Bakar Kiasan: Flexible Contract Checking for Critical Systems using Symbolic Execution

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What is SPARK?

One of the best available commercially supported frameworks for code-level development of safety critical systems

- 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
  - Examiner is implemented in SPARK

What is SPARK?

Language and verification framework designed for critical systems

Interface Specification Language

Annotations for pre/ post-conditions, assertions, loop invariants, information flow specifications

+

Programming Language

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

SPARK Contracts

SPARK includes annotations for assertions, pre/post-conditions that can be used to express *software contracts*

Simple pre-condition with existential quantification…

```
function FindSought
 (A: Table; Sought: Integer) return Index;
--# pre for some M in Index => ( A(M) = Sought );
--# return Z => (( A(Z) = Sought) and
--#     (for all M in Index range 1 .. (Z - 1) =>
--#          (A(M) /= Sought)));
```

Post-condition constraining return value to inputs using universal quantification…

"SPARK Examiner with Run-time Checker…", p. 22

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

Automated Verification Tools

Examiner
simple static analysis and verification condition generator

Simplifier
decision procedure package that simplifies and tries to automatically prove verification conditions

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

Uses of SPARK

SPARK has been (is being) used in a number of safety and security critical applications

- Tokeneer -- biometrics and smart authentication in card technology. Demonstration project sponsored by Praxis and NSA
  - http://www.adacore.com/home/products/sparkpro/tokeneer/
- Several large scale security critical projects at Rockwell Collins such as the Janus crypto-graphic engine.
- Avionics systems in the Lockheed C130J and EuroFighter Typhoon projects
- iFACTS - United Kingdom next generation air-traffic control system (team of 100+ developers at Praxis).
- [Rockwell Collins] development of certified embedded security devices

…this talk will emphasize experiences with Rockwell Collins on a DoD-funded research project that involved developing a prototype of high-speed crypto-controller

What are the obstacles?

Unfortunately, none of projects makes extensive use of SPARK's contract language (most don't use it at all)

Let's review what developers must do to verify SPARK contracts

Run the Examiner

```
function Value_Present (A: AType; X : Integer) return Boolean
 --# return for some M in Index => (A(M) = X);
is
  Result : Boolean;
begin
  Result := False;
  for I in Index loop
    if A(I) = X then
      Result := True;
      exit;
    end if;
    --# assert I in Index and
    --#    not Result and
    --# (for all M in Index range Index'First .. I => (A(M) /= X));
  end loop;
  return Result;
end Value_Present;
```

Simple post-condition

Developer must insert loop invariants

Examiner
simple static analysis and verification condition generator

Verification conditions written in a separate "proof language" called FDL

Run the Simplifier

1 of 7 Verification Conditions written in FDL proof language…

```
function_value_present_3.
H1:     true .
H2:     for_all(i___1: integer, ((i___1 >= index__first) and (
            i___1 <= index__last)) -> ((element(a, [i___1]) >=
            integer__first) and (element(a, [i___1]) <=
            integer__last))) .
H3:     x >= integer__first .
H4:     x <= integer__last .
H5:     index__first >= index__first .
H6:     index__first <= index__last .
H7:     not (element(a, [index__first]) = x) .
         ->
C1:     index__first >= index__first .
C2:     index__first <= index__last .
C3:     not false .
C4:     for_all(m_: integer, ((m_ >= index__first) and (m_ <=
            index__first)) -> (element(a, [m_]) <> x)) .
C5:     for_all(i___1: integer, ((i___1 >= index__first) and (
            i___1 <= index__last)) -> ((element(a, [i___1]) >=
            integer__first) and (element(a, [i___1]) <=
            integer__last))) .
C6:     x >= integer__first .
C7:     x <= integer__last .
C8:     index__first >= index__first .
C9:     index__first <= index__last .
C10:    index__first >= index__first .
C11:    index__first <= index__last .
```

Simplifier
decision procedure package that simplifies and tries to automatically prove verification conditions

4 of 7 VCs proved, the rest are simplified

Feed Into the Proof Checker

1 of 3 Remaining Verification Conditions…

```
function_value_present_6.
H1:    for_all(m_ : integer, 1 <= m_ and m_ <= 10 -> element(a, [m_]) <> x) .
H2:    for_all(i___1 : integer, 1 <= i___1 and i___1 <= 10 -> integer__first <=
          element(a, [i___1]) and element(a, [i___1]) <= integer__last) .
H3:    x >= integer__first .
H4:    x <= integer__last .
H5:    integer__size >= 0 .
H6:    integer__first <= integer__last .
H7:    integer__base__first <= integer__base__last .
H8:    integer__base__first <= integer__first .
H9:    integer__base__last >= integer__last .
H10:   index__size >= 0 .
H11:   index__base__first <= index__base__last .
H12:   index__base__first <= 1 .
H13:   index__base__last >= 10 .
       ->
C1:    not for_some(m_ : integer, m_ >= 1 and m_ <= 10 and element(a, [m_]) = x)
           .
```

Proof Checker

semi-automated framework for manually caring out proof steps to discharge remaining verification conditions

Manually carry out proofs

Feed Into the Proof Checker

Proofs steps that must be manually entered to prove 1 of the 3 remaining VCs…

```
6.
 replace c # 1 : not for_some(_1, _2) by for_all(_1, not _2) using quant.
 y
 replace h # 11 : not (_1 and _2) by not _1 or not _2 using logical.
 replace c # 1 : not (_1 and _2) by not _1 or not _2 using logical.
 y
 replace c # 1 : not _1 or _2 by _1 -> _2 using logical.
 y
 replace c # 1 : not _1 = _2 by _1 <> _2 using negation(1).
 y
 unwrap h # 1.
 unwrap c # 1.
 inst int_M__1 with int_m__1.
 replace c # 1 : int_m__1 >= 1 by not 1 > int_m__1 using neg
 y
 replace c # 1 : not _1 > _2 by _1 <= _2 using negation.
 y
 done
```

Commands / rules to remember when operating proof checker

…no lemmas, no tactics, etc.
About 15 mins for an expert to prove this very simple method/contract

All or Nothing Useful

```
function Value_Present (A: AType; X : Integer) return Boolean
 --# return for some M in Index => (A(M) = X);
is
  Result : Boolean;
begin
  Result := False;
  for I in Index loop
    if A(I) = X then
      Result := True;
      exit;
    end if;
    --# assert I in Index and
    --#    not Result and
    --# (for all M in Index range Index'First .. I => (A(M) /= X));
  end loop;
  return Result;
end Value_Present;
```

Places where VCs need to be discharged in proof checker

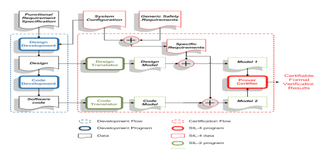
Some paths are verified; some paths are not verified – not very useful

Rockwell Collins Workaround

Customer

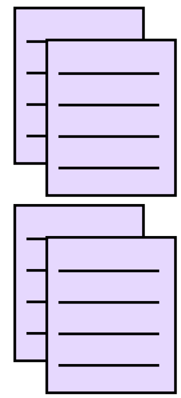
Detailed contract specs from customer in Z

Prover Model Checker



Expressed design in Prover modeling language and checked for array size = 3

SPARK



Translated to SPARK code (no contracts)

Obstacles

- Loop invariants required
- In many cases, developers get only segmented evidence of a contract's correctness (all or nothing)
- Basic behavioral properties have to be specified in a separate "proof language" (FDL)
- Technique is not connected with other quality assurance techniques (e.g., testing)

In reality, the burden of use is so high that it is preventing almost everyone from using it – We want to change that!

