millisecond => Millisecond'First);
    else
      Result :=
        Result - Year_Day(Days_In(Index, The_Year));
    end if;
  end loop;
end Time_Of;
end loop;
raise Lexical_Error;
end Time_Of;

function Period_Of (The_Time : in Time) return Period is
begin
  if The_Time.The_Hour >= Noon then
    return PM;
  else
    return AM;
  end if;
end Period_Of;

function Time_Of (The_Time : in Time) return Calendar.Time is
begin
  return Calendar.Time_Of
    (Year => Calendar.Year_Number(The_Time.The_Year),
     Month => Calendar.Month_Number(The_Time.The_Month),
     Day => Calendar.Day_Number(The_Time.The_Day),
     Seconds => Calendar.Day_Duration
       (Integer(The_Time.The_Hour) * Seconds_Per_Hour) +
       Calendar.Day_Duration
       (Integer(The_Time.The_Minute) * Seconds_Per_Minute) +
       Calendar.Day_Duration(The_Time.The_Second) +
       Calendar.Day_Duration(The_Time.The.Millisecond /
       Milliseconds_Per_Second));
end Time_Of;

function Time_Of (The_Time : in Calendar.Time) return Time is
  Result : Time;
  Total_Duration : Calendar.Day_Duration;
  Seconds : Natural;
begin
  Calendar.Split(The_Time,
    Year => Calendar.Year_Number(Result.The_Year),
C.2 Package Body of Calendar.Utilities

Month =>
  Calendar.Month_Number(Result.The_Month),
Day =>
  Calendar.Day_Number(Result.The_Day),
Seconds =>
  Total_Duration);
Seconds := DurationUtilities.Floor(Total_Duration);
Result.The_Hour := Hour(Seconds / Seconds_Per_Hour);
Seconds := Seconds mod Seconds_Per_Hour;
Result.The_Minute :=
  Minute(Seconds / Seconds_Per_Minute);
Result.The_Second :=
  Second(Seconds mod Seconds_Per_Minute);
Result.The_Millisecond :=
  Millisecond
  (DurationUtilities.Real_Part
   (Total_Duration) * Milliseconds_Per_Second);
return Result;
end Time_Of;

function Time_Image_Of (The_Time : in Time;
                      Time_Form : in Time_Format := Full)
return String is
begin
  case Time_Form is
  when Full =>
    if The_Time.The_Hour > Noon then
      return (Image_Of(Natural(
        The_Time.The_Hour - 12)) &
        Time_Separator &
        Image_Of(Natural(The_Time.The_Minute)) &
        Time_Separator &
        Image_Of(Natural(The_Time.The_Second)) &
        Time_Separator &
        Image_Of(Natural(
          The_Time.The_Millisecond / 10)) &
        " PM");
    else
      return (Image_Of(Natural(The_Time.The_Hour)) &
        Time_Separator &
        Image_Of(Natural(The_Time.The_Minute)) &
        Time_Separator &
when Military =>
  return (Image_Of(Natural(The_Time.The_Hour)) &
    Time_Separator &
    Image_Of(Natural(The_Time.The_Minute)) &
    Time_Separator &
    Image_Of(Natural(The_Time.The_Second)) &
    Time_Separator &
    Image_Of(Natural(The_Time.The_Millisecond) / 10));
end case;
end Time_Image_Of;

function Date_Image_Of (The_Time : in Time;
  Date_Form : in Date_Format := Full)
return String is
begin
  case Date_Form is
  when Full =>
    return (Month_Name'Image(Month_Name'Val(
      The_Time.The_Month - 1)) &
      Natural_Utilties.Image_Of(
        Natural(The_Time.The_Day)) &
      Comma &
      Natural_Utilties.Image_Of(
        Natural(The_Time.The_Year)));
  when Month_Day_Year =>
    return (Image_Of(Integer(The_Time.The_Month)) &
      Date_Separator &
      Image_Of(Integer(The_Time.The_Day)) &
      Date_Separator &
      Image_Of(Integer(The_Time.The_Year) (4 .. 5));
  end case;
end Date_Image_Of;

function Value_Of (The_Date : in String;
  The_Time : in String;
  Date_Form : in Date_Format := Full;
C.2 Package Body of Calendar_Utilsities

Time_Form : in Time_Format := Full)

return Time is
Result : Time;
Left_Index : Positive;
Right_Index : Positive;
begin

  case Date_Form is
    when Full =>
      Right_Index := String_Utilities.Location_Of
                     (The_Character => Blank,
                      In_The_String => The_Date);
      Result.The_Month := Month(Month_Name'Pos
                                 (Month_Name'Value
                                  (The_Date
                                   The_Date'First ..
                                   (Right_Index - 1))
                                   + 1));
      Left_Index := Right_Index + 1;
      Right_Index := String_Utilities.Location_Of
                     (The_Character => Comma,
                      In_The_String =>
                      The_Date(Left_Index..The_Date'Last));
      Result.The_Day := Day(Natural_Utilities.Value_Of
                             (The_Date(Left_Index..
                                       (Right_Index - 1))));
      Left_Index := Right_Index + 1;
      Result.The_Year := Year(Natural_Utilities.Value_Of
                               (The_Date(Left_Index..
                                          The_Date'Last)));
    when Month_Day_Year =>
      Right_Index := String_Utilities.Location_Of
                     (The_Character => Date_Separator,
                      In_The_String => The_Date);
      Result.The_Month :=
                         Month(Natural_Utilities.Value_Of
                              (The_Date(The_Date'First .. (Right_Index - 1))));
      Left_Index := Right_Index + 1;
      Right_Index := String_Utilities.Location_Of
                     (The_Character => Date_Separator,
                      In_The_String =>
APPENDIX C

The_Date(Left_Index ..
    The_Date'Last));
Result.The_Day := Day(Natural_Utilities.Value_Of
    (The_Date
        (Left_Index ..
        (Right_Index - 1)));
Left_Index := Right_Index + 1;
Result.The_Year := Year(Natural_Utilities.Value_Of
    (The_Date
        (Left_Index ..
        The_Date'Last)) +
    Natural(Century_Offset));

end case;
Right_Index := String_Utilities.Location_Of
    (The_Character => Time_Separator,
    In_The_String =>
    The_Time);
Result.The_Hour := Hour(Natural_Utilities.Value_Of
    (The_Time
        (The_Time'First ..
        (Right_Index - 1)));
Left_Index := Right_Index + 1;
Right_Index := String_Utilities.Location_Of
    (The_Character => Time_Separator,
    In_The_String =>
    The_Time(Left_Index..The_Time'Last));
Result.The_Minute := Minute(Natural_Utilities.Value_Of
    (The_Time
        (Left_Index ..
        (Right_Index - 1)));
Left_Index := Right_Index + 1;
Right_Index := String_Utilities.Location_Of
    (The_Character => Time_Separator,
    In_The_String =>
    The_Time(Left_Index..The_Time'Last));
Result.The_Second := Second(Natural_Utilities.Value_Of
    (The_Time
        (Left_Index ..
        (Right_Index - 1)));
Left_Index := Right_Index + 1;
case Time_Form is
    when Full =>
        Right_Index := String_Utilities.Location_Of
            (The_Character => Blank,
            In_The_String =>
            The_Time(Left_Index ..
            (Right_Index - 1))));
The TIME (Left_INDEX ..
The_TIME'Last));
Result.The_Millisecond :=
' Millisecond (Natural_Utilities.Value_Of
(The_TIME (Left_INDEX .. (Right_INDEX - 1))));
Left_INDEX := Right_INDEX + 1;
if Period'Value(The_TIME (Left_INDEX ..
The_TIME'Last)) = PM
 then
   if Result.The_Hour /= Noon then
      Result.The_Hour :=
         Result.The_Hour + Noon;
   end if;
   end if;
when MILITARY =>
Result.The_Millisecond :=
' Millisecond (Natural_Utilities.Value_Of
(The_TIME (Left_INDEX .. The_TIME'Last)));
end case;
return Result;
exception
   when CONSTRAINT_ERROR =>
      raise Lexical_ERROR;
end Value_Of;

function Duration_Of (The_Interval : in Interval)
return Duration is
begin
   return (Duration (Integer (The_Interval.Elapsed_Days)
      * Seconds_Per_Day) +
          Duration (Integer (The_Interval.Elapsed_Hours)
      * Seconds_Per_Hour)
 +
          Duration (Integer (The_Interval.Elapsed_Minutes)
      * Seconds_Per_Minute) +
          Duration (The_Interval.Elapsed_Seconds) +
          Duration (The_Interval.Elapsed_Milliseconds
      / 1000));
end Duration_Of;

function Interval_Of (The_Duration : in Duration)
return Interval is
   Result : Interval;
The_Seconds : Duration := The_Duration;

begin

Result.Elapsed_Days := Duration_Utility.Floor(
The_Seconds / Seconds_Per_Day);

The_Seconds :=
The_Seconds -
Duration(Integer(Result.Elapsed_Days) * Seconds_Per_Day);
Result.Elapsed_Hours :=
Hour(Duration_Utility.Floor((The_Seconds / Seconds_Per_Hour));

The_Seconds :=
The_Seconds -
Duration(Integer(Result.Elapsed_Hours) * Seconds_Per_Hour);

Result.Elapsed_Minutes :=
Minute(Duration_Utility.Floor((The_Seconds / Seconds_Per_Minute));

The_Seconds :=
The_Seconds -
Duration(Integer(Result.Elapsed_Minutes) * Seconds_Per_Minute);

Result.Elapsed_Seconds :=
Second(Duration_Utility.Floor((The_Seconds));

The_Seconds :=
The_Seconds - Duration(Result.Elapsed_Seconds);

Result.Elapsed_Milliseconds :=
Millisecond(Duration_Utility.Floor(The_Seconds * 1000));

return Result;
end Interval_Of;

function Image_Of (The_Interval : in Interval)
return String is
begin

return (Image_Of(Natural(The_Interval.Elapsed_Days)) &
Time_Separator &
Image_Of(Natural(The_Interval.Elapsed_Hours)) &
Time_Separator &
Image_Of(Natural(The_Interval.Elapsed_Minutes)) &
Time_Separator &
Image_Of(Natural(The_Interval.Elapsed_Seconds)) &
Time_Separator &
Image_Of(Natural(}
The Interval.Elapsed_Milliseconds));

end Image_Of;

function Value_Of (The_Interval : in String) return Interval is
  Result : Interval;
  Left_Index : Positive;
  Right_Index : Positive;
begin
  Right_Index := String_Utilities.Location_Of
    (The_Character => Time_Separator,
     In_The_String => The_Interval);
  Result.Elapsed_Days := Natural_Utilities.Value_Of
    (The_Interval
     (The_Interval'First ..
     (Right_Index - 1)));
  Left_Index := Right_Index + 1;
  Right_Index := String_Utilities.Location_Of
    (The_Character => Time_Separator,
     In_The_String =>
     The_Interval(Left_Index ..
     The_Interval'Last));
  Result.Elapsed_Hours := Hour(Natural_Utilities.Value_Of
    (The_Interval
     (Left_Index ..
     (Right_Index - 1)));
  Left_Index := Right_Index + 1;
  Right_Index := String_Utilities.Location_Of
    (The_Character => Time_Separator,
     In_The_String =>
     The_Interval(Left_Index ..
     The_Interval'Last));
  Result.Elapsed_Minutes :=
    Minute(Natural_Utilities.Value_Of
       (The_Interval
        (Left_Index .. (Right_Index - 1)));
  Left_Index := Right_Index + 1;
  Right_Index := String_Utilities.Location_Of
    (The_Character => Time_Separator,
     In_The_String =>
     The_Interval(Left_Index ..
     The_Interval'Last));
  Result.Elapsed_Seconds :=
    Second(Natural_Utilities.Value_Of
(The_Interval
  (Left_Index .. (Right_Index - 1))));
Left_Index := Right_Index + 1;
Result.Elapsed_Milliseconds :=
  Millisecond
  (NaturalUtilities.Value_Of
    (The_Interval
      (Left_Index .. The_Interval'Last)));
return Result;
except
  when Constraint_Error =>
    raise Lexical_Error;
end Value_Of;

end CalendarUtilities;
Appendix D:  Package Calendar

This appendix shows the Calendar package of the Ada Reference Manual.
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package calendar is
  type time is private;

  subtype year_number is integer range 1901 .. 2099;
  subtype month_number is integer range 1 .. 12;
  subtype day_number is integer range 1 .. 31;
  subtype day_duration is duration range 0.0 .. 86_400.0;

  function clock return time;

  function year (date : time) return year_number;
  function month (date : time) return month_number;
  function day (date : time) return day_number;
  function seconds (date : time) return day_duration;

  procedure split (date : in time;
                   year : out year_number;
                   month : out month_number;
                   day : out day_number;
                   seconds : out day_duration);

  function time_of (year : year_number;
                    month : month_number;
                    day : day_number;
                    seconds : day_duration := 0.0) return time;

  function "+" (left : time; right: duration) return time;
  function "+" (left : duration; right: time ) return time;
  function "-" (left : time; right: duration) return time;
  function "-" (left : time; right: time )
               return duration;

  function "<" (left, right : time) return boolean;
  function "<=" (left, right : time) return boolean;
  function ">" (left, right : time) return boolean;
  function ">=" (left, right : time) return boolean;

  time error : exception;
-- can be raised by time_of, "+" and "-"

private
  -- implementation-dependent
end;
Appendix E: Full Output from the Penelope Verification

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the Under Secretary of Defense, Research and Engineering. Portions of this text
are copyright Grady Booch, part of the Ada Booch components 1984-1992.

