Introduction to Ada & SPARK

Ada - Genesis

http://en.wikipedia.org/wiki/Ada_Lovelace

- In 1970s, US DoD was concerned by number of obsolete, hardware-dependent, non-modular languages
- Working group to formulate requirements for programming languages for DoD projects
  - no existing language met the requirements
  - one of four proposals selected as DoD’s language mandated for new projects
  - called “Ada” after Ada Lovelace, world’s first programmer

Ada - Genesis

"…none of the evidence we have so far can inspire confidence that this language has avoided any of the problems that have afflicted other complex language projects of the past.

It is not too late! I believe that by careful pruning of the Ada language, it is still possible to select a very powerful subset that would be reliable and efficient in implementation and safe and economic to use."

-- Professor Tony Hoare
-- 1980 ACM Turing Award Lecture

…some people argue that perhaps the SPARK subset corresponds to what he might have had in mind.

Ada - Genesis

By 1987:

- Reduced the number of languages in DoD software from 450 to 37
- Ada was mandated for all projects where new code was 30% or more of total

Examples of systems programmed largely in Ada

- Boeing 777 -- nearly all software in Ada
- French TGV automatic train control system (Alsys World Dialogue, vol. 8, no. 2, Summer 1994)
- European Space Agency GPS Receiver for space applications
- Swiss Postbank Electronice Funds Transfer system
- Commercial launch platforms (Ariane 4, Ariane 5, Atlas V)
- Satellites and space probes from the European space agency
- Many US DoD weapons platforms such as Crusader, HIMARS, Tomahawk, B1-B Bomber, Patriot Missile Defense System, etc.

Ada Information Clearing House http://www.adaic.org/

Also http://www.seas.gwu.edu/~mfeldman/ada-project-summary.html

Ada - Overview

- Designed for large, long-lived applications,
  - Safety-critical / high-security
  - Embedded, real-time systems
  - e.g., commercial and military aircraft avionics, air traffic control, railroad systems, and medical devices.
- First internationally standardized (ISO) language (Ada 95, Ada 05, Ada 12)

Ada - Overview

- Strong typing with explicit scalar ranges
- Packages: Data abstraction
- Generic programming/templates
- Exception handling
- Concurrent programming
- Standard libraries for I/O, string handling, numeric computing, containers

Ada - Overview

- Facilities for modular organization of code
- Object orientated programming
- Systems programming
- Real-time programming
- Distributed systems programming
- Numeric processing
- Interoperablity: Interfaces to other languages (C, COBOL, Fortran)

Goal: Correctness by construction

- Correct by virtue of techniques used for construction
- Design By Contract (DBC)
  - A program unit is both a
    - **client**, when using services provided by other entities
    - **supplier**, when providing services to other entities
  - Contracts specify the rights and responsibilities of both clients and suppliers:
    - Contract specifies the interface to a module: module is "correct" if it satisfies its contract
    - Compositional: rights may be assumed in order to discharge responsibilities

- Represent the effects of a sequence of components as the composition of the effects of its components