Our Work

Better integration of contract checking into SPARK developer workflows

Functional Contracts (pre/post, assertions)

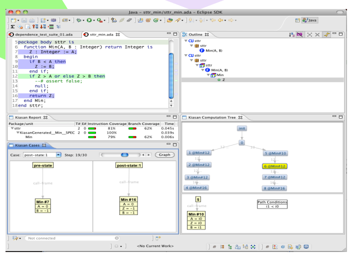
Developers

```
procedure Add(E: Element_Type)
 --# pre Member_Count < Size_Range'Last;
 --# post (isMember(E, Elem_Array, Member_Count) -> (
 --#         Elem_Array = Elem_Array~ and Member_Count = Member_Count~))
 --#   and (not isMember(E, Elem_Array, Member_Count) -> (
 --#         Elem_Array = Elem_Array~[Member_Count => E]
 --#         and Member_Count = Member_Count~ + 1));
```

Automatic Checking

Kiasan

Symbolic Execution Engine



SPARK Eclipse IDE

Use symbolic execution, not just for bug-finding or test-case generation, but for contract checking that complements the existing facilities of SPARK

Themes

- Highly automated; payback is on par with investment;
- Meaningful checking without loop invariants (bounded loop unfolding)
- When verification engine processes code, communicate "knowledge" gained to developer
- Keep focus on the source code level, instead of using a separate formalism like FDL
- SPARK supports only declarative contracts; we want to support both declarative and executable specs
- Connect to other quality assurance techniques; phrase results in terms of what developers already understand

Symbolic Execution [King:ACM76]

```
void foo(int x,
      int y,int z) {
  z = x + y;
  if (z > 0){
    z++;
  }
}
```

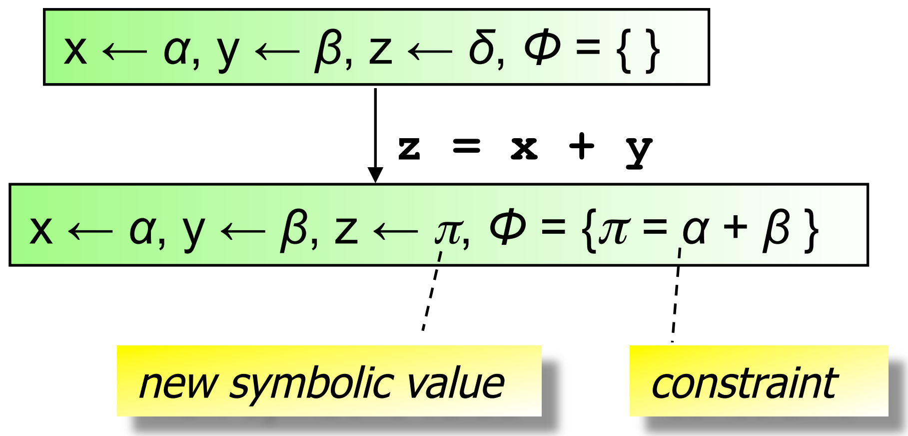
symbolic values

constraints

$x \leftarrow \alpha,\ y \leftarrow \beta,\ z \leftarrow \delta,\ \Phi = \{\ \}$

Symbolic Execution [King:ACM76]

```
void foo(int x,
         int y,int z) {
   z = x + y;
   if (z > 0){
     z++;
   }
}
```



Symbolic Execution [King:ACM76]

```
void foo(int x,
         int y,int z) {
   z = x + y;
   if (z > 0){
      z++;
   }
}
```

$x \leftarrow \alpha$, $y \leftarrow \beta$, $z \leftarrow \delta$, $\Phi = \{\,\}$

`z = x + y`

$x \leftarrow \alpha$, $y \leftarrow \beta$, $z \leftarrow \pi$, $\Phi = \{\pi = \alpha + \beta\}$

`z > 0`

$x \leftarrow \alpha$, $y \leftarrow \beta$, $z \leftarrow \pi$, $\Phi = \{\pi = \alpha + \beta,\ \pi > 0\}$

new constraint for conditional

Symbolic Execution [King:ACM76]

```
void foo(int x,
      int y,int z) {
  z = x + y;
  if (z > 0){
    z++;
  }
}
```

$x \leftarrow \alpha,\ y \leftarrow \beta,\ z \leftarrow \delta,\ \Phi = \{\ \}$

`z = x + y`

$x \leftarrow \alpha,\ y \leftarrow \beta,\ z \leftarrow \pi,\ \Phi = \{\pi = \alpha + \beta\}$

`z > 0`

$x \leftarrow \alpha,\ y \leftarrow \beta,\ z \leftarrow \pi,\ \Phi = \{\pi = \alpha + \beta,\ \pi > 0\}$

`z++`

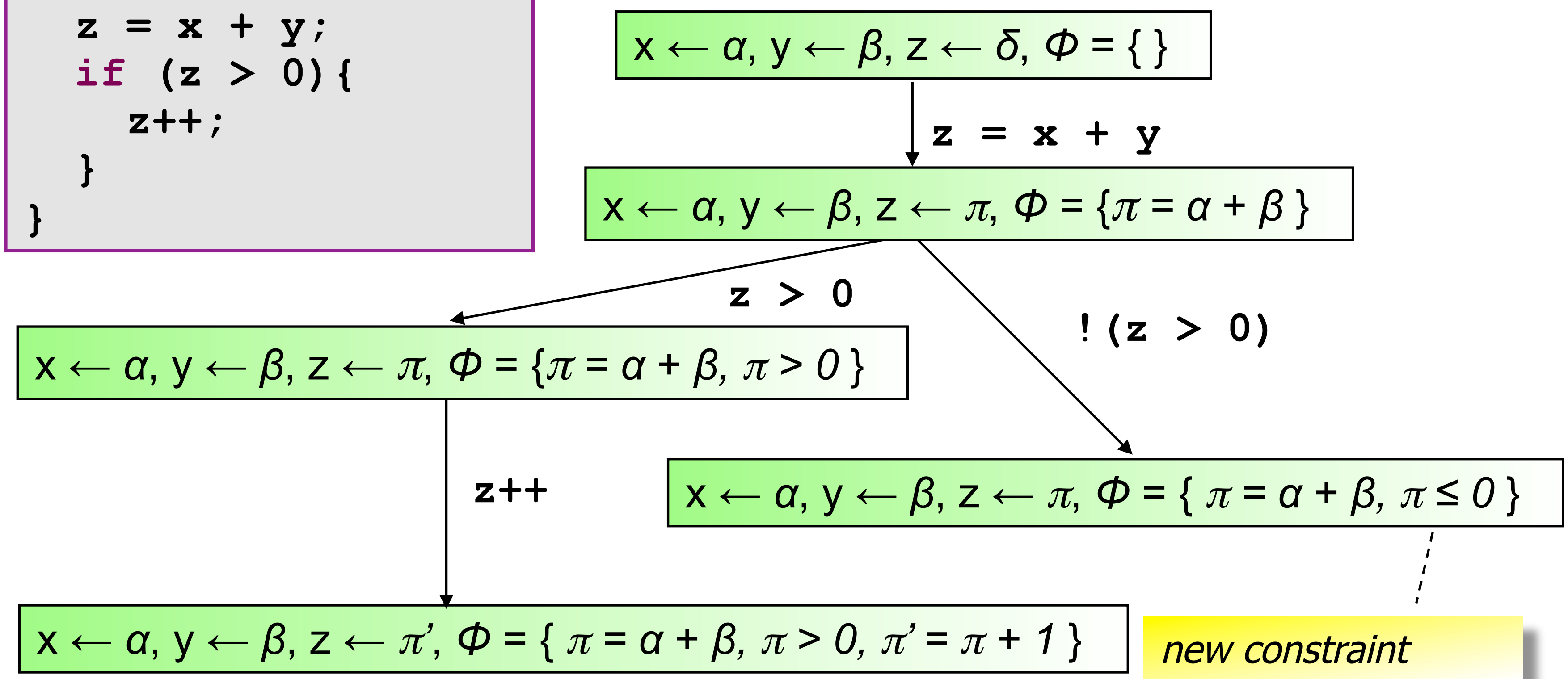
$x \leftarrow \alpha,\ y \leftarrow \beta,\ z \leftarrow \pi',\ \Phi = \{\ \pi = \alpha + \beta,\ \pi > 0,\ \pi' = \pi + 1\ \}$

new symbolic value

new constraint

Symbolic Execution [King:ACM76]

```
void foo(int x,
       int y,int z) {
   z = x + y;
   if (z > 0){
      z++;
   }
}
```



…symbolic execution characterizes (theoretically) infinite number of real executions!