--! Verification status: Not verified
   (21 VCs generated; 2 VCs hidden; 16 VCs proved)
--! TRAIT Z IS
--! DECLARES
--! INTRODUCES
--! Int_identity: Int -> Int;
--! AXIOMS: FORALL [n:Int]
--! Int_identity: (Int_identity(n)=n);
--! END AXIOMS;
--! LEMMAS: FORALL [a:Int, m:Int, m1:Int, m2:Int]
--! mod_lower: ((m>0)->(0<=(a MOD m)));
--! mod_upper: ((m>0)->((a MOD m)<m));
--! mod_ident: (((0<=a) AND (a<m))>((a MOD m)=a));
--! mod_transitive: ( 
    ( ((m1/=0) AND (m2/=0)) AND ((m1 MOD m2)=0) )
    AND
    ((a MOD m1)=0))
   ->
   ((a MOD m2)=0);
--! mod_subtract: ( 
    ( ((m>0) AND (m<=a)) AND (a<=(2*m)-1)) )
   ->
   ((a MOD m)=(a-m));
--! div_upper: (((0<=a) AND (a<m))>((a/m)=0));
--! END LEMMAS;
--! TRAIT fixed_point IS
--! DECLARES
--! SORT fixnum IS AnyRecordSort;
--! INTRODUCES
--! good_fixnum: fixnum -> Bool;
--! abstract: fixnum -> Rational;
--! pair: Int, Int -> fixnum;
--! Int_to_fixnum: Int -> fixnum;
--! "*": fixnum, fixnum -> fixnum;
--! "*": fixnum, Int -> fixnum;
--! "*": Int, fixnum -> fixnum;
APPENDIX E

-- "": fixnum, fixnum -> fixnum;
-- "": fixnum, Int -> fixnum;
-- "": fixnum, fixnum -> fixnum;
-- "": fixnum, fixnum -> fixnum;
-- "": fixnum, fixnum -> Bool;
-- "": fixnum, fixnum -> Bool;
-- "": fixnum, fixnum -> Bool;
-- NonZero: fixnum -> Bool;
-- IntegerPart: fixnum -> Int;
-- RealPart: fixnum -> fixnum;
-- Floor: fixnum -> Int;
-- Ceiling: fixnum -> Int;
-- fixnum_abs: fixnum -> fixnum;
-- AXIOMS: FORALL [m:fixnum, n:fixnum, i:Int, j:Int]
-- good_fixnum: (good_fixnum(m)=(m.denom>0));
-- concrete_equality: 
-- ((m.numer=n.numer) AND (m.denom=n.denom))
-> (m=n));
-- abstract_equality: ( 
  (good_fixnum(m) AND good_fixnum(n))
  AND
  ((m.numer*n.denom)=Int_identity((m.denom*n.numer))))
-> (abstract(m)=abstract(n));
-- pair_numer: (pair(i, j).numer=i);
-- pair_denom: (pair(i, j).denom=j);
-- Int_to_fixnum: (Int_to_fixnum(i)=pair(i, 1));
-- times_ff_numer: 
  (good_fixnum(m) AND good_fixnum(n))
-> (((m*n).numer=Int_identity((m.numer*n.numer))));
-- times_ff_denom: 
  (good_fixnum(m) AND good_fixnum(n))
-> (((m*n).denom=Int_identity((m.denom*n.denom))));
-- times_fi_numer: 
  good_fixnum(m)
-> (((m*i).numer=Int_identity((m.numer*i))));
-- times_fi_denom: (good_fixnum(m)->(m*i).denom=m.denom));
-- times_if_numer: ( 
  (good_fixnum(m) AND good_fixnum(n))
-> (((m*i).denom=Int_identity((m.numer*i))));
-- times_if_denom: (good_fixnum(m)->((m*i).denom=m.denom));
--
good_fixnum(m)
  ->
    ((i\*m).numer=Int_identity((i\*m.numer))));
--| times_if_denom: (good_fixnum(m)->((i\*m).denom=m.denom));
--| divides_ff_numer: ( (good_fixnum(m) AND good_fixnum(n)) AND NonZero(n))
  ->
    ((m/n).numerator=Int_identity((m.numerator\*n.denominator)));
--| divides_ff_denom: ( (good_fixnum(m) AND good_fixnum(n)) AND NonZero(n))
  ->
    ((m/n).denominator=Int_identity((m.denominator\*n.numerator)));
--| divides_if_numer: ( (good_fixnum(m) AND (i\/=0))
  ->
    ((m/i).numerator=m.numerator));
--| divides_if_denom: ( (good_fixnum(m) AND (i\/=0))
  ->
    ((m/i).denominator=Int_identity((m.denominator\*i)));
--| plus_ff_numer: ( (good_fixnum(m) AND good_fixnum(n))
  ->
    (m+n).numerator = Int_identity(((m.numerator\*n.denominator)+(n.numerator\*m.denominator))));
--| plus_ff_denom: ( (good_fixnum(m) AND good_fixnum(n))
  ->
    ((m+n).denominator=Int_identity((m.denominator\*n.denominator)));
--| minus_ff_numer: ( (good_fixnum(m) AND good_fixnum(n))
  ->
    (m-n).numerator = Int_identity(((m.numerator\*n.denominator)-(n.numerator\*m.denominator))));
--| minus_ff_denom: ( (good_fixnum(m) AND good_fixnum(n))
  ->
    ((m-n).denominator=Int_identity((m.denominator\*n.denominator)));
--| fixnum_lt: ( (good_fixnum(m) AND good_fixnum(n))

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->
  (m<n)
  =
    (Int_identity((m.numer*n.denom))
    <
    Int_identity((n.numer*m.denom))));
--| fixnum_le: (good_fixnum(m) AND good_fixnum(n))
  ->
    (m<=n)
    =
    (Int_identity((m.numer*n.denom))
    <=
    Int_identity((n.numer*m.denom))));
--| fixnum_ge: (good_fixnum(m) AND good_fixnum(n))
  ->
    (m>=n)
    =
    (Int_identity((m.numer*n.denom))
    >=
    Int_identity((n.numer*m.denom))));
--| IntegerPart: (good_fixnum(m)
  ->
    (IntegerPart(n)=Int_identity((n.numer/n.denom))));
--| RealPart: (good_fixnum(m)
--> (RealPart(m)=fixnum_abs((m-Int_to_fixnum(IntegerPart(n))))));
--| Floor: (good_fixnum(m)
--> (Floor(m) = Int_identity(
    ( IF ((m.numer<0) AND ((m.numer MOD m.denom)/=0))
        THEN ((m.numer/m.denom)-l)
        ELSE (m.numer/m.denom))));
--| fixnum_abs: (good_fixnum(m)
--> (fixnum_abs(m) = (IF (m<Int_to_fixnum(O)) THEN ((-1)*m) ELSE m)));
--| END AXIOMS;
--| LEMMAS: FORALL [m:fixnum, n:fixnum, p:fixnum, i:Int,
  n1:Int, d1:Int, n2:Int, d2:Int]--| good_fixnum_real_part: (good_fixnum(m)
--> good_fixnum(RealPart(m)));
--| concrete_equality_pair: (FORALL n1:Int, d1:Int, n2:Int,
  d2:Int:(((n1*d2)=(n2*d1))-->pair(n1, d1)=pair(n2, d2)));
--| floorX: ((Int_to_fixnum(O)<=m)-->(0<=Floor(m)));
--| pair_plus: (pair(n1, d1)+pair(n2, d2)
  = pair((Int_identity((n1*d2))+Int_identity((n2*d1))),
  (d1*d2)));
--| pair_minus: (pair(n1, d1)-pair(n2, d2)
  = pair((Int_identity((n1*d2))-Int_identity((n2*d1))),
  (d1*d2)));
--| divides_pi: (FORALL n:Int, d:Int,
  i:Int:(((d/=0) AND (i/=0))-->((pair(n, d)/i)=pair(n, (d*i)))));
--| END LEMMAS;
--| TRAIT sort_names IS
--| DECLARES
--| SORT calendar_time_sort IS Int;
--| SORT century IS (twentieth, twentyfirst);
--| SORT years IS Int;
--| SORT months IS Int;
--| SORT year_days IS Int;
--| SORT month_days IS Int;
--| SORT absolute_days IS Int;
--| SORT hours IS Int;
--| SORT minutes IS Int;
--| SORT seconds IS Int;
--| SORT milliseconds IS Int;
--| SORT time_sort IS AnyRecordSort;
--| SORT duration_sort IS fixnum;
--| SORT month_name_sort IS (January, February, March, April, May, June, July, August, September, October, November, December);
--| SORT day_name_sort IS (Monday, Tuesday, Wednesday, Thursday, Friday, Saturday, Sunday);
--| SORT period_sort IS (am, pm);
--| SORT time_format_sort IS (full, military);
--| SORT date_format_sort IS (full, month_day_year);
--| SORT interval_sort IS AnyRecordSort;
--| SORT catu IS Int;
--| INTRODUCES
--| month_name_sort_tic_pos: month_name_sort -> Int;
--| month_name_sort_tic_val: Int -> month_name_sort;
--| good_day_name: day_name_sort -> Bool;
--| day_name_sort_tic_pos: day_name_sort -> Int;
--| day_name_sort_tic_val: Int -> day_name_sort;
--| day_name_sort_increment: day_name_sort, Int -> day_name_sort;
--| milliseconds_tic_first: -> milliseconds;
--| seconds_tic_first: -> seconds;
--| minutes_tic_first: -> minutes;
--| hours_tic_first: -> hours;
--| years_tic_first: -> years;
--| months_tic_first: -> months;
--| months_tic_last: -> months;
--| month_name_sort_tic_first: -> month_name_sort;
--| month_name_sort_tic_last: -> month_name_sort;
--| time_sort_tic: -> time_sort;
--| month_days_tic: -> month_days;
--| extract_year: calendar_time_sort -> years;
--| extract_month: calendar_time_sort -> months;
--| extract_day: calendar_time_sort -> month_days;
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-- extract_duration: calendar_time_sort -> duration_sort;
-- seconds_to_duration: seconds -> duration_sort;
-- "+": calendar_time_sort, duration_sort -> calendar_time_sort;
-- "-": calendar_time_sort, duration_sort -> calendar_time_sort;
-- calendar_time_sort_identity:
  calendar_time_sort -> calendar_time_sort;
-- duration_sort_identity: duration_sort -> duration_sort;
-- good_duration: duration_sort -> Bool;
-- good_day: absolute_days -> Bool;
-- good_hour: hours -> Bool;
-- good_minute: minutes -> Bool;
-- good_second: seconds -> Bool;
-- good_millisecond: milliseconds -> Bool;
-- good_interval: interval_sort -> Bool;
-- AXIOMS: FORALL [the_duration:duration_sort, n:Int, the_day_name:day_name_sort, offset:Int, the_interval:interval_sort, the_day:absolute_days, the_hour:hours, the_minute:minutes, the_second:seconds, the_millisecond:milliseconds]
  months_tic_first: (months_tic_first=1);
  months_tic_last: (months_tic_last=12);
  month_pos_january: (month_name_sort_tic_pos(January)=0);
  month_pos_february: (month_name_sort_tic_pos(February)=1);
  month_pos_march: (month_name_sort_tic_pos(March)=2);
  month_pos_april: (month_name_sort_tic_pos(April)=3);
  month_pos_may: (month_name_sort_tic_pos(May)=4);
  month_pos_june: (month_name_sort_tic_pos(June)=6);
  month_pos_july: (month_name_sort_tic_pos(July)=6);
  month_pos_august: (month_name_sort_tic_pos(August)=7);
  month_pos_september: (month_name_sort_tic_pos(September)=8);
  month_pos_october: (month_name_sort_tic_pos(October)=9);
  month_pos_november: (month_name_sort_tic_pos(November)=10);
  month_pos_december: (month_name_sort_tic_pos(December)=11);
  month_val_0: (month_name_sort_tic_val(0)=January);
  month_val_1: (month_name_sort_tic_val(1)=February);
  month_val_2: (month_name_sort_tic_val(2)=March);
  month_val_3: (month_name_sort_tic_val(3)=April);
  month_val_4: (month_name_sort_tic_val(4)=May);
  month_val_5: (month_name_sort_tic_val(5)=June);
  month_val_6: (month_name_sort_tic_val(6)=July);
  month_val_7: (month_name_sort_tic_val(7)=August);
  month_val_8: (month_name_sort_tic_val(8)=September);
  month_val_9: (month_name_sort_tic_val(9)=October);
  month_val_10: (month_name_sort_tic_val(10)=November);
-- | month_val_11: (month_name_sort_tic_val(11)=December);
-- | good_day_name: (good_day_name(the_day_name)
-- = ((Monday<=the_day_name) OR (the_day_name<=Sunday)));
-- | day_val_0: (day_name_sort_tic_val(0)=Monday);
-- | day_val_1: (day_name_sort_tic_val(1)=Tuesday);
-- | day_val_2: (day_name_sort_tic_val(2)=Wednesday);
-- | day_val_3: (day_name_sort_tic_val(3)=Thursday);
-- | day_val_4: (day_name_sort_tic_val(4)=Friday);
-- | day_val_5: (day_name_sort_tic_val(5)=Saturday);
-- | day_val_6: (day_name_sort_tic_val(6)=Sunday);
-- | first_millisecond: (milliseconds_tic_first=0);
-- | first_second: (seconds_tic_first=0);
-- | first_minute: (minutes_tic_first=0);
-- | first_hour: (hours_tic_first=0);
-- | first_year: (years_tic_first=1901);
-- | first_month: (month_name_sort_tic_first=January);
-- | last_month: (month_name_sort_tic_last=December);
-- | duration_sort_identity: (duration_sort_identity(the_duration)
-- = the_duration);
-- | day_name_sort_increment: (day_name_sort_increment(the_day_name, offset)
-- = day_name_sort_tic_val(
--     ((day_name_sort_tic_pos(the_day_name)+offset) MOD 7)));
-- | good_duration: (good_duration(the_duration)
-- = good_fixnum(the_duration));
-- | good_day: (good_day(the_day)=(0<=the_day));
-- | good_hour: (good_hour(the_hour)
-- = ((0<=the_hour) AND (the_hour<24)));
-- | good_minute: (good_minute(the_minute)
-- = ((0<=the_minute) AND (the_minute<60)));
-- | good_second: (good_second(the_second)
-- =
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(((0<=the_second) AND (the_second<60)));

--| good_millisecond: ( good_millisecond(the_millisecond)

= 

(((0<=the_millisecond) AND (the_millisecond<1000)));

--| good_interval: ( good_interval(the_interval)

=

(

(

(

good_day(the_interval.elapsed_days)

AND

good_hour(the_interval.elapsed_hours))

AND

good_minute(the_interval.elapsed_minutes))

AND

good_second(the_interval.elapsed_seconds))

AND

good_millisecond(the_interval.elapsed_milliseconds));

--| END AXIOMS;

--| LEMMAS: FORALL [the_day_name:day_name_sort, the_pos:Int,

the_second:seconds]

--| day_name_sort_tic_pos: ( ( 

( 

(day_name_sort_tic_pos(Monday)=0)

AND

(day_name_sort_tic_pos(Tuesday)=1))

AND

(day_name_sort_tic_pos(Wednesday)=2))

AND

(day_name_sort_tic_pos(Thursday)=3))

AND

(day_name_sort_tic_pos(Friday)=4))

AND

(day_name_sort_tic_pos(Saturday)=5))

AND

(day_name_sort_tic_pos(Sunday)=6));