$$\mathcal{A}(S_1\,;\ S_2\,;\ S_3\,;\ \ldots\ ;\ S_n)$$

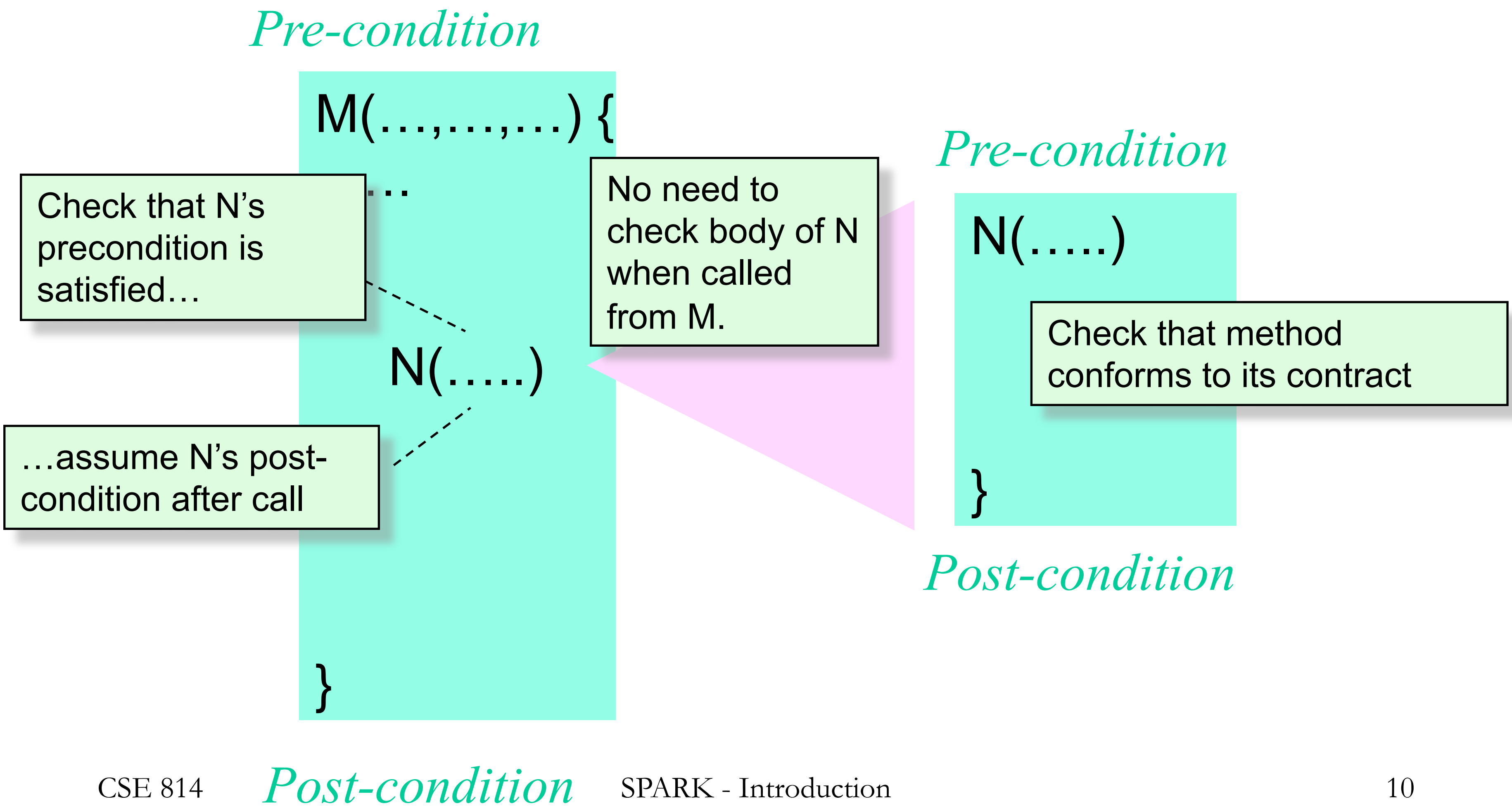
$$\equiv$$

$$\mathcal{A}(S_1) \circ \mathcal{A}(S_2) \circ \mathcal{A}(S_3) \circ \cdots \circ \mathcal{A}(S_n)$$

Sequence of statements: S_1 ; S_2 ; S_3 ; … ; S_n;

