Copies: Reference vs. Shallow vs. Deep
Writing Complete Postconditions

EECS3311 A: Software Design
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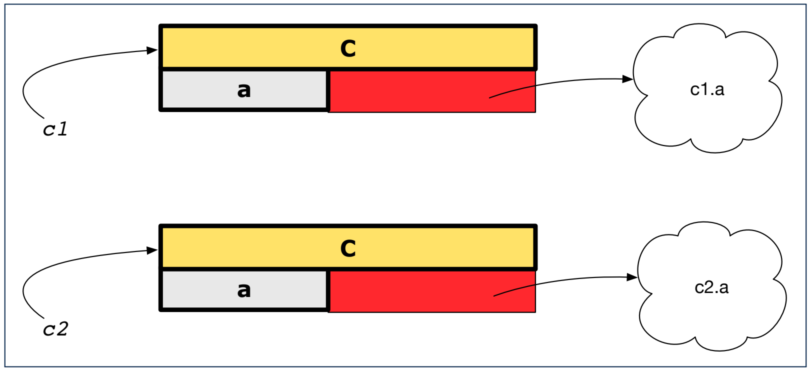
Copying Objects

Say variables `c1` and `c2` are both declared of type `C`. [*c1, c2: C*]

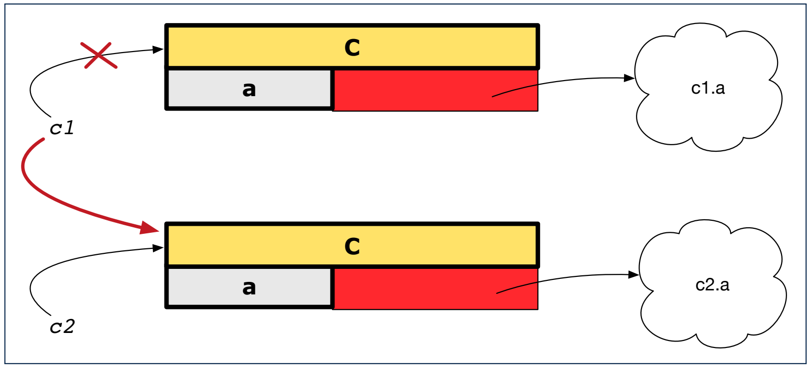
- There is only one attribute `a` declared in class `C`.
- `c1.a` and `c2.a` are references to objects.



Copying Objects: Reference Copy

Reference Copy `c1 := c2`

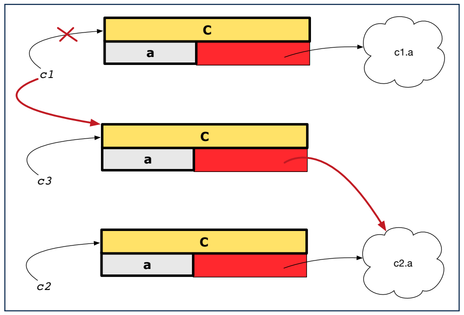
- Copy the address stored in variable `c2` and store it in `c1`.
  ⇒ Both `c1` and `c2` point to the same object.
  ⇒ Updates performed via `c1` also visible to `c2`. [***aliasing***]



Copying Objects: Shallow Copy

Shallow Copy `c1 := c2.twin`

- Create a temporary, behind-the-scene object `c3` of type `C`.
- Initialize each attribute `a` of `c3` via ***reference copy***: `c3.a := c2.a`
- Make a ***reference copy*** of `c3`: `c1 := c3`
  ⇒ `c1` and `c2` ***are not*** pointing to the same object. [`c1 /= c2`]
  ⇒ `c1.a` and `c2.a` ***are*** pointing to the same object.
  ⇒ ***Aliasing*** still occurs: at 1st level (i.e., attributes of `c1` and `c2`)



Copying Objects: Deep Copy

Deep Copy `c1 := c2.deep_twin`

- Create a temporary, behind-the-scene object `c3` of type `C`.
- *Recursively* initialize each attribute `a` of `c3` as follows:

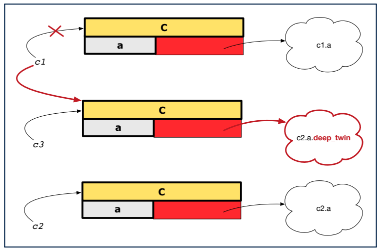
  Base Case: `a` is primitive (e.g., `INTEGER`). ⇒ `c3.a := c2.a`.