--| day_name_sort_tic_pos_range: ( 
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(0<=day_name_sort_tic_pos(the_day_name))
AND
(day_name_sort_tic_pos(the_day_name)<=6));

-- J day_name_sort_tic_val_range: ( (0<=the_pos) AND (the_pos<=6))

->

( (Monday<=day_name_sort_tic_val(the_pos))
AND
(day_name_sort_tic_val(the_pos)<=Sunday)));

-- J seconds_to_duration: ( seconds_to_duration(the_second) =

pair(the_second, 1));

-- END LEMMAS;

-- TRAIT conversion_factors IS

-- DECLARES

-- INTRODUCES

-- days_to_hours: -> hours;

-- hours_to_minutes: -> minutes;

-- hours_to_seconds: -> seconds;

-- days_to_seconds: -> seconds;

-- minutes_to_seconds: -> seconds;

-- days_to_milliseconds: -> milliseconds;

-- seconds_to_milliseconds: -> milliseconds;

-- seconds_to_catu: -> catu;

-- milliseconds_to_catu: -> catu;

-- AXIOMS:

-- hours_to_minutes: (hours_to_minutes=60);

-- days_to_hours: (days_to_hours=24);

-- minutes_to_seconds: (minutes_to_seconds=60);

-- seconds_to_milliseconds: (seconds_to_milliseconds=1000);

-- days_to_seconds: ( days_to_seconds =

((days_to_hours*hours_to_minutes)*minutes_to_seconds));

-- hours_to_seconds: ( hours_to_seconds =

(hours_to_minutes*minutes_to_seconds));

-- milliseconds_to_catu: (milliseconds_to_catu>0);

-- seconds_to_catu: ( seconds_to_catu =
(seconds_to_milliseconds*milliseconds_to_catu));

-- END AXIOMS;
-- LEMMAS;
-- END LEMMAS;
-- TRAIT time_representations IS
-- DECLARES
-- INTRODUCES
-- days_in_month: months, years -> month_days;
-- is_leap_year: years -> Bool;
-- is_non_leap_centennial: years -> Bool;
-- days_in_year: years -> year_days;
-- days_of_years_since_1900: years -> absolute_days;
-- seconds_since_1900: time_sort -> seconds;
-- days_since_Jan: months, years -> year_days;
-- day_name_of: years, year_days -> day_name_sort;
-- day_of_year: years, months, month_days -> year_days;
-- month_of: years, year_days -> months;
-- day_of_month: years, year_days -> month_days;
-- year_of: absolute_days -> years;
-- good_year: years -> Bool;
-- good_month: months -> Bool;
-- good_month_day: month_days -> Bool;
-- good_date: years, months, month_days, duration_sort -> Bool;
-- good_time: time_sort -> Bool;
-- good_year_and_day: years, year_days -> Bool;
-- day_name_sort_val: Int -> day_name_sort;
-- time_of: years, months, duration_sort -> calendar_time_sort;
-- AXIOMS: FORALL [the_month:Int, the_year:Int,
the_time:time_sort, the_year_day:Int, the_month_day:Int,
the_absolute_day:Int]
-- days_in_January: (days_in_month(1, the_year)=31);
-- days_in_February: (if is_leap_year(the_year) THEN 29 ELSE 28));
-- days_in_March: (days_in_month(3, the_year)=31);
-- days_in_April: (days_in_month(4, the_year)=30);
-- days_in_May: (days_in_month(5, the_year)=31);
-- days_in_June: (days_in_month(6, the_year)=30);
-- days_in_July: (days_in_month(7, the_year)=31);
-- days_in_August: (days_in_month(8, the_year)=31);
```plaintext
--| days_in_September: (days_in_month(9, the_year)=30);
--| days_in_October: (days_in_month(10, the_year)=31);
--| days_in_November: (days_in_month(11, the_year)=30);
--| days_in_December: (days_in_month(12, the_year)=31);
--| leap_year: (is_leap_year(the_year)
  =
  ( ((the_year MOD 4)=0)
  AND
  (NOT is_non_leap_centennial(the_year))));
--| non_leap_centennial: (is_non_leap_centennial(the_year)
  =
  (((the_year MOD 100)=0) AND ((the_year MOD 400)/=0)));
--| days_in_year: (days_in_year(the_year)
  =
  (IF is_leap_year(the_year) THEN 366 ELSE 365));
--| days_since_1900_0: (days_of_years_since_1900(1900)=0);
--| days_since_1900_1: (the_year>1900)
  ->
  (days_of_years_since_1900(the_year)
  =
  (days_in_year((the_year-1))
  +
  days_of_years_since_1900(((the_year-1)))));
--| days_since_January_0: (days_since_Jan(1, the_year)=0);
--| days_since_January_1: (the_month>1)
  ->
  (days_since_Jan(the_month, the_year)
  =
  (days_in_month((the_month-1), the_year)
  +
  days_since_Jan(((the_month-1), the_year))));
--| good_year: (good_year(the_year)
  =
  
```
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\[
((1901 <= \text{the\_year}) \text{ AND } (\text{the\_year} <= 2099));
\]

-- good_month:
\[
good\_month(\text{the\_month}) =
((1 <= \text{the\_month}) \text{ AND } (\text{the\_month} <= 12));
\]

-- good_month_day:
\[
good\_month\_day(\text{the\_month\_day}) =
((1 <= \text{the\_month\_day}) \text{ AND } (\text{the\_month\_day} <= 31));
\]

-- good_time:
\[
good\_time(\text{the\_time}) =
(\text{the\_time}.\text{the\_year}
  (1901 <= \text{the\_time}.\text{the\_year})
  \text{ AND }
  (\text{the\_year} <= 2099)
  \text{ AND }
  (1 <= \text{the\_time}.\text{the\_month})
  \text{ AND }
  (\text{the\_month} <= 12)
  \text{ AND }
  (1 <= \text{the\_time}.\text{the\_day})
  \text{ AND }
  (\text{the\_time}.\text{the\_day} <=
    \text{days\_in\_month(\text{the\_time}.\text{the\_month},
    \text{the\_time}.\text{the\_year}))
    \text{ AND }
    (0 <= \text{the\_time}.\text{the\_hour})
    \text{ AND }
    (\text{the\_time}.\text{the\_hour} < \text{days\_to\_hours}))
\]
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AND (0<=the_time.the_minute))
AND (the_time.the_minute<hours_to_minutes))
AND (0<=the_time.the_second))
AND (the_time.the_second<minutes_to_seconds))
AND (0<=the_time.the_millisecond))
AND (the_time.the_millisecond<seconds_to_milliseconds)));

--| good_year_and_day: (good_year_and_day(the_year, the_year_day)
  =
      ((1901<=the_year) AND (the_year<=2099))
 AND (1<=the_year_day)
 AND (the_year_day<=days_in_year(the_year))));

--| day_name: (day_name_of(the_year, the_year_day)
 =
      day_name_sort_tic_val(
 (days_of_years_since_1900(the_year)+the_year_day-1))
 MOD 7));

--| day_of_year: (day_of_year(the_year, the_month, the_month_day)
 =
 (days_since_Jan(the_month, the_year)+the_month_day));

--| month_of: (days_since_Jan(the_month, the_year)<the_year_day)
 AND (the_year_day
 <=
 (days_since_Jan(the_month, the_year)
days_in_month(the_month, the_year))

->

  (month_of(the_year, the_year_day)=the_month));

--| day_of_month: ( 
  day_of_month(the_year, the_year_day)
  =
    ( 
      the_year_day
      - 
      days_since_Jan(month_of(the_year, the_year_day), 
      the_year));

--| year_of: ( 
  (days_of_years_since_1900(the_year)<the_absolute_day) 
  AND 
  (the_absolute_day<=days_of_years_since_1900((the_year+1))))

->

  (year_of(the_absolute_day)=the_year));

--| seconds_since_1900: ( 
  seconds_since_1900(the_time)
  =
    ( 
      ( 
        ( 
          days_of_years_since_1900(the_time.the_year) 
          * 
          days_to_seconds) 
        + 
        Int_identity( 
          ( 
            days_since_Jan(the_time.the_month, 
            the_time.the_year) 
            + 
            days_to_seconds))
        + 
        Int_identity((the_time.the_hour*hours_to_seconds))
        + 
        Int_identity((the_time.the_minute*minutes_to_seconds))
        + 
        Int_identity((the_time.the_second*seconds_to_seconds)))
      + 
      duration_sort_identity(the_time.the_second)));
--| day_name_of: (day_name_of(1900, 1)=Tuesday);
--| days_in_months: (
    days_in_month(the_month, the_year)
    =
    ( IF (the_month=1)
      THEN 31
      ELSE IF (the_month=2)
        THEN ( IF is_leap_year(the_year) THEN 29 ELSE 28)
        ELSE IF (the_month=3)
          THEN 31
          ELSE IF (the_month=4)
            THEN 30
            ELSE IF (the_month=5)
              THEN 31
              ELSE IF (the_month=6)
                THEN 30
                ELSE IF (the_month=7)
                  THEN 31
                  ELSE IF (the_month=8)
                    THEN 31
                    ELSE IF (the_month=9)
                      THEN 30
                      ELSE IF (the_month=10)
                        THEN 31
                        ELSE IF (the_month=11)
                          THEN 30
                          ELSE 31))))))))));

--| number_of_months: ( 
    good_mon_h(the_month)
  -> 
  ( ( }
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( ( ( ( ( ((the_month=1) OR (the_month=2))
OR (the_month=3))
OR (the_month=4))
OR (the_month=5))
OR (the_month=6))
OR (the_month=7))
OR (the_month=8))
OR (the_month=9))
OR (the_month=10))
OR (the_month=11))
OR (the_month=12)));

--| days_in_month_range: ( good_month(the_month)
->
( (1<=days_in_month(the_month, the_year))
AND (days_in_month(the_month, the_year)<=31)))

--| days_since_January_positive: ( good_month(the_month)
->
(0<=days_since_Jan(the_month, the_year)))

--| days_since_January_upper_bound: ( (good_month(the_month) AND good_year(the_year))
->
(days_since_Jan(the_month, the_year)<=335));
days_in_year_identity: (  
days_in_year(the_year)  
=  
  (  
    days_since_Jan(months_tic_last, the_year)  
    +  
    days_in_month(months_tic_last, the_year))  
);  

END LEMMAS;

TRAIT time_representation_conversions IS  
DECLARATIONS  
INTRODUCES  
time_to_cal_time: time_sort -> calendar_time_sort;  
cal_time_to_time: calendar_time_sort -> time_sort;  
round_cal_time_down_to_milliseconds:  
  calendar_time_sort -> calendar_time_sort;  
interval_to_duration: interval_sort -> duration_sort;  
round_duration_down_to_milliseconds:  
duration_sort -> time_sort;  
duration_to_interval: duration_sort -> interval_sort;  
AXIOMS: FORALL [the_time:time_sort,  
the_calendar_time:calendar_time_sort,  
the_interval:interval_sort, the_duration:duration_sort,  
the_second:seconds]  
time_to_cal_time: (  
  time_to_cal_time(the_time)  
=  
  (  
    seconds_since_1900(the_time.the_year)*seconds_to_catu)  
  +  
    (  
      calendar_time_sort_identity(the_time.the_millisecond)  
      *  
      milliseconds_to_catu))  
);  

round_cal_time_down: (  
round_cal_time_down_to_milliseconds(the_calendar_time)  
=  
  (  
    the_calendar_time  
    -  
    (the_calendar_time MOD milliseconds_to_catu))  
);  
time_to_cal_time: (  
  time_to_cal_time(the_time)  
=  
  (  
    seconds_since_1900(the_time.the_year)*seconds_to_catu)  
    +  
    (  
      calendar_time_sort_identity(the_time.the_millisecond)  
      *  
      milliseconds_to_catu))  
);
round_cal_time_down_to_milliseconds(the_calendar_time))
->
(cal_time_to_time(the_calendar_time)=the_time));

--| interval_to_duration: ( interval_to_duration(the_interval) =
{
{
( seconds_to_duration( (the_interval.elapsed_days*days_to_seconds)) +
 seconds_to_duration( (the_interval.elapsed_hours*hours_to_seconds)) +
 seconds_to_duration( (the_interval.elapsed_minutes*minutes_to_seconds)) +
 seconds_to_duration(the_interval.elapsed_seconds)) +
( seconds_to_duration(the_interval.elapsed_milliseconds) /
 seconds_to_milliseconds)));

--| good_interval_to_good_duration: ( good_interval_to_good_duration =
{
 good_interval(the_interval) AND
 (the_duration=interval_to_duration(the_interval)))
->
good_duration(the_duration));

--| round_duration_down: ( round_duration_down_the_milliseconds(the_duration) =
{
 seconds_to_duration( Floor((the_duration*seconds_to_milliseconds)) /
 seconds_to_milliseconds));

--| good_seconds_to_good_duration: ( good_seconds_to_good_duration =
good_second(the_second) ->
good_duration(seconds_to_duration(the_second)));
APPENDIX E

END AXIOMS;

LEMMA: FORALL [d:duration_sort, d2:duration_sort, m:duration_sort, n:duration_sort, p:duration_sort]

good_duration_pair: (FORALL m:Int,
  d: Int::((d/=0)->good_duration(pair(n, d))));

good_duration_sum: (good_duration(d1) AND good_duration(d2))
->
good_duration((d1+d2));

subtract_duration_equals: (FORALL m:duration_sort,
  n:duration_sort, p:duration_sort::((m=(n-p))->((m+p)=n)));

END LEMMAS;

PACKAGE builtin IS
  TYPE duration IS RECORD
    sign: integer;
    whole_part: integer;
    fraction: integer;
  END RECORD;
  TYPE string IS ARRAY(integer) OF character;
FUNCTION duration_ize(seconds : Int integer) RETURN duration;
  WHERE
  RETURN seconds_to_duration(seconds);
  END WHERE;

END builtin;

WITH builtin;

PACKAGE calendar IS
  TYPE time IS NEW integer;
  TYPE year_number IS NEW integer;
  TYPE month_number IS NEW integer;
  TYPE day_number IS NEW integer;
  TYPE day_duration IS NEW builtin.duration;
FUNCTION clock RETURN time;
  WHERE
  END WHERE;

FUNCTION year(date : Int time) RETURN year_number;
  WHERE
  RETURN extract_year(date);
  END WHERE;

FUNCTION month(date : Int time) RETURN month_number;


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```
FUNCTION day(date : IN time) RETURN day_number;
  WHERE
  RETURN extract_day(date);
  END WHERE;

