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

EECS3311 A: Software Design
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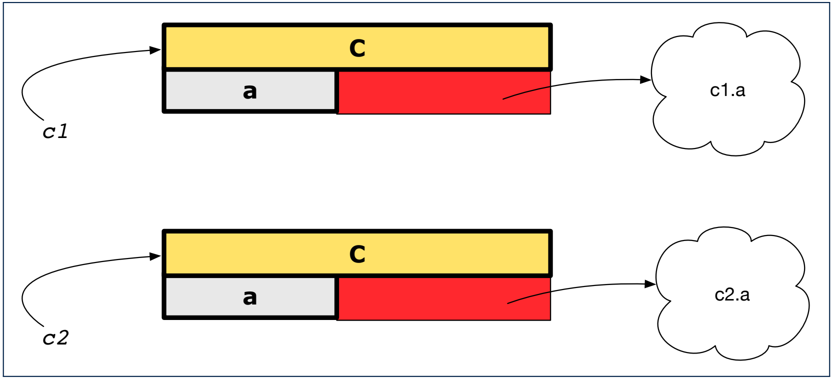
## Copying Objects

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.

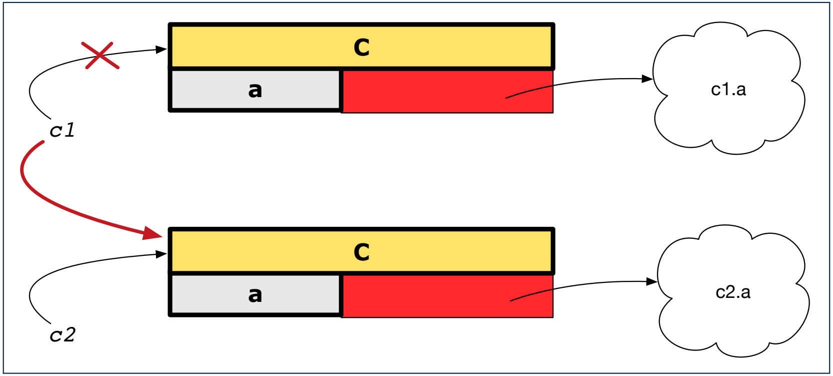


# Copying Objects: Reference Copy

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**

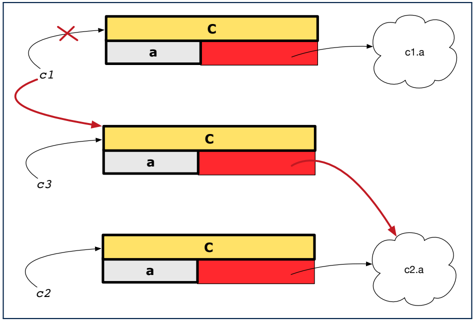
`c1 := c2.twin`

- 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:

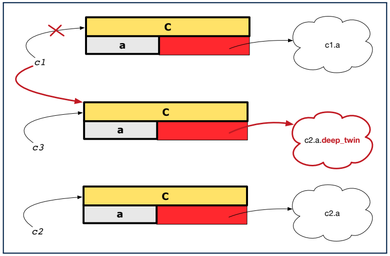
  **Base Case**: `a` is primitive (e.g., `INTEGER`). ⇒ `c3.a := c2.a`.

  **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

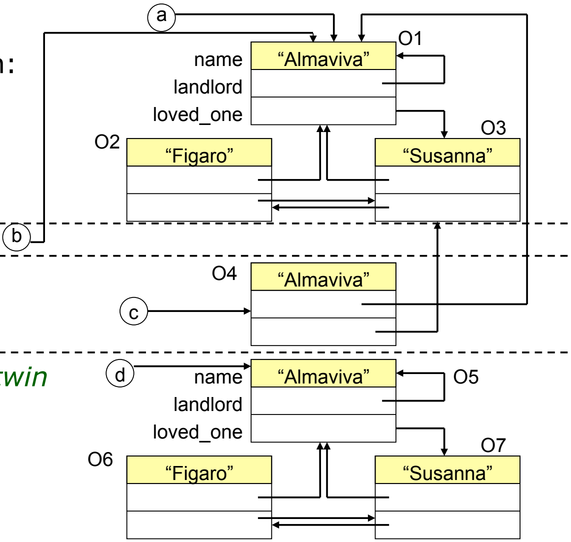
- Initial situation:

- 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).