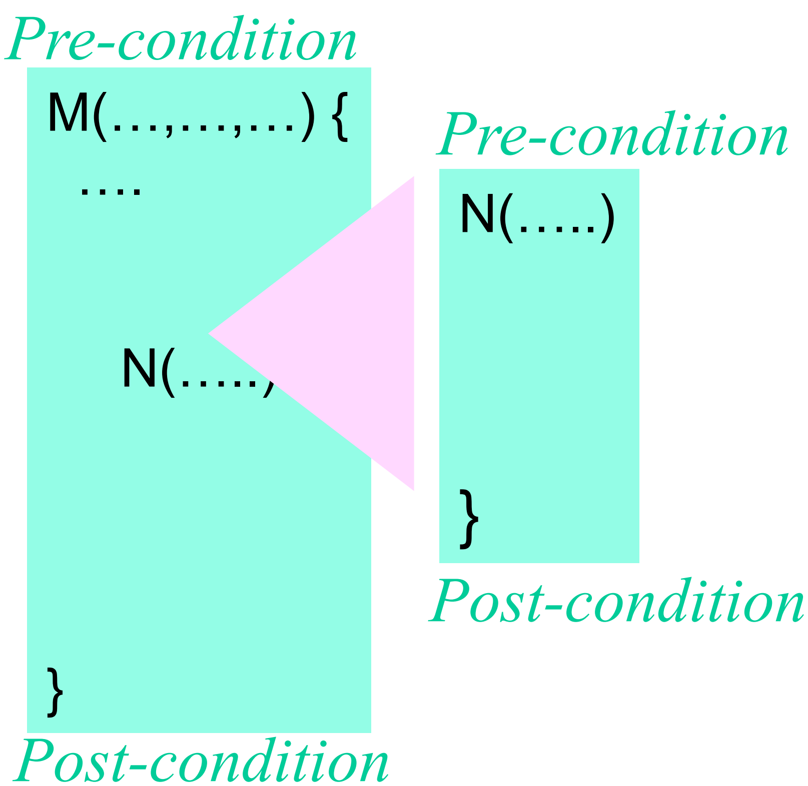
Abstraction & composition

Affects of a unit specified by its contract



Abstraction & composition

Affects of a unit specified by its contract



- allows each method to be checked in isolation
- allows analysis without access to procedure bodies
  - early during development
  - before programs are complete or compile-able
- if a method is changed, only need to check that one method (not the entire code base)
- enables checking to be carried out in parallel

Correctness by construction

- Need interface specs (contracts) that are:
  - Unambiguous (precise)
  - Complete (no exploitable "loop holes")
  - Consistent (no contradictions)
  - Accurate (say what is "meant")
- Would like static analysis that is
  - Sound (no false negatives)
  - Accurate (few false positives)
  - Deep (reveals subtle application-specific flaws)
  - Fast (scalable)
  - Modular (compositional)

What is Spark?

Programming Language

Subset of Ada appropriate for critical systems -- no heap data, pointers, exceptions,, gotos, aliasing

What is Spark?

Interface Specification Language

Aspects & pragmas for pre/post-conditions, assertions, loop invariants, information flow specifications

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Automated Verification Tools

Flow analysis
static analysis to check aspects related to data flow, initialization of variables

Dynamic analysis
dynamic check of pre/post-conditions, loop invariants, loop variants on an execution path

Proof Checker
semi-automated framework for caring out proof steps to discharge verification conditions.