FUNCTION seconds(date : IN time) RETURN day_duration;
  WHERE
  RETURN extract_duration(date);
  RETURN result SUCH THAT good_duration(result);
  END WHERE;

PROCEDURE split(date : IN time;
  year : OUT year_number;
  month : OUT month_number;
  day : OUT day_number;
  seconds : OUT day_duration);
  WHERE
  OUT (year=extract_year(date));
  OUT (month=extract_month(date));
  OUT (day=extract_day(date));
  OUT (seconds=extract_duration(date));
  END WHERE;

FUNCTION time_of(year : IN year_number;
  month : IN month_number;
  day : IN day_number;
  seconds : IN day_duration) RETURN time;
  WHERE
  IN good_date(year, month, day, seconds);
  RETURN time_of(year, month, day, seconds);
  END WHERE;

FUNCTION "+"(left : IN time;
  right : IN builtin.duration) RETURN time;
  WHERE
  RETURN (left+right);
  END WHERE;

FUNCTION "-"(left : IN time;
  right : IN builtin.duration) RETURN time;
```
FUNCTION "<"(left, right : IN time) RETURN boolean;
--- WHERE
--- RETURN (left<right);
--- END WHERE;

FUNCTION "<="(left, right : IN time) RETURN boolean;
--- WHERE
--- RETURN (left<=right);
--- END WHERE;

FUNCTION ">"(left, right : IN time) RETURN boolean;
--- WHERE
--- RETURN (left>right);
--- END WHERE;

FUNCTION ">="(left, right : IN time) RETURN boolean;
--- WHERE
--- RETURN (left>=right);
--- END WHERE;

FUNCTION day_duration_ize(seconds : IN integer)
  RETURN day_duration;
--- WHERE
--- RETURN seconds_to_duration(seconds);
--- END WHERE;

END calendar;

WITH builtin;
PACKAGE integer_utilities IS
  TYPE number IS NEW integer;
  TYPE base IS NEW integer;
  TYPE numbers IS ARRAY(integer) OF number;
  FUNCTION min(left : IN number;
    right : IN number) RETURN number;
  --- WHERE
  --- RETURN (IF (left<right) THEN left ELSE right);
  --- END WHERE;
FUNCTION min(the_numbers: IN numbers) RETURN number;
--| WHERE
--| END WHERE;

FUNCTION max(left: IN number;
    right: IN number) RETURN number;
--| WHERE
--| RETURN (IF (left>right) THEN left ELSE right);
--| END WHERE;

FUNCTION max(the_numbers: IN numbers) RETURN number;
--| WHERE
--| END WHERE;

FUNCTION is_positive(the_number: IN number) RETURN boolean;
--| WHERE
--| RETURN (the_number>0);
--| END WHERE;

FUNCTION is_natural(the_number: IN number) RETURN boolean;
--| WHERE
--| RETURN (the_number>=0);
--| END WHERE;

FUNCTION is_negative(the_number: IN number) RETURN boolean;
--| WHERE
--| RETURN (the_number<0);
--| END WHERE;

FUNCTION is_zero(the_number: IN number) RETURN boolean;
--| WHERE
--| RETURN (the_number=0);
--| END WHERE;

FUNCTION is_odd(the_number: IN number) RETURN boolean;
--| WHERE
--| RETURN ((the_number MOD 2)=1);
--| END WHERE;

FUNCTION is_even(the_number: IN number) RETURN boolean;
--| WHERE
--| RETURN ((the_number MOD 2)=0);
--| END WHERE;
FUNCTION image_of(the_number : IN number;
   with_the_base : IN base) RETURN builtin.string;
   --| WHERE
   --| END WHERE;

FUNCTION value_of(the_image : IN builtin.string;
   with_the_base : IN base) RETURN number;
   --| WHERE
   --| END WHERE;

END integer_utilities;

WITH builtin;
PACKAGE duration_utilities IS
   TYPE number IS NEW builtin.duration;
   FUNCTION integer_part(the_number : IN number) RETURN integer;
      --| WHERE
      --| IN good_duration(the_number);
      --| RETURN IntegerPart(the_number);
      --| END WHERE;

FUNCTION real_part(the_number : IN number) RETURN number;
      --| WHERE
      --| IN good_duration(the_number);
      --| RETURN RealPart(the_number);
      --| RETURN result SUCH THAT good_duration(result);
      --| END WHERE;

FUNCTION floor(the_number : IN number) RETURN integer;
      --| WHERE
      --| IN good_duration(the_number);
      --| RETURN Floor(the_number);
      --| END WHERE;

FUNCTION ceiling(the_number : IN number) RETURN integer;
      --| WHERE
      --| IN good_duration(the_number);
      --| RETURN Ceiling(the_number);
      --| END WHERE;

END duration_utilities;

WITH builtin, calendar;
PACKAGE calendar_utilities IS
TYPE natural IS NEW integer;
TYPE string IS ARRAY(integer) OF character;
TYPE year IS NEW calendar.year_number;
TYPE month IS NEW integer;
TYPE day IS NEW integer;
TYPE hour IS NEW integer;
TYPE minute IS NEW integer;
TYPE second IS NEW integer;
TYPE millisecond IS NEW integer;
TYPE time IS RECORD
  the_year: year;
  the_month: month;
  the_day: day;
  the_hour: hour;
  the_minute: minute;
  the_second: second;
  the_millisecond: millisecond;
END RECORD;
TYPE interval IS RECORD
  elapsed_days: natural;
  elapsed_hours: hour;
  elapsed_minutes: minute;
  elapsed_seconds: second;
  elapsed_milliseconds: millisecond;
END RECORD;
TYPE year_day IS NEW integer;
TYPE month_name IS (january, february, march, april, may,
  june, july, august, september, october, november, december);
TYPE day_name IS (monday, tuesday, wednesday, thursday,
  friday, saturday, sunday);
TYPE period IS (am, pm);
TYPE time_format IS (full, military);
TYPE date_format IS (full, month_day_year);
FUNCTION natural_ize(m : IN integer) RETURN natural;
  --| WHERE
  --|   IN (0<=m);
  --|   RETURN m;
  --| END WHERE;
FUNCTION integer_ize(m : IN integer) RETURN integer;
  --| WHERE
  --|   RETURN m;
  --| END WHERE;
FUNCTION year_day_ize(m : IN integer) RETURN year_day;
--| WHERE
--|    IN ((1<=m) AND (m<366));
--|    RETURN m;
--| END WHERE;

FUNCTION day_ize(m : IN integer) RETURN day;
--| WHERE
--|    IN ((1<=m) AND (m<31));
--|    RETURN m;
--| END WHERE;

FUNCTION hour_ize(m : IN integer) RETURN hour;
--| WHERE
--|    IN ((0<=m) AND (m<24));
--|    RETURN m;
--| END WHERE;

FUNCTION minute_ize(m : IN integer) RETURN minute;
--| WHERE
--|    IN ((0<=m) AND (m<60));
--|    RETURN m;
--| END WHERE;

FUNCTION second_ize(m : IN integer) RETURN second;
--| WHERE
--|    IN ((0<=m) AND (m<60));
--|    RETURN m;
--| END WHERE;

FUNCTION millisecond_ize(m : IN integer) RETURN millisecond;
--| WHERE
--|    IN ((0<=m) AND (m<1000));
--|    RETURN m;
--| END WHERE;

FUNCTION millisecond_ize(m : IN builtin.duration)
    RETURN millisecond;
--| WHERE
--|    RETURN Floor((1000*m));
--| END WHERE;

FUNCTION year_number_ize(the_year : IN year)
    RETURN calendar.year_number;
--| WHERE
--|   IN good_year(the_year);
--|   RETURN the_year;
--| END WHERE;

FUNCTION month_number_ize(the_month : IN month)
  RETURN calendar.month_number;
--| WHERE
--|   IN good_month(the_month);
--|   RETURN the_month;
--| END WHERE;

FUNCTION day_number_ize(the_day : IN day)
  RETURN calendar.day_number;
--| WHERE
--|   IN good_month_day(the_day);
--|   RETURN the_day;
--| END WHERE;

FUNCTION year_tic_first RETURN integer;
--| WHERE
--|   RETURN years_tic_first;
--| END WHERE;

FUNCTION month_name_tic_pos(the_month : IN month_name)
  RETURN month;
--| WHERE
--|   RETURN month_name_sort_tic_pos(the_month);
--| END WHERE;

FUNCTION month_name_tic_val(index : IN integer)
  RETURN month_name;
--| WHERE
--|   IN good_month((index+1));
--|   RETURN month_name_sort_tic_val(index);
--| END WHERE;

FUNCTION day_name_tic_pos(the_day : IN day_name)
  RETURN integer;
--| WHERE
--|   RETURN day_name_sort_tic_pos(the_day);
--| END WHERE;

FUNCTION day_name_tic_val(index : IN integer) RETURN day_name;
--| WHERE
--| RETURN day_name_sort_tic_val(index);
--| RAISE constraint_error <=> IN (index<0)
OR (index>6));
--| END WHERE;

FUNCTION millisecond_tic_first RETURN millisecond;
--| WHERE
--| RETURN milliseconds_tic_first;
--| END WHERE;

FUNCTION second_tic_first RETURN second;
--| WHERE
--| RETURN seconds_tic_first;
--| END WHERE;

FUNCTION minute_tic_first RETURN minute;
--| WHERE
--| RETURN minutes_tic_first;
--| END WHERE;

FUNCTION hour_tic_first RETURN hour;
--| WHERE
--| RETURN hours_tic_first;
--| END WHERE;

FUNCTION month_tic_first RETURN month;
--| WHERE
--| RETURN months_tic_first;
--| END WHERE;

FUNCTION month_tic_last RETURN month;
--| WHERE
--| RETURN months_tic_last;
--| END WHERE;

FUNCTION is_leap_year(the_year : IN year) RETURN boolean;
--| WHERE
--| RETURN is_leap_year(the_year);
--| END WHERE;

FUNCTION days_in(the_year : IN year) RETURN year_day;
APPENDIX E

--| WHERE
--| IN good_year(the_year);
--| RETURN days_in_year(the_year);
--| END WHERE;

FUNCTION days_in(the_month : IN month;
    the_year : IN year) RETURN day;
--| WHERE
--| IN good_month(the_month);
--| IN good_year(the_year);
--| RETURN days_in_month(the_month, the_year);
--| END WHERE;

FUNCTION month_of(the_month : IN month) RETURN month_name;
--| WHERE
--| IN good_month(the_month);
--| RETURN month_name_sort_tic_val((the_month-1));
--| END WHERE;

FUNCTION month_of(the_month : IN month_name) RETURN month;
--| WHERE
--| RETURN (month_name_sort_tic_pos(the_month)+1);
--| END WHERE;

FUNCTION day_of(the_year : IN year;
    the_day : IN year_day) RETURN day_name;
--| WHERE
--| IN good_year_and_day(the_year, the_day);
--| RETURN day_name_of(the_year, the_day);
--| END WHERE;

FUNCTION day_of(the_time : IN time) RETURN year_day;
--| WHERE
--| IN good_time(the_time);
--| RETURN day_of_year(the_time.the_year,
    the_time.the_month, the_time.the_day);
--| END WHERE;

FUNCTION time_of(the_year : IN year;
    the_day : IN year_day) RETURN time;
--| WHERE
--| IN good_year_and_day(the_year, the_day);
--| RETURN t SUCH THAT (
(   (   (   (t.the_year=the_year)
      AND
      (t.the_month=month_of(the_year, the_day))
      AND
      (t.the_day=day_of_month(the_year, the_day))
      AND
      (t.the_hour=0))
      AND
      (t.the_minute=0))
      AND
      (t.the_second=0))
      AND
      (t.the_millisecond=0));
--| END WHERE;

FUNCTION period_of(the_time : IN time) RETURN period;
--| WHERE
--|   IN good_time(the_time);
--|   RETURN (IF (the_time.the_hour<A2) THEN am ELSE pm);
--| END WHERE;

FUNCTION time_of(the_time : IN time) RETURN calendar.time;
--| WHERE
--|   IN good_time(the_time);
--|   RETURN time_to_cal_time(the_time);
--| END WHERE;

FUNCTION time_of(the_time : IN calendar.time) RETURN time;
--| WHERE
--|   RETURN cal_time_to_time(the_time);
--| END WHERE;

FUNCTION duration_of(the_interval : IN interval)
   RETURN builtin.duration;
--| WHERE
--|   RETURN interval_to_duration(the_interval);
--|   RETURN result SUCH THAT good_duration(result);
--| END WHERE;

FUNCTION interval_of(the_duration : IN builtin.duration) RETURN
interval;
--| WHERE
--| RETURN duration_to_interval(the_duration);
--| END WHERE;

END calendar_utilities;

WITH integer_utilities, duration_utilities, builtin;

PACKAGE BODY calendar_utilities IS
  TYPE month_day IS ARRAY(month) OF day;
  century_offset : Integer := 1900;
  days_per_year : year_day := 365;
  first_day : day_name := tuesday;
  seconds_per_minute : Integer := 60;
  seconds_per_hour : Integer := (60*seconds_per_minute);
  seconds_per_day : Integer := (24*seconds_per_hour);
  milliseconds_per_second : Integer := 1000;
  noon : Integer := 12;
  time_separator : Character := ':';
  date_separator : Character := '/';
  blank : Character := ' ';
  comma : Character := ',';
  zero : Character := '0';

FUNCTION "+"(m, n : IN builtin.duration)
  RETURN builtin.duration;
  WHERE
  IF good_duration(m);
  IF good_duration(n);
  RETURN (m+n);
  RETURN result SUCH THAT good_duration(result);
  END WHERE;

FUNCTION "-"(m, n : IN builtin.duration)
  RETURN builtin.duration;
  WHERE
  IF good_duration(m);
  IF good_duration(n);
  RETURN (m-n);
  RETURN result SUCH THAT good_duration(result);
  END WHERE;

FUNCTION "*"(m, n : IN builtin.duration)
  RETURN builtin.duration;
  WHERE
FUNCTION "\""(m, n : IN builtin.duration)
  RETURN builtin.duration;
  WHERE
  good_duration(m);
  good_duration(n);
  m/=Int_to_fixnum(0);
  RETURN (m/\n  RETURN result SUCH THAT good_duration(result);
  END WHERE;

FUNCTION "\""(m : IN builtin.duration;
  n : IN integer) RETURN builtin.duration;
  WHERE
  good_duration(m);
  RETURN (m*\n  RETURN result SUCH THAT good_duration(result);
  END WHERE;

FUNCTION days_per_month(the_month : IN month) RETURN integer;
  WHERE
  ((1<=the_month) AND (the_month<=12));
  RETURN ( ( (((month_days_tic[1=>31][2=>28][3=>31])}
FUNCTION is_leap_year(the_year : IN year) RETURN Boolean
| WHERE * * *
| RETURN is_leap_year(the_year);
| END WHERE;
| VC Status: proved
| BY instantiation of axiom leap_year
| in trait time_representations
| WITH the_year FOR the_year:Int
| BY instantiation of axiom non_leap_centennial
| in trait time_representations
| WITH the_year FOR the_year:Int
| BY instantiation of lemma mod_transitive in trait Z
| WITH 100, 4, the_year FOR m1:Int, m2:Int, a:Int
| BY left substitution of 1
| BY left substitution of 2
| BY simplification
| BY synthesis of TRUE
| □

BEGIN
IF ((the_year MOD 100)=0) THEN
RETURN ((the_year MOD 400)=0);
ELSE
RETURN ((the_year MOD 4)=0);
ENDIF;
END is_leap_year;
FUNCTION days_in(the_year : IN year) RETURN year_day
| WHERE
| GLOBAL days_per_year : IN ;
| IN (days_per_year=365);
| RETURN days_in_year(the_year);
| END WHERE;
| VC Status: proved
| BY axiom days_in_year in trait time_representations
| WITH the_year FOR the_year:Int
| substituting for left
---! BY simplification
---! BY synthesis of TRUE
---! □

IS

BEGIN

IF is_leap_year(the_year) THEN
  RETURN (days_per_year+1);
ELSE
  RETURN days_per_year;
END IF;

FUNCTION days_in(the_month : IN month; the_year : IN year) RETURN days
--- WHERE
--- | IN good_month(the_month);
--- | IN good_year(the_year);
--- | RETURN days_in_month(the_month, the_year);
--- | END WHERE;
--- VC Status: proved
--- | BY axiom month_pos_february in trait sort_names
--- | WITH FOR
--- | substituting for left
--- | BY instantiation of lemma number_of_months
--- | in trait time_representations
--- | WITH the_month FOR the_month: Int
--- | BY analysis of IMPLIES, in 3
--- | BY hypothesis
--- | AND THEN
--- | BY contradiction, in 1
--- | BY axiom good_month in trait time_representations
--- | WITH the_month FOR the_month: Int
--- | substituting for left
--- | BY contradiction, in 1
--- | BY lemma days_in_months in trait time_representations
--- | WITH the_month, the_year FOR the_month: Int, the_year: Int
--- | substituting for left
--- | BY cases, using (the_month=1)
--- | CASE TRUE
--- | BY left substitution of 4
--- | BY synthesis of TRUE
CASE FALSE
   BY cases, using (the_month=2)
CASE TRUE
   BY left substitution of 5
   BY axiom days_in_February
      in trait time_representations
      substituting for left
   BY simplification
   BY synthesis of TRUE
CASE FALSE
   BY simplification
   BY cases, using (the_month=3)
CASE TRUE
   BY left substitution of 4
   BY synthesis of TRUE
CASE FALSE
   BY cases, using (the_month=4)
CASE TRUE
   BY left substitution of 5
   BY synthesis of TRUE
CASE FALSE
   BY cases, using (the_month=5)
CASE TRUE
   BY left substitution of 6
   BY synthesis of TRUE
CASE FALSE
   BY cases, using (the_month=6)
CASE TRUE
   BY left substitution of 7
   BY synthesis of TRUE
CASE FALSE
   BY cases, using (the_month=7)
CASE TRUE
   BY left substitution of 8
   BY synthesis of TRUE
CASE FALSE
   BY cases, using (the_month=8)
CASE TRUE
   BY left substitution of 9
   BY synthesis of TRUE
CASE FALSE
   BY cases, using (the_month=9)
CASE TRUE
BY left substitution of 10
BY synthesis of TRUE
CASE FALSE
BY cases, using (the_month = 10)
CASE TRUE
BY left substitution of 11
BY synthesis of TRUE
CASE FALSE
BY cases, using (the_month = 11)
CASE TRUE
BY left substitution of 12
BY synthesis of TRUE
CASE FALSE
BY cases, using (the_month = 12)
CASE TRUE
BY left substitution of 13
BY synthesis of TRUE
CASE FALSE
BY array simplification
BY simplification
BY synthesis of TRUE

IS

BEGIN