  Recursive Case: `a` is referenced. ⇒ `c3.a := c2.a.deep_twin`
- Make a ***reference copy*** of `c3`: `c1 := c3`

  ⇒ `c1` and `c2` ***are not*** pointing to the same object.

  ⇒ `c1.a` and `c2.a` ***are not*** pointing to the same object.

  ⇒ ***No aliasing*** occurs at any levels.



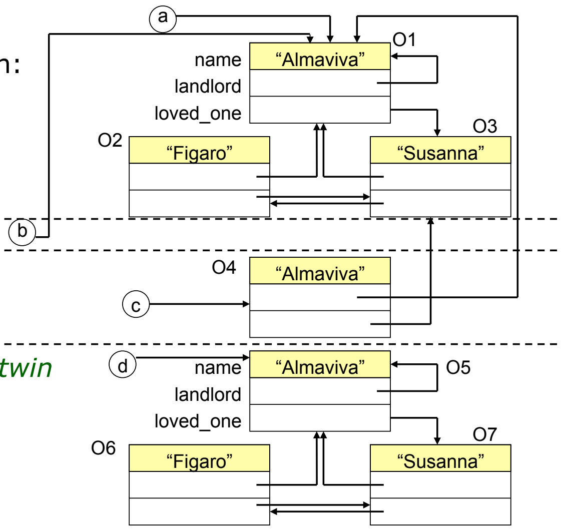
Copying Objects

- Initial situation:
- Result of:

b := *a*

c := *a.twin*

d := *a.deep_twin*



Example: Collection Objects (1)

- In any OOPL, when a variable is declared of a ***type*** that corresponds to a ***known class*** (e.g., `STRING`, `ARRAY`, `LINKED_LIST`, etc.):

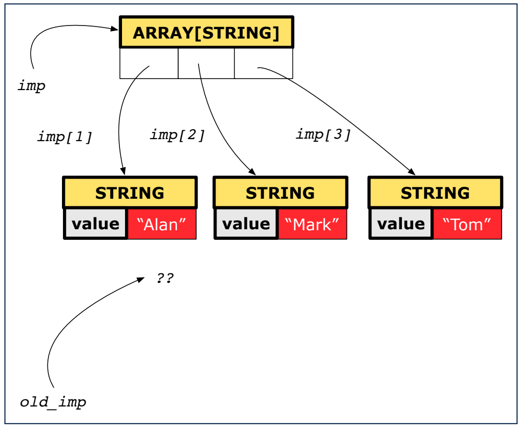
  At *runtime*, that variable stores the *address* of an object of that type (as opposed to storing the object in its entirety).
- Assume the following variables of the same type:

```
local
  imp : ARRAY[STRING]
  old_imp: ARRAY[STRING]
do
  create {ARRAY[STRING]} imp.make_empty
  imp.force("Alan", 1)
  imp.force("Mark", 2)
  imp.force("Tom", 3)
```

- ***Before*** we undergo a change on `imp`, we "*copy*" it to `old_imp`.
- ***After*** the change is completed, we compare `imp` vs. `old_imp`.
- Can a change always be *visible* between "***old***" and "***new***" `imp`?

Example: Collection Objects (2)

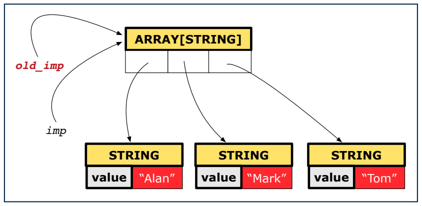
- Variables `imp` and `old_imp` store address(es) of some array(s).
- Each "slot" of these arrays stores a `STRING` object's address.