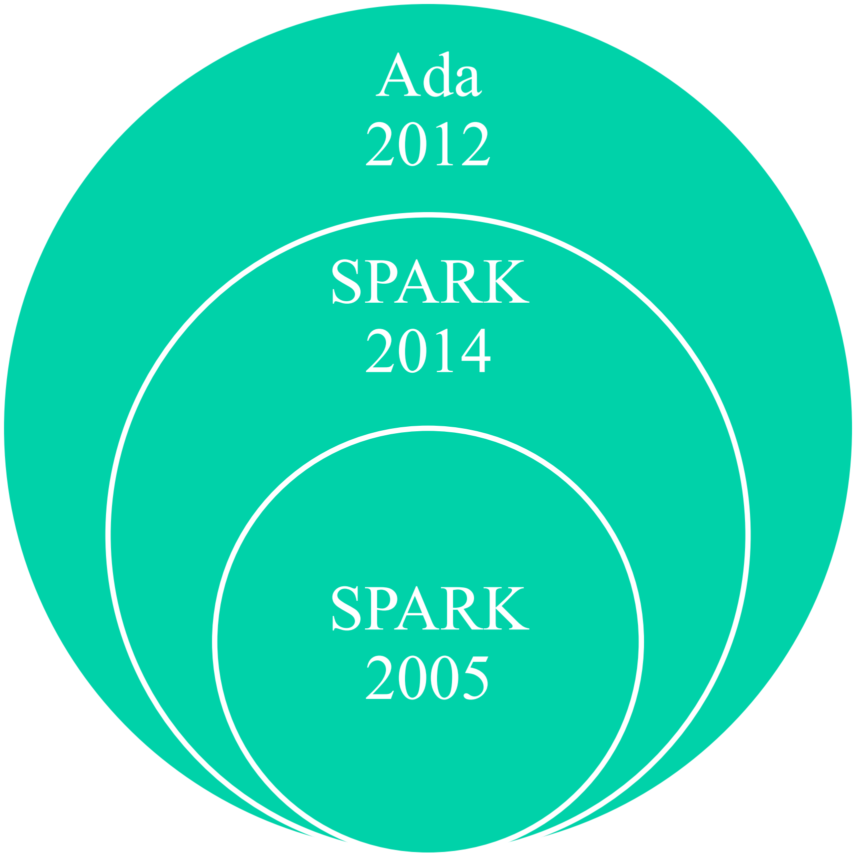
SPARK 2014 Language: Guiding Principles

- Support the largest practical subset of Ada 2012 that is
  - Unambiguous & amenable to ***sound*** formal verification
  - DO-333 says: "…an analysis method can only be regarded as formal analysis if its determination of a property is sound. Sound analysis means that the method never asserts a property to be true when it is not true."
- What does "unambiguous" mean in practice?
  - No erroneous behaviour, no unspecified lang. features.
  - Limit implementation-defined features to as small a set as possible, and allow these to be configured for a particular implementation.

SPARK 2014 Language: Guiding Principles

- Designed to be a “formal method” as defined by DO-333.
- Support both static and dynamic verification of contracts.
- Practical note: started with the full-blown GNAT compiler infrastructure, so many “difficult” language features are just removed or expanded out by the compiler.

The SPARK 2014 language



What is left out of Ada

- Things that make formal reasoning harder:
  - Access types (pointers)
  - Unstructured control flow (goto's)
  - Exception handling
  - Aliasing of outputs of subprograms
  - Side-effects in expressions and functions
  - Tasks (concurrency)
  - Dynamic arrays ?

Why no access types (pointers)

- Access types only make sense in connection with dynamic storage allocation.
- But dynamic allocation is a real problem, hard to prove that storage is never exhausted.

Why no goto's?

- Are inherently non-compositional
  - The effect of a sequence of code cannot be represented as the composition of the effects of its components.
- Not needed

$$\mathcal{A}(S_1 ;\ S_2 ;\ S_3 ;\ \ldots\ ;\ S_n) \not\equiv \mathcal{A}(S_1) \circ \mathcal{A}(S_2) \circ \mathcal{A}(S_3) \circ \cdots \circ \mathcal{A}(S_n)$$

Sequence of statements: $S_1 \;;\; S_2 \;;\; S_3 \;;\; \ldots \;;\; S_n;$

Why no exceptions handling

- Exception handling makes the control flow of a program much more complex
- Certifiable programs cannot have unexpected exceptions

Why no aliasing?

- Can lead to language ambiguities: e. g., Multiply(A, B, A)

```
procedure Multiply(X, Y : in Matrix; Z : out Matrix) is
begin
  Z := Matrix'(Matrix_Index => (Matrix_Index => 0));
  for I in Matrix_Index loop
    for J in Matrix_Index loop
      for K in Matrix_Index loop
        Z(I, J) := Z(I, J) + X(I,K) * Y(K, J);
      end loop;
    end loop;
  end loop;
end Multiply
```

Why no aliasing?

- Complicates analysis of procedure/function calls
  - Meaning of statements in body depends on calling context
  - Compromises compositional methods
  - e.g., x := y + 1; z := y + 1;

Why no side-effects in functions?

- Can lead to language ambiguities, e.g.,

```
X : Integer := 1;

function F(Y : Integer) return Integer is
  X := Y + 1;
  return X;
end F;

function G(Y : Integer) return Integer is
  return 2 * Y
end G;
```

```
Y := F(X) + G(X)
```

- Complicates analysis of function/procedure calls

```
foo( F(X), G(X) )
```

Why no dynamic arrays?

- Need to bound the amount of storage space a program uses to know it will function correctly
  - Sizes of arrays calculated statically
  - Bound on stack size calculated statically

Why no tasks (concurrency)?

- The effect of a sequence of code cannot be represented as the composition of the effects of its sequential components
  - Cannot reason about the effects of a module by examining its code in isolation
  - Need to consider potential "interference" from modules executed by other tasks
- Non-determinacy is a concern

What is SPARK?