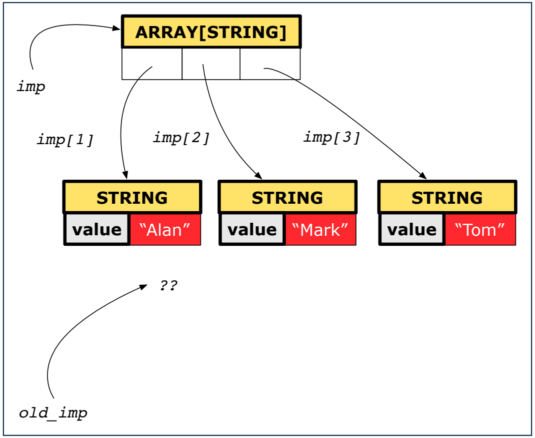
- Assume the following variables of the same type:

```
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)

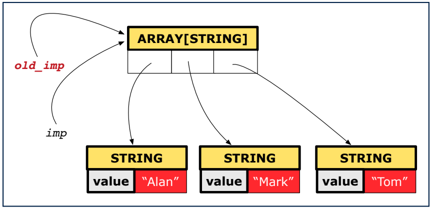
- Variables `imp` and `old_imp` store address(es) of some array(s).
- Each "slot" of these arrays stores a `STRING` object's address.



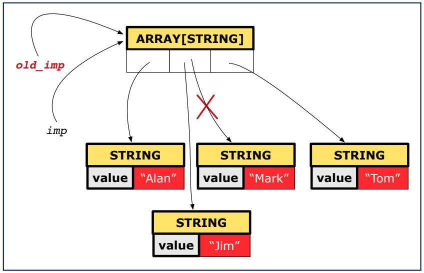
## Reference Copy of Collection Object

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

Before Executing L3



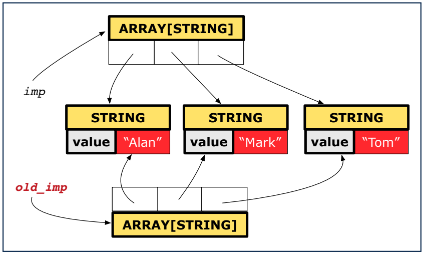
After Executing L3



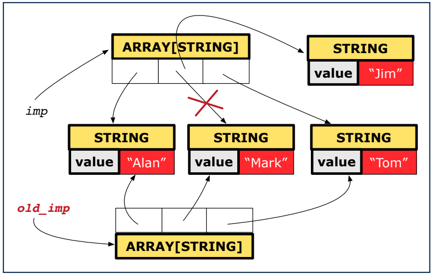
## Shallow Copy of Collection Object (1)

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

Before Executing L3



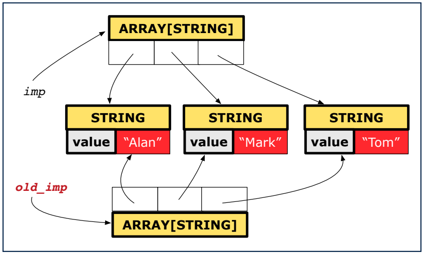
After Executing L3



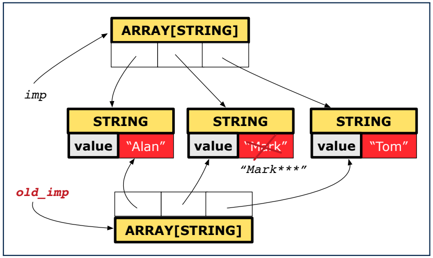
# Shallow Copy of Collection Object (2)

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

Before Executing L3



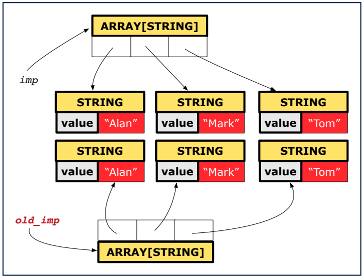
After Executing L3



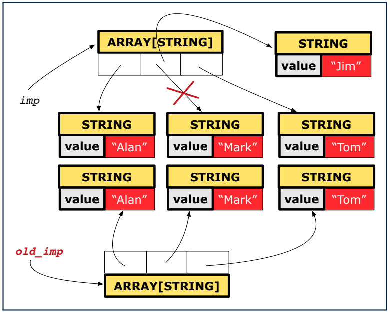
## Deep Copy of Collection Object (1)

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

Before Executing L3



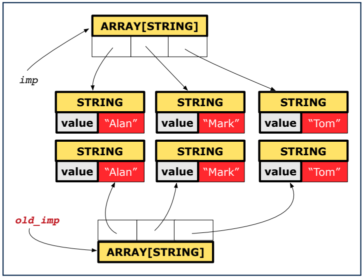
After Executing L3



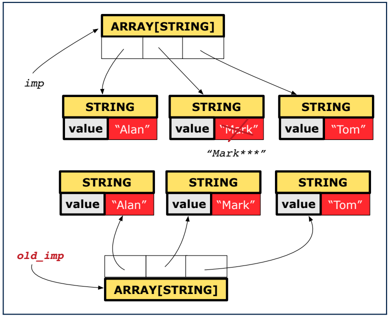
## Deep Copy of Collection Object (2)