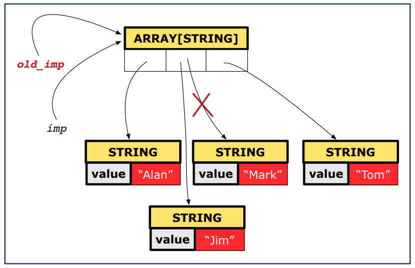
Reference Copy of Collection Object

```
1  old_imp := imp
2  Result := old_imp = imp  -- Result = true
3  imp[2] := "Jim"
4  Result :=
5    across 1 |..| imp.count is j
6    all imp [j] ~ old_imp [j]
7    end -- Result = true
```

Before Executing L3



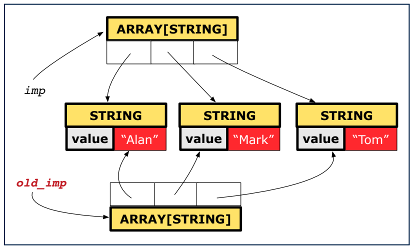
After Executing L3



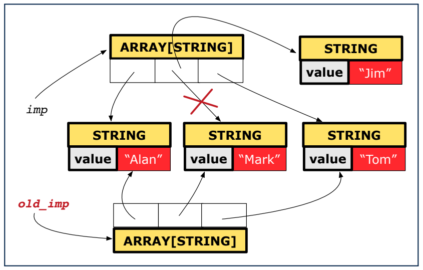
Shallow Copy of Collection Object (1)

```
1  old_imp := imp.twin
2  Result := old_imp = imp  -- Result = false
3  imp[2] := "Jim"
4  Result :=
5    across 1 |..| imp.count is j
6    all imp [j] ~ old_imp [j]
7    end -- Result = false
```

Before Executing L3



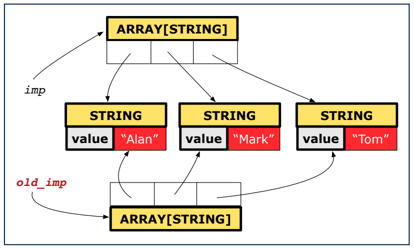
After Executing L3



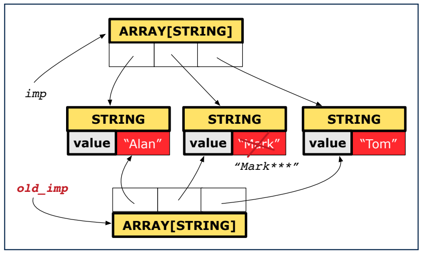
Shallow Copy of Collection Object (2)

```
1  old_imp := imp.twin
2  Result := old_imp = imp  -- Result = false
3  imp[2].append ("***")
4  Result :=
5    across 1 |..| imp.count is j
6    all imp [j] ~ old_imp [j]
7    end -- Result = true
```

Before Executing L3



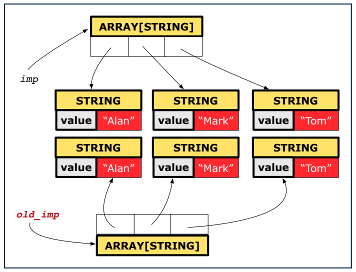
After Executing L3



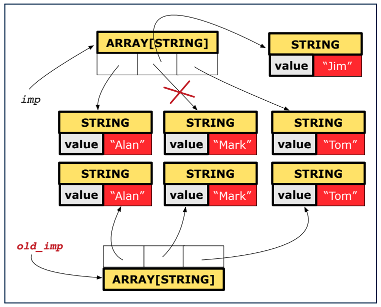
Deep Copy of Collection Object (1)

```
1  old_imp := imp.deep_twin
2  Result := old_imp = imp  -- Result = false
3  imp[2] := "Jim"
4  Result :=
5    across 1 |..| imp.count is j
6    all imp [j] ~ old_imp [j] end -- Result = false
```