IF (the_month=(month_name_tic_pos(february)+1)) THEN
  IF is_leap_year(the_year) THEN
    RETURN (days_per_month((month_name_tic_pos(february)+1)) +1);
  ELSE
    RETURN days_per_month(the_month);
  END IF;
ELSE
  RETURN days_per_month(the_month);
END IF;
END days_in;
FUNCTION month_of(the_month : IN month) RETURN month_name
WHERE * * *
  IN good_month(the_month);
RETURN month_name_sort_tic_val((the_month-1));
END WHERE;
VC Status: proved
APPENDIX E

--! BY synthesis of TRUE

IS

BEGIN
  RETURN month_name_tic(val((the_month-1))); 
END month_of; 

FUNCTION month_of(the_month : IN month_name) RETURN month
--| WHERE 
--|   RETURN (month_name_sort_tic_pos(the_month)+1); 
--| END WHERE; 
--! VC Status: proved 
--! BY synthesis of TRUE 
--! □

IS

BEGIN
  RETURN (month_name_tic_pos(the_month)+1); 
END month_of; 

FUNCTION day_of(the_year : IN year; 
  the_day : IN year_day) RETURN day_name 
--| WHERE 
--|   GLOBAL first_day : IN ;
--|   IN (first_day=tuesday); 
--|   IN good_year_and_day(the_year, the_day); 
--|   RETURN day_name_of(the_year, the_day); 
--| END WHERE; 
--! VC Status: proved 
--! BY contradiction, in 2 
--! BY axiom good_year_and_day in trait time_representations 
--! WITH the_year, the_day FOR the_year:Int, 
  the_year_day:Int 
--! substituting for left 
--! BY contradiction, in 2 
--! BY axiom first_year in trait sort_names 
--! WITH FOR 
--! substituting for left 
--! BY simplification 
--! BY axiom day_name in trait time_representations 
--! WITH 1901, 1 FOR the_year:Int, the_year_day:Int
--! substituting for left
---! BY axiom days_since_1900_1 in trait time_representations
---! WITH 1901 FOR the_year: Int
---! substituting for left
---! BY axiom days_since_1900_0 in trait time_representations
---! WITH FOR
---! substituting for left
---! BY claiming (days_in_year(1900)=365)
---! BY axiom days_in_year in trait time_representations
---! WITH 1900 FOR the_year: Int
---! substituting for left
---! BY instantiation of axiom leap_year
in trait time_representations
---! WITH 1900 FOR the_year: Int
---! BY instantiation of axiom non_leap_centennial in trait
time_representations
---! WITH 1900 FOR the_year: Int
---! BY left substitution of 6
---! BY left substitution of 7
---! BY synthesis of TRUE
---! THEN
---! BY instantiation of axiom day_val_1
in trait sort_names
---! WITH FOR
---! BY simplification
---! BY synthesis of TRUE
---! □

IS
result : day_name := first_day;
index : integer;
PROCEDURE increment(the_day : IN OUT day_name;
offset : IN natural)
---! WHERE
---! IN good_day_name(the_day);
---! IN (offset>=0);
---! IN (offset<=6);
---! OUT (the_day

  =
  day_name_sort_increment(IN the_day, offset));
---! OUT good_day_name(the_day);
---! END WHERE;
---! VC Status: proved
--! BY simplification
--! BY instantiation of lemma day_name_sort_tic_pos_range
    in trait sort_names
--! WITH the_day FOR the_day_name:day_name_sort
--! BY simplification
--! BY axiom day_name_sort_increment in trait sort_names
--! WITH the_day, offset FOR
    the_day_name:day_name_sort, offset:Int
--! substituting for left
--! BY instantiation of lemma mod_lower in trait Z
--! WITH 7, (day_name_sort_tic_pos(the_day)+offset)
    FOR m:Int, a:Int
--! BY instantiation of lemma mod_upper in trait Z
--! WITH 7, (day_name_sort_tic_pos(the_day)+offset)
    FOR m:Int, a:Int
--! BY axiom good_day_name in trait sort_names
--! WITH
day_name_sort_tic_val(
    ((day_name_sort_tic_pos(the_day)+offset) MOD 7)) FOR
    the_day_name:day_name_sort
--! substituting for left
--! BY instantiation of lemma day_name_sort_tic_val_range
    in trait sort_names
--! WITH
    ((day_name_sort_tic_pos(the_day)+offset) MOD 7) FOR
    the_pos:Int
--! BY simplification
--! BY instantiation of lemma mod_subtract in trait Z
--! WITH 7, (day_name_sort_tic_pos(the_day)+offset)
    FOR m:Int, a:Int
--! BY simplification
--! BY cases, using ( (day_name_sort_tic_pos(the_day)+offset)
< 7)
--! CASE TRUE
--! BY lemma mod_ident in trait Z
--! WITH (day_name_sort_tic_pos(the_day)+offset),
    7 FOR a:Int, m:Int
--! substituting for left
--! BY simplification
--! BY synthesis of TRUE
--! CASE FALSE
--! BY simplification
BEGIN
    the_day:=day_name_tic_val((day_name_tic_pos(the_day)+offset));
EXCEPTION
    WHEN constraint_error =>
        the_day:=day_name_tic_val((day_name_tic_pos(the_day)+offset)-7));
END increment;
BEGIN
    index:=(year_tic_first()+1);
    --! VC Status: ** not proved **
    --! BY simplification
    --! BY instantiation of axiom day_name in trait time_representations
        --! WITH (index-1), 1 FOR the_year:Int, the_year_day:Int
    --! BY instantiation of lemma day_name_sort_tic_val_range in trait sort_names
    --! WITH ((days_of_years_since_1900((index-1))+1) MOD 7) FOR the_pos:Int
    --! BY instantiation of lemma mod_upper in trait Z
        --! WITH 7, (days_of_years_since_1900((index-1))+1) FOR m:Int, a:Int
    --! BY instantiation of lemma mod_lower in trait Z
        --! WITH 7, (days_of_years_since_1900((index-1))+1) FOR m:Int, a:Int
    --! BY axiom good_day_name in trait sort_names
        --! WITH result FOR the_day_name:day_name_sort
    --! substituting for left
    --! BY simplification
    --! BY synthesis of IF,
        --! 1. (years_tic_first<index)
        --! 2. (index<=(1+the_year))
        --! 3. (result=day_name_of((index-1), 1))
        --! 4. (result = day_name_sort_tic_val((days_of_years_since_1900((index-1))))
APPENDIX E

MOD
7)))
--! 5. (0 <=
((1+days_of_years_since_1900((index-1))) MOD 7))
--! 6. (((i+days_of_years_since_1900((index-1))) MOD 7)
<=
6)
--! 7. (monday
<=
day_name_sort_tic_val(((1 +
days_of_years_since_1900((index-1)))
MOD
7)))
--! 8. (day_name_sort_tic_val(((1 +
days_of_years_since_1900((index-1)))
MOD
7))
<=
sunday)
--! 9. (index<=the_year)
--! >>
(IF is_leap_year(the_year)
THEN (good_day_name(day_name_sort_increment(result, 2))
-> (day_name_sort_increment(result, 2)
= day_name_of(index, 1))) ELSE (good_day_name(day_name_sort_increment(result, 1))
-> (day_name_sort_increment(result, 1)
= day_name_of(index, 1))))
--! <proof>
--! AND
--! BY instantiation of lemma mod_lower in trait Z
--! WITH 7, the_day FOR m:Int, a:Int
--! BY instantiation of lemma mod_upper in trait Z
--! WITH 7, the_day FOR m:Int, a:Int
--! BY simplification
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--! 1. (years_tic_first<=index)
--! 2. (index<=(1+the_year))
--! 3. (result=day_name_of((index-1), 1))
--! 4. (result =

   day_name_sort_tic_val((days_of_years_since_1900((index-1))
   MOD
   7))
--! 5. (0 <=
<=
   ((1+days_of_years_since_1900((index-1))) MOD 7))
--! 6. (((1+days_of_years_since_1900((index-1))) MOD 7)
<=
6)
--! 7. (monday <=

   day_name_sort_tic_val(((1 +
   days_of_years_since_1900((index-1)))
   MOD
   7))
--! 8. (day_name_sort_tic_val(((1 +
   days_of_years_since_1900((index-1)))
   MOD
   7))
<=
   sunday)
--! 9. (index>the_year)
--! 10. (0<=(the_day MOD 7))
--! 11. ((the_day MOD 7)<6)
--! >> ((0<(the_day MOD 7))
AND
   (good_day_name(
       day_name_sort_increment(result, ((the_day MOD 7)-1)))
   ->
   (day_name_sort_increment(result, ((the_day MOD 7)-1))
   =
   day_name_of(the_year, the_day)))
--! <proof>
APPENDIX E

--! □
WHILE (index<=the_year) LOOP
   --| INVARIANT (  
      (years_tic_first+1)<=index)  
      AND  
      (index<=(the_year+1))  
      AND  
      (result=day_name_of((index-1), 1));
IF is_leap_year(the_year) THEN
   increment(result, 2);
ELSE
   increment(result, 1);
END IF;
index:=(index+1);
END LOOP;
increment(result, natural_ize(((the_day MOD 7)-1)));
RETURN result;
END day_of;

FUNCTION day_of(the_time : IN time) RETURN year_day
   --| WHERE * * *
   --|   IN good_time(the_time);
   --|   RETURN day_of_year(the_time.the_year,
      the_time.the_month, the_time.the_day);
   --| END WHERE;
--! VC Status: proved
--! BY simplification
--! BY instantiation of axiom days_since_January_0
      in trait time_representations
--!   WITH the_time.the_year FOR the_year:Int
--! BY instantiation of axiom months_tic_first
      in trait sort_names
--!   WITH FOR
--! BY simplification
--! BY simplification
--! BY contradiction, in 1
--! BY axiom good_time in trait time_representations
--!   WITH the_time FOR the_time:AnyRecordSort
--! substituting for left
--! BY contradiction, in 1
--! BY simplification
--! BY synthesis of TRUE
--! □
IS
result : natural := 0;
index : month;

BEGIN
index := month_tic_first();
--! VC Status: proved
--! BY simplification
--! BY contradiction, in 2
--! BY axiom good_time in trait time_representations
--! WITH the_time FOR the_time:AnyRecordSort
--! substituting for left
--! BY contradiction, in 2
--! BY simplification
--! BY synthesis of IF,
--! BY axiom days_since_January_1
   in trait time_representations
--! WITH (1+index), the_time.the_year FOR the_month:
   Int, the_year: Int
--! substituting for left
--! BY instantiation of lemma days_in_month_range in trait
   time_representations
--! WITH index, the_time.the_year FOR the_month: Int,
   the_year: Int
--! BY simplification
--! BY axiom good_month in trait time_representations
--! WITH index FOR the_month: Int
--! substituting for left
--! BY instantiation of axiom months_tic_first
   in trait sort_names
--! WITH FOR
--! BY simplification
--! BY simplification
--! BY axiom good_year in trait time_representations
--! WITH the_time.the_year FOR the_year: Int
--! substituting for left
--! BY simplification
--! BY synthesis of TRUE
--! AND
--! BY instantiation of lemma days_since_January_positive
in trait time_representations
--! WITH index, the_time.the_year FOR the_month: Int,
   the_year: Int
--! BY simplification
APPENDIX E

--! BY axiom day_of_year in trait time_representations
--! WITH the_time.the_year, index, the_time.the_day
FOR the_year: Int, the_month: Int, the_month_day: Int
--! BY simplification
--! substituting for left
--! BY instantiation
of lemma days_since_January_upper_bound
in trait time_representations
--! WITH index, the_time.the_year FOR the_month: Int,
the_year: Int
--! BY instantiation of axiom good_month
in trait time_representations
--! WITH index FOR the_month: Int
--! BY instantiation of axiom good_year
in trait time_representations
--! WITH the_time.the_year FOR the_year: Int
--! BY instantiation of lemma days_in_month_range in trait
time_representations
--! WITH the_time.the_month, the_time.the_year FOR
the_month: Int, the_year: Int
--! BY simplification
--! BY synthesis of TRUE
--! □

WHILE (index<=(the_time.the_month-1)) LOOP
--! INVARIANT (
( (result=days_since_Jan(index, the_time.the_year))
AND
good_time(the_time))
AND
(months_tic_first<=index))
AND
(index<=the_time.the_month));
result:=(result+
natural_ize(days_in(index, the_time.the_year)));
index:=(index+1);
END LOOP;
RETURN year_day_ize((result+natural_ize(the_time.the_day)));
END day_of;
FUNCTION time_of(the_year: IN year;
the_day: IN year_day) RETURN time
--! WHERE ** *
--! IN good_year_and_day(the_year, the_day);
RETURN t SUCH THAT (  
(  
(  
(  
(t. the_year=the_year)  
AND  
(t. the_month=month_of(the_year, the_day)))  
AND  
(t. the_day=day_of_month(the_year, the_day)))  
AND  
(t. the_hour=0))  
AND  
(t. the_minute=0))  
AND  
(t. the_second=0))  
AND  
(t. the_millisecond=0));

END WHERE;

VC Status: proved

BY axiom months_tic_first in trait sort_names

WITH FOR

substituting for left

BY axiom months_tic_last in trait sort_names

WITH FOR

substituting for left

BY contradiction, in 1

BY axiom good_year_and_day in trait time_representations

WITH the_year, the_day FOR the_year: Int,
the_year_day: Int

substituting for left

BY contradiction, in 1

BY simplification

BY axiom good_year in trait time_representations

WITH the_year FOR the_year: Int

substituting for left

BY simplification

BY axiom good_month in trait time_representations

WITH 1 FOR the_month: Int

BY lemma days_in_month_range

in trait time_representations

BY analysis of FOR ALL, in 5

WITH 1, the_year FOR the_month: Int, the_year: Int
APPENDIX E

--! BY simplification
--! BY axiom days_since_January_0
    in trait time_representations
--! WITH the_year FOR the_year: Int
--! substituting for left
--! BY instantiation of lemma days_in_year_identity
    in trait time_representations
--! WITH the_year FOR the_year: Int
--! BY instantiation of axiom months_tic_last
    in trait sort_names
--! WITH the_year
--! BY simplification
--! BY synthesis of TRUE
--! □

IS
    result : year_day := the_day;
    temp : time;
    index : month;
BEGIN
    index := month_tic_first();
    --! VC Status: proved
    --! BY simplification
    --! BY instantiation of lemma days_in_month_range
        in trait time_representations
    --! WITH index, the_year FOR the_month: Int, the_year: Int
    --! BY simplification
    --! BY axiom good_month in trait time_representations
    --! WITH index FOR the_month: Int
    --! substituting for left
    --! BY simplification
    --! BY axiom months_tic_first in trait sort_names
    --! BY axiom months_tic_last in trait sort_names
    --! BY simplification
    --! BY simplification
    --! BY synthesis of IF,
    --! BY instantiation of axiom month_of
        in trait time_representations
    --! WITH index, the_year, the_day FOR the_month: Int,
        the_year: Int, the_year_day: Int
    --! BY simplification
    --! BY axiom day_of_month in trait time_representations
    --! WITH the_year, the_day FOR the_year: Int,
the_year_day:Int
--! substituting for left
--! BY simplification
--! BY axiom first_hour in trait sort_names
--! BY axiom first_minute in trait sort_names
--! BY axiom first_second in trait sort_names
--! BY axiom first_millisecond in trait sort_names
--! BY simplification
--! BY simplification
--! BY synthesis of TRUE
--! AND
--! BY instantiation of axiom days_since_January_1
--! in trait time_representations
--! WITH (i+index), the_year FOR the_month:Int,

the_year:Int
--! BY simplification
--! BY synthesis of TRUE
--! [] WHILE (index<=month_tic_last()) LOOP
--! INVARIANT ( ( (days_since_Jan(index, the_year)+result)=the_day) AND

() ( (months_tic_first<=index) AND

(index<=months_tic_last)) AND

good_year(the_year))

AND

(result>0))

AND

( the_day <=

( days_since_Jan(months_tic_last, the_year) +

days_in_month(months_tic_last, the_year))));

IF (result<=year_day_ize(days_in(index, the_year))) THEN

temp.the_year:=the_year;

temp.the_month:=index;
temp.the_day:=day_ize(result);
temp.the_hour:=hour_tic_first();
temp.the_minute:=minute_tic_first();
temp.the_second:=second_tic_first();
temp.the_millisecond:=millisecond_tic_first();
RETURN temp;
ELSE
result:=(result-year_day_ize(days_in(index, the_year)));
END IF;
index:=(index+1);
END LOOP;
RAISE lexical_error;
END time_of;
FUNCTION period_of(the_time : IN time) RETURN period
--| WHERE
--| GLOBAL noon : IN ;
--| IN (noon=12);
--| IN good_time(the_time);
--| RETURN (IF (the_time.the_hour<12) THEN am ELSE pm);
--| END WHERE;
--| VC Status: proved
--| BY simplification
--| BY synthesis of TRUE
--| []
IS
BEGIN
IF (the_time.the_hour>=noon) THEN
RETURN pm;
ELSE
RETURN am;
END IF;
END period_of;
FUNCTION time_of(the_time : IN time) RETURN calendar.time
--| WHERE
--| GLOBAL seconds_per_hour, seconds_per_minute,
milliseconds_per_second : IN ;
--| IN good_time(the_time);
--| RETURN time_to_cal_time(the_time);
--| END WHERE;
--| VC Status: ** not proved **
--| BY contradiction, in 1
---! BY axiom good_time in trait time_representations
---! WITH the_time FOR the_time:AnyRecordSort
---! substituting for left
---! BY contradiction, in 1