```
old_imp := imp.deep_twin
Result := old_imp = imp  -- Result = false
imp[2].append ("***")
Result :=
  across 1 |..| imp.count is j
  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 $\boxed{:=}$, 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

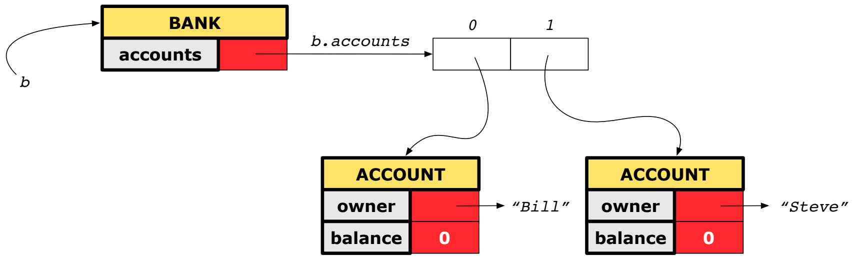
We examine 5 different versions of a command

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

| 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

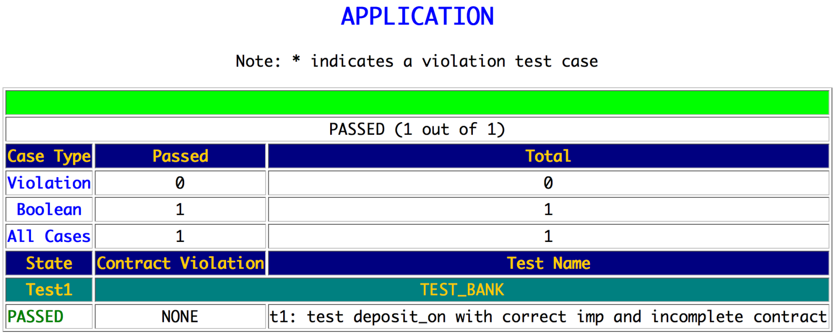
```
class BANK
  deposit_on_v1 (n: STRING; a: INTEGER)
    require across accounts is acc some acc.owner ~ n end
    local i: INTEGER
    do
      from i := accounts.lower
      until i > accounts.upper
      loop
        if accounts[i].owner ~ n then accounts[i].deposit(a) end
        i := i + 1
  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

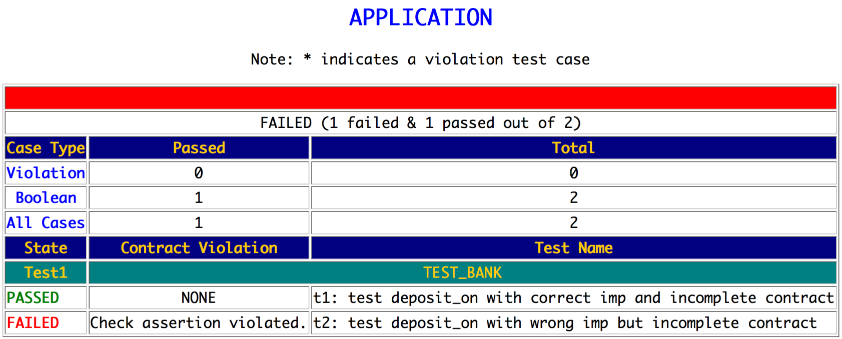
Current postconditions lack a check that accounts other than `n` are unchanged.

## 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

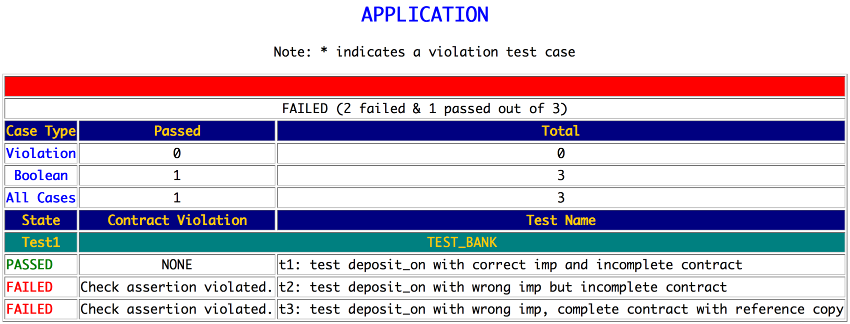
```
class BANK
 deposit_on_v3 (n: STRING; a: INTEGER)
   require across accounts is acc some acc.owner ~ n end
   local i: INTEGER
   do ...
     -- imp. of version 1, followed by a deposit into 1st account
     accounts[accounts.lower].deposit(a)
   ensure
     num_of_accounts_unchanged: accounts.count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

