AdaCore

Adding contracts to the GCC GNAT Ada standard libraries

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- Adding contracts to the GCC GNAT Ada Standard libraries
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Ada and SPARK

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- Strongly typed, with type constraints

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type Small_Int is range -100 .. 100;
subtype Small_Nat is Small_Int range 0 .. 100;
type Small_Int_Arr is array (1 .. 10) of Small_Int;
```

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```

- Checks introduced at runtime

```
X : Small_Int := …;               A : Small_Int_Arr := …;
Y : Small_Nat := X;               X := A (Y);
--  range check                   --  index check
```

Ada and SPARK - Contract-based programming in Ada

- Pre and postconditions for subprograms

```
procedure Increment (X : in out Integer) with
  Pre  => X < Integer’Last,
  Post => X > X’Old;
```

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- Pre and postconditions for subprograms

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procedure Increment (X : in out Integer) with
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- Strong and weak type invariants

```
subtype Sorted_Arr is Small_Int_Arr with
  Dynamic_Predicate =>
    (for all I in 1 .. 9 => Sorted_Arr (I) < Sorted_Arr (I + 1));
```

Ada and SPARK - Contract-based programming in Ada

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subtype Sorted_Arr is Small_Int_Arr with
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- Contracts checked at runtime when assertions are enabled

Ada and SPARK - Formal Verification of Ada

SPARK:

- Verifies formally absence of run-time errors and contracts

```
A : Sorted_Arr := (0, 1, 2, 3, 4, 5, 6, 7, 8, 9);
--  predicate check proved

X : Integer := 15;
Increment (X);
--  precondition proved
```

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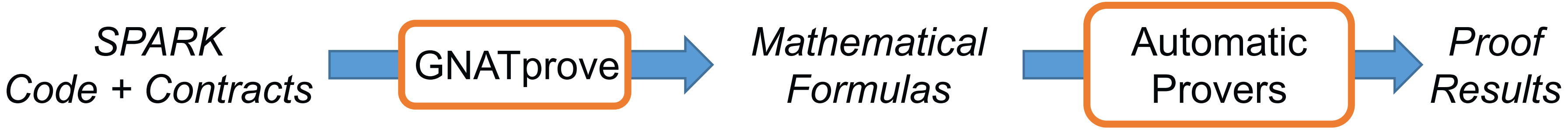
```

- Uses deductive verification



SPARK Code + Contracts

GNATprove

Mathematical Formulas

Automatic Provers

Proof Results

Context

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- Analysis is modular; each subprogram is analyzed separately, trusting the contracts of called subprograms
- When using unannotated subprograms, the analysis is weakened

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Example:

Using `Ada.Strings.Unbounded` and `Ada.Text_IO` in proof

```
p.adb:9:15: warning : assuming "Append" has no effect on global items
p.adb:9:15: warning : no Global contract available for "Append"
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Have subprograms from these libraries really no effect on global items? Can we be more precise about their effects?

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Have subprograms from these libraries really no effect on global items? Can we be more precise about their effects?

⟶ We need to annotate the subprograms to have correct assumptions

Model global effects of subprograms

Model global effects - `Ada.Strings.Unbounded`

Subprograms from `Ada.Strings.Unbounded` actually have no effect on global items

Model global effects - `Ada.Strings.Unbounded`

Subprograms from `Ada.Strings.Unbounded` actually have no effect on global items

```
procedure Append
  (Source   : in out Unbounded_String;
   New_Item : Unbounded_String)
with Global => null;
```

Adding the Global annotations removes the previous warnings

Model global effects - `Ada.Text_IO`

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One solution: create a virtual object to represent the file system