---! BY analysis of AWD, in 1
---! BY instantiation of lemma days_in_month_range
---! in trait time_representations
---! WITH the_time.the_month, the_time.the_year FOR
---! the_month:In!, the_year:In!
---! BY simplification
---! BY axiom good_year in trait time_representations
---! WITH the_time.the_year FOR the_year:In!
---! substituting for left
---! BY axiom good_month in trait time_representations
---! WITH the_time.the_month FOR the_month:In!
---! substituting for left
---! BY axiom good_month_day in trait time_representations
---! WITH the_time.the_day FOR the_month_day:In!
---! substituting for left
---! BY simplification
---! BY claiming (days_in_month(the_time.the_month, the_time.the_year)
<=
31)
---! BY hypothesis
---! THEN
---! BY simplification
---! 1. (1901<=(the_time.the_year))
---! 2. ((the_time.the_year)<=2099)
---! 3. (0<(the_time.the_month))
---! 4. ((the_time.the_month)<=12)
---! 5. (0<(the_time.the_day))
---! 6. ((the_time.the_day)
<=

    days_in_month((the_time.the_month), (the_time.the_year)))
---! 7. (0<=(the_time.the_hour))
---! 8. ((the_time.the_hour)<days_to_hours)
---! 9. (0<=(the_time.the_minute))
---! 10. ((the_time.the_minute)<hours_to_minutes)
---! 11. (0<=(the_time.the_second))
---! 12. ((the_time.the_second)<minutes_to_seconds)
---! 13. (0<=(the_time.the_millisecond))
---! 14. ((the_time.the_millisecond)
APPENDIX E

seconds_to_milliseconds)
--! 15. (days_in_month((the_time.the_month), (the_time.the_year)) <= 31)
--! 16. good_duration(
  seconds_to_duration(((the_time.the_millisecond) / milliseconds_per_second)))
--! 17. good_duration(seconds_to_duration((the_time.the_second)))
--! 18. good_duration(
  seconds_to_duration(((the_time.the_minute) * seconds_per_minute)))
--! 19. good_duration(
  seconds_to_duration(((the_time.the_hour) * seconds_per_hour)))
--! 20. good_duration(
  seconds_to_duration(((the_time.the_minute) * seconds_per_minute)) +
  seconds_to_duration(((the_time.the_hour) * seconds_per_hour)))
--! 21. good_duration((
  seconds_to_duration(((the_time.the_hour) * seconds_per_hour)) +
  seconds_to_duration(((the_time.the_minute) * seconds_per_minute)) +
  seconds_to_duration((the_time.the_second)))))
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--!
22.
good_duration(((
    seconds_to_duration(((the_time.the_hour)
    *
    seconds_per_hour))
    +
    seconds_to_duration((the_time.the_second)))
    +

    seconds_to_duration(((the_time.the_minute)
    *
    seconds_per_minute)))
    +

    seconds_to_duration(((the_time.the_millisecond)
    /
    milliseconds_per_second))))

--!
>> (good_date((the_time.the_year),
(thead_time.the_month),
(thead_time.the_day),
(((
    seconds_to_duration(((the_time.the_hour)
    *
    seconds_per_hour))
    +
    seconds_to_duration((the_time.the_second)))
    +

    seconds_to_duration(((the_time.the_minute)
    *
    seconds_per_minute)))
    +

    seconds_to_duration(((the_time.the_millisecond)
    /
    milliseconds_per_second))))

AND
((
    time_of((the_time.the_year),
(thead_time.the_month),
(thead_time.the_day),
(((
    seconds_to_duration(((the_time.the_hour)
APPENDIX E

\[
\begin{align*}
& \text{seconds_per_hour)} \\
& + \text{seconds_to_duration((the_time.the_second))} \\
& + \text{seconds_to_duration((the_time.the_minute)} \\
& + \text{seconds_per_minute)} \\
& + \text{seconds_to_duration((the_time.the_millisecond)} \\
& / \text{milliseconds_per_second)))) \\
& = \text{time_to_cal_time(the_time))}
\end{align*}
\]

BEGIN
RETURN calendar.time_of(year_number_ize(the_time.the_year),
month_number_ize(the_time.the_month),
day_number_ize(the_time.the_day),
(

(calendar.day_duration_ize((
    integer_ize(the_time.the_hour)*
    seconds_per_hour))+
    calendar.day_duration_ize((
    integer_ize(the_time.the_minute)*
    seconds_per_minute))+
    calendar.day_duration_ize(the_time.the_second))+
    calendar.day_duration_ize((the_time.the_millisecond/
    milliseconds_per_second))));
END time_of;
FUNCTION time_of(the_time : IN calendar.time) RETURN time
WHERE
GLOBAL seconds_per_hour, seconds_per_minute, milliseconds_per_second : IN ;
RETURN cal_time_to_time(the_time);
IS
result : time;

BEGIN
calendar.split(the_time,
the_year,
the_month,
the_day,
total_duration);
-- To mollify our aggressive aliasing checks;
result.the_year:=the_year;
result.the_month:=the_month;
result.the_day:=the_day;

--! PRECONDITION = (good_duration(total_duration)
AND
((0<=(Floor(total_duration)/seconds_per_hour))
AND
((Floor(total_duration)/seconds_per_hour)<24))
AND
((0
<=
((Floor(total_duration) MOD seconds_per_hour)
/seconds_per_minute))
AND
((Floor(total_duration) MOD seconds_per_hour)
/seconds_per_minute)<
60))
AND
((0
<=
((Floor(total_duration) MOD seconds_per_hour)
MOD seconds_per_minute))
seconds_per_minute))
AND (((Floor(total_duration) MOD seconds_per_hour)
    MOD seconds_per_minute)
< 60))
AND (good_duration(total_duration)
AND ((good_duration(RealPart(total_duration))
AND 

    good_duration((RealPart(total_duration)
    ...
    milliseconds_per_second)))
    -> (((result.the_hour
    => (Floor(total_duration)
        / seconds_per_hour))[.the_minute
    => ((Floor(total_duration)
        MOD seconds_per_hour)
        / seconds_per_minute)][.the_second
    => ((Floor(total_duration)
        MOD seconds_per_hour)
        MOD seconds_per_minute)][.the_millisecond
    => Floor((1000
        *
        (RealPart(total_duration)
        *
        milliseconds_per_second)))]
    = cal_time_to_time(the_time)))))))))
seconds:=duration_utilities.floor(total_duration);
result.the_hour:=hour_ize((seconds/seconds_per_hour));
seconds:=(seconds MOD seconds_per_hour);
result.the_minute:=minute_ize((seconds/seconds_per_minute));
result.the_second:=second_ize((seconds MOD
seconds_per_minute));
result.the_millisecond:=millisecond_ize((
duration_utilities.real_part(total_duration)*
milliseconds_per_second));
RETURN result;
END time_of;
FUNCTION duration_of(the_interval : IN interval) RETURN builtin
duration
--| WHERE
--| GLOBAL seconds_per_day, seconds_per_hour,
seconds_per_minute : IN ;
--| IN (seconds_per_hour=hours_to_seconds);
--| IN (seconds_per_minute=minutes_to_seconds);
--| IN (seconds_per_day=days_to_seconds);
--| IN good_interval(the_interval);
--| RETURN interval_to_duration(the_interval);
--| RETURN result SUCH THAT good_duration(result);
--| END WHERE;
--| VC Status: proved
--| BY axiom Int_identity in trait Z
--| WITH (the_interval.elapsed_days*days_to_seconds)
  FOR n:Int
--| substituting for left
--| BY lemma seconds_to_duration in trait sort_names
--| WITH (the_interval.elapsed_days*seconds_per_day)
  FOR the_second:Int
--| substituting for left
--| BY simplification
--| BY instantiation of lemma good_duration_pair
  in trait time_representation_conversions
--| WITH (seconds_per_day*the_interval.elapsed_days), 1
  FOR n:Int, d:Int
--| BY simplification
--| BY axiom good_second in trait sort_names
--| WITH (the_interval.elapsed_milliseconds/1000) FOR
  the_second:Int
--| substituting for left
--| BY instantiation of axiom good_interval
  in trait sort_names
--| WITH the_interval FOR the_interval:AnyRecordSort
--| BY contradiction, in 4
--| BY left substitution of 7
--| BY contradiction, in 4
--| BY analysis of AND, in 4
APPENDIX E

--! BY instantiation of axiom good_millisecond
   in trait sort_names
--! WITH the_interval.elapsed_milliseconds FOR
   the_millisecond:Int
--! BY contradiction, in 11
--! BY left substitution of 12
--! BY contradiction, in 11
--! BY claiming ((the_interval.elapsed_milliseconds/1000)=0)
--! BY lemma div_upper in trait Z
--! WITH the_interval.elapsed_milliseconds, 1000 FOR
   a:Int, m:Int
--! substituting for left
--! BY hypothesis
--! THEN
--! BY simplification
--! BY synthesis of TRUE
--! []

IS
temp : builtin.duration;

BEGIN
  temp:=builtin.duration_ize((
    integer_ize(the_interval.elapsed_days)*seconds_per_day));
--! WC Status: proved
--! BY lemma pair_minus in trait fixed_point
--! WITH
  (Int_identity((the_interval.elapsed_days*days_to_seconds))
   +
   Int_identity((the_interval.elapsed_hours*hours_to_seconds)))/,
   1,
   (the_interval.elapsed_hours*seconds_per_hour), 1 FOR n1:
   Int, d1:Int, n2:Int, d2:Int
--! substituting for left
--! BY axiom Int_identity in trait Z
--! WITH
  (Int_identity((the_interval.elapsed_days*days_to_seconds))
   +
   Int_identity((the_interval.elapsed_hours*hours_to_seconds))) FOR n:
   Int
--! substituting for left
APPENDIX E

--! BY axiom Int_identity in trait Z
--! WITH (the_interval.elapsed_hours*seconds_per_hour)
FOR n:Int
--! substituting for left
--! BY axiom Int_identity in trait Z
--! WITH (the_interval.elapsed_hours*hours_to_seconds)
FOR n:Int
--! substituting for left
--! BY axiom Int_identity in trait Z
--! WITH (the_interval.elapsed_days*days_to_seconds)
FOR n:Int
--! substituting for left
--! BY contradiction, in
--! BY axiom Int_identity in trait Z
--! WITH (the_interval.elapsed_days*days_to_seconds)
FOR n:Int
--! substituting for left
--! BY contradiction, in
--! BY simplification
--! BY synthesis of TRUE
--! []

--! ASSERT ( ( temp = pair( Int_identity( (the_interval.elapsed_days*days_to_seconds)), 1)) AND good_interval(the_interval))
AND ( (good_duration(temp) AND ( good_interval(the_interval)
AND good_second( (the_interval.elapsed_milliseconds/1000)))
AND (seconds_per_hour=hours_to_seconds)
AND

(seconds_per_minute=minutes_to_seconds));

--! USE lemma subtract_duration_equals IN TRAIT
time_representation_conversions

WITH

temp,
pair(

  Int_identity(  
    (the_interval.elapsed_days*days_to_seconds)) +

  Int_identity(  
    (the_interval.elapsed_hours*hours_to_seconds)),

  1),
pair(((the_interval.elapsed_hours*seconds_per_hour), 1)
FOR
m:AnyRecordSort, n:AnyRecordSort, p:AnyRecordSort

--! substituting for left;

--! USE lemma good_duration_pair IN TRAIT
time_representation_conversions

WITH
(  
  the_interval.elapsed_hours*seconds_per_hour), 1
FOR

m:Int, d:Int;

--! USE lemma good_duration_sum IN TRAIT
time_representation_conversions

WITH

(temp,
pair(((the_interval.elapsed_hours*seconds_per_hour), 1)
FOR
d1:AnyRecordSort, d2:AnyRecordSort;

--! USE lemma seconds_to_duration IN TRAIT sort_names

WITH

(the_interval.elapsed_hours*seconds_per_hour)
FOR

the_second:Int

--! substituting for left;
temp:=(temp+

  builtin.duration_ize(
    integer_ize(the_interval.elapsed_hours)*

  builtin.duration_ize(
    integer_ize(the_interval.elapsed_hours)*
seconds_per_hour));
--! VC Status: proved
--! BY lemma pair_minus in trait fixed_point
--! WITH

  ()

    Int_identity(
      (the_interval.elapsed_days*days_to_seconds))
  +
    Int_identity(
      (the_interval.elapsed_hours*hours_to_seconds))
  +
    Int_identity(
      (the_interval.elapsed_minutes*minutes_to_seconds)),

  1, (the_interval.elapsed_minutes*seconds_per_minute), 1
FOR n1:Int, d1:Int, n2:Int, d2:Int
--! substituting for left
--! BY axiom Int_identity in trait Z
--! WITH

  ()

    Int_identity(
      (the_interval.elapsed_days*days_to_seconds))
  +
    Int_identity(
      (the_interval.elapsed_hours*hours_to_seconds))
  +
    Int_identity(
      (the_interval.elapsed_minutes*minutes_to_seconds))

FOR n:Int
--! substituting for left
--! BY axiom Int_identity in trait Z
--! WITH

  (the_interval.elapsed_hours*seconds_per_minute) FOR n:Int
--! substituting for left
--! BY axiom Int_identity in trait Z
--! WITH

  (the_interval.elapsed_minutes*seconds_per_minute) FOR n:Int
--! substituting for left
--! BY axiom Int_identity in trait Z
--! WITH (the_interval.elapsed_hours*hours_to_seconds)

FOR n:Int
--! substituting for left
--! BY axiom Int_identity in trait Z
WITH (\text{the\_interval.elapsed\_days*days\_to\_seconds})
\text{FOR n: Int}
--! substituting for left
--! BY contradiction, in I
--! BY axiom Int\_identity in trait Z
--! WITH (\text{the\_interval.elapsed\_days*days\_to\_seconds})
\text{FOR n: Int}
--! substituting for left
--! BY axiom Int\_identity in trait Z
--! WITH (\text{the\_interval.elapsed\_hours*hours\_to\_seconds})
\text{FOR n: Int}
--! substituting for left
--! BY simplification
--! BY synthesis of TRUE
--! \box{}
--! ASSERT

\text{(}
  \text{(}
    \text{temp = pair(}
      \text{(}
        \text{Int\_identity(}
          \text{(the\_interval.elapsed\_days*days\_to\_seconds)})
        +
        \text{Int\_identity(}
          \text{(the\_interval.elapsed\_hours*hours\_to\_seconds)}),
        1))
  \text{AND}
  \text{good\_interval(\text{the\_interval})}
  \text{AND}
  \text{(}
    \text{good\_duration(temp)}
    \text{AND}
    \text{(seconds\_per\_minute=minutes\_to\_seconds)}
  \text{AND}
  \text{(}
    \text{good\_interval(\text{the\_interval})}
    \text{AND}
    \text{good\_second(}
      \text{(the\_interval.elapsed\_milliseconds/1000))})
\text{)));
--! USE lemma subtract\_duration\_equals IN TRAIT
time\_representation\_conversions
WITH
  temp,
  pair(
    (
      Int_identity(
        (the_interval.elapsed_days*days_to_seconds))
      +
      Int_identity(
        (the_interval.elapsed_hours*hours_to_seconds)))
      +
      Int_identity(
        (the_interval.elapsed_minutes
         * minutes_to_seconds))), 1),
  pair(
    (the_interval.elapsed_minutes*seconds_per_minute), 1)
FOR m:AnyRecordSort, n:AnyRecordSort, p:AnyRecordSort
--! substituting for left;
--! PRECONDITION = (good_duration(temp)
AND
(good_duration(temp)
AND
(((temp
  +

pair(((the_interval.elapsed_minutes)
  * seconds_per_minute),
  1))
  =

pair(((
    Int_identity(((the_interval.elapsed_days)
      * days_to_seconds))
      +
    Int_identity(((the_interval.elapsed_hours)
      *
hours_to_seconds)) +

Int_identity(((the_interval.elapsed_minutes) *
  minutes_to_seconds)),
1))
AND
good_interval(the_interval)
AND
(good_interval(the_interval)
AND

good_second(((the_interval.elapsed_milliseconds)
  / 1000))));

--! USE lemma good_duration_pair IN TRAIT
time_representation_conversions

WITH
  (the_interval.elapsed_minutes*seconds_per_minute), i
FOR
  n:Int, d:Int;

--! USE lemma good_duration_sum IN TRAIT
time_representation_conversions

WITH
  temp,
  pair(  
    (the_interval.elapsed_minutes*seconds_per_minute),
    1)
FOR
  d1:AnyRecordSort, d2:AnyRecordSort;

--! USE lemma seconds_to_duration IN TRAIT sort_names

WITH
  (the_interval.elapsed_minutes*seconds_per_minute)
FOR
  the_second:Int

--! substituting for left;
  temp:=(temp+
    builtin.duration_ize((
      integer_ize(the_interval.elapsed_minutes)*
      seconds_per_minute)));
APPENDIX E

--! VC Status: proved
--! BY lemma pair_minus in trait fixed_point
--! WITH

( ( Int_identity( the_interval.elapsed_days*days_to_seconds)) + Int_identity( the_interval.elapsed_hours*hours_to_seconds)) + Int_identity( the_interval.elapsed_minutes*minutes_to_seconds)) + Int_identity( the_interval.elapsed_seconds), 1, the_interval.elapsed_seconds, 1 FOR n1:Int, d1:Int, n2: Int, d2:Int
--! substituting for left
--! BY axiom Int_identity in trait Z
--! WITH

( ( Int_identity( the_interval.elapsed_days*days_to_seconds)) + Int_identity( the_interval.elapsed_hours*hours_to_seconds)) + Int_identity( the_interval.elapsed_minutes*minutes_to_seconds)) + Int_identity( the_interval.elapsed_seconds) FOR n:Int
--! substituting for left
--! BY axiom Int_identity in trait Z
--! WITH (the_interval.elapsed_days*days_to_seconds) FOR n:Int
--! substituting for left
--! BY axiom Int_identity in trait Z
--! WITH (the_interval.elapsed_hours*hours_to_seconds) FOR n:Int
--! substituting for left
--! BY axiom Int_identity in trait Z
APPENDIX E