Before Executing L3



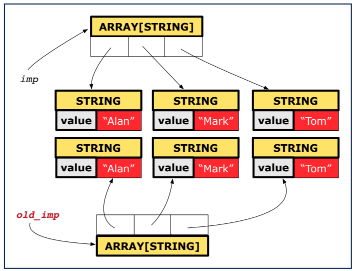
After Executing L3



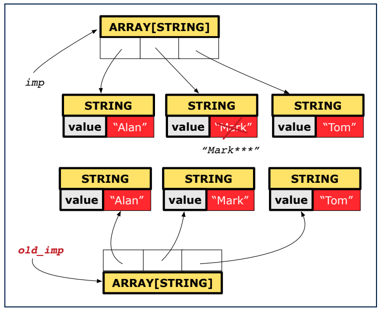
Deep Copy of Collection Object (2)

```
1  old_imp := imp.deep_twin
2  Result := old_imp = imp  -- Result = false
3  imp[2].append ("***")
4  Result :=
5    across 1 |..| imp.count is j
6    all imp [j] ~ old_imp [j] end -- Result = false
```

Before Executing L3



After Executing L3



How are contracts checked at runtime?

- All contracts are specified as Boolean expressions.
- Right **before** a feature call (e.g., `acc.withdraw(10)`):
  - The current state of `acc` is called its ***pre-state***.
  - Evaluate *pre-condition* using ***current values*** of attributes/queries.
  - Cache values, via `:=`, of ***old** expressions* in the *post-condition*.

e.g., **old** *accounts[i].id* [*old_accounts_i_id* := *accounts[i].id*]

e.g., (**old** *accounts[i]*).*id* [*old_accounts_i* := *accounts[i]*]

e.g., (**old** *accounts[i].**twin***).*id* [*old_accounts_i_twin* := *accounts[i].**twin***]

e.g., (**old** *accounts*)[*i*].*id* [*old_accounts* := *accounts*]

e.g., (**old** *accounts.**twin***)[*i*].*id* [*old_accounts_twin* := *accounts.**twin***]

e.g., (**old** ***Current***).*accounts*[*i*].*id* [*old_current* := ***Current***]

e.g., (**old** ***Current.twin***).*accounts*[*i*].*id* [*old_current_twin* := ***Current.twin***]

- Right **after** the feature call:
  - The current state of `acc` is called its ***post-state***.
  - Evaluate *invariant* using ***current values*** of attributes and queries.
  - Evaluate *post-condition* using both ***current values*** and ***"cached" values*** of attributes and queries.

When are contracts complete?

- In *post-condition*, for *each attribute*, specify the relationship between its ***pre-state*** value and its ***post-state*** value.
  - Eiffel supports this purpose using the **old** keyword.
- This is tricky for attributes whose structures are **composite** rather than **simple**:

  e.g., *ARRAY*, *LINKED_LIST* are composite-structured.
  e.g., *INTEGER*, *BOOLEAN* are simple-structured.
- **Rule of thumb:** For an attribute whose structure is composite, we should specify that after the update:
  1. The intended change is present; **and**
  2. *The rest of the structure is unchanged* .
- The second contract is much harder to specify:
  - Reference aliasing [ref copy vs. shallow copy vs. deep copy]
  - Iterable structure [use `across`]

Account

```
class
  ACCOUNT

inherit
  ANY
    redefine is_equal end

create
  make

feature -- Attributes
  owner: STRING
  balance: INTEGER

feature -- Commands
  make (n: STRING)
    do
      owner := n
      balance := 0
    end
```

```
  deposit(a: INTEGER)
    do
      balance := balance + a
    ensure
      balance = old balance + a
    end

  is_equal(other: ACCOUNT): BOOLEAN
    do
      Result :=
            owner ~ other.owner
        and balance = other.balance
    end
end
```