- Developed by Praxis High Integrity Systems
  - http://www.praxis-his.com/sparkada/
- Marketed in a partnership with AdaCore
  - http://www.adacore.com/
  - integrated with AdaCore GnatPro compiler and integrated development environment
- SPARK tools are GPL open source

Precise Interface Specifications

Producing appropriate interface specification is a key element of *the design process*

- Important properties should be exposed
  - usage requirements / guarantees of the unit
  - in some domains, non-functional properties such as worse-case execution time and use of system resources (e.g., threads) are also important
- Implementation details should be hidden
  - hide (if at all possible) data structure choices

...a good programming language should facilitate these tasks!

Ada / Spark Interfaces

Ada interfaces

- Interfaces and implementations are *lexically* distinct
- Parameters modes declare whether parameter is input, output, or both

SPARK interfaces

- Specify intended data and information flow
  with Global …   with Depends …   with Abstract_State …
  with Refined_Global …   with Refined_State …
  with Refined_Depends …
- Specify intended behavior (for formal verification)
  with Pre …   with Post …   pragma Assert …
  pragma Loop_Invariant …   pragma Loop_Variant …

SPARK Program

A SPARK program is a set Ada packages

Package Specification

```
package MyPackage
  with SPARK_mode
is

  type MyPublicType is…
  G1: …
  G2: …

  procedure P(in X, out Y)
    with Global => …,
         Pre -> …,
         Post => …;

end MyPackage;
```

Package Body

```
package body MyPackage
is
  G3: …

  type MyPrivateType is…

  procedure P(in X, out Y) is
  begin
    …P implementation…
  end P;

begin
  …initialization…
end MyPackage;
```

- Package specification declares the public interface of the package
  - Ada elements: types, procedures/functions, public global variables
  - SPARK elements: data flow and procedure contracts
- Package body provides the implementations of procedures, initialization of package globals, and private types and variables

Purpose of Contracts

- Make code clearer at specification level
  - more abstract ("what" not "how")
- Introduce redundancy, compiler can check
- Allow error checks to be made
- Support verification

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Tools in Action: Examine

exchange.ads

```
1 package Exchange
2     with SPARK_Mode
3 is
4
5     procedure Exchange(X, Y: in out Float);
6
7 end Exchange;
```

exchange.adb

```
package body Exchange
    with SPARK_Mode
is

    procedure Exchange(X, Y: in out Float) is
    begin
        X := Y;
        Y := X;
    end Exchange;

end Exchange;
```

Phase 1 of 2: frame condition computation ...

Phase 2 of 2: analysis of data and information flow ...

exchange.ads:5:23: warning: unused initial value of "X"

Tools in Action: Examine

exchange.ads

```
package Exchange
    with SPARK_Mode
is

    procedure Exchange(X, Y: in out Float)
      with Depends => (X => Y,
                       Y => X);

end Exchange;
```

exchange.adb

```
package body Exchange
    with SPARK_Mode
is

    procedure Exchange(X, Y: in out Float) is
    begin
        X := Y;
        Y := X;
    end Exchange;

end Exchange;
```

warning: unused initial value of "X"

warning: missing dependency "null => X"

warning: missing dependency "Y => Y"

warning: incorrect dependency "Y => X"

Tools in Action: Examine

exchange.ads

```ada
package Exchange
    with SPARK_Mode
is

    procedure Exchange(X, Y: in out Float)
      with Depends => (X => Y,
                       Y => X);

end Exchange;
```

exchange.adb

```ada
package body Exchange
    with SPARK_Mode
is

    procedure Exchange(X, Y: in out Float)
    begin
          T  := X;
          X  := Y;
          Y  := T;
    end Exchange;

end Exchange;
```

Error: T is undefined

Tools in Action: Examine

exchange.ads

```ada
package Exchange
   with SPARK_Mode
is

   procedure Exchange(X, Y: in out Float)
     with Depends => (X => Y,
                      Y => X);

end Exchange;
```

exchange.adb

```ada
package body Exchange
   with SPARK_Mode
is

   T: Float;

   procedure Exchange(X, Y: in out Float)
   begin
      T := X;
      X := Y;
      Y := T;
   end Exchange;

end Exchange;
```

warning: unused initial value of "T”