```haskell
--! WITH (the_interval.elapsed_minutes*minutes_to_seconds) FOR n:Int
--! substituting for left
--! BY axiom Int_identity in trait Z
--! WITH the_interval.elapsed_seconds FOR n:Int
--! substituting for left
--! BY contradiction, in I
--! BY axiom Int_identity in trait Z
--! WITH (the_interval.elapsed_days*days_to_seconds)

FOR n:Int
--! substituting for left
--! BY axiom Int_identity in trait Z
--! WITH (the_interval.elapsed_hours*hours_to_seconds)

FOR n:Int
--! substituting for left
--! BY axiom Int_identity in trait Z
--! WITH (the_interval.elapsed_minutes*minutes_to_seconds) FOR n:Int
--! substituting for left
--! BY simplification
--! BY synthesis of TRUE
--! □

--!
--! ASSERT (

( temp = pair(

( Int_identity(

(the_interval.elapsed_days*days_to_seconds))
+

Int_identity(

(the_interval.elapsed_hours*hours_to_seconds))
+

Int_identity(

the_interval.elapsed_minutes * minutes_to_seconds)), 1))

AND

(good_interval(the_interval) AND good_duration(temp)))
AND
(good_interval(the_interval)
AND
good_second(((the_interval.elapsed_milliseconds/1000)));

--! USE lemma subtract_duration_equals IN TRAIT
time_representation_conversions

WITH
temp,
pair(
  ( ( Int_identity( (the_interval.elapsed_days*days_to_seconds))
    + Int_identity( ( the_interval.elapsed_hours
                      * hours_to_seconds)))
    + Int_identity( ( the_interval.elapsed_minutes
                      * minutes_to_seconds)))
    + Int_identity(the_interval.elapsed_seconds), 1),
pair(the_interval.elapsed_seconds, 1)
FOR
m:AnyRecordSort, n:AnyRecordSort, p:AnyRecordSort
--! substituting for left;
--! USE lemma good_duration_pair IN TRAIT
time_representation_conversions
WITH the_interval.elapsed_seconds, 1 FOR n:Int, d:Int;
<statement>
--! USE lemma good_duration_sum IN TRAIT
time_representation_conversions

WITH
temp, pair(the_interval.elapsed_seconds, 1)
FOR
d1:AnyRecordSort, d2:AnyRecordSort;
--! USE lemma seconds_to_duration IN TRAIT sort_names
WITH the_interval.elapsed_seconds FOR the_second: Int
--! substituting for left;
 temp := (temp +
     builtin.duration_ize (the_interval.elapsed_seconds));
--! VC Status: ** not proved **
--! BY left substitution of i
--! BY axiom Int_identity in trait Z
--! WITH
(

      Int_identity(
          (the_interval.elapsed_days*days_to_seconds))
      +
      Int_identity(
          (the_interval.elapsed_hours*hours_to_seconds))
      +
      Int_identity(
          (the_interval.elapsed_minutes*minutes_to_seconds))
      +
      Int_identity (the_interval.elapsed_seconds)) FOR n: Int
--! substituting for left
--! BY axiom Int_identity in trait Z
--! WITH
(