Bank

```
class BANK
create make
feature
  accounts: ARRAY[ACCOUNT]
  make do create accounts.make_empty end
  account_of (n: STRING): ACCOUNT
    require -- the input name exists
      existing: across accounts is acc some acc.owner ~ n end
        -- not (across accounts is acc all acc.owner /~ n end)
    do ... ensure Result.owner ~ n end
  add (n: STRING)
    require -- the input name does not exist
      non_existing: across accounts is acc all acc.owner /~ n end
        -- not (across accounts is acc some acc.owner ~ n end)
    local new_account: ACCOUNT
    do
      create new_account.make (n)
      accounts.force (new_account, accounts.upper + 1)
    end
end
```

Roadmap of Illustrations

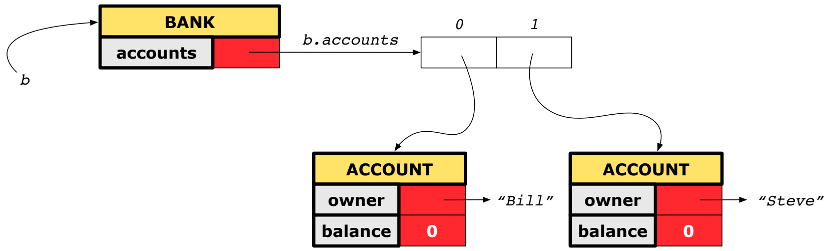
We examine 5 different versions of a command

$$deposit\_on\ (n : STRING; a : INTEGER)$$

VERSION	IMPLEMENTATION	CONTRACTS	SATISFACTORY?
1	Correct	Incomplete	No
2	Wrong	Incomplete	No
3	Wrong	Complete (reference copy)	No
4	Wrong	Complete (shallow copy)	No
5	Wrong	Complete (deep copy)	Yes

Object Structure for Illustration

We will test each version by starting with the same runtime object structure:



Version 1: Incomplete Contracts, Correct Implementation

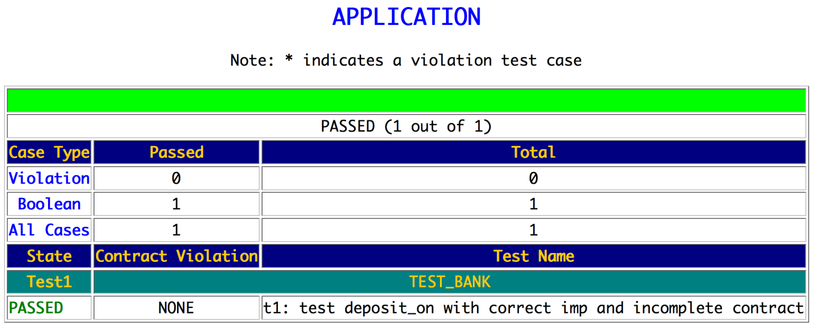
```
class BANK
  deposit_on_v1 (n: STRING; a: INTEGER)
    require across accounts is acc some acc.owner ~ n end
    local i: INTEGER
    do
      from i := accounts.lower
      until i > accounts.upper
      loop
        if accounts[i].owner ~ n then accounts[i].deposit(a) end
        i := i + 1
      end
    ensure
      num_of_accounts_unchanged:
        accounts.count = old accounts.count
      balance_of_n_increased:
        Current.account_of(n).balance =
          old Current.account_of(n).balance + a
    end
end
```

Test of Version 1

```
class TEST_BANK
  test_bank_deposit_correct_imp_incomplete_contract: BOOLEAN
    local
      b: BANK
    do
      comment("t1: correct imp and incomplete contract")
      create b.make
      b.add ("Bill")
      b.add ("Steve")

      -- deposit 100 dollars to Steve's account
      b.deposit_on_v1 ("Steve", 100)
      Result :=
           b.account_of("Bill").balance = 0
        and b.account_of("Steve").balance = 100
      check Result end
  end
end
```