. . .

warning: missing dependency "T => X”

Tools in Action: Examine

exchange.ads

```ada
package Exchange
   with SPARK_Mode
is

   procedure Exchange(X, Y: in out Float)
     with Depends => (X => Y,
                      Y => X);

end Exchange;
```

exchange.adb

```ada
package body Exchange
   with SPARK_Mode
is

   procedure Exchange(X, Y: in out Float) is
      T: Float;
   begin
      T := X;
      X := Y;
      Y := T;
   end Exchange;

end Exchange;
```

Phase 1 of 2: frame condition computation ...

Phase 2 of 2: analysis of data and information flow ...

Summary logged in . . .

process terminated successfully, elapsed time: 00.75s

Tools in Action: Prove

exchange.ads

```ada
package Exchange
   with SPARK_Mode
is

   procedure Exchange(X, Y: in out Float)
     with Depends => (X => Y,
                      Y => X),
          Post => (X = Y'Old and Y = X'Old);

end Exchange;
```

exchange.adb

```ada
package body Exchange
   with SPARK_Mode
is

   procedure Exchange(X, Y: in out Float) is
      T: Float;
   begin
      T := X;
      X := Y;
      Y := T;
   end Exchange;

end Exchange;
```

. . .

Phase 3 of 3: generation and proof of VCs ...

analyzing Exchange, 0 checks

analyzing Exchange.Exchange, 1 checks

exchange.ads:8:19: info: postcondition proved

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Tools in Action: Prove

inc.ads

```ada
package Inc
    with SPARK_Mode
is

    type T is range -128 .. 128;

    procedure Inc (X: in out T);

end Inc;
```

inc.adb

```ada
1  package body Inc
2      with SPARK_Mode
3  is
4
5      procedure Inc (X: in out T) is
6      begin
7         X := X + 1;
8      end Inc;
9
10 end Inc;
```

. . .

Phase 3 of 3: generation and proof of VCs ...

analyzing Inc, 0 checks

analyzing Inc.Inc, 1 checks

inc.adb:7:14: warning: range check might fail

Tools in Action: Prove

```
type T is range -128 .. 128;

procedure Inc (X : in out T)
is begin
  X := X + 1;
end;
```

Type declarations are contractual:

- Inc has the right to assume no RTE at entry
- Inc has responsibility to guarantee no RTE while executing

VC's:

H1: x >= -128
H2: x <= 128
->
C1: x + 1 >= -128
C2: x + 1 <= 128

GNATProve →

VC's:

H1: x >= -128
H2: x <= 128
->
C1: true
C2: x <= 127

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Tools in Action: Prove

inc.ads

```ada
package Inc
    with SPARK_Mode
is

   type T is range -128 .. 128;

   procedure Inc (X: in out T)
      with Pre => (X < T'Last);

end Inc;
```

inc.adb

```ada
1  package body Inc
2     with SPARK_Mode
3  is
4
5     procedure Inc (X: in out T) is
6     begin
7        X := X + 1;
8     end Inc;
9
10 end Inc;
```

. . .

Phase 3 of 3: generation and proof of VCs ...

analyzing Inc, 0 checks

analyzing Inc.Inc, 1 checks

inc.adb:7:14: info: range check proved

Tools in Action: Prove

```
type T is range -128 .. 128;
procedure Inc(…) with
    Pre => (X < T'Last);
procedure Inc (X : in out T) is
   begin X := X + 1; end;
```

Pre-condition is contractual:

- Inc has the right to assume
  - No RTE at entery
  - X < T'Last at entry
- Inc has responsibility to guarantee no RTE

VC's:

```
 H1:  x >= -128
 H2:  x <  128
      ->
 C1:  x + 1 >= -128
 C2:  x + 1  <= 128
```

GNATProve →

VC's:

```
 H1:  x >= -128
 H2:  x <= 128
      ->
 C1:  true
 C2:  true
```

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Acknowledgements & references

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- Many slides adapted from
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- Slides 16-18 from Altran Tutorial on Spark 2014.