      Int_identity(
          (the_interval.elapsed_days*days_to_seconds))
      +
      Int_identity(
          (the_interval.elapsed_hours*hours_to_seconds))
      +
      Int_identity(
          (the_interval.elapsed_minutes*minutes_to_seconds))
      *
      Int_identity (the_interval.elapsed_seconds))
1000) + Int_identity(the_interval.elapsed_milliseconds) FOR n: Int
--! substituting for left
--! BY claiming ( Int_identity( ((the_interval.elapsed_milliseconds/1000)*1000)) = Int_identity(the_interval.elapsed_milliseconds))
--! BY axiom Int_identity in trait Z
--! WITH ((the_interval.elapsed_milliseconds/1000)*1000) FOR n:Int
--! substituting for left
--! BY axiom Int_identity in trait Z
--! WITH the_interval.elapsed_milliseconds FOR n:Int
--! substituting for left
--! 1. (temp = pair((((
  Int_identity(((the_interval.elapsed_days)
  *
  days_to_seconds)) +

  Int_identity(((the_interval.elapsed_hours)
  *
  hours_to_seconds)))

  Int_identity(((the_interval.elapsed_minutes)
  *
  minutes_to_seconds)))

  Int_identity((the_interval.elapsed_seconds))),
  1)))
--! 2. good_interval(the_interval)
--! 3. good_duration(temp)
--! 4. good_second(((the_interval.elapsed_milliseconds)/1000))
--! >> (((the_interval.elapsed_milliseconds)/1000)*1000) =
(the_interval.elapsed_milliseconds)
--! <proof>
--! THEN
--! BY claiming (pair(

( (Int_identity(
    (the_interval.elapsed_days*days_to_seconds))
  + Int_identity(
    (the_interval.elapsed_hours*hours_to_seconds)))
  + Int_identity(
    (the_interval.elapsed_minutes*minutes_to_seconds)))
  + Int_identity(the_interval.elapsed_seconds)), 1)

= pair(

( ( (Int_identity(
    (the_interval.elapsed_days*days_to_seconds))
  + Int_identity(
    (the_interval.elapsed_hours*hours_to_seconds)))
  + Int_identity(
    (the_interval.elapsed_minutes
    * minutes_to_seconds)))
  + Int_identity(the_interval.elapsed_seconds))
  * 1000, 1000))

--! BY lemma concrete_equality_pair
in trait fixed_point

--! WITH
\[ \text{Int}_\text{identity} \left( \text{Int}_\text{identity} \left( \text{Int}_\text{identity} \left( \text{the_interval}.\text{elapsed_seconds} \right) \right) \right) \]

\[ + \text{Int}_\text{identity} \left( \text{Int}_\text{identity} \left( \text{Int}_\text{identity} \left( \text{the_interval}.\text{elapsed_seconds} \right) \right) \right) \]

\[ + \text{Int}_\text{identity} \left( \text{Int}_\text{identity} \left( \text{Int}_\text{identity} \left( \text{the_interval}.\text{elapsed_seconds} \right) \right) \right) \]

\[ + \text{Int}_\text{identity} \left( \text{Int}_\text{identity} \left( \text{Int}_\text{identity} \left( \text{the_interval}.\text{elapsed_seconds} \right) \right) \right) \]

\[ \ldots \]

\[ \text{ASSERT} ( \]

\[ ( \]

\[ \text{temp} = \]

\[ \text{pair} ( \]

\[ ( \]

\[ \text{Int}_\text{identity} ( \]
(the_interval.elapsed_days
  * days_to_seconds))
+ Int_identity(
    (the_interval.elapsed_hours
  * hours_to_seconds)))
+ Int_identity(
    (the_interval.elapsed_minutes
  * minutes_to_seconds))
+ Int_identity(the_interval.elapsed_seconds), 1))
AND good_interval(the_interval))
AND good_duration(temp))
AND good_second(the_interval.elapsed_seconds/1000));
-- USE lemma pair_minus IN TRAIT fixed_point

WITH
(
  (
    (Int_identity("the interval elapsed days" * "days to seconds")
+ Int_identity(
    (the_interval.elapsed_hours
  * "hours to seconds")))
+ Int_identity(
    (the_interval.elapsed_minutes
  * "minutes to seconds")))
+ Int_identity(the_interval.elapsed_seconds), 1))
\begin{verbatim}
+ Int_identity(
    (the_interval.elapsed_minutes * minutes_to_seconds))
+ Int_identity(the_interval.elapsed_seconds))
+ 1000)
+ Int_identity(the_interval.elapsed_milliseconds)),
  1000, (the_interval.elapsed_milliseconds/1000), 1
FOR
ni:Int, di:Int, n2:Int, d2:Int
--! substituting for left;
--! USE lemma subtract_duration_equals IN TRAIT
  time_representation_conversions
WITH
  temp, pair(
    (ni, di)
    (ni, di)

    Int_identity(
      (the_interval.elapsed_days
       * days_to_seconds))
    + Int_identity(
      (the_interval.elapsed_hours
       * hours_to_seconds))
    + Int_identity(
      (the_interval.elapsed_minutes
       * minutes_to_seconds)))
\end{verbatim}
+ Int_identity(the_interval.elapsed_seconds))
  * 1000)
+ Int_identity(the_interval.elapsed_milliseconds)), 1000),
pair((the_interval.elapsed_milliseconds/1000), 1)
FOR m:AnyRecordSort, n:AnyRecordSort, p:AnyRecordSort
--! substituting for left;
--! USE lemma seconds_to_duration IN TRAIT sort_names
WITH
(the_interval.elapsed_milliseconds/1000)
FOR
the_second:Int
--! substituting for left;
--! USE axiom good_seconds_to_good_duration IN TRAIT
time_representation_conversions
WITH
(the_interval.elapsed_milliseconds/1000)
FOR
the_second:Int;
--! USE lemma good_duration_sum IN TRAIT
time_representation_conversions
WITH
temp,
  seconds_to_duration(
    (the_interval.elapsed_milliseconds/1000))
FOR
d1:AnyRecordSort, d2:AnyRecordSort;
--! USE axiom Int_identity IN TRAIT Z
WITH
{
  {
    {
      Int_identity(
        (the_interval.elapsed_days*days_to_seconds))
+ Int_identity(
  (the_interval.elapsed_hours
   * hours_to_seconds)))
+ Int_identity(
  (the_interval.elapsed_minutes
   * minutes_to_seconds)))
+ Int_identity(the_interval.elapsed_seconds))
* 1000) FOR n:Int
--! substituting for left;
--! PRECONDITION = (good_duration(
  seconds_to_duration(((the_interval.elapsed_milliseconds
   )
   /1000)))
-> ((good_duration(temp)
  AND
  good_duration(
    seconds_to_duration(
      (the_interval.elapsed_milliseconds)
      /1000))))
AND
  good_duration(
    seconds_to_duration(
      (the_interval.elapsed_milliseconds)
      /1000))))
AND
  good_duration((temp +
    seconds_to_duration(
      (the_interval.elapsed_milliseconds)
      /1000))))
->
(good_interval(the_interval)
AND
((temp
+

seconds_to_duration(
(
(the_interval.elapsed_milliseconds)
/
1000))
=

pair((
Int_identity(((
Int_identity(
((the_interval.elapsed_days)
*

days_to_seconds))
+

Int_identity(
((the_interval.elapsed_hours)
*

hours_to_seconds)))
+

Int_identity(
((the_interval.elapsed_minutes)
*

minutes_to_seconds)))
+

Int_identity(
(the_interval.elapsed_seconds))
*

1000))
+

Int_identity(
(the_interval.elapsed_milliseconds)),
1000)))));

temp:=(temp+
builtin.duration_ize((the_interval.elapsed_milliseconds/
1000))));
--! USE lemma pair_plus IN TRAIT fixed_point

WITH

  ( ( Int_identity( the_interval.elapsed_days*days_to_seconds )
    + Int_identity( the_interval.elapsed_hours*hours_to_seconds )
    + Int_identity( the_interval.elapsed_minutes
          * minutes_to_seconds )
    + Int_identity( the_interval.elapsed_seconds ), 1,
    the_interval.elapsed_milliseconds, 1000
  FOR n1:Int, d1:Int, n2:Int, d2:Int
--! substituting for left;
--! USE axiom Int_identity IN TRAIT Z

WITH

  ( Int_identity( the_interval.elapsed_days*days_to_seconds )
    + Int_identity( the_interval.elapsed_hours*hours_to_seconds )
    + Int_identity( the_interval.elapsed_minutes
          * minutes_to_seconds )
    FOR n:Int
--! substituting for left;
--! USE lemma pair_plus IN TRAIT fixed_point

WITH

( ( Int_identity(
    (the_interval.elapsed_days*days_to_seconds))
  + Int_identity(
    (the_interval.elapsed_hours*hours_to_seconds)))
  + Int_identity(
    (the_interval.elapsed_minutes
     * minutes_to_seconds)), 1, the_interval.elapsed_seconds, 1
FOR nl:Int, d1:Int, n2:Int, d2:Int
--! substituting for left;
--! USE axiom Int_identity IN TRAIT Z

WITH

( Int_identity(
    (the_interval.elapsed_days*days_to_seconds))
  + Int_identity(
    (the_interval.elapsed_hours*hours_to_seconds)))
FOR n:Int
--! substituting for left;
--! USE lemma pair_plus IN TRAIT fixed_point

WITH

( Int_identity(
    (the_interval.elapsed_days*days_to_seconds))
  + Int_identity(
    (the_interval.elapsed_hours*hours_to_seconds))),
1, (the_interval.elapsed_minutes*minutes_to_seconds), 1
FOR
n1:Int, d1:Int, n2:Int, d2:Int
--! substituting for left;
--! USE lemma pair_plus IN TRAIT fixed_point

WITH
(\text{the\_interval.elapsed\_days*days\_to\_seconds}, 1, 1)\\n\text{WITH} (\text{the\_interval.elapsed\_hours*hours\_to\_seconds}, 1)
FOR
n1:Int, d1:Int, n2:Int, d2:Int
--! substituting for left;
--! USE axiom seconds\_to\_milliseconds IN TRAIT conversion\_factors
--! substituting for left;
--! USE lemma divides\_pi IN TRAIT fixed_point

WITH
\text{the\_interval.elapsed\_milliseconds, 1, 1, second\_to\_milliseconds}\ FOR\ n1:Int, d1:Int, i:Int
--! substituting for left;
--! USE lemma seconds\_to\_duration IN TRAIT sort\_names

WITH
\text{the\_interval.elapsed\_days*days\_to\_seconds}\ FOR\ the\_second:Int
--! substituting for left;
--! USE lemma seconds\_to\_duration IN TRAIT sort\_names

WITH
\text{the\_interval.elapsed\_hours*hours\_to\_seconds}\ FOR\ the\_second:Int
--! substituting for left;
--! USE lemma seconds\_to\_duration IN TRAIT sort\_names

WITH
\text{the\_interval.elapsed\_minutes*minutes\_to\_seconds}\ FOR\ the\_second:Int
--! substituting for left;
--! USE lemma seconds\_to\_duration IN TRAIT sort\_names
WITH the_interval.elapsed_seconds FOR the_second: Int
  --! substituting for left;
  --! USE lemma seconds_to_duration IN TRAIT sort_names
  WITH the_interval.elapsed_milliseconds FOR the_second: Int
  --! substituting for left;
  --! USE axiom interval_to_duration IN TRAIT
  time_representation_conversions
WITH the_interval FOR the_interval: AnyRecordSort
  --! substituting for left;
  --! SIMPLIFIED PRECONDITION;
  --! USE axiom good_interval_to_good_duration IN TRAIT
  time_representation_conversions

  WITH
    the_interval, temp
  FOR
    the_interval: AnyRecordSort, the_duration: AnyRecordSort;
  --! PRECONDITION = ((temp =
    interval_to_duration(the_interval))
  AND
    good_duration(temp));
  RETURN temp;
END duration_of;

FUNCTION interval_of(the_duration: IN builtin.duration) RETURN
  interval
  WHERE
    --! GLOBAL seconds_per_day, seconds_per_hour,
    seconds_per_minute: IN;
    --! IN good_duration(the_duration);
    --! RETURN duration_to_interval(the_duration);
    --! END WHERE;
  --! VC Status: hidden
  --! □

IS
  result: interval;
  the_seconds: builtin.duration := the_duration;

BEGIN
  result.elapsed_days := duration_utilities.floor((the_seconds/
    seconds_per_day));
  the_seconds := (the_seconds -
    builtin.duration_ize((integer_ize(result.elapsed_days)*
seconds_per_day));
result.elapsed_hours:=hour_ize(duration_utilities.floor((
    the_seconds/seconds_per_hour)));
the_seconds:=(the_seconds-
builtin.duration_ize((integer_ize(result.elapsed_hours)*
    seconds_per_hour)));
result.elapsed_minutes:=minute_ize(duration_utilities.floor((
    the_seconds/seconds_per_minute)));
the_seconds:=(the_seconds-
builtin.duration_ize((integer_ize(result.elapsed_minutes)*
    seconds_per_minute)));
result.elapsed_seconds:=
    second_ize(duration_utilities.floor(the_seconds));
the_seconds:=(the_seconds-
builtin.duration_ize(result.elapsed_seconds));
--! PRECONDITION = (((Int_to_fixnum(0)<=(the_seconds*1000))
    ->
    (0<=Floor((the_seconds*1000)))))
    ->
    (good_duration(the_seconds)
    AND
    (good_duration((the_seconds*1000))
    ->
    (((0<=Floor((the_seconds*1000)))
      AND
      (Floor((the_seconds*1000))<1000))
      AND
      ((result[.elapsed_milliseconds>=
        Floor((the_seconds*1000))])
        =
        duration_to_interval(the_duration))));
--! INSTANTIATE lemma floor1 IN TRAIT fixed_point
WITH (the_seconds*1000) FOR m:AnyRecordSort;
result.elapsed_milliseconds:=
    millisecond_ize(
        duration_utilities.floor((the_seconds*1000)));
RETURN result;
END interval_of;
END calendar_utilities;
REFERENCES

References


**Title and Subtitle:** Using Penelope to Assess the Correctness of NASA Ada Software: A Demonstration of Formal Methods as a Counterpart to Testing

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**Abstract:**
Life-critical applications warrant a higher level of software reliability than has yet been achieved. Since it is not certain that traditional methods alone can provide the required ultrareliability, new methods should be examined as supplements or replacements. This paper describes a mathematical counterpart to the traditional process of empirical testing.

ORA's Penelope verification system is demonstrated as a tool for evaluating the correctness of Ada software. Grady Booch's Ada calendar utility package, obtained through NASA, was specified in the Larch/Ada language. Formal verification in the Penelope environment established that many of the package's subprograms met their specifications. In other subprograms, failed attempts at verification revealed several errors that had escaped detection by testing.

**Subject Terms:** Life-critical software; Ultrareliability; Formal methods; Formal specification; Formal verification safety