Test of Version 1: Result



APPLICATION

Note: * indicates a violation test case

PASSED (1 out of 1)		
Case Type	Passed	Total
Violation	0	0
Boolean	1	1
All Cases	1	1
State	Contract Violation	Test Name
Test1	TEST_BANK	
PASSED	NONE	t1: test deposit_on with correct imp and incomplete contract

Version 2: Incomplete Contracts, Wrong Implementation

```
class BANK
  deposit_on_v2 (n: STRING; a: INTEGER)
    require across accounts is acc some acc.owner ~ n end
    local i: INTEGER
    do ...
      -- imp. of version 1, followed by a deposit into 1st account
      accounts[accounts.lower].deposit(a)
    ensure
      num_of_accounts_unchanged:
        accounts.count = old accounts.count
      balance_of_n_increased:
        Current.account_of(n).balance =
          old Current.account_of(n).balance + a
    end
end
```

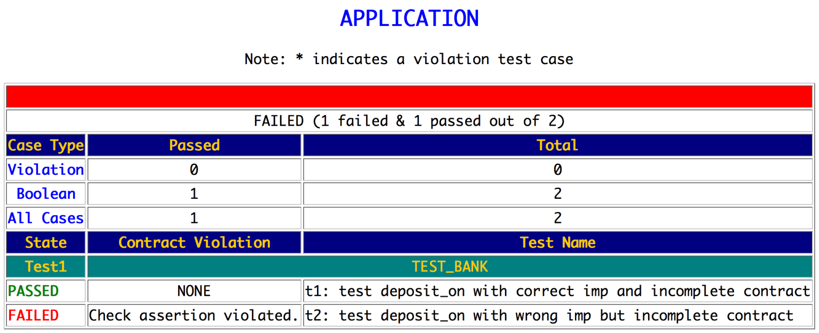
Current postconditions lack a check that accounts other than `n` are unchanged.

Test of Version 2

```
class TEST_BANK
test_bank_deposit_wrong_imp_incomplete_contract: BOOLEAN
  local
    b: BANK
  do
    comment("t2: wrong imp and incomplete contract")
    create b.make
    b.add ("Bill")
    b.add ("Steve")

    -- deposit 100 dollars to Steve's account
    b.deposit_on_v2 ("Steve", 100)
    Result :=
         b.account_of("Bill").balance = 0
      and b.account_of("Steve").balance = 100
    check Result end
  end
end
```

Test of Version 2: Result



APPLICATION

Note: * indicates a violation test case

FAILED (1 failed & 1 passed out of 2)		
Case Type	Passed	Total
Violation	0	0
Boolean	1	2
All Cases	1	2
State	Contract Violation	Test Name
Test1	TEST_BANK	
PASSED	NONE	t1: test deposit_on with correct imp and incomplete contract
FAILED	Check assertion violated.	t2: test deposit_on with wrong imp but incomplete contract

Version 3: Complete Contracts with Reference Copy

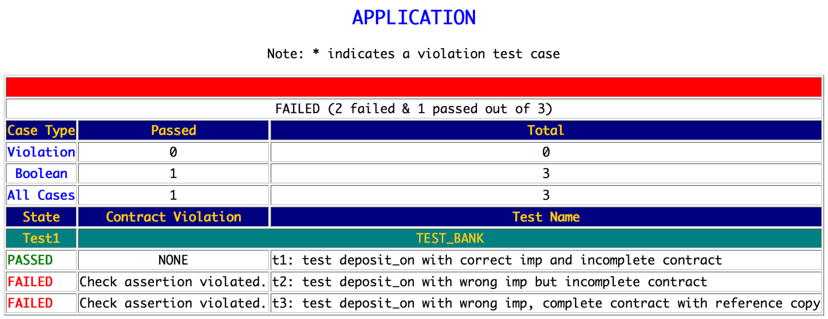
```
class BANK
  deposit_on_v3 (n: STRING; a: INTEGER)
    require across accounts is acc some acc.owner ~ n end
    local i: INTEGER
    do ...
      -- imp. of version 1, followed by a deposit into 1st account
      accounts[accounts.lower].deposit(a)
    ensure
      num_of_accounts_unchanged: accounts.count = old accounts.count
      balance_of_n_increased:
        Current.account_of(n).balance =
          old Current.account_of(n).balance + a
      others_unchanged :
        across old accounts is acc
        all
          acc.owner /~ n implies acc ~ Current.account_of(acc.owner)
        end
    end
end
```