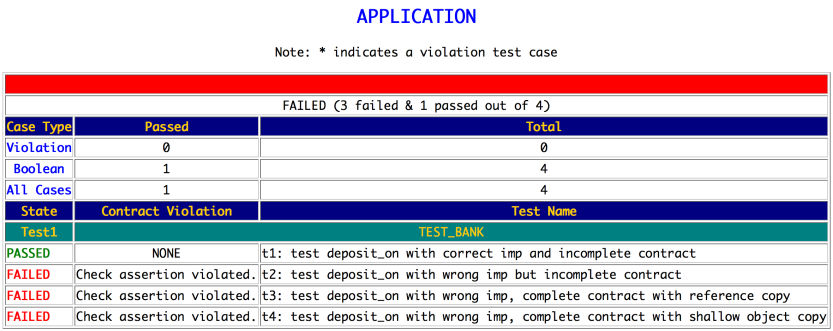
```
class BANK
  deposit_on_v4 (n: STRING; a: INTEGER)
    require across accounts is acc some acc.owner ~ n end
    local i: INTEGER
    do ...
      -- imp. of version 1, followed by a deposit into 1st account
      accounts[accounts.lower].deposit(a)
    ensure
      num_of_accounts_unchanged: accounts.count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

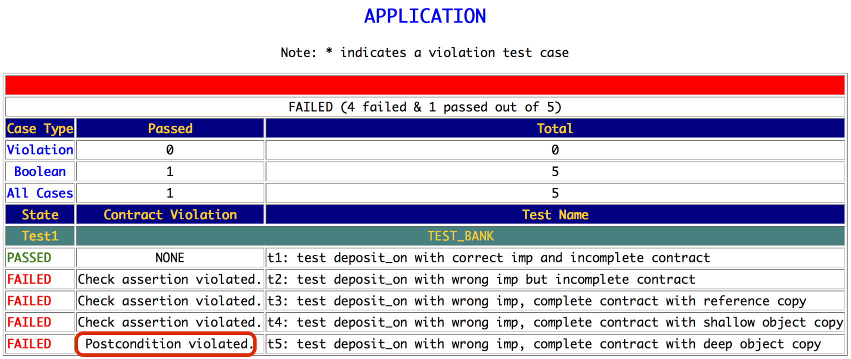
```
class BANK
 deposit_on_v5 (n: STRING; a: INTEGER)
   require across accounts is acc some acc.owner ~ n end
     local i: INTEGER
   do ...
     -- imp. of version 1, followed by a deposit into 1st account
     accounts[accounts.lower].deposit(a)
   ensure
     num_of_accounts_unchanged: accounts.count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

Copying Objects
Copying Objects: Reference Copy
Copying Objects: Shallow Copy
Copying Objects: Deep Copy
Example: Copying Objects
Example: Collection Objects (1)
Example: Collection Objects (2)
Reference Copy of Collection Object
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How are contracts checked at runtime?
When are contracts complete?

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Account

Bank

Roadmap of Illustrations

Object Structure for Illustration

Version 1:
Incomplete Contracts, Correct Implementation

Test of Version 1

Test of Version 1: Result

Version 2:
Incomplete Contracts, Wrong Implementation

Test of Version 2

Test of Version 2: Result

Version 3:
Complete Contracts with Reference Copy

Test of Version 3

## Index (3)

Test of Version 3: Result

Version 4:
Complete Contracts with Shallow Object Copy

Test of Version 4

Test of Version 4: Result

Version 5:
Complete Contracts with Deep Object Copy

Test of Version 5

Test of Version 5: Result

Exercise