```
package Ada.Text_IO with
  Abstract_State => File_System
is
…
   procedure Get (File : File_Type; Item : out String) with
     Global => (In_Out => File_System);
…
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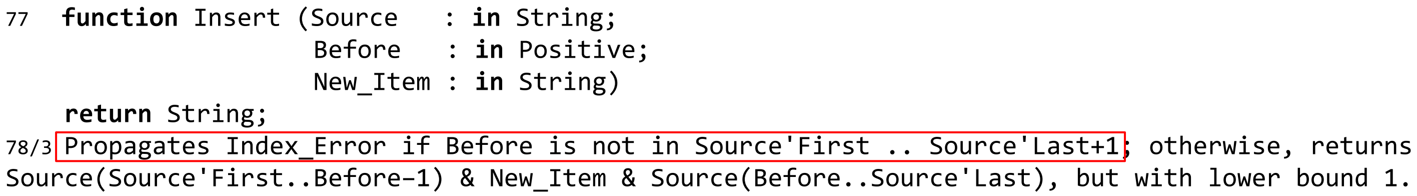
   procedure Get (File : File_Type; Item : out String) with
     Global => (In_Out => File_System);
…
```

This way, we are able to model the effects of subprograms on the file system; the warnings are removed and the assumptions are correct.

Protect from run-time errors

Protect from run-time errors - Ada Reference Manual

The Ada Reference Manual states:



```
77   function Insert (Source   : in String;
                      Before   : in Positive;
                      New_Item : in String)
      return String;
```

78/3 Propagates Index_Error if Before is not in Source'First .. Source'Last+1; otherwise, returns Source(Source'First..Before-1) & New_Item & Source(Before..Source'Last), but with lower bound 1.

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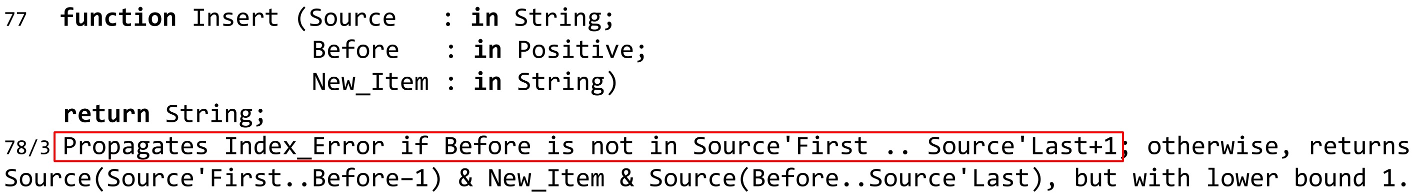

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Source(Source'First..Before-1) & New_Item & Source(Before..Source'Last), but with lower bound 1.
```

The following code fails at runtime:

```
procedure Main with SPARK_Mode is
   Str_1 : String := “abc”; --  Source’Last = 3
   Str_2 : String (1 .. 4);
begin
   Str_2 := Insert (Str_1, 5, “d”); --  5 is not in 1 .. 4
end Main;
```

But SPARK doesn’t say anything about it!

Protect from run-time errors - Adding preconditions

Add a precondition:

```
function Insert
  (Source   : String;
   Before   : Positive;
   New_Item : String) return String
with
  Pre => Before - 1 in Source'First - 1 .. Source'Last
           and then Source'Length <= Natural'Last - New_Item'Length;
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   New_Item : String) return String
with
  Pre => Before - 1 in Source'First - 1 .. Source'Last
           and then Source'Length <= Natural'Last - New_Item'Length;
```

Re-run the proof:

```
main.adb:5:16: medium: precondition might fail
      5 |      Str_2 := Insert (Str_1, 5, "d");
        |               ^~~~~~~~~~~~~~~~~~~
```

Now SPARK detects that the parameters don’t satisfy the precondition

Protect from run-time errors - Second example

Another extract from the Reference Manual:

```
6 procedure Open(File : in out File_Type;
                 Mode : in File_Mode;
                 Name : in String;
                 Form : in String := "");
...
```

8 The exception Status_Error is propagated if the given file is already open. The exception Name_Error is propagated if the string given as Name does not allow the identification of an external file; in particular, this exception is propagated if no external file with the given name exists. The exception Use_Error is propagated if, for the specified mode, the external environment does not support opening for an external file with the given name (in the absence of Name_Error) and form.

```
12 procedure Delete(File : in out File_Type);
...
```

14 The exception Status_Error is propagated if the given file is not open. The exception Use_Error is propagated if deletion of the external file is not supported by the external environment.

```
27   function Is_Open(File : in File_Type) return Boolean;
```

28/3 Returns True if the file is open (that is, if it is associated with an external file); otherwise, returns False.