Test of Version 3

```
class TEST_BANK
  test_bank_deposit_wrong_imp_complete_contract_ref_copy: BOOLEAN
    local
      b: BANK
    do
      comment("t3: wrong imp and complete contract with ref copy")
      create b.make
      b.add ("Bill")
      b.add ("Steve")

      -- deposit 100 dollars to Steve's account
      b.deposit_on_v3 ("Steve", 100)
      Result :=
           b.account_of("Bill").balance = 0
        and b.account_of("Steve").balance = 100
      check Result end
    end
end
```

Test of Version 3: Result



APPLICATION

Note: * indicates a violation test case

FAILED (2 failed & 1 passed out of 3)		
Case Type	Passed	Total
Violation	0	0
Boolean	1	3
All Cases	1	3
State	Contract Violation	Test Name
Test1	TEST_BANK	
PASSED	NONE	t1: test deposit_on with correct imp and incomplete contract
FAILED	Check assertion violated.	t2: test deposit_on with wrong imp but incomplete contract
FAILED	Check assertion violated.	t3: test deposit_on with wrong imp, complete contract with reference copy

Version 4:
Complete Contracts with Shallow Object Copy

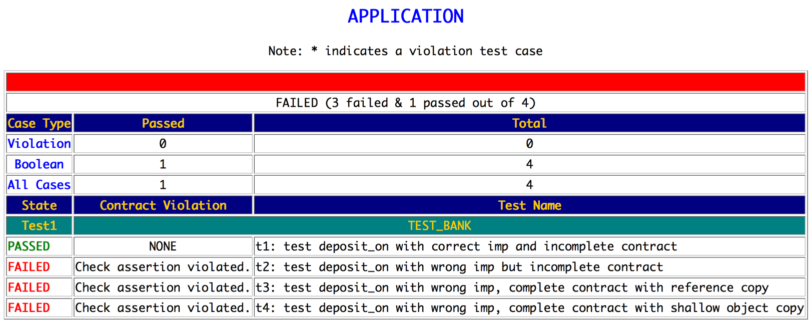
```
class BANK
  deposit_on_v4 (n: STRING; a: INTEGER)
    require across accounts is acc some acc.owner ~ n end
    local i: INTEGER
    do ...
      -- imp. of version 1, followed by a deposit into 1st account
      accounts[accounts.lower].deposit(a)
    ensure
      num_of_accounts_unchanged: accounts.count = old accounts.count
      balance_of_n_increased:
        Current.account_of(n).balance =
          old Current.account_of(n).balance + a
      others_unchanged :
        across old accounts.twin is acc
        all
          acc.owner /~ n implies acc ~ Current.account_of(acc.owner)
        end
    end
end
```

Test of Version 4

```
class TEST_BANK
  test_bank_deposit_wrong_imp_complete_contract_shallow_copy: BOOLEAN
    local
      b: BANK
    do
      comment("t4: wrong imp and complete contract with shallow copy")
      create b.make
      b.add ("Bill")
      b.add ("Steve")

      -- deposit 100 dollars to Steve's account
      b.deposit_on_v4 ("Steve", 100)
      Result :=
           b.account_of("Bill").balance = 0
        and b.account_of("Steve").balance = 100
      check Result end
    end
end
```