Kiasan -- Solving Constraints

```
void foo(int x,
         int y,int z) {
   z = x + y;
   if (z > 0){
      z++;
   }
}
```

x=-1, y=2, z=0

$x \leftarrow \alpha,\ y \leftarrow \beta,\ z \leftarrow \delta,\ \Phi = \{\ \}$

`z = x + y`

$x \leftarrow \alpha,\ y \leftarrow \beta,\ z \leftarrow \pi,\ \Phi = \{\pi = \alpha + \beta\}$

`z > 0`

$x \leftarrow \alpha,\ y \leftarrow \beta,\ z \leftarrow \pi,\ \Phi = \{\pi = \alpha + \beta,\ \pi > 0\}$

`!(z > 0)`

$x \leftarrow \alpha,\ y \leftarrow \beta,\ z \leftarrow \pi,\ \Phi = \{\pi = \alpha + \beta,\ \pi \leq 0\}$

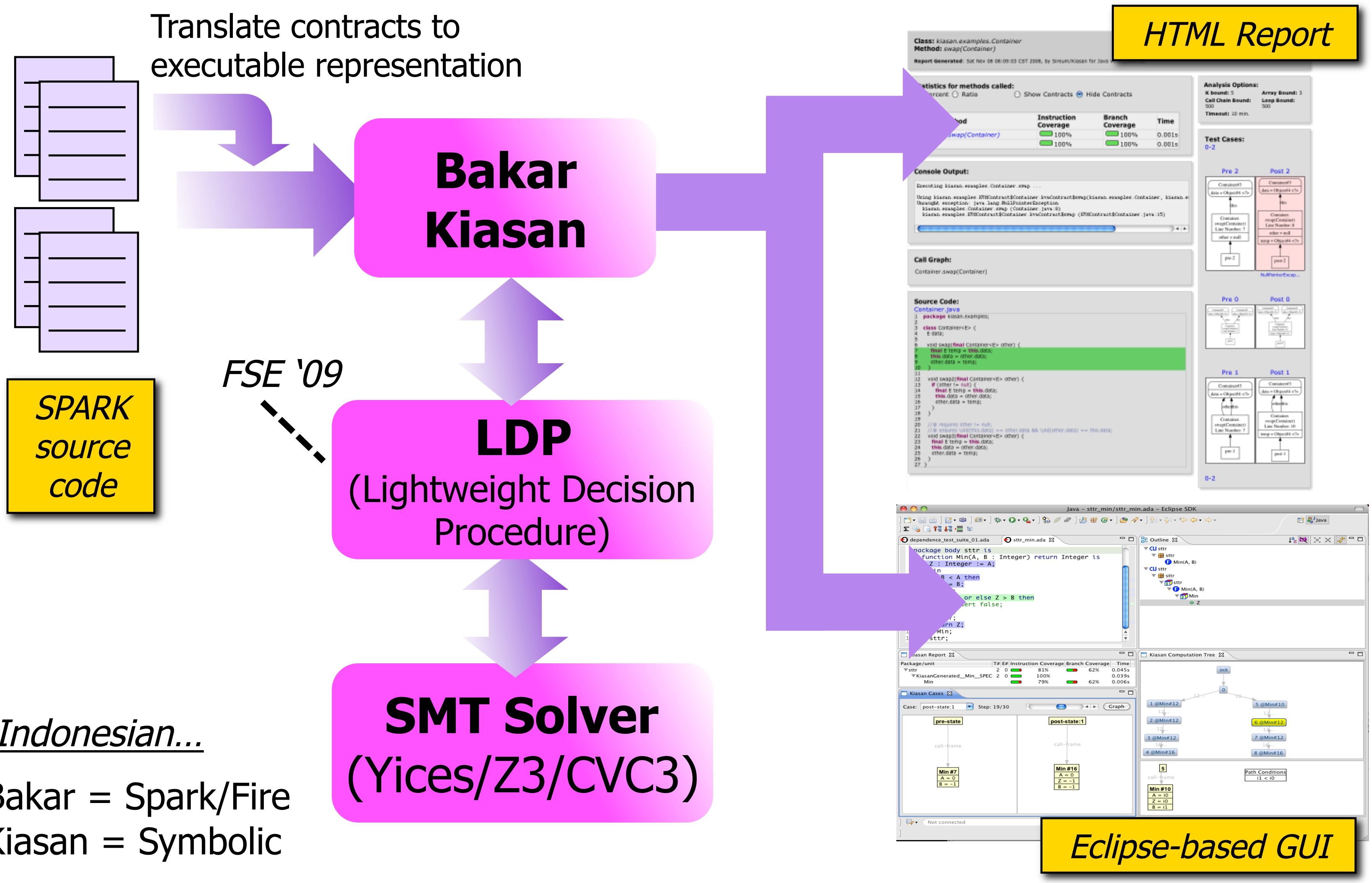
`z++`

$x \leftarrow \alpha,\ y \leftarrow \beta,\ z \leftarrow \pi',\ \Phi = \{\pi = \alpha + \beta,\ \pi > 0,\ \pi' = \pi + 1\}$

The path condition *characterizes the set of program states that flow to this point in the path.*

Solving constraints on input variables yields input values (a test case) that drives execution down the current path.

Bakar Kiasan Architecture



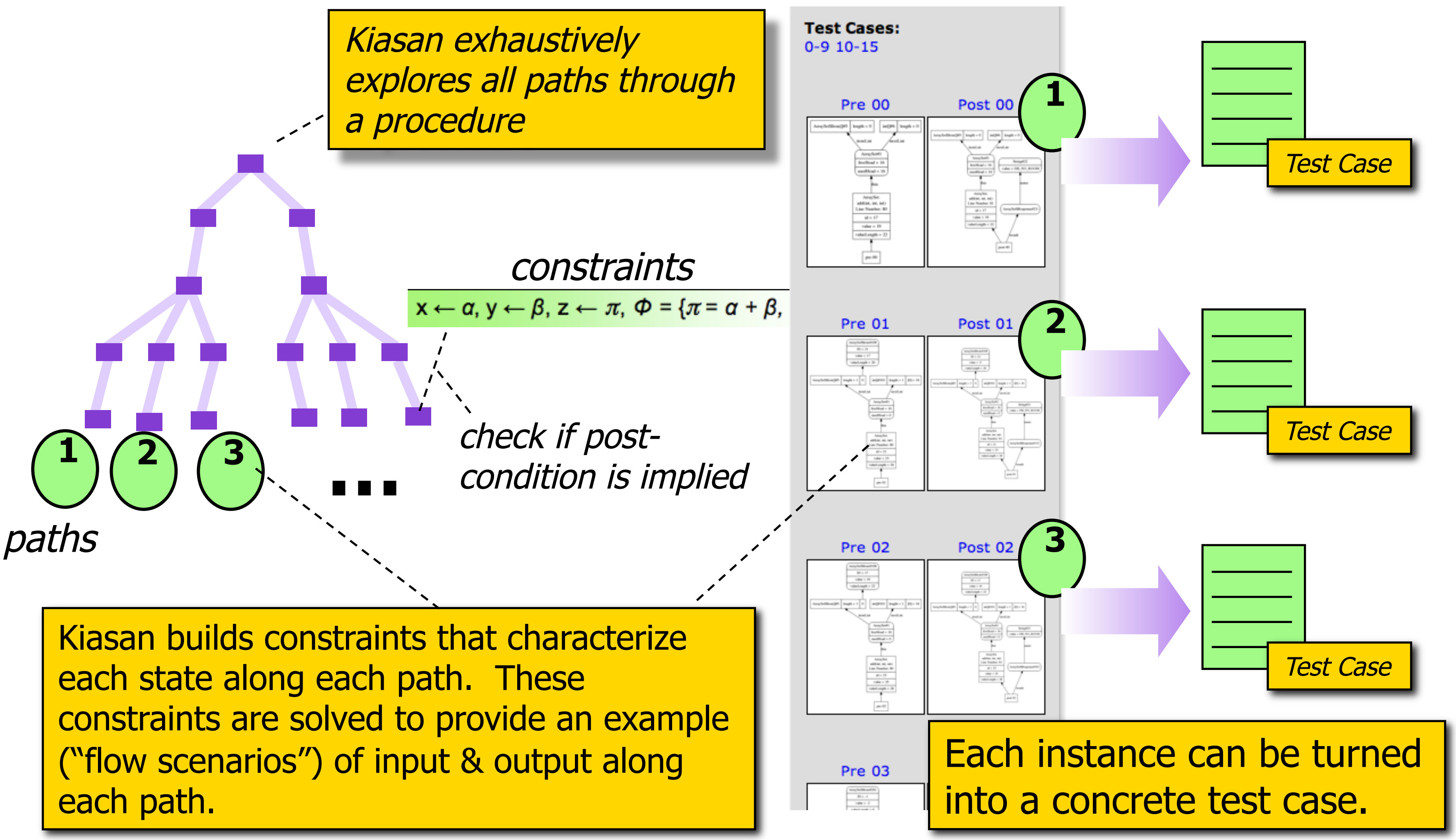
<u>*In Indonesian…*</u>

Bakar = Spark/Fire
Kiasan = Symbolic

Visualizing Properties of Paths

Verification *(bounded, in some cases)*

Examples / Tests

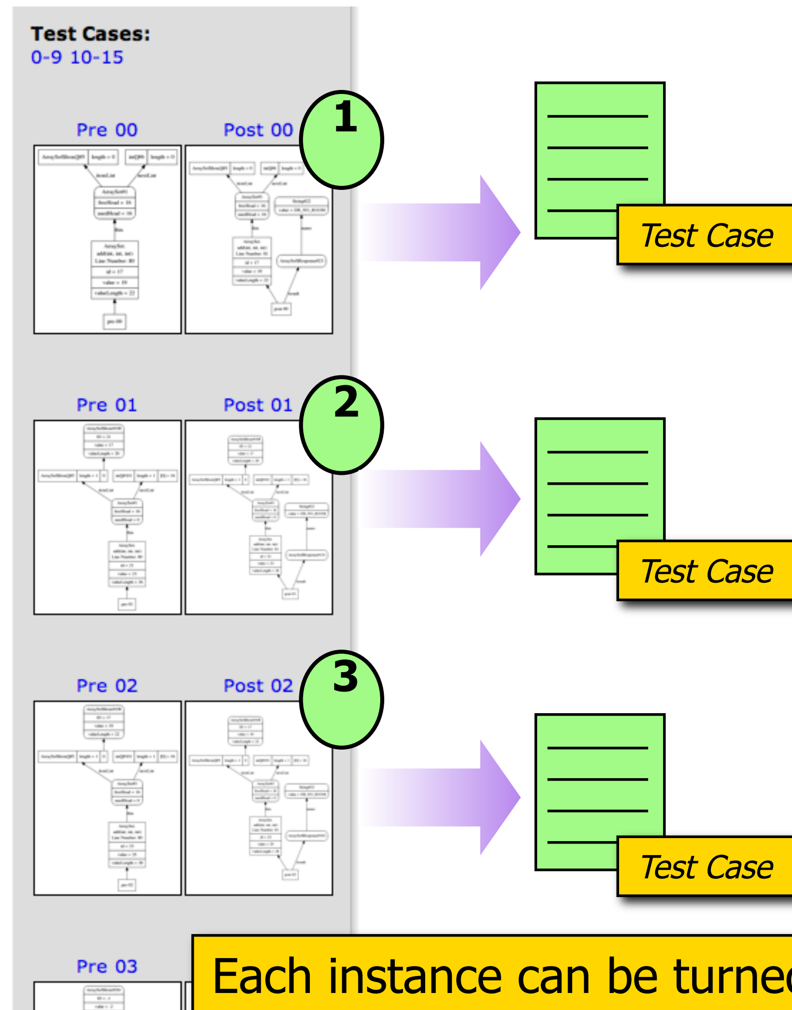


Kiasan Output

Why provide examples/tests if we are verifying?

- Tests provide “evidence” to people not familiar with formal methods that something “interesting” is happening in the tool
- When a bug is found along one path, the test provides a counter-example illustrating the bug
- Kiasan’s exhaustive exploration automatically yields test suites with very high levels of MCDC coverage

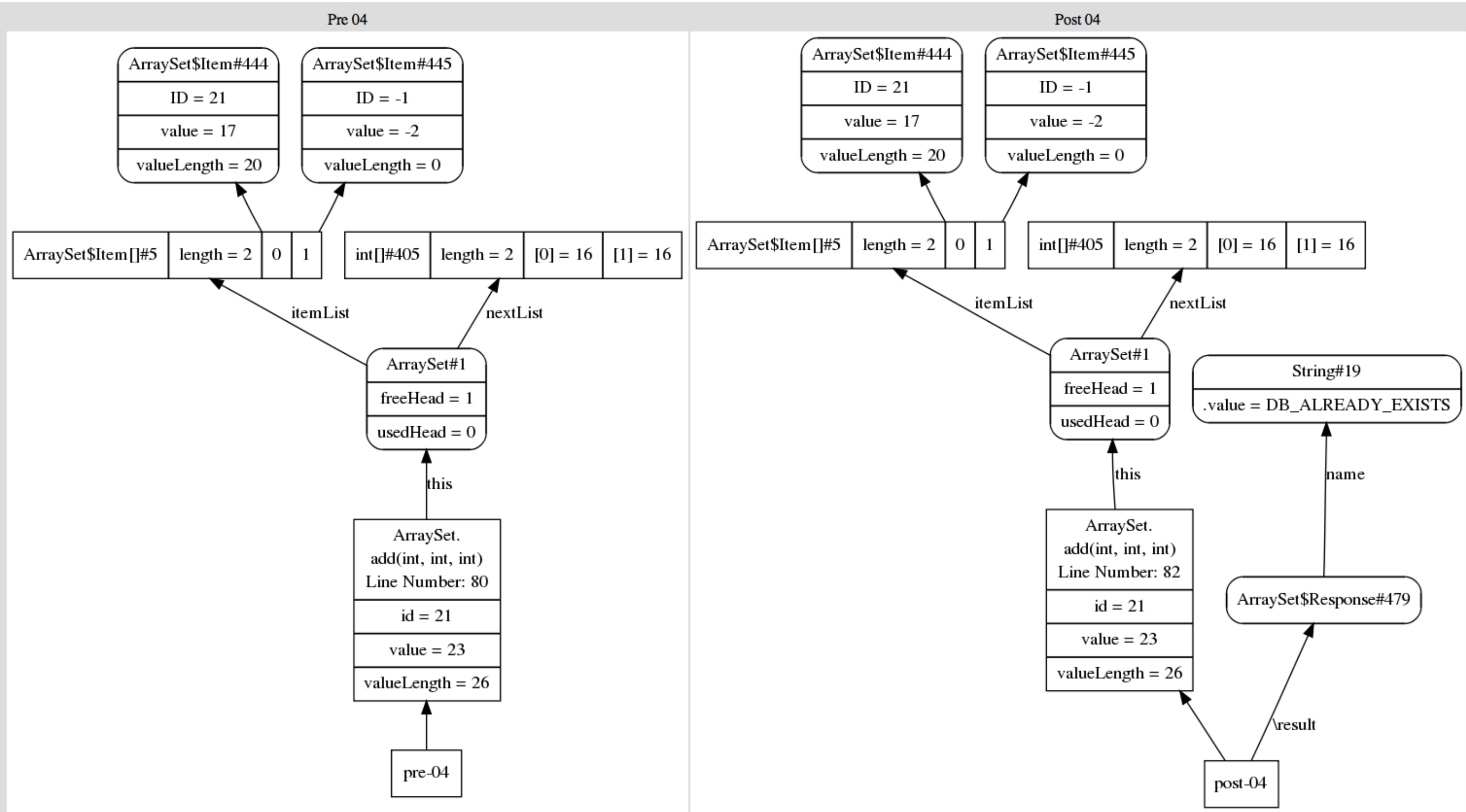
NB: Jeff Joyce (DO-178C FM) – explain formal method contribution in terms of coverage / tests



Each instance can be turned into a concrete test case.

Kiasan Output

Sample path input/output for a more complicated example with nested arrays/records



Input -- program state at start of path

Output -- program state at end of path

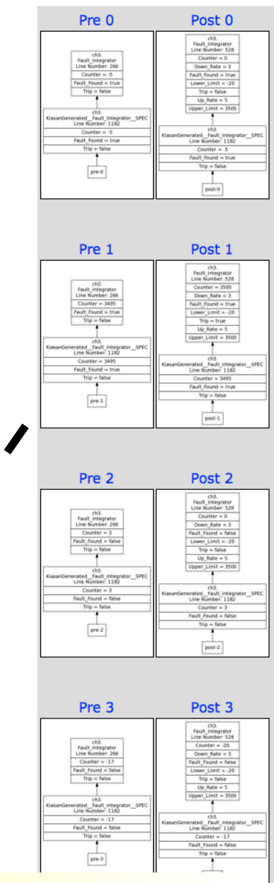
Early Payback

Kiasan does not need contracts to provide useful semantic information – immediately can explore to look for possible run-time exceptions

```
procedure Fault_Integrator(Fault_Found : in Boolean;
                           Trip : in out Boolean;
                           Counter : in out Integer)
is
```

```
   if Fault_Found then
      Counter := 
      if Counter >= Upper_Limit then
        Trip := True; Counter := Upper_Limit;
      end if;
   else
      Counter := Counter - Down_Rate;
      if Counter <= Lower_Limit then
        Trip := False; Counter := Lower_Limit;
      end if;
   end if;
end Fault_Integrator;
```

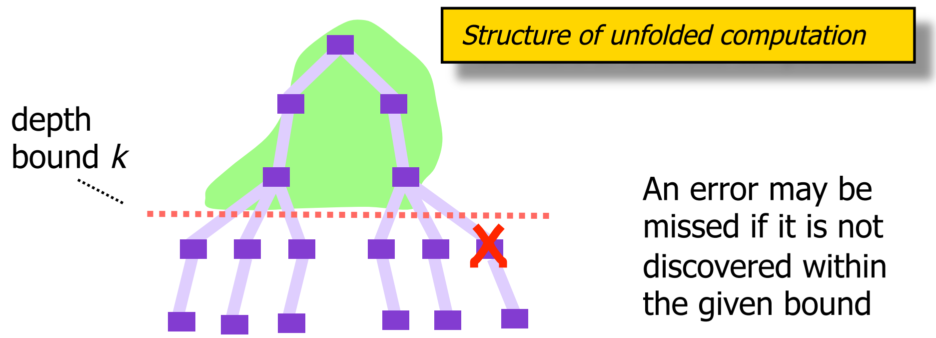
Fully Covered Line



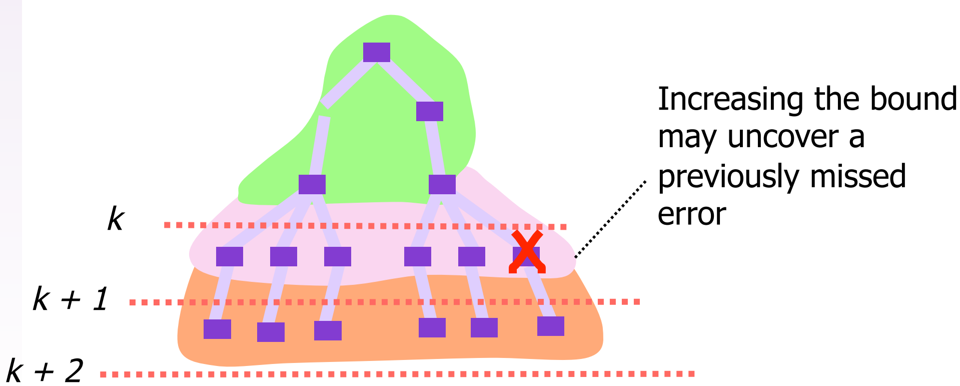
This procedure has four paths, so Kiasan provides four "examples".

Controlling Cost/Coverage

To ensure the path exploration always terminates, Kiasan uses several bounding techniques which are configurable by the user



Increasing *k* increases coverage & cost



- Start with small bounds
- Coverage information provided by the tool indicates if your missing any statements / branches

- Increase bounds to increase coverage
  - increasing bounds increases time required for analysis
  - run analysis with high bounds for high-confidence as part of over-night regression testing
- Most bugs are found with relatively low bounds

Coverage Information

Package Name: *ArraySet*

Report Rendered: Mon Apr 18 12:36:56 PDT 2011, by Sireum/Kiasan for SPARK v0.1.20100729

Branches Covered For Tests: 23/24 (95.83%)

Branches Covered For Package: 23/69 (33.33%)

Method Covered:

Percent / Ratio

Method	T	E	Instruction Coverage	Branch Coverage	Time
Add	34	0	94.12%	83.33%	0.016s
Delete	10	0	100%	100%	0.050s
Get_Value	10	0	100%	100%	0.020s

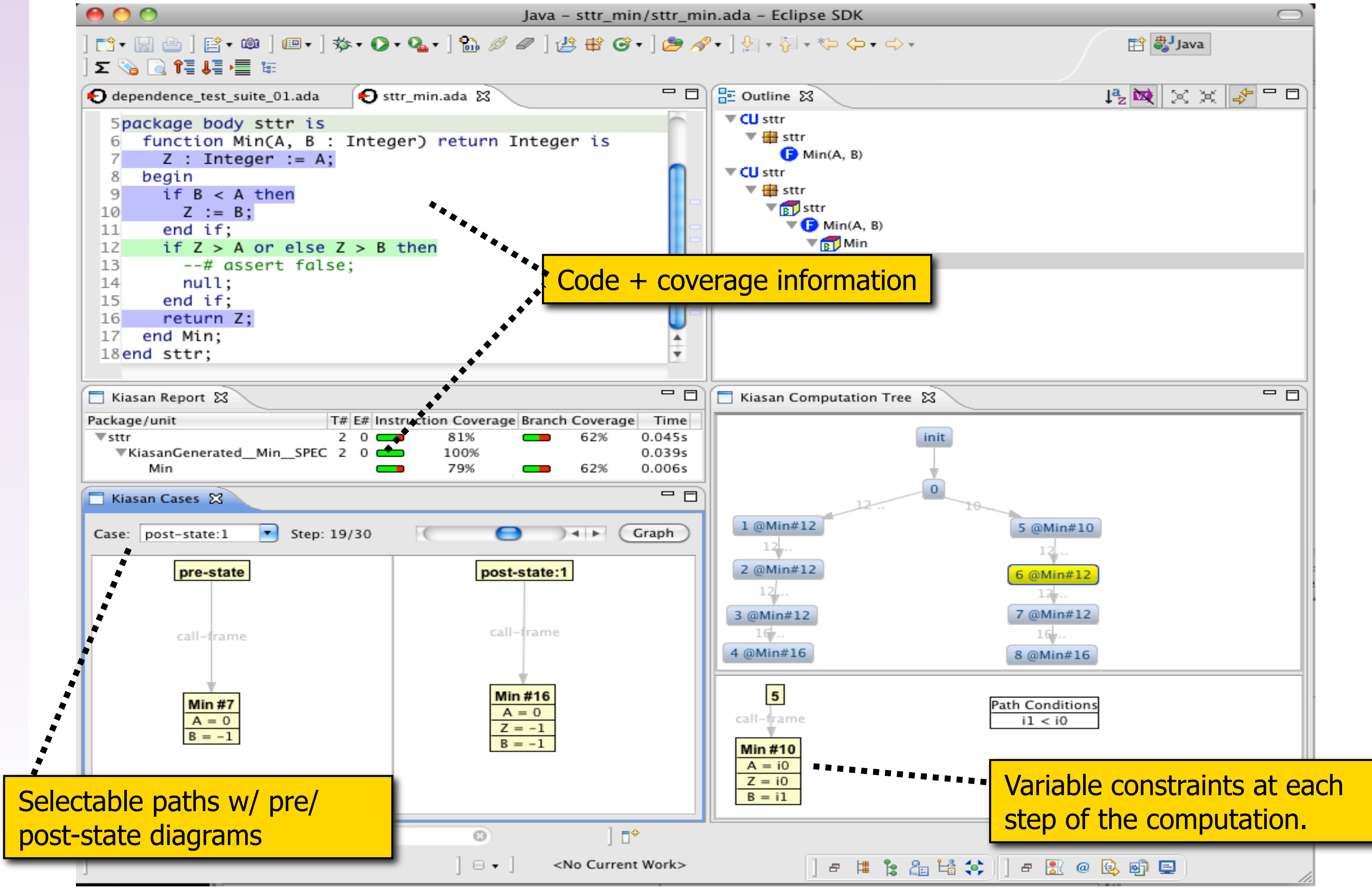
Source Code:

```
with ArraySetDefs;
with ArraySetUnsigned;
use type ArraySetDefs.ID_Type;

package body ArraySet
--# own State is Item_List, Next_List, Free_Head, Used_Head;
is
  Max_Items : constant := 3; -- belt: originally 16

  type Item_Type is record
    ID         : ArraySetDefs.ID_Type;
    Value      : ArraySetDefs.Value_Type;
  end record;

  subtype Item_List_Index_Type is ArraySetUnsigned.Word range 0 .. Max_Items - 1;
  subtype Link_Type is ArraySetUnsigned.Word range 0 .. Max_Items;

  type Item_List_Type is array (Item_List_Index_Type) of Item_Type;
  type Next_List_Type is array (Item_List_Index_Type) of Link_Type;

  Item_List : Item_List_Type;
  Next_List : Next_List_Type;

  Terminator : constant := Link_Type'Last;
  Inf_Length : constant := Max_Items + 1;
  Free_Head : Link_Type;
  Used_Head : Link_Type;

  ------------------Invariant

  ---
  --- @param head the index of the start of a list (expected to be either
  ---             Free_Head or Used_Head)
  --- @return the number of elements reachable from head, or Inf_Length
  ---         if the list is cyclic.
  ---
  function Size_Of_List(head : Link_Type) return ArraySetUnsigned.Word
    --# global in Next_List;
  is
    Cursor : Link_Type;
    Result : ArraySetUnsigned.Word := 0;
  begin
    Cursor := head;
    while Cursor /= Terminator and Result < Inf_Length loop
      Result := Result + 1;
```

Summary of coverage information

Source code. Green code indicates executable code that is covered by analysis. Yellow code indicates that code is partially covered (e.g., only one branch of a conditional)

Working at Source Code Level



Benefits of Bakar Kiasan

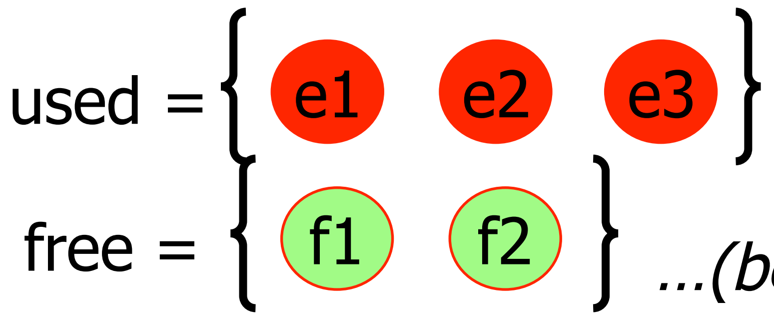
Bakar Kiasan provides a number of capabilities that help integrate SPARK contract checking directly into developer workflows

- Helpful visualization of paths explored
- Connection to existing quality assurance techniques that developers are familiar with (i.e., testing)
- Capabilities are brought together in the Eclipse IDE
- Technique can be applied very early in the development (even before contracts are written)

Example - Rockwell Collins

RC ATC engineers have chosen to implement many of the data structures necessary for embedded security devices using array based linked lists.

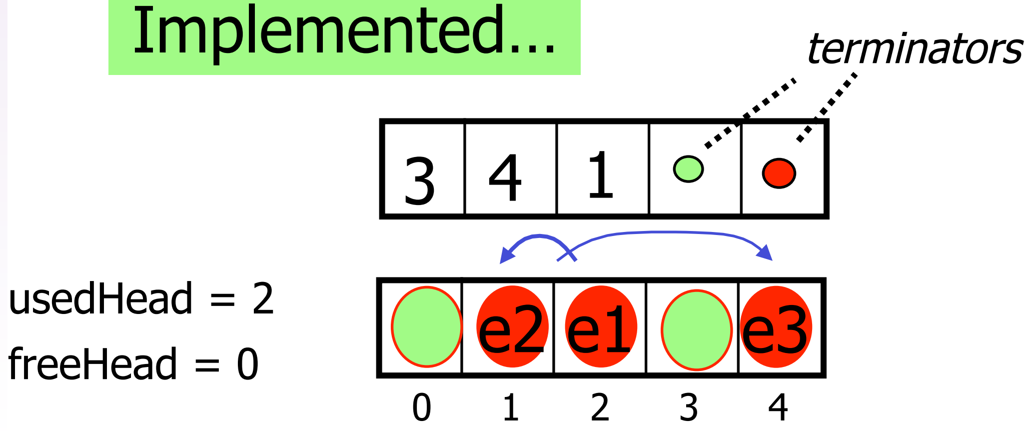
Conceptually…



…database entries

…(behind the scenes) free slots

Implemented…



…"Next" array

…"Item" array

Example Properties (excerpts)

Example Representation Invariants

- [Item list] -- IDs are unique and all entries have non-null IDs and values
- [Free list] -- all entries have null IDs and value
- [Item,Free list] -- from each list head (free, item) a terminator is in the set Reachable(*head*)
- [Item, Free list] -- no cycles exist in the item or free lists
- [Item/Free list] -- item and free lists are disjoint and cover all positions in the array

Enhancing Contract Functionality

Existing SPARK contract notation is limited to first-order logic. Plus, any "helper functions" are treated as uninterrupted functions.

```
--# (Response = ... -> (
--#   (for all I in Item_List_Index_Type =>
--#     (ID /= Item_List~(I).ID)) and then
--#   (for some I in Item_List_Index_Type =>
--#     (ID = Item_List(I).ID))))
--#  and then …
```

Example invariants are extremely cumbersome to specify under these limitations

Bakar Kiasan adds support for functions in contracts whose semantics is specified directly using SPARK functions (guaranteed "pure")

```
--# post Invariant(...)
--#   and then
--#   (Response = ... <->
--#     contains(ID, ...) = False)
--#   and then
--#
```

```
function Invariant(...)
  is begin … end
```

```
function contains(...)
  is begin … end
```

Example Walkthrough

Delete for Linked Integer Set

```
procedure Delete
  (ID           : in  LinkedIntegerSetDefs.ID_Type;
   Response     : out LinkedIntegerSetDefs.Response_Type)
  --# global in out Item_List, Next_List, Free_Head, Used_Head;
  --# pre Invariant(Next_List, Free_Head, Used_Head, Item_List);
  --# post Invariant(Next_List, Free_Head, Used_Head, Item_List)
  --#   and then
  --#   (Response = LinkedIntegerSetDefs.DB_Does_Not_Exist <->
  --#     contains(ID, Used_Head~, Item_List~, Next_List~) = False)
  --#   and then
  --#   (Response = LinkedIntegerSetDefs.DB_Success <->
  --#     (contains(ID, Used_Head~, Item_List~, Next_List~) = True
  --#      and then
  --#      contains(ID, Used_Head, Item_List, Next_List) = False));
```

Example Walkthrough

Delete for Linked Integer Set

```
procedure Delete
   (ID           : in  LinkedIntegerSetDefs.ID_Type;
    Response     : out LinkedIntegerSetDefs.Response_Type)
   --# global in out Item_List, Next_List, Free_Head, Used_Head;
   --# pre Invariant(Next_List, Free_Head, Used_Head, Item_List);
   --# post Invariant(Next_List, Free_Head, Used_Head, Item_List)
   --#   and then
   --#   (Response = LinkedIntegerSetDefs.DB_Does_Not_Exist <->
   --#     contains(ID, Used_Head~, Item_List~, Next_List~) = False)
   --#   and then
   --#   (Response = LinkedIntegerSetDefs.DB_Succes
   --#     (contains(ID, Used_Head~, Item_List~, Ne
   --#      and then
   --#      contains(ID, Used_Head, Item_List, Next_List) = False));
```

Pre-condition: The 'package invariant' is satisfied

Example Walkthrough

Executable code can be accessed from within contracts

```
procedure Delete
```

```
function Invariant return Boolean
  --# global Next_List, Free_Head, Used_Head, Item_List;
is
begin
  return
    Used_Elements_Invariant and then
    Free_Elements_Invariant and then
    not Is_Cyclic(Free_Head) and then
    not Is_Cyclic(Used_Head) and then
    Size_Of_List(Free_Head) + Size_Of_List(Used_Head) =
      Max_Items;
  end Invariant;
```

Example Walkthrough

Executable code can be accessed from within contracts

```
procedure Delete
```

```
function Invariant return Boolean
  --# global Next_List, Free_Head, Used_Head, Item_List;
is
begin
  return
    Used_Elements_Invariant and then
    Free_Elements_Invariant and then
    not Is_Cyclic(Free_Head) and then
    not Is_Cyclic(Used_Head) and then
    Size_Of_List(Free_Head) + Size_Of_List(Used_Head) =
      Max_Items;
  end Invariant;
```

Example Walkthrough

Executable code can be accessed from within contracts

```
procedure Delete
  (ID              : in   LinkedIntegerSetDefs.ID_Type;
```

```
function Invariant return Boolean
  --# global Next_List, Free_Head, Used_Head, Item_List;
```

```
function Used_Elements_Invariant return Boolean
  --# global Item_List, Next_List, Used_Head;
is
  Cursor : Link_Type;
  Result : Boolean := True;
begin
  Result := Is_Set;
  Cursor := Used_Head;
  while Result and then Cursor /= Terminator loop
    Result := Item_List(Cursor).ID /= LinkedIntegerSetDefs.Null_ID
      and then
      Item_List(Cursor).Value /= LinkedIntegerSetDefs.Null_Value;
    Cursor := Next_List(Cursor);
  end loop;
  return Result;
end Used_Elements_Invariant;
```

Example Walkthrough

Executable code can be accessed from within contracts

```
procedure Delete
```

```
function Invariant return Boolean
```

```
function Used_Elements_Invariant return Boolean
  --# global Item_List, Next_List, Used_Head;
is
  Cursor : Link_Type;
  Result : Boolean := True;
begin
  Result := Is_Set;
  Cursor := Used_Head;
  while Result and then Cursor /= Terminator loop
    Result := Item_List(Cursor).ID /= LinkedIntegerSetDefs.Null_ID
      and then
      Item_List(Cursor).Value /= LinkedIntegerSetDefs.Null_Value;
    Cursor := Next_List(Cursor);
  end loop;
  return Result;
end Used_Elements_Invariant;
```

Elements reachable from Used_Head must form a set

Example Walkthrough

Executable code can be accessed from within contracts

```
procedure Delete
```

```
function Invariant return Boolean
```

```
function Used_Elements_Invariant return Boolean
  --# global Item_List, Next_List, Used_Head;
is
  Cursor : Link_Type;
  Result : Boolean := True;
begin
  Result := Is_Set;
  Cursor := Used_Head;
  while Result and then Cursor /= Terminator loop
    Result := Item_List(Cursor).ID /= LinkedIntegerSetDefs.Null_ID
      and then
      Item_List(Cursor).Value /= LinkedIntegerSetDefs.Null_Value;
    Cursor := Next_List(Cursor);
  end loop;
  return Result;
end Used_Elements_Invariant;
```

Elements reachable from Used_Head must have non-null IDs and values

Example Walkthrough

Delete for Linked Integer Set

```
procedure Delete
  (ID          : in  LinkedIntegerSetDefs.ID_Type;
   Response    : out LinkedIntegerSetDefs.Response_Type)
  --# global in out Item_List, Next_List, Free_Head, Used_Head;
  --# pre Invariant(Next_List, Free_Head, Used_Head, Item_List);
  --# post Invariant(Next_List, Free_Head, Used_Head, Item_List)
  --#   and then
  --#   (Response = LinkedIntegerSetDefs.DB_Does_Not_Exist <->
  --#     contains(ID, Used_Head~, Item_List~, Next_List~) = False)
  --#   and then
  --#   (Response = LinkedIntegerSetDefs.DB_Success <->
  --#     (contains(ID, Used_Head~, Item_List~, Next_List~) = True
  --#      and then
  --#      contains(ID, Used_Head, Item_List, Next_List) = False));
```

Example Walkthrough

Delete for Linked Integer Set

```
procedure Delete
   (ID            : in  LinkedIntegerSetDefs.ID_Type;
    Response      : out LinkedIntegerSetDefs.Response_Type)
  --# global in out Item_List, Next_List, Free_Head, Used_Head;
  --# pre Invariant(Next_List, Free_Head, Used_Head, Item_List);
  --# post Invariant(Next_List, Free_Head, Used_Head, Item_List)
  --#   and then
  --#   (Response = LinkedIntegerSetDefs.DB_Does_Not_Exist <->
  --#     contains(ID, Used_Head~, Item_List~, Next_List~) = False)
  --#   and then
  --#   (Response = LinkedIntegerSetDefs.DB_Success <->
  --#     (contains(ID, Used_Head~, Item_List~, Next_List~) = True
  --#      and then
  --#      contains(ID, Used_Head, Item_List, Next_List) = False));
```

Case where ID was not in the DB

Example Walkthrough

Delete for Linked Integer Set

```
procedure Delete
   (ID            : in  LinkedIntegerSetDefs.ID_Type;
    Response      : out LinkedIntegerSetDefs.Response_Type)
   --# global in out Item_List, Next_List, Free_Head, Used_Head;
   --# pre Invariant(Next_List, Free_Head, Used_Head, Item_List);
   --# post Invariant(Next_List, Free_Head, Used_Head, Item_List)
   --#    and then
   --#    (Response = LinkedIntegerSetDefs.DB_Does_Not_Exist <->
   --#      contains(ID, Used_Head~, Item_List~, Next_List~) = False)
   --#    and then
   --#    (Response = LinkedIntegerSetDefs.DB_Success <->
   --#      (contains(ID, Used_Head~, Item_List~, Next_List~) = True
   --#       and then
   --#       contains(ID, Used_Head, Item_List, Next_List) = False));
```

Case where ID was found and removed

Linked Integer Set : Add

Add for Linked Integer Set

```
procedure Add
   (ID              : in  LinkedIntegerSetDefs.ID_Type;
    Value           : in  LinkedIntegerSetDefs.Value_Type;
    Response        : out LinkedIntegerSetDefs.Response_Type)
  --# pre Invariant(Next_List, Free_Head, Used_Head, Item_List)
  --#   and then (ID /= LinkedIntegerSetDefs.Null_ID)
  --#   and then (Value /= LinkedIntegerSetDefs.Null_Value);
  --#
  --# post Invariant(Next_List, Free_Head, Used_Head, Item_List)
  --#   and then
  --#   (Response = LinkedIntegerSetDefs.DB_Success -> (
  --#     (for all I in Item_List_Index_Type =>
  --#       (ID /= Item_List~(I).ID)) and then
  --#     (for some I in Item_List_Index_Type =>
  --#       (ID = Item_List(I).ID))))
  --#   and then
  --#   (Response = LinkedIntegerSetDefs.DB_Already_Exists -> (
  --#     for some I in Item_List_Index_Type => (
  --#       ID = Item_List~(I).ID and then ID = Item_List(I).ID)))
  --#   and then ...;
```

Linked Integer Set : Add

Add for Linked Integer Set

```
procedure Add
   (ID              : in   LinkedIntegerSetDefs.ID_Type;
    Value           : in   LinkedIntegerSetDefs.Value_Type;
    Response        : out  LinkedIntegerSetDefs.Response_Type)
  --# pre Invariant(Next_List, Free_Head, Used_Head, Item_List)
  --#    and then (ID /= LinkedIntegerSetDefs.Null_ID)
  --#    and then (Value /= LinkedIntegerSetDefs.Null_Value);
  --#
  --# post Invariant(Next_List, Free_Head, Used_Head, Item_List)
  --#    and then
  --#    (Response = LinkedIntegerSetDefs.DB_Success -> (
  --#      (for all I in Item_List_Index_Type =>
  --#        (ID /= Item_List~(I).ID)) and then
  --#      (for some I in Item_List_Index_Type =>
  --#        (ID = Item_List(I).ID))))
  --#    and then
  --#    (Response = LinkedIntegerSetDefs.DB_Already_Exists -> (
  --#      for some I in Item_List_Index_Type => (
  --#        ID = Item_List~(I).ID and then ID = Item_List(I).ID)))
  --#    and then ...;
```

Demo

Performance Evaluation

- Can we provide a significant increase in automation of contract checking over existing SPARK tools?
- Scalability
  - Can be applied during the typical code/test/debug loop
  - Can the technique scale to sizes of data structures that would be reasonable for embedded systems

Experimental Results

Increase in Automation

- The existing SPARK tools were only able to fully check one method. The rest would have to be proved manually
  - Some of these contracts are 15-20x as complex as the simple example shown earlier that took 15 mins to manually check

Auto discharged VCs / Total VCs

Package.Procedure Name	VC
Sort.Bubble	13/18
Sort.Insertion	10/14
Sort.Selection	28/30
Sort.Shell	17/18
IntegerSet.Get_Element_Index	8/11
IntegerSet.Add	3/5
IntegerSet.Remove	5/6
IntegerSet.Empty	3/3
LinkedIntegerSet.Get_Value	9/10
LinkedIntegerSet.Add	14/16
LinkedIntegerSet.Delete	18/21
LinkedIntegerSet.Init	16/17
MMR.Fill_Mem_Row	8/10
MMR.Zero_Mem_Row	6/7
MMR.Zero_Flags	6/7
MMR.Read_Msgs	3/4
MMR.Send_Msg	4/5
MMR.Route	62/67

Only procedure contract that was checked automatically by the Praxis SPARK tools

- Kiasan provides completely automated checking (*caveat: bounded size data structures*) for all these examples

Experimental Results

Increase in Automation

- Most of these examples used "helper functions" (predicates) in contracts
  - Bakar Kiasan – specified/checked directly in SPARK
  - Praxis SPARK – requires adding rewrite rules in FDL and manually discharging in Proof Checker

Contract Helper Functions / (other)

Package.Procedure Name	Helper
Sort.Bubble	3/0
Sort.Insertion	3/0
Sort.Selection	3/0
Sort.Shell	3/0
IntegerSet.Get_Element_Index	0/0
IntegerSet.Add	4/3
IntegerSet.Remove	4/1
IntegerSet.Empty	0/0
LinkedIntegerSet.Get_Value	6/0
LinkedIntegerSet.Add	6/1
LinkedIntegerSet.Delete	6/0
LinkedIntegerSet.Init	5/0
MMR.Fill_Mem_Row	0/1
MMR.Zero_Mem_Row	0/1
MMR.Zero_Flags	0/0
MMR.Read_Msgs	6/5
MMR.Send_Msg	3/3
MMR.Route	9/2

E.g., six predicates used in LinkedIntegerSet examples

Experimental Results

Scalability *(k = array size)*

Time (secs)

- Easily fits in the code/test/debug loop for small k
- Previous Rockwell Collins approach using Prover maxed out at k=3
  - Plus, Kiasan works directly on SPARK code and doesn't require manual translation

Package.Procedure Name	VC	k=3	k=4	k=5	k=6	k=7	k=8
Sort.Bubble	13/18	0.17	0.96	2.09	8.43	71.72	890.18
Sort.Insertion	10/14	0.15	0.98	2.06	8.24	70.72	892.17
Sort.Selection	28/30	0.16	1.06	2.28	9.95	90.14	1356.18
Sort.Shell	17/18	0.15	0.98	2.12	8.47	74.09	941.99
IntegerSet.Get_Element_Index	8/11	0.04	0.05	0.06	0.07	0.08	0.10
IntegerSet.Add	3/5	0.24	0.44	0.62	0.79	0.80	1.04
IntegerSet.Remove	5/6	0.16	0.30	0.56	0.96	1.21	1.36
IntegerSet.Empty	3/3	0.02	0.02	0.02	0.02	0.02	0.02
LinkedIntegerSet.Get_Value	9/10	0.64	0.88	1.13	1.51	2.19	2.85
LinkedIntegerSet.Add	14/16	0.43	0.73	1.66	5.26	34.96	379.34
LinkedIntegerSet.Delete	18/21	0.52	0.72	1.03	1.56	2.10	2.75
LinkedIntegerSet.Init	16/17	0.05	0.04	0.04	0.05	0.05	0.05
MMR.Fill_Mem_Row	8/10	0.18					
MMR.Zero_Mem_Row	6/7	0.19					
MMR.Zero_Flags	6/7	0.05					
MMR.Read_Msgs	3/4	1.71					
MMR.Send_Msg	4/5	0.50					
MMR.Route	62/67	13.90					

Experimental Results

Scalability *(k = array size)*

- Scales well for methods which don't contain quantification
- Larger bounds can be explored as part of a nightly regression test process
- Implementation can be easily distributed

Time (secs)

Package.Procedure Name	VC	k=3	k=4	k=5	k=6	k=7	k=8
Sort.Bubble	13/18	0.17	0.96	2.09	8.43	71.72	890.18
Sort.Insertion	10/14	0.15	0.98	2.06	8.24	70.72	892.17
Sort.Selection	28/30	0.16	1.06	2.28	9.95	90.14	1356.18
Sort.Shell	17/18	0.15	0.98	2.12	8.47	74.09	941.99
IntegerSet.Get_Element_Index	8/11	0.04	0.05	0.06	0.07	0.08	0.10
IntegerSet.Add	3/5	0.24	0.44	0.62	0.79	0.80	1.04
IntegerSet.Remove	5/6	0.16	0.30	0.56	0.96	1.21	1.36
IntegerSet.Empty	3/3	0.02	0.02	0.02	0.02	0.02	0.02
LinkedIntegerSet.Get_Value	9/10	0.64	0.88	1.13	1.51	2.19	2.85
LinkedIntegerSet.Add	14/16	0.43	0.73	1.66	5.26	34.96	379.34
LinkedIntegerSet.Delete	18/21	0.52	0.72	1.03	1.56	2.10	2.75
LinkedIntegerSet.Init	16/17	0.05	0.04	0.04	0.05	0.05	0.05
MMR.Fill_Mem_Row	8/10	0.18					
MMR.Zero_Mem_Row	6/7	0.19					
MMR.Zero_Flags	6/7	0.05					
MMR.Read_Msgs	3/4	1.71					
MMR.Send_Msg	4/5	0.50					
MMR.Route	62/67	13.90					

Kiasan Methodology

- Checking in IDE
  - start with small bounds
  - incrementally check
  - scenario and test case generation for violations
- More exhaustive checking
  - higher bounds with overnight/parallel checking
  - Kiasan tells you if coverage criteria has been met
- Code understanding
  - select any block of code,
    Kiasan generates flow scenarios giving path coverage
- Test case generation for regression testing
  - automatically generate tests (full MCDC coverage) from code
- Add loop invariants for complete verification

Summary

- Considered the challenge of contract checking in SPARK – one of the best commercially supported frameworks for code-level safety critical software development
- Demonstrated how symbolic execution can potentially change the status quo for the use of SPARK contracts
  - **From** very rarely used
    to useable by typical developers within the normal code-test-debug loop
- Demonstrated how Bakar Kiasan can provide checking of very complex contracts from embedded security applications
  - Flexible combination of declarative and executable specs
- Illustrated multiple ways of leveraging the information produced by symbolic execution
  - Pre/post-state visualization
  - Test case generation
  - Bridging the gap between formal methods and testing

Next Steps…

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- Around 90% of SPARK handled – extend to 100%
- SPARK contract language needs to be enhanced
  - Package invariants, data abstractions & refinement
- Public release planned
- Evaluation in Rockwell Collins research projects