Protect from run-time errors - Second example

Let’s add preconditions…

```
procedure Open
  (File : in out File_Type;
   Mode : File_Mode;
   Name : String;
   Form : String := "")
with
  Pre    => not Is_Open (File),
  Global => (In_Out => File_System);

procedure Delete (File : in out File_Type) with
  Pre    => Is_Open (File),
  Global => (In_Out => File_System);
```

Protect from run-time errors - Second example

And try:

```
1 procedure Main with SPARK_Mode is
2    File_1, File_2 : File_Type;
3 begin
4    Delete (File_1); --  wrong usage; File_1 is not open
5    Open (File_2, In_File, “hello_world.txt”);
6    Delete (File_2);
7 end Main;
```

```
main.adb:4:04: medium: precondition might fail, cannot prove Is_Open (File)
```

Protect from run-time errors - Second example

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6    Delete (File_2);
7 end Main;
```

Preconditions are not enough to prove the correct usage of the library:

```
main.adb:4:04: medium: precondition might fail, cannot prove Is_Open (File)
main.adb:4:12: high: "File_1" is not initialized
main.adb:5:04: medium: precondition might fail, cannot prove not Is_Open (File)
main.adb:5:10: high: "File_2" is not initialized
main.adb:6:04: medium: precondition might fail, cannot prove Is_Open (File)
```

Protect from run-time errors - Add more contracts

Let’s add more contracts:

```
type File_Type is limited private with
     Default_Initial_Condition => (not Is_Open (File_Type));

procedure Open
  (File : in out File_Type;
   Mode : File_Mode;
   Name : String;
   Form : String := "")
with
  Pre    => not Is_Open (File),
  Post   => Is_Open (File),
  Global => (In_Out => File_System);

procedure Delete (File : in out File_Type) with
  Pre    => Is_Open (File),
  Post   => not Is_Open (File),
  Global => (In_Out => File_System);
```

Protect from run-time errors - And try them out

And re-run the proof:

```
main.adb:2:04: info: initialization of "File_1" proved
main.adb:2:12: info: initialization of "File_2" proved
main.adb:4:04: medium: precondition might fail, cannot prove Is_Open (File_1)
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Now we are able to prove when `Status_Error` won’t be raised at run-time.

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Now we are able to prove when `Status_Error` won’t be raised at run-time.

However, this is not the only error:

- `Mode_Error` is related to modes (`In_File`, `Out_File`, …)
- `Name_Error` is raised when the file does not exist on the file system
- `End_Error` is raised when a file terminator is read in a procedure
- `Use_Error` is related to the external environment

Add complete contracts to subprograms

Add complete contracts - Going further...

Take the example with string handling again:

```
procedure Main with SPARK_Mode is
   Str_1 : String := “abc”;
   Str_2 : String (1 .. 4);
begin
   Str_2 := Insert (Str_1, 4, “d”);
   pragma Assert (Str_2 = “abcd”);
end Main;
```

An assertion has been added after the call to verify that Str_2 is equal to “abcd” after the call.

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An assertion has been added after the call to verify that Str_2 is equal to “abcd” after the call.

But it is not proved:

```
main.adb:3:04: info: initialization of "Str_2" proved
main.adb:5:13: info: precondition proved
main.adb:5:13: medium: length check might fail
main.adb:6:19: medium: assertion might fail, cannot prove Str_2 = "abcd"
```

Add complete contracts - Going further...