Test of Version 4: Result



APPLICATION

Note: * indicates a violation test case

FAILED (3 failed & 1 passed out of 4)		
Case Type	Passed	Total
Violation	0	0
Boolean	1	4
All Cases	1	4
State	Contract Violation	Test Name
Test1	TEST_BANK	
PASSED	NONE	t1: test deposit_on with correct imp and incomplete contract
FAILED	Check assertion violated.	t2: test deposit_on with wrong imp but incomplete contract
FAILED	Check assertion violated.	t3: test deposit_on with wrong imp, complete contract with reference copy
FAILED	Check assertion violated.	t4: test deposit_on with wrong imp, complete contract with shallow object copy

Version 5:
Complete Contracts with Deep Object Copy

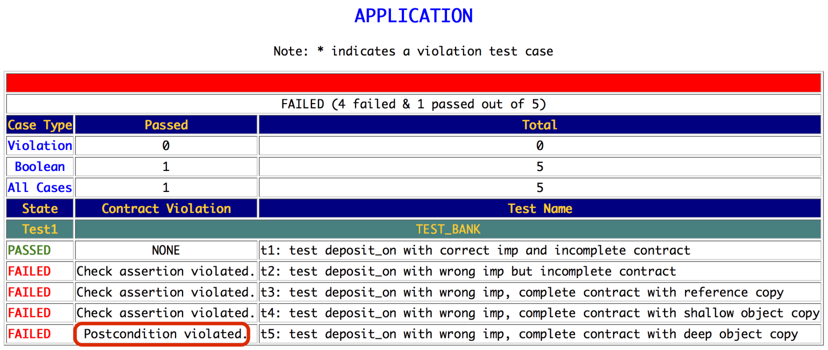
```
class BANK
  deposit_on_v5 (n: STRING; a: INTEGER)
    require across accounts is acc some acc.owner ~ n end
      local i: INTEGER
    do ...
      -- imp. of version 1, followed by a deposit into 1st account
      accounts[accounts.lower].deposit(a)
    ensure
      num_of_accounts_unchanged: accounts.count = old accounts.count
      balance_of_n_increased:
        Current.account_of(n).balance =
          old Current.account_of(n).balance + a
      others_unchanged :
        across old accounts.deep_twin is acc
        all
          acc.owner /~ n implies acc ~ Current.account_of(acc.owner)
        end
    end
end
```

Test of Version 5

```
class TEST_BANK
  test_bank_deposit_wrong_imp_complete_contract_deep_copy: BOOLEAN
   local
     b: BANK
   do
     comment("t5: wrong imp and complete contract with deep copy")
     create b.make
     b.add ("Bill")
     b.add ("Steve")

     -- deposit 100 dollars to Steve's account
     b.deposit_on_v5 ("Steve", 100)
     Result :=
          b.account_of("Bill").balance = 0
       and b.account_of("Steve").balance = 100
     check Result end
   end
end
```

Test of Version 5: Result



APPLICATION

Note: * indicates a violation test case

FAILED (4 failed & 1 passed out of 5)		
Case Type	Passed	Total
Violation	0	0
Boolean	1	5
All Cases	1	5
State	Contract Violation	Test Name
Test1	TEST_BANK	
PASSED	NONE	t1: test deposit_on with correct imp and incomplete contract
FAILED	Check assertion violated.	t2: test deposit_on with wrong imp but incomplete contract
FAILED	Check assertion violated.	t3: test deposit_on with wrong imp, complete contract with reference copy
FAILED	Check assertion violated.	t4: test deposit_on with wrong imp, complete contract with shallow object copy
FAILED	Postcondition violated.	t5: test deposit_on with wrong imp, complete contract with deep object copy

Exercise

- Consider the query *account_of (n: STRING)* of *BANK*.
- How do we specify (part of) its postcondition to assert that the state of the bank remains unchanged:
  - `accounts = old accounts` [×]
  - `accounts = old accounts.twin` [×]
  - `accounts = old accounts.deep_twin` [×]
  - `accounts ~ old accounts` [×]
  - `accounts ~ old accounts.twin` [×]
  - `accounts ~ old accounts.deep_twin` [✓]
- Which equality of the above is appropriate for the postcondition?
- Why is each one of the other equalities not appropriate?

Index (1)

Index (2)

Index (3)

Index (4)