Indeed, we don’t have any information on Str after the call to Insert:

```
function Insert
  (Source   : String;
   Before   : Positive;
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with
  Pre => Before - 1 in Source'First - 1 .. Source'Last
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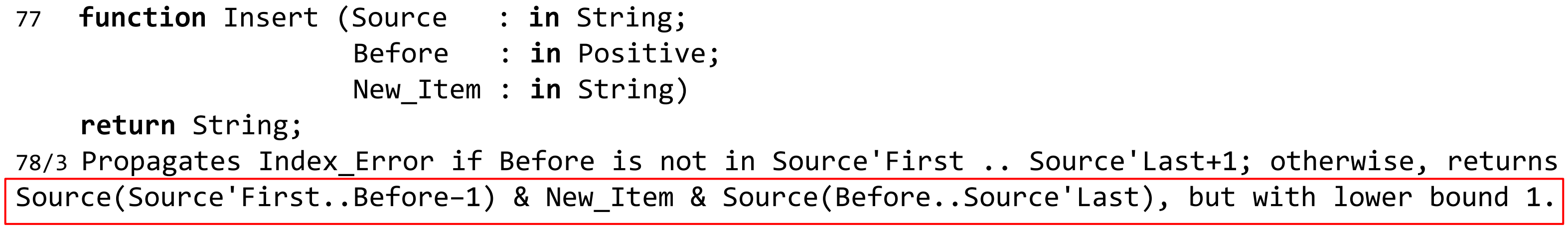

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Add complete contracts - Add postconditions

We need to reflect that through a postcondition:

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Post   =>
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    and then
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      = Source (Source'First .. Before - 1)
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      = Source (Source'First .. Before - 1)
    and then
      Insert'Result
        (Before - Source'First + 1
         .. Before - Source'First + New_Item'Length)
      = New_Item
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    and then
      Insert'Result (1 .. Before - Source'First)
      = Source (Source'First .. Before - 1)
    and then
      Insert'Result
        (Before - Source'First + 1
         .. Before - Source'First + New_Item'Length)
      = New_Item
    and then
      (if Before - 1 < Source'Last
       then
         Insert'Result
           (Before - Source'First + New_Item'Length + 1
            .. Insert'Result'Last)
         = Source (Before .. Source'Last))
```

Add complete contracts - Results

And now the assertion is proved:

```
main.adb:3:04: info: initialization of "Str_2" proved
main.adb:5:13: info: precondition proved
main.adb:5:13: info: length check proved
main.adb:6:19: info: assertion proved
```

The library `Ada.Strings.Fixed` provides different kinds of operations on Strings:

- Search subprograms
- String translations
- String transformations
- String selectors
- String constructors

Related works

Related works - Projects

On standard libraries:

- C standard libraries:
  - annotated header files packaged with Frama-C
  - external work on annotating header files done by GrammarTech
- Java standard libraries:
  - some libraries are annotated for OpenJML
- Community participation: *annotationsforall.org*

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On third-party libraries:

- SPARK binding of TweetNaCl and Libsodium libraries

  github.com/isavialard/TweetNaCl_binding

  github.com/isavialard/Libsodium_binding
- SPARK binding and partial verification of CycloneTCP

  github.com/AdaCore/Http_Cyclone

Related works - Planned next steps

- Specifying more GCC GNAT Ada standard libraries

- Verifying a given implementation of the library

Conclusion

- There are different levels of detail
- These levels can serve for different purposes
- This is a substantial effort

Online resources

- Blogpost on annotating third-party libraries

  blog.adacore.com/secure-use-of-cryptographic-libraries-spark-binding-for-libsodium

- Online Ada and SPARK Courses

  learn.adacore.com

- Download page for the SPARK toolset

  adacore.com/download

- Source code of the SPARK proof tool

  github.com/AdaCore